2007 International Sherwood Fusion Theory Conference April 23-25, 2007 Annapolis, Maryland

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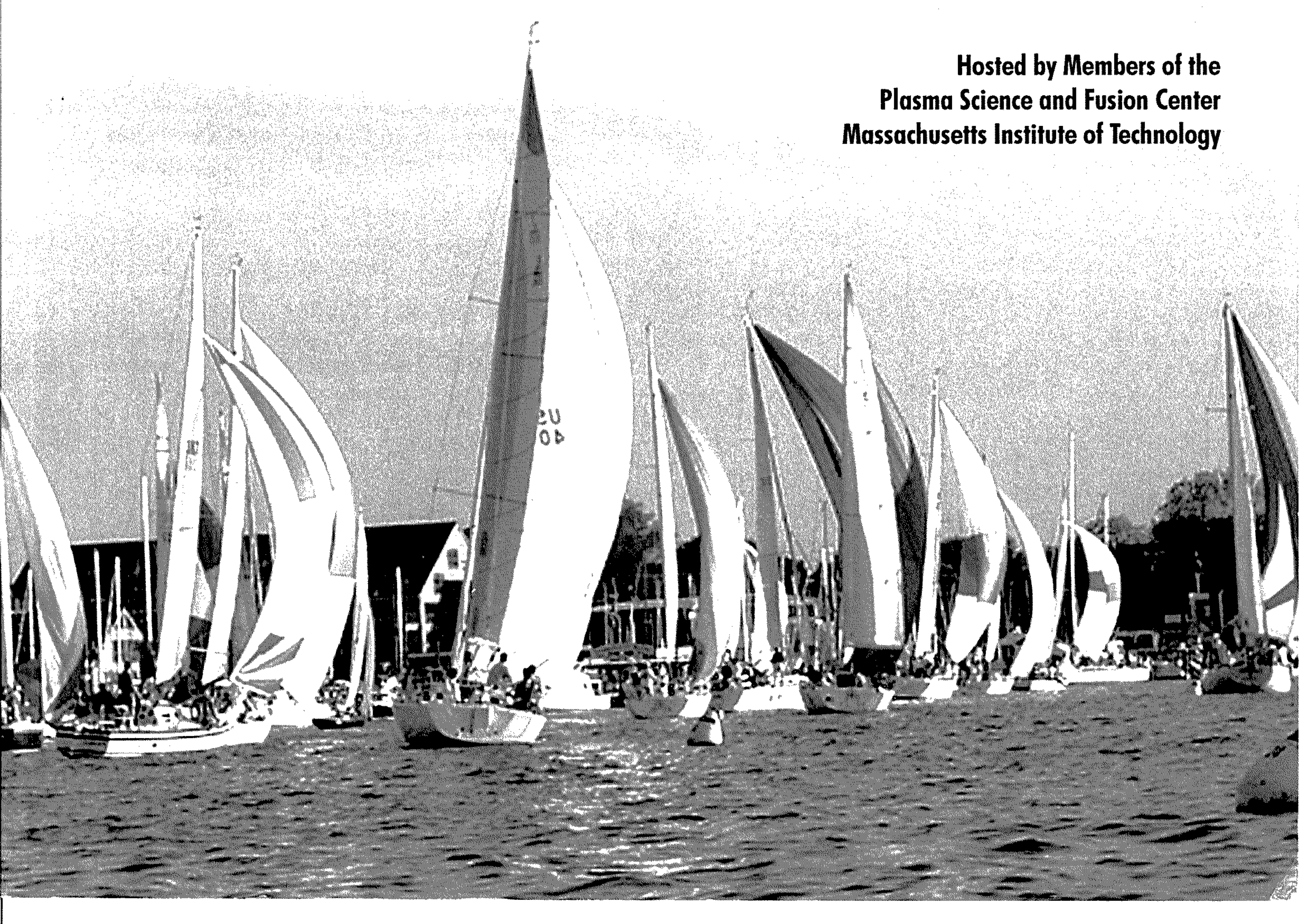
April 23-25
Annapolis, Maryland

Hosted by Members of the
Plasma Science and Fusion Center
Massachusetts Institute of Technology



International Sherwood Fusion Theory Conference

April 23-25, 2007
Loews Hotel Annapolis
Annapolis, Maryland

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Plasma Science and Fusion Center
Massachusetts Institute of Technology

Executive Committee

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Registration Schedule

Sunday, April 22	17:00 to 19:00
Monday, April 23	07:30 to 11:30 and 13:00 to 17:00
Tuesday, April 24	07:30 to 12:00
Wednesday, April 25	07:30 to 10:00

Social Schedule

Sunday, April 22	19:00 to 21:00	Welcome Reception
Monday, April 23	08:30 to 10:00	Companions Breakfast
Tuesday, April 24	12:00 to 17:30	Free Afternoon
Tuesday, April 24	18:00 to 19:30	Conference Banquet

Program Organization

The program consists of 3 invited review papers, 14 oral contributed papers selected out of 31 oral submissions, and poster presentations. The total number of presentations is 161. Satellite meetings are also scheduled during the conference.

Meeting Program

All technical sessions will be held in the Loews Annapolis Hotel, Ballroom B&C

- The **review talks** will be held at 8:30 Monday through Wednesday (1A, 2A, 3A)
- The **oral sessions** will be held
  - 1B at 09:30 Monday morning
  - 1D at 13:30 Monday afternoon
  - 2B at 09:30 Tuesday morning
  - 2D at 19:30 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 Meeting

Saturday, April 21, 08:30 to 18:00 and Sunday April 22, 08:30 to 13:00
Catamaran Room, Loews Annapolis Hotel

CEMM Meeting

Sunday, April 22, 13:00 to 18:00
Catamaran Room, Loews Annapolis Hotel

Sherwood Executive Committee Meeting

Tuesday, April 24, 12:45 to 15:45
Thomas Point Room, Loews Annapolis Hotel

Review Talks
(Ballroom B&C)

1A01 T.M. Antonsen, Jr.
"Ultra-Intense Laser Pulse Interaction with Gases, Cluster Gases and Structured Plasmas"

2A01 Y. Kevrekidis
"Equation-Free Modeling and Computation for Complex/Multiscale Systems"

3A01 D. Lathrop
"Laboratory and Planetary Flows of Relevance to Plasma Physics with a Focus on Liquid Metals"

Oral Talks
(Ballroom B&C)

1B01 J.W. Van Dam, L.-J. Zheng, and M. Kotschenreuther
"Direct drive by cyclotron heating can explain spontaneous rotation in tokamaks"

1D01 A. Hassam
"Velocity shear stabilization of ideal interchange instabilities in centrifugally confined plasmas"

1D02 A.I.D. Macnab, R.D. Milroy, C.C. Kim, and C.R. Sovinec
"Extended MHD Simulations of Rotation and Translation in Field-Reversed Configurations"

1D03 B. Hu and R. Betti
"Suppression of resistive wall mode at low plasma rotation"

1D04 F. Militello, F.L. Waelbroeck, R. Fitzpatrick, and W. Horton
"Interaction Between Magnetic Islands and Electrostatic Turbulence"

2B01 A.M. Dimits
"Energy Conservation in Linear and Perturbative δf-PIC Simulations"

2D01 F. Jenko, T. Görler, and T. Dannert
"Scale separation of ion and electron heat transport"

2D02 M. Barnes and W. Dorland
"Velocity space resolution in continuum gyrokinetic simulations"

2D03 D.R. Ernst, N. Basse, W. Dorland, C.L. Fiore, E.S. Marmar, L. Lin, A. Long, V. Navkal, M. Porkolab, K. Zeller, and K. Zhurovich
"Observation of TEM Turbulence and New Effects of Collisions"

2D04 G. Plunk
"Gyrokinetic Secondary Instability Theory For Electron and Ion Temperature Gradient Driven Turbulence"

3B01 M. Choi, V.S. Chan, M.S. Chu, L.L. Lao, and A.D. Turnbull
"Interaction of Fast Wave Accelerated Beam Ions with Ideal Kink Instability in the DIII-D Tokamak"

3B02 A. Yu. Pigarov, R.D. Smirnov, S.I. Krasheninnikov, D. Benson, M. Rosenberg, Y. Tanaka, C.H. Skinner, and A.L. Roquemore
"Dust Transport in Tokamaks"

3B03 Z. Xiong, X.Q. Xu, W.M. Nevins, and R.H. Cohen (presented by X.Q. Xu)
"TEMPEST Simulations of the Radial Electric Field Dynamics in the Neoclassical Plasmas"

3B04 R. Fitzpatrick
"Interaction of scrape-off layer currents with magnetohydrodynamical instabilities in tokamak plasmas"

Poster Sessions

Poster Session 1C
Monday, April 23, 10:00 to 12:00, Atrium

1C01 G.W. Hammett, E.A. Belli, N.F. Loureiro, and W. Dorland
"Effects of Shaping on the Dimits Nonlinear Shift, Implementation of Equilibrium Sheared Flows in GS2, and Improved Restarting for GMRES Algorithms"

1C02 E. Asp, W. Horton, L. Porte, S. Alberti, E. Fable, Y. Martin, O. Sauter, G. Turri, and the TCV Team
"Transport Analysis of Multi-Phase H-Mode Shot at TCV

1C03 J.R. Myra
"Current carrying blob-filaments and application to ELM dynamics"

1C04 E.D. Held, J.-Y. Ji, J.W. James, M. Addae-Kagyah and M. Sharma
"Rethinking Parallel Closures for NTM and ELM Simulations"

1C05 W. Horton, J.H. Kim, G.D. Chagelishvili, and J. Bowman
"Anistropic and Transient Dynamics in the Drift Wave Turbulence"

1C06 J.N. Leboeuf, V.K. Decyk, A. Dimits, and D. Shumaker
"Real geometry gyrokinetic PIC computations of ion turbulence in tokamak discharges with SUMMIT/PG3EQ_NC"

1C07 I. Holod
"Discrete particle noise in gyrokinetic particle-in-cell simulations of plasma turbulence"

1C08 W. Zhang and Z. Lin
"Lower-hybrid-drift instabilities in current-sheet equilibrium"

1C09 P.T. Bonoli, M. Porkolab, J.C. Wright, R.W. Harvey, C.E. Kessel, Y. Peysson and J. Decker
"Comparison of Lower Hybrid Current Drive Predictions from Different Simulation Models in Reactor Relevant Regimes"

1C10 J.R. Cary and N. Xiang
"Nonlinear wave coupling in inhomogeneous media"

1C11 V.I. Shevchenko and V.L. Galinsky
"Second order Fermi acceleration of electrons in LHCD"

1C12 N. Xiang and J.R. Cary
"Nonlinear self-interactions of electron Bernstein waves in an inhomogeneous plasma"

1C13 M. Tushentsov, B. Breizman, and A. Arefiev
"Modeling of Plasma detachment in a magnetic nozzle"

1C14 R.A. Bayliss, C.R. Sovinec, N.W. Eidietis, B.A. Nelson, and T.R. Jarboe
"Nonlinear MHD simulation of DC helicity injection in spherical tokamaks"

1C15 H. Ohtani, R. Horiuchi, and W. Horton
"Three dimensional particle simulations of driven magnetic reconnection"

1C16 A. Pletzer, S.E. Kruger, A. Hakim, S. Vadlamani, M. Miah, J.R. Cary, R. Cohen, T. Rognlien, T. Epperly, D. McCune, S. Krasheninnikov, A. Pigarov, J. Larson, L.C. McInnes, and D. Estep
"The FACETS Project"

1C17 C. Holland, G.R. Tynan, G.R. McKee, M.W. Shafer, R.J. Fonck, J. Candy, R.E. Waltz, and R.V. Bravenec
"Comparison of Gyrokinetic Simulation Against Core Turbulence Fluctuation Measurements via Synthetic Diagnostics"

1C18 N. Joiner and A. Hirose
"Gyrokinetic simulation of skindepth sized ballooning modes"

1C19 S. Shasharina, C. Li, N. Wang, and R. Pundaleeka
"Distributed technologies and XML for HDF5 data"

1C20 R.E. Waltz, G.M.Staebler, and J. Candy
"Gyrokinetic Simulation of Toroidal Angular Momentum Transport"

1C21 X.Q. Xu and Z. Xiong
"TEMPEST Simulations of the neoclassic radial electric field and bootstrap current"

1C22 B.N. Rogers, S. Kobayashi, P. Ricci, and W. Dorland
"Gyrokinetic simulations of particle transport, plasma turbulence and zonal flows in a closed field line geometry"

1C23 A.Y. Aydemir
"Edge and scrape-off layer flows and their role in L-H transition and core rotation"

1C24 S.I. Krasheninnikov, T.T. Soboleva, A.Y. Pigarov, and I.V. Dobrovolskaia
"Thermal instability caused by plasma-wall interactions"

1C25 L.-J. Zheng, J.W. Van Dam, M.T. Kotschenreuther, H. Takahashi, and E.D. Fredrickson
"ELMs explained as resistive vacuum modes excited by SOL current onset"

1C26 Y. Xiao and Z. Lin
"Gyrokinetic Study of Trapped Electron Mode in the Edge Plasma"

1C27 F. Bombarda, A. Airoldi, B. Coppi, G. Cenacchi, P. Detragiache, and D. Farina
"Relevant Advances of the Ignitor Program"

1C28 C. Di Sanzo, B. Coppi, and M. Landreman
"Confinement Regime Transition Connected to Spontaneous Rotation Reversal and Collision Rates at the Plasma Edge"

1C29 V.V. Mirnov, W.X. Ding, and D.L. Brower
"Finite Electron Temperature Effects on Interferometric Measurements in Fusion Plasmas"

1C30 M.K. Addae-Kagyah and E.D. Held
"An Upgrade of the Unified Fluid/Kinetic Models of Magnetized Plasmas"

1C31 N.N. Gorelenkov, H.L. Berk, E. Fredrickson, and S.E. Sharapov
"Global beta-induced Alfvén-acoustic modes in JET and NSTX"

1C32 E. Hameiri
"Shocks and Discontinuities in the Hall-MHD Model"

1C33 C.C. Hegna and J.D. Callen
"A closure scheme for modeling RF modifications to the fluid equations"

1C34 N. Chakrabarti, R. Singh, P.K. Kaw, and P.N. Guzdar
"Nonlinear excitation of geodesic acoustic modes by drift wave like modes"

1C35 S.C. Jardin, N. Ferraro, J. Breslau, A. Bauer, K. Jansen, M. Shephard, and the M3D team
"Two-fluid Extended-MHD Calculations of Collisionless Reconnection in Magnetized Plasmas with a Strong Guide Field"

1C36 V.S.Lukin and S.C. Jardin
" 'Sawteeth' and non-axisymmetric equilibria of the internal kink mode in a periodic boundary driven screw-pinch"

1C37 N.M. Ferraro, S.C. Jardin, and J.A. Breslau
"Calculations of extended magnetohydrodynamic equilibria with an implicit, high-order finite element code"

1C38 I. Shamim, C. Teodorescu, P.N. Guzdar, A.B. Hassam, R. Clary, R. Ellis, and R. Lunsford
"Model for the High-Rotation to Ordinary-Mode Transitions observed in MCX"

1C39 S.E. Kruger, I. Joseph, T.E. Evans, and R.A. Moyer
"Modeling of the Plasma Response to Resonant Magnetic Perturbations with the NIMROD Code"

1C40 J.P. Freidberg and L. Guazzotto
"A family of analytic equilibrium solutions for the Grad-Shafranov equation"

1C41 B. Li, L.-J. Zheng, and R.D. Hazeltine
"Bifurcated states of the error-field-induced magnetic islands"

1C42 N.F. Loureiro and A.H. Boozer
"Magnetic Islands Driven by External Perturbations"

1C43 D.A. Monticello, A.H. Reiman, and D. Raburn
"Calculations of helically symmetric equlibria with PIES"

1C44 P. Zhu and C.C. Hegna
"Intermediate Nonlinear Ballooning Instability"

1C45 J.D. Callen
"Derivation of Paleoclassical Key Hypothesis"

1C46 C.J. McDevitt and P.H. Diamond
"Low-*q* resonances, transport barriers, and secondary electrostatic convective cells"

1C47 G. Vahala, M. Soe, J. Yepez, and L. Vahala
"Extremely Parallelized 3D Entropic Lattice Boltzmann Simulations of Navier-Stokes Turbulence on 1600^3-grids"

Poster Session 1E
Monday, April 23, 15:30 to 17:30, Atrium

1E01 Ö.D. Gürcan, P.H. Diamond, and T.S. Hahm
"Self-consistent Dynamics of Intrinsic Toroidal and Poloidal Rotation"

1E02 K. Gustafson, B. Dorland, D. del Castillo Negrete, M. Barnes, and I. Brömstrup
"Finite ion temperature effects and anomalous diffusion: passive tracers in two-dimensional plasma turbulence models"

1E03 D.P. Brennan and C. Holland
"Turbulent Transport Effects on Resistive Instabilities"

1E04 J. Pratt, W. Horton, J.-H. Kim, and H.L. Berk
"Drift Wave Fluctuations in Tandem Mirrors with Anchor Cells and Sheared Flows"

1E05 F. Rousseau and B. Coppi
"Influence of Angular Momentum Transport on Rotating Plasma Structures in the Gravity of a Central Object"

1E06 H. Sugama, T.-H. Watanabe, S. Fernando i Margalet, W. Horton, and J. Kim
"Gyrokinetic Simulation and Closure Model of Zonal Flows in Ion and Electron Temperature Gradient Turbulence"

1E07 J.-H. Kim, W. Horton, S.M. Kaye, H. Park, and B. Leblanc
"Electron Transport Analysis in NSTX"

1E08 E. Wang and S. Cowley
"Investigation of Long Wavelength ETG Modes"

1E09 J. Preinhaelter, J. Urban, H.P. Laqua, L. Vahala, and G. Vahala
"O-X-B Mode Conversion Simulations for EBW Heating in the WEGA Stellarator"

1E10 A.S. Richardson, E.R. Tracy, and A.N. Kaufman
"Higher order corrections to the metaplectic formulation of linear mode conversion"

1E11 R.A. Kolesnikov, W.W. Lee, H. Qin, and E. Startsev
"Simulation of propagation and absorption of IBW via reduced 5D high frequency gyrokinetic (HFGK) particle simulation"

1E12 E.A. Startsev and W.W. Lee
"Gyrokinetic Particle Simulation of Shear-Alfvén Waves"

1E13 V.A. Izzo, I. Joseph, L.L. Lao, and A.M. Garofalo
"DIII-D Plasma Response to Asymmetric Magnetic Perturbations"

1E14 G. Dif-Pradalier, V. Grandgirard, Y. Sarazin, X. Garbet, and Ph. Ghendrih
"Gyrokinetic Equilibrium and Self-Generated Flows in Tokamak Plasmas"

1E15 M. Miah, J. Carlsson, S.E. Kruger, A. Hakim, and J.R. Cary
"Parallel Infrastructure and Components for Whole-Device Modeling"

1E16 B. Keating, G. Vahala, L. Vahala, and M. Soe
"Large Eddy Simulations of MHD using the Lattice Boltzmann Algorithm"

1E17 G. Rewoldt, W.M. Tang, Y. Chen, and S.E. Parker
"Progress for NSTX Application of GEM Code"

1E18 I. Broemstrup, W. Dorland, K. Schneider, and M. Farge
"Coherency in plasma turbulence"

1E19 F.D. Halpern, G. Bateman, C.M. Wolfe, A.H. Kritz, A.Y. Pankin, R. Budny, and D. McCune
"Integrated Simulations of Turbulence Driven Toroidal Momentum Transport in Tokamak Plasmas"

1E20 C. Akcay, R.G. O'Neill, T.R. Jarboe, B.A. Nelson, A.J. Redd, and R.J. Smith
"Initial comparison of HIT-SI measurements to NIMROD calculations"

1E21 D.C. Barnes
IMP – symmetric, energy-conserving, implicit, low-noise kinetic algorithm"

1E22 P.J. Catto, A.N. Simakov, and B. LaBombard
"Magnetic topology effects on Alcator C-Mod flows"

1E23 F.I. Parra and P.J. Catto
"Extension of electrostatic gyrokinetics to retain long wavelength effects"

1E24 G. Kagan and P.J. Catto
"Electrostatic gyrokinetics in an axisymmetric torus"

1E25 D.A. Russell, D.A. D'Ippolito, and J.R. Myra
"Reduced-model SOL turbulence simulations"

1E26 A.V. Arefiev and B.N. Breizman
"Expansion of micro-clusters with a two-component electron distribution"

1E27 I. Calvo and B. Carreras
"One-dimensional transition model with momentum conservation"

1E28 F. Ebrahimi, V.V. Mirnov, S.C. Prager, and D.D. Schnack

"Momentum transport from current-driven reconnection in toroidal and disk configurations"

1E29 L. Chacón, A.N. Simakov, and A. Zocco
"Coalescence of Magnetic Islands in the Low Resistivity Hall MHD Regime"

1E30 S.J. Allfrey, P. Popovich, and S.C. Cowley
"The neoclassical tearing mode: An anomalous transport process"

1E31 P. Popovich, S.J. Allfrey, and S.C. Cowley
"Transport and the neoclassical tearing mode"

1E32 A. Hakim, P. Stoltz, and S.E. Kurger
"Algorithms for Two-Fluid plasma equations"

1E33 E.R. Solano
"Plasma evolution towards critical equilibria and diamagnetism"

1E34 C. Carey and C. Sovinec
"MHD kink instability driven by differential rotation and line-tied kink modes in the Rotating Wall Machine"

1E35 M.S. Chance, J. Chen, L.-P. Ku, D. McCune, S.C. Jardin, J. Manickam, and S. Sabbagh
"Ballooning and Local Shear Properties of NSTX Plasmas"

1E36 M.S. Chu, M.S. Chance, Y.Q. Liu, M. Okabayashi, H. Reimerdes, and H. Takahashi
"Feedback Coil Geometry and its Effect on Structure of the Resistive Wall Mode"

1E37 R.F. Schmitt and A.H. Boozer
"Stellarator Coil Optimization"

1E38 G.L. Delzanno, L. Chacón, and J.M. Finn
"Electrostatic mode associated with pinch velocity in RFPs"

1E39 C.R. Sovinec, J.R. King, N.A. Murphy, and V.V. Mirnov
"Numerical Results on Two-Fluid Reconnection and Relaxation with Guide Field"

1E40 E. Tassi, F. Militello, F. Porcelli, and R.J. Hastie
"Tearing Mode Saturation in Reversed Field Pinches with Locally Linear Force-Free Magnetic Fields"

1E41 F.L. Waelbroeck, P.J. Morrison, E. Tassi, and D. Grasso
"Hamiltonian theory of the nonlinear collisionless tearing mode"

1E42 P.J. Morrison, E. Tassi, D. Grasso, and F. Waelbroeck
"Hamiltonian Structure of a Collisionless Reconnection Model Vavlid for High and Low β Plasmas"

1E43 J.A. Breslau, J.K. Park, W. Park, A.H. Boozer, and J.E. Menard
"Investigations of Error Field Effects in NSTX with M3D"

1E44 X.Z. Tang and A.H. Boozer
"Emergence of large scale magnetic fields by relaxation in laboratory and astrophysical plasmas"

1E45 B. Coppi
"Theoretical Resolution of Magnetic Reconnection in High Energy Plasmas"

1E46 L. Chen and F. Zonca
"Radial structures and nonlinear excitation of Geodesic Acoustic Modes"

1E47 G.L. Delzanno, E.G. Evstatiev, and J.M. Finn
"The role of resistivity on line-tied kink modes"

1E48 Z. Lin, L. Chen, P.H. Diamond, T.S. Hahm, S. Ethier, and S. Klasky
"Turbulent transport via wave-particle decorrelation in collisionless plasmas"

Poster Session 2C
Tuesday, April 24, 10:00 to 12:00, Atrium

2C01 A. Cardinali, L. Morini, C. Castaldo, and F. Zonca
"Analysis of the Validity of the Asymptotic Techniques in the Lower Hybrid Wave Equation Solution for Reactor Applications"

2C02 J. Seol, C.C. Hegna, and J.D. Callen
"ECRH and its effects on neoclassical transport in stellerators"

2C03 E.R. Tracy, A.N. Kaufman, A.S. Richardson, and N. Zobin
"A canonical normal form for multidimensional mode conversion"

2C04 J.C. Wright, P.T. Bonoli, and M. Brambilla
"Three dimensional calculations of plasma admittance in the ion cyclotron frequency range"

2C05 G. Bateman, A.H. Kritz, A.Y. Pankin, D.M. McCune, R.V. Budny, and F.D. Halpern
"Porcelli Sawtooth Trigger Module in PTRANSP"

2C06 E.V. Belova, R.C. Davidson, H. Ji, M. Yamada, and S.P. Gerhardt
"Hybrid simulations of rotational instabilities in FRCs"

2C07 N. Phillips, B. Keating, G. Vahala, and L. Vahala
"Quasi-Equilibria Lattice Boltzmann Schemes for MHD Turbulence"

2C08 J. Carlsson and J.R. Cary
"Block quasi-Newton solver for transport equations"

2C09 B.I. Cohen, E.B. Hooper, L.L. LoDestro, J. Jayakumar, H.S. McLean, L.D. Pearlstein, R.D. Wood, A.D. Turnbull, and C.R. Sovinec
"NIMROD Simulations of the SSPX Spheromak Studying Viscosity and Artificial Density Diffusivity, and Linear MHD Stability Analysis of SSPX"

2C10 D.A. Spong, D. del-Castillo-Negrete, and S.P. Hirshman
"Singular value decomposition methods for noise reduction in particle-based transport calculations"

2C11 S. Vadlamani, S.E. Kruger, C. Sovinec, C. Carey, and X.S. Li
"Investigation of the extended MHD NIMROD code parallel performance scalings"

2C12 G.Y. Fu
"Nonlinear Simulations of Energetic Particle-driven Instabilities in Tokamaks and Spherical Torus"

2C13 C.M. Wolfe, F.D. Halpern, A.H. Kritz, G. Bateman, A.Y. Pankin, A. Eriksson, and J. Weiland
"Comparison of GLF23 and Weiland Transport Models"

2C14 M. Kotschenreuther, P. Valanju, and S.M. Mahajan
"Doubling Reactor Beta with X-Divertors'

2C15 C. Crabtree
"Non-Ideal Toroidal Ballooning Modes with Large Pressure Gradients"

2C16 S.V. Adamenko and V.I. Vysotskii
"The Theory of Neutronization and Protonization of Nuclei in Gravitating Heavy Stars and at Shock Self-Compression of a Target in a Laboratory Electron-Nuclear Collapse"

2C17 T. Stoltzfus-Dueck, J.A. Krommes, and S.J. Zweben
"Modeling of Coherent Structure Formation in Tokamak Edge Turbulence"

2C18 A.N. Simakov
"A drift ordered short mean-free path description for partially ionized magnetized plasma"

2C19 F. Castejón, S. Eguilior, I. Calvo, and D. López-Bruna
"Dynamics of plasma electric field of positive radial electric field created by ECRH-pump out"

2C20 M. Landreman, B. Coppi, and C. Di Sanzo
"Correlation Between Accretion Theory and Toroidal Rotation Experiments"

2C21 J.M. TenBarge, R.D. Hazeltine, and S.M. Mahajan
"Thermodynamics of an Anisotropic Relativistic Plasma"

2C22 R.B.White and L. Zakharov
"Canonical variables for Guiding Center Motion"

2C23 P. Angelino, V. Grandgirard, Y. Sarazin, G. Dif-Pradalier, S. Jolliet, A. Bottino, X. Garbet, Ph. Ghendrih, B.F. McMillan, T.M. Tran, and L. Villard
"Effects of plasma elongation on Geodesic Acoustic Modes"

2C24 K.C. Shaing, M.S. Chu, S.A. Sabbagh, and M. Peng
"Critical Toroidal Rotation Profile for Resistive Wall Modes in Tokamaks"

2C25 L. Guazzotto and J.P. Freidberg
"Equilibrium solution with plasma flow and vacuum region"

2C26 R. Neches, S.C. Cowley, P.A. Gourdain, J.N. Leboeuf
"Analysis of Unity Beta Equilibria"

2C27 T. Rafiq, C.C. Hegna, and J.D. Callen
"Drift resistive ballooning modes in three-dimensional configurations"

2C28 J.W. James and E.D. Held
"Non-local calculation of parallel heat flow in the vicinity of magnetic islands"

2C29 R. Samtaney and S.C. Jardin
"Motion of a Localized High-Density Region Across Magnetic Flux Surfaces"

2C30 S.R. Keating and P.H. Diamond
"Turbulent resistivity in wavy two-dimensional magnetohydrodynamic turbulence"

2C31 B.K. Shivamoggi
"Collisionless MHD Turbulence in Two Dimensions"

2C32 D. Lazanja and A.H. Boozer
"Separating Magnetic Field Boundary Conditions into Parts Produced by Internal and External Sources"

2C33 A.D. Turnbull
"Sturmian Behavior of the Unstable Ideal MHD Spectrum in Axisymmetric Toroidal Equilibria"

2C34 X. Liu and C.C. Hegna
"Finite Ion Orbit Effects on Magnetic Islands in Toroidal Plasmas"

2C35 V.V. Mirnov, C.C. Hegna, and S.C. Prager
"Transition from Two Fluid to Resistive MHD Dynamos in Cylindrical Reversed Field Pinch"

2C36 L.E. Zakharov
"The theory of variances of equilibrium reconstruction"

2C37 H.E. Mynick and A.H. Boozer
"Zonal flow shielding in stellarators and tokamaks"

2C38 D. Hatch and P.W. Terry
"Weak Turbulence Breakdown in Nonlinear Particle Flux for Collissionless Trapped Electron Mode Turbulence"

2C39 H. Qu, Z. Lin, and L. Chen
"Gyrokinetic theory and simulation of mirror instability"

2C40 V. Tangri and P.W. Terry
"Anomalous impurity ion heating from Alfvénic cascade in the RFP"

2C41 W.X. Wang, S. Ethier, T.S. Hahm, S.M. Kaye, W.W. Lee, J. Manickam, G. Rewoldt, and W. Tang
"Comparison of turbulence fluctuation spectrum between experiment and computer simulation in NSTX"

2C42 W. Dorland
"Collisionless Heating in Gyrokinetic Turbulence"

2C43 G. Spizzo, R.B. White, S. Cappello, L. Marrelli, and F. Sattin
"Chaos generated pinch effect in toroidal confinement devices"

2C44 A. Wurm, D. del-Castillo-Negrete
"Chaotic Transport and separatrix reconnection in an area-preserving self-consistent nontwist map model"

2C45 C.C. Kim
"Simulation of FLR effects on RFP tearing modes"

2C46 J.-K. Park, A.H. Boozer, J.E. Menard, A.G. Glasser, and M.S. Chance
"Ideal response of tokamak plasma to three dimensional magnetic perturbation

2C47 A.J. Cole, C.C. Hegna, and J.D. Callen
"Effect of neoclassical toroidal viscosity on error-field penetration thresholds in tokamak plasmas"

2C48 Y. Nishimura, Z. Lin, and L. Chen
"Electromagnetic gyrokinetic particle simulations in a global field aligned mesh"

2C49 D. del-Castillo-Negrete
"Nonlocality and perturbative transport"

Monday morning, April 23

8:30 – 9:30

Loews Ballroom B&C

Review Talk 1A

Ultra-Intense Laser Pulse Interaction with Gases, Cluster Gases and Structured Plasmas*

T.M. Antonsen Jr,
Institute for Research in Electronics and Applied Physics,
University of Maryland, College Park MD 20742

Interest in the study of the propagation of intense optical pulses in plasma and in gas has been stimulated by the development of lasers capable of producing ultra-intense, ultra-short pulses. With these lasers a variety of novel laser matter interaction phenomena have been investigated including: self-focusing harmonic generation, ionization induced blue shifting, refraction, pulse shortening, and coherent scattering, plasma wave generation and Raman instability. The applications of these pulses are extensive and include plasma based particle accelerators, x-ray lasers, and soft x-ray generation for lithography and microscopy.

A common theme in laser-plasma applications is the need to confine or guide the radiation for a distance greater than a Rayleigh length to enhance its interaction with the medium. Such guiding can be realized either through the process of self-focusing or through the use of preformed channels. However, guiding of this type constrains the guided radiation to have particular dispersive qualities. Specifically, the phase velocity along the axis of propagation is super-luminal, and the group velocity is sub-luminal. This leads to consideration of corrugated, or periodic, plasma structures that have more versatile dispersive properties.

Corrugated channels can form spontaneously under the right conditions of plasma density and incident laser pulse angle. However, recently it has been shown that channels with prescribed period (1mm - ~ 35 μm) can be formed under a variety of controlled conditions. This opens a number of interesting possibilities including the direct acceleration of particles, phase matching of nonlinearly generated harmonics, and the generation of intense short pulses of THz radiation by laser pulses or electron beams.

* In collaboration with H. Milchberg, J. Cooley, A. Gupta, T. Taguchi, J. Palastro, Z. Bian, J-Z Wu, K-Y Kim, I. Alexeev, B. Layer, A. Yorke, V Kumarappan, and Supported by DoE and NSF

Monday morning, April 23

9:30 – 10:00

Loews Ballroom B&C

Oral Session 1B

Direct drive by cyclotron heating can explain spontaneous rotation in tokamaks

J. W. Van Dam, L.-J. Zheng, and M. Kotschenreuther
Institute for Fusion Studies, University of Texas at Austin, Austin, TX 78712

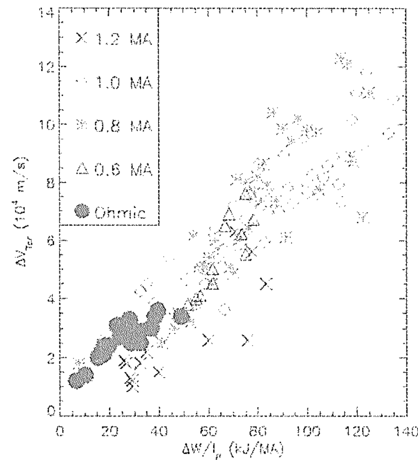

FIG. 1: Experimental scaling in Alcator C-Mod [from Rice *et al.*, Nucl. Fusion **41**, 277 (2001)]

Spontaneous plasma rotation during ion and electron cyclotron wave heating has been observed in Alcator C-Mod, DIII-D, JET, and Tore Supra, despite the lack of auxiliary mechanical momentum input.[1] Previous theoretical explanations for this spontaneous rotation were based on neoclassical effects, radial orbit shifts of cyclotron-heated energetic ions, turbulence-induced toroidal stress, or ion pressure gradient-driven electrostatic modes.[2] Here we provide an alternative explanation by showing that cyclotron wave heating can directly drive intrinsic tokamak plasma rotation through resonance with the precessional motion of trapped particles. Even with the cyclotron heating applied symmetrically, without a preferred toroidal direction, we find that, when FLR effects and magnetic field inhomogeneity are taken into account, the toroidal momentum input due to cyclotron wave heating is unbalanced in the toroidal direction. The cyclotron-heated fast particles can transfer their momentum to the bulk plasma through collisions. Using quasilinear theory, we have calculated the toroidal torque exerted on the plasma by cyclotron waves and established a relationship between the toroidal momentum input and the energy input. Our theory reproduces many characteristic features of spontaneous rotation: (a) scaling with stored energy and plasma current; (b) rotation direction for ICRF heating (co-current) and ECH (counter-current); (c) rotation direction for off-axis heating during ITB discharges; (d) inverted rotation profile during the L-H mode transition; (e) magnitude of rotation; and (f) inter-machine scalings with normalized beta and temperature ratio.[3] Our theory does not explain spontaneous rotation observed in purely Ohmic tokamak plasmas, which is smaller and mostly in the edge region; recent work[4] has shown another mechanism for this case. For core rotation, our theory provides significant agreement with experimental observations.

Research supported by DOE Grant DE-FG02-04ER54742.

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[3] J. E. Rice *et al.*, 21st IAEA Fusion Energy Conf., Chengdu, China, EX/P3-12 (2006) J. S. DeGrassie *et al.*, Bull. Am. Phys. Sci. **51**, 99 (2006).

[4] A. Aydemir, Bull. Am. Phys. Sci. **51**, 177 (2006), submitted to Phys. Plasmas.

Monday morning, April 23

10:00 to 12:00

Atrium

Poster Session 1C

Effects of Shaping on the Dimits Nonlinear Shift, Implementation of Equilibrium Sheared Flows in GS2, and Improved Restarting for GMRES Algorithms*

Gregory W. Hammett, *Princeton Plasma Physics Laboratory*,
Emily A. Belli, *General Atomics*,
Nuno F. Loureiro, William Dorland, *Univ. of Maryland*

We have used the GS2 nonlinear gyrokinetic code to study the effect of flux surface shape on tokamak core plasma turbulence.[1] It is well known that experiments observe a very strong improvement of confinement with increased elongation and triangularity (at fixed q_{95}, so that the plasma current increases). We find that the Dimits nonlinear shift is larger with higher elongation and triangularity gradient. The Dimits shift is the phenomenon where the nonlinear turbulence level does not become significant until the driving gradients exceed a threshold that is higher than the linear critical gradients required for driving a linear instability. The dependence of the Dimits shift on plasma shaping can be understood physically as due to the fact that the Rosenbluth-Hinton residual flows are larger at higher shaping, because of the reduction in banana widths (and thus reduction of neoclassical polarization shielding) at higher plasma current. Xiao and Catto[2] recently derived an analytic calculation of the effects of shaping on the Rosenbluth-Hinton flows, providing a nice analytic confirmation of our results.

We have recently extended GS2 to include equilibrium-scale flows, which may driven by beam injection, neoclassical effects, etc. [GS2 always included small-scale zonal flows that are self-consistently driven by turbulence. But for simplicity it neglected equilibrium-scale zonal flows (which are not radially periodic on the simulation scale).] The implementation algorithm and tests will be shown.

Finally, we will present results on improved versions of restarted GMRES (Generalized Minimum RESidual), a Krylov algorithm for the iterative solution of large matrix problems. There are simple examples, such as an elliptic Poisson problem, for which the standard algorithm does not converge very quickly. The recently developed "Loose GMRES" algorithm[3] often leads to much faster convergence. We show that these improvements can be interpreted physically by an analogy to wave equations vs. diffusion equations, and mathematically to techniques known as Dynamic Relaxation, 2cd order Richardson Iteration, or Chebyshev acceleration. We have developed a code that implements a version of LGMRES(1,1), generalized to be applicable as a nonlinear Newton-Krylov solver.

References

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

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TRANSPORT ANALYSIS OF MULTI-PHASE H-MODE SHOT AT TCV

E. Asp[1], W. Horton[2], L. Porte[1], S. Alberti[1], E. Fable[1], Y. Martin[1], O. Sauter[1], G. Turri[1] and the TCV Team

[1]Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, Association Euratom-Confédération Suisse, CH-1015 Lausanne, Switzerland.
[2]Institute for Fusion Studies, University of Texas at Austin, Austin, Texas 78712, United States

The Tokamak à Configuration Variable (TCV) is well suited for studies of electron transport due to its well developed electron cyclotron resonance heating (ECRH) system. Ion heating can be achieved through thermal equilibration in high density plasmas. Such plasmas can be heated by the third harmonic X-mode (X3), which allows for H-mode studies with strong electron heating. In the discharge analyzed here, TCV shot 29892, X3 heating was applied to an ohmic ELMy H-mode[1]. The first phase, with full X3 power, exhibits large ELMs and significant sawtooth activity. The power is then modulated and the plasma undergoes a transition to a stationary ELM-free H-mode phase where the confinement stays high. After a minor disruption, MHD is present and the confinement decays while maintaining the stationary ELM-free regime. Therefore, this shot comprises four different H-mode phases to be analyzed and compared, one ohmic followed by three with strong electron heating. The two final phases are similar to improved H-mode regimes.

The transport analysis is carried out with ASTRA. As sawteeth are present, to different degrees, throughout the shot, the sawtooth model is activated to adjust the q-profile accordingly. The GLF transport model is included in the interpretative mode to investigate the differences in the growthrates of the main microinstabilites, the diffusion coefficients and the overall confinement in the four distinct H-mode intervals.

1. L. Porte et al., Proceedings of 21st IAEA Fusion Energy Conference, EX/P6-20

Current carrying blob-filaments and application to ELM dynamics

J.R. Myra

Lodestar Research Corporation, Boulder, Colorado

Previous work by several authors has examined the properties of density (pressure) blob filaments. The dynamics of these coherent structures, created by edge turbulence, is governed in part by dipole and higher-order parallel currents. Here the model is extended by considering blob-filaments which carry much larger net monopole parallel current. This provides a simple paradigm for current carrying ELM filaments, such as observed on MAST.[1] In the following, for brevity, these current carrying filamentary blobs are referred to as ELMs, although the model is not claimed to be a complete ELM model. In particular, this work emphasizes physics that is complementary to, but compatible with, the Alfvén wave dynamics of high beta blobs considered previously.[2]

The basic idea is that pedestal instabilities are driven by a combination of edge current and pressure gradients.[3] Nonlinear saturation of these instabilities reduces the drives by removing filaments of plasma pressure and current, which propagate outward. Thus, it is postulated that each ELM filament carries with it the density, temperature, *and parallel current* of the creation (instability) zone. It is first shown that in the SOL, the parallel current convects with the density and temperature of the ELM. The dynamics of these current-carrying filaments is studied in the reduced MHD approximation, keeping the (typically large) magnetostatic forces due to the current, as well as the usual curvature and grad-B forces that characterize electrostatic blob dynamics. On creation, the filament is repelled from the oppositely directed current "hole" it leaves behind, causing the ELM to be initially accelerated away from the main plasma. This magnetostatic current repulsion is a different mechanism than that which gives rise to "explosive" pressure-gradient-driven ballooning.[4] The ELM can also decelerate near the main chamber wall due to interaction with image currents. Results for the stability of an ELM-filament that is freely propagating in the SOL will be presented.

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1C4

Rethinking Parallel Closures for NTM and ELM Simulations

E. D. Held, Jeong-Young Ji, J. W. James, M. Addae-Kagyah and M. Sharma
Department of Physics, Utah State University, Logan, Utah 84322

The ITER tokamak will operate in regime where pressure gradients may likely drive instabilities such as neoclassical tearing modes (NTMs) in the core and edge localized modes (ELMs) in the pedestal region. Important requirements for simulating such instabilities using macroscopic plasma fluid codes are physically correct forms for the parallel heat flows and stresses. Previous work has approached the parallel closures problem in the plasma core and edge using distinct, nearly-collisionless and collisional theories, respectively. With regards to NTMs in the plasma interior, however, parallel transport in the vicinity of magnetic islands is most likely moderately collisional. This is due to that fact that rapid parallel equilibration leads to long temperature gradient scale lengths along the magnetic field. Furthermore, although appropriate near the bottom of the pedestal region, a collisional plasma assumption for the top of the pedestal in ITER is not valid. In this talk, we present recent advances in calculating parallel closures for arbitrary collisionality. These closures stem from a solution of a lowest-order drift kinetic equation that includes time dependence, free streaming and particle trapping in general magnetic geometry, and an exact treatment of the linearized, Coulomb collision operator. In addition to writing the parallel closures formally in terms of integrals of thermodynamic drives along particle characteristics, we discuss a numerical approach to directly solving the drift kinetic equation. Expansion of the distribution function's velocity dependence in orthogonal polynomials permits a massively parallel, numerical solution to separated equations involving time, particle speed and three spatial variables. Final consideration will be given to the implementation of this solution in the plasma fluid code, NIMROD, with a discussion of future applications to NTM and ELM simulations.

Anistropic and Transient Dynamics in the Drift Wave Turbulence

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

G. D. Chagelishvili
Center for Plasma Astrophysics, Abastumani Astrophysical Observatory, Ave. A. Kazbegi 2, Tbilisi 0160, Georgia

J. Bowman
Department of Mathematical and Statistical Sciences, University of Alberta, Edmonton, Alberta, Canada, T6G 2G1

The spectral evolution of drift wave turbulence in the presence of a uniformly sheared poloidal flow is investigated for anisotropic and transient dynamics. Analytic models of (1) the propagation of the "center of mass" of $E(t)$ in $\vec{k}$-spectrum from the shear flow $k_x = k_{x0} - k_y V_y' t$, (2) the local growth/decay $\gamma(k_x, k_y)$ and the nonlinear mode coupling dynamics $N_{\vec{k}}[\phi_{\vec{k}}]$ are developed and compared with direct numerical simulation(DNS). For $N_{\vec{k}}$, the results show that the shear flow produces an anistropic, intermittent spectrum with features similar to those observed in fluid turbulence and in the Gamma 10 images of intermittent vortices. Movies of the $\vec{k}$-space dynamics make clear the strong anisotropic "transverse cascade" accompanied by strong and temporal intermittency of the shear flow controlled drift wave turbulence.

Internatioanl Scence and Technology Centers(www.istc.ru) ISTC grand G-1217.

Real geometry gyrokinetic PIC computations of ion turbulence in tokamak discharges with SUMMIT/PG3EQ_NC

J. N. Leboeuf, V. K. Decyk, UCLA
A. Dimits, D. Shumaker, LLNL

The PG3EQ_NC module within the SUMMIT Gyrokinetic PIC FORTRAN90 Framework makes possible 3D nonlinear toroidal computations of ion turbulence in the real geometry of DIII-D discharges. This is accomplished with the use of local, field line following, quasi-ballooning coordinates and through a direct interface with DIII-D equilibrium data via the EFIT and ONETWO codes, as well as Holger Saint John's PLOTEQ code for the (R, Z) position of each flux surface. This is also achieved by ongoing implementation of Miller equilibrium capabilities in SUMMIT/PG3EQ_NC. The effect of real geometry is being elucidated with CYCLONE shot #81499 by comparing results for growth rates and diffusivities from PGEQ_NC to those of its circular counterpart. The PG3EQ_NC module is also being used to model ion channel turbulence in DIII-D discharges # 118561 and 120327. Linear results will be compared to growth rate calculations with the GKS code. Nonlinear results will also be compared with scattering measurements of turbulence, as well as with accessible measurements of fluctuation amplitudes and spectra from other diagnostics.

This work is performed for USDoE by UCLA under (NCTE) grant DE-FG02-04ER54740 and UC-LLNL under contract W-7405-ENG-48.

Discrete particle noise in gyrokinetic particle-in-cell simulations of plasma turbulence

I. Holod
Department of Physics and Astronomy
University of California, Irvine, CA 92697, USA

The studies of discrete particle noise have been done based on the gyrokinetic simulations of plasma using the gyrokinetic toroidal particle code (GTC). Statistical properties and associated transport of random fluctuations are first studied in a system with submarginal background gradients, such that no instabilities develop. Simulations in the parameter regime approaching marginality from below have subsequently been done to study the effects of nonlinearity of the dielectric constant. The fluctuation correlation function and fluctuation spectra have been constructed from the direct simulation measurements of electrostatic potential. Noise driven transport is calculated using the quasilinear expression for the diffusion coefficient and the obtained noise spectrum. The obtained theoretical value for the diffusion coefficient is compared with the measured value from the simulation, demonstrating good agreement. It has been shown that for the realistic parameters, the noise driven transport depends linearly on entropy of the system, which, in particular, makes possible to estimate the noise contribution to the total transport during simulations.

1C8

Lower-hybrid-drift instabilities in current-sheet equilibrium in presence of a guide field

Wenlu ZHANG and Zhihong LIN

Department of Physics and Astronomy, University of California, Irvine, CA, USA

Drift instabilities in one-dimensional current-sheet configuration in presence of a guide magnetic field, with lower-hybrid frequencies, are investigated. Nonlocal two-fluid stability analysis is carried out, and a class of unstable modes with multiple eigenstates are found by numerical means. It is found that the most unstable modes correspond to quasi-electrostatic, short-wavelength perturbations in the lower-hybrid frequency range, with wave functions localized at the edge of the current sheet where the density gradient is maximum. It is also found that there exist quasi-electromagnetic modes located near the center of the current sheet where the current density is maximum, with both kink- and sausage-type polarizations. These modes are low-frequency, long-wavelength perturbations. It turns out that the current-driven modes are low-order eigensolutions while the lower-hybrid-type modes are higher-order states, and there are intermediate solutions between the two extreme cases. Attempts are made to interpret the available simulation results.

Comparison of Lower Hybrid Current Drive Predictions from Different Simulation Models in Reactor Relevant Regimes

P.T. Bonoli, M. Porkolab, J. C. Wright, MIT, PSFC, Cambridge, MA 02139 (USA)
R. W. Harvey, CompX, Del Mar, CA 92014 (USA)
C. E. Kessel, PPPL, Princeton, NJ 08543 (USA)
Y. Peysson and J. Decker, Association EURATOM-CEA, CEA, Cadarache, FRANCE

Lower hybrid (LH) waves have the attractive property of damping strongly via electron Landau resonance on relatively fast tail electrons at $(2.5-3)\times v_{te}$, where $v_{te} = (2T_e/m_e)^{1/2}$ is the electron thermal speed. Consequently these waves are well-suited to driving current in the plasma periphery where the electron temperature is lower, making lower hybrid current drive (LHCD) a promising technique for off – axis ($r/a \geq 0.60$) current profile control in reactor grade plasmas. It is therefore important to develop a predictive capability in this area. In order to assess this capability we have compared the predictions of four simulation models for LHCD using parameters typical of plasmas in the ITER device. Two of the simulation codes LSC [1] and ACCOME-LH [2], employ a Green's function treatment [3] of the Fokker Planck equation from which the driven current is formulated by convolving the resulting response function (χ) with the wave-induced RF flux ($\mathbf{\Gamma}_{rf}$):

$$J_{rf} = \int d^3p \frac{\partial f_e}{\partial p} \bullet \Gamma_{rf}, \qquad \Gamma_{rf} = -D_{QL} \frac{\partial f_e}{\partial p_{\parallel}}. \qquad (1)$$

Here $\mathbf{\Gamma}_{rf}$ is computed from a 1D ($v_{//}$) Fokker Planck – toroidal ray tracing code. The other two codes, CQL3D-GENRAY [3] and DKE [4] perform direct 2D ($v_{//}$, $v_{\perp}$) numerical solutions of the Fokker Planck equation in conjunction with toroidal ray tracing modules. In the very low (zero) RF power limit where distortion of the electron distribution is negligible it is found that adjoint methods agree quite closely with 2D numerical solutions as expected [5]. However, as the LHRF power is increased, significant differences are seen in the spatial damping profiles, presumably due to 2D velocity space effects. Interesting enough, the integrated currents from the two different methods remain about the same, even though the spatial profiles of absorption and current density differ. We have performed a detailed power scan for the ITER parameters in order to quantify the threshold power at which the 2D velocity space distortion in $f_e(v_{//}, v_{\perp})$ becomes important.

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Nonlinear wave coupling in inhomogeneous media

J.R. Cary[1,2], N. Xiang[1]

[1] Center for Integrated Plasma Studies and Department of Physics, University of Colorado, Boulder, CO 80309

[2] Tech-X Corporation, Boulder, CO 80303

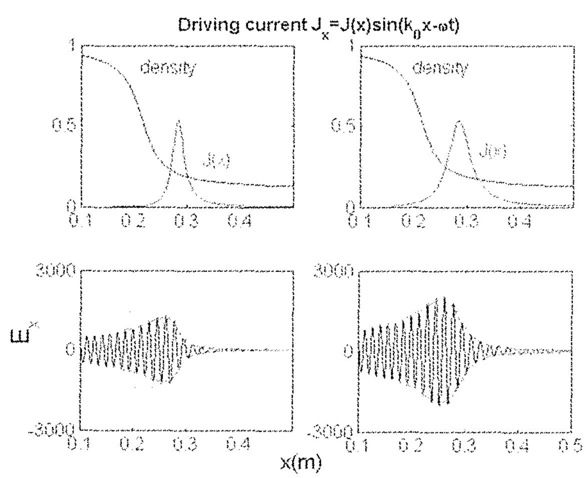
Abstract

The equation describing the nonlinear coupling of waves for homogeneous plasma comes from the nonlinear currents as drivers for the linear modes. For homogeneous plasma, expansion of the dielectric matrix near resonance then unambiguously provides an evolution that is first order in space and time. However, for inhomogeneous media, there is ambiguity in the placement of the spatial derivative, as it might act on the linear dielectric term, and the degree to which this is so is unknown. We unambiguously derive the evolution equation from the principle that the derivative must act on the dielectric term as a whole, along with conservation of energy. This results in the equation,

$$\omega\partial_k\left(D_\mu\right)\partial_x A + \tfrac{1}{2}\omega\partial_x\partial_k\left(D_\mu\right)A = J_s,$$

where A is the amplitude of the driven mode, D_μ is the eigenvalue of the dielectric matrix, and J_S is the driving current.

We have shown analytically that the above equation is rigorously true for cold plasma. We have furthermore shown it to be true for electron Bernstein mode propagation (see figure), thus providing convincing evidence that it works for kinetic modes as well.



Electron Bernstein electric field (bottom panel) as computed from a localized current source (top panel). Black is computed by a δf simulation in VORPAL. Blue is the amplitude computed without the new term arising from inhomogeneity. Red is the amplitude computed with the new term.

Second order Fermi acceleration of electrons in LHCD

V.I. Shevchenko, V.L. Galinsky

University of California, San Diego, ECE Department, La Jolla, CA 92093-0407, USA

Due to resonant interaction with lower hybrid waves in the LHCD problem, part of electrons are accelerated and, as a result of this, the tail of energetic electrons is formed on the electron distribution function. This distribution can be unstable with respect to cyclotron excitation of lower hybrid waves in different part of the spectrum - so called fan instability [1, 2] that is an effective mechanism of pitch angle diffusion of the tail electrons. In this case the tail electrons interact simultaneously with both (i) LH waves that accelerate them (Landau resonance) and (ii) waves excited in the process of the fan instability (anomalous Doppler resonance) that lead to their pitch angle diffusion. Since velocity diffusion lines of electrons formed due to heir interaction with each type of waves intersect, this interaction can lead not only to pitch angle diffusion but also to heating of electrons mainly in perpendicular direction. We investigated this heating mechanism of the tail electrons.

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Nonlinear self-interactions of electron Bernstein waves in an inhomogeneous plasma

Nong Xiang[1], John R. Cary[1,2]

[1] University of Colorado,
CO 80309
[2] Tech-X Corporation,
5621 Arapahoe Ave.
Boulder CO 80303

Abstract

The nonlinear dynamics of the electron Bernstein waves in an inhomogeneous plasma is simulated via both the δf and full particle-in-cell (PIC) simulations. It is shown that the nonlinear self-interaction of the electron Bernstein wave (EBW) can give rise to the second harmonic generation at a pump power much lower than the electron thermal energy. The theory describing this nonlinear wave coupling in an inhomogeneous plasma is presented. It is found that the amplitude of the second harmonic EBW excited can exceed that of the fundamental wave if the field of the fundamental EBW is sufficiently large. The theoretical predictions are confirmed by both the δf and full PIC simulations. With a high incident power, the generations of the non-propagation third and fourth harmonic modes are also observed.

Modeling of plasma detachment in a magnetic nozzle

M. Tushentsov, B. Breizman, and A. Arefiev

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

Some plasma-based space propulsion systems rely on a magnetic nozzle to generate a directed plasma flow. The strong magnetic field of the nozzle guides the plasma towards the thruster exhaust. In order to produce thrust, the ejected plasma must disengage from the nozzle. The detachment should occur when the kinetic energy of the plasma exceeds the energy density of the expanding magnetic field.[1] The magnetic field in the detached plume is almost entirely due to the plasma currents. This picture is very similar to what happens in the solar wind as it moves away from the Sun.[2] We have developed a Lagrangian fluid code to model the process for an axisymmetric nozzle within the framework of ideal MHD. The code implements a reduced model that consists of truncated steady-stated MHD equations and takes advantage of the plasma flow paraxiality. These simplifications enable the code to perform a broad parameter scan with modest computational requirements (single workstation). The vacuum magnetic field, which is not paraxial at the nozzle exhaust, is calculated for a given magnetic coil configuration. From the computed steady-state flow configuration, the code evaluates magnetic nozzle efficiency, defined as the ratio of the axial momentum flux in the outgoing flow to the axial momentum flux in the incoming flow. The code makes it possible to optimize nozzle efficiency by interactively adjusting the magnetic coil configuration. To benchmark the code, we have reproduced the idealized analytical picture of plasma detachment described in Ref. 1. We have then used the code to investigate more realistic nozzle configurations that are not analytically tractable. Our simulations for relevant plasma characteristics and magnetic coil configuration demonstrate efficient detachment of the super-Alfvénic plasma flow from the nozzle. The code is applied to interpret recent experimental data from the Detachment Demonstration Experiment (DDEX)[3] facility at NASA Marshall Space Flight Center.

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1C14
Nonlinear MHD simulation of DC helicity injection in spherical tokamaks

R. A. Bayliss,* C. R. Sovinec, and N.W. Eidietis
University of Wisconsin—Madison

B.A. Nelson and T.R. Jarboe
University of Washington

Natural elongation and small aspect ratio contribute to the enhanced confinement of the spherical tokamak (ST) over the conventional tokamak configuration. However, due to its small central column, the effectiveness of Ohmic drive in an ST is limited hence a noninductive means of forming plasma is beneficial. Three dimensional nonlinear MHD computations using the NIMROD code [Sovinec et. al. JCP **195**, 355 (2004)] have been performed to study DC helicity injection in ST's. Current drive via DC helicity injection has been successfully employed to produce a tokamak-like plasma with either a poloidal-gap voltage known as coaxial helicity injection (CHI) [used in HIT-II and NSTX] or a biased cathode gun configuration [used in CDX and Pegasus]. The computations for both experimental configurations are done in a realistic geometry and are the first CHI simulations in ST's which self-consistently evolve pressure. For gun-driven cases the formation, merger, and relaxation of the current filaments to the tokamak-like plasma are simulated. In coaxial helicity injection the numerical studies follow the "bubble-burst" formation and subsequent excitation and saturation of a kink-mode. The linear properties of the current-driven instability are also studied. Over the lifetime of a non-Ohmically driven experimental shot, the extent to which the merged plasma exhibits amplification of poloidal flux reported in Pegasus, and HIT-II will be explored along with the application of Ohmic drive to the startup plasma.

*Electronic address: `rabayliss@wisc.edu`

Three dimensional particle simulations of driven magnetic reconnection

H. Ohtani and R. Horiuchi
National Institute for Fusion Science, Graduate University for Advanced Studies, Toki 509-5292, Japan

W. Horton
Institute for Fusion Studies, The University of Texas at Austin, Austin, Texas 78712

New full Lorentz force particle simulations of the classical problem of driven magnetic reconnection are presented with detailed diagnostics of the fluid flow velocities, densities and temperatures of the ions and electrons resolved in the inflow regions and the outflow regions. The changes in the energy components with special focus on the drop in reversed field magnetic energy and the increase in the flow kinetic energies and the thermal electron and ion energies are reported. We use a variable ion-to-electron mass ratio and scale the ion thermal heating in the out flow region with the fractional power of the ion mass from the collisionless "viscous heating" produced by the force from the divergence of the off-diagonal ion stress tensor from chaotic and meandering ion orbits. We report that there is significant electron heating and out-of-plane magnetic field from the out flow of the electrons. The low frequency fluctuations in the simulations are analyzed with respect to the kinetic LHDI instability.

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The FACETS Project

A. PLETZER, S.E. KRUGER, A. HAKIM, S. VADLAMANI, M. MIAH, J.R. CARY, Tech-X Corporation, R. COHEN, T. ROGNLIEN, T. EPPERLY, Lawrence Livermore National Lab, D. MCCUNE, Princeton Plasma Physics Lab, S. KRASHENINNIKOV, A. PIGAROV, Univ. of California-San Diego, J. LARSON, L. C. MCINNES, Argonne National Lab., D. ESTEP, Colorado State Univ.

There is a need in the fusion community to develop an integrated modeling capability for simulating burning plasmas in ITER-like devices. This need is being addressed by building the Framework Application for Core-Edge Transport Simulation (FACETS), a project which is aimed at providing a parallel, scalable infrastructure allowing for the coupling of multi-physics packages (transport models, MHD equilibrium solvers, plasma-wall interaction, sources and sinks). The challenges facing FACETS include time scales varying many orders of magnitudes from plasma-wall interaction ($\sim$1 μs) and turbulent mixing ($\sim$1ms), to the slow evolution of averaged profiles ($\sim$1 s), extending to discharge durations exceeding 100 seconds. Here, we report on the progress of building FACETS. As an initial test application, we show how to assemble a simple core-edge model in concurrent composition, i.e. core and edge running on disjoint sets of processes. The coupling between the one-dimensional core and the two-dimensional edge models involves solving an implicit set of equations to ensure consistency of fluxes and continuity of fields across the core-edge interface.

Comparison of Gyrokinetic Simulation Against Core Turbulence Fluctuation Measurements via Synthetic Diagnostics*

C. Holland[1], G.R. Tynan[1], G.R. McKee[2], M.W. Shafer[2], R.J. Fonck[2], J. Candy[3], R.E. Waltz[3], and R.V. Bravenec[4]

[1]University of California-San Diego, La Jolla, California, USA
[2]University of Wisconsin, Madison, Wisconsin, USA
[3]General Atomics, San Diego, California, USA
[4]University of Texas, Austin, Texas, USA

Validation of plasma turbulence simulations requires extensive direct comparisons against experimental measurements, taken under conditions for which the simulation model is believed to be accurate. Recent upgrades to the beam emission spectroscopy (BES) system on the DIII-D tokamak now allow for spatio-temporally resolved measurements of core turbulence measurements, where the gyrokinetic equation is believed to be an accurate description of small-scale drift-wave turbulence. Equally important advances in numerical algorithms and available computing power now make physically realistic gyrokinetic simulations feasible for times long enough to allow for meaningful comparisons against the measurements. Utilizing these advances, we have begun a comprehensive program of direct comparison between BES measurements and results from the gyrokinetic code GYRO, and will describe initial results from the modeling of a slowly evolving L-mode discharge. Comparisons of fluctuation amplitudes, frequency spectra, correlation times and lengths will be presented, in addition to turbulent fluxes. An important component of this process is the use of a "virtual" or "synthetic" diagnostic [1] which describes the inherent spatial sensitivity of the BES system (including realistic geometry, optics, and neutral beam characteristics), as well as the fact that the BES system measures light intensity fluctuations, rather than the density and temperature fluctuations that are the "canonical" variables of plasma turbulence models. The impact of these effects is also discussed.

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Gyrokinetic simulation of skindepth sized ballooning modes

N.Joiner and A.Hirose

University of Saskatchewan
Saskatoon, Canada

Understanding which microinstabilities are responsible for particle and heat loses in Tokamaks is important in order to predict regimes of low transport. An electron temperature gradient driven ballooning mode has been reported to exist when both the ions and electrons have a Boltzmann response [1], at perpendicular scales on the order of the collisionless skindepth. This mode may coexist with the Electron Temperature Gradient (ETG) mode, and therefore could play a role in the saturation of ETG turbulence. In this work we present an investigation of both the linear stability and resulting nonlinear heat flux of the skindepth sized ballooning mode using the gyrokinetic code GS2 [2,3]. The linear mode is not found to be as unstable as predicted by the theory [1], and although heat fluxes large enough to be significant to experiment are seen in the simulations, obtaining a well converged result has proven to be difficult.

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1C19

Distributed technologies and XML for HDF5 data

Svetlana Shasharina, Chuang Li, Nanbor Wang, and Roopa Pundaleeka

Tech-X Corporation, 5621 Arapahoe Ave, Suite A, Boulder, CO 80303, USA

Abstract

Transferring full simulation data generated at remote supercomputers to local machines for analysis and visualization might be prohibitive because of the size of the data, limited bandwidth and/or limited local storage. In addition, not all the data is of the same interest at the same time. Thus, scientists need a solution for querying and accessing subsets of remote simulation data through an easy-to-use interface. Recently, most of fusion codes switched to using HDF5. This paper describes several approaches to provide an access to remote HDF data through an interface similar to the local HDF API and compares their performances. It also gives some details about the winning solution (a Globus-based Web Service).[1] The service is installed at NERSC and being tested by VORPAL[2] and NIMROD[3] teams.

To facilitate HDF5 data interchange and analysis tools interoperability we are also developing the Fusion Simulation Markup Language (FSML) based on the eXtensible Markup Language (XML). Currently, we have a schema accommodating physics data coming from multiple simulations and organized by time steps. Physics data is characterized by its name and units and can be of arbitrary float types. The data might reside on structured and unstructured meshes. FSML C++ readers allow reading physics and geometry data in a uniform way. We tested our reader using M3D,[4] NIMROD and VORPAL codes. AVS-Express modules using the readers provide a uniform way to visualize data from these codes.

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1 HDF5 Web Service: https://collaborate.txcorp.com/collaborate/distributed-technologies/fusion-data-grids-project/.

2 VORPAL: http://www-beams.colorado.edu/vorpal/.

3 NIMROD: http://www.nimrodteam.org/.

4 M3D: http://w3.pppl.gov/~jchen/.

Gyrokinetic Simulation of Toroidal Angular Momentum Transport*

R.E. Waltz, G.M. Staebler, and J. Candy

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

Recent experimental results in C-mod (J.E. Rice et al.) and DIII-D (deGrassie et al.) indicate that tokamaks have an intrinsic *source* of toroidal rotation with an inward or *pinched flow*. This has motivated us to carefully re-examination the formulation of toroidal angular momentum and poloidal rotation continuity equations found in Staebler 2004 [1] paper. Our work provides a more explicit formulation for evaluating the turbulent components with the GYRO gyrokinetic code [2] simulations in real tokamak geometry. While GYRO with finite parallel velocity shear providing a Kelvin-Helmholtz drive has been simulating toroidal angular momentum transport since 2003, the radial flow of toroidal angular momentum is now broken into components from the radial-parallel, and radial-perpendicular stress tensors, as well as the convective flow of toroidal angular momentum to better understand the origin of *pinched flows* and how they are affected by ExB velocity shearing. Previous quasi-linear estimates in slab geometry treating parallel and ExB shear independently found *pinched flows* possible [3]. Parallel velocity shear and perpendicular ExB shear are, of course, physically related via radial force balance and the ion pressure gradient profile. Finite parallel velocity (not just sheared parallel velocity) has recently been added to test a possible additional source of pinching in toroidal geometry [4]. Mapping the parametric dependence of core toroidal angular momentum transport and pinch conditions is our key focus. We also use GYRO to evaluate a possible *source* of toroidal angular momentum from the small non-ambipolar component of radial magnetic flutter particle flow. In the core at least, the turbulent viscose transport and source forcing are expected to be small compared to the strong neoclassical magnetic pumping which drags the poloidal rotation to the neoclassical level. However a key point of Ref. 1 is that turbulence can provide some *shift* in the neoclassical poloidal rotation. We use GYRO simulations to determine the size of the shift at finite rho-star.

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TEMPEST Simulations of the neoclassic radial electric field and bootstrap current*

X. Q. Xu, and Z. Xiong

Lawrence Livermore National Laboratory, Livermore, CA 94550 USA

TEMPEST is a a fully nonlinear (full-f) five dimensional (3d2v) gyrokinetic continuum edge-plasma code. The geometry can be circular annulus or that of a diverted tokamak and so includes boundary conditions for both closed magnetic flux surfaces and open field lines. The most of simulations presented here are carried out for large aspect ratio circular geometry. The ion density and temperature profiles are initialized as a tanh function of radius centered around the middle of simulation domain $[N(x) = n_0 + n_m \tanh((x - x_m)/\Delta_n)]$. Two electron models are used. For calculation of the electric field, the electron model is Boltzmann $n_e = \langle n_i(\psi, \theta, t = 0)\rangle \exp(e\phi/T_e)/\langle \exp(e\phi/T_e)\rangle$, where $\langle\rangle$ represents the flux surface average. This choice of coefficient for Boltzmann electron model means that there is no cross field electron transport. For the calculation of the bootstrap current, a kinetic electron model is used. The neoclassical radial electric field from TEMPEST simulations agrees with the standard neoclassical expression $\langle U_{i\|}\rangle = (cT_i/Z_i e B_p)\,[k(\partial \ln T_i/\partial r) - (\partial \ln P_i/\partial r) - (Z_i e/T_i)(\partial\langle\Phi\rangle/\partial r)]$. The radial electric field is generated due to the neoclassical polarization and the relative maximum charge separation is only 0.4%. A time history of the flux surface averaged electric potential shows clean geodesic acoustic oscillations generated by the initial conditions, which then relax to a steady state, consistent with the previous studies [1,2]. The bootstrap current from TEMPEST simulations with both kinetic ions and electrons are compared with Sauter's model [3]. Comparisons with theory for systematic scans in safety factor q and collisionality will be discussed. The impact of the magnetic separatrix and the Scrape-Off-Layer physics on the radial electric field and bootstrap current will be reported.

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1C22

Gyrokinetic simulations of particle transport, plasma turbulence and zonal flows in a closed eld line geometry

B. N. Rogers, S. Kobayashi

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

P. Ricci

Centre de Recherches en Physique des Plasmas (CRPP), Lausanne, Switzerland

W. Dorland

University of Maryland, College Park, MD

Abstract

Plasma turbulence due to small scale entropy modes is studied with gyrokinetic simulations in a simple closed field line geometry, the Z-pinch, in low-β parameter regimes that are stable to ideal interchange modes. We find an enormous variation in the nonlinear dynamics and particle transport as a function of the plasma β, the density gradient, and the plasma collisionality. At very low values of $\beta \ll 1$, the dynamics are interchange-like and electrostatic with $k_{\|} \simeq 0$. The transport in this regime is governed by the damping and stability properties of spontaneously formed zonal flows in the system. As in toroidal systems, the zonal flows can lead to a strong nonlinear suppression of transport below a critical gradient that is determined by the stability of the zonal flows. In contrast, at small but finite β, new electromagnetic modes emerge with finite $k_{\|}$. In some parameter regimes these modes saturate at high amplitudes and drive very large transport levels.

1C23

Edge and scrape-off layer flows and their role in L-H transition and core rotation

A. Y. Aydemir

Institute for Fusion Studies

The University of Texas at Austin

Austin, TX 78712 USA

Shear flows in the scrape-off layer (SOL) and the edge pedestal region of tokamaks are shown to arise naturally out of transport processes in a magnetohydrodynamic (MHD) model. In quasi-steady-state conditions, collisional resistivity coupled with a simple bootstrap current model necessarily leads to poloidal and toroidal flows, mainly localized to the edge and SOL. Role of these flows in the grad$-B$ direction dependence of the power threshold for the L (low) to H (high) transition, and their effect on core rotation are discussed. Theoretical predictions based on symmetries of the underlying equations, coupled with computational results, are found to be in agreement with observations in Alcator C-Mod [Phys. Plasmas **12**, 056111-1 (2005)]. Effects of these self-consistent flows on linear peeling/ballooning modes and their nonlinear consequences are also examined.

1C24

Thermal instability caused by plasma-wall interactions*

S. I. Krasheninnikov[1], T. T. Soboleva[2], A. Yu. Pigarov[1], and I. V. Dobrovolskaia[1]

[1]*University of California at San Diego, 9500 Gilman Dr., La Jolla 92093 USA*
[2] *ICN, Universidad Nacional Autónoma de México, México D.F. 04510, Mexico*

In Ref. [1] it was shown both analytically and numerically that the interactions of plasma with first wall saturated with hydrogen can cause thermal instability resulting in massive desorption of gas from the wall. In a tokamak it can lead to the formation of MARFE, transition to detachment, or even disruption. The physics of this instability is related to the positive loop associated with an increase in neutral desorbing rate with increasing wall temperature and the further increase of wall temperature caused by an increase of heat flux to the wall caused by charge exchange and radiation loss of plasma energy.

In this paper, we extend 0-D model from Ref. [1] by using 1-D approximation for plasma and wall energy and particle balance. We analyze both stability condition and growth rate of thermal instability and compare our results with both 0D model from Ref. [1] and available experimental data.

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ELMs explained as resistive vacuum modes excited by SOL current onset

L.-J. Zheng,[a] J. W. Van Dam,[a] M. T. Kotschenreuther,[a]
H. Takahashi,[b] and E. D. Fredrickson[b]
[a]Institute for Fusion Studies, University of Texas at Austin, Austin, TX 78712
[b]Princeton Plasma Physics Laboratory, Princeton, NJ 08543

Abstract: Various theories[1] for ELMs have been proposed before, for example, peeling-ballooning, edge Taylor relaxation, blobs, *etc.* Here we present an alternative theoretical explanation, motivated by the recent DIII-D experimental observation that ELMs and SOL current onset occur simultaneously and the strength of the SOL current is consistent with the magnitude of the magnetic perturbations measured at the wall (see Fig. 1a).[2] We propose that the excitation of resistive vacuum external modes (RVMs) during SOL current onset could be an explanation for ELMs. Although wall effects are weak for high-n modes, a vacuum region with resistive plasma can play a similar role to a resistive wall. High-n RVMs can be excited above a critical plasma beta limit and then resonantly enhanced by SOL current onset. In turn, enhanced MHD activity causes stronger radial transport and induces a larger SOL current. This process explains the initial bursting nature of ELMs. The radial transport also reduces the pedestal pressure gradient, which stabilizes RVMs in the later ELM stage. The ELM cycle repeats when heating again increases the beta value. Using the Staebler and Hinton model[3] for describing the SOL current, the RVM equation with SOL current as a source term can reproduce the ELM cycles (see Figs. 1b and 1c).

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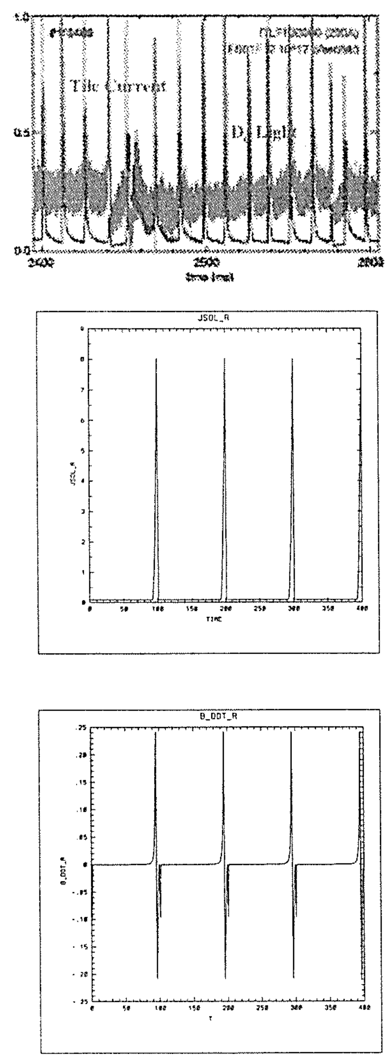

FIG. 1: a) DIII-D experimental observation[2] showing the coexistence of ELMs (in blue) and SOL current (in red); b) theoretical result for SOL current; c) theoretical result for $\delta\dot{B}$.

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Gyrokinetic Study of Trapped Electron Mode in the Edge Plasma

Yong Xiao and Zhihong Lin

Physics and Astronomy, University of California at Irvine

Global gyrokinetic particle simulations using the GTC code find that the trapped electron mode (TEM) can be driven unstable in regions with steep density gradient. The short wavelength fluctuations of TEM turbulence is found to be capable of driving a large electron heat flux without driving significant ion heat and particle fluxes. The properties of the TEM turbulence is studied using plasma parameters relevant to tokamak edge regions with high value of safety factor and short scale length of pressure gradients. The relative importance of zonal flow and GAM in regulating the turbulence will be clarified.

Relevant Advances of the Ignitor Program*

F. Bombarda[1], A. Airoldi[2], B. Coppi[3],G. Cenacchi[4], P.Detragiache[1], D. Farina[2]
[1]ENEA, Italy
[2]Istituto Fisica del Plasma, CNR, Milan Italy
[3]Massachusetts Institute of Technology, Cambridge, MA, USA
[4] Formerly ENEA, Italy

The main purpose of the Ignitor experiment [1] is to identify the "fusion reactor physics" relevant to devices capable of producing net energy. That reactor relevant plasma regimes require $Q > 50$ is well understood by now [2] and consistent with this, Ignitor is designed to produce regimes close to ignition $(Q \rightarrow \infty)$ where the "thermonuclear instability" can set in with all its associated non-linear effects. At this time the only appropriate magnet solution to reach this objective is the adoption of normal-conducting [2] cryogenic technology. Furthermore, experiments without a divertor chamber, a characteristic of the Ignitor design, can sustain higher currents and therefore achieve better confinement parameter [2] for equal overall sizes and magnetic field values, relative to devices that have this component. The broader range of accessible plasma regimes, adopting both "extended first-wall" and "double-null" plasma equilibrium configurations in Ignitor, are discussed. In fact, since the process of attaining ignition has been investigated extensively by a appropriate numerical simulations [1], the more recent efforts have been devoted to identify the conditions where the thermonuclear instability is barely prevented over the entire length of the current pulse, to define the parameter space that can be covered by accessing H-mode regimes, and to simulate the plasma performances at lower field and currents. While tritium is the necessary step forward of any advanced fusion facility, Ignitor can provide novel and important results even when limited to operate with H, D, and He plasmas in the early phase of its experimental life. The completion of the detailed machine design, the technological solutions adopted for the Ignitor design, and the ongoing R&D activities are also described. The role of Ignitor, in the context of a "science first" approach to the development of a fusion energy program, is identified. *Sponsored in part by ENEA of Italy and by the U.S. D.O.E.

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Confinement Regime Transition Connected to Spontaneous Rotation Reversal and Collision Rates at the Plasma Edge*

C. Di Sanzo, B. Coppi and M. Landreman
Massachusetts Institute of Technology

The transition between the L and the H confinement regimes is associated with the reversal of the phase velocity of the unique kind of collisional ballooning modes that can be excited at the edge of the plasma column. These modes are driven by the combined effects of the plasma pressure gradient and the magnetic field curvature, and involve in an essential way the electron-ion collision rate (resistivity) to break the "frozen in law", and the ion-neutral and the ion-ion collision rates. According to the "accretion theory" [1,2,3] the excited modes eject plasma angular momentum in the same direction as that of their phase velocity and the plasma spontaneous rotation resulting from the recoil is inverted when the phase velocity is inverted. The reversal of spontaneous rotation in the transition from the L to the H-regime is a well established experimentally. The relevant reversal condition is observed to be of the same type as that found years ago [4] in order to identify for the first time collisional drift modes in Q-machine experiments. Accordingly, a transition parameter can be written as $H_c = -\left(\mathrm{v}_{*e}^{T}/\mathrm{v}_{\mathrm{di}}\right)\omega_A^2/\left(D_m k^2 \nu_i\right)$ with $H_c > 1$ corresponding to the H-regime. Here ν_i is the total ion transverse momentum loss rate (collisional and anomalous), k is the transverse mode number, $\mathrm{v}_{*e}^{T} = -c/(eB)\left[(dT_e/dr)(1+\alpha_T) + (T_e/n)dn/dr\right]$, $\alpha_T \simeq 0.7$, $\mathrm{v}_{di} = \left[c/(eBn)\right](dp_i/dr)$, $\omega_A = \left|k_{\|}\mathrm{v}_A\right|$, $D_m = \nu_{ei}^{\|} c^2/\omega_{pe}^2$, and $\mathrm{v}_A^2 \equiv B^2/(4\pi n m_i)$ and ρ_i is the ion gyro radius. The relative effect of ion collisions becomes important as the edge temperature decreases and the density increases. Then the mode phase velocity is in the direction of the ion diamagnetic velocity. When the effects of ion collisions tend to fade away, the mode phase velocity is in the opposite direction and the mode growth rate increases. The quality of confinement that improves as the H-regime is accessed is associated with the rate of expulsion of angular momentum. Accordingly, recent experiments indicate that the spontaneous rotation slows down when the neutral population at the edge is increased. *Sponsored in part by the U.S. Department of Energy.

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Finite Electron Temperature Effects on Interferometric Measurements in Fusion Plasmas

V. V. Mirnov[1,2], W. X. Ding[1,3], D. L. Brower[1,3]

[1]Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas
[2] University of Wisconsin-Madison, WI 53706
[3]Plasma Science and Technology Institute, Univ. of California at Los Angeles, CA 90095

The refractive indices and evolution of polarization for high-frequency electromagnetic waves in magnetized plasmas are of major interest for plasma density and magnetic field diagnostics. Recently, the effects of thermal electron motion were investigated and found to be measurable in the electron temperature range typical for JET , ITER and other high-temperature tokamaks [1]. The lowest order linear corrections in τ ($= T_e/m_ec^2 << 1$) to interferometric effects (including conventional interferometry, Faraday rotation and Cotton-Mouton effects) were calculated on the basis of non-relativistic dielectric tensor ε_{ij} for magnetized plasmas. This approach was justified by arguing that at wave frequencies ω significantly higher than the electron gyrofrequency ω_{ce} relativistic effects can be ignored. We revisit this problem by analyzing the relativistic kinetic equation for a high-temperature magnetized plasma and show that relativistic corrections are important for $\omega >> \omega_{ce}$. They are also linear with τ, being comparable to the non-relativistic corrections but with opposite sign. Indeed, the non relativistic thermal corrections are caused by the Doppler shift of the frequency $\omega - \mathbf{kv}$. After averaging over the Maxwellian distribution, these dispersive corrections lead to a decrease of the refractive index $N=kc/\omega$ by a factor $\propto \tau N^2$. In contrast, relativistic corrections are not $\mathbf{k}$ dependent and result from a relativistic increase of the electron mass $m_e\gamma$ in the ω_{pe} and ω_{ce} terms. This is caused by the γ dependence on velocity, $\gamma - 1 \approx \tau$, that increases the refractive indices. We find that the combination of both mechanisms results in a relative change of the interferometric phase, Faraday angle and Cotton-Mouton effect by factors $(N^2 - 5/2)\tau$, $(3N^2 - 5)\tau$ and $(12N^2 - 15/2)\tau$, respectively. The coefficients $N^2 \approx 1$, $3N^2 \approx 3$ and $12N^2 \approx 12$ were found in [1] while the additional factors -5/2, - 5 and -15/2 result from the relativistic calculations. Thus, both dispersive and relativistic effects are essential to correctly interpret interferometric measurements. For plasma with $T_e \sim 10$ keV, the thermal corrections are 3% for the interferometric phase, - 4% for the Faraday effect and 9% for the Cotton-Mouton effect.

*Supported by the U.S. DoE and NSF.

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AN UPGRADE OF THE UNIFIED FLUID/KINETIC MODELS OF MAGNETIZED PLASMAS

M.K. Addae-Kagyah, E.D. Held

Physics Department, Utah State University
Logan, UT 84322-4415

A method for upgrading the three fundamental plasma fluid evolution equations with more physically accurate kinetic closures is presented. The resulting unified fluid/kinetic equations for three perturbed plasma fluid quantities (density, parallel flow and temperature), developed in a sheared slab geometry, are off-shoots of the previous work by Chang and Callen. This hybrid approach to plasma kinetic modeling effectively incorporates kinetic physics into fluid models and provides accurate description of micro-instabilities. The method is more robust, in assessing the behavior of plasma systems of arbitrary collisionality and adiabaticity, than several regime-dedicated models (such as MHD). The generalized kinetic closures (based on the CEL ansatz) are formulated as in the work of Chang and Callen (in which the the plasma drift kinetic equation (DKE) is Fourier-transformed, in time and space). Held's work on generalized closures; and Ji and Held's work on exact linearized Coulomb collision operators also provided the theoretical basis and justification for this work. Two specific aspects of the fluid/kinetic model were overhauled to improve accuracy and physical responsiveness. First, the approximate Lorentz scattering operator, applied in Chang and Callen; and Held et al, is replaced by the exact linearized Coulomb collision operator. Second, the steady state assumption (in the DKE), applied in Held et al, is obviated, and the time-dependent term ($\partial F / \partial t$) is retained. The physical repercussion is that the kinetic distortion, F, solved for in the DKE, is time-dependent, and yields more accurate closure relations for $\hat{\boldsymbol{b}}.\nabla.\Pi_{\parallel}$ and $\vec{\boldsymbol{q}}$, as well as other higher-order moments of F. In effect, the plasma evolution equations (for momentum and energy), closed with such upgraded closures, would capture more accurate kinetic physics in simulations, and also highlight many kinetic-based phenomena which are inaccessible through pure fluid models. The accuracy and efficacy of this upgraded model is tested and validated through the analysis and simulation of ion stress damping of ion acoustic modes. Preliminary results of these tests indicate that the upgraded model captures more kinetic physics, and is robust.

Global beta-induced Alfvén-acoustic modes in JET and NSTX

N. N. Gorelenkov[†], H. L. Berk[‡], E. Fredrickson[†], S. E. Sharapov[♭]

[†]Princeton Plasma Physics Laboratory, Princeton University; [‡]IFS, Austin, Texas; [♭]Euroatom/UKAEA Fusion Assoc., Culham Science Centre, Abingdon, Oxfordshire

An area where up to now there has only been sporadic investigation [1, 2] but where pertinent wave particle interactions in burning plasma regimes need to be investigated, is the study of the linear interaction of two fundamental waves in MHD theory, the Alfvén and acoustic waves. The interaction is mediated by finite pressure, plasma compressibility and geodesic curvature. As a result of such interaction additional gaps in the coupled Alfvén - acoustic continuum emerge [2, 3] and here we present an analytic model for the structure of these gaps. In addition their Alfvén - acoustic continuum has extrema with respect to the radial position, which arise in the gaps or in the low shear regions. We find numerically that global modes may occur adjacent to these extrema points. We call these modes Beta-induced Alfvén - Acoustic eigenmodes (BAAE) and we find that these modes can arise in both relatively low and high beta plasmas.

Here we investigate whether unexplained data in JET (relatively low beta) and NSTX (relatively high beta) can be attributed to the excitation of BAAE's. Numerical calculations for monotonic and reversed q-profiles on JET (using the ideal MHD code NOVA) show that the BAAE modes evolve from almost zero frequency when q_0 or q_{min} crossed rational values to a maximum value around $f \simeq 40kHz$ in the plasma frame, limited by the Alfvén - Acoustic gap frequency. Although JET observations show a qualitatively similar frequency evolution, they are bounded by a lower frequency value of $f \simeq 14kHz$. Near the lowest possible frequency of the mode, the wave form is quite similar to that of a shear-Alfvén wave which is characterized by line bending polarization with a modified dispersion from the conventional shear-Alfvén wave dispersion.

In NSTX with plasma beta around 20% the same BAAEs are found numerically and there are oscillations in NSTX that can be explained as being due to BAAE instabilities. They are localized near the region of low shear in plasmas with a reversed magnetic shear profile as evidenced in both NOVA simulations and in the reflectometer observations. In this case the frequency is about half of the TAE frequency, which in NSTX is close to the geodesic acoustic modes (GAMs) frequency.

In contrast to the mostly electrostatic polarization of GAMs, the new global modes contain an electromagnetic component due to the interaction with the Alfvén branch. As these global modes have a substantial magnetic component, the resulting component of the phase velocity along the field line is substantially greater than the sound velocity. Consequently, the use of fluid equations is justified, but with an appropriate modification of the adiabaticity index which is determined by kinetic theory for a collisionless plasma which will also induce an intrinsic damping term.

By understanding the range of BAAE frequency excitation we may be able to extend the use of so-called MHD spectroscopy and by using frequency observations in this new regime to determine q_0. Such an observation would be a very important diagnostic tool for ITER and other burning plasma experiments. This observation would also help infer the central plasma beta and the ion and electron temperatures.

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SHOCKS AND DISCONTINUITIES IN THE HALL-MHD MODEL

Eliezer Hameiri
Courant Institute of Mathematical Sciences
New York University, New York, NY

There are a number of papers published in the literature[1,2] which present fundamentally incorrect results about shocks and other discontinuities possible within the Hall-MHD model. The basic mistake is that the previous works assume that the jump conditions across a discontinuity must be local, connecting values of every field profile in the same location on both sides of the discontinuity. But this is incorrect, since the electrons are "massless" within this model and are thus able to travel with "infinite" speed within the surface of discontinuity entering in one location and exiting in another.

In order to resolve this issue, we first work out an explicit example of a discontinuous magnetic field in a cylindrical configuration, where nonlocality of the jump condition can be demonstrated. We then work out the shock structure problem for general shocks, and show that only a small number of discontinuities is allowed within the Hall-MHD model. As the shock strength diminishes, we show that the results converge to the dispersion relations of Hall-MHD waves.

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A closure scheme for modeling RF modifications to the fluid equations*

C. C. Hegna and J. D. Callen
Department of Engineering Physics, Unverisy of Wisconsin
Madison, WI 53706-1609

Abstract

In an effort to combat the deleterious effects of neoclassical tearing modes in high performance tokamaks, a campaign to use localized current drive [principally electron cyclotron current drive (ECCD)] has proven effective [1]. Prior theoretical efforts to model this physics relied on using a modified Rutherford equation including the effects of an ad hoc RF current drive term [2,3]. Seeking a more rigorous fluid model for use in MHD simulation codes, we outline a procedure treating this problem as a closure issue. The fluid equations are evolved with the addition of RF sources coupled with a closure scheme modified by the RF physics. Starting from a kinetic equation of the form $df/dt = C(f) + Q(f)$, where $C(f)$ and $Q(f)$ represents the collision operator and effects of the RF fields, respectively, one can take moments and construct the usual fluid equations. These equations are augmented by additional terms due to the RF source. A complete derivation requires the specification of the closure moments; calculations for the stress tensors and heat fluxes are needed. If we treat the RF term as producing a small distortion of the distribution function from Maxwellian, a problem similar to classic Spitzer problem can be formulated. Using a Chapman-Enskog-like approach, a kinetic equation for the distortion away from the Maxwellian can be derived that includes the RF-induced contributions to the fluid equations as sources. This kinetic equation will be solved in a number of limiting cases. Discussions of how more detailed solutions might be obtained will be addressed.

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Nonlinear excitation of geodesic acoustic modes by drift wave like modes*

N. Chakrabarti
Saha Institute of Nuclear Research, 1/AF Bidhannagar, Kolkata 700064, India

R. Singh and P. K. Kaw
Institute for Plasma Research, Bhat, Gandhinagar,382428, India

P. N. Guzdar
Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, MD 20742, USA

In this paper we present mode-coupling methods for the nonlinear excitation of the geodesic acoustic modes (GAMs) in tokamak plasmas by drift waves. The first approach is a coherent parametric process, which leads to a three-wave resonant interaction. This investigation allows for the drift waves and the GAMs to have comparable scales. The second approach uses the wave-kinetic equations for the drift waves which then couples to the GAMs. This requires that the GAM scale length be large compared to the drift-wave wave packets. A specific scaling of the radial wave number of the GAM excited by the drift waves is derived, which is in agreement with some recent observations as well as numerical simulations.

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1C35

Two-fluid Extended-MHD Calculations of Collisionless Reconnection in Magnetized Plasmas with a Strong Guide Field

S.C. Jardin[1], N. Ferraro[1], J. Breslau[1], A. Bauer[2], K. Jansen[2], M. Shephard[2], and the M3D team

[1]*Princeton University Plasma Physics Laboratory, P. O. Box 451, Princeton, NJ 08543*

[2]*Renssalaer Polytechnic Institute, Troy, NY*

We have developed a new, high-order, implicit method for solving the time-dependent extended-magneto-hydrodynamic (X-MHD) equations in two dimensions [1], [2], [4] and have applied this to the problem of collisionless magnetic reconnection in the presence of a strong guide field. The reconnection calculations extend the GEM [5], [4] reconnection problem to include a strong background (guide) magnetic field as is present in a fusion plasma. We find that the background field significantly delays the onset of the fast reconnection phase and reduces the maximum reconnection rate and the amplitude of the velocities that develop in the reconnection region. The flow structure changes to be nearly incompressible and its localization presents severe resolution requirements. These calculations are performed with a new simulation code, M3D-C^1, which uses a fully unstructured triangular mesh that is packed into regions with high gradients, but the time-step is limited only by resolution requirements. Each finite element contains a complete 4th degree polynomial with additional terms to provide C^1 continuity across element boundaries as required to efficiently solve the stream function/ potential form of the equations including the high-order derivatives that appear in the electron and ion viscosities.

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"Sawteeth" and non-axisymmetric equilibria of the internal kink mode in a periodic boundary driven screw-pinch.

V. S. Lukin[a], S. C. Jardin
Princeton Plasma Physics Laboratory

Abstract

We numerically study the non-linear evolution of the m=n=1 internal kink mode in 2D helical geometry. Initial value problem is solved with a macroscopic modeling code SEL[1], by making full use of adaptive implicit time-stepping and adaptive grid of spectral elements. Incompressible Hall MHD equations are presently evolved and are being extended to a two-pressure system with anisotropic temperature dependent diffusion coefficients. Both resistive and two-fluid evolution of the ideally unstable initial condition through a reconnection cycle is demonstrated. A new self-generated quasi-equilibrium is then observed to be produced by an axial electric field applied at the boundary and an assumed peaked radial profile of conductivity. Plasma is then shown to enter into a "sawtooth-like" periodic behavior which appears to be independent of the initial conditions. The dependence of the period and shape of the sawteeth on plasma viscosity, screw-pinch aspect ratio, and other plasma parameters is evaluated. Additionally, existence of a family of stable ideal and resistive non-axisymmetric equilibria in a low aspect ratio screw-pinch is demonstrated. [1] A.H. Glasser and X.Z. Tang, Comp. Phys. Comm. **164**, 237 (2004).

[a] *E-mail address: vlukin@princeton.edu*

Calculations of extended magnetohydrodynamic equilibria with an implicit, high-order finite element code

N. M. Ferraro, S. C. Jardin, and J. A. Breslau

Princeton Plasma Physics Laboratory, Princeton, NJ 08543-0451

A. C. Bauer

Rensselaer Polytechnic Institute, Troy, NY 12180-3590

M3D-C^1 is a code for the numerical simulation of the nonlinear, axisymmetric extended magnetohydrodynamic (X-MHD) equations, in slab or toroidal geometry. Toroidal equilibria are calculated as the steady state of the axisymmetric X-MHD equations and include the e ects of gyroviscosity [1], Hall terms, and self-consistent flow. The calculation is extended across the separatrix into a vacuum region that is represented as a high-resistivity plasma. These high-resolution equilibria can form the starting point for linear and non-linear two-fluid studies of 3D perturbations and instabilities. In order to achieve a high degree of computational efficiency, the code employs an implicit time advance, reduced quintic finite elements [2], a fully unstructured mesh, and parallelization. The continuous first-derivative (C^1) property of the finite elements enables the use of the flux- and stream-function forms of the magnetic field and velocity without needing to define auxiliary variables. The relatively low asymptotic degrees of freedom of the finite element allow direct matrix inversion using SuperLU_dist [3]. Simulations of magnetic reconnection, in which high resolution near the X-point is necessary, demonstrate the substantial advantage in computational efficiency conferred by the unstructured mesh.

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Model for the High-Rotation to Ordinary-Mode Transitions observed in MCX.

Imran Shamim, Catalin Teodorescu, P. N. Guzdar, A. B. Hassam, R. Clary, R. Ellis, R. Lunsford

University of Maryland, College Park

The Maryland Centrifugal Experiment (MCX) undergoes a transition in which it makes an abrupt transition from a good confinement high-rotation state (HR-mode) to a lower rotation confined state (the O mode). To model this transition a 2D time-dependent MHD code is used to determine the dynamical equilibrium states of the MCX configuration. An additional momentum loss term is added to the system of equations to model the coupling of the plasma to the neutrals in the vicinity of the two insulators at the mirror throats. An input momentum source is treated as a control parameter to drive the poloidal rotation which in the machine is accomplished by the radial electric field and the ensuing ExB rotation. It is found that for small values of the source, the confined state is a low confined state since the plasma is not effectively centrifugally confined and hence experiences additional drag from the neutrals in the vicinity of the insulators. However, at a critical forcing the plasma makes an abrupt transition to a good centrifugally confined state in which the plasma has pulled away from the end insulator plates. As it pulls away the drags from the neutrals in the throat region decreases which further increases the rotation thereby leading to better centrifugal confinement. The good confined state is reached when the momentum source balances the diffusive.
In the experiment it the reverse transition that occurs.

Modeling of the Plasma Response to Resonant Magnetic Perturbations with the NIMROD Code

S.E. KRUGER, Tech-X Corporation, I. JOSEPH, Univ. of California-San Diego, T.E. EVANS, General Atomics, R.A. MOYER, Univ. of California-San Diego

Resonant magnetic perturbations (RMPs) have successfully been used to control ELMs in the DIII-D tokamak[1] In these experiments, internal coils are used to tailor the mode amplitude spectrum at the separatrix with the goal of affecting transport at the edge. Intuitively, inducing islands at the separatrix would cause a stochastic edge and enhanced electron temperature transport; however, experimental evidence shows that both the ion and electron temperature gradients are relatively unchanged, while the density gradient is substantially reduced. Modeling of these experiments by initial-value extended magnetohydrodynamics codes is attractive because the essential features, magnetic reconnection, parallel and perpendicular transport, and ELM stability have all been independently studied with these codes. The challenge of modeling the experimental device lies in the extreme range of time scales with the ramp rate of I-coil currents being on the order of milliseconds and the Alfven time being sub-microseconds. Here we show results of modeling just the the field error penetration problem. We extend the numerical simulations of Fitzpatrick[2] to three-dimensional geometry (slabs, cylinders, and tori) and two-fluid physics.

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A family of analytic equilibrium solutions for the Grad-Shafranov equation

J.P. Freidberg, L. Guazzotto
Plasma Science and Fusion Center
Massachusetts Institute of Technology

In toroidal system, such as the tokamak, magnetohydrodynamic equilibrium is routinely described by means of the well known Grad-Shafranov (GS) equation. Despite this, analytic solutions of the equation are few and far between, and the equilibrium is normally computed with the help of numerical tools. Equilibrium codes are nowadays very reliable. Even so, it is worthwhile to investigate the existence of analytic equilibria of the GS equation, for two reasons. First, it is useful to provide one more benchmark case to test existing codes. Second, the possibility of expressing all equilibrium properties exactly may allow us to study stability problem without the use of big stability codes, or to have an arbitrarily accurate input equilibrium for such codes. In this work, we present a technique to solve the GS equation for special, but realistic, profiles of the free functions of the magnetic flux. Our solution allows us to retain arbitrary plasma elongation and triangularity while setting the edge current and pressure gradient to zero.

1C41

Bifurcated states of the error-field-induced magnetic islands

B. Li, L.-J. Zheng, and R. D. Hazeltine
Institute for Fusion Studies, University of Texas at Austin, Austin, TX 78712

Abstract

We find that the formation of the magnetic islands due to error fields shows bifurcation when neoclassical effects are included.[1] The result is displayed in Fig. 1. In this figure, the island width shows two branches, denoted by $\hat{w}_{\pm}$, respectively. The quantity $\hat{J}_e$ specifies the strength of the error field, with $\hat{J}_e = 0.2$ corresponding roughly $\delta B \sim 10^{-4}$. The bifurcation, which follows from including bootstrap current terms in a description of island growth in the presence of error fields, offers possible theoretical explanations for three experimentally observed phenomena: (1) the bifurcation feature of the critical rotation frequency with respect to the rotation braking by error field or by counter neutral beam injection observed in DIII-D[2] and JT-60 tokamaks;[3] (2) the hard beta limit encountered by the JT-60 tokamak without ferritic steel tiles;[3] and (3) the sudden rotation speed drop at the beta value between the no wall limit and the onset of resistive wall modes observed in DIII-D tokamak.[4]

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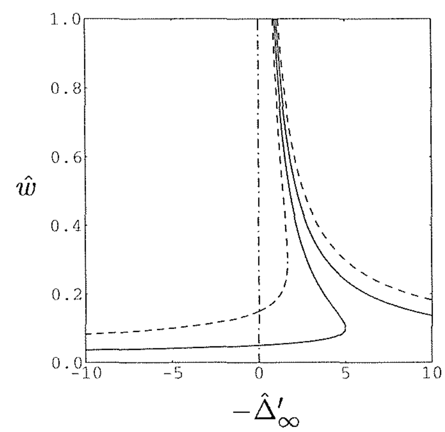

FIG. 1: Island width $\hat{w}$ versus $-\hat{\Delta}'_{\infty}$, with $\hat{J}_e$ as parameter. The solid curve is for $|\hat{J}_e| = 0.2$ and the dashed curve for $|\hat{J}_e| = 0.6$. The lower left curve is the $\hat{w}_+$ ($\hat{J}_e < 0$) solution, the upper right curve is the $\hat{w}_-$ ($\hat{J}_e > 0$) solution and the middle curve is the $\hat{w}_-$ ($\hat{J}_e < 0$) solution.

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1C42
Magnetic Islands Driven by External Perturbations

N. F. Loureiro,[a,b] A. H. Boozer,[c]

[a] *CMPD, University of Maryland, College Park, MD 20742, USA*
[b] *PPPL, Princeton University, Princeton, NJ 08543, USA*
[c] *Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10027*

We have made a computational study of time evolution of externally driven islands using both single fluid reduced-MHD and a two fluid model that contains the effects of the ion finite Larmor radius. The work is focused on two applications. (1) The response of a stellarator plasma to island causing perturbations and (2) the shielding of driven islands by plasma rotation, which is major issue for ITER. A stellarator with a small equilibrium current allows essentially complete experimental control on the perturbation that drives an island–its strength and its time history. The shielding current that is concentrated in the spatial region of the island produces a magnetic field that can be detected outside of the plasma and provides a simple method of comparing theory and experiment over a wide range of physics regimes. In a tokamak, such as ITER, the plasma can amplify externally produced perturbations making the magnetic perturbation that drives the island far stronger than would be expected from the field produced by currents outside the plasma alone. A major issue is degree to which plasma rotation relative to the external perturbation can sustain a shielding current concentrated in the spatial region of the island. The sustainment of the shielding current makes the steady-state island width far narrower than would otherwise be expected. We are making computational studies of this shielding and the drag force on the plasma rotation, which is the source of energy for maintenance of the shielding currents against the dissipation of plasma resistivity.

Calculations of helically symmetric equilibria with PIES

D. A. Monticello, A. H. Reiman, and D. Raburn
Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton NJ 08543, USA

We present calculations of helically symmetric equilibria with the PIES code. A number of improvements have been made to the PIES code that should improve its convergence properties. We have tested these improvements on helical equilibria. Comparison with a helical Grad-Shafranov solver will be presented. Results from a Newton solver will also be presented.

Intermediate Nonlinear Ballooning Instability *

P. Zhu and C. C. Hegna
Center for Plasma Theory and Computation
University of Wisconsin-Madison

Abstract

Filamentary finger structures and their localization in the bad curvature region have been observed in recent MAST experiments [1] and NIMROD simulations [2] due to edge localized modes (ELMs). They are the indications that the ballooning instability of the pedestal region continues to play a dominant role in the nonlinear development of ELMs. In this work, we derive a set of MHD equations for the ballooning instability in the intermediate nonlinear regime. In this regime, the plasma displacement across the field line in the direction of pressure gradient is comparable to the mode width in the same direction. This width is also at the order of the pedestal width near marginal stability. Thus in the intermediate regime, the nonlinear displacement of ballooning instability is able to distort and destruct the entire pedestal region. This work is an extension of an earlier theory on the intermediate nonlinear regime of a line-tied g mode, which is a prototype model for ELMs [3,4]. Comparison with the theory on the ballooning instability in early nonlinear phase [5] will be discussed.

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Derivation of Paleoclassical Key Hypothesis

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

Recently, a derivation has been developed [1] for the key hypothesis of the paleoclassical model [2] — that electron guiding centers diffuse radially with thin annuli of poloidal magnetic flux ψ_p in axisymmetric current-carrying, resistive toroidal (e.g., tokamak) plasmas. The hypothesis results from transforming the drift-kinetic-equation (DKE) from laboratory to poloidal flux coordinates ψ_p, θ, ζ in situations where ψ_p is governed by a diffusion equation. In driven-dissipative poloidal magnetic field systems such as tokamaks, the particle trajectories are no longer governed by Hamilton's equations — at least not on the magnetic field diffusion time scale $\tau_\eta \equiv a^2/6D_\eta$. To determine the effective guiding center trajectories in such a situation one analyzes the mathematical charactertistic curves of the transformed DKE. On the bounce and drift time scales the guiding center trajectories exhibit the usual Hamiltonian-based oscillations about average ψ_p surfaces (banana center for trapped particles). In particular, they are governed by the constancy of the guiding center canonical toroidal angular momentum $p_{\zeta g} = mIv_\parallel/B - q\psi_p$; they are thus "tied to" the local poloidal flux ψ_p. On the longer magnetic field diffusion time scale $\tau_\eta \equiv a^2/6D_\eta$ the poloidal flux $\psi_p(\bar{\rho}_g)$ at the average radial guiding center position $\bar{\rho}_g \equiv \bar{\mathbf{x}}_g \cdot \boldsymbol{\nabla}\rho$ ($\rho \equiv \sqrt{\psi_t/\psi_t(a)}$) and hence $p_{\zeta g}$ are found [1] to obey a magnetic diffusion equation, which yields an equation for the average radial guiding center position $\bar{\rho}_g$:

$$\frac{\partial \bar{\rho}_g}{\partial t} + \bar{u}_G \frac{\partial \bar{\rho}_g}{\partial x} = -\bar{u}_{\dot{\psi}} + \bar{D}_\eta \frac{\partial^2 \bar{\rho}_g}{\partial x^2}, \qquad \bar{D}_\eta \equiv \frac{D_\eta}{\bar{a}^2} \equiv \frac{\eta_\parallel^{\mathrm{nc}}/\mu_0}{\bar{a}^2}, \quad \text{magnetic diffusivity,} \tag{1}$$

in which x is a dimensionless local radial coordinate, $\bar{u}_G$ is the "Grid velocity" of toroidal flux surfaces relative to laboratory coordinates and $\bar{u}_{\dot{\psi}} \equiv -\dot{\psi}/\psi_p'$, $\dot{\psi} \equiv D_\eta \Delta_0^+ \psi_0 - S_\psi$ ($\neq 0$ for transients). The radial motion $\bar{u}_{\dot{\psi}}$, advection $\bar{u}_G$ and diffusion $\bar{D}_\eta$ of the average guiding center position $\bar{\rho}_g$ adds a τ_η time-scale Fokker-Planck-type spatial diffusion operator $\mathcal{D}\{f\}$ to the usual drift-kinetic equation to yield the magnetic-field-diffusion-modified drift-kinetic equation in ψ_p, θ, ζ magnetic flux coordinates:

$$\left.\frac{\partial f}{\partial t}\right|_{\psi_p} + (\mathbf{v}_\parallel + \mathbf{v}_D)\cdot\boldsymbol{\nabla} f + \dot{\varepsilon}_g \frac{\partial f}{\partial \varepsilon_g} = \mathcal{C}\{f\} + \mathcal{D}\{f\}, \quad \text{magnetic flux } \psi_p \text{ MDKE.} \tag{2}$$

For spatial distributions $f(\rho)$, the flux-surface-average of this Fokker-Planck spatial diffusion operator is [1]

$$\langle \mathcal{D}\{f(\rho)\}\rangle \simeq \bar{u}_{\dot{\psi}} \frac{\partial f}{\partial \rho} + \frac{1}{V'}\frac{\partial}{\partial \rho}\left(V'\bar{u}_G f + \frac{\partial}{\partial \rho}(V'\bar{D}_\eta f)\right), \quad \text{paleoclassical F-P spatial operator,} \tag{3}$$

in which $\mathcal{O}\{\epsilon^2, B_p^2/B_t^2\}$ terms have been neglected and $V' \equiv dV/d\rho$ where $V(\rho)$ is the ρ flux surface volume.

All three terms in $\mathcal{D}\{f\}$ are $\mathcal{O}\{\delta^2\}$ in the small gyroradius expansion. The $\bar{u}_{\dot{\psi}}\, \partial f/\partial \rho$ term in (3) accounts for ψ_p transient effects; the $\bar{u}_G$ advection term causes transport fluxes to be determined relative to ψ_t surfaces [3,4b]. Both terms are needed to obtain the proper neoclassical fluid moment equations [4]. The $\bar{D}_\eta$ diffusion contribution is the new, paleoclassical feature that results from analyzing the second order diffusive mathematical characteristic curves (effective guiding center trajectories for non-Hamiltonian systems) on the magnetic diffusion time scale τ_η. The $\mathcal{D}\{f\}$ operator should be included in the ψ_p-coordinate DKE for any axisymmetric resistive, current-carrying plasma for which, since $\eta\,\langle \mathbf{J}\cdot\mathbf{B}\rangle \propto D_\eta\, \Delta^+ \psi_p$, the poloidal flux and hence guiding centers are diffusing radially, irrespective of how current is driven and even in steady-state ($\dot{\psi} = 0$) with $\partial\psi_p/\partial t|_{\mathbf{x}} = 0$ — because, mathematically, ψ_p obeys a diffusion equation and is the coordinate being transformed to, and physically, in driven-dissipative $\mathbf{B}_p$ field systems the thin poloidal flux annulus $\delta\psi_g$ (and hence $p_{\zeta g}$) is always locally diffusing radially [2b]. Since the guiding centers are tied to $\delta\psi_g$, in transforming to the ψ_p (and hence $p_{\zeta g}$) coordinate one is effectively transforming to a locally diffusing radial coordinate system. Implications of adding the paleoclassical $\mathcal{D}\{f\}$ to the usual DKE and gyrokinetics will also be discussed — for density, momentum and heat transport, and possibly on microinstabilities.

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Low-q resonances, transport barriers, and secondary electrostatic convective cells

C.J. McDevitt and P.H. Diamond

Center for Astrophysics and Space Sciences and Department of Physics,

University of California at San Diego, La Jolla, CA 92093-0424, USA

Recent experimental observations have illuminated key characteristics of internal transport barrier (ITB) formation near low-q surfaces in off-axis minimum-q (OAMq) discharges. These observations[1] point to the presence of mean profile flattening localized to a low-q surface in the absence of observable magnetic field perturbations. This necessitates an electrostatic description of ITB formation which accounts for both strong transport in the immediate vicinity of the low-q surface, as well as the formation of an ITB nearby the surface. Here, a low-m electrostatic convective cell driven by modulational instability of the background drift wave turbulence is discussed in the context of ITB formation. In contrast to pure $m = n = 0$ zonal flows, convective cells are also capable of intense mixing near low-q resonant surfaces, thus relaxing the ∇T profile near the $\mathbf{k} \cdot \mathbf{B} = 0$ resonance. Thus, convective cells offer a more complete explanation of the phenomenology. Field line bending coupled with collisional viscosity are found to strongly damp the intensity of the vortical flows except in the relevant case of weak magnetic shear. In that case however, the saturated intensity of the vortical flow asymptotes to a value similar to that found in previous studies of the drift wave-zonal flow system. Furthermore, collisionless saturation mechanisms such as nonlinear wave trapping are found to be largely circumvented due to the mixing of micro-turbulence by the convective cell. Specifically, finite-m cells introduce a small non-integrable perturbation to the Hamiltonian of the system, this perturbation is shown to convert closed ray trajectories into chaotic orbits, densely filling regions of phase space. This ray chaos, induced by the finite-m component of the cellular flow, allows previously trapped drift wave packets to access a larger region of phase space, facilitating a more efficient transfer of energy to the low-m flow. Thus, low-m convective cells are likely to play a strong role in the regulation of turbulent transport near low-q resonances in weak shear regimes. In this analysis, emphasis is placed on understanding the self-consistent evolution of the shear flow and turbulence profiles near the low-q surface, and how these contribute to shaping the spatial structure of the mean profiles.

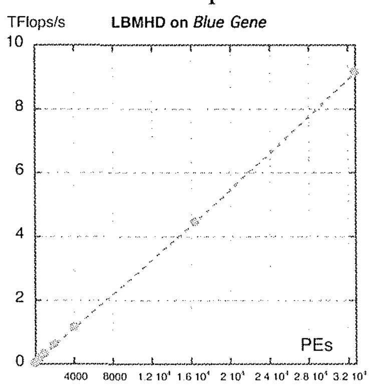
[1] M. E. Austin, *et al.*, Phys. Plasmas 13, 082502 (2006)

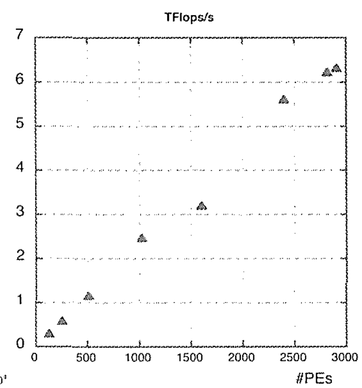
Extremely Parallelized 3D Entropic Lattice Boltzmann Simulations of Navier-Stokes Turbulence on 1600^3-grids

George Vahala[1], Min Soe[2], Jeffrey Yepez[3] and Linda Vahala[4]

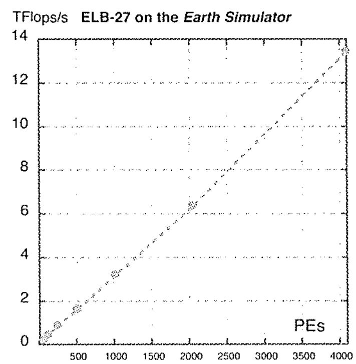
[1] William & Mary, Williamsburg, VA
[2] Rogers State Univesity, Claremore, OK
[3] Air Force Research Labs., Hanscom, MA
[4] Old Dominion University, Norfolk, VA

The parallelization of Entropic Lattice Boltzmann alogirthms for fluid and MHD turbulence is impressive :





ELB-27 on IBM-P5



By projecting the continuum equations into a higher dimensional phase space, the resultant mesoscopic dynamics are very simplified and readily computed. The nonlocal gradients in the continuum limit are modeled by appropriate local moments in mesoscopic space. In this way the Reynolds stresses and $\nabla \cdot \mathbf{B}$ are determined by local operations.

Various velocity lattices will recover the Navier-Stokes equations to first order in the Chapman-Enskog expansion : in particular the ELB-27, -19 and -15 velocity models. While the ELB algorithms are highly efficient and parallelizeable, they require significant memory: the ELB-27 model requires close to 1kB/grid point. The lower symmetry algorithm ELB-15 reduces this by nearly a factor of 2.

Here we compare the turbulence statistics (spectra, correlation tensors ...) of these three entropic lattice Boltzmann schemes as well as those arising from the Large Eddy Simulation – Lattice Boltzmann scheme.

These computations were performed on both 512^3, 1024^3 and 1600^3 spatial grids on DoD and NERSC supercomputers, with data visualization help from NAVO and Hanscom.

* work supported by DoD and DoE

Monday afternoon, April 24

13:30 – 15:30

Ballroom B&C

Oral Session 1D

Velocity shear stabilization of ideal interchange instabilities in centrifugally confined plasmas

Adil Hassam
University of Maryland

Plasma is created in a magnetic field of simple mirror plus solenoid geometry in the Maryland Centrifugal Experiment (MCX). An axial central core is biased at high voltage with respect to the outer vessel making for a radial electric field that rotates the plasma azimuthally. The fusion science idea is that the outward centrifugal force will confine the plasma to the central portion, given the inward parallel component of the centrifugal force. The figure of merit for efficacious confinement is high sonic rotation Mach number, M_s. MCX routinely operates with M_s in the range 2-3. The centrifugal force clearly adds to the already unfavorable curvature of the field indicating strong flute interchange instabilities. The expected shear in the rotation profile, however, should be strong enough to stabilize the ideal interchange; the figure of merit is again high M_s. MCX routinely operates with relatively quiescent voltage and current traces stretching over 1000's of instability time scales. Doppler spectroscopy shows a sheared rotation profile with the shear frequency more than 5 times larger than the interchange growth rate. 3D nonlinear numerical simulations show laminar profiles at these Mach numbers. While residual instability and turbulence on MCX cannot be ruled out, the absence of disruptive behavior and momentum confinement times much longer than growth times is indicative of velocity shear stabilization. Profile effects are also important for stability and these will be discussed. The possibility of magnetorotational instabilities in the system will be assessed. We show that the MRI may not manifest in this system on account of the strong magnetic field but that the associated Parker instability is possible. The nonlinear state of the latter in the system is, in fact, self-organized centrifugal confinement and thus even desirable. Underlying theory, numerical simulations, and experimental data from MCX will be presented. Centrifugally confined plasmas stabilized by supersonic velocity shear can in principle scale up to fusion reactors for $M_s \sim 5$.

Extended MHD Simulations of Rotation and Translation in Field-Reversed Configurations

A. I. D. Macnab[a], R. D. Milroy[a], C. C. Kim[a] and C. R. Sovinec[b]
[a]Plasma Science and Innovation Center, University of Washington, Seattle, Washington 98195
[b]Plasma Science and Innovation Center, University of Wisconsin, Madison, Wisconsin 53706

Field-Reversed Configurations (FRC) occupy an intriguing regime of magnetic fusion energy[1] research because of their experimentally observed macroscopic stability and potential as a simply connected, high-beta, fusion reactor. The NIMROD[2] code's ability to treat two-fluid effects and its ability to resolve highly anisotropic heat conduction and viscosity allows us to capture more detailed FRC physics than previous calculations. When the tangential electric field on the end boundaries is set to zero and the Hall term is included in the calculation, the open field-line plasma spins up due to end-shorting effects, which in turn couples to the main FRC plasma through shear viscosity. The spin-up rate is found to be sensitive to the open field-line plasma profile. Results of these calculations will be compared with previous analysis and experimental observations. We are also investigating recent observations[3] that imply that a small toroidal field could help stabilize the n=2 rotational instability. Preliminary results indicate that a combination of a relatively weak toroidal magnetic field and the inclusion of the Hall term in the calculation can lead to a change in the character of the mode and a dramatic reduction in its growth rate. Recent modifications to the radial boundary conditions capture most of the effects of multiple discrete coils found in many FRC experiments. With this enhancement combined with the ability to include Hall physics, we have begun testing the ability of the code to predict FRC formation and translation, as well as toroidal field generation due to non-symmetric formation.

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

[2] C.R. Sovinec, et al., JCP 195, 355 (2004)

[3] H.Y. Guo, et al., Phys. Rev. Lett. 95, 175001 (2005)

Suppression of resistive wall mode at low plasma rotation

Bo Hu and R. Betti
University of Rochester, Rochester, NY 14627

H. Reimerdes and A. M. Garofalo
Columbia University, New York, NY 10027

J. Manickam
Princeton Plasma Physics Laboratory, Princeton, NJ 08543

Abstract

Disruptions in high-beta tokamak plasmas can occur when the pressure-driven external kink modes become unstable. These external kink modes are converted into slowly growing resistive wall modes (RWM) in the presence of a resistive wall. In the last decade, it has been observed in several tokamaks that the resistive wall modes are fully suppressed by fast plasma toroidal rotation. Mainstream theories [1,2] predict the critical rotation frequency required for RWM suppression to be about 2% of the Alfvén frequency. In those theories, the kinetic effects associated with the plasma diamagnetic frequencies and trapped-particle precession drift frequencies are neglected.

Recent experiments [3,4] have shown that the RWM suppression occurs at rotation frequencies significantly lower (about 0.3% of the Alfvén frequency) than previously predicted. In such slowly rotating plasmas, the "standard" dissipation induced by the shear Alfvén continuum resonance and ion transit/bounce resonance with the plasma rotation frequency is not large enough to suppress the RWM. Thus, the "standard" theories fail to explain the experimental observations of the RWM suppression in slowly rotating plasmas. Instead, the kinetic contribution from the trapped-particle precession-drift motion is large enough to efficiently stabilize the RWM up to the ideal wall limit. These results are consistent with previous predictions of the RWM suppression by trapped particles in the contest of ITER-plasma RWM stability [5,6].

In this work, we present the theory of the RWM stabilization at low plasma rotation and show how such theory can be used to explain the recent experimental results from DIII-D [3] and JT-60U [4].

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[2] L.-J. Zheng, M. Kotschenreuther and M. S. Chu, Physical Review Letters, **95**, 255003 (2005).
[3] H. Reimerdes *et al.*, Physical Review Letters, **98**, 055001 (2007).
[4] M. Takechi *et al.*, Physical Review Letters, **98**, 055002 (2007).
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INTERACTION BETWEEN MAGNETIC ISLANDS AND ELECTROSTATIC TURBULENCE

F.Militello[1,2], F.L. Waelbroeck[1,2], R. Fitzpatrick[2], W. Horton[2]

[1]Center for Multiscale Plasma Dynamics
[2]Institute for Fusion Studies, University of Texas at Austin, Austin, Texas 78712, United States

The interaction between micro-turbulence and a macroscopic magnetic island is of interest in connection with neoclassical tearing modes and the ergodic magnetic limiter in tokamaks as well the island divertor in stellarators. Here this interaction is investigated numerically in a periodic slab. The evolution of the size of the island is assumed to be slow compared to the turbulent relaxation time. The island can thus be treated as a structure rotating rigidly with a velocity determined by poloidal force balance. In a frame moving with the island the evolution is electrostatic and the rotation velocity appears as a potential drop between the edges of the simulation domain. The results of nonlinear simulations using a 2-D version of the Hasegawa-Wakatani model generalized to take into account the effect of magnetic shear are presented. This is the simplest model of turbulence that can describe the effect of the island on turbulence (through the magnetic shear) as well as the effect of the turbulence on the island (through the polarization current). As a first step, the stability of the system has been investigated with linear code. For simplicity, the Schmidt number, μ/D, has been taken equals to unity while the diffusion is varied. The numerical results show that there is an upper value of the diffusion, D_l, such that for $D>D_l$ the system is stable. Modes with even parity become unstable for $D_l>D>D_2$, while for $D< D_2$ both even and odd modes are present. The regime $D_l>D>D_2$ is particularly interesting, since the turbulence can be suppressed by enforcing an odd parity in the nonlinear code. When turbulence is suppressed this way and D is decreased, a series of bifurcations appear and give rise to multiple island states, distinguished by different rotation velocities. For all values of the parameters, there is an exact solution, called here universal root, such that the density is unperturbed and the electrons are at rest in the frame of the island (i.e. the island rotates at the electron diamagnetic velocity). It is shown that turbulence causes some of the otherwise stable laminar states, including the universal root, to become unstable and produces currents that affect the growth of the magnetic island.

Monday afternoon, April 23

15:30 – 17:30

Atrium

Poster Session 1E

1E1

Self-consistent Dynamics of Intrinsic Toroidal and Poloidal Rotation

Ö. D. Gürcan* and P. H. Diamond

Center for Astrophysics and Space Sciences,

University of California, San Diego,

9500 Gilman Dr., La Jolla, CA92093-0424

T. S. Hahm

Princeton Plasma Physics Laboratory, Princeton, NJ 08543-0451 USA

Abstract

Electric field shear driven residual stress is introduced as a key player in the generation of intrinsic rotation. A family of self-consistent models, which describe the evolution of toroidal momentum, density and pressure, where the radial electric field shear plays the role of both the residual stress, effectively generating net angular momentum via the edge boundary condition, and depleting and thus self-regulating the turbulence that leads to anomalous transport. We also investigate the effects of poloidal rotation on toroidal momentum transport, and introduce a simple self-consistent model that also evolves poloidal momentum. We will present the results of this study.

*Electronic address: `ogurcan@ucsd.edu`; URL: `http://diamnd.ucsd.edu`

Finite ion temperature effects and anomalous diffusion: passive tracers in two-dimensional plasma turbulence models

K. Gustafson*, B. Dorland*, D. del Castillo Negrete†, M. Barnes*, I. Brömstrup*

Models of fluid and plasma turbulence constrained to two-dimensions (2-D) have been studied extensively in past decades. Recent interest in the anomalous dispersion of passive particles in 2-D plasma models such as Hasegawa-Mima (HM) and Hasegawa-Wakatani has been enabled by advances in computer hardware. Simulation is necessary for studying the transport of these particles because their orbits are nonintegrable. Our ultimate goal is better understanding of turbulent transport, with possible applications to zonal flows and neo-classical pinch effects.

We study non-self consistent particle displacements in flows given by the HM equation, which describes the $\mathbf{E} \times \mathbf{B}$ flow of cold ions in a strong magnetic field. When dissipation and forcing are added to the HM equation, it becomes a simple model for anisotropic turbulence. We expand on previous studies from other groups by incorporating a finite ion temperature, i.e. a Maxwellian spread of ion gyroradii, by spatially averaging particle velocities over the rings defined by their randomly assigned gyroradii. These methods are tested, first on linearized models, and then with fully nonlinear simulations of the HM equation.

Along the way, we test the ability of a fractional diffusion (FD) model to fit our data. Our results agree with earlier conclusions that the diffusion and advection of passive particles in these models is anomalous, in the sense that the statistics are non-Gaussian. We find finite ion temperature has a significant effect on the dispersion of the particles, and certain results may be well-suited to description by special FD equation solutions.

*Department of Physics, University of Maryland, College Park
†Oak Ridge National Laboratory, Oak Ridge TN

1E3
Turbulent Transport Effects on Resistive Instabilities

D.P. Brennan[1] and C. Holland[2]
[1] *Department of Physics, University of Tulsa, Tulsa, OK*
[2] *Department of Mechanical and Aerospace Engineering, University of California, San Diego, CA*

The development of a resistive MHD mode theory in the presence of turbulent transport is investigated. Turbulent transport is known to be dominant in toroidal confinement, and transport effects are known to be important in resistive MHD stability, although to date mainly ad-hoc diffusive forms have been used in theoretical approaches to describing MHD instabilities. We investigate the effects of turbulence on the linear resistive stability as well as the effects of a finite magnetic island structure on the local turbulent fields. An analytic description is presented of the stability of resistive tearing and interchange modes self consistently in the presence of turbulence in simplified geometry. Initial formulations have resulted in a coupled set of partial differential equations for the electric potential and magnetic flux solutions for the resistive mode and the turbulence separately. The effects on small and large islands are investigated with turbulent mechanics in the thermal and magnetic fluctuations. A key goal is to modify the island evolution equation with a simple reduced solution to account for ITG turbulence.

Drift Wave Fluctuations in Tandem Mirrors with Anchor Cells and Sheared Flows

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

We investigate drift wave fluctuations in the central cell of a model tandem mirror that is terminated with quadrupole anchors. Nonlinear numerical simulations for the canonical drift wave models are investigated searching for the resonance of the $m = 2$ quadrupole structure with the drift waves and the associated radial transport. The radial electric field create a 2D drift mode structure; the shear in the rotational frequency of the electric field reduces transport of particles in the radial direction. Using the Euler potentials α and β to represent the 3D magnetic surfaces, we integrate test particle motions in a model of the GAMMA 10 device. Calculations are performed on the NSF TeraGrid parallel computing network.

Work supported by the Department of Energy Grant DE-FG02-04ER5474.

Influence of Angular Momentum Transport on Rotating Plasma Structures in the Gravity of a Central Object*

F. Rousseau and B. Coppi
Massachusetts Institute of Technology

The presence of an angular momentum transport process is shown to have a significant influence on the axisymmetric, differentially rotating plasma structures that can exist in the prevalent gravity of a central object. These configurations can consist of sequences of plasma rings [1] associated with pairs of counter-streaming toroidal currents [2] and arising from a small "seed" vertical field. In this case there is a sequence of O-lines on the equatorial plane and X-lines above and below the equatorial plane where the poloidal magnetic field vanishes.

Poloidal currents are directly associated with the rate of local angular momentum transport which may be represented by an effective (viscous) diffusion coefficient and produce a toroidal field component that is nul on the equatorial plane. The **vertical** components of the poloidal current densities are **up-down anti-symmetric** and are consistent with the symmetries of the currents associated with a jet that may emerge from the innermost ring. In addition, the condition that the radial components of the current densities be contained within the plasma structure determines the vertical profile of the relevant magnetic surfaces among those possible in the absence of angular momentum transport [3].

In the case where a small plasma accretion velocity is present, the considered configuration is envisioned to be converted into a quasi-tri-dimensional one and to become a weakly spiraling structure. Then the plasma can be expected to flow toward the central object along the spiraling O- and X-lines. *Sponsored in part by the U.S. Department of Energy.

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Gyrokinetic Simulation and Closure Model of Zonal Flows in Ion and Electron Temperature Gradient Turbulence

H. Sugama, T.-H. Watanabe, and S. Ferrando i Margalet
National Institute for Fusion Science, Graduate University for Advanced Studies, Toki 509-5292, Japan

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

In the fusion research, numerous theoretical and experimental studies have been done on zonal flows as an attractive mechanism for realizing a good plasma confinement. The accurate theoretical descriptions of zonal-flow behaviors are critical in correctly predicting the turbulent transport of fusion plasmas. While linear mode properties of the electrostatic ion and electron temperature gradient (ITG and ETG) instabilities are isomorphic, their different nonlinear saturation processes are associated with zonal flows. We investigate nonlinear saturation processes of the toroidal ETG turbulence by means of the gyrokinetic-Vlasov (GKV) simulation [1] performed on Earth Simulator. Large modulation of streamer-like potential structures of nonlinearly excited mode is clearly found in case with a wide flux tube simulation box. We also present a novel kinetic-fluid model [2], which describes collisionless time evolution of zonal flows. In the new zonal-flow closure relations, the parallel heat fluxes are written by the sum of short- and long-time-evolution parts. The former part is given in the dissipative form of the parallel heat diffusion and relates to collisionless damping processes. The latter is derived from the long-time-averaged gyrocenter distribution and plays a major role in describing low-frequency or stationary zonal flows, for which the parallel heat fluxes are expressed in terms of the parallel flow as well as the nonlinear-source and initial-condition terms. It is shown analytically and numerically that, when applied to the zonal flow driven by either ITG and ETG turbulence, the kinetic-fluid equations including the new closure relations can reproduce the same long-time zonal-flow responses to the initial condition and to the turbulence source as those obtained from the gyrokinetic model.

References

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Electron Transport Analysis in NSTX

J.-H. Kim, W. Horton

Institute for Fusion Studies, University of Texas at Austin

S.M. Kaye, H. Park, B. Leblanc

PPPL, Princeton University

(Dated: February 23, 2007)

We present the electron transport analysis of the NSTX data based on the nonlinear gyrofluid models of ITG/TEM and ETG. The simulation observes that there is strong electron heat flux peaked at $k_y \rho_e \sim 0.2$ and electrostatic potential and density turbulence at $k_y \rho_e \sim 0.3$. The full k-space of the heat flux and the density fluctuations are shown which enables the comparison of the high-k scattering data for modes with $k_y \sim 0$ and $k_x = 21.2$, 17.5, 14.6 10.6 cm^{-1} with the modes that dominate the thermal flux with $k_y \gg k_x$. The corresponding NSTX experiment shows bifurcation into and out of the H-mode. The electromagnetic scattering shows strong supression of the large scale ITG/TEM scale modes but a weak effect on the ETG modes. Correspondingly, the electron power balance χ_e drops has a modest drop from the suppression of longwave lengths but remains well above 1 m^2/s consistent with presence of the the short wavelength turbulence.

The (β_e, L_s/R)-dependence of electron heat flux obtained from the computations are compared with the analytic ETG heat flux formulae given by Horton et al. [1]. The statististical analysis from the nonlinearly saturated ETG turbulence simulation will be presented with emphasis on the dynamics of the the relative phase angle between the electron temperature and potential (density) phase angles that control the convective thermal flux contributions. A simple realtime quick-look predictor of the strength of the ITG and ETG turbulence is proposed and applied to historical NSTX discharge shot 120967.

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Investigation of Long Wavelength ETG Modes

Eric Wang, Steve Cowley
UCLA

Simulations of ETG turbulence with adiabatic ions at low shear (s = .1) suggest that the greatest energy transfer is through long wavelength modes (k_\theta \rho < .1). Results showing that the long wavelength must be nonlinearly generated are presented along with analysis of the behavior of zonal flows in this regime.

O-X-B Mode Conversion Simulations for EBW Heating in the WEGA Stellarator

J. Preinhaelter[1], J. Urban[1], H.P. Laqua[2], L. Vahala[3] and G. Vahala[4]

[1] EURATOM/IPP.CR Association, Prague, Czech Republic
[2] Max-Planck-Institut für Plasmaphysik, EURATOM Ass. Greifswald, Germany
[3] Old Dominion University, Norfolk, VA
[4] William & Mary, Williamsburg, VA

The WEGA stellarator discharges are maintained by 2.45 GHz microwaves, yielding overdense plasmas. Since the plasma density is typically greater than the critical density $n_{cut-off} \approx 7.5\times10^{16} m^{-3}$, only electron Bernstein waves (EBWs) can propagate within the plasma and lead to plasma heating. Typical electron temperatures are $T_e \approx 10\ eV$, ion temperatures $T_i \approx 2\ eV$ and magnetic field $B \approx 87\ mT$. From experiments, one deduces EC resonance heating due to the dependence on the magnitude of the magnetic field. The optimal scenario is typically achieved at magnetic field $B\left(R_0\right) = 0.65\ B_{ce}$, with strong Doppler shift of the absorption as well as off-axis power deposition.

We simulate EBW propagation in this stellarator using O-X-B mode conversion theory and ray-tracing. It is difficult to perform detailed analysis since the upper hybrid resonance lies far outside the last closed flux surface with fluctuating plasma profiles and ergodic magnetic field lines. Hence an averaged and extrapolated configuration is used in our simulations. Even with this approximation, the simulations clearly point to novel features in the propagation: parallel wave number increases to ≈ 30 along with the production of energetic electrons from RF heating. We see strong resonant absorption at the Doppler shifted electron cyclotron resonance and the energy deposition region moving towards the plasma center as the magnetic field decreases from $0.85\ B_{ce}$ to $0.65\ B_{ce}$.

* work supported by DoE

Higher order corrections to the metaplectic formulation of linear mode conversion

A. S. Richardson, E. R. Tracy, A. N. Kaufman*
Dept. of Physics, College of William & Mary, *U. C. Berkeley and LBNL

The phenomenon of linear mode conversion occurs when two types of wave modes in an inhomogeneous medium resonantly exchange energy. This is an important effect to consider when studying plasmas, since there can be many different wave modes present in plasmas, and since plasmas are inhomogeneous due to variations in density and magnetic field. For example, the ion-hybrid resonance which is used for heating plasmas can be considered as a type of mode conversion among RF waves [1,2].

In previous work [1,2,3] it was shown that phase space ray-tracing techniques can be effectively used to solve wave problems exhibiting mode conversion. In the vicinity of a mode conversion, there are two roots of the dispersion relation $\det(\mathbf{D}) = 0$, where $\mathbf{D}(x,k)$ is the symbol of the dispersion matrix [4]. These two curves in phase space locally have a hyperbolic structure (an "avoided crossing"). Linearizing the (x,k)-dependence of the dispersion matrix about the center of the hyperbola, and converting this linearized symbol back to an operator, gives a set of coupled equations which can be solved for the local wave fields. Matching these local solutions onto uncoupled WKB solutions (which are a good approximation to the solutions far from the mode conversion region) gives transmission and conversion coefficients for the incoming and outgoing waves. These coefficients can be used to treat the mode conversion as a ray-splitting process, where amplitude on the incoming ray is split onto the two types of outgoing rays.

In this work, we study the effects of higher order terms in the dispersion matrix near a mode conversion. It is shown that the corrections due to these higher order terms gives a better matching between the local solution in the mode conversion region, and the far-field WKB solutions for the incoming and outgoing waves. This matching is demonstrated by comparison of the asymptotic solution with a numerical solution for a simple one-dimensional conversion.

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Simulation of propagation and absorption of IBW via reduced 5D high frequency gyrokinetic (HFGK) particle simulation.

R. A. Kolesnikov, W. W. Lee, H. Qin, E. Startsev

Princeton Plasma Physics Laboratory

We developed a reduced 5D high frequency gyrokinetic (HFGK) algorithm for particle-in-cell simulation of arbitrary frequency phenomena in magnetized plasmas. This new algorithm is based on the gyrocenter-gauge kinetic theory [H. Qin, W.M. Tang, W.W. Lee and G. Rewoldt, Phys. Plasmas **6**, 1575 (1999)], which utilizes the separation of the ion gyromotion from its gyrocenter motion. While the 5D HFGK description [R. A. Kolesnikov, W. W. Lee, H. Qin, E. Startsev, APS (2006)] is an alternative to the original 6D Lorentz-force description for $\rho / L_B << 1$, the former approach takes much less computer time since the gyrophase dependence is removed from the kinetic system (but which still describes an arbitrary frequency dynamics). We performed a nonlinear δf particle simulation of electrostatic system in slab geometry using the new 5D HFGK algorithm. We study propagation of the ion Bernstein wave (IBW) launched by an antenna in inhomogeneous system as well as its absorption near resonant layer via linear and nonlinear mechanisms. Illustrations of numerical efficiency of the new 5D algorithm compared to the direct 6D Lorentz-force simulation are given.

Gyrokinetic Particle Simulation of Shear-Alfvén Waves*

E. A. Startsev and W. W. Lee

Princeton Plasma Physics Laboratory, Princeton, NJ 08543

A generalization of the split-weight scheme for finite-beta simulation [1] to multi-dimensional plasmas is presented. The original scheme is based on the concept of perturbative particle simulation, where only the non-adiabatic response of the electrons, δh, is followed in time, where $\delta h = F - (1+\psi)F_0$, F is the distribution, F_0 is the background,

$$\psi \equiv \phi + \int (\partial A_{\|}/\partial t) dx_{\|}/c$$

and ϕ and $A_{\|}$ are the perturbed potentials. The procedure involves solving the gyrokinetic Poisson's equation and Ampere's law for ϕ, $A_{\|}$, $\partial\phi/\partial t$, $\partial A_{\|}/\partial t$, and $\partial^2 A_{\|}/\partial t^2$, which, in turn, needs the zeroth, first, second and third velocity-space moments for δh as input. The new scheme further separates the fast electron response associated with quasi-static bending of the magnetic field lines from δh. This new term, δg, is related to the field line bending in the presence of inhomogeneity. Specifically, through the use of

$$\hat{\mathbf{b}} \cdot \nabla(F_0 + \delta g) = 0,$$

where $\hat{\mathbf{b}} = \hat{\mathbf{b}}_0 + \delta\mathbf{B}/B_0$, we further separates the plasma response as $F = (1+\psi)F_0 + \delta g + \delta h$, where

$$\delta g = \int dx_{\|}\boldsymbol{\kappa} \cdot (\nabla A_{\|} \times \hat{\mathbf{b}}_0).$$

where $\boldsymbol{\kappa}$ is the zeroth order spatial inhomogeneity. For this scheme, only δh is followed dynamically in time. This new scheme is free of numerical instabilities and allows accurate simulation of shear-Alfvén waves for a plasma with $\beta \equiv c_s^2/v_A^2 \approx 10\%$. Finite-$\beta$ stabilization of drift waves and ion temperature gradient modes in slab geometry has also been recovered in agreement with those discussed in Refs. [2] and [3].

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DIII-D Plasma Response to Asymmetric Magnetic Perturbations*

V.A. Izzo[1], I. Joseph[1], L.L. Lao[2], A.M. Garofalo[3]

[1]University of California-San Diego, La Jolla, California, USA
[2]General Atomics, San Diego, California, USA
[3]Columbia University, New York, New York, USA

DIII-D equilibria are perturbed by toroidally asymmetric fields both in the form of intrinsic error fields and fields directly applied by the C-coils and I-coils. These fields are applied for ELM control, rotation control, and other plasma physics experiments. Using the NIMROD code, the vacuum magnetic fields associated with the intrinsic and applied error fields are superimposed on an EFIT-reconstructed equilibrium as an initial condition. The calculations include a small vacuum region, but the simulation boundary must be placed interior to the I-coils, which are inside the limiter. The NIMROD ideal conductor boundary conditions hold the normal component of the perturbing fields constant at the simulation boundary and do not allow the flux to escape. The plasma evolves in response to the applied fields until a new steady-state 3D equilibrium solution is achieved. Several examples of applied fields with predominantly n=1 or n=3 components are presented, for various equilibrium conditions. The stability properties of the resulting 3D equilibria with respect to peeling-ballooning modes, locked modes, etc., can be subsequently investigated with NIMROD.

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1E14

Gyrokinetic Equilibrium and Self-Generated Flows in Tokamak Plasmas

G. Dif-Pradalier, V. Grandgirard, Y. Sarazin, X. Garbet, Ph. Ghendrih
Association Euratom-CEA, CEA/DSM/DRFC Cadarache, France

A proper choice of the initial state of the plasma is found to be crucial in gyrokinetic simulations where the equilibrium and the fluctuations are resolved simultaneously in a full torus geometry. Recently, the generation of large scale flows have been reported in toroidal geometry whenever the initial conditions depart from an equilibrium solution of the gyrokinetic equation. In the collisionless regime, such flows remain linearly undamped and compete with the onset of turbulence. In this paper, the dynamics of these flows is derived analytically, and successfully compared to 5D gyrokinetic simulations.

The GYSELA 5D code solves the full ion distribution function in a full torus. In such a toroidal geometry, the curvature and *grad-B* drifts tend to generate a vertical charge separation. This charge imbalance is naturally compensated by parallel flows when initialising the system with a canonical state, *i.e.* a distribution function depending on the motion invariants only. In this case, the fluid drift velocities are recovered up to the first order in $\rho_\star = \rho_i/a$, ratio of the ion Larmor radius over the tokamak minor radius.

Conversely, initialising the system with a non-canonical state, namely a distribution function that is constant on magnetic flux surfaces, leads to the onset of large-scale $\mathbf{E} \times \mathbf{B}$ flows. They result from the vertical charge imbalance governed by the vertical drifts. We analytically derive a precise picture at short times of this spontaneous dynamics. Firstly, up-down asymmetric Geodesic Acoustic Modes (GAMs) develop, linearly in time. Then, purely poloidal flows are generated with a quadratic dependance on time, and become prominent. Finally, left-right asymmetric GAMs also develop quadratically in time. The saturation time of such modes is computed analytically, allowing one to estimate the saturation level of these flows. These analytical results are successfully compared to the numerical results. In particular, one finds that the velocity shear induced by such modes can compete with the linear growth rate of the instability at large enough $\rho_\star$, potentially preventing the onset of turbulence.

When the system is initialised in the so-called canonical state, any mismatch between the parallel flow and the vertical charge separation leads to the same kind of large scale electric field, although at reduced magnitude. The magnitude of the up-down asymmetric GAMs and poloidal flows is analytically predicted to scale like $\rho_\star^2$, whereas the magnitude of the left-right asymmetric GAMs is predicted to scale like $\rho_\star^4$. These dependencies are well verified in the GYSELA 5D simulations.

Parallel Infrastructure and Components For Whole-Device Modeling

M. MIAH , J. CARLSSON , S.E. KRUGER , A. HAKIM , J.R. CARY , Tech-X Corporation

The FMCFM project is developing infrastructure and components to support whole-device modeling for the fusion program. This infrastructure supports parallelism, greater flexibility, the use of advanced parallel solver systems (like PETSc), coupling of disparate components, and advanced solution methods. This infrastructure has been tested by applying it to the Grad-Shafranov system. This has enabled exploration of parallelization limits and the flexibility of the infrastructure by assessing its ability to generalize to alternate specifications of the equilibrium as well as include additional physics, such as poloidal flow and two-fluid physics, both of which have received considerable interest recently[1,2]. It will also exercise advanced (Newton-like) solvers and assist in developing requirements for coupling components in a parallel environment.

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1E16

Large Eddy Simulations of MHD using the Lattice Boltzmann Algorithm

Brian Keating[1], George Vahala[1], Linda Vahala[2] and Min Soe[3]

[1] William & Mary, Williamsburg, VA
[2] Old Dominion University, Norfolk, VA
[3] Rogers State University, Claremore, OK

For high Reynolds number turbulence, the resource requirements for a full space-time DNS simulation scales as Re^3 – which is far beyond any foreseeable computational resources. For problems that require instantaneous fields, one is forced into an LES in which one filters out the unresolvable small scales in the simulation but must then deal with the effects of the subgrid scales on the resolvable scales. Most LES research has started with the continuum equations and then filtered out the subgrid scales. This leads to a closure problem that can only be solved phenomenologically. Moreover, at the continuum description level there is an absence of scale separation between the resolved and unresolved structures – which thus does not permit a first principles theory for the eddy transport coefficients.

LES modeling on the LB algorithm for 2D Navier-Stokes has been attempted by Ansumali et. al. [2005] who noted that the LES filtering operation $\Im$ does not commute with the asymptotic Chapman-Enskog expansion $\mathbb{C}$. The Smagorinsky LES-LB algorithm is just $\Im\left[\mathbb{C}[LB]\right] = \Im[NS]$ -- with no scale separation. However the Ansumali $\mathbb{C}\left[\Im[LB]\right]$ does have a separation of scales resulting in closure and no free parameters.

Here we apply this $\mathbb{C}\left[\Im[LB]\right]$ procedure to construct a first-principles theory of LES-MHD. Because $\nabla\cdot\mathbf{B}$ is determined from simple local moments at the mesoscopic kinetic level, the algorithm (by appropriate choice of relaxation distribution functions) will automatically preserve $\nabla\cdot\mathbf{B} = 0 + O\left(10^{-17}\right)$ throughout the simulations.

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Progress for NSTX Application of GEM Code

G. Rewoldt and W.M. Tang

Princeton Plasma Physics Laboratory

Y. Chen and S.E. Parker

University of Colorado - Boulder

Recent work has made the GEM (Gyrokinetic ElectroMagnetic) particle-in-cell simulation code [Y. Chen and S.E. Parker, J. Comput. Phys. **220**, 839 (2007)] usable with realistic experimentally-derived input data for tokamaks, obtained from TRANSP and NCLASS, and this code is currently in a development phase. The GEM code is now a radially-global code which includes trapped electrons, an impurity species and a hot beam species in addition to electrons and ions, electron collisions, A-parallel (but not A-perpendicular), equilibrium ExB (perpendicular) velocities, and zonal flows. It employs the Miller MHD equilibrium, which allows for ellipticity, triangularity, and Shafranov shift. This version of GEM is applicable for modes such as ITG-TEM modes, kinetic ballooning modes, and microtearing modes. Recently, convergence studies have been carried out to determine needed resolutions, box sizes, time steps, and particle numbers for calculating nonlinear particle and energy fluxes. Work in currently under way to implement a particle-weight resetting scheme, and to add equilibrium parallel ion flows to the calculation. Preliminary results from the GEM code will be presented for experimentally-derived cases for NSTX.

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Coherency in plasma turbulence

I. Broemstrup[1], W. Dorland[1], K. Schneider[2], M. Farge[3]

(1) Department of Physics, Univ. of Maryland, College Park
Center for Multiscale Plasma Dynamics, (CMPD)
(2) Universités d'Aix - Marseille & CMI, Université de Provence
(3) Laboratorie de Météorologie Dynamique, Ecole Normale Supérieure, Paris

Direct numerical simulations of plasma turbulence have become an important tool for interpreting experimental data from tokamaks. There is, however, relatively little exploration of the fluctuation data that is produced by gyrokinetic simulations in the literature. In preparation for more detailed experimental validation of predictions from gyrokinetic simulations of plasma turbulence, we present studies of turbulence that is well described by simpler models: Hasegawa-Mima and a finite Ion-Temperature fluid model. Numerical results from a spectral fluid code will be compared to the results obtained with a gyrokinetic code. To study coherent structures, the data is projected onto an orthogonal wavelet basis and a nonlinear thresholding is applied to the wavelet coefficients. The denoised data is then reconstructed in physical space. Using this procedure we analyze the spatial and frequency spectra and test them against theoretical expectations. This will go along with a detailed discussion about the importance of conserved quantities in these systems and their influence on the spectral behavior.

1E19

Integrated Simulations of Turbulence Driven Toroidal Momentum Transport in Tokamak Plasmas*

F.D. Halpern[1], G. Bateman[1], C.M. Wolfe[1], A.H. Kritz[1], A.Y. Pankin[1]
R. Budny[2] and D. McCune[2]

[1]Lehigh University, Bethlehem, PA, US
[2]Princeton Plasma Physics Laboratory, Princeton NJ, US

Integrated modeling simulations using the PTRANSP code are carried out to predict the toroidal momentum and rotational frequency of L-mode, H-mode, and optimized shear discharges with internal transport barriers in JET and DIII-D tokamak plasmas. The toroidal momentum transport equation implemented in PTRANSP includes anomalous diffusion of momentum transport, convection, and neutral beam torque sources that are computed using the NUBEAM code. Anomalous thermal transport and toroidal momentum transport are computed using the GLF23 model [1] and the new Weiland 19 model [2]. The evolution of the radial profile of toroidal velocity affects the computation of **E**×**B** flow shear, which is incorporated self-consistently into the predictive thermal transport equation that is used to evolve the temperature profiles. In simulations of H-mode discharges, the width and temperature of the H-mode pedestal is computed using a theory-based model [3]. Simulation results for toroidal momentum, rotational frequency, and temperature profiles are compared against experimental data. In addition, a stand-alone code is utilized to carry out side-by-side, systematic comparisons of momentum diffusivity between the GLF23 model and the Weiland 19 model. The dependence of toroidal momentum transport on plasma parameters such as temperature gradient, radial gradient of toroidal velocity, plasma beta, and magnetic shear s is examined.

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Initial comparison of HIT-SI measurements to NIMROD calculations

Cihan Akcay, R. Griff O'Neill, Thomas R. Jarboe, Brian A. Nelson, Aaron J. Redd, Roger J. Smith University of Washington

A key scientific goal in the HIT-SI program is to compare the experimental current drive results to the predictions of NIMROD resistive MHD calculations. As a first comparison, only a resistive MHD model is implemented that uses constant density and viscosity, and zero beta. Thus, only the magnetic field and velocity are time-advanced. More complete physics models will be adapted later. The simulations require the resistivity, density, injector current, injector flux, and injector oscillation frequency as input. This requires measurement of the experimental electron temperature and density so that the calculations can be run at experimentally relevant parameters. The electron temperature is measured with a Langmuir double probe mounted on an actuator which is swept with a continuous triangle wave through the discharge to provide time resolved data. The density is measured by a combination of Langmuir probing and FIR interferometry. The FIR instrument uses two optically pumped difluoromethane gas lasers to produce a heterodyne beat of up to 2 MHz. The experimentally measured ratio of toroidal current to injector current is compared to that predicted by the NIMROD resistive MHD model at comparable parameters. Initial results of our simple model indicate poor agreement between the experimental and computational data, with the experimental data showing much greater toroidal currents than predicted. When we run the computational model at very low values of resistivity, and high values of injector lambda (well outside of the experimental regime), we observe significant toroidal current formation as seen in the experiment. In these cases, the calculated B field profile is in good agreement with the Taylor state and the experimental B profiles as measured by an internal magnetic probe array.

IMP – symmetric, energy-conserving, implicit, low-noise kinetic algorithm

D. C. Barnes
Center for Integrated Plasma Studies
U. of Colorado, Boulder

The correct way to separate a low-collisionality kinetic problem into fluid and particle closure portions is to employ not the particle velocity $\mathbf{v}$, but the particular velocity $\mathbf{w} = \mathbf{v} - \mathbf{u}$ both to compute particle motion and closure moments. Using this observation, we formulate a time-implicit, δf method and show that: 1) The electric field $\mathbf{E}$ does not enter the problem directly, eliminating the most difficult part of the implicit particle advance; 2) A fundamental symmetry implies that there exists a conserved energy for the discrete system; 3) Particle weights cannot grow secularly with time; 4) Implicit time differencing and orbit averaging are incorporated in a natural manner. A 2-D code, IMP2 (Implicit Moment – Particle, 2-dimension), has been written and applied to the gravitational instability, reproducing both two-fluid (Hall MHD) and gyro-viscous stabilization in appropriate parameter regimes. While the present formulation is limited to uniform temperature, transverse electric polarization, and is linearized, these are not essential features. The extensions to the general case are described and progress on initial implementation reported.

Magnetic topology effects on Alcator C-Mod flows

Peter J. Catto[1], Andrei N. Simakov[2] and Brian LaBombard[1]

[1]MIT Plasma Science and Fusion Center, Cambridge, MA 02139
[2]Los Alamos National Laboratory, Los Alamos, NM 87545

catto@psfc.mit.edu

We consider the effects of magnetic topology changes on a divergence free plasma flux flowing within magnetic flux surfaces inside and beyond the separatrix of a tokamak. In particular, we investigate the effect of magnetic topology on tokamak ion (and impurity) flows by considering the consequences of (i) the reversal of toroidal and poloidal magnetic fields and currents, (ii) a switch from lower to upper X-point operation, (iii) poloidal magnetic field or plasma current reversal, and (iv) toroidal magnetic field reversal. Alcator C-Mod scrape-off layer (SOL) measurements are interpreted using the properties found for cases (i) and (ii). In case (ii) we observe that single null operation introduces up-down asymmetric contributions to the flows not present in symmetric double null operation, and that these portions of the flow must change sign in switching from lower to upper null. We verify that the superposition of one half the lower and upper single null axisymmetric magnetic fields (and currents that create them) must be equivalent to an up-down symmetric double null configuration to the order required. We next observe that reversed magnetic field operation in upper null would be equivalent to normal operation in lower null if the C-Mod chamber were strictly up-down symmetric since the second configuration could be obtained from the first by turning over the tokamak. However, reversing all the axisymmetric magnetic field components and the currents used to produce them in lower null gives a reversed field lower null configuration. Thus case (i) is not the same as turning over a lower single null tokamak which also reverses the asymmetric portion of the magnetic field. Therefore, it is helpful to think of a reversed magnetic field topology change as involving two steps. The first going from lower single null to upper single null with the corresponding asymmetric magnetic field, currents, and flow changes; and the second turning the tokamak over to get the desired magnetic field reversed configuration with a lower null and all fields, flows and currents reversed. In the final state only the symmetric fields, currents and flows are reversed. Up-down asymmetries in C-Mod complicate the interpretation of the measurements, but in some cases these asymmetries can be factored out.

Extension of electrostatic gyrokinetics to retain long wavelength effects

Felix I. Parra and Peter J. Catto
Plasma Science and Fusion Center, MIT, Cambridge, MA

We outline our efforts to develop an electrostatic nonlinear gyrokinetic model that combines neoclassical transport and turbulent fluctuations up to wavelengths of the order of the ion Larmor radius. Our objective is to solve self-consistently for the different species distribution functions and the electrostatic potential. A set of gyrokinetic variables is defined so that the gyrophase dependent part of the distribution is absorbed into the gyrokinetic variables by extending the linear treatment of Lee, Myra and Catto [1] to retain usual nonlinear gyrokinetic modifications [2, 3]. Each variable is defined to order δ^2 by requiring that its time derivative is gyrophase independent to order $\delta^2\Omega$, where $\delta = \rho / L << 1$ is the ratio of the ion gyroradius and the characteristic length of the plasma and Ω is the gyrofrequency. The resulting gyrokinetic equation is valid for arbitrary perpendicular wavelengths and allows us to evaluate the gyrophase independent part of the distribution function through order δ, while retaining gyrophase dependent information through order δ^2 for long wavelengths (so that the gyroviscosity can be directly evaluated to lowest order). When calculating the potential, the Poisson's equation usually employed in gyrokinetics is inadequate because the terms that provided the potential and zonal flow for short wavelengths become infinitesimally small at long wavelengths. Furthermore, a generalization of the Poisson's equation is impractical to the order required to recover neoclassical modifications. As a result, an alternate evaluation of the electrostatic potential is being pursued from conservation of toroidal angular momentum by using a moment procedure to determine the viscosity. In such an evaluation the effects of neoclassical transport and turbulence will enter as viscosity and Reynolds stresses, respectively.

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1E24

Electrostatic gyrokinetics in an axisymmetric torus

Grigory Kagan and Peter J. Catto

Plasma Science and Fusion Center
Massachusetts Institute of Technology

Abstract

A gyrokinetic change of variables useful for axisymmetric toroidal plasmas is introduced. In contrast to typical gyrokinetic treatments, canonical angular momentum is taken as the gyrokinetic radial variable rather than the radial guiding center location. This choice automatically allows the isothermal tokamak limit to be recovered [1]. By taking the solution in this limit as a zero order distribution function, a delta f version of the gyrokinetic equation in the new variables can be obtained. Such an approach allows strong density gradients, while allowing zonal flow behavior in the presence of stronger toroidal rotation. Moreover, neoclassical collision effects naturally enter when the gyrokinetic change of variables is applied to the collision operator.

The new, nonlinear gyrokinetic variables are constructed to higher order than is typically the case by generalizing the linear procedure of Lee, Myra and Catto [2]. The resulting variables retain gyroviscous efects, and yield a gyrokinetic equation valid through one order higher in gyroradius over scale length than typical treatments. Interestingly, with the canonical angular momentum as one of the variables the higher order magnetic moment variable is modified compared to standard gyrokinetics because the gyroaverage is performed holding canonical angular momentum fixed rather than guiding center location.

Finally, the nonlinear gyrokinetic equation obtained may be useful in analyzing turbulence in the tokomak pedestal and scrape-off layer.

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Reduced-model SOL turbulence simulations

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

Lodestar Research Corporation, Boulder, Colorado, USA

We report recent progress on modelling cross-field turbulent transport using Lodestar's SOLT (scrape-off layer turbulence) reduced-model code, restricted to two, coupled 2D regions.[1] In this "two-region model" (TRM) incarnation of SOLT, the full 2D turbulence and linear eigenmode structure are resolved on two planes representing the outer midplane and the divertor region, while the parallel variation in current density is treated in a two-point approximation that couples the two regions. The need to resolve the parallel variation in eigenmode and turbulent ("blob") structure is most acute in the presence of strong variation ("ballooning") along field lines, e.g., in the presence of X-points and/or at high collisionality.[2-5] The model includes parallel transport of charge, particles and heat between regions. One of the important questions in interpreting the simulation results is whether they can be related to the various analytic scalings that comprise the blob model.[1,6-9] Previously we have described TRM simulations of initialized blobs and used the code to verify the "blob correspondence principle."[1] Some preliminary turbulence simulations were also reported at recent meetings. Here, we emphasize the application of the TRM-SOLT code to study important questions in SOL turbulence:[10] (i) the physics of disconnection and its effect on turbulent transport; (ii) dependence of the turbulent flux (or blob creation) on collisionality and magnetic geometry; and (iii) the use of turbulence statistics (e.g., skewness) to infer the blob birth zone and the "blob packing fraction." The trends shown in these simulations shed light on recent experimental data and 3D simulations of the resistive-X point and resistive ballooning parameter regimes.

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Expansion of micro-clusters with a two-component electron distribution

Alexey V. Arefiev and Boris N. Breizman

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

This work deals with a mechanism of ion acceleration in exploding micro-clusters that are responsible for fusion reactions in experiments with laser-irradiated deuterium gas jets [1]. The neutron yield in these experiments results from clusters whose radius is much greater than the quiver amplitude of a free electron in the laser field. Only such large clusters produce ions with energies above 10 keV [2], needed to account for the measured neutron yield. In large clusters, the laser pulse creates a two-component non-Maxwellian electron distribution that consists of a cold core and a hot-electron halo that undergoes stochastic heating. The hot electrons expand together with an equal number of ions, while the cold component essentially remains at rest during the expansion. For a sufficiently short laser pulse, electron heating and ion acceleration are separated in time, so that the problem of ion acceleration becomes a problem of collisionless plasma expansion into a vacuum for a given initial two-component electron distribution. We solve the problem exactly for a "water-bag" distribution function of the hot electrons. The hot electrons are assumed to have no angular momentum, since the stochastic heating results primarily from the radial component of the electric field at the cluster surface. This choice of the electron distribution enables us to find the corresponding time-of-flight spectrum of the accelerated ions with a fully self-consistent treatment of the hot electrons, including the effect of their adiabatic cooling. A large part of the time-of-flight spectrum scales as t^{-2}, reflecting the fact that the hot electrons have no angular momentum. The calculated spectrum of fast ions is consistent with recent experimental measurements. The mechanism of ion acceleration in large exploding clusters includes acceleration in a double layer at the cold core edge followed by additional acceleration in a rarefaction wave. This mechanism produces a substantial number of ions with energies greater than the cut-off energy of the initial hot electron "water-bag" distribution, enabling an enhanced neutron yield. The presented mechanism and the high energy ion tail are robust features of large clusters with a hot electron minority, not limited to the specific "water-bag" distribution.

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One-dimensional transition model with momentum conservation

I. Calvo[1], B. A. Carreras[2]

[1] *Laboratorio Nacional de Fusión, Asociación EURATOM-CIEMAT, 28040 Madrid, Spain*

[2] *Oak Ridge National Laboratory, Oak Ridge, TN 37831-2001, USA*

In ref. [1] a simple model for the transition from the low confinement mode (L mode) to the high confinement mode (H mode) was proposed. This is a local (i.e. zero-dimensional) model combining turbulence suppression by sheared electric field and poloidal flow amplification by turbulence. The model consists of two envelope equations for the fluctuation intensity and the mean poloidal shear flow. A later extension of the model [2] included a third equation to account for the contribution of the pressure gradient to the radial electric field. The model has two critical points, the second one causing a first order transition that has been associated with the L to H transition. The first critical point leads to a second order transition, which has recent and successfully been used to explain the emergence of the plasma edge shear flow layer in TJ-II [3]. We focus here on this type of transition and present a 1-D extension of the model.

We discuss here the formulation of the model including radial dependence in a way that the Reynolds stress conserves momentum [4]. The model is defined by three 1-D PDEs describing the evolution of the turbulent fluctuation level E, the averaged poloidad velocity shear U and the pressure gradient N. It predicts a second-order phase transition with order parameter U and control parameter Γ, the energy flux, which enters the model through the boundary conditions. For Γ below a critical value Γ_c the stable stationary solutions have $U = 0$, whereas for $\Gamma > \Gamma_c$ such solutions are unstable and undergo a transition to states with $U \neq 0$ and reduced turbulence fluctuations. We perform a detailed stability analysis of the model, identifying the critical point and the nature of the instabilities, which depend on the values of the parameters. Then, we study the dynamics near marginal stability and derive an equation for the weakly non-linear dynamics of U. Numerical as well as approximate analytical stationary solutions near (and above) the critical point are provided.

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Momentum transport from current-driven reconnection in toroidal and disk configurations

Fatima Ebrahimi, V. V. Mirnov, S. C. Prager, and D. D. Schnack

University of Wisconsin and Center for Magnetic Self-Organization in Lab and Astrophysical Plasmas

Toroidal rotation is often observed in both astrophysical and laboratory plasmas. It is also observed in both settings that toroidal angular momentum can be rapidly transported in the radial direction. In the toroidal laboratory configuration of the reversed field pinch (RFP), rapid momentum transport occurs during a reconnection event. In astrophysical plasmas, such as in accretion disks, as matter falls radially in toward the central compact object, angular momentum is transported radially outward. In both astrophysical and laboratory cases, the momentum transport is faster than can be explained by collisional viscosity. The leading explanations of momentum transport are stresses (Maxwell and Reynolds) arising from MHD instabilities. In astrophysical disks, flow-driven instabilities are believed to cause momentum transport, and theoretical models and computations have been well developed to study this effect. Here, we examine theoretically momentum transport from current-driven instabilities, a process that is important in laboratory plasmas, and might also apply to astrophysical situations. We first calculate momentum transport from current-driven reconnection in an RFP with sheared flow, considering both the effect of a single tearing mode and multiple tearing modes. We find that a single tearing mode transports momentum, via Maxwell and Reynolds stresses, more rapidly than classical viscous forces. Moreover, the transport is enhanced by nonlinear coupling of multiple modes. We then expand the computations to model momentum transport from current-driven instabilities in a accretion disk-like geometry. Preliminary single and multiple mode computations in this geometry will be presented.

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1E29

Coalescence of Magnetic Islands in the Low Resistivity Hall MHD Regime*

Luis Chacón, Andrei N. Simakov, and Alessandro Zocco

Los Alamos National Laboratory,Los Alamos, NM 87544

Abstract

We revisit the well-known problem of the coalescence of magnetic islands in the context of Hall MHD. Unlike previous work, we focus on regimes of small resistivity ($S \sim 10^6$) and where the ion skin depth $d_i << L$ (system size). These conditions are of relevance, for instance, in fusion experiments, the solar corona, and the earth's magnetotail. We aim to address under which conditions such systems can exhibit fast reconnection. First, we revisit the resistive MHD problem to further understand the well-known sloshing result [1]. Next, the interaction between the ion inertial length, d_i, and the dynamically evolving current sheet scale length, δ_J, is established [2]. Initially, $d_i << \delta_J$. If η is such that δ_J dynamically thins down to d_i prior to the well-known sloshing phenomena, then sloshing is avoided. This results in peak reconnection rates which are η-independent and scale as $d_i^{1/2}$. However, if d_i is small enough that resistivity prevents δ_J from thinning down to this scale prior to sloshing, then reconnection (and sloshing) proceeds as in the resistive MHD model. Finally, we discuss our development of a semi-analytical model to describe the well-known sloshing result in the resistive MHD model [3], and its extension to Hall and electron MHD.

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1E30

The neoclassical tearing mode: An anomalous transport process.

S.J. Allfrey, P. Popovich and S.C. Cowley

Center for Multi-Scale Plasma Dynamics, Department of Physics & Astronomy, UCLA, Box 951547, Los Angeles, CA 90095-1547

The behavior of the Neoclassical tearing mode (NTM) is recognized as a key determinant of tokamak plasma transport. In the envisaged ITER scenario, control of NTMs will be crucial for successful performance.

Island evolution is determined by several competing mechanisms. Helical flattening of the pressure and the resulting perturbation in the bootstrap current provide a driving term for the island growth. This helical flattening (along field lines) is countered by cross field, anomalous, transport. The contribution of the polarization current can be stabilizing or destabilizing, depending on the island rotation. This rotation frequency is set by the ion and electron viscosities which, again, are anomalous. Thus island evolution is essentially determined by micro-turbulent (anomalous) processes.

As described in the accompanying work [1], we have developed an NTM evolution model in which the integrated Fokker-Planck equations are reduced to a set of 2D equations for the evolution of n, T, ϕ and $\mathbf{j}$ in terms of a set of corresponding fluxes. There we used neoclassical transport (as a proxy) to calculate the required fluxes, in order to provide a closed problem. However, the 'true' (anomalous) fluxes can be obtained from a flux-tube turbulence code. The separation of scales (turbulence smaller than the island) and times (turbulent transport faster than the island evolution) allows us to consider the island as a large (relative to the turbulence length scale) and slowly evolving structure for which local flux-tube calculations of transport is appropriate.

Here we describe how our NTM model [1] can be coupled to an existing flux tube turbulence code, to provide a consistent numerical scheme for the calculation of the evolution of neoclassical tearing modes in a turbulent plasma.

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Transport and the neoclassical tearing mode

P. Popovich, S.J. Allfrey and S.C. Cowley

Center for Multi-Scale Plasma Dynamics, Department of Physics & Astronomy, UCLA, Box 951547, Los Angeles, CA 90095-1547

Understanding of the evolution of the NTMs and their effect on transport is of crucial importance for the design of future fusion devices. Due to very long discharges in ITER, the islands can, potentially, grow to a significant fraction of the minor radius, increasing transport and significantly degrading confinement.

We have developed a model of the NTM based on an expansion of the Fokker-Planck equation. We are interested in the islands of the size such that the parallel transport around the island along the magnetic field lines happens on the same time scale as the radial transport across the island, $\chi_\parallel/l_\parallel^2 \sim \chi_\perp/w^2$. Assuming classical diffusion along the field lines and gyro-Bohm-like transport in the perpendicular direction, we obtain the scaling for the island width as $w \sim \sqrt{\rho_i L}$, which is the minimum island width for bootstrap drive (due to profile flattening). Using $\rho^{*1/2}$ as the expansion parameter, solution of the Fokker-Planck equation yields 2-D equations for the evolution of the electron and ion distribution functions. These equations are solved subject to boundary conditions provided by matching to an external MHD solution.

A fully consistent island evolution model should include turbulent (anomalous) transport for the correct calculation of *e.g.* radial fluxes and anomalous viscosity (which determines island rotation and hence the stabilizing or destabilizing role of the polarization current). As a first step and a "proxy" for turbulent transport, we use a neoclassical model. A neoclassical description allows us to develop a closed model that both consistently includes transport effects on the island growth and provides the appropriate basis for the inclusion of micro-turbulent transport as described in [1].

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Algorithms for Two-Fluid plasma equations.

A. HAKIM, P. STOLTZ, S.E. KURGER, Tech-X Corporation

Fluid models of plasmas are a common tool to study fusion devices. In this work algorithms for the solution of Two-Fluid plasma equations are presented. The Two-Fluid model is more general than the often used magnetohydrodynamic (MHD) model. The model takes into account electron inertia, charge separation and the full electromagnetic field equations and allows for separate electron and ion motion. Finite Lamor Radii effects are taken into account by self consistently evolving the anisotropic pressure tensor equations. The algorithm presented is the high resolution wave propagation method. The wave propagation method is based on solutions to the Riemann problem at cell interfaces. Operator splitting is used to incorporate the Lorentz and electromagnetic source terms. To preserve the divergence constraints on the electric and magnetic fields the so called perfectly-hyperbolic form of Maxwell equations are used which explicitly incorporate the divergence equations into the time stepping scheme. Benchmark results with MHD shock problems, magnetic reconnection and a gravitational instability are presented. A detailed study of the Lower Hybrid Drift Instability (LHDI) in slab geometries is also presented. The LHDI is known to be a source of anomalous resistivity in Field-Reversed Configuration (FRC) plasmas. The numerically computed resistivity is compared to the Chodura resistivity expression commonly used in resistive MHD calculations of FRCs.

1E33

Plasma evolution towards critical equilibria and diamagnetism

Emilia R. Solano

Asociación EURATOM/CIEMAT para Fusión,
Avda. Complutense 22, E-28040, Madrid, Spain

Abstract:

Evolution of plasma current density profiles, $j_{toroidal}$ and $j_{poloidal}$, is studied in the presence of localised non-inductive co-current drive, from either bootstrap or external sources.

It is shown that in a fast, transient, time-scale, introduction of co-current drive induces a back-electromotive force that leads the toroidal current density profile towards criticality in the Grad-Shafranov equation [1], while the poloidal current density profile evolves towards diamagnetism. Criticality indicates that a new solution branch becomes accessible to the equation. In diamagnetic regions of the plasma, the two components of j×B, namely $j_{toroidal} \times B_{poloidal}$ and $j_{poloidal}, \times B_{toroidal}$, have the same sign, and a larger pressure gradient can be supported. Combined, criticality and diamagnetism lead naturally to the electromagnetic capability of sustaining a larger pressure gradient. Could the transport barrier formation process be explained this way?

A simple cylindrical model provides predictions from this conjecture, which can be easily tested in a tokamak with localised current drive sources, such as electron-cyclotron current drive or lower hybrid current drive.

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MHD kink instability driven by differential rotation and line-tied kink modes in the Rotating Wall Machine

Christopher Carey, Carl Sovinec
University of Wisconsins

Recent observations of extragalactic outflows from active galactic nuclei suggest that these jets are permeated with helical magnetic fields. Thus, extragalactic jets may resemble a screw pinch topology and be susceptible to the current driven kink instability. We are conducting numerical MHD simulations which will address the issues of collimation and stability of the extragalactic jet system. In these simulations an initial seed field is twisted by a differentially rotating flow boundary condition. Initial calculations search for two dimensional axisymmetric equilibria for this system. Observations of extragalactic jets find that these systems produce collimated particle outflows extending up to megaparsec length scales. We find that a finite plasma pressure must be included in the system to achieve a collimated equilibrium outflow. For calculations which reach a collimated state, the linear stability of the quasi-equilibria are calculated. Linear calculations indicate that for some cases these quasi-equilibria are kink unstable. These calculations are extended to three dimensions to study the nonlinear saturation of the kink instability. These three dimensional calculations indicate that the kink instability leads to conversion of the toroidal magnetic flux, which is injected by the differentially rotating boundary, to poloidal magnetic flux. Examination of this flux conversion process in the extragalactic jet system could lead to a better understanding of how the jet distributes magnetic energy to the medium which surrounds it.

The Rotating Wall Machine (RWM) at the University of Wisconsin is studying the effects of different boundary conditions on the kink instability in a cylindrical line tied geometry. The motivation of the experiment is to study methods of stabilizing the external kink mode in a Tokamak fusion device. Initial calculations evolve the linearized MHD equations from an equilibrium which is relevant to the RWM. These calculations are used to determine the stability criterion of the system based on the total current in the plasma. The total plasma current which is necessary to drive the instability in the calculation is shown to be in good agreement with that which is measured in the experiment. The radial component of the magnetic field of the fastest growing eigenmode near marginal stability is shown to agree with experimental results as well.

Ballooning and Local Shear Properties of NSTX Plasmas*

M. S. Chance, J. Chen, L-P. Ku, D. McCune, S. C. Jardin, J. Manickam[a] and S. Sabbagh[b]

[a] *Princeton Plasma Physics Laboratory, Princeton, New Jersey.*
[b] *Columbia University, New York.*

Abstract

The NSTX device can exhibit interesting magnetic field properties because of its small aspect ratio legacy. The magnetic field lines are very non-uniformly distributed in the poloidal cross-section, spending much less time in the outer major radius region of the plasma, not unlike the configuration obtained in a high β discharge with a substantial Shafranov shift or a bean-shaped plasma. The local magnetic shear is thus expected to exhibit strong inhomogeneity within magnetic surfaces, including the very likely existence of substantial regions of vanishing local shear even when the global shear is strong. The shear properties is reflective on many physical aspects, most obviously on the ballooning modes where the field lines interchange are facilitated in the regions of low local shear. We examine the magnetic configuration in a variety of equilibria in the NSTX device together with the effect on ballooning modes. This entails obtaining appropriate models of the equilibria, a sufficiently accurate refinement of these for stabilitiy studies and finally, a mapping for the additional quantities for the stability codes. The intercommunication between the various codes necessary for this is carried out within the SWIM framework[1].

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Feedback Coil Geometry and its Effect on Structure of the Resistive Wall Mode*

M.S. Chu[1], M.S. Chance[2], Y.Q. Liu[3], M. Okabayashi[2], H. Reimerdes[4], H. Takahashi[2]

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608 USA
[2]Princeton Plasma Physics Laboratory, Princeton, New Jersey USA
[3]Chalmers University of Technology, Göteborg, Sweden
[4]Columbia University, New York, New York USA

The NMA [1] stability code has been used to study the effect of the feedback coil geometry on the performance of feedback to the resistive wall mode (RWM). In the present formulation, the plasma is assumed to obey ideal MHD with no flow. During the open loop operation, the complete dynamics of the plasma-resistive wall system can be shown to obey an ortho-normal set of open loop eigenfunctions, with the eigenvalues being their open loop growth or damping rate. Usually, only one of these eigenfunctions could be unstable and appears as the naturally growing RWM, with all others appearing as damped (resistive wall) modes. The formulation of NMA is based on this set of normal modes. The effect of feedback on stability is determined completely by a characteristic equation which depends on the feedback circuit and the properties of the normal modes. These properties are the open loop growth rate, the coupling of the coils to them, and the ability of the sensor to detect them. The mode structure during feedback operation is shown explicitly as mixing of the different open loop eigenfunctions. Thus, it is predicted that the mode structure would undergo distortion during the feedback operation. This distortion is large if the feedback coil preferentially excites the stable eigenfunctions instead of coupling mainly to the unstable RWM. Distortion can be minimized by judicious design of the feedback coil. The implication of this optimization on present and future feedback systems is presented.

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Stellarator Coil Optimization

R.F. Schmitt, A.H. Boozer
Department of Applied Physics and Applied Mathematics, Columbia University

Coil design is critical to the cost and viability of stellarator fusion reactors. Coil design is a complex inverse problem with many subtleties. The complexity and inefficiency of the coils increases exponentially with the number of magnetic features retained. The physics properties of a stellarator plasma are determined by the shape of the outermost surface. Only a limited set of shape parameters are essential to that design. The optimal coil set for a given plasma equilibrium controls only the essential shape parameters. The study of small perturbations about the essential shape parameters yields the magnetic features that the coils must produce. This study allows the design of a coil set that possesses minimal complexity and a minimal ratio of the magnetic field on the coil surface to that on the plasma surface. Coil set designs for several plasmas are presented.

1E38

Electrostatic mode associated with pinch velocity in RFPs

Gian Luca Delzanno, Luis Chacón, John M. Finn

LANL

Abstract

We present a systematic study of single helicity (SH) states and quasi-single helicity (QSH) states in RFPs. We begin with cylindrical paramagnetic pinch equilibria with uniform resistivity, characterized by a single dimensionless parameter proportional to the toroidal electric field, or the RFP toroidal current parameter Θ. For sufficiently high Θ, there are several unstable $m = 1$ ideal MHD instabilities, typically one of which is nonresonant, with $1/n$ just above $q(r = 0)$. We evolve these modes nonlinearly to saturation for low Hartmann number H. We then obtain the $m = k = 0$ mean-field profiles, which typically have toroidal field reversal, and study their stability. For typical cases, these profiles may remain unstable to tearing modes, but only for sufficiently high H. For lower H these states are stable. We show results indicating the proximity of these thresholds to the thresholds between SH and QSH behavior in 3D simulations. Next, we analyze fully three-dimensional runs and repeat the analysis based on the $m = k = 0$ mean-field profiles. We conclude that the existence of single-helicity states is only qualitatively related to the stability properties of its mean-field and it is due to the helical structure of these states. Also, we show the importance of the radial paramagnetic pinch flow at low Hartmann number and how it gives unstable electrostatic (hydrodynamic) modes.

Numerical Results on Two-Fluid Reconnection and Relaxation with Guide Field*

C. R. Sovinec, J. R. King, N. A. Murphy, and V. V. Mirnov
University of Wisconsin-Madison

A number of numerical studies have considered two-fluid reconnection in the limit where the perpendicular non-reconnecting component of magnetic field is small or vanishes at the reconnection site. For dynamics in magnetically confined plasmas, the opposite limit is more relevant. An analytical study has charted different regimes of linear tearing in slab geometry [1], which has been used to benchmark two-fluid development for the NIMROD code [2]. Here, we extend the slab geometry tests to the limit where the equilibrium scale is larger than all but the domain size. Results from similar tests in cylindrical geometry are also described. Another benchmark compares the quasilinear predictions of Hall and MHD dynamo effects from analytical theory and computation. Both show the Hall contribution to be strong but limited to the microscopic tearing scale, while the weaker MHD dynamo effect extends across the ion scale. Two-dimensional nonlinear evolution (computed by the code) leads to a qualitatively different outcome. As the island grows, the Hall electric field follows the separatrix, and its average contribution (dynamo effect) spreads to the macroscopic scale.

The two-fluid developments in NIMROD are being applied to MRX, among a number of configurations. Two-fluid results for co- and counter-helicity reconnection investigating the importance of guide-field and communication to device-size scales are described.

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TEARING MODE SATURATION IN REVERSED FIELD PINCHES WITH LOCALLY LINEAR FORCE-FREE MAGNETIC FIELDS

E. Tassi[1], F.Militello[2], F. Porcelli[1], R. J. Hastie[3]

[1] Burning Plasma Research Group, Dipartimento di Energetica, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[2]Center for Multiscale Plasma Dynamics and Institute for Fusion Studies, University of Texas at Austin, Austin, Texas 78712, United States
[3]Culham Science Centre, EURATOM/UKAEA Fusion Association, Abingdon, OX14 3DB, United Kingdom

An investigation of the nonlinear saturation of tearing modes in Reversed Field Pinches is presented. The analysis is valid for a class of force-free equilibria for which the ratio μ between the parallel current density and the magnetic field is constant over a region including the resonant surface. This class of equilibria includes the classical Bessel function model [1] as a particular case. The treatment of the problem is fully analytical and is based on a perturbative method previously applied to a number of tokamak-relevant cases (e.g. [2,3] and references therein). Our analysis shows that for the considered equilibria the tearing mode saturates at an amplitude proportional to the Δ' linear stability parameter, with a proportionality coefficient depending only on the value of μ at the resonant surface. This result is then applied to a class of piecewise constant-μ equilibria which were recently shown [4] to be potentially of interest for explaining the formation of cyclic Quasi Single Helicity states, e.g. [5]. It is found that for such equilibria the saturated island width increases when increasing the height of the step in the μ profile.

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Hamiltonian theory of the nonlinear collisionless tearing mode

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

E. Tassi, D. Grasso
Dipartimento di Energetica, Politenico di Torino, Torino 10129, Italy.

The Hamiltonian formalism constitutes an effective framework for investigating the dynamics of fluid models.[1] In particular, it provides techniques for finding conserved quantities 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. A particularly appealing feature of the Hamiltonian formalism is that it readily provides first integrals of the equations governing the structure and propagation of nonlinear structures such as magnetic islands and modons, or solitary waves.[2]

Here a newly developed noncanonical Hamiltonian formulation for a two-fluid model describing collisionless reconnection is used to investigate the effect of electron inertia on the nonlinear growth of tearing modes. A variational principle is used to obtain a pair of equilibrium equations that take the form of coupled nonlinear elliptic equations for the magnetic flux and the ion stream-function. These equations generalize the Grad-Shafranov equation of MHD. Solutions will be presented for magnetic islands in various regimes determined by the relative size of the island half-width compared to the electron skin depth, the ion-sound Larmor radius, and the ion skin-depth.

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Hamiltonian Structure of a Collisionless Reconnection Model Valid for High and Low β Plasmas

P.J. Morrison[1], E. Tassi[2], D. Grasso[2], and F. Waelbroeck[1]

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Abstract

The noncanonical Hamiltonian formulation of a recently derived four-field model describing collisionless reconnection is presented. The corresponding Lie-Poisson bracket is shown to be a sum of a direct and semi-direct product forms and to possess four infinite independent families of Casimir invariants. Three out of four of these families are directly associated with the existence of Lagrangian invariants of the model. Two of the invariants generalize previously discovered invariants of a two-field model for reconnection in low-β plasmas. Finally a variational principle is given for deriving general equilibrium equations and an example of an equilibrium solution is described explicitely.

[1] Department of Physics and Institute for Fusion Studies, University of Texas, Austin, Texas 78712.
[2] Dipartimento di Energetica, Politecnico di Torino, Torino, 10129, Italy.

Investigations of Error Field Effects in NSTX with M3D

J.A. Breslau, J.K. Park, W. Park, A.H. Boozer, and J.E. Menard
Princeton Plasma Physics Laboratory

It has been demonstrated that RWM stabilization by plasma rotation in NSTX is impeded by the presence of a moving non-axisymmetric component to the toroidal field during the discharge [1]. Confinement is improved by active correction of this error field, while its exact cause is still under investigation. A numerical study of the effects of the error field on magnetic island formation has been conducted with ideal linear codes [2]. We now extend these results by conducting nonlinear, non-ideal studies of these effects using the M3D code [3]. Preliminary results will be presented, showing the effects of 3D perturbations on the equilibrium in the form of current sheet development and island formation. These will be benchmarked against the prior linear results. This is to be followed up by investigations of mode locking and consequent rotation damping.

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Emergence of large scale magnetic fields by relaxation in laboratory and astrophysical plasmas

X. Z. Tang[1] and A. H. Boozer[2]

[1]Los Alamos National Laboratory, Los Alamos, NM 87545
[2]Columbia University, New York, NY 10027

Magnetic relaxation is an extreme form of self-organization by which magnetic energy and helicity injected on small scales are transported to and accumulated on system scale magnetic fields by plasma fluctuations. It is distinct from the conventional MHD dynamo envisioned for planetary, star, and galactic disk magnetic fields, in that the energy drive comes from external magnetic helicity injection and the flow energy is sub-dominant compared with the magnetic energy throughout the process.

Many fusion concepts rely on magnetic relaxation to generate and sustain the confining magnetic field. Examples include the reversed field pinch (RFP), spheromak, spherical torus with a plasma center column (ST-PCC), and spherical torus under co-axial helicity injection (ST-CHI). Naturally occurring plasmas such as that in the astrophysical radio lobes powered by the accretion disks of super-massive black holes are also subject to magnetic relaxation, although on a much grander spatial scale. Furthermore, astronomical observation and theoretical consideration suggest that the large scale magnetic fields in the radio lobes are likely the result of magnetic self-organization rather than a flow driven MHD dynamo.

A unified physics description of these relaxation processes can be obtained by an analogy to the familiar driven nonlinear oscillator. The fully relaxed Taylor state that minimizes the magnetic energy while conserving the magnetic helicity, corresponds to the limit of a driven linear oscillator. Similar as a linear resonance at the fundamental frequency of the harmonic oscillator that causes diverging power consumption, the primary resonance at the spatial eigen-frequency of the first force-free Chandrasekhar-Kendall mode poses a barrier that forces the inputed energy onto the system scale magnetic fields, for example, a laboratory spheromak. In a doubly connected torus such as RFP and ST, the toroidal flux conserver brings additional subtleties to the resonance physics. The plasma can no longer resonant at the eigen-frequencies of Chandrasekhar-Kendall modes that carry toroidal flux. Instead, the flux constraint up-shifts the resonance to a new class of flux-free modes that have a vacuum field contribution from the image current in the flux conserver. The implication of this constrained resonance on RFP and ST-CHI operations will be elucidated.

A recent work shows that the resonance physics can be extended to a partially relaxed plasma as long as the deviation from the fully relaxed Taylor state, for example, a flux-dependent $j_{\|}/B$, is a function of the poloidal magnetic flux normalized by the peak poloidal flux at the magnetic axis. This is a form of nonlinear resonance in spatial rather than temporal frequencies that is of general interests and strongly supports the magnetic self-organization paradigm. The practical importance of this nonlinear resonance in the spheromak and astrophysical radio lobes will be illustrated.

Like a generic nonlinear oscillator, the linear and nonlinear resonances are regularized by any of plasma inertia, finite pressure, and non-uniform normalized parallel current density in a partially relaxed plasma that are not functions of the poloidal flux normalized by the peak flux at the magnetic axis. In place of a resonance barrier, new branches of bifurcated regularized solutions become energetically accessible to the plasma. They also have distinct physics interpretation and significance, and are intimately connected to the nonlinear dynamics that facilitate the relaxation. Both fusion and astrophysical examples will be drawn to illustrate the physics. Potential validating experiments are also proposed.

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Theoretical Resolution of Magnetic Reconnection in High Energy Plasmas*

B. Coppi
M.I.T., Cambridge, MA, USA

The formation of macroscopic reconnected magnetic structures (islands) have been observed in advanced experiments on weakly collisional, well confined plasmas while established theories of the drift-tearing modes, [1,2,3] which depend strongly on the electron temperature gradient and can describe the formation of these structures, had predicted practically inaccessible excitation thresholds for them in these regimes. The relevant theoretical dilemma is resolved as mesoscopic modes that depend critically on the ratio of the transverse (to the magnetic field) to the longitudinal thermal conductivity $D_{\perp}^{e}/D_{\parallel}^{e}$, can produce large scale magnetic reconnection. These modes are envisioned to emerge from a background, which can be coherent, of collisionless microscopic reconnecting modes driven by the electron temperature gradient, that create a sequence of adjacent strings of magnetic islands and increase considerably the ratio $D_{\perp}^{e}/D_{\parallel}^{e}$ over its classical value [4,5]. The mesoscopic reconnecting mode is treated by a singular perturbation analysis [5] involving three asymptotic regions and the small parameters $\left(D_{\perp}^{e}/D_{\parallel}^{e}\right)^{1/4}$ and $\varepsilon_{*}^{1/4}$, where $\varepsilon_{*} \equiv D_{m}/D_{A}$, D_{m} is the magnetic diffusion coefficient, $D_{A} \sim \mathrm{v}_{A}^{2} r_{Te}/\left(D_{B} k_{\perp}\right)$, $r_{Te} \equiv \left(-d \ln T_{e}/dr\right)^{-1}$, $k_{\perp}$ is the transverse mode number, $\mathrm{v}_{A}^{2} = B^{2}/\left(4\pi n m_{i}\right)$ and $D_{B} = cT_{e}/\left(eB\right)$. It is a pleasure to thank C. Crabtree and V. Roytershteyn for their collaboration on different parts of the subject treated in this paper. *Sponsored in part by the U.S. Department of Energy.

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Radial structures and nonlinear excitation of Geodesic Acoustic Modes*

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

Geodesic Acoustic Modes [1] (GAM) are toroidally symmetric normal modes unique to toroidal plasmas, whose mode structure is nearly poloidally symmetric. They exist since the charge separation effect, due to ion radial magnetic drifts associated with geodesic curvature, causes a finite parallel a.c. electric field ($\propto T_e/T_i$) and a perturbed ion diamagnetic current to ensure quasi-neutrality via electron and ion dynamic responses, respectively. In this paper, we show that GAMs constitute a continuous spectrum due to radial inhomogeneities. The existence of singular layer, thus, suggests linear mode conversion to short-wavelength kinetic GAM (KGAM) via finite ion Larmor radii. This result is demonstrated by derivations of the GAM mode structure and dispersion relation in the singular layer. At the lowest order in $k_r\rho_i$, with k_r the radial wave vector and ρ_i the ion Larmor radius, the well known kinetic dispersion relation of GAM is recovered [2]. At the next relevant order, $O(k_r^2\rho_i^2)$, we show that KGAM propagates in the low-temperature and/or high safety-factor domain; i.e., typically, radially outward. Our analyses also confirm that GAM and Beta induced Alfvén Eigenmodes (BAE) are degenerate in the long wavelength limit, where diamagnetic effects are ignored, even when finite Larmor radius corrections are accounted for. As reported earlier [3, 4], this is not a coincidence and is due to the fact that, at long wavelengths, shear Alfvén wave compressibility due to geodesic curvature coupling at $k_\parallel = 0$ is identical to the corresponding dynamics of electrostatic waves with $k_\phi = k_\theta = 0$, provided that diamagnetic effects are neglected.

Geodesic Acoustic Modes are important to turbulence transport studies, since their low-frequency radial structures can scatter drift-wave (DW) fluctuations, which are primarily responsible for collisionless transports, to stable short-wavelength domain and, thereby, suppress the DW turbulence transport. In this work, we show that, while KGAM is linearly stable due to ion Landau damping, it can be nonlinearly excited by finite-amplitude DW turbulence via 3-wave parametric interactions. The resultant 3-wave driven-dissipative nonlinear system then exhibits the typical prey-predator self-regulatory dynamics.

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The role of resistivity on line-tied kink modes

G.L. Delzanno, E. G. Evstatiev, J. M. Finn
LANL

The study of MHD linear stability with line-tying has been the subject of intense research in the solar physics community for several decades, in an attempt to understand the dynamics of solar flares and the related mechanisms of energy release (see the review paper [1]). In the astrophysical context, line-tying of flux tubes to an accretion disk is considered an important effect. In recent years experiments on two cylindrical devices [2-3] have brought even further interest on this subject. It is important to notice, however, that applications to solar physics or to laboratory experiments span a wide range of values of the Lundquist number S, $S>10^{10}$ in the solar corona while S~50 for the experiments. Therefore, the aim of this work is to shed light on the role of resistivity on the linear stability of line-tied kink modes in cylindrical geometry. In order to do this, we use the method we recently proposed in Ref. [4]. The method consists of summing up a number of one-dimensional (radial) eigenfunctions to obtain the full two-dimensional solution of the problem and has been successfully applied to both ideal and resistive MHD [4].

By allowing the motion of the plasma relative to the magnetic field, resistivity can potentially affect the problem in two ways. First, it disallows perfect line-tying at the two end-plates of the cylinder. Second, some of the radial eigenfunctions used to construct the full solution of the problem can be unstable tearing modes instead of stable ideal modes, thus opening the possibility of tearing-like instabilities in line-tied configurations. We address these two issues by investigating different equilibria where the field line pitch as a function of radius can be monotonically increasing (tokamak-like), monotonically decreasing (RFP-like) or constant. We show that resistivity fundamentally affects the threshold for marginal stability: small values of resistivity can destabilize the system and give rise to slowly growing modes below ideal stability, while large values of resistivity provide strong stabilization [5-6]. Furthermore, resistive modes appear as a consequence of pure resistive diffusion and there are no tearing-like instabilities in the line-tied system: resistivity acts globally on the plasma column rather than in boundary layers [5-6].

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1E48

Turbulent transport via wave-particle decorrelation in collisionless plasmas

Z. Lin, L. Chen
University of California, Irvine, California 92697, USA
zhihongl@uci.edu

P. H. Diamond
University of California, San Diego, California 92093, USA

T. S. Hahm, S. Ethier
PPPL, Princeton University, Princeton, New Jersey 08543, USA

S. Klasky
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

Large scale, gyrokinetic particle simulations show that wave-particle decorrelation is the dominant mechanism responsible for the electron heat transport driven by the toroidal electron temperature gradient (ETG) turbulence characterized by radial streamers. We find that the radial transport is driven by the local fluctuation intensity and that the phase-space island overlapping leads to a diffusive process with a time scale close to the wave-particle decorrelation time controlled by the interactions between the electron parallel motion and radial *ExB* drift, the magnetic shear, and the parallel spectral width of fluctuations. The kinetic time scales relevant to the transport process are much shorter than the fluid turbulence auto-correlation time, eddy turnover time, and linear growth time. Therefore the ETG transport is not induced by the streamer trapping of electrons. The extrapolation of the transport level from present-day tokamak to future larger devices, e.g., ITER, could be over-pessimistic, if the simplistic mixing length argument is invoked with the streamer length as the random walk spatial step size and the linear growth time as the time step size.

Tuesday morning, April 24

8:30 – 9:30

Ballroom B&C

Review Talk 2A

Equation-Free Modeling and Computation for Complex/Multiscale Systems

Y. Kevrekidis, Princeton University

In current modeling practice for complex/multiscale systems, the best available descriptions often come at a fine level (atomistic, stochastic, microscopic, individual-based) while the questions asked and the tasks required by the modeler (prediction, parametric analysis, optimization and control) are at a much coarser, averaged, macroscopic level. Traditional modeling approaches start by first deriving macroscopic evolution equations from the microscopic models, and then bringing our arsenal of mathematical and algorithmic tools to bear on these macroscopic descriptions. Over the last few years, and with several collaborators, we have developed and validated a mathematically inspired, computational enabling technology that allows the modeler to perform macroscopic tasks acting on the microscopic models directly.

We call this the “equation-free” approach, since it circumvents the step of obtaining accurate macroscopic descriptions. We will argue that the backbone of this approach is the design of (computational) experiments. Traditional continuum numerical algorithms can thus be viewed as protocols for experimental design (where “experiment” means a computational experiment set up and performed with a model at a different level of description). Ultimately, what makes it all possible is the ability to initialize computational experiments at will. Short bursts of appropriately initialized computational experimentation through matrix-free numerical analysis and systems theory tools like variance reduction and estimation- bridge microscopic simulation with macroscopic modeling. I will also discuss some recent developments in data mining algorithms, exploring large complex data sets to find good "reduction coordinates".

Tuesday morning, April 24

9:30 – 10:00

Ballroom B&C

Oral Session 2B

Energy Conservation In Linear And Perturbative δf-PIC Simulations*

A. M. Dimits
Lawrence Livermore National Laboratory

Energy conservation is a topic of some interest in fluid and kinetic simulation of plasmas. In particular, since the fluid or kinetic equations underlying simulation codes often possess an exact "physical" (kinetic-internal + kinetic-flow + field) energy invariant, good conservation of a discretization of this energy invariant is generally considered a necessary condition for the integrity of the simulations. However, this has also been the topic of some confusion. "Flux-tube" δf gyrokinetic codes have been used widely in the simulation of microinstability-driven transport in magnetic-fusion plasmas [1,2,3]. A key aspect of these codes is that the "parallel" nonlinearity (associated with the acceleleration due to the self-consistent electric field along the equilibrium magnetic field) is neglected, since it is formally of higher order in the gyrokinetic smallness parameter than the dominant linear and nonlinear terms [4]. Careful derivations have been undertaken of gyrokinetic equations that conserve energy and retain the parallel nonlinearity [5]. This has led to a belief that for nonlinear gyrokinetic simulations "without this term, the energy conservation cannot be satisfied in the simulation" [6]. For example, the difficulty of formulating and calculating a physical energy invariant for flux-tube gyrokinetic simulations led to the use of a free-energy quantity (entropy + field-energy) as a measure of the simulation integrity in early work [1]. Here, it is shown that linear and flux-tube- δf (including δf -PIC) simulations do indeed have a well-defined physical energy invariant, which can be calculated and tracked. The key point is that the higher-order part of δf, which is needed to calculate the perturbed kinetic energy, can be formally obtained from the next-order equation in a perturbative treatment of the parallel acceleration term. This latter equation has the same characteristics (which do not contain the parallel acceleration by the self-consistent electric field) as the lower-order equation on which the simulations are based, and its solution can be represented using additional weights at the marker particle positions. Applications of the resulting diagnostic both to understanding the physical energy balance in and to tracking the integrity of simulations of Landau-damped plasma oscillations and geodesic acoustic modes, and of ion-temperature-gradient driven turbulence will be shown.

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Tuesday morning, April 24

10:00 – 12:00

Atrium

Poster Session 2C

Analysis of the Validity of the Asymptotic Techniques in the Lower Hybrid Wave Equation Solution For Reactor Applications

A. Cardinali, L. Morini*, C. Castaldo, F. Zonca

Associazione Euratom-ENEA sulla Fusione, C.P. 65 - I-00044 - Frascati, Rome, Italy
*Enea Student

The wave propagation of the Lower Hybrid (LH) in a tokamak plasma 2D geometry can be correctly described only with a full wave approach based on full numerical techniques [1] or on a semi-analytical approach, by reducing the wave equation in two nested equations of the first order, as shown in Ref. [2]. In this work, in order to test and compare the full numerical solution with that obtained by applying the WKB asymptotic expansion, we present a rigorous WKB solution of the wave equation for the first two orders of the expansion parameter, obtaining, at the first order, the equation for phase and, at the next order, the equation for the amplitude of the field. The non-linear PDE for the phase will be solved in a pseudo-toroidal geometry (circular and concentric magnetic surfaces) by the method of characteristics. The associated system of ODE's for the position and the wave-number is obtained and analytically solved by choosing an appropriate expansion parameter. The quasi-linear PDE for the WKB amplitude is also analytically solved, allowing the reconstruction of the wave electric field inside the plasma. The solution will be also solved numerically and a comparison with the analytical solution will be addressed. Further developments, consisting in generalizing the solution to a Solov'ev analytical equilibrium geometry, will also be presented. A discussion of the validity of the WKB approximation based on the obtained results will be also given.

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ECRH and its effects on neoclassical transport in stellarators

JaeChun Seol, C. C. Hegna, and J. D. Callen
Engineering Physics Department, University of Wisconsin-Madison

Energetic electron populations can substantially modify the neoclassical transport properties in stellarators. A model accounting for this change in transport is developed assuming the presence of electron cyclotron resonance heating (ECRH). The quasilinear diffusion coefficient for second harmonic X-mode ECRH is developed for a bumpy stellarator. Care is taken in accounting for the pitch-angle dependence of the quasilinear diffusion coefficient since application to experiments with narrow resonance zones are of interest. Weakly relativistic effects are considered through the the mass effect on the cyclotron frequency. Collisionless loss zones for trapped particles exist in the velocity space of the three dimensional magnetic configurations. The radio-frequency (rf) waves accelerate trapped electrons into the direct loss zone in bumpy stellarators and produce a direct loss flux. An analytical expression for this loss flux is derived analytically that is proportional to the rf field strength and the value of the zeroth order distribution function at the minimum speed for collisionless loss. The direct loss flux of electrons is another source of a non-ambipolar particle flux in bumpy stellarators. This additional non-ambipolar flux helps the ambipolarity equation which generally has multiple roots for the radial electric field. Electron root (large positive E_r) easily obtained if the electrons are in the $1/\nu$ regime and the ions are in the ν regime. Implications for ECRH in the HSX stellarator will be discussed.
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A canonical normal form for multidimensional mode conversion

E. R. Tracy[1], A. N. Kaufman[3], A. S. Richardson[1] and N. Zobin[2]
[1]Physics Department and [2]Mathematics Department, William and Mary
Williamsburg, VA, 23187-8795
[3]Physics Department UC Berkeley and LBNL
Berkeley, CA 94720

Linear conversion occurs when two wave types, with distinct polarization and dispersion characteristics, are locally resonant in a nonuniform plasma [1]. In recent work, we have shown how to incorporate a ray-based (WKB) approach to mode conversion in numerical algorithms [2,3]. The method uses the ray geometry in the conversion region to guide the reduction of the full *NXN*-system of wave equations to a 2X2 coupled pair which can be solved and matched to the incoming and outgoing WKB solutions. The algorithm in [2] assumes the ray geometry is hyperbolic and that, in ray phase space, there is an 'avoided crossing', which is the most common type of conversion. Here, we present a new formulation that can deal with more general types of conversion [4]. This formalism is based upon the fact (first proved in [5]) that it is always possible to put the 2X2 wave equation into a 'normal' form, such that the diagonal elements of the dispersion matrix Poisson-commute with the off-diagonals (at leading order). Therefore, if we use the *diagonals* (rather than the eigenvalues or the determinant) of the dispersion matrix as ray Hamiltonians, the off-diagonals will be conserved quantities. When cast into normal form, the 2X2 dispersion matrix has a very natural physical interpretation: the diagonals are the uncoupled ray hamiltonians and the off-diagonals are the (locally constant) coupling. We further discuss how to extend these results beyond leading order, and how to incorporate the normal form into ray tracing algorithms.

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Three dimensional calculations of plasma admittance in the ion cyclotron frequency range *

J. C. Wright, P. T. Bonoli[†], M. Brambilla[‡]

Using the full-wave code, TORIC [M. Brambilla, Plasma Phys. Controlled Fusion **41**, 1 (1999)], we construct the linear response matrix, the admittance, for the RF driven plasma, where the admittance, **Y**, is defined as $B = \mathbf{Y} \bullet E$. In this work, TORIC was modified to allow excitation of the (E_η, E_ζ) electric field components at the plasma surface, corresponding to a single poloidal and toroidal mode number combination (m,n). This leads to the tensor response: $\mathbf{Y} = \begin{pmatrix} Y_{\eta\eta} & Y_{\eta\zeta} \\ Y_{\zeta\eta} & Y_{\zeta\zeta} \end{pmatrix}$, where each of the $\mathbf{Y}_n$ submatrices is $N_m \times N_m$ in size. It is shown that the admittance matrix is equivalent to a Green's function calculation for the full-wave system and in addition, the net work done in the calculation is on the order of twice a single full-wave calculation. We will also present results from the FELICE one dimensional finite Larmor radius full wave code that quantify the two dimensional effects on the admittance. The two dimensional results show an asymmetry depending on the toroidal mode number due to the interaction with the poloidal field. They also demonstrate a strong delta function like response in that the magnetic response tends to be peaked at the driven mode - in this, there is similarity to the one dimensional calculations. Finally, we will discuss applications to antenna coupling calculations, specifically with the TOPICA code [Lancellotti, V., *et al.*, Nucl. Fusion **46**, 476 (2006)].

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[†]*Plasma Science and Fusion Center (MIT), Cambridge, Massachusetts 02139.*
[‡]*IPP-MPI - Euratom Association - Boltzmannstr. 2, D-85748 Garching, Germany*

Porcelli Sawtooth Trigger Module in PTRANSP*

G. Bateman[1], A.H. Kritz[1], A.Y. Pankin[1],
D.M. McCune[2], R.V. Budny[2] and F.D. Halpern[1]

[1]Lehigh University, Bethlehem, PA
[2]Princeton Plasma Physics Laboratory, Princeton, NJ

The NTCC Porcelli sawtooth trigger module (http://w3.pppl.gov/NTCC) [1,2] is implemented and tested in the PTRANSP predictive integrated modeling code. Once a sawtooth crash is triggered, the changes in the plasma profiles caused by the crash are computed using the Porcelli option in the NTCC KDSAW module. Predictive simulations are carried out using the Porcelli sawtooth model together with the GLF23 and MMM95 transport models. The NTCC PEDESTAL module is used to compute the height and width of the temperature pedestal at the edge of H-mode discharges. An implementation of Newton's method in PTRANSP is used to control the numerical problems associated with solving transport equations with stiff transport models [3]. Simulation results are compared with experimental data for the period and amplitude of sawtooth oscillations in tokamak plasmas. One of the difficult issues associated with the implementation of the Porcelli sawtooth model has to do with the different time step lengths in the PTRANSP code. The transport equations are advanced using relatively short transport time steps while fast neutral beam and alpha particles slow down on relatively longer heating time steps. Since sawtooth crashes redistribute the fast neutral beam and alpha particles within the sawtooth mixing region, it was initially anticipated that the full computation of each sawtooth crash could only be carried out at the end of the longer heating time steps. Since this restriction would lead to inaccuracies in the timing of sawtooth crashes, changes to the PTRANSP code have been made to allow for the triggering of sawtooth crashes at the end of the shorter transport time steps.

* This work is supported by DOE contracts DE-FG02-92-ER-54141 and DE-AC02-76CH0307.

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Hybrid simulations of rotational instabilities in FRCs*

E. V. Belova, R. C. Davidson, H. Ji, M. Yamada, S. P. Gerhardt
Princeton Plasma Physics Laboratory

Three-dimensional nonlinear hybrid simulations have been performed to study the ion toroidal spin-up and rotational instabilities in FRC experiments, including the effects of finite toroidal magnetic field. The initial configuration is assumed to have zero ion rotation and dimensionless parameters corresponding to the FRX-L plasma. The ion spin-up in the simulations is related to the particle loss caused by the resistive poloidal flux decay. In about 20-30 Alfven times, the ion rotational velocity becomes comparable to the ion diamagnetic velocity. The n=1 tilt instability is the most unstable linear mode for the initial (non-rotating) configuration. However, at $t \sim 30t_A$, growth of the n=2 and n=3 rotational modes can be seen depending on the initial conditions. The rotational mode has the largest amplitude in the nonlinear regime. Another set of nonlinear simulations was performed including finite initial toroidal field with peak value of up to 30% of external field. It is found that the ion toroidal spin-up is not modified significantly by the finite initial toroidal magnetic field. A separate set of linearized simulations for a non-rotating FRC configuration shows that a small equilibrium toroidal field has a weak destabilizing effect on the MHD modes due to the effective reduction of the average ion Larmor radius, and correspondingly weaker finite-Larmor-radius stabilization. In contrast to the linear behavior, the finite toroidal field is found to have a significant stabilizing effect in the nonlinear phase of the simulations, reducing the growth rates and nonlinear amplitudes of the rotational modes. The physical mechanism for the toroidal field stabilization of the rotational modes is being investigated.

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Quasi-Equilibria Lattice Boltzmann Schemes for MHD Turbulence

Nate Phillips[1], Brian Keating[1], George Vahala[1] and Linda Vahala[2]

[1] William & Mary, Williamsburg, VA
[2] Old Dominion University, Norfolk, VA

Lattice Boltzmann (LB) schemes are a mesoscopic representations of fluid equations which, in this higher dimensional space, lead to very efficient trajectory solutions. These solutions are then projected back to physical space by Chapman-Enskog asymptotics. Thus nonlocal macroscopic convective derivatives are modeled by local kinetic moments, resulting in codes that are extremely well parallelized. For MHD

$$\frac{\partial f_i}{\partial t} + \mathbf{e}_i \cdot \nabla f_i = -\frac{1}{\tau_v}\left[f_i - f_i^{eq}\right] , \quad \frac{\partial \mathbf{g}_i}{\partial t} + \mathbf{e}_i \cdot \nabla \mathbf{g}_i = -\frac{1}{\tau_m}\left[\mathbf{g}_i - \mathbf{g}_i^{eq}\right]$$

where $\sum_i f_i = \rho$, $\sum_i f_i \mathbf{e}_i = \rho \mathbf{u}$ .... , $\sum_i \mathbf{g}_i = \mathbf{B}$, ... and $\mathbf{e}_i$ are the lattice velocity vector. and $\nabla \cdot \mathbf{B} = 0$ to machine accuracy (errors of 10^{-17}). Unfortunately, the straightforward LB-MHD model permits limited ranges of Reynolds and magnetic Reynolds numbers. Entropic LB enforces the extremization of a discrete H-theorem $H = \sum_i f_i \ln\left(f_i / w_i\right) + ..$ subject to appropriate constraints. We discuss attempts at Entropic LB-MHD.

From plasma rotation and momentum transport studies at JET, de Vries et. al. (2006) have found that the Prandtl number is significantly less than one. This implies more rapid heat diffusivity than momentum diffusivity. We discuss the application of quasi-equilibria LB to MHD. Ansumali et. al. (2006) first considered quasi-equilibria for 2D Navier-Stokes turbulence introducing an intermediate quasi-equilibria

$$\frac{\partial f_i}{\partial t} + \mathbf{e}_i \cdot \nabla f_i = -\frac{1}{\tau_{v1}}\left[f_i - f_i^{*}\left(M,N\right)\right] - \frac{1}{\tau_{v2}}\left[f_i^{*}\left(M,N\right) - f_i^{eq}\left(M\right)\right]$$

where the f^* are the quasi-equilibria that depend on both the locally conserved fields M and the quasi-conserved slow fields N (heat flux … for Pr $<$ 1) and $\tau_{v1} < \tau_{v2}$. We extend these ideas to LB-MHD.

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Block quasi-Newton solver for transport equations

Johan Carlsson and John R. Cary

Tech-X Corporation

A new quasi-Newton algorithm has been developed for systems in which the Jacobian has a block structure, as is the case for finite-difference approximations of transport equations where the fluxes depend only on the local field values and their gradients. A primary goal of this work is to minimize the number of numerically expensive flux calculations (e.g. diffusivities). Secondary design considerations were 2nd order temporal and spatial discretizaton error, good numerical stability, and a modular design. A test suite has also been developed to allow validation of the solver.

Like the most common quasi-Newton algorithm, the Broyden method, our new quasi-Newton approach uses flux evaluations from previous Newton iterations to approximate the Jacobian. Assuming that the flux evaluations dominate the computation time, the approximate Jacobian is thus free. Our approximation of the Jacobian, which we call the hyper-secant approximation, requires the solution of a small, dense linear system per radial grid point per iteration. Unlike the Broyden Jacobian, the hyper-secant approximation converges toward the finite-difference Jacobian after sufficiently many iterations.

We will present numerical studies of spatial and temporal accuracy as well as stability for time steps exceeding the CFL limit by many orders of magnitude.

NIMROD Simulations of the SSPX Spheromak Studying Viscosity and Artificial Density Diffusivity, and Linear MHD Stability Analysis of SSPX

B.I. Cohen, E.B. Hooper, L.L. LoDestro, J. Jayakumar, H.S. McLean, L.D. Pearlstein, R.D. Wood
Lawrence Livermore National Laboratory, Livermore, CA 94550
A.D. Turnbull
General Atomics, San Diego, CA 92121
C.R. Sovinec
University of Wisconsin, Madison, WI 53706

We continue to use the NIMROD code to simulate SSPX discharges for both the original capacitor bank and the new 32-module, more powerful capacitor bank. We have undertaken limited sensitivity studies with respect to the scalar kinematic viscosity, a tensor viscosity (parallel and perpendicular components), the artificial density diffusivity, and the toroidal resolution. The temporal histories of the magnetic fluctuations, quality of the magnetic surfaces, and electron temperatures are sensitive to changes in these parameters. The close coupling of the MHD equations and the sensitivity to parameters makes quantitative comparison of electron temperatures in NIMROD to those in SSPX challenging. A parallel viscosity that is additive to the scalar kinematic viscosity (required for numerical convergence) has been included in the simulations. For a fixed kinematic viscosity, including finite parallel viscosity reduces the electron temperature, and the effect is even larger at lower kinematic viscosities. Simulations with toroidal mode numbers n=0-21 showed that the mode energy dropped rapidly above a transition of n=5-7 for kinematic viscosities between 10 and 1000 m^2/s, suggesting that a maximum mode number of 10 would give the best trade-off between accuracy and speed of calculation. The artificial density diffusivity introduces an energy sink at the magnetic axis where the density peaks; reducing the diffusivity leads to higher temperatures.

Past analysis of SSPX has included equilibrium reconstruction assuming simple current profiles and minimizing the RMS error with respect to magnetic probe measurements. The results typically show a good correlation between the toroidal mode numbers n of measured magnetic fluctuations and low-order rational surfaces at the same n in the reconstructed q profile. Recent progress in SSPX has resulted in high electron temperatures and good core-plasma energy confinement ($T_e > 350$eV and radial electron thermal diffusivity approaching tokamak L-mode values). Together, these results suggest that the quality of SSPX magnetic surfaces is sufficiently good that a standard toroidal linear MHD stability analysis is appropriate, which is addressed here. Equilibria are generated by the 1&1/2D Corsica code. Beginning with a reconstructed equilibrium, the plasma β is artificially elevated well above SSPX β's, until DCON (fast-running stability assessment) predicts robust ideal instability. With this equilibrium we performed a benchmark of an ideal-MHD internal kink, using GATO (linear toroidal ideal-MHD eigenvalue code) and NIMROD (linearized option, non-ideal, 3D initial-value code) and obtained excellent agreement in growth rates and eigenfunctions. For an external-mode benchmark, an SSPX-like equilibrium was generated with vanishing current on the open field-lines (GATO assumes a vacuum outside the separatrix); excellent agreement was again obtained. We are now analyzing SSPX discharges to assess β limits and will report progress.

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2C10

Singular value decomposition methods for noise reduction in particle-based transport calculations

D.A. Spong, D. del-Castillo-Negrete, and S.P. Hirshman
Oak Ridge National Laboratory
Oak Ridge, TN 37830, USA

Particle based (e.g., Monte Carlo) calculations are widely used in the study of transport in fusion plasmas and many other areas. The appeal of these methods is rooted in the fact that the numerical integration of particles is in principle more straightforward than the numerical solution of the corresponding partial-differential equation for the particle distribution function. This is particularly clear in the case of high dimensional problems in complicated geometries, and in problems with boundary layers for which grid resolution is a critical issue. However, a major drawback of particle methods is the inherent noise caused by limited statistical sampling with finite number of particles. Thus, a key issue for the success of particle simulations is the development of noise reduction, smoothing techniques. The goal of this contribution is to explore the use of noise-filtering techniques based on singular value decomposition (SVD) methods.

For two-dimensional steady state problems the method is based on low-rank truncations of the SVD of a coarse-grained representation of the particle distribution function. For time-dependent two-dimensional problems we propose the use of generalized low rank approximation (GLRA) methods in which the time is treated as a third dimension. The proposed algorithms are tested with particle simulation data of collisional relaxation. As an application of the methods we consider transport in a magnetically confined plasma in toroidal geometry. The particle data is obtained with a delta-f particle code that follows the guiding center orbits in a prescribed equilibrium magnetic field and incorporates collisions using a Monte Carlo (Langevin) operator based on pitch angle and energy scattering terms, taking into account the full velocity-dependent potentials. The reduction of the noise level is studied as a function of the number of particles and the rank of the SVD and GLRA truncation.

Investigation of the extended MHD NIMROD code parallel performance scalings.

S. Vadlamani, S. E. Kruger [1], C. Sovinec , C. Carey [2],

and Xiaoye Sherry Li [3]

[1] Tech-X Corp., [2] Univ. of Wisconsin, [3] Computational Research Division, LBNL

Considerable effort has been put forth in efforts to simulate Edge Localized Modes (ELMs) with nonlinear extended magnetohydrodynamic codes in order to understand the effects of ELMs on plasma confinement properties[3]. These simulations have led to new numerical challenges. The disparate time scales demand implicit treatment, but the required operators for the two-fluid physics leads to non-symmetric matrices. The broad linear spectrum means greater resolution is required, further increasing the condition number of the matrices. Thus, an effective preconditioner is necessary. SuperLU, a direct linear solver, has proven to be an effective preconditioner for NIMROD's three-dimensional matrices[1, 2]. Because the majority of the simulation time is spent in matrix solves, effective use of computational resources requires effective linear solves. This work presents results from investigations regarding the parallel scaling of NIMROD for the nonlinear ELMs problem. This work will detail development with SuperLU via a distributed matrix interface and METIS/ParMETIS orderings. Effectiveness of various decomposition patterns will be presented.

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2C12

Nonlinear Simulations of Energetic Particle-driven Instabilities in Tokamaks and Spherical Torus*

G.Y. Fu

Princeton Plasma Physics Laboratory, Princeton, NJ

Understanding of nonlinear behavior of energetic particle-driven instabilities in tokamaks is of fundamental importance for burning plasmas. Here we report recent advances in self-consistent nonlinear simulations of shbone instability in tokamak [1] and beam-driven Alfven modes in NSTX using the extended MHD code M3D[2]. Hybrid simulations of energetic particle-driven shbone instability in a circular tokamak show dynamic mode saturation as the particle distribution is attened and mode frequency is reduced strongly. MHD nonlinearity reduces the mode saturation level. The M3D code was also used to simulate bean driven Alfven modes in NSTX plasmas with mutliple modes. The calcualted mode frequencies and nonlinear frequency chirping agree well with the observations. It is found that mode saturation level of each toroidal mode can be enhanced signi cantly by presence of other unstable toroidal modes indicating strong nonlinear interaction between different modes. It is also found that a linearly stable n=2 mode can be nonlinearly driven by an n=1 mode at signi cant mode amplitude.

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2C13

Comparison of GLF23 and Weiland Transport Models*

C.M. Wolfe[1], F.D. Halpern[1], A.H. Kritz[1], G. Bateman[1], A.Y. Pankin[1]
A. Eriksson[1†] and J. Weiland[2]

[1]Lehigh University, Bethlehem, PA US
[2]Chalmers University, Göteborg, Sweden

The GLF23 model [1] and two versions of the Weiland model [2,3] for anomalous transport in tokamaks are compared in systematic scans over plasma parameters. The Weiland 14 model, which is part of the Multi-Mode MMM95 transport model [2], is compared with the new Weiland 19 model [3], which includes an improved treatment of finite beta effects, particularly at low and negative magnetic shear values in elongated plasmas. The comparisons are made by evaluating the models using a stand-alone driver program that accepts local plasma parameters in the form of a standardized input and presents the output for the transport computed by the different models in a standardized form. The dependence of ion thermal diffusivity on plasma parameters such as temperature gradient, electron density gradient, safety factor q, magnetic shear s, plasma elongation, inverse aspect ratio, and ratio of ion to electron temperature are examined. In addition, the dependence on key dimensionless parameters such as the plasma beta β, collisionality ν_*, and normalized ion gyro-radius ρ_* are presented. Although the threshold and stiffness of the transport as a function temperature gradient are very different when computed by the GLF23 and Weiland models, it is found that the transport computed as a function of normalized temperature gradients by the different models overlaps in the confinement region of conventional H-mode discharges. The differences between the models become more significant under conditions of low magnetic shear and moderately high beta in elongated plasmas.

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†Present address: Chalmers University, Göteborg, Sweden

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Doubling Reactor Beta with X-Divertors

M. Kotschenreuther, P. Valanju, S. M. Mahajan

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

The unique capabilities of X-divertors lets reactors operate in a regime of relatively low edge density which is what is needed for density peaking and hence for enhancing beta while maintaining MHD stability. Density peaking causes higher bootstrap currents that, in turn, allows higher beta for a given beta normal.

Low edge density is possible because: 1) the enhanced heat capacity of an X-divertor allows a reactor to operate with a vanishing demand on the SOL radiative ability, and 2) its long line length better shields the plasma from impurities despite higher SOL temperatures.

The X-divertor enables sufficiently low edge density so that hot neutrals can penetrate to the core to provide fueling consistent with the density peaking. We demonstrate core fueling with the kinetic neutral code NUT.

Using high-bootstrap fraction VMEC equilibria, we demonstrate a beta enhancement of > 2.5 at fixed beta normal and fixed bootstrap fraction.

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Non-Ideal Toroidal Ballooning Modes with Large Pressure Gradients

Chris Crabtree

Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA 02139 USA

High-confinement regime tokamak discharges are frequently plagued by Edge-Localized Modes (ELMs) which are the primary means for degrading confinement in this regime. ELMs are thought to be the result of pressure gradient driven instabilities, *i.e.* ballooning modes, localized around the maximum pressure gradient near the edge of the plasma. This edge region is characterized by large pressure gradients, moderate collisionality, and sometimes non-zero toroidal mass flow. In this work we examine three different aspects of the non-ideal linear stability problem. First, we consider an alternate ordering, which accounts for the large pressure gradients, and derive a ballooning mode linear eigenvalue problem applicable to ELMs. Second, we examine closely the topology of ballooning modes, paying, in particular, attention to the mode properties on the inboard side of the torus and the role of parallel electric fields in this region. Finally, in the context of ELMs we compare the disconnected mode approximation [1] to the standard ballooning transformation [2, 3, 4, 5].

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2C16

THE THEORY OF NEUTRONIZATION AND PROTONIZATION OF NUCLEI IN GRAVITATING HEAVY STARS AND AT SHOCK SELF-COMPRESSION OF A TARGET IN A LABORATORY ELECTRON-NUCLEAR COLLAPSE

Stanislav V. Adamenko[1], Vladimir I. Vysotskii[1,2]
[1]Electrodynamics Laboratory "Proton-21", Kiev, Ukraine
[2]Kiev Shevchenko National University, Kiev, Ukraine

We consider the peculiarities of the fundamental nuclear transformations running both in the shell of a heavy star compressed by the strong gravitational field and during the laboratory electron-nucleus collapse where the compression occurs at the expense of the electron-nucleus interaction in a volume occupied by a degenerate electron gas, define their analogs, and analyze the differences.

It is shown that the account of relativistic and nonlinear corrections to the Coulomb electron-nucleus interaction gives the possibility to realize two alternative ways for the evolution of the star matter which depend on both the rate of compression upon the gravitational collapse and the initial isotope composition of a star on the stage preceding the collapse [1].

Upon the relatively slow compression of a heavy star in the process of gravitational collapse after the attainment of the threshold electron density, there occur the stage-by-stage neutronization of nuclei and the formation of a neutron star with a great concentration of neutrons and a low concentration of protons and electrons. This process is characterized by the presence of a bounded interval of the density of a relativistic degenerate gas of electrons ("the neutronization corridor"), in the scope of which the neutronization runs with a decrease in the Fermi energy and the release of energy in the form of fast neutrinos.

At a higher electron density, the process of protonization becomes energy-gained. In this case, an increase in both the charge of nuclei and the concentration of degenerate electrons causes the continuous increase in the binding energy of electrons and nuclei which turns out to be more significant than the increase in the Fermi energy of electrons. The transition of nuclei through "the neutronization corridor" into "the protonization zone", which ranges up to the nuclear density of a substance, is possible only in the case of a very fast compression of a heavy star. Such a process leads to the possibility of the formation of proton stars with a very small residual concentration of neutrons and a great (nuclear) concentration of protons and electrons [1].

It is shown that analogous effects can be realized during the laboratory electron-nucleus collapse. Due to a microscopic size of the collapse zone, a great velocity of its formation, and a relatively low rate of neutronization, the passage of the electron-nucleus substance through "the neutronization corridor" weakly affects its state. In this case, the main mechanism of transformations is the process of protonization with a simultaneous increase in the concentration of degenerate electrons.

At destruction of protonized matter the processes of Coulomb explosion and creation of relativistic protons take place. In experiments on achievement of a collapse conditions of a matter during the shock compression performed at Kiev Electrodynamics Laboratory "Proton-21" protonization processes play extremely important role. In each experiment a lot of heavy particles (relativistic protons with energy 1-10 GeV) are emitted from a collapse zone with a very high energy. Preliminary estimate of their quantity gives the value of 10^7 to 10^8. The total number of emitted protons with energy of 0.5 to 10^3 keV is about 10^{17} to 10^{18}.

It was supposed that the same processes are the reasons of creation of cosmic rays of superhigh energy (relativistic protons with energy of 10^{20}-10^{22} eV) at the decay of fragments of proton stars [1].

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2C17

Modeling of Coherent Structure Formation in Tokamak Edge Turbulence

T. Stoltzfus-Dueck, J. A. Krommes, and S. J. Zweben

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

Particle and heat transport due to advection of filamentary coherent structures ("blobs") has been observed in many plasma devices, including tokamaks, spherical tori, stellarators and even linear devices. Perhaps the clearest evidence of the form and dynamics of these structures is given by the Gas Puff Imaging (GPI) data taken on the National Spherical Torus Experiment (NSTX)[1] and other devices. Although analytical models have been proposed for the propagation of isolated blobs[2] and several numerical simulations of model equations have produced examples of blob formation,[3,4] there are currently few quantitative, testable theoretical predictions related to structure formation. As preparation for the modeling of blob formation on NSTX, equations are derived that are appropriate for the NSTX edge while being as simple as possible. Linear stability of the equations is explored, including the possible roles of drift waves and low- and high[5]-k resistive ballooning modes. Scaling of the equations and resulting implications for, and constraints on, edge transport are described. The numerical methods used for nonlinear simulation of blob formation are presented. Emphasis is placed on a combination of correct leading-order physics, appropriate to the NSTX edge, with tractability for use in the analysis of code results and eventual comparison with probe and GPI data.

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A drift ordered short mean-free path description for partially ionized magnetized plasma*

Andrei N. Simakov

Los Alamos National Laboratory
Los Alamos, NM 87544

Abstract

Effects of neutral particles, most prominently the associated heat flux and viscosity, can be very important or even dominant at the edge of a tokamak and so must be self-consistently accounted for in a description of magnetized tokamak edge plasma. To the best of our knowledge, this has only been done so far for short mean-free path plasma under MHD-like Braginskii's orderings i.e. assuming that species' velocities are on the order of the ion thermal speed [1]. Since plasma flows in modern tokamaks are usually slow compared with the ion thermal speed (at least in the absence of strong external momentum sources) it is more appropriate to use drift orderings in which the plasma flow velocity is instead comparable with the diamagnetic heat flow divided by pressure. Employing drift orderings and evaluating species' distribution functions through second order in the small gyroradius and mean-free path expansion parameters allows accounting for the important effects of heat fluxes on species' momentum transport (viscosities), which are missing from the large flow ordered treatments [1]. In this work we consider short mean-free path plasma consisting of electrons and single species of singly-charged ions and neutrals. We neglect neutral-neutral and elastic electron-neutral collisions and approximate the neutral-ion charge-exchange cross-section with a constant. We employ drift orderings to evaluate ion, neutral, and electron heat fluxes, viscosity tensors, and momentum and energy exchange terms and formulate a self-consistent system of electron, ion, and neutral fluid equations, thereby generalizing the drift-ordered treatment [2] of fully ionized plasma.

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Dynamics of plasma electric field of positive radial electric field created by ECRH-pump out.

F. Castejón, S. Eguilior, I. Calvo, and D. López-Bruna

Laboratorio Nacional de Fusión.
Asociación EURATOM/CIEMTA para Fusión. 28040-Madrid (Spain)

Previous works show the existence of an outward particle flux when Electron Cyclotron Resonance Heating (ECRH) is applied to plasmas confined in stellarators [1]. This flux is manifested experimentally through hollow density profiles that are usually accompanied by peaked temperature ones [2]. The resulting confinement regime is characterised by having a positive intense radial electric field and an improved electron heat confinement and is called CERC (Core Electron Root Confinement) by the Stellarator Profile Data Base collaboration group [3].

This extra flux, called pump-out usually, can be explained in terms of the increasing of particles that enter the loss cone in momentum space due to the enhancement of their perpendicular momentum. Those particles are lost in a short time scale giving an enhancement of outward flux, which changes the ambipolarity flux balance condition and causes an increase of the positive electric field. The field provokes an extra poloidal plasma rotation. In this work, a simplified procedure to estimate the outward flux, including collisions and diffusion in momentum space driven by microwaves is presented and the dynamics of the electric field is estimated.

Once the collisions are taken into account, it is demonstrated that the time scale for the field change is mainly given by the poloidal viscosity. The experiments that include this changing of the electron confinement are therefore useful to evaluate such quantity. In particular, the typical time for this change is of the order of 50 μs in TJ-II, larger than the collision time and shorter than the confinement time.

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Correlation Between Accretion Theory and Toroidal Rotation Experiments*

M. Landreman, B. Coppi, and C. Di Sanzo
Massachusetts Institute of Technology

The experimental observations that are consistent with the main point of the accretion theory [1,2,3] of the spontaneous rotation phenomenon include the following: i) the reversal of rotation of the plasma column in the transition from the L-regime to the H-regime that is attributed, by the theory, to the inversion of the phase velocity direction of the modes excited at the edge of the plasma column. ii) the strong effects of the magnetic field topology of the outermost magnetic surfaces and of the edge plasma regimes on the magnitude and direction of the spontaneous rotation. iii) the penetration of the angular momentum from the outer edge toward the center of the plasma column during the transition from the L-regime to the H-regime. iv) the influence of the neutral population on the rotation velocity and on the L-H transition.

In particular, experiments have shown, in agreement with the detailed theory of the collisional ballooning modes excited at the edge of the plasma column that are proposed as responsible for the ejection of angular momentum, that neutrals have a damping effect on the spontaneous rotation present in the H-regime. Moreover, the threshold for transition into the H-regime appears to become harder when the neutral population at the edge, inside the separatrix, is increased.

The transition from a phase velocity of these modes in the ion diamagnetic velocity in the H-regime is of the same type that was found [4] for the switching in order to arrive at the first experimental identification of collisional drift modes. For this a linear Q-machine was used and the transition marked the switch-off and on of modes with different mode numbers. *Sponsored in part by the U.S. Department of Energy.

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Thermodynamics of an Anisotropic Relativistic Plasma

Jason M. TenBarge, R. D. Hazeltine, and S. M. Mahajan
Institute for Fusion Studies
The University of Texas at Austin

Thermodynamics is an important tool for investigating properties of many astrophysical phenomena, such as shocks and jets. These phenomena are typically anisotropic and relativistic; therefore, they are beyond the limitations of conventional thermodynamic treatments. A thermodynamic model based on an explicitly covariant fluid closure, in which the electromagnetic field is assumed to dominate is presented. The model allows for the computation of anisotropic (gyrotropic) expressions for the entropy density (flow), evolution, and (positive definite) production.

2C22

Canonical variables for Guiding Center Motion [1]

R. B. White, L. Zakharov
Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543-0451

Abstract

The motion of charged particles in electromagnetic elds is one of the oldest problems of plasma physics. The evaluation of the con nement of particles in fusion devices and the determination of particle di usion requires following particle orbits for very long times, and this is facilitated by averaging over the cyclotron motion to produce guiding center equations. For the purpose of introducing perturbations, and for an improved understanding of the long time properties of the equations of motion, it is useful to identify the canonical momenta associated with a Hamiltonian formulation of the guiding center equations. Several di erent atttempts at constructing a simple Hamiltonian formulation of the guiding center motion have been made over the years [2]. We show that the commonly accepted use of Boozer coordinates does not produce canonical variables, and that the guiding center motion is in error by a secular drift term, albeit small.

In addition, Boozer coordinates are not convenient for equilibria at high beta or with strong shaping. We construct canonical variables and equations of motion for general coordinates, and display a particular choice of coordinates that are automatically Hamiltonian, although not being straight eld line coordinates. The guiding center code ORBIT has been modi ed to accept equilibria using arbitrary coordinate systems, and we present comparisons using equal arc and Boozer coordinates.

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Effects of plasma elongation on Geodesic Acoustic Modes

P. Angelino[1], , V. Grandgirard[1], Y. Sarazin[1], G. Dif-Pradalier[1], S. Jolliet[2], A. Bottino[3] X. Garbet[1], Ph. Ghendrih[1], B. F. McMillan[2], T. M. Tran[2], L. Villard[2]

[1]*Association Euratom - CEA, CEA/DSM/DRFC Cadarache*

13108 Saint-Paul-lez-Durance, France

[2]*Centre de Recherches en Physique des Plasmas, Association Euratom - Confédération Suisse*

EPFL, Lausanne, Switzerland

[3]*Max Plank Institut für Plasmaphysik, IPP-EURATOM Association*

Garching, Germany

Drift waves turbulence is known to self-organize to form axisymmetric macroscopic flows. The basic mechanism for macroscopic flows generation is called inverse energy cascade. Essentially, it is an energy transfer from the short wavelengths to the long wavelengths in the turbulent spectrum due to nonlinear interactions. A class of macroscopic flows, the poloidally symmetric zonal flows, is widely recognized as a key constituent in nearly all cases and regimes of microturbulence, also because of the realization that zonal flows are a critical agent of self-regulation for turbulent transport. In tokamaks and other systems of curved magnetic confinement, axisymmetric flows exist in two branches, a zero frequency branch and a finite frequency branch, named Geodesic Acoustic Modes (GAMs). The finite frequency is due to the geodesic curvature of the magnetic field. There is a growing body of evidence that suggest strong GAM activity in most devices. Theoretical investigation of the GAMs is still an open field of research. Part of the difficulty of modelling the GAMs stems from the requirement of running global codes. Another issue is that one cannot determine a simple one to one relation between turbulence stabilization and GAM activity. We focus on the study of ion temperature gradient (ITGs) turbulence in realistic tokamak magnetohydrodynamic equilibria. Analytical and numerical analyses are applied to the study of geometrical effects on zonal flows oscillations. In particular, we show results on the effects of the plasma elongation on the GAM amplitude and frequency and on the zonal flow residual amplitude.

2C24

Critical Toroidal Rotation Profile for Resistive Wall Modes in Tokamaks

K. C. Shaing[1], M. S. Chu[2], S. A. Sabbagh[3], and M. Peng[4]

[1]University of Wisconsin,
[2]General Atomics
[3]Columbia University
[4]Oak Ridge National Laboratory

It is well known that the resistive wall modes in tokamaks can be stabilized by the toroidal plasma rotation. The critical toroidal rotation speed is reduced when the enhanced plasma inertia is included in the polarization current density. Here, we develop a model to calculate the critical plasma rotation profile, when the plasma rotation profiles are actively controlled externally. This is accomplished by including the neoclassical dissipation mechanism associated with the perturbed parallel plasma viscosity, and its corresponding inertia enhancement factor in the ambipolarity condition. We will compare out results with the well known $\omega_A/(4q^2)$ scaling when the external control of the toroidal plasma rotation is removed. Here $\omega_A = V_A/R$ is the toroidal Alfven angular frequency, V_A is the Alfven speed, R is the major radius, and q is the safety factor.

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Equilibrium solution with plasma flow and vacuum region

L. Guazzotto, J.P. Freidberg
Plasma Science and Fusion Center
Massachusetts Institute of Technology

Plasma rotation is ubiquitous in current day tokamaks. Toroidal rotation, either induced by means of neutral beams (e.g. in NSTX and DIII-D) or appearing spontaneously (e.g. in Alcator C-Mod, JET and Tore Supra) is routinely observed in modern tokamak experiments. It is well known that tokamak equilibria in the presence of macroscopic plasma rotation can be considerably different from static equilibria, if the rotation becomes comparable to some plasma characteristic speed. Despite this, plasma rotation is normally not included in equilibrium reconstruction calculations, and only recently commonly used tools such as EFIT started including toroidal flows in the equilibrium model. To the best of the authors' knowledge, no tool presently exists, which self consistently takes into account arbitrary (poloidal and toroidal) rotation in equilibrium reconstructions. In this work, we describe the first step towards the development of such a tool, presenting a free-boundary extension of the code FLOW [1], which self-consistently solves the equilibrium problem in the vacuum region and in the plasma, with arbitrary rotation. Details of the implementation and sample applications are discussed.

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Analysis of Unity Beta Equilibria

R. Neches, S.C. Cowley, P.A. Gourdain, J.N. Leboeuf
University of California, Los Angeles

The characteristics of extreme-ß equilibria are investigated using a high resolution numerical Grad-Shafranov solver and a collection of tools based on the analytic unity-ß result obtained by Cowley *et. al*. Results from each method are qualitatively and quantitatively compared across a spectrum of mutually relevant parameters. These comparisons corroborate the theoretical results and provide benchmarks for high-resolution results available from the numerical solver. These techniques facilitate exploration of many properties of high-ß equilibria, such as a highly diamagnetic plasma and its ramifications for stability and transport as ß approaches unity.

2C27

Drift resistive ballooning modes in three-dimensional configurations*

T. Rafiq, C. C. Hegna and J. D. Callen

Department of Engineering Physics,University of Wisconsin,
Madison,Wisconsin 53706-1609

Drift resistive ballooning modes (DRBM) could be unstable and responsible for edge plasma fluctuations and anomalous transport in tokamaks and stellarators. A linear stability theory of DRBM is investigated using a two fluid model. The electron inertia, parallel ion dynamics, transverse particle diffusion and perpendicular viscous stress terms are included in calculations for arbitrary three-dimensional electron ion plasmas. The temperature perturbations and equilibrium gradients are ignored for simplicity. DRBM eigenvalues and eigenfunctions are calculated for a variety of equilibria including axisymmetric shifted circular geometry (s-α model) and configurations of interest to the Helically Symmetric Stellarator (HSX). The electron inertia effects are found to be important for HSX parameters where the frequency of mode is greater than the electron collision frequency and therefore the electromagnetic skin depth effects become significant. Attempts to generalize previous analytic calculations of RBM stability using a two scale analysis on (s-α) equilibria [1] to more general 3-D equilibria will be addressed.

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Non-local calculation of parallel heat flow in the vicinity of magnetic islands*

J. W. James, E. D. Held
Physics Department, Utah State University
Logan, UT 84322-4415

Abstract

In this work, we review the derivation and implementation into the NIMROD† code of non-local closures‡ for $\vec{q}_{\|}$ in the electron and ion plasma temperature equations which are valid in all geometries and for plasmas of all collisionalities.

Then, using NIMROD, we study the effect of this general closure on plasma heat flow and temperature and we calculate an effective radial thermal diffusivity directly from $\vec{q}_{\|}$. These results are then compared with similar NIMROD calculations using diffusive and flux-limited closures instead of the general form.

All calculations are made in sheared slab geometry for a single helicity magnetic island and for two overlapping islands. For the case of two overlapping islands, comparisons are drawn between the effective radial thermal diffusivity calculated via the general closure and the diffusivity predicted by stochastic transport models. Techniques used to approximate field line integrations in the implementation of this closure will also be reviewed.

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Motion of a Localized High-Density Region Across Magnetic Flux Surfaces

Ravi Samtaney & Stephen C. Jardin
Princeton Plasma Physics Laboratory, Princeton University

Injecting small pellets of frozen hydrogen into a tokamak is a proven method of fueling. Previous results of 3D extended MHD simulations of pellets injection into tokamaks are in qualitative agreement with experiments, i.e., high-field-side (HFS) fueling is more efficient than low-field-side (LFS) fueling. A key issue is identifying and quantifying the pellet-mass redistribution processes involving the density equilibrating along field lines and transport across surfaces (in the large-major-radius direction). At least two viewpoints exist: one is that the transport of mass across flux surface is accompanied by reconnection; while the other one suggests that the flow in the vicinity of the pellet is in the low-magnetic-Reynolds number regime so that high-density cloud simply slips through the magnetic field. We present results from idealized simulations of the motion of localized regions of high-density plasma as they move across magnetic field lines and identify the mechanisms, which are related to the motion of the ablated pellet mass across flux surfaces in a tokamak (See Figure 1 for a time sequence of density images). We interpret the rapid motion of the pellet mass due to a nonlinear manifestation of the interchange instability. The numerical method is based on generalized upwinding techniques. We employ the Chombo framework for adaptive mesh refinement to mitigate the need for large spatial resolution requirements.

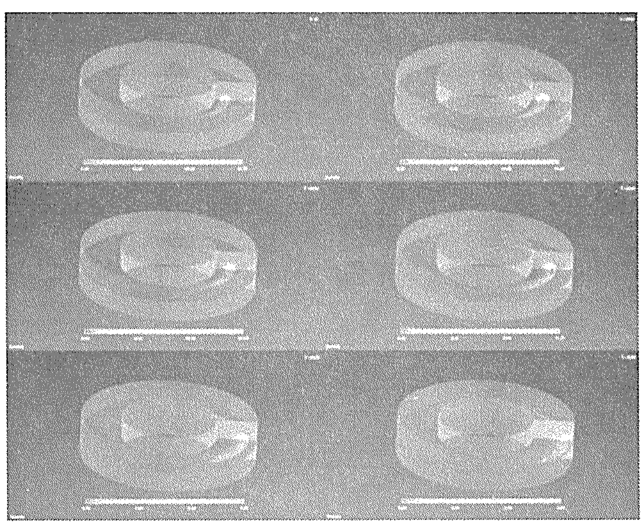

Figure 1: Time sequence of density images of a localized high-density region across magnetic flux surfaces.

Turbulent resistivity in wavy two-dimensional magnetohydrodynamic turbulence

Shane R. Keating and P. H. Diamond
University of California, San Diego

February 22, 2007

Abstract

The theory of turbulent resistivity in 'wavy' magnetohydrodynamic turbulence in two dimensions is presented. The goal is to explore the theory of quenching of turbulent resistivity in a regime for which the mean field theory can be rigorously constructed at large magnetic Reynolds number Rm. This is achieved by extending the simple two-dimensional problem to include body forces such as bouyancy or the Coriolis force, which convert large scale eddys into weakly interacting dispersive waves. The turbulence-driven spatial flux of magnetic potential is calculated to fourth order in wave slope — the same order to which one usually works in wave kinetics. However, spatial transport, rather than spectral transfer, is the object here. Remarkably, adding an additional restoring force to the already tightly constrained system of high Rm magnetohydrodynamic turbulence in two dimensions can actually increase the turbulent resistivity, by admitting a spatial flux of magnetic potential which is not quenched at large Rm, although it is restricted by the conditions of applicability of weak turbulence theory. The absence of Rm-dependent quenching in this wave-interaction-driven flux is a consequence of the presence of irreversibility due to resonant nonlinear three-wave interactions, which are independent of collisional resistivity. The broader implications of this result for the theory of mean field electrodynamics are discussed.

2C31

Collisionless MHD Turbulence in Two Dimensions

Dr. Bhimsen K. Shivamoggi
University of Central Florida

Abstract:
In recognition of the collisionless nature of high-temperature plasmas in both space and fusion systems a formulation of 2D collisionless MHD turbulence is given [1]. Effects of electron inertia and electron pressure are included. Particular emphasis is placed on the departures from the 2D classical MHD turbulence results [2] – [4] produced by the collisionless MHD effects. The formulation given here predicts the existence of vortices with length scales of the order of the ion-sound gyroradius $#61554;s in a collisionless MHD turbulence system. These vortices may be viewed as consequences of spectral energy pile-up in kinetic Alfven turbulence and appear to be confirmed by the recent in situ European multi-satellite observations [5]. [5] reported detection of short-scale (of the order of s) vortices in the earth's magnetospheric cusp region and interpreted them as a manifestation of kinetic Alfven turbulence.

Keywords:
MHD Turbulence

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Separating Magnetic Field Boundary Conditions into Parts Produced by Internal and External Sources

David Lazanja and Allen H. Boozer

Department of Applied Physics and Applied Mathematics
Columbia University

Given the total magnetic field on a toroidal plasma surface, a method for decomposing the field into a part due to internal currents and a part due to external currents is presented. The method exploits Laplace theory which is valid in the vacuum region between the plasma surface and the chamber walls. The method is developed for the full three dimensional case which is necessary for studying stellarator plasma configurations.

The total magnetic field in a toroidal plasma is a superposition of the vacuum field produced by external coils and the field produced by plasma currents. Plasma equilibrium codes or perturbed equilibrium codes compute the total magnetic field at all points within the plasma, including the surface. The total field at the plasma surface from such codes can serve as the input boundary condition to the method presented here. The method, therefore, determines the field at the plasma boundary which external coils must produce in order to support the plasma configuration being studied.

Several test cases are presented for toroidal surfaces which verify the method and computational robustness of the code.

Sturmian Behavior of the Unstable Ideal MHD Spectrum in Axisymmetric Toroidal Equilibria*

A.D. Turnbull
General Atomics, P.O. Box 85608, San Diego, California 92186-5608 USA

Numerical calculations in widely different examples of axisymmetric toroidal equilibria with q below 1 have revealed sequences of unstable ideal modes that are global eigenmode manifestations of Mercier instability. The numerical calculations were performed with a new version of the full ideal MHD code GATO [1] in which the continuum has been restabilized [2] to yield marginal points to high accuracy; previously, the continuum was numerically destabilized by the Finite Hybrid Element Method [3]. Calculations were performed for the ideal n = 1 internal kink mode in equilibria with q below 1 and slightly inverted shear as well as for an SSPX Spheromak equilibrium for intermediate n = 8. These modes exhibit the Sturmian behavior expected from spectral theory for the ideal MHD operator that the eigenvalues are ordered strictly with the number of zero crossings [4]. Numerically, the eigenvalues extend into the stable continuum and full convergence studies are needed to confirm if they actually have an accumulation point at marginal stability. For the SSPX example, the exponential accumulation near the marginal point is clearly exhibited; 18 separate modes on the unstable side of the continuum were resolved, becoming increasingly localized around the innermost q = 5/8 surface, with the first mode on the stable side of the continuum being the resonant m/n = 5/8 continuum mode. In the tokamak examples, the first few are of the same order of magnitude growth rate as the ideal internal kink. With nonideal effects, the more localized modes near marginal stability presumably become irrelevant in practice. Nevertheless, the existence of multiple unstable modes may influence the interpretation of the tokamak sawtooth instability. There are also likely confinement implications even when the modes are stabilized by nonideal effects.

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Finite Ion Orbit Effects 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 ion population with an isolated magnetic island in a high aspect ratio tokamak plasma is presented. We examine islands whose characteristic widths are larger than the ion gyro radius but comparable to the ion banana width. In this regime, the trapped ions do not respond to the island electrostatic potential and helical magnetic geometry due to the banana drifts. When solving the drift kinetic equation for ions, a change in coordinates is used to account for this behavior. A bounce averaging procedure is developed to separate out and solve the lower order distribution function. A two-fluid model is used to determine the electrons response. Quasineutrality leads to a self-consistent calculation for the electrostatic potential. An iteration procedure is introduced to calculate the potential, which is shown to be a combination of functions of the helical flux surfaces and the topologically toroidal flux surfaces. These results are contrasted with the results of small ion orbit case. The contribution to the perturbed current is composed of the helical flux surface-averaged bootstrap current and the perpendicular ion polarization current. The closure parallel current ($J_{//}$) is calculated and compared with some recent numerical results[1]. Using this current in the Rutherford equation, the island width evolution equation is determined. A pair of self-consistent equations for the island width, w, and its rotation frequency, ω, is to be derived. The results are to be compared with calculations for large island width so as to yield a description of magnetic island width evolution from sub-banana width to macroscopic scale lengths.

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2C35

Transition from Two Fluid to Resistive MHD Dynamos in Cylindrical Reversed Field Pinch

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

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

In the Madison Symmetric Torus reversed field pinch (RFP) experiment, tearing instabilities are observed to generate magnetic field, flow velocity and current density fluctuations that follow a temporally cyclic sawtooth behavior. One of the consequences of these instabilities is the production of dynamos, fluctuation-induced mean electromotive forces in the generalized Ohm's law that surge during sawtooth crashes. In two-fluid theories, the dynamo is produced from the combination of the MHD ($\mathbf{v}\times\mathbf{B}$) and Hall ($\mathbf{j}\times\mathbf{B}$) contributions to Ohm's law. We report new results on the physics of two-fluid dynamos with particular focus on edge-resonant m=0 tearing modes. The two fluid quasilinear theory was originally derived for a sheared slab in [1] and generalized to cylindrical geometry in [2] where the effects of current gradient and field line curvature were calculated for core resonant modes in the electron MHD (EMHD) approximation. The quadrupole structure of the out-of-plane component is strongly deformed by the equilibrium current gradient while field line curvature results in an oscillatory character of EMHD tearing instability in RFP. We extend this work by considering the influence of slow ion motion on the EMHD dynamics. This allows us to follow the transition from two fluid to single fluid regimes of the dynamo. It is shown that the two fluid effects are also important for understanding the dynamo through their influence on the phase between the fluctuations. In particular, the two-fluid theory yields a non-zero flux surface averaged Hall dynamo that is absent in resistive MHD.

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2C36

The theory of variances of equilibrium reconstruction[1]

Leonid E. Zakharov
Princeton Plasma Physics Laboratory, MS-27 P.O. Box 451, Princeton NJ 08543-0451

Equilibrium reconstruction has established itself as one of main tokamak diagnostics which provides the basic data on magnetic configuration. The approach relies on the Grad-Shafranov equation, which solution is adjusted to the different kinds of measurements (magnetic fluxes, fields, pitch angles, etc). The result of reconstruction is the current density and the pressure profiles which cannot be measured directly.

The relationship between the current density and the pressure with the measured signals is not straightforward. Some variations of the current density or pressure may have a little effect on the signals. Also the finite accuracy of measurements allows a certain level of variances in reconstructed profiles. So far in practice, in order to provide stability of iterations the equilibrium reconstruction technique artificially limits variations in plasma profiles while fitting the signals. Even the resulting fit to measurements seems to be good, without assessment of all possible variances the value of such reconstruction is questionable.

Here a rigorous theory and numerical technique is presented which addresses this long standing problem of variances. It uses the Singular Value Decomposition (SVD) technique for converting the uncertainties in measurements info uncertainties in the reconstruction profiles. At the same time, it provides a recipe of how to choose the number of allowed variances in order to satisfy both stability and accuracy of reconstruction. The associated technique was incorporated into the ESC code. Calculations of characteristic cases with different plasma cross-sections, aspect ratios and current distributions are presented.

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2C37

Zonal flow shielding in stellarators and tokamaks

H.E. Mynick[1], A.H. Boozer[2]

[1]Princeton Plasma Physics Laboratory, Princeton, NJ 08543
[2]Dept. of Applied Physics & Mathematics, Columbia University, New York, NY 10027

We present an analytic study of the shielding of zonal flows in stellarators and tokamaks, using the action-angle formalism. This framework permits one to solve the kinetic equation without expansion of that equation in small parameters of radial excursions and timescale, resulting in expressions for the dielectric shielding more general than obtained previously.[1,2] From these expressions, we find a ``drift polarization current'' $J^{p,d}$, not considered in earlier analyses, which can appreciably modify the previous results. In contrast to the gyro (``classical'') and bounce (``neoclassical'') polarization contributions $J^{p,g}$, $J^{p,b}$ found previously, to which only ions contribute, electrons can also contribute to $J^{p,d}$. It is shown that for each mechanism of collisional transport, there is a corresponding shielding mechanism, of closely related form and scaling. The effect of these generalized expressions on the evolution and size of zonal flows, and their implications for stellarator design are considered.

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Weak Turbulence Breakdown in Nonlinear Particle Flux for Collisionless Trapped Electron Mode Turbulence

David Hatch and P.W. Terry
University of Wisconsin-Madison 53706

Central density peaking at low collisionality is an important aspect of particle transport, particularly in burning plasma devices like ITER. Central peaking can be accomplished through a pinch, and trapped electron dynamics at low collisionality have long been known to yield a particle pinch in conjunction with ITG-driven fluctuations. This pinch is generally described and conceptualized within the quasilinear approximation. However, recent work has shown that there is an inward flux component in collisionless trapped electron mode turbulence produced by a nonlinear cross phase. The result was obtained for a weak turbulence regime, consistent with near threshold conditions. We describe the extension of this work to the strong turbulence regime, using asymptotic analysis and a numerical nonlinear algebraic equation solver to examine the statistical closure equations. First, asymptotic analysis was applied to the statistical closure equations, including the nonlinear frequency expressions. It was found that weak turbulence is not a valid approximation in this regime due to the fact that the linear frequencies become non-dispersive for small wavenumbers, allowing significant cancellation in the linear frequency triplets. The breakdown of weak turbulence theory may also be affected by the anisotropy of the turbulence. A particle flux scaling was derived in the strong turbulence regime and shown to differ significantly from the weak turbulence particle flux scaling. Namely, the inward flux component due to the eigenmode cross-correlation was reduced to the same order as the other particle flux components. The asymptotic analysis indicated the possibility of multiple solutions in the strong turbulence regime. Therefore a numerical solver was implemented to verify the scalings derived with the asymptotic balances, examine behavior in other ordering regimes, consider the possibility of multiple solutions, and further explore the differences between weak and strong turbulence theory. The results of these analyses will be presented.

This research was performed under DOE Grant DE-FG02-89ER53291 and an appointment to the U.S. Department of Energy, Fusion Energy Sciences Fellowship Program, administered by the Oak Ridge Institute for Science and Education under contract number DE-AC05-06OR23100 between the U.S. Department of Energy and Oak Ridge Associated Universities.

Gyrokinetic theory and simulation of mirror instability

Hongpeng Qu, Zhihong Lin and Liu Chen

Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA

The mirror instability is a low frequency electromagnetic mode destabilized by pressure anisotropy in high-β plasmas. The finite Larmor radius (FLR) effects play an important role in determining the threshold and the growth rate of the mirror instability. In this study, a general dispersion relation of the mirror mode with FLR effects is derived by using gyrokinetic theory. It shows that both the FLR effects and the coupling to the slow sound wave are stabilizing. A gyrokinetic particle simulation code has been developed for simulation of compressible magnetic turbulence driven by the mirror instability. Results of the linear simulation of mirror mode agree well with the analytic dispersion relation. Nonlinear simulations of single mode find that the mirror instability saturates via wave-particle trapping. Nonlinear simulation of multiple modes are being carried out to study the effects of mode coupling.

Anomalous impurity ion heating from Alfvénic cascade in the RFP

Varun Tangri and P.W. Terry
University of Wisconsin-Madison, Madison, Wisconsin 53706

Abstract

In Reversed Field Pinch (RFP) plasmas, ion and impurity heating greatly exceeds the heating predicted from Ohm's Law with Sptizer resistivity. We study the impulsive, anisotropic heating of a multi-species RFP plasma during a sawtooth crash. A previous ion heating model [Mattor et al., Comments Plasma Phys. Controlled Fusion **15**, 65 (1992)] introduced a useful energy budget that tracked energy flow from its input, primarily as the toroidal Ohmic current, and showed the fractions going to large scale tearing activity, to electrons, via finite resistivity, and to the turbulent cascade extending to small scale. The cascade energy was assumed to dissipate on ions and electrons through gyro-resonant damping and electron Landau damping, allowing for a calculation of the relative heating rates of ions and electrons. Observations indicate that the spectrum falloff over the scales of the cascading fluctuations leaves too little energy at the ion cyclotron resonance for this mechanism to explain observations. We extend this model to include gyro-resonant damping of cascade energy on impurity species typically present in MST plasmas, noting that the heavier mass of impurities makes them resonant at lower frequencies where more energy is present in the fluctuations. We address the anisotropy of the gyro-resonant heating and the subsequent relaxation of anisotropically heated impurities through collisional equilibration. In this process it is necessary to model the effects of anomalous heat losses.

Extensive simulations of the model have shown that collisional energy transfer from anomalously heated impurities might be able to account for the observed high temperature of the bulk ions. Collisional relaxation of the perpendicular and parallel impurity and ion energy may be significant for isotropization of ion energy. Lower density plasmas are found to have a higher temperature. The results are compared with experimental observations in the laboratory and the solar corona.

Comparison of turbulence fluctuation spectrum between experiment and computer simulation in NSTX

W.X. Wang, S. Ethier, T. S. Hahm, S. M. Kaye, W.W. Lee, J. Manickam, G. Rewoldt and W. Tang

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

Global gyrokinetic simulations have been carried out to investigate both turbulent and neoclassical transport properties for experiments of axisysmmetric devices. This study contributes several interesting footnotes to the observation that the ion transport is at neoclassical levels in the National Spherical Torus Experiment (NSTX). Nonlinear turbulence simulations using the General Geometry GTC code show that ion temperature gradient, (ITG), driven turbulence has significant fluctuation amplitude, but drives insignificant ion energy transport in NSTX (about neoclassical level, sometimes even below neoclassical level). This distinguished feature is particularly in contrast to anomalous transport in other machines, such as DIIID, where ITG turbulence is shown to drive large transport (10 x neoclassical level), even though the mean turbulence fluctuation levels for the two machines are actually comparable. It is also found that self-consistent equilibrium EXB flows, which are determined by neoclassical dynamics and calculated by GTC-Neo, a global PIC simulation code, can strongly stabilize ITG modes. Ion-ion collisions are shown to enhance ITG driven thermal transport, but not significantly. Studies to identify the source of the anomalous electron transport in NSTX plasmas are underway. Ongoing investigations with GTC are focusing on high-k fluctuations associated with trapped electron modes, and trapped electron effect on ITG turbulence in the NSTX discharges. This work was supported by U.S. DOE Contract DE-AC02-76-CH03073 and SciDAC GPS Center.

Collisionless Heating in Gyrokinetic Turbulence

W. Dorland, University of Maryland, College Park, 20742

Heating in weakly collisional, turbulent plasma in the gyrokinetic regime (strong guide field, low frequencies compared to cyclotron frequencies, small perturbations, weak or strong turbulence) is usually associated with Landau and Barnes damping, which in turn are associated with parallel acceleration of particles by turbulent electric and magnetic fields. We discuss a novel form of heating observed in gyrokinetics which is distinct from these conventional processes. A simple theoretical framework is presented to explain the mechanism, which might be called "perpendicular phase mixing". The theoretical framework allows one to distinguish and separate two components of heating (acceleration and thermalization) and to identify different mechanisms for each. Numerical results are shown which support the theory.

Chaos generated pinch e ect in toroidal confinement devices [1]

G. Spizzo[1], R. B. White[2], S. Cappello[1], L. Marrelli[1], F. Sattin[1]
[1]Consorzio RFX, Euratom-ENEA Association,
Corso Stati Uniti, 4 35127 Padova - Italy
[2]Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543-0451

Abstract

Particle transport in a toroidal plasma con nement device can be non-di usive when magnetic chaos is present but the system is not too far above stochastic threshold . In some conditions a phenomenological t to the results gives a di usion constant and also a convective inward pinch velocity. [2] We show that the combination of di usion and pinch is actually an expression of the subdi usive and nonlocal nature of the transport, brought about by the existence of a spectrum of long distance Levy ights.[3] The e ect is illustrated by numerical modelling of the magnetic structure[4] and associated particle transport in conditions relevant for the reversed- eld pinch experiment at the Consorzio RFX. [5] Simulations give values of di usion and pinch consistent with experiments. Simulations consist of guiding center calculations of particle motion in the expermentially observed spectrum of tearing modes, and in integration of the Montroll equation [6] with a kernel derived from the guiding center simulations. Similar results can be expected in other systems with chaos induced particle transport. One candidate is electron transport in tokamaks.

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Chaotic Transport and separatrix reconnection in an area-preserving self-consistent nontwist map model

A. Wurm[1], D. del-Castillo-Negrete[2]

[1] *Dept. of Phys. and Bio. Sciences, Western New England College, Springfield, MA 01119*

[2] *Oak Ridge National Laboratory, Fusion Energy Division, Oak Ridge, TN 37831*

Abstract

As simple models for degenerate Hamiltonian systems, nontwist maps, i.e., maps that violate the twist condition, have been used to describe, e.g., magnetic field lines in toroidal plasma devices with reversed magnetic shear profiles (e.g. [1]). Previous studies have mostly focussed on systems with few degrees-of-freedom.

Here we study the nontwist version of an area-preserving self-consistent map model (with many degrees of freedom) that was previously obtained as a space-time discretization of the single wave model[2], which is a mean field Hamiltonian model describing, e.g., the dynamics of marginally stable fluids and (Vlasov-Poisson) plasmas (e.g. [3,4]). *Self-consistent* in this context refers to the fact that part of the influence of the charged particles on the electric field is retained in the model.

We investigate the role of the self-consistent dynamics on separatrix reconnection and the breakup of shearless invariant curves. Both problems are now relatively well understood in uncoupled maps (e.g. [5]), but little is known about the self-consistent problem.

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Simulation of FLR effects on RFP tearing modes.

Charlson C. Kim
Plasma Science and Innovation Center
University of Washington
and
the NIMROD team

The Plasma Science and Innovation Center (PSI Center) extends and applies MHD codes to understand and eventually predict emerging concept (EC) experiments. Kinetic effects such as finite Larmour radius (FLR), Landau resonances and phase space anisotropies are known to significantly impact the dynamics of many EC experiments.

The PSI Center has extended the hybrid kinetic-MHD implementation in NIMROD[1] from the drift kinetic model to the full kinetic model to include sufficient physics to accurately account for many of these effects, in particular FLR effects. The full kinetic implementation uses the Boris push to advance the Lorentz equations of motion and the δf method to compute moments of the particle distribution function. These moments (in our applications, the kinetic pressure tensor) are coupled to the MHD equations evolved in NIMROD. With this technique, we simulate the effects of an energetic minority species on the plasma dynamics. However, satisfaction of the gyro-frequency Courant condition may place a severe restriction on the particle time step relative to MHD time scales. For computational efficiency, we orbit average the kinetic contribution (the δf PIC) over the MHD time step.

We present simulation results from our first application of the FLR effects on RFP tearing modes. Linear analysis by Svidzinski[2] has shown that FLR effects significantly reduce tearing modes in RFPs. Reduced model simulations show good agreement with the analytic predictions. More detailed models indicate that there may exist a regime where FLR effects have some stabilizing influence but may also excite particles modes. We present our simulation model and findings from these simulations.

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2C46

Ideal response of tokamak plasma to three dimensional magnetic perturbation

Jong-kyu Park,[1] Allen H. Boozer,[2] Jonathan E. Menard,[1] Allan G. Glasser,[3] and Morrel S. Chance[1]

[1]*Princeton Plasma Physics Laboratory*

[2]*Columbia University*

[3]*Los Alamos Laboratory*

A nominally axisymmetric plasma configuration, such as a tokamak or a spherical torus, is highly sensitive to non-axisymmetric magnetic perturbations due to currents outside of the plasma. The high sensitivity means that the primary interest is in the response of the plasma to very small perturbations, $\left|\vec{b}/\vec{B}\right| \approx 10^{-2}$ to 10^{-4}, which can be calculated using the theory of perturbed equilibria. The IPEC (Ideal Perturbed Equilibrium Code) has been developed on this purpose, based on the DCON and VACUUM codes coupled using the theory of perturbed equilibria. This code computes the unique three dimensional equilibrium that arises when an axisymmetric equilibrium is perturbed by a given externally produced magnetic field. IPEC determines the basic features of the perturbed equilibrium such as the displacement $\vec{\xi}(\psi, \theta, \varphi)$ of the magnetic surfaces and the perturbed field $\vec{b}(\psi, \theta, \varphi)$. The code also determines the singular current $(j_{\|}/B)_{mn}$ that arises at each rational surface $q = m/n$ to preserve ideal MHD constraints and the variation in the magnetic field strength $(\vec{B} \cdot \vec{b})_L$ in the perturbed magnetic surfaces. The normal magnetic field produced by the current $(j_{\|}/B)_{mn}$ is equal or opposite to the field that opens a magnetic island. The opening of an island is associated with the locking of plasma to the external perturbation. The variation in the field strength $(\vec{B} \cdot \vec{b})_L$ gives an effect of the perturbation on the drift trajectories of particles. As an example of application, unresolved experimental results for Locked Mode in DIII-D device have been analyzed and IPEC finds consistent results with the experiments. Other predictions by the IPEC code differ from previous expectation and will be presented and discussed.

Effect of neoclassical toroidal viscosity on error-field penetration thresholds in tokamak plasmas

A.J. Cole, C.C. Hegna, J.D. Callen
University of Wisconsin, Madison, WI 53706

A model [1] for field error penetration is developed that includes both resonant and non-resonant perturbed 3-D magnetic fields. The non-resonant components give rise to a global toroidal neoclassical viscous torque while a single resonant component produces a localized electromagnetic braking torque on its respective resonant surface. The neoclassical toroidal viscous torque tries to keep the plasma flowing at a rate comparable to the ion diamagnetic flow. A phenomenological cross-field viscous torque is included which resists the resonant electromagnetic torque in the vicinity of the resonant surface. Integration of the toroidal momentum balance equation across the resonant layer gives a steady-state torque balance equation whose solution determines the "critical" resonant error-field strength—termed the *penetration threshold*—above which rotational shielding is lost and the resonant surface is locked to the laboratory frame. Such locking occurs in low-density start-up plasmas and leads to plasma disruptions or confinement degradation.

The toroidal momentum balance equation includes resonant electromagnetic (T_{EM}), non-resonant neoclassical ($\nu_{\|}$), cross-field viscous ($\mu_{\perp}$), and source (S_0) torques:

$$T_{E,M}\frac{\delta(r-r_s)}{r} - \nu_{\|} b_{eff}^2(r) R_0 \left[V_\phi(r) - V_*^{NC}(r)\right] + \frac{1}{r}\frac{d}{dr}\left(\mu_{\perp}(r) r R_0 \frac{dV_\phi(r)}{dr}\right) = -S_0. \quad (1)$$

When neoclassical damping is large enough, this equation admits a WKB-type solution indicating that neoclassical damping acts to enhance cross-field viscosity in the vicinity of the resonant surface. This enhancement makes the plasma overall less sensitive to error-field penetration than previous theory predicted [2]. In particular, with the inclusion of neoclassical toroidal viscous damping, we find that the penetration threshold depends more strongly on density than previous theory would indicate—a result in qualitative agreement with empirical scaling [3].

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2C48

Electromagnetic gyrokinetic particle simulations in a global field aligned mesh

Y. Nishimura, Z. Lin, and L. Chen
Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA

W. Wang and G. Rewoldt
Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA

Electromagnetic gyrokinetic simulation in global toroidal geometry is developed based on a uid-kinetic hybrid electron model [1-3] which preserves the linear and the nonlinear wave-particle interactions. A global eld aligned mesh provides us with the highest possible computational efficiency without any approximation in geometry to describe the structure of the toroidal drift wave eigenmode. In a typical GTC simulation [4], for example, sixty-four toroidal planes are employed for the ITER-size plasma, while thousands are required for a conventional mesh to resolve the ion Larmor radius scale in the toroidal direction. With the global eld aligned mesh, the GTC code now has the capability of simulating long wavelength (low-n) to short wavelength (high-n) electromagnetic phenomena simultaneously without any restrictions on the toroidal mode numbers. Long wavelength Alfven wave properties such as continuum damping and toroidal gap generation are revealed. In the presence of the instability drive, nite-beta stabilization of the ion temperature gradient (ITG) mode and the onset of the kinetic ballooning mode are demonstrated. To gain con dence in studying the transport properties, benchmarks with a microintability eigenmode calculation [5] are pursued. A further focus will be the nonlinear saturation mechanism of the electromagnetic ITG instabilities [6]. A nonlinear numerical scheme to separate the zonal eld and the zonal current, and initial nonlinear simulation results, will be presented. This work is supported by U.S. Department of Energy, Grant No. DE-FG02-03ER54724, Cooperative Agreement No. DE-FC02-04ER54796, and in part by the SciDAC Center for Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas.

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2C49

Nonlocality and perturbative transport

Diego del-Castillo-Negrete
Oak Ridge National Laboratory
Oak Ridge, TN 37830, USA

Perturbative transport experiments follow the transient response of the plasma to externally applied small perturbations, e.g. plasma edge cooling and heating power modulation. These experiments provide valuable time dependent transport information in a relatively controlled setting that can be used for validating and testing transport models. In the case of cold pulses, it has been observed that perturbations travel from the edge to the core at speeds significantly faster than the typical diffusive time scales raising doubts on the validity of the standard, local diffusion transport paradigm. Despite the fact that it is recognized that non-locality plays an important role in the fast propagation of pulses [1], little work has been done on non-local transport modeling of perturbative transport.

In this contribution we present a non-local transport model to describe non-diffusive transport in general and fast cold pulse propagation in particular. By non-locality we mean a change in the transport properties of the system, e.g. the heat flux, in a region before there are any apparent changes in the local thermodynamic parameters, e.g. the local temperature gradient. Following Ref.[2], we model the non-local response of the plasma using fractional derivative operators. Fractional derivatives are integro-differential operators and are a natural tool to describe non-local flux-gradient relations. Also, these operators incorporate in a unifying framework non-Gaussian statistics (Levy processes), non-diffusive scaling, and memory (non-Markovian) effects.

It is shown that the proposed non-local model captures the basic phenomenology of fast pulse propagation. We present numerical and analytical results on the dependence of the pulse shape and speed on the degree of non-locality and on the asymmetry in the non-local response. We also discuss how heating power modulation data can be used to experimentally infer the order and asymmetry of the fractional operators.

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Tuesday evening, April 24

19:30 – 21:30

Ballroom B&C

Oral Session 2D

2D1

Scale separation of ion and electron heat transport

F. Jenko[a], T. Görler[a], and T. Dannert[b]

[a]*Max-Planck-Institut für Plasmaphysik, D-85748 Garching, Germany*

[b]*Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland*

Traditionally, turbulent transport is thought to be carried mainly by long-wavelength modes with $k_\perp \rho_i \sim 0.2$. While this seems to be generally true for the ion heat channel, there is experimental evidence that the electron heat fluxes behave differently – both in transport barriers and beyond. Thus, theory and simulation are challenged to explain these findings.

Here, we will examine the spectral properties of electron heat transport from TEM and ETG turbulence, focussing on contributions from shorter wavelengths than the ones mentioned above. This is done by means of nonlinear gyrokinetic simulations with the GENE code. Some simulations treat both ion and electron space-time scales fully self-consistently and are therefore very challenging from a computational point of view.

In a first step, pure TEM turbulence is investigated. Here, the plasma parameters are chosen such that both ITG and ETG modes are linearly stable. This corresponds (more or less) to the situation in various dedicated experiments over the last several years. We find that under these conditions, the electron heat fluxes exhibit clear peaks around $k_\perp \rho_i \sim 0.2$, and fall off quickly for higher wavenumbers – in line with the usual expectations.

In a second step, we study the case in which TEMs, ITG modes, and ETG modes all coexist. It is shown that the spectral properties change completely: A wide range of wavenumbers with $k_\perp \rho_i \gg 0.2$, from ion scales all the way to electron scales, can contribute to the overall electron heat transport. This implies that the latter is now dominated by high-wavenumber TEMs and ETG modes, while the direct contribution from long-wavelength ITG modes is relatively small. Special attention is being paid to steep gradient regimes like edge transport barriers where ITG modes and TEMs are strongly suppressed, and ETG modes exist on spatial scales down to $k_\perp \rho_i \ll 1$.

Velocity space resolution in continuum gyrokinetic simulations

M. Barnes, W. Dorland
CMPD, University of Maryland, College Park

In the absence of collisions, particle distribution functions can develop fine scales in velocity space. Consequently, resolving weakly-collisional plasma dynamics in kinetic simulations is regarded as challenging. However, gyrofluid simulations showed that with adequate models of collisionless physics, it is possible to reproduce fully gyrokinetic, nonlinear heat fluxes to within a factor of approximately two. It is therefore interesting to look more closely at velocity space resolution issues in gyrokinetic simulations. Here, we present results from a study of velocity space resolution requirements for a number of problems in weakly-collisional plasmas, using the continuum gyrokinetic code GS2. Problems considered include the long-time limit of linear Landau-damped ion acoustic waves, linear Barnes-damped kinetic Alfven waves, unstable toroidal ITG modes, neoclassical ion thermal conduction, and ITG turbulence. For each problem, we compare the numerically generated distribution functions with theoretical expectations and provide quantitative measures of the quality of the numerical results. We also present model collision operators which provide physically correct results for the measureable quantities of interest in collisionless problems with reasonable velocity space resolution requirements.

Observation of TEM Turbulence and New Effects of Collisions

D. R. Ernst, N. Basse, W. Dorland,* C. L. Fiore, E. S. Marmar, L. Lin, A. Long, V. Navkal, M. Porkolab, K. Zeller, and K. Zhurovich

MIT Plasma Science and Fusion Center, Cambridge, Massachusetts, USA
*Department of Physics, Univ. of Maryland, College Park, Maryland, USA

Evidence of trapped electron mode (TEM) turbulence in density fluctuation spectra is presented. The evidence, based on measurements of the density fluctuation wavelength spectrum by Phase Contrast Imaging (PCI), comes from an Alcator C-Mod ITB experiment. The measured wavelength spectrum is closely reproduced, in a first of kind comparison, by nonlinear gyrokinetic simulations, using the GS2 code augmented by a new synthetic PCI diagnostic.[1] The measured spectrum is a linear combination of radial and poloidal wavelength spectra from the simulation. The nonlinear radial mode-number spectrum peaks at k_r=0, while the poloidal wavelength spectrum peaks at longer wavelengths than those of maximum linear growth. This anisotropy is reminiscent of beam emission spectroscopy measurements on TFTR.[2] The TEM fluctuations are associated with the steep density gradient in an internal transport barrier. This provides spatial localization for the chordal PCI measurement, and allows us to utilize a radially local flux-tube simulation. The simulations also reproduce the relative increase in fluctuation level when TEMs are destabilized by on-axis heating. In addition, the simulated particle and energy fluxes agree with the results of transport analysis, within measurement uncertainty.[3]

The newly discovered nonlinear upshift of the TEM critical density gradient3 is shown to increase strongly with collisionality,1 consistent with the strong damping of TEMs by detrapping, and the relatively weak collisional damping of zonal flows. The role of secondary instability in the upshift is explored through stability analysis of primaries. Further, we have included finite Larmor radius terms in the linearized GS2 Lorentz collision operator, which suppress TEM growth for $k_\theta\rho_i$>2 at relevant collisionalities. We have also implemented collisional energy scattering in GS2, and explore its effects. Research supported by U.S. Dept. of Energy.

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Gyrokinetic Secondary Instability Theory For Electron and Ion Temperature Gradient Driven Turbulence

Gabriel Plunk

UCLA

Secondary instability theory has proven a useful tool in understanding tokamak turbulence. It has been successfully used to estimate saturation amplitudes, predict the spectrum in simulations of fully developed tokamak turbulence and help understand the observed breakdown of "isomorphism" between ITG and ETG turbulence (Jenko, Dorland, Phys. Rev. Lett., Vol. 89, No. 22). This work presents a fully gyrokinetic secondary instability theory. The local kinetic dispersion relation is solved to generate a primary mode. The secondary mode is a perturbation to the primary mode and satisfies an integral equation with a periodic kernel. Finite Larmor radius (FLR) and other kinetic effects are treated exactly capturing $k\rho > 1$ as well as $k\rho \ll 1$ quasi-singular behavior. It is therefore well suited to describe the intermediate regime of ITG/ETG coupling. The secondary instability of toroidal ($k_\parallel = 0$) and slab ($L_T/R = 0$) primary modes are computed along with spectral characteristics and parametric dependence. The novel features of fully gyrokinetic secondary modes include a surprisingly robust growth rate at high $k\rho$ and, in the case of ETG, a strong sensitivity to the kinetic form of the primary mode. The convergence properties of the computation of the secondary instability of ETG toroidal modes underscores the need for proper k-space resolution in simulations. Parametric dependence of secondary mode growth rate and radial wavenumber spectrum give a novel way to predict turbulence properties at different tokamak operating points and suggest a possible mechanism for enhanced transport suppression.

Wednesday morning, April 25

8:30 – 9:30

Ballroom B&C

Review Talk 3A

Laboratory and planetary flows of relevance to plasma physics with a focus on liquid metals

Daniel P. Lathrop
University of Maryland
Institute for Research in Electronics and Applied Physics
Institute for Physical Sciences and Technology
Departments of Physics and Geology

Theory, observation, numerics and experiments have been working toward understanding the conditions in planetary cores and stellar atmospheres. This is not easy work given the inherent turbulent flows. These problems overlap in part with the questions that face the plasma physics community in understanding plasma confinement devices, stars, proto-planetary disks, and the interstellar media. Many groups have contributed to progress in understanding, in part, of these systems. Computational progress has been pursued on a variety of turbulence models. Direct computation, with limited turbulence by a worrisome increase in diffusivity, has led to significant advances. Experiments, with realistic levels of turbulence, have seen dynamo action, turbulent induction, inertial waves, the magneto-rotational instability, and a host of other phenomena. While these have been in liquid metals, one might hope that an understanding of these systems, and a discussion between scientists working in this and plasma theory, might lead to new progress. In this talk I'll report on Coriolis effects in rotating flows, magneto-rotational instability experiments, and international efforts toward understanding dynamo action.

Wednesday morning, April 25

10:00 – 12:30

Ballroom B&C

Oral Session 3B

Interaction of Fast Wave Accelerated Beam Ions with Ideal Internal Kink Instability in the DIII-D Tokamak*

M. Choi, V.S. Chan, M.S. Chu, L.L. Lao, A.D. Turnbull

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

In the present work, we show that ORBIT-RF [1] coupled with TORIC [2] simulations on the interactions of beam ion-fast wave (FW) in the DIII-D moderate to high harmonic FW heating experiments can reproduce the observed energetic tails, and we confirm its sawtooth stabilization effect in the context of Porcelli model [3] combined with ideal MHD stability theory.

Delay or suppression of the sawtooth instability when q_0 (central safety factor) drops below 1 has been a critical issue in the conventional tokamak plasma as well as for burning plasma experiment such as ITER. DIII-D experiments using neutral beam injection and FW [5] have demonstrated that beam ions accelerated by FW can significantly modify sawtooth activities, depending on the plasma and wave conditions. We evaluate the kinetic contribution of beam ion tails generated by FW to MHD stability with the distribution function of fast ions with finite orbit calculated from ORBIT-RF. We run ORBIT-RF with FW solutions from TORIC to obtain agreement with neutron rate measurements. The calculated beam ion tails also agree qualitatively with experiments. The ideally perturbed potential energy is calculated using either a numerically fitted formula [5] or the numerical solution from GATO [6]. We evaluate separately the contributions from the ideal unstable mode and trapped ion populations at several refined time slices during one monster sawtooth cycle, and, then apply the Porcelli sawtooth crash criteria and kinetic stabilization models to each equilibrium at the selected times. Simulation results show that FW-accelerated beam ions account for the change of sawtooth behavior in DIII-D moderate to high harmonic FW heating experiments, but, its crucial kinetic stabilizing contribution strongly depends on both magnetic shear at $q = 1$ surface and the radius of $q = 1$ surface.

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*Work supported by U.S. DOE under DE-FG03-95ER54309.

3B2

Dust Transport in Tokamaks

A.Yu. Pigarov, R.D. Smirnov, S.I. Krasheninnikov, D. Benson, M. Rosenberg, Y. Tanaka[3)], C.H. Skinner[2)], A.L. Roquemore[2)]

[1)]University of California at San Diego, La Jolla CA

[2)]Princeton Plasma Physics Laboratory, Princeton NJ

[3)]Kanazawa University, Kanazawa, Japan

The word *industry* includes *dust*, i.e. highlighting in this manner an important role of dust in safety, technology, and public health. Fusion devices are not an exception, since the dust particle inventories of 1-100 g are found in current tokamaks. Substantially larger dust inventories up to 100 kg are expected in the next-step tokamaks (e.g., ITER) and these inventories have set rigorous limits on safe operation time. Therefore, understanding, diagnosing, and controlling the formation and transport of dust particles as well as development of predictive theory and dust modeling capabilities are key issues of ongoing research.

In the report, recent advances in the dust transport studies in tokamaks will be discussed. Topics include: (1) physical model for dust transport; (2) modeling results on dynamics of dust particles in tokamak plasma with DUSTT code; (3) dynamics and lifetime of dust particles made of different materials; (4) conditions necessary for particle growth in the plasma; (5) dust interaction with material surfaces; (6) dust particle diagnostics, modeling and measurements; (7) density profiles for dust particles and impurity atoms associated with dust ablation in tokamak plasmas which are calculated with DUSTT/UEDGE by using a statistical averaging technique; (8) possible effects of dust on plasma parameters; and (9) the roles of dust in material/tritium migration.

TEMPEST Simulations of the Radial Electric Field Dynamics in the Neoclassical Plasmas*

Z. Xiong, X. Q. Xu, W. M.Nevins, and R. H. Cohen

Lawrence Livermore National Laboratory, Livermore, CA 94550 USA

The Geodesic-Acoustic Mode (GAM) is an asymmetric mode, which involves parallel ion dynamics, cross-field drifts, and acceleration. Earlier GAM theory and simulations focused on the large aspect ratio, small orbit regime. Recently Sugama and Watanabe found that the damping rate is sensitive to $k_\perp \rho_i$ at large q due to the effect of large banana orbits [1]. In our 4D TEMPEST GAM simulations, the charge is radially separated by an initial sinusoidal perturbation of the ion density. The electron model is Boltzmann $n_e = \langle n_i(\psi, \theta, t=0)\rangle \exp(e\phi/T_e)/\langle \exp(e\phi/T_e)\rangle$, where $\langle\rangle$ represents the flux surface average. This choice of coefficient for Boltzmann electron model means that there is no cross field electron transport. Both radial and poloidal boundary conditions are periodic. The full-f, self-consistent TEMPEST simulation results of collisionless damping of geodesic acoustic modes and zonal flow are presented. Good agreement is shown between theory [1,2] and simulations for the frequency of GAMs and damping rate. The large effect of the orbit size dramatically enhances the GAM damping rate by sampling the multiple resonant surfaces. For the same parameters, the damping rate is almost zero if the finite banana orbit effect is ignored. The simulations shows that the GAM damping rate has a strong dependence on the safety factor q. For q=10, there is almost no damping.

In an uniform plasma, the electric potential after initial perturbation relaxes to the Rosenbluth-Hinton residual in the small banana orbit limit. While in non-uniform plasmas with the density and temperature profiles initialized as a tanh function of radius centered around the middle of simulation domain $[N(x) = n_0 + n_m \tanh((x - x_m)/\Delta_n)]$, the GAMs have clearly been observed in TEMPEST simulations with gyrokinetic Poisson field solver. However, the steady state electric potential has been modified. An initially Maxwellian distribution relaxes to a state with a finite radial electric field which is satisfied the standard neoclassical flow expression $\langle U_{i\|}\rangle = (cT_i/Z_i e B_p)\,[k(\partial \ln T_i/\partial r) - (\partial \ln P_i/\partial r) - (Z_i e/T_i)(\partial\langle\Phi\rangle/\partial r)]$. The radial electric field is generated due to the intrinsic neoclassical polarization. The self-consistent bootstrap current from TEMPEST simulations with both kinetic ions and electrons are compared with Sauter's model [3].

Comparisons with theory for systematic scans in safety factor q, collisionality, and pressure gradient scale length will be discussed. The impact of the magnetic separatrix and the Scrape-Off-Layer physics on the GAM, the radial electric field and bootstrap current will be reported.

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*Work performed for U.S. DOE by U.C. LLNL under Contract W7405-ENG-48

Interaction of scrape-off layer currents with magnetohydrodynamical instabilities in tokamak plasmas

R. Fitzpatrick,
Institute for Fusion Studies, U. Texas at Austin, USA

Magnetohydrodynamical instabilities in tokamaks are often observed in combination with surprisingly large currents flowing in the scrape-off layer [1, 2]. The origin of these currents is not fully understood. Nor is their likely effect on the instabilities with which they are associated.

A simple theoretical model has been developed which describes how current eddies can be excited inductively in the scrape-off layer (SOL) of a large aspect-ratio, low-β, circular cross-section tokamak by time-varying magnetohydrodynamical instabilities originating from within the plasma. These current eddies flow parallel to the magnetic field in the SOL, and return through the wall. Such current eddies are impossible on closed magnetic flux-surfaces, since the force generated as the return currents flow across magnetic field-lines could not be balanced. However, on the open flux-surfaces in the SOL, the force can be balanced by mechanical stresses within the wall. It follows that the open magnetic flux-surfaces in the SOL possess a degree of freedom denied to the closed flux-surfaces just inside the SOL. Hence, we would indeed expect particularly large current eddies to be generated inductively in the SOL in response to MHD activity inside the plasma. The model allows the size of these currents to be calculated.

The model is used to study the interaction of SOL currents with tearing modes and resistive wall modes in a typical tokamak plasma. SOL currents are found to be fairly effective at braking the rotation of tearing modes, and to have a significant destabilizing effect on resistive wall modes.

References

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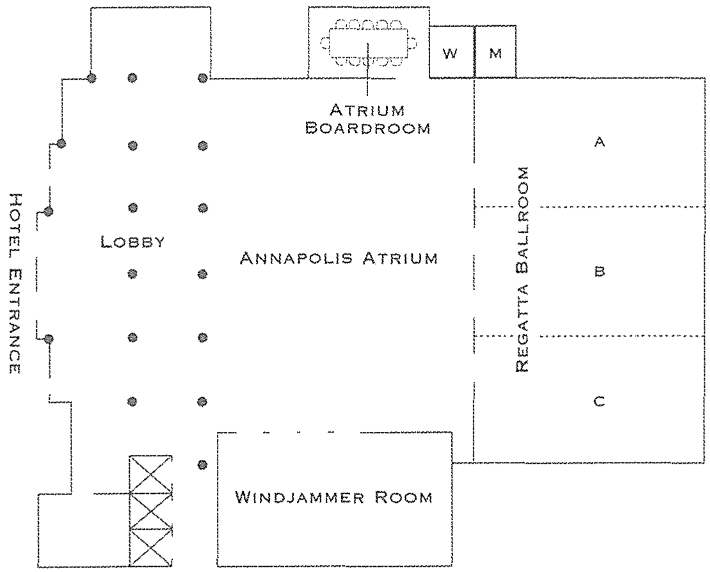
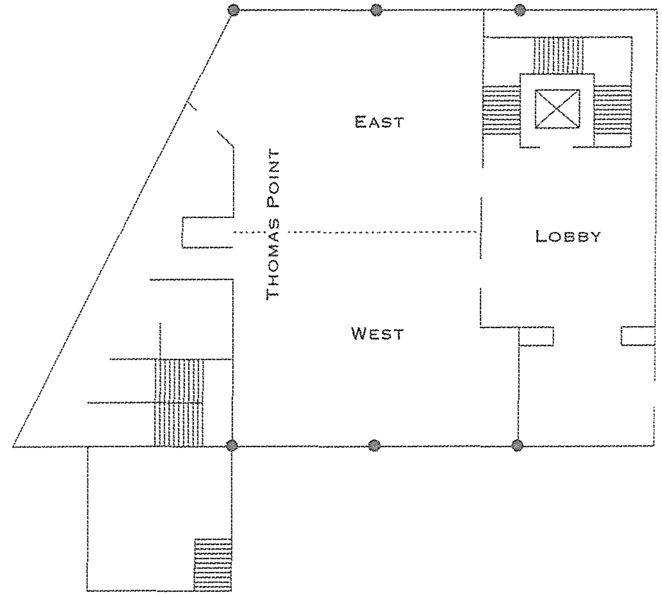
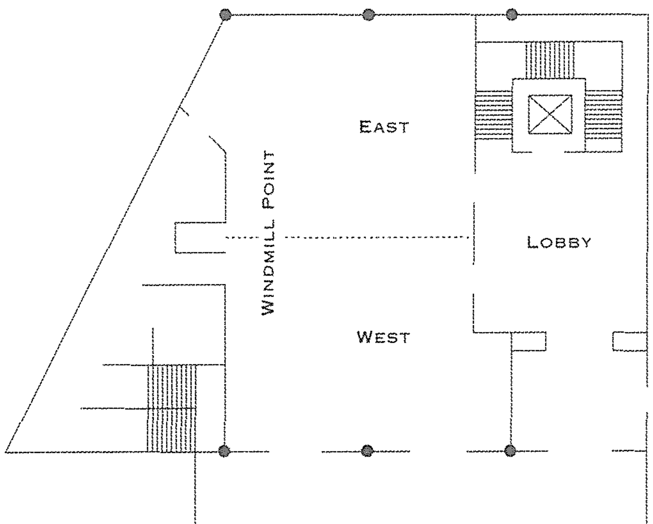
LOEWS HOTEL - FLOOR PLAN

Main Building: First Floor



Powerhouse: First Floor





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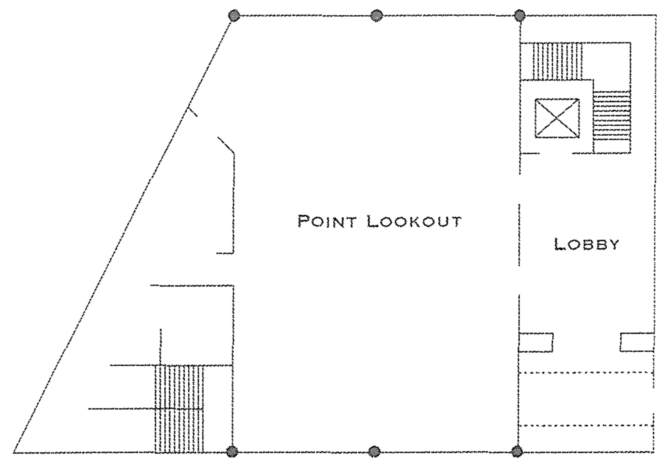

Powerhouse: Third Floor

Program at a Glance

Monday, April 23

08:20. Welcome: Paul Bonoli, Local Organizing Committee, Ballroom B&C, Lobby Level Loews Hotel Annapolis

08:30. Review Talk 1A. Ultra-Intense Laser Pulse Interaction with Gases, Cluster Gases and Structured Plasmas. *T.M. Antonsen, Jr.*
Chair: Peter Catto

09:30. Oral Session 1B. Direct Drive by Cyclotron Heating Can Explain Spontaneous Rotation in Tokamaks. *J.W. Van Dam*
Chair: Peter Catto

10:00. Poster Session 1C.
Coffee Break during Poster Session.

12:00. Lunch

Oral Session 1D. Chair: Gene Tracy

13:30. Velocity Shear Stabilization of Ideal Interchange Instabilities in Centrifugally Confined Plasmas. *A. Hassam*

14:00. Extended MHD Simulations of Rotation and Translation in Field-Reversed Configurations. *A.I.D. Macnab*

14:30. Suppression of Resistive Wall Mode at Low Plasma Rotation. *B. Hu*

15:00. Interaction Between Magnetic Islands and Electrostatic Turbulence. *F. Militello*

15:30. Poster Session 1E.
Coffee/Beverage Break during Poster Session

Tuesday, April 24

8:30. Review Talk 2A. Equation-Free Modeling and Computation for Complex/Multiscale Systems. *Y. Kevrekidis*
Chair: François Waelbroeck

9:30. Oral Session 2B. Energy Conservation in Linear and Perturbative δf-PIC Simulations. M. Dimits
Chair: Bruce Cohen

10:00. Poster Session 2C.
Coffee Break during Poster Session

12:00 Lunch

18:00 Conference Dinner. Loews Hotel Ballroom A&B, Lobby Level

Oral Session 2D. Chair: Barrett Rodgers

19:30. Scale Separation of Ion and Electron Heat Transport. *F. Jenko*

20:00. Velocity Space Resolution in Continuum Gyrokinetic Simulations. *M. Barnes*

20:30. Observation of TEM Turbulence and New Effects of Collisions. *D. R .Ernst*

21:00. Gyrokinetic Secondary Instability Theory for Electron and Ion Temperature Gradient Driven Turbulence. *G. Plunk*

Wednesday, April 25

08:30. Review Talk 3A. Laboratory and planetary flows of relevance to plasma physics with a focus on liquid metals . *D. Lathrop*
Chair: Paul Bonoli

09:30 Coffee Break

Oral Session 3B. Chair: Johan Carlsson

10:00. Interaction of Fast Wave Accelerated Beam Ions with Ideal Internal Kink Instability in the DIII-D Tokamak. *M. Choi*

10:30. Dust Transport in Tokamaks. *A. Yu. Pigarov*

11:00. TEMPEST Simulations of the Radial Electric Field Dynamics in the Neoclassical Plasmas. *Z. Xiong (presented by X.Q. Xu)*

11:30. Interaction of Scrape-Off Layer Currents with Magnetohydrodynamical Instabilities in Tokamak Plasmas. *R. Fitzpatrick*