2005 International Sherwood Fusion Theory Conference April 11-13, 2005 Stateline, Nevada

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April 11-13
Stateline, Nevada

Sponsored by the Sherwood Executive Committee

International Sherwood Fusion Theory Conference

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Harveys Hotel
Stateline, Nevada

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Executive Committee

Philip Snyder *(Chair),* General Atomics
Curt Bolton, US Department of Energy
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Cover Photo: Nearby Emerald Bay that opens to Lake Tahoe; courtesy of R.A. Jong, skibuff.

Registration Schedule

Sunday, April 10	18:00 to 21:00
Monday, April 11	7:30 to 11:30 and 13:00 to 17:00
Tuesday, April 12	7:30 to 11:30
Wednesday, April 13	7:30 to 10:00

Event Schedule

Sunday, April 10	18:00 to 20:00	Welcome Reception
Monday, April 11	8:30 to 10:00	Companions Breakfast
Tuesday, April 12	12:30 to 17:30	Open Afternoon
Tuesday, April 12	17:30 to 19:00	Conference Banquet

Program Overview

The program consists of 3 invited review papers, 14 oral contributed papers selected out of 33 oral submissions and poster presentations. The total number of presentations is 166. Satellite meetings are also scheduled during the conference.

Program Schedule

All technical sessions will be held in Harveys Hotel conference level.

- The **review and oral sessions** will be held:
  - **O1** at 8:30 Monday morning
  - **O2** at 13:30 Monday afternoon
  - **O3** at 8:30 Tuesday morning
  - **O4** at 10:30 Tuesday morning
  - **O5** at 8:30 Wednesday morning
  - **O6** at 10:30 Wednesday morning
- The **poster sessions** will be held:
  - **P1** at 10:00 Monday morning
  - **P2** at 15:30 Monday afternoon
  - **P3** at 19:30 Tuesday evening

Satellite Meetings

NIMROD Meeting
Saturday, April 9, 8:30 to 18:00
Conference Level, Harveys Hotel

CEMM Meeting
Sunday, April 10, 8:30 to 18:00
Conference Level, Harveys Hotel

Special Session on Cluster Architecture
Monday, April 11, 17:30 to 19:30
Conference Level, Harveys Hotel

Sherwood Executive Committee Meeting
Tuesday, April 12, 12:30 to 15:30
Conference Level, Harveys Hotel

Marilyn Stewart

Agenda for the International Sherwood Fusion Theory Conference

April 11-13, 2005
Harveys Hotel
Stateline, NV

Monday, April 11

Oral Session O1 – Chair: Gary Staebler

8:20 – 8:30 Welcome and meeting arrangements – T.D. Rognlien, LLNL

8:30 – 9:30 Review paper: *Photonic band gap materials: engineering the fundamental properties of light*, Sajeev John, Univ. Toronto

9:30 – 10:00 *Natural velocity of magnetic islands*, F.L. Waelbroeck, IFS, Univ. Texas

Poster Session P1

10:00 – 12:00 Posters with coffee

12:00 – 1:30 Lunch

Oral Session O2 – Chair: Carl Sovinec

1:30 – 2:00 *Gyrokinetic simulations of ion and impurity transport,* C. Estrada-Mila, Univ. Calif., San Diego

2:00 – 2:30 *Intermittent transport and scaling of the scrape-off-layer width in tokamaks,* A.Y. Aydemir, IFS, Univ. Texas

2:30 – 3:00 *Gyrokinetic δf simulation of the collisionless and semicollisional tearing mode instability*, W. Wan, Univ. Colorado

3:00 – 3:30 *Equation free projective integration: A novel scheme for modeling multiscale processes in plasmas,* M.A. Shay, Univ. Maryland

Poster Session P2

3:30 – 5:30 Posters with coffee

Special Session/Discussion on Cluster Architecture – Chair: Vincent Chan

5:30 – 7:30 Presentations by C. Bolton, V. Decyk, E Valeo, J. Candy, and D. Ernst

Tuesday, April 12

<u>Oral Session O3</u> – Chair: Peter Catto

8:30 – 9:30 Review paper: *Scrape-off layer flows, magnetic topology, and the flow boundary conditions imposed at the separatrix in a tokamak plasma,* B. LaBombard, MIT

9:30 – 10:00 *Particle noise induced diffusion and its effects on ETG simulations,* G.W. Hammett, PPPL

10:00 – 10:30 Coffee break

<u>Oral Session O4</u> – Chair: Steve Jardin

10:30 – 11:00 *Rotation, error field, and wall thickness effects on resistive wall modes in ITER,* L.J. Zheng, IFS, Univ. Texas

11:00 – 11:30 *Nonlinear dynamics of energetic particle-driven fishbone instability in tokamak plasmas,* G.Y. Fu, PPPL

11:30 – 12:00 *Modelling nonperturbative frequency sweeping,* R.G.L. Vann, Univ. Warwick

12:00 – 12:30 *Nonlinear evolution of edge localized modes,* D.P. Brennan, MIT, General Atomics

12:30 – 5:30 Open time

5:30 – 7:00 Conference dinner with discussion

<u>Poster Session P3</u>

7:30 – 9:30 Poster Session 3

Wednesday, April 13

<u>Oral Session O5</u> – Chair: John Cary

8:30 – 9:30 Review paper: *Unique MHD properties of spherical torus plasmas,* J. Menard, PPPL

9:30 – 10:00 *Self-organized temperature redistribution during sawtooth oscillation on TEXTOR,* H. Park, PPPL

10:00 – 10:30 Coffee break

<u>Oral Session O6</u> – Chair: Tom Rognlien

10:30 – 11:00 *Gyrokinetic simulations of Z-pinch,* P. Ricci, Dartmouth College

11:00 – 11:30 *On the possibility of the sheath-driven, finite-beta modes localized near the divertor plate,* R.H. Cohen, LLNL

11:30 – 12:00 *Time and space dependent parallel viscous force,* A.L. Garcia–Perciante, Univ. Wisc.

12:00 Conference adjourned

Poster Sessions

Poster Session P1

P1-01 M. Ottaviani , N. Arcis, and D.F. Escande
"Perturbative approach to the nonlinear growth and saturation of the tearing mode for any current gradient, with an application to the forced reconnection problem"

P1-02 S.G. Shasharina , N. Wang, R. Pundaleeka, and C. Li
"Fusion Web Service and Fusion Simulation Markup Language"

P1-03 J.R. Cary , S.G. Shasharina, and R. Pundaleeka
"FarSight: Remote Visualization of Simulation Data"

P1-04 J.L.V. Lewandowski
"Global Gyrokinetic Particle-in-cell Simulations with Trapped Electrons"

P1-05 Loren Steinhauer
"Equilibrium of flowing "nearby fluids" "

P1-06 T. Onjun
"Models for Predicting the Pedestal at the Edge of H-mode Tokamak Plasmas"

P1-07 J.E. Kinsey , J. Candy, and R.E. Waltz
"Gyrokinetic Simulations of the Effect of ExB Shear, Safety Factor, and Magnetic Shear on Driftwave Transport"

P1-08 G.M. Staebler , J.E. Kinsey, and R.E. Waltz
"Benchmarking of a New Fast Gyro-Landau Fluid"

P1-09 R.E. Waltz , and J. Candy
"Heuristic Theory and Simulation of Nonlocal Transport"

P1-10 Y. Chen , and S.E. Parker
"Effects of magnetic fluctuations and plasma shaping on turbulence and transport"

P1-11 R.A. Nebel , L. Chacon, J. Park, and E. Evstatiev
"Plasma Compression in the Periodically Oscillating Plasma Sphere"

P1-12 J.N. Leboeuf , M. Ashour-Abdalla, J. M. Bosqued, D. Schriver, V. Sotnikov, and N. Cornilleau-Wehrlin
"Ion Velocity Space Shell Instabilities"

P1-13 M. Romanelli , A. Airoldi, F. Bombarda, G. Cenacchi, B. Coppi, and P. Detragiache
"IGNITOR: The scientific program"

P1-14 V.A. Izzo , and R.S. Granetz
"MHD simulations of disruption mitigation by high-pressure gas jet"

Poster Sessions

P1- 15 Nong Xiang , John Cary, Daniel C. Barnes, and Johan Carlsson
"Low noise electromagnetic delta- f particle- in- cell simulation of electron Bernstein waves"

P1- 16 P. J. Catto , and A.N. Simakov
"The Neoclassical Radial Electric Field of a Collisional Tokamak"

P1- 17 H.E. Mynick , A.H. Boozer, and T.S. Pedersen
"Transport Studies in the Columbia Non- neutral Torus"

P1- 18 A.N. Kaufman , E.R. Tracy, and A.J. Brizard
"Triplication of Budden resonance by a sheared- flow layer"

P1- 19 D.A. Knoll , and L. Chacon
"Coalescence of Magnetic Islands in the High Lunquist Number, Hall MHD, Regime"

P1- 20 R.D. Milroy , E.D. Held, T.R. Jarboe, G. Marklin, B.A. Nelson, U. Shumlak, C.R. Sovinec, and S. Woodruff
"The Plasma Science and Innovation Center (PSI- Center)"

P1- 21 D. Strintzi , B.D. Scott, and A.J. Brizard
"Nonlocal nonlinear electrostatic gyrofluid equations: a four- moment model"

P1- 22 D.D. Schnack , A.Y. Pankin, and C.R. Sovinec
"Implementation of Ion Gyro- Viscosity in the NIMROD Code"

P1- 23 M. Lehrman , and A.B. Rechester
"Global Invariants of Hydrodynamic Turbulence in the Pipe"

P1- 24 Shuichi Ohsaki , and Zensho Yoshida
"Hall effect on turbulence and relaxation process of flowing plasmas"

P1- 25 S.E. Sharapov , Yu.F. Baranov, C. Boswell, C.D. Challis, and N.P. Young
"Transitions in Alfven Eigenmode Spectrum in Advanced Scenarios on JET"

P1- 26 L.E. Sugiyama , W. Park, and H.R. Strauss
"Two- Fluid Magnetic Islands in Toroidal Configurations"

P1- 27 E.G. Evstatiev , P.J. Morrison,
"Surfaces of Section Analysis of the Beam- - Plasma System with Two Electromagnetic Waves"

P1- 28 A. S. Ware , R. Sanchez, D.A. Spong, D. del- Castillo- Negrete, and E. Mondloch
"Impact of Three- Dimensional Geometry on Ballooning Stability"

P1- 29 S. M. Mahajan , and P. N. Guzdar
" 1D Hall- MHD Theory for the H mode Pedestal"

Poster Sessions

P1-30 P. N. Guzdar , and R. G. Kleva
"The Effect of parallel flow gradients on the threshold for L-H transitions"

P1-31 T. Rafiq , C.C. Hegna, and M Persson
"Influence of geometry on drift waves in tokamaks and stellarators"

P1-32 A.K. Sen , and V. Sokolov
"Search For Zonal Flow in a Basic Experiment and Theory"

P1-33 F. Winterberg
"Conjectured Manipulation of the Zero Point Vacuum Energy Through Powerful Electric Discharges and its Possible Significance for CTR"

P1-34 A.J. Cole , and R. Fitzpatrick
"Error-field Penetration Thresholds in a Two-Fluid Model"

P1-35 Yu Lin , Xueyi Wang, Zhihong Lin, and Liu Chen
"A gyrokinetic Electron and Fully Kinetic Ion Plasma Simulation Model"

P1-36 Linda Vahala , George Vahala, Jonathan Carter, Min Soe, and Angus Macnab
"Application of Lattice Boltzmann Algorithms to Plasma Physics"

P1-37 George Vahala , Jeffrey Yepez, Linda Vahala, and Min Soe
"Entropic Lattice Boltzmann Methods for Turbulence"

P1-38 X. Liu , and C. Hegna
"Finite Ion Orbit Effects on Magnetic Islands in Toroidal Plasmas"

P1-39 P.A. Gourdain , R. Y. Neches, S. C. Cowley, and J.N. Leboeuf
"Multigrid algorithm for high beta tokamak equilibria"

P1-40 Josef Preinhaelter , Jakub Urban, Linda Vahala, George Vahala, and Gary Taylor
"Time Development of Electron Cyclotron Emission in NSTX"

P1-41 L. Chacon
"Progress on PIXIE3D, a parallel, implicit, extended MHD code"

P1-42 S.J. Allfrey , A. Bottino, R. Hatzky, P. Angelino, and L. Villard
"Application of a `direct' delta-f PIC scheme to gyrokinetic ITG simulations in toroidal MHD equilibria"

P1-43 V. Stefan
"Enhanced Thermonuclear Yield Due to Low-Harmonic Relativistic Electron Bernstein Modes in Spherical Tokamak Plasmas"

P1-44 A. Cardinali , C Castaldo, and F. Zonca
"Numerical study of the wave equation in the Lower Hybrid frequency in a toroidal plasma"

Poster Sessions

P1-45 E. Asp , J. Weiland, X. Garbet, V. Parail, and P. Strand
"Pinch effects and stiffness of the Weiland model"

P1-46 Eliezer Hameiri , Akihiro Ishizawa, and Akio Ishida
"The waves in Hall- MHD plasmas"

P1-47 P.R. Garabedian
"Nonlinear stability of the LHD and the DIII- D"

P1-48 P.B. Snyder , H.R. Wilson, and X.Q. Xu
"Nonlinear Dynamics of ELMs"

P1-49 Jim Reynolds , and Carl Sovinec
"Computational Studies of Dynamo Suppression in The Reversed Field Pinch During PPCD"

P1-50 D.C. Barnes , T. Munsat, S. Parker, J. Peoble, C.R. Sovinec, and N. Murphy
"One- and two- fluid computational studies of Field- Reversed Configuration (FRC) formation and stability"

P1-51 D.A. Spong , S.P. Hirshman, D.J. Strickler, and J.F. Lyon
"Plasma flow characteristics and flexibility studies of quasi- symmetric stellarators"

P1-52 A.V. Arefiev , and B.N. Breizman
"Axial cavity for helicon waves in a nonuniform plasma"

Poster Sessions

Poster Session P2

P2-01 B.N. Breizman , M.S. Pekker, and S.E. Sharapov
"Plasma pressure effect on Alfvén cascade modes"

P2-02 S. Hu , and L. Chen
"Discrete Alfven Eigenmodes Destabilizeded by Energetic Particles in High-Beta Tokamaks"

P2-03 C. S. Jones , and J. M. Finn
"MHD Equilibrium Reconstruction from Correlated Experimental Data"

P2-04 B. Hu , R. Betti, and J. Manickam
"Kinetic effects on resistive wall mode in tokamaks"

P2-05 B.I. Cohen , E.B. Hooper, and C.R. Sovinec
"NIMROD Simulations of SSPX Spheromak Physics"

P2-06 J. Seol , and C.C. Hegna
"Nonlinear electron cyclotron resonance heating in stellarators"

P2-07 P. Zhu , A. Bhattacharjee, and K. Germaschewski
"Nonlinear Rayleigh-Taylor-Parker Instability: Direct MHD Simulations"

P2-08 S.C. Jardin , J.A. Breslau, J. Chen, and N. Ferraro
"Fully Implicit Solution of the Full 2-Fluid MHD equations in 2-dimensions using High-order Finite Elements with C1 Continuity"

P2-09 G. Lapenta , R.A. Nebel, and J. Park
"Kinetic Simulation of Inertial-Electrostatic Confinement Experiments at Los Alamos National Laboratory"

P2-10 G. Pautasso , G. Lapenta, and G.L. Delzanno
"Kinetic Reconnection in Force Free and Cusp Configurations"

P2-11 G.L. Delzanno , J. M. Finn, R.A. Nebel, C. Bathke, L. Chacon, and G. Lapenta
"Single and Multiple Helicity States in RFPs"

P2-12 E. Camporeale , and G. Lapenta
"Simulation of 3D Kinetic Reconnection"

P2-13 J. M. Finn , and L. Chacon
"Volume preserving integrators for solenoidal fields on a grid"

P2-14 D.D. Ryutov , B.I. Cohen, R.H. Cohen, E.B. Hooper, and C.R. Sovinec
"Assessing the role of artificial diffusivity in the NIMROD simulations of the Livermore spheromak "

P2-15 F. Ebrahimi , S.C. Prager, and C.R. Sovinec
"The MHD dynamics of momentum transport and plasma flows"

P2-16 C.M. McDevitt , and P.H. Diamond
"Dynamic Sub-Grid Scale Modeling of Tearing Mode interaction with Turbulence"

P2-17 Ö. D. Gürcan , and P.H. Diamond
"Turbulence spreading modelling in temperature gradient driven turbulence"

P2-18 Y. Kagei , Y. Kishimoto, T. Miyoshi, and Y. Suzuki
"A Finite Volume Approach to Compressible MHD Simulations of High Beta Tokamak Plasmas"

P2-19 H.R. Strauss , W. Park, R. Paccagnella, B. Hientzsch, J. Breslau, S. Jardin, G.Y. Fu, and L.E. Sugiyama
"Resistive Plasma Resistive Wall Modes"

P2-20 R. Fitzpatrick , and F.L. Waelbroeck
"Determining the phase-velocity of magnetic islands in two-fluid plasmas"

P2-21 P.A. Cassak , M.A. Shay, and J.F. Drake
"Hysteresis and the Onset of Fast Magnetic Reconnection"

P2-22 J.C. Perez , and W. Horton
"Pseudospectral simulations of shear-flow-suppressed turbulent transport in the Helimak and Large Plasma Device experiments"

P2-23 S.R. Hudson , A. Reiman, D.A. Monticello, and C.C. Hegna
"Comparison of theoretical estimates of magnetic island width with numerical"

P2-24 A.J. Brizard
"Conservation properties of a guiding-center Fokker-Planck collision operator"

P2-25 A.N. Simakov , and P. J. Catto
"Gyroviscosity and (ion) perpendicular viscosity for plasma of arbitrary collisionality"

P2-26 A.Y. Pankin , G. Bateman, D.P. Brennan, A.H. Kritz, D.D. Schnack, and P.B. Snyder
"Extended MHD stability analysis for transport modeling of ELMs"

P2-27 V. Roytershteyn , B. Coppi, and C. Yarim
"Magnetic Reconnection and Associated Transport of Plasma Thermal Energy"

P2-28 A.H. Glasser , V.D. Liseikin, I.A. Kitaeva, V.S. Lukin, and A.N. Simakov
"Harmonic Grid Generation for the Tokamak Edge Region"

P2-29 B. Coppi
""Crystal" Magnetic Structure in Axisymmetric Plasma Accretion Disks"

Poster Sessions

P2-30 M. Salvetti , and B. Coppi
"The Columbus Concept within a Science Based Approach to Fusion Research"

P2-31 A.B. Rechester , and R.B. White
"Symbolic Signal Processing for Tokamak Turbulence"

P2-32 M. Lontano , and B. Coppi
"Consistency of the Accretion Theory of the Spontaneous Rotation Phenomenon with Recent Experiments"

P2-33 D. A. Maslovsky , and A.H. Boozer
"Multimode Analysis of the Resistive Wall Mode Instability"

P2-34 S. Markidis , and G. Lapenta
"Parsek: an Implicit Parallel Particle-in-Cell"

P2-35 J. C. Wiley , M. Kotschenreuther, and P. Valanju
"Simulation of Turbulence and Blobs in Helimak and tokamak SOL"

P2-36 V.V. Mirnov , C.B. Forest, and C.C. Hegna
"Effect of external plasma on kink stability of line tied screw pinch"

P2-37 J.J. Ramos
"Long mean-free-path collisional effects in the fluid description of magnetized plasmas"

P2-38 M.K. Addae-Kagyah , E.D. Held, and C.R. Sovinec
"Simulation Studies of Generalized Parallel Ion Stress Tensor in Slab Geometry"

P2-39 A. Wurm , and P.J. Morrison
"Hamiltonian and Lagrangian structure of some gyroviscous magnetofluid models"

P2-40 C.C. Hegna
"The effect of plasma flow on ballooning instabilities in 3-D equilibria"

P2-41 K. C. Shaing
"Pressure Anisotropy for Fluid Equation Closure in Long Mean Free Path Regimes for Tokamaks"

P2-42 J.A. Breslau , W. Park, S.C. Jardin, and H.R. Strauss
"Numerical modeling of the sawtooth crash in a small tokamak"

P2-43 L. Chen , Z. Lin, and F. Zonca
"Nonlinear Toroidal Mode Coupling: a New Paradigm for Drift Wave Turbulence in Toroidal Plasmas"

P2-44 L.E. Zakharov , and B. Stratton
"Reconstruction of soft X-ray emissivity from NSTX plasma"

Poster Sessions

P2- 45 M.S. Chance , A.D. Turnbull, M.S. Chu, M. Okabayashi, and N. Pomphrrey
"SVD Analysis of the Mirnov Loop Data in Tokamaks"

P2- 46 P.J. Morrison , Sunghwan Jung, Harry Swinney,
"On the statistical mechanics of two- dimensional turbulence"

P2- 47 B. A. Shadwick , and G. M. Tarkenton
"Hamiltonian Hybrid Fluid- Kinetic Model of Low Temperature, Relativistic Plasmas"

P2- 48 E.D. Held
"A Hybrid Chapman- Enskog/Moment- Approach for Deriving General Closure Relations"

P2- 49 C.R. Sovinec , H. Tian, and D.C. Barnes
"Analysis of Numerical Algorithms for Two- Fluid Multiscale Computation"

P2- 50 H. Tian , and C.R. Sovinec
"Numerical Study of Hall Dynamo Effect Driven by Two- Fluid Tearing Instability"

Poster Session P3

P3-01 A. B. Hassam , D. J. Adler, and A. M. Rey
"Divergent Subcritical Convection in Magnetized Plasma from Asymmetric Sourcing"

P3-02 G. Marklin , U. Shumlak, and T.R. Jarboe
"Resistive MHD Simulation of HIT-SI using MH4D"

P3-03 F. Halpern , G. Bateman, and A.H. Kritz
"Improvements to the ISLAND Module for Computing Saturated Tearing Modes in Tokamaks"

P3-04 X.Z. Tang , and A.H. Boozer
"Constrained resonance: flux amplification in helicity injected spherical Tokamaks and current limiting mechanisms in RFPs"

P3-05 N. D. Daniels , A. S. Ware, D. E. Newman, B. A. Carreras, and C. Hidalgo
"Hysteresis Effects in Edge Poloidal Flow Generation"

P3-06 N.N. Gorelenkov , H.L. Berk, R. Nazikian, and G.J. Kramer
"Beam ion distribution function model and Alfven Eigenmode stability"

P3-07 J. Peoble , W. Wan, F. Ebrahimi, D. Barnes, and S. Parker
"Comparisons of resistive MHD and gyrokinetic simulations of the slab tearing mode instability"

P3-08 Z. Lin
"Electron Temperature Gradient Turbulence"

P3-09 K. Fuchss , A. Wurm, A. Apte, and P.J. Morrison
"Meanders and non-standard reconnection/collision processes in the standard nontwist map"

P3-10 C.C. Kim , and C.R. Sovinec
"Hybrid Kinetic-MHD Simulations of the Resistive Kink Mode"

P3-11 D. del-Castillo-Negrete
"A fractional diffusion model of nonlocal heat transport"

P3-12 L. Guazzotto , R. Betti, and J.P. Freidberg
"Progress in the development of a linear MHD stability code for axisymmetric plasmas with arbitrary equilibrium flow."

P3-13 M.V. Umansky , B. Dudson, A. Kirk, T.D. Rognlien, and X.Q. Xu
"Modeling of edge plasma turbulence in a spherical tokamak"

P3-14 J. D. Hanson , J. Shields, S.P. Hirshman, S. F. Knowlton, L. Lao, and E. L. Lazarus
"Equilibrium Reconstruction in Stellarators: V3FIT."

P3-15 V.A. Svidzinski , V.V. Mirnov, and S.C. Prager
"Ion heating by collisional damping of tearing modes in RFPs"

P3-16 S.E. Kruger , and D.D. Schnack
"Implementation of Field Error and Resistive Wall Boundary Conditions in Finite Element Codes"

P3-17 Brent Goode , J.R. Cary, and L.A. Berry
"Plasma Response to Waves in Arbitrary Magnetic Field Geometry"

P3-18 C. Crabtree , Z.M. Sheng, and L. Chen
"Nonlinear dynamics of sub-cyclotron motion"

P3-19 Bernhard Hientzsch
"Spectral Elements for two-dimensional resistive MHD"

P3-20 J.H. Kim
"Simulation of Sub-critical Turbulence by Shear Flows"

P3-21 W. Park , J.A. Breslau, J. Chen, G.Y. Fu, S.C. Jardin, S. Klasky, J. Menard, H. Park, H.R. Strauss, and L.E. Sugiyama
"Nonlinear Plasma Simulation Studies using M3D"

P3-22 J.A. Carlsson , D.C. Barnes, J.R. Cary, and N. Xiang
"On the fully implicit field solver in the Particle-In-Cell code VORPAL"

P3-23 Y. Nishimura , Z. Lin, L. Chen, J. Lewandowski, W. Wang, M. Adams, S. Ethier, and S. Klasky
"Alfven wave dynamics in gyrokinetic particle simulations"

P3-24 E.V. Belova , R.C. Davidson, H. Ji, and M. Yamada
"Numerical study of the conducting shell and NBI stabilization of the MHD modes in the FRC"

P3-25 J. D. Callen
"Key Physics Involved In Paleoclassical Transport Model"

P3-26 X.Q. Xu , M. R. Dorr, J. A. Hittinger, G. D. Kerbel, W.M. Nevins, Z. Xiong, B.I. Cohen, and R.H. Cohen
"Status of Continuum Edge Gyrokinetic Code Physics Development"

P3-27 Z. Xiong , J. A. Hittinger, M. R. Dorr, W.M. Nevins, and X.Q. Xu
"Towards an Efficient Field Solve for Edge-Plasma Simulations"

P3-28 T. D. Polo , and K. C. Shaing
"Time Dependent Plasma Viscosity and Poloidal Flow Damping with Orbit Squeezing in Tokamaks"

P3-29 W.M. Nevins , D. Dimits, and G. Hammett
"Discrete Particle Noise in PIC Simulations of Plasma Microturbulence"

P3-30 J.W. James , E.D. Held, and S.E. Kruger
"Calculation of Parallel Heat Flow in Chaotic Magnetic Fields"

P3-31 J.C. Kniep , J.N.G. Leboeuf, and V. K. Decyk
"Gyrokinetic Particle in Cell Calculations of Ion Temperature Gradient Turbulence with Strong Flow and Parallel Nonlinearity Corrections"

P3-32 S. Ku , S. Koh, C. S. Chang, and R. J. Goldston
"Non- Maxwellian ion distribution function in the steep gradient region of tokamak plasma edge"

P3-33 D. R. Ernst , K. Zeller, and W. Dorland
"Nonlinear Upshift of the Critical Density Gradient for TEM Turbulence and the Role of Collisions"

P3-34 W.X. Wang , S. Ethier, T.S. Hahm, W.W. Lee, J.L.V. Lewandowski, Z. Lin, J. Manickam, G. Rewoldt, and W.M. Tang
"Ion Temperature Gradient Turbulence in Shaped Plasmas"

P3-35 V. K. Decyk , J.N. Leboeuf, A. Dimits, and D. Shumaker
"Gyrokinetic PIC Study of Shaping Effects on ITG Turbulence"

P3-36 A.G. Tarditi
" Field Reversed Configuration for Direct Fusion Propulsion "

P3-37 J. Kesner , D.T. Garnier, A.K. Hansen, and M.E. Mauel
"Hot Electron Instability in a Dipole Confined Plasma"

P3-38 A.M. Dimits , W.M. Nevins, and D.E. Shumaker
"Gyrokinetic Simulations of ITG and ETG Turbulence"

P3-39 H.E. St. John , M. Murakami, and L.L. Lao
"Computational Aspects of Modeling ITER AT Time Dependent and Time Independent Configurations"

P3-40 R.A. Moyer , T.E. Evans, M.J. Schaffer, A. Runov, R. Schneider, S. Kasilov, P.B. Snyder, S.E. Kruger, and D.P. Brennan
"Modeling Plasma Effects of Edge Resonant Magnetic Perturbations on Divertor Tokamaks"

P3-41 L.A. Zepeda- Ruiz , J. Marian, G. Gilmer, C. Mundy, E. Bringa, and T.D. Rognlien
"Simulations of carbon sputtering and plasma- sheath chemistry interactions at fusion reactor divertor plates "

P3-42 J.J. Ramos
"The general expression of the gyroviscous force"

P3- 43 L.L. LoDestro , T.D. Rognlien, M.V. Umansky, and X.Q. Xu
"Coupled BOUT/UEDGE study of edge- plasma turbulence on the transport timescale"

P3- 44 F. Bombarda , and B. Coppi and Ignitor Project Group
"Recent Advances in the Ignitor Program"

Abstracts

Monday, April 11

Oral Session *O1*

at 8:30 am

Oral Session *O2*

at 1:30 pm

Photonic Band Gap Materials: Engineering the Fundamental Properties of Light

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Abstract

Photonic Band Gap (PBG) materials are artificial, periodic, dielectrics that enable engineering of the most fundamental properties of electromagnetic waves. These properties include the laws of refraction, diffraction, and spontaneous emission of light. Unlike traditional semiconductors that rely on the propagation of electrons through an atomic lattice, PBG materials execute their novel functions through selective trapping or "localization of light" using engineered defects within the dielectric lattice. This is of great practical importance for all-optical communications and information processing. Three dimensional (3D) PBG materials offer a unique opportunity for simultaneously (i) synthesizing micron-scale 3D optical circuits that do not suffer from diffractive losses and (ii) engineering the electromagnetic vacuum density of states in this 3D optical micro-chip. This combined capability opens a new frontier in integrated optics as well as the basic science of radiation-matter interactions.

We review recent approaches to micro-fabrication of photonic crystals with a large 3D PBG centered near 1.5 microns. These include direct laser-writing techniques and holographic lithography. We demonstrate a nearly universal approach to ultra-dense, three-dimensional, integrated optics in general 3D PBG architectures. These 3D optical circuit paths are constructed using broadband, loss-less, chip-to-chip interconnects between 2D micro-chip layers, intercalated within the 3D PBG host material. Unlike electronic micro-circuitry, each air-wave-guide path can simultaneously conduct hundreds of wavelength channels of information, throughout the 3D micro-chip. Unlike traditional wave-guides that confine light in a high refractive index medium using total internal reflection, these air-wave-guides operate using the principle of light localization for confinement of light along a low refractive index path.

In addition to exhibiting diffraction-less flow of light through micron-scale bends, this optical micro-chip allows the engineering of very large and abrupt changes in the local electromagnetic density of states as a function of frequency. This leads to unprecedented frequency selective control of spontaneous emission, modification of the blackbody radiation spectrum, and some fundamentally new optical functions unattainable in conventional photonics.

Natural velocity of magnetic islands

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Magnetic islands are observed to affect the performance of stellarators, reversed-field pinches, and tokamaks. It is important to understand the factors that determine their size. A key agent in the evolution of magnetic islands is the polarization current. This current is caused by the distortion of the plasma flows under the influence of the magnetic island. Its effect depends on the difference between the velocity of the island and the velocity of the surrounding plasma, that is, on the phase velocity of the island. Interest in the possible stabilizing effect of the polarization current has been fueled by concerns regarding the effect of neoclassical tearing modes on burning plasma experiments.

An important consideration in determining the phase velocity is the degree of density flattening across the island. If a density gradient is maintained inside the separatrix, the electrons experience a diamagnetic drift and the "frozen-in" property requires that the island's phase velocity match the electron drift velocity. We will show that if, by contrast, the density is flattened inside the island, the dominance of the ion viscosity compared to the electron viscosity causes the island to propagate at a velocity close to that of the ions.[1] Scott *et al.* have shown that the density is flattened by sound waves when the amplitude of the mode is such that the sound frequency exceeds the diamagnetic drift frequency.[2]

Recently, Ottaviani *et al.* have questioned the role of sound waves in density flattening, proposing instead that collisional parallel transport is the dominant mechanism for flattening.[3] In this talk, we restrict attention to the regime where the island width $W \ll \rho_s L_s/L_n$, so that acoustic effects are unimportant, but we retain the parallel transport effects pointed out in reference [3]. Here ρ_s is the ion Larmor radius calculated with the electron temperature and L_s, L_n are the magnetic shear and density scale lengths. We solve numerically and analytically the system of coupled equilibrium and transport equations derived previously by Connor *et al.*,[4] and use the results to determine the phase velocity and the effect of the polarization current.

Two solution branches arise, corresponding to islands propagating with the ions and with the electrons. For the ion branch the polarization current is stabilizing.[1] For the electron branch, the phase-velocity depends on the ratio W/ρ_s. For $\rho_s \ll W \ll \rho_s L_s/L_n$ the Reynolds stress causes the phase-velocity to exceed the electron drift velocity and the polarization current is destabilizing. For $W \ll \rho_s$, the situation is reversed provided that the density and temperature gradients point in the same direction.

Acknowledgements This work was funded by the U.S. Department of Energy Contract No. DE-FG03-96ER-54346 and DE-FC02-04ER54785.

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Gyrokinetic Simulations of Ion and Impurity Transport*

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J. Candy and R.E. Waltz

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Abstract

We present a systematic study of turbulent particle and energy transport, for both pure and impure plasmas, using a computational approach. Two codes were used for our studies: the reduced gyrofluid transport model GLF23, [1] and the Eulerian gyrokinetic code GYRO.[2] All the results presented come from electrostatic nonlinear flux-tube simulations in toroidal geometry, with trapped and passing particles, kinetic electrons and an evolution equation for each ion species. The methodology employed for this research was to initially find interesting qualitative characteristics of the transport using GLF23, and subsequently analyze them in more detail using the quantitative realism of GYRO.

For pure plasmas we looked at the effect of temperature gradients and electron collisions, finding that the former plays the dominant role in pinch formation (flow against density gradients), while the later generally opposes it. In multicomponent plasmas, the effects of impurity density gradients and dilution were considered. For moderate values of the helium density gradient, a helium pinch can be created. We also found that the simple $D - v$ (diffusion versus convective velocity) model[3] of impurity flow is consistent with results obtained from the simulations. Further, we found that the direction of the density gradient introduces substantial qualitative and quantitative changes to the plasma – for example, a plasma with impurities peaked in the core has better energy confinement than a plasma with impurities peaked at the edge. Finally, we examined the validity of different approximations to transport in multiple-species plasmas; specifically, the *dilution model*. For GYRO simulations of deuterium plasmas with helium impurities, it was found that it is best to approximate such a plasma with the simplest alternative – a pure plasma. However, for GLF23 we found that the model is a good approximation. The final study considers the flow of reactor-relevant D-T plasmas. Contrary to what is normally assumed, the turbulent flows of deuterium and tritium are not equal but show an asymmetry. Starting from an optimal 50-50 mixture, the asymmetry favors the build-up of tritium in the core. A quasilinear model shows that this asymmetry is caused by FLR effects. However, a small steepening of the tritium profile can restore equal flows of D and T so fuel separation is not expected to be a problem.

*Work supported by the U.S. Department of Energy under Grant Nos. DE-FG03-95ER54309 and the SciDAC Plasma Microturbulence Project.

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Intermittent transport and scaling of the scrape-off-layer width in tokamaks

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

Non-diffusive nature of transport in the scrape-off layer (SOL) of tokamaks is now widely recognized[1]. The characteristic density scale-length λ_n, expected to be only a few gyroradii-wide based on purely diffusive processes, is observed to be much longer ($\lambda_n \sim 10^2\rho_s$), with relatively flat profiles extending into the far SOL[2]. Consistent with this profile-data are the wide-spread observations of intermittent, convective transport in the SOL[3], involving coherent structures generally referred to as "blobs" or "fronts," for which a clear theoretical explanation has emerged only recently in the works of Krasheninnikov[4] and co-workers.

In the first part of this two-part work, we re-examine the long-time dynamics of blobs. Since they resemble shock-wave solutions of the Burger's equation, we find that a balance between convection and dissipation plays a crucial role in the long-term survival of dipolar blobs (those with a dipole potential field); they are unstable in the absence of dissipative effects. We also observe (still within a commonly used two-field model) spontaneusly-generated coherent structures with a predominantly mono-polar potential field; for these, dissipation's role seems to be confined to controlling their decay rate.

In the second part, assuming that the convective transport is driven by the SOL interchange/ballooning modes, we derive an expression for the mean density profile $\overline{n}(x)$ and find it in good agreement with the results of extensive nonlinear calculations. We also show that there is no simple scaling law, $\lambda_n \sim R^\nu$, with a constant ν, for the density scale-length $\lambda_n \equiv -\overline{n}/(d\overline{n}/dx)$ in terms of the machine size R. In the limit where perpendicular diffusion dominates (for blobs or fronts of typical size) over parallel losses along the open field lines, the coefficient ν is always less than 1/2; as the connection length $L \equiv qR \to \infty$ at fixed D (particle diffusivity), we have $\nu \to 0$. The major tokamaks operating today tend to fall in this limit, thus providing a possible explanation for the observations of nearly flat profiles. In the opposite and physically uninteresting limit where the parallel losses dominate, we find $\nu \simeq 1/2$. In both these limits, however, λ_n is typically much longer than a simple diffusion scale-length. For comparison, we note that an analysis based on ballistically propagating blobs with a power-law distribution of sizes[5] leads to $\lambda_n \sim R^{1/3}$, whereas a more recent work[6], under our assumptions, predicts the scaling $\lambda_n \sim R^{1/8}$.

A wide range of numerical results illuminating these points will be presented.

[1]See, for example, J. A. Boedo *et al.*, Phys. Plasmas **8**, 4826 (2001), and J. L. Terry *et al.*, Phys. Plasmas **10**, 1739 (2003), and the references therein.

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Gyrokinetic δf simulation of the collisionless and semicollisional tearing mode instability

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University of Colorado, Boulder, CO 80309

The evolution of collisionless and semi-collisional tearing mode instabilities is studied[1] using a three-dimensional particle-in-cell simulation model that utilizes the δf-method and a novel algorithm[2] to accurately solve the Ampere's equation for experimentally relevant β values, $\beta m_i/m_e \gg 1$. We use the model of drift-kinetic electrons and gyrokinetic ions. Linear simulation results are benchmarked with eigenmode analysis for the case of fixed ions. The nonlinear dynamics of magnetic islands is studied and the results compared with previous theoretical studies[3] on the saturation level and the electron bounce frequency. A collision operator is included in the electron drift kinetic equation to study the simulation in the semi-collisional regime. The algebraical growth stage has been observed and compared quantitatively with theory. Nonlinear saturation of the island is observed at a level below predicted by recent MHD theories[4]. Island saturation level depends on collisionality at low collisionality, and becomes independent of collisionality, consistent with MHD[4], at higher collisionality. If the width of the equilibrium current is small we confirmed the approximations made by previous theories that the ions motion can be neglected, but for the case that the width of the equilibrium current is large, we observed an odd parity instability with gyrokinetic ion simulation. This instability is believed to be related to the ion dynamics within the inner region.

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Equation free projective integration: A novel scheme for modeling multiscale processes in plasmas

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Abstract

We examine a novel simulation scheme called "equation free projective integration"[1] which has the potential to allow global simulations which still include microscale physics, a necessary ingredient in order to model multiscale problems. Such codes could be used to examine the global effects of reconnection and turbulence in tokamaks, the Earth's magnetosphere, and the solar corona. Using this method to simulate the propagation and steepening of a 1D ion acoustic wave, we have already achieved excellent agreement between full particle codes and equation free with a factor of 20 speed-up. In still larger systems with multiple dimensions, the speed-up should be many times larger. In this method of simulation, the global plasma variables stepped forward in time are not time-integrated directly using dynamical differential equations, hence the name "equation free." Instead, these variables are represented on a microgrid using a kinetic simulation. This microsimulation is integrated forward long enough to determine the time derivatives of the global plasma variables, which are then used to integrate forward the global variables with much larger timesteps. Results will be presented of the successful application of equation free to 1-D ion acoustic wave steepening with a PIC code serving as the underlying kinetic model. Initial results of this technique applied to reconnection will also be discussed.

[1] I. G. Kevrekidis et. al., “Equation-free multiscale computation: Enabling microscopic simulators to perform system-level tasks,” arXiv:physics/0209043.

Abstracts

Tuesday, April 12

Oral Session *O3*

at 8:30 am

Oral Session *O4*

at 10:30 am

Scrape-off layer flows, magnetic topology, and the flow boundary conditions imposed at the separatrix in a tokamak plasma

B. LaBombard, M. Greenwald, A.E. Hubbard, J.W. Hughes,
J.H. Irby, Y. Lin, B. Lipschultz, E.S. Marmar, J.E. Rice, N. Smick, J.L. Terry,
S.M. Wolfe, S.J. Wukitch and the Alcator C-Mod Team

M.I.T. Plasma Science and Fusion Center, Cambridge, MA, USA

Plasma flow along magnetic field lines with velocities approaching a fraction of the local sound speed has been seen in the scrape-off layers (SOL) of many tokamaks [1]. While near-sonic flows are expected close to material surfaces, these flows are detected far from any surface. They are recognized as potentially important, affecting the impurity compression of the divertor, the transport of impurities into the confined plasma, and perhaps the balance of material erosion and redeposition between divertor legs, all of which can impact future reactors such as ITER. Experiments aimed at sorting out the underlying drive mechanisms on Alcator C-Mod have uncovered an unexpected and remarkable interplay among various phenomena: anomalous cross-field transport, strong plasma flow along magnetic field lines, magnetic X-point topology and edge plasma toroidal rotation. Ballooning-like cross-field transport appears to be a dominant flow drive mechanism. Plasma streams along magnetic field lines from low- to high-field regions in response to poloidal pressure variations; these are maintained by poloidally asymmetric cross-field transport. The poloidal location of an X-point or limiter contact point determines the magnitude and direction of these *transport-driven* parallel flows - circulating the confined plasma in the co-current (counter-current) direction for lower (upper) X-point with $Bx\nabla B$ pointing down. This 'flow boundary condition' impacts the confined plasma, accounting for a corresponding positive (negative) increment in central plasma co-rotation. Experiments in ICRF-heated discharges further suggest that this boundary condition and its X-point dependence may explain the sensitivity of L-H power threshold to X-point location. In a set of otherwise similar discharges, the L-H transition is seen to be coincident with central rotation achieving roughly the same value, *independent* of X-point location. With $Bx\nabla B$ pointing away from the X-point (i.e., with the flow boundary condition *impeding* co-current rotation), the same characteristic rotation can be achieved only with *higher* auxiliary input power. Remarkably, L-H power thresholds in lower-limited discharges are identical to lower X-point discharges; SOL flows are also similar, suggesting a connection [2].

[1] See references in B. LaBombard, *et al.*, Nucl. Fusion **44** (2004) 1047.

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Particle Noise-Induced Diffusion and Its Effects on ETG Simulations

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# Lawrence Livermore National Laboratory, Livermore, CA

Abstract

Krommes' calculation of the noise spectrum of electrostatic fluctuations due to discrete gyrokinetic particles [1] is extended here to the case of ITG/ETG simulations with an adiabatic species, including the effects of finite-size particles and numerical filtering, and including a renormalized estimate of nonlinear effects on dielectric shielding. The resulting k spectrum is

$$S_{noise}(\vec{k}_\perp) = \sum_{k_z} \frac{w_{rms}^2 S_{filt}^2(\vec{k})\Gamma_0(k_\perp\rho)}{N_{tot}[2-\Gamma_0(k_\perp\rho)]\big[2-(1-S_{filt}(\vec{k}))\Gamma_0(k_\perp\rho)\big]}$$

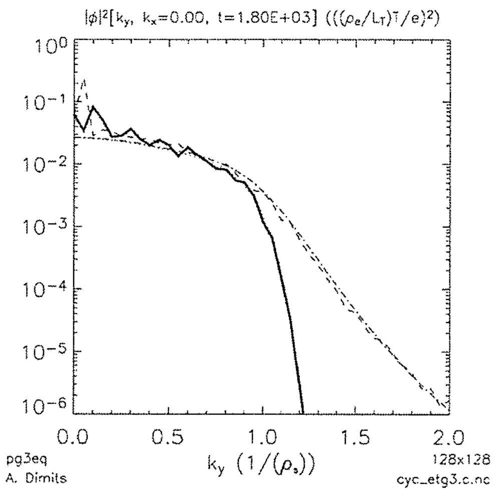

Figure 1. Comparison of expected noise spectrum (dotted & dash-dot) with PG3EQ PIC simulations, vs. k_y (solid) and vs. k_x (dashed), at late times in an ETG simulation when noise dominates. Note there are no free parameters in this comparison.

where w_{rms} is the rms particle weight, S_{filter} represents finite-size particles and filtering, and N_{tot} is the total number of particles (see Fig.1). Summing over all k gives an RMS noise $e\Phi_{noise}/T \sim w_{rms}/(nV_{smooth})^{1/2}$, where nV_{smooth} is the number of particles per effective smoothing volume. A renormalized calculation of the test-particle diffusion in this spectrum of fluctuations gives $D_{noise} \sim (cT/eB)^2\ w^2_{rms}/(nV_{smooth})\ (k_\perp{}^2_{max}/|k_{||max}v_t|)\ \log(1+ |k_{||max}v_t| /(D\ k_\perp{}^2_{max}))$. Because ETG eddies are very extended radially but still fairly narrow poloidally, it only takes a small amount of D_{noise} (relative to Jenko-Dorland's predictions of large ETG χ_e) to give $k_\perp^2 D_{noise} \sim \gamma_{linear}$, where the simulations become unreliable and turbulence can be suppressed. The RMS particle weight grows in time, as given by the Lee-Tang Entropy balance $dw^2_{rms}/dt = 2\chi/L_T^2$, Because ITG eddies are less elongated and give a lower value of normalized chi, noise is less of an issue for ITG simulations, and adequate convergence is obtained with fewer particles. A model is presented that explains how noise can enhance transport in ITG simulations, while reducing transport in ETG simulations. This model is compared with simulations. These results suggest that recent PIC simulations of ETG [4] are dominated by noise that suppresses the turbulence.

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[3] F. Jenko and W. Dorland, Phys. Rev. Lett. 89, 225001 (2002).
[4] Z. Lin, L. Chen, Y. Nishimura, et al. IAEA-CN/TH/8-4 (20th IAEA Fusion EnergyConf. 2005)

Rotation, error field, and wall thickness effects on resistive wall modes in ITER

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Abstract

The effects of rotation, error field, and finite wall thickness on resistive wall modes are important issues for ITER. Because ITER has subsonic rotation, one needs a high resolution numerical code near the singular layers to study the rotation effect. The AEGIS (Adaptive EiGenfunction Independent Solution) code is a newly developed linear adaptive shooting code [1] that fits this need. In the ideal MHD limit, AEGIS agrees with GATO in all respects, such as beta limit, growth rate, critical wall position, and detailed eigenmode profile. AEGIS can go beyond ideal MHD to investigate rotation and kinetic effects.

Our studies of the rotational effect [2] found that the shear Alfvén continuum damping can significantly stabilize resistive wall modes in ITER, as shown in Fig. 1.

Our studies of error fields and their rotational braking effect found that the torque is given by

$$\tau_\phi \propto (\delta W_e - \delta W_\infty)\delta W_R/(\delta W_\infty^2 + \delta W_R^2),$$

where δW_∞ is the no wall energy, δW_e is the energy with conducting wall at the location of the error field coil structure, and δW_R is the rotation induced imaginary part of the energy integral. Numerical results show that toroidal sideband coupling can make error-field amplification significantly different from the single mode estimate. We also found that a liquid metal wall can shield the error field.

Our studies of the wall thickness effect [3] found that the dependence of the resistive wall mode growth rate on the wall thickness does not follow the thin-wall estimate (Fig. 2). The part of the wall that is outside the critical conducting wall position does not contribute to stabilization.

Details will be presented.

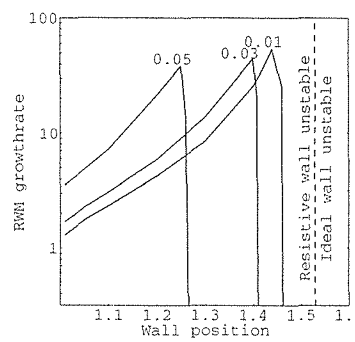

FIG. 1: The dependence of the RWM growthrate on the wall position for different rotation frequencies.

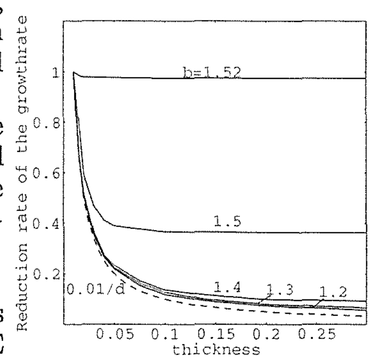

FIG. 2: Dependence of the RWM growth rate on the wall thickness for difftrent wall positions b. The dashed line is the scaling in the thin wall model.

Acknowledgment We are indebted to A. Turnbull for his help in benchmarking with GATO. Research supported by DOE grant DE-FG02-04ER54742.

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Nonlinear Dynamics of Energetic Particle-driven Fishbone Instability in Tokamak Plasmas*

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

The fishbone instability, discovered first in PDX tokamak in 1983[1], is an $(n, m) = (1, 1)$ internal kink mode driven unstable by energetic trapped particles via precessional resonance. In this work, we investigate the nonlinear dynamics of the fishbone instability. In particular, we focus on the precessional branch of the fishbone[2] where the mode frequency is determined by energetic particle's precessional frequency. In this case both fluid nonlinearity and kinetic nonlinearity are expected to be important since the mode is in resonance with both the shear Alfven continuum and the trapped particle's precessional drift frequency. Previous nonlinear studies of fishbone used reduced models including only kinetic nonlinearity[3] or fluid nonlinearity[4]. In contrast, our work includes *both* fluid and kinetic nonlinearity.

Global particle/MHD hybrid simulations of fishbone have been carried out using M3D code[5]. The code has previously been used to study nonlinear saturation of beam-driven TAEs in NSTX[6]. In the hybrid model, the bulk plasma is described by full MHD model while energetic ions are described by drift-kinetic particles. For moderate dissipation (viscosity), the fishbone mode exhibits a single radial layer at q=1 surface and the mode saturates mainly due kinetic nonlinearity via nonlinear wave-particle trapping. A strong chirping in mode frequency is found with a factor of two reduction in frequency. The fluid nonlinearity does not affect the nonlinear dynamics significantly in this case. On the other hand, for small dissipation, the fishbone mode exhibits double layer structure near the q=1 surface. The fluid nonlinearity is found to change the nonlinear dynamics qualitatively. The initial growth rate is enhanced by fluid nonlinearity while the saturation level is reduced significantly as compared to the cases with only kinetic nonlinearity. Details of the nonlinear simulation results will be discussed.

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[6] G.Y. Fu, J. Breslau, W. Park et al., 2004 IAEA Fusion Energy Conference.

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

prefer oral

Modelling nonperturbative frequency sweeping

R. G. L. Vann[1], R. O. Dendy[2,1], M. P. Gryaznevich[2], S. D. Pinches[3] and S. E. Sharapov[2]
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High frequency magnetohydrodynamic (MHD) activity in tokamak plasmas may be driven by energetic ion populations. The time evolution of this MHD behaviour, notably frequency sweeping, provides insights into the changing properties of both the energetic particle population and the ambient plasma. To extract this information, it is necessary to model the self-consistent nonlinear interaction of the energetic particles with the MHD modes, incorporating energetic particle resonance and background damping; this is done by applying a fully nonlinear self-consistent numerical implementation [2] of the Berk-Breizman augmentation of the Vlasov-Maxwell system (hereafter "VM(BB)"). Perturbative frequency sweeping observations [3,4] have already been successfully modelled using the VM(BB) system. In this paper we report new results on modelling nonperturbative frequency sweeping.

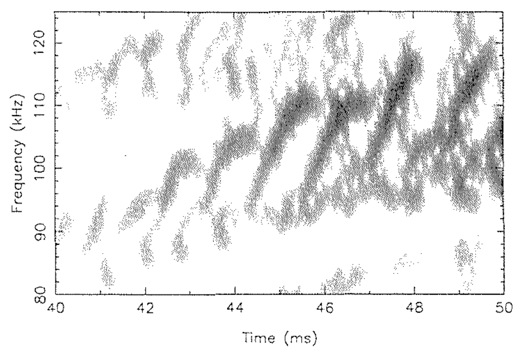

Figure 1: MAST shot 11005

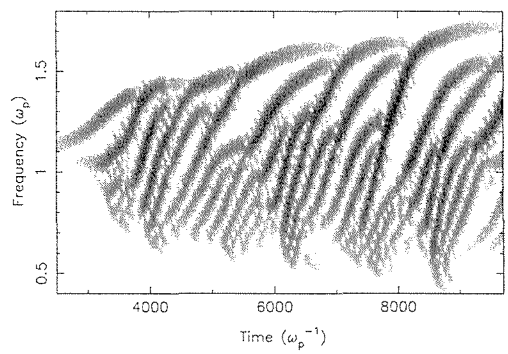

Figure 2: VM(BB) simulation

Plasma waves driven by energetic particles are said to be nonperturbative if their dispersion properties are modified significantly by the energetic particle population [1]. Figure 1 shows data from MAST that is believed to reflect this effect. In this paper we present for the first time self-consistent nonlinear modelling of nonperturbative frequency sweeping using VM(BB) (Fig. 2). In both Fig. 1 and Fig. 2 we note that: the sweeping rate is approximately constant until it begins to die; modes are born at different frequencies; the sweeping is predominantly in one direction only. The nonperturbative frequency sweeping shown in Fig. 2 occurs for fixed model parameters, suggesting that Fig. 1 need not imply evolving plasma properties. In this respect it resembles recent modelling [4] of perturbative frequency sweeping.

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This work was funded in part by Euratom and the UK EPSRC.

Nonlinear Evolution of Edge Localized Modes in Extended MHD*

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[4]SAIC, San Diego, California.

Abstract

A predictive understanding of edge localized modes (ELMs), including onset conditions and dynamic evolution, is crucial to present day tokamaks and next generation burning plasma experiments such as ITER. The study of the nonlinear evolution of ELMs using extended MHD codes has only recently begun. A new initiative was formed to study the dynamic evolution of ELMs with the 3D extended MHD code NIMROD. This paper summarizes recent results from this effort. The first objective is to understand the basic physics of the nonlinear ELM evolution in resistive MHD, and the dynamics of thermal energy transport in mode structures. For this study, a simple equilibrium configuration was constructed to be unstable only to a robust edge instability with parameters typical of DIII-D H-mode discharges. NIMROD linear results compare favorably to those from the linear ideal ELITE and GATO codes in both the mode structure and ballooning/pealing characteristics of these modes. Furthermore, the growth rates in NIMROD depend weakly on the resistivity and viscosity in the vicinity of the mode, with overstable resistive components to the modes evident at low n. The early nonlinear evolution of the edge mode shows an energy spectrum peaked at high and low n, with high n~20 modes having largest growth rates and the low n~1 modes being nonlinearly driven by nearest neighbor coupling of high n modes. The mode structure shows filaments of high temperature flowing outward. Thermal anisotropy and rotational shear weakly affect growth rates but significantly modify the mode structure. Separately, hyperviscosity has been applied to stabilize the high n modes and retain toroidal resolution. In these cases, low n modes remain unstable and eventually nonlinearly couple and drive high n modes unstable, despite the artificially applied stabilizing hyperviscous force. The stability boundary in (s,α) space is reached below the ideal boundary and nonlinear simulations from cases near this boundary in different regions differ somewhat in unstable spectrum and therefore mode structure. Challenges to the numerical simulation well into the late nonlinear phase are significant, with coupling always causing increased growth rates for groups of driven modes regardless of linear characteristics. Also, high k, fast moving structures are eventually inevitable for strongly unstable modes.

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

Abstracts

Wednesday, April 13

Oral Session *O5*

at 8:30 am

Oral Session *O6*

at 10:30 am

Unique MHD Properties of Spherical Torus Plasmas

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Abstract

The low-aspect-ratio "spherical torus/tokamak" (ST) is presently being investigated as a compact and high-β alternate concept while simultaneously contributing to the understanding of MHD physics across toroidal confinement systems. The largest present-day ST devices routinely create low collisionality plasmas with strong shaping, high β, and rapid toroidal rotation with a large population of super-Alfvénic fast-ions from unidirectional neutral beam (NB) heating. The ST configuration offers unique access to low internal inductance $l_i \geq 0.5$, high elongation $\kappa \leq 2.7$, toroidal $\beta \leq 40\%$, central β values of order unity, near sonic toroidal flow speeds up to 50% of the Alfvén speed, and large flow shear and diamagnetic frequencies comparable to typical ideal mode growth rates. Further, centrifugal forces from rapid rotation modify the equilibrium force balance and can decouple the plasma density and pressure iso-surfaces from magnetic flux surfaces. These unique plasma properties affect the entire spectrum of MHD modes normally encountered in tokamak plasmas. For internal kink modes, strong flow-shear combined with enhanced diamagnetic stabilization effects from high β may slow the growth of the 1/1 internal kink potentially leading to mode saturation instead of cyclic sawtooth activity. In NSTX, pressure-driven external kink growth is suppressed by close-fitting passive conductors. The residual Resistive Wall Mode (RWM) instability can be stabilized by plasma rotation and dissipation allowing sustained operation above the no-wall limit. The high edge-q of the ST enhances the toroidal inertia, and the high ratio of v_{sound} to $v_{Alfvén}$ provides a unique opportunity to understand the q and aspect ratio scaling of the RWM critical rotation frequency. Present ST plasmas operate at lower magnetic Lundquist number S than similarly-sized tokamaks potentially destabilizing the resistive-plasma RWM. Edge Localized Mode (ELM) stability is enhanced by the strong intrinsic shaping of the ST and strong sheared-rotation. Recent ELM stability analysis on MAST indicates that between ELM crashes, sheared rotation increases the marginally stable edge pressure gradient and current density, and the modes can flatten the rotational shear leading to very rapid growth and triggering of the ELM crash. For neoclassical tearing modes, theory and experiment indicate that stabilizing curvature effects enhanced by high-β and low-A become comparable to the destabilizing bootstrap drive possibly reducing the overall drive and size of NTMs in ST plasmas. However, enhanced toroidal coupling and larger q=1 radius lead to NTM triggering at lower β values when sawteeth are present. For energetic particle modes, present ST experiments operate with typical beam injection velocities $v_{fast} = 2\text{-}4 \times v_A$. In contrast to conventional aspect ratio, the NBI ions can therefore satisfy a Doppler-shifted resonance with Global Alfvén Eigenmodes (GAE) at the 1st cyclotron harmonic resulting in high predicted growth rates up to 1% of Ω_{ci} and exceeding growth-rates predicted for TAE modes. Compressional Alfvén Eigenmodes (CAEs), TAEs, and "bounce" and "precession" fish-bone modes are also commonly observed in ST plasmas, and the magnitude of fast-ion diffusion and/or loss resulting from *AE activity is presently being investigated. Finally, plasma formation without a central solenoid is a challenging yet essential technical requirement for future large ST devices. Plasma currents exceeding 300kA have been generated with merging compression and coaxial helicity injection, and new techniques such as electron-beam injection and induction with external poloidal field coils are being studied both experimentally and through non-linear simulation.

*In collaboration with: E. Belova, R. Betti, R. Buttery, R. Fonck, E.D. Fredrickson, D.A. Gates, L. Guazzotto, C. Hegna, W. Heidbrink, T. Jarboe, R. Maingi, J. Manickam, S.S. Medley, M. Ono, Y. Ono, W. Park, R. Raman, S.A. Sabbagh, S. Saarelma, P.B. Snyder, A. Sontag, H. Strauss, D. Stutman, A. Sykes, Y. Takase, X. Tang, K. Tritz, H.R. Wilson, W. Zhu. This work supported by the US DoE, UK EPSRC, and EURATOM.

Self-organized temperature redistribution of m=1 mode (sawtooth) oscillation on TEXTOR*

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[#] *Partners in the Trilateral Euregio Cluster*

Abstract

A novel 2-D Electron Cyclotron Emission Imaging (ECEI) system [1] for measuring electron temperature fluctuations has been applied to study the physics of the sawtooth oscillation in TEXTOR. 2-D images with high spatial resolution [128 pixels covering 8 cm (radial) x 16 cm (vertical)], and high temporal resolution (up to ~5 microsec) have revealed the details of 2-D images of the electron temperature fluctuations during the precursor phase and the crash time of m=1 (sawtooth) oscillations, with a level of detail that is not accessible through conventional methods (1-D ECE and/or tomography). It appears that the crash is global in toroidal extent, but localized in the poloidal plane. A new paradigm for the m=1 oscillation has been developed based on the evolution of the 2-D electron temperature image with the accumulated knowledge from previous experimental results [2] on TEXTOR such as the "current sheet" and "current profile". Heat from the m=1 mode can be transported to the region outside the inversion radius through the magnetic reconnection along the magnetic pitch of the q=1 surface. The reconnection is due to the combination of the local magnetic shear and the local magnetic field from the current carrying m/n=1/1 layer outside the inversion radius. This process is similar to the magnetic reconnection process of the two layers of magnetic surfaces that have same direction.

*This work is supported by the US DOE contract Nos. DE-AC02-76-CH0-3073, DE-FG03-95ER-54295 and W-7405-ENG-48 and NOW and EURATOM.

[1] H. Park et al., Rev. Sci. Instrum. 75, 3787, 2004

[2] H. Soltwisch et al., Plasma Phys. & Control. Fusion 37, 667 (1995)

Gyrokinetic simulations of Z-pinch

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Abstract

In this work we present nonlinear gyrokinetic simulations of small-scale turbulence in a Z-pinch magnetic geometry, performed using the GS2 code. We explore the dynamics of the turbulent transport as a function of various parameters in the system, including the plasma β, the collisionality, and the strength of the plasma gradients.

In good agreement analytic calculations, at sufficiently steep gradients we observe an ideal interchange instability with $\gamma \sim \gamma_I = C_s(rL)^{-1/2}$ (C_s being the sound speed, r the curvature radius and L an equilibrium plasma-gradient scale length). At weaker gradients somewhat below the ideal threshold, we also observe the so-called entropy mode, which has $\gamma \sim (k_\perp \rho_i)\ \gamma_I$, where $k_\perp$ is the wavenumber perpendicular to the equilibrium magnetic field and ρ_i is the ion Larmor radius. This mode has peak growth rates at $k_\perp \rho_i \sim 1$, where $\gamma \sim \gamma_I$, , and arises from higher-order FLR terms that are normally absent, for example, in a two-fluid treatment. The particle transport driven by this mode varies dramatically depending on the proximity of the system to the ideal interchange stability boundary. Early in the simulation, the break-up of the linear modes by the Kelvin-Helmholtz instability generates a strong burst of **ExB** flows directed along the symmetry axis (i.e., the z direction in cylindrical coordinates) with $k_\perp \rho_i \sim 0.5$. Within about a factor of two from the ideal threshold, these zonal flows are observed to be strongly unstable and quickly break-up, leading to large transport with $D \sim \gamma_I \rho_i^2$. For only moderately weaker gradients, however, that at the level of linear theory appear comparable, the transport can be an order of magnitude smaller or more. The zonal flows in this case are much more stable and can persist for long periods (hundreds or thousands of ideal growth times, depending on the level of collisionality). The physics of this zonal-flow decay process and its impact on the transport will be discussed.

On the possibility of the sheath-driven, finite-beta modes localized near the divertor plate

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Abstract

It is shown that, in a finite beta plasma, there may exist sheath driven modes whose amplitude decreases exponentially with the distance from the divertor plate. The modes are sensitive to the radial tilt of the divertor plate. The short-wavelength branch of the instability, with the cross-field wavelength $\lambda/2\pi$ of order of a few ion gyroradii, is present in the case of a "positive" tilt of the divertor plate, whereas the long-wavelength branch, with $\lambda/2\pi$ of order of 10 or more gyroradii is unstable for the opposite sign of the tilt. The parallel e-folding length becomes less than the distance from the plate to the X point (thereby making the mode insensitive to the processes near the X-point and the upper scrape-off layer) at plasma betas exceeding $(2\text{-}3)\cdot 10^{-4}$. A detailed analysis of the dispersion relations is provided. The signatures of the instability that can be used for its identification are discussed: i) phase velocity and wave-numbers of the most unstable modes; ii) correlations between fluctuations of various parameters; and iii) the differences between fluctuations in the common and private flux regions. Plasma transport in the divertor legs can be enhanced.by this instability, thereby reducing the heat load on the divertor plate, without having any appreciable negative effect on core plasma confinement. Optimization of the radial tilt in order to maximize radial transport in divertor legs.is carried out. It is also pointed out that an analog of these modes may exist in linear plasma devices with shaped end electrodes. This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Time and space dependent parallel viscous force*

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Fluid moment equations describing the macroscopic behavior of magnetized plasmas require kinetic-based closures for the viscous forces. In particular, the parallel component of the force balance is crucial for the analysis of the macroscopic dynamics of toroidal plasmas in the low collisionality regime. The damping force in this equation is the parallel viscous force, $\mathbf{B} \cdot \nabla \cdot \mathbf{\Pi}_{\|}$, for which a time and space dependent closure is required. Flux-surface averaged, frequency-dependent closures have been calculated in all collisionality regimes by various authors [1, 2].

In this work [3], a *time-dependent* closure is obtained using a Chapman-Enskog-like procedure in a drift-kinetic theory. Using a bumpy cylinder magnetic field model in the low collisionality regime ($\nu_* \ll 1$) we obtain a frequency-dependent closure for which the inverse Laplace transform does not have a simple analytical expression. Introducing this result in the parallel Ohm's law, we obtain corrections to the frequency-dependent electrical conductivity. Also, a parallel flow evolution equation is obtained from the total parallel force balance; it can be inverted to yield an integral equation in time. Expressions for the explicit time dependence of $\langle \mathbf{B} \cdot \nabla \cdot \mathbf{\Pi}_{\|} \rangle$ and of the flow evolution are calculated in a small field strength modulation ($\epsilon \equiv \Delta B/B \ll 1$) approximation.

In steady state, we show that the poloidally varying part of $\mathbf{B} \cdot \nabla \cdot \mathbf{\Pi}_{\|}$ exceeds the averaged closure by a factor of $1/\epsilon$ in a large aspect ratio expansion. To calculate this varying component, the first order drift-kinetic equation is integrated along field lines to calculate the lowest order even term in the distribution function. Unlike the collisional regime, $\Pi_{\|}$ is not simply sinusoidal but instead expressed in terms of incomplete elliptic functions. We suggest how time dependence can be introduced in the calculation by expanding the solution for the pitch-angle part of the distribution function in Cordey eigenfunctions.

As an application, we investigate the effect of the large poloidally varying parallel viscosity on shear flow evolution and turbulence. By extending a phase transition model developed by Diamond et. al. [4] for self-consistently calculating the relationship between fluctuation level, shear flow and Reynolds stress, we explore the implications of the anisotropic viscous damping of the poloidal flow on the L-H transition.

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

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

[2] See for example M. N. Rosenbluth, R. D. Hazeltine, and F. L. Hinton, Phys. Fluids **15**, 116 (1972) and C. T. Hsu, K. C. Shaing, and R. Gormley, Phys. Plasmas **1**, 132 (1994).

[3] A. L. Garcia-Perciante, J. D. Callen, K. C. Shaing and C. C. Hegna (submitted to Phys. Plasmas 2004).

[4] P. H. Diamond, Y. M. Liang, B. A. Carreras and P. W. Terry, Phys. Rev. Lett. **72**, 2565 (1994).

Abstracts

Monday, April 11

Poster Session *P1*

at 10:00 am

Perturbative approach to the nonlinear growth and saturation of the tearing mode for any current gradient, with an application to the forced reconnection problem

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Within the traditional framework of low-β, reduced MHD, a new systematic perturbation expansion provides the equation ruling the nonlinear growth and the saturation of a single helicity thin magnetic island, in slab or cylindrical geometry, in the Δ' regime characteristic of tearing modes. The relevant small expansion parameter is the width of the nonlinear boundary layer, which is proportional to the magnetic island width w. When the technique is applied to the generic case, characterized by an arbitrary current gradient on the rational surface, the final equation includes all the terms of order $w \ln(1/w)$ [1] and of order w [2-3], which have the same magnitude for practical purposes. Moreover, the evolution of the mean magnetic field is also given consistently with the island evolution and provides an accurate estimate of the change of magnetic flux occurring during the reconnection process.

The technique is also applied to the case where the island is subject to a static forcing provided by an external magnetic perturbation. The ensuing system of coupled evolution equations, for the island width and for the relative phase between the island and the perturbation, exhibits one or three fixed points, depending on the value of Δ' and on the strength of the external perturbation. Of these, only the fixed point having an island width larger than one obtained in the absence of forcing is stable. The island width of the stable fixed point exhibits three scaling regimes in terms of Δ' and of the forcing strength. For large negative Δ' the Hahm-Kulsrud scaling [4] is recovered.

We have also recovered the above results with an alternative, more direct, approach, in which the magnetic flux function is employed as an independent variable, which provides an independent check. Excellent agreement with available numerical data in the appropriate limit was also obtained.

Besides giving a systematic solution to long-standing problems, the new techniques appear amenable to application to more general problems involving rotating islands, as in the case of a plasma with sheared mass flow and/or diamagnetic effects, since they do not rely on the condition that certain fields, and in particular the current density, be flux functions.

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[2] D.F. Escande, M. Ottaviani, Phys. Lett. **A 323**, 278 (2004); F. Militello and F. Porcelli, Phys. Plasmas **11**, L13 (2004)

[3] R. J. Hastie, F. Militello, F. Porcelli, N. Arcis, D.F. Escande, and M. Ottaviani, paper PS/1-1, 20-th IAEA Fusion Energy Conference, Vilamoura, (2004).

[4] T. S. Hahm and R. M. Kulsrud, Phys. Fluids **28**, 2412 (1985)

Fusion Web Service and Fusion Simulation Markup Language

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Abstract

Simulations and experiments in the fusion and plasma physics community generate large datasets at remote sites. Visualization and analysis of these datasets are difficult because of the incompatibility among the various data formats adopted by simulation, experiments, and analysis tools, and the large sizes of analyzed data. Until now nuclear fusion has been using domain-specific solutions for distributed data storage, acquisition and analysis, not well suited for heterogeneous settings and modern data sizes.

Problems like these are what Grid technologies, [1] particularly Globus,[2] and Web Services are addressing. In the presented work we will compare performance, flexibility and ease of use of new technologies, including Globus, Web Services, CORBA and MDSplus, [3] as data transfer mechanisms for HDF5 and MDSplus data and describe the architecture and status of the Fusion Web Service - based on gSoap[4] - for accessing remote and heterogeneous fusion data. The service will be designed to use mechanisms appropriate for various networks configurations (like Internet, ESNet and LAN).

To facilitate data interchange and analysis tools interoperability we are also developing the Fusion Simulation Markup Language (FSML) based on the eXtensible Markup Language (XML).[5] When finished, this system will include metadata markups and schemas for describing semantically and structurally similar data coming from fusion and plasma simulations, and libraries for parsing FSML documents and accessing data from major data visualization and analysis tools. We will present the status of this work: a prototype XML schema based on data structures generated by two MHD codes: M3D[6] and NIMROD, [7] and a prototype API's for parsing files using this schema and reading data from C++ and AVS/Express.[8]

The work is supported by a DOE/SBIR grants DE-FG03-02ER83555 and DE-FG03-02ER84101.

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1 I. Foster, C. Kesselman, S. Tuecke, *The Anatomy of the Grid: Enabling Scalable Virtual Organizations*, International J. Supercomputer Applications, **15**(3), 2001.

2 http:://www.globus.org.

3 T. Fredian and J. Stillerman, *MDSplus Remote Collaboration Support* – Internet and the World Wide Web, Fusion Engineering and Design **43**, (1999).

4 http://www.cs.fsu.edu/~engelen/soap.html

5 http://www.w3.org/XML/.

6 http://w3.pppl.gov/~jchen/.

7 http://www.nimrodteam.org/.

8 http://www.avs.com/.

FarSight: Remote Visualization of Simulation Data

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Abstract

Visualization is increasingly important for understanding the large 3D data sets produced by high-performance computing. Hybrid PIC-fluid simulations, like VORPAL,[1] or large MHD codes, like Nimrod[2] and M3D,[3] can easily produce multiple gigabytes per slice. Transferring such files is often problematic in terms of data transfer speed (many institutions have just T1 or slower connections) and also in data storage and centralization (one would want all raw data to be in one secure storage location). Moreover, quite often locally unavailable hardware (i.e. a supercomputer) is required to visualization and data processing. In this situation, remote visualization is the only solution. On the other hand viewing and manipulating remote images over a Wide Area Network is typically very slow.

Our application *FarSight* addresses these needs. It allows for running remote simulations and data analysis and visualization applications, sharing the visualization results in a collaborative manner and rendering the visualization objects locally. In this paper we present the architecture of FarSight and discuss its status.

The latest thrust of the FarSight development was to provide the capability to bring 2D and 3D visualization objects obtained on a remote server using NIMROD and give a user the means to manipulate them locally. These objects can be brought on demand or automatically, as they get generated on a remote site in a "live" simulation. Since the sizes of the visualization objects are typically smaller then the generated data, FarSight efficiently solves the problem of getting remote simulation data and visualizing it. Instead of a scientist running multiple scripts for managing the remote visualization, FarSight provides a significant level of automation for the management of remote simulation data.

The work is supported by a DOE/SBIR grant DE-FG03-01ER83311.

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1 http://www-beams.colorado.edu/vorpal/.

2 http://www.nimrodteam.org/.

3 http://w3.pppl.gov/~jchen/.

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

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The treatment of electron dynamics in global, toroidal, gyrokinetic Particle-in-Cell (PIC) codes represents a major challenge. It was recently demonstrated, it is physically and computationally meaningful to follow dynamically only the nonadiabatic part of the electron response. This approach, however, requires the global solution of a Poisson-like equation for the so-called polarization field, $\chi \equiv \partial\Phi/\partial t$, where Φ is the electrostatic potential. In this talk, we will present well-benchmarked numerical simulations for one-dimensional drift waves using the splitting scheme; it will be shown that the splitting scheme yields more accurate growth rate (linear regime) and better conservation properties (nonlinear regime) than the standard δf scheme. The generalization of the splitting scheme to fully three-dimensional toroidal plasmas will be described. As it turns out, the overall viability of the scheme depends crucially on the efficiency of the solution of the Poisson-like equation for χ. To address this issue, a finite-difference based matrix A is generated and the inversion of $A\mathrm{x} = \mathrm{b}$ (where the number of unknowns is typically in the range of $N \in [10^5 - 10^7]$) is carried out using the PETSC[1] library routines. A complementary approach based on the finite element method can also be used to perform the inversion of A. An algebraic multigrid (AMG) solver from the hypre[2] library is used as a preconditioner for the matrix A. Preliminary results of ITG turbulence with trapped electrons will be reported.

* Work supported by US Department of Energy.

[1] http://wwww-unix.mcs.anl.gov/petsc/petsc-2
[2] http://www.llnl.gov/CAS/groups/casc-sag.html

Equilibrium of flowing "nearby fluids"*

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Abstract

The formalism for two-fluid (Hall MHD) equilibria has been developed elsewhere [1,2] and limited examples of equilibria have been computed. The formalism has been adapted to the special requirements of a nearly single-fluid equilibrium where the ratio of the ion skin depth to the plasma size is a small parameter ε. The system of partial differential equations is "stiff" and not amenable to computation in practical geometry without some means of "softening". An expansion procedure in ε leads to what is called "nearby-fluids equilibrium" because the characteristic ion and electron surfaces nearly concide. The expansion in ε removes the stiffness of the equations. The $O(1)$ flows follow field lines $u_\theta/u_z = B_\theta/B_z$ (cylindrical coordinates). Cross-field (diamagnetic) drifts appear in the $O(\varepsilon)$ correction. The elliptic-hyperbolic threshold for nearby-fluids is also explored, i.e. the point beyond which equilibrium solutions would lead to shocks and thus inescapable dissipation that would obviate an equilibrium. This threshold differs from the threshold for a full two-fluid treatment (ε not small).

An algorithm is constructed for computing the flowing equilibria of a two-dimensional "nearby-fluids" plasma. It employs the successive-overrelaxation technique applied to a partial differential equation that amounts to an "equilibrium-with-flow" extension of the Grad-Shafranov equation. The solution algorithm is coded in Visual Basic in an Excel-based platform for rapid computation on a PC.

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*Supported by US Department of Energy

Models for Predicting the Pedestal at the Edge of H-mode Tokamak Plasmas

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Predictive models are developed for the pedestal at the edge of type I ELMy H-mode plasmas. Theory motivated models are used for these pedestal width and pressure gradient, while the pedestal density is obtained from experimental data in this study. The pedestal pressure gradient is assumed to be limited by the ballooning mode instability, where the effect of second stability of ballooning mode is included. In addition, the effect of the bootstrap current, which reduces the magnetic shear in the steep pressure gradient region at the edge of the H-mode plasma, is included in the determination of the magnetic shear. The reduction of magnetic shear due to the bootstrap current can result in access to second stability of ballooning mode instability. The predictions of pedestal temperatures, pedestal width and pedestal gradient are compared with high resolution pedestal data for type I ELMy H-mode discharges obtained from the latest public version (version 3.2) in the International Tokamak Physics Activity Edge (ITPA) Pedestal Database.

Gyrokinetic Simulations of the Effects of $E \times B$ Shear, Safety Factor, and Magnetic Shear on Driftwave Transport*

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The effects of $E \times B$ velocity shear, safety factor, and magnetic shear are investigated in nonlinear gyrokinetic turbulence simulations using the GYRO code with and without kinetic electrons. GYRO is a physically comprehensive continuum global gyrokinetic code.[1,2] The stabilization of long wavelength driftwave turbulence by $E \times B$ rotational shear and magnetic shear have long been suggested as key mechanisms in the formation of core and edge transport barriers in tokamaks. Previous work has tended to focus on studying these effects on unstable ion temperature gradient (ITG) modes rotating in the ion direction. The results presented here examine the scaling of particle and heat transport with $E \times B$ shear, magnetic shear, and safety factor in ITG/TEM simulations and compare the results where the unstable modes are rotating primarily in the ion direction to results obtained where the modes are primarily in the electron direction.

The impact of $E \times B$ shear stabilization in electrostatic flux-tube simulations is well modeled by a simple quench rule with the turbulent diffusivity scaling like $(1-\gamma_E/\gamma_{max})$ where γ_E is the $E \times B$ shear rate and γ_{max} is maximum linear growth rate without $E \times B$ shear.[3] The quench rule was originally deduced from adiabatic electron ITG simulations. We find it also applies in the presence of kinetic electrons for long wavelength driven transport. In the absence of parallel velocity shear, we find that the quench point is robustly at γ_E/γ_{max} = 2±0.5 for both adiabatic and kinetic electron scans around several reference cases. This is twice the value previously found in gyrofluid ITG simulations. In kinetic electron simulations of peaked density cases, where the unstable modes are primarily in the electron direction, the $E \times B$ shear quench point occurs at somewhat higher values in the range of γ_E/γ_{max} = 2.1-2.5. While the quench point is amazingly robust, adiabatic simulations reveal that the quench point appears to minimize where γ_{max} maximizes with respect to magnetic shear.

We also present results of a systematic study of the effects of magnetic shear and safety factor on driftwave transport. For the standard case, the ratio of ion to electron heat transport is larger at moderately positive magnetic shear compared to reversed shear with the ion heat transport exhibiting a stronger safety factor scaling for positive shear. The particle transport changes from being negative (inward pinch) at positive shear to positive (outward) for negative shear. For the case with an MHD $\alpha = 1$, the magnetic shear dependence of the transport is significantly stronger going from weak to moderately positive shear compared to the results with $\alpha = 0$.

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Benchmarking of a New Fast Gyro-Landau Fluid Eigenmode Code for Linear Stability*

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Abstract

A new gyro-Landau fluid (GLF) system of equations has been developed in order to improve the accuracy of the linear drift-ballooning mode stability calculations. The GLF systems can be solved more quickly than initial value gyrokinetic codes and so are useful for quasilinear transport modeling. The new GLF system improves the treatment of trapped and passing particles in a unified set of equations using three moments for trapped particles and twelve for passing for each species. The ion equations can be reduced to six moments if trapping effects are neglected for the ions. A model for the loss of bounce averaging when the mode frequency exceeds the bounce frequency allows the equations to seamlessly include every drift-wave from the lowest frequency trapped ion modes to the high frequency electron temperature gradient modes. The fit of the GLF density response function to the kinetic response function has only 8% error over a wide range of frequency and trapped fraction. The GLF equations are solved as a linear eigenmode system using an expansion in Hermite basis functions for the coordinate along the magnetic field direction. The width of the Gaussian in the Hermite basis function is chosen to maximize the growthrate of a two-basis function solution. The eigenmode is then refined by adding more basis functions keeping the width fixed. A database of gyrokinetic initial value runs is used to benchmark the GLF code. The database is grouped into three cases: the STD case, which scans about plasma conditions typical of the L-mode or H-mode core, the NCS case, with plasma conditions similar to the internal transport barrier of a negative central shear discharge, and the PED case, with conditions similar to the steep gradient region of the H-mode edge. In all of these cases, the new GLF system has good accuracy even with a low resolution four-basis function solution. This new eigenmode solver has applications as a fast linear stability code for data analysis or as the heart of a quasilinear transport model.

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Heuristic Theory and Simulation of Nonlocal Transport *

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Abstract

The global gyrokinetic code GYRO [1] is used to simulate ion temperature gradient (ITG) turbulent transport with piecewise flat profiles to illustrate the breaking of gyroBohm scaling by a nonlocal mechanism. The nonlocal drainage of the turbulence from unstable regions and spreading into stable (or less unstable) regions breaks the gyroBohm scaling toward Bohm in unstable regions and toward super-gyroBohm in stable (or less unstable) regions [2,3]. A heuristic model for this nonlocal process is formulated in terms of a nonlocal growth rate resulting from a locally weighted radial average of the local linear ballooning mode growth rate. A nonlocality length L measured in ion gyroradii provides the exponential scale for the local weighting. The nonlocal growth rate will be incorporated into a local gyroBohm-scaled transport model (like GLF23 [4]) in place of the local growth rate. The resulting nonlocal transport model will provide some transport in locally stable regions. A heuristic theory of this nonlocal transport mechanism based on the partial formation of global modes in toroidal geometry is detailed. The theory argues that the nonlocality length L increases with gyroradius and decreases with the square root of the local linear growth rate. Comparisons to previous descriptions of turbulence spreading [5] are made.

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Effects of Magnetic Fluctuations and Plasma Shaping on Turbulence and Transport

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Abstract. GEM[1] is an explicit δf particle code that has fully kinetic electron dynamics and magnetic field perturbations. GEM operates both globally, with arbitrary flux-surface shapes and equilibrium profiles, and in the flux-tube geometry. Previous flux-tube simulation for a typical H-mode plasma using Cyclone Base Case parameters[2], shows a weak stabilizing effect of magnetic perturbation on Ion-Temperature-Gradient-Driven turbulence at low β ($\beta \leq 0.6\%$), but increasing transport as β increases, leading to unsaturated transport near the experimental value ($\beta > 1\%$). This difficulty is not resolved by including the equilibrium sheared flow at the experimental level. This difficulty is not seen in general geometry simulations, which tend to show a weaker finite β stabilization effect on the ITG modes and ion transport than flux-tube simulations. The effect of elongation and Shafranov shift, on the other hand, is readily observed. Both tend to shift the instability spectrum toward higher n modes, due to finite Larmor radius effect. The effect of magnetic perturbation on electron transport is observed to be important, due to magnetic fluttering. Saturation of the ITG modes is observed to follow the four-wave coupling scheme of Chen et. al.[3]. Zonal field (surface-averaged $A_{||}$) is also strongly generated. Further details will be reported.

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Plasma Compression in the Periodically Oscillating Plasma Sphere

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Abstract

Theoretical studies.[1,2] have suggested that a tiny oscillating ion cloud immersed in a uniform electron background may undergo a self-similar collapse that can result in the periodic and simultaneous attainment of ultra-high densities and temperatures. The oscillating ion cloud (referred to as the Periodically Oscillating Plasma Sp here or POPS) is in local thermodynamic equilibrium at all times independent of the collisionality of the plasma (i.e. these self-similar solutions are exact solutions of the Vlasov equation). POPS is stable to multidimensional perturbations, while its self-similar solutions appear to be attractors.[3] Theoretical projections have indicated that such a system may have net fusion gain even for an advanced fuel such as D-D. In addition, these systems have very favorable reactor attributes in that the total power scales inversely with the size, leading naturally to a modular, high mass power density device.

Recent experimental work has demonstrated the existence of the POPS resonance.[4] However, there are several issues that need to be resolved in order to determine the efficacy of this scheme. Perhaps the most important issue is the effect of space charge neutralization on the plasma compression. An analytic formalism has shown that it is possible to program the distribution function of the injected electrons to completely mitigate space charge effects during the ion cloud collapse. If this can be achieved, the required compression ratios for POPS can be drastically reduced. This also eliminates the requirement that the average electron dens ity must be much greater than the average ion density (i.e. POPS may now be possible in quasi-neutral plasmas). However, it is still likely that there will be an ultimate stability limit imposed by the two-stream instability.[5,6]

This new formalism is presently being incorporated into the 1-D particle simulation code.[6] Results will be presented..

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Ion Velocity Space Shell Instabilities*

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Fusion products in the form of Alpha particles in burning plasmas are born as mono-energetic isotropic shells in velocity space in a background of colder ions and electrons. Velocity space ion shell distributions have also been observed recently by the Cluster satellites in space at the plasma sheet boundary layer against a background of colder electrons and colder ions. The stability of velocity space shell distributions in magnetized plasmas has been studied for electrons [Sentman, et al., Phys. Fluids **29**, 2569 (1986); Phys. Fluids **30**, 1575 (1987)] for ions [Brecht et al., Phys Fluids **21**, 447 (1978); Janhunen et al., Ann. Geophys. **21**, 881 (2003)] and for fusion products [Mai and Horton, Phys. Fluids **18**, 356 (1975)]. The free energy of the shells destabilizes waves at harmonics of the cyclotron frequency, which in turn slow the shells down. Here, we report on particle-in-cell (PIC) simulations of velocity space ion shell distributions in a background of colder ions and electrons and a strong magnetic field as occurs in space and in magnetic fusion confinement devices. Such simulations are now possible with so-called guiding center PIC codes [Lee and Okuda, Journ. Comp. Phys. **26**, 139 (1978)] where electrons are described in the drift kinetic approximation but the full dynamics of the ions is treated. The parallel acceleration of the electrons is retained but their perpendicular dynamics is described to lowest order by the E x B drift. Time integration of the ion orbits is performed using the leapfrog scheme. The absence of perpendicular electron inertia complicates the integration of the electron orbits. Robust energy conservation is however achieved by a time centered, second order time accurate, combination of the leapfrog scheme for the parallel advance and of a mid-point trapezoidal predictor-corrector scheme for the perpendicular advance. In the electrostatic approximation of interest here, Poisson's equation is solved for the potential with the charge density obtained by accumulation from the particles' positions. This solution is carried out in Fourier space and the electric field is obtained from spatial finite differences of the potential. This combination insures numerical stability and reinforces energy conservation [Byers et al., Journ. Comp. Phys. **115**, 352 (1994)]. The guiding center PIC simulations have been performed for an ion shell energy to thermal cold ion energy ratio of 200 to 2000 and an ion shell energy to thermal electron energy ratio of 200. These were carried out for ion to electron mass ratios of 100 and 1600. Characteristic signatures of the simulations include loss of free energy of the ion shell accounted for by increases in wave energy, electron kinetic energy and kinetic energy of the cold ions. The most strongly excited waves are propagating perpendicular to the magnetic field and resonate at harmonics of the ion cyclotron frequency below the plasma frequency of the shell ions. Saturation of the electrostatic wave energy is accompanied by parallel electron heating and more importantly perpendicular heating of the cold ions. This perpendicular heating is due to a linear stochastic heating mechanism already identified in the case of electron shells [Sentman et al., Phys. Fluids **29**, 2569 (1986)]. Implications for Cluster observations in space and burning plasmas in magnetic fusion confinement devices will be discussed.

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IGNITOR: The Scientific Program

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Abstract

One of the main achievements in the design of the Ignitor machine is to have conceived a device capable of producing up to 11 MA of toroidal plasma currents with about 9 MA of poloidal current within relatively small dimensions ($R_0 \cong 1.32$ m, $a \times b \cong 0.47 \times 0.86$ m^2) and with reasonable safety factors against macroscopic plasma instabilities. If we consider that the only existing machine that can carry up to 3 MA is the JET device, which is considerably larger ($R_0 \cong 3$ m, $a \times b \cong 1.2 \times 1.44$ m^2), the operation of Ignitor will be in itself an important achievement, especially since none of the experiments carried out so far with D-T fuel were actually close to the conditions necessary for truly burning plasmas (i.e., $T_e \cong T_i$, $Z_{eff} \cong 1$, good α-particle confinement). Ignitor [1] has high magnetic field (B_T = 13 T), relatively low aspect ratio (R_0/a=2.8) and considerable plasma cross section elongation and triangularity (κ=1.83, δ=0.4). The main heating mechanism is Ohmic heating through the high plasma current, although an ICRH system is foreseen as auxiliary heating. Particle fuelling is provided through gas puffing and high speed pellet injection (H or D, possibly also T pellets). The experiment is the first as such that has been proposed and designed to achieve fusion ignition conditions in well confined deuterium-tritium plasmas. Demonstration of ignition, the study of the physics of the ignition process, and the heating and control methods for a magnetically confined burning plasma are the most pressing issues in present day research on nuclear fusion and they are specifically addressed by the Ignitor experiment. These goals need to be pursued as soon as the machine proves to be technically ready, and no major unexpected obstacles hinder the plasma performance.

On the way to reach its main goals, and after, Ignitor will produce intermediate results and explore plasma regimes that are not accessible to other existing or planned experiments, as well as provide much needed assessments for some of the most critical extrapolation involved in designing burning plasma experiments. High magnetic field experiments can overlap with the envisioned operational regimes of large-scale devices in terms of the relevant dimensionless plasma parameters but at the same time they can explore different paths in the approach to ignition and thus open the way for better types of fusion reactors. It is important to note that, while tritium is the necessary step forward of any new fusion facility of conventional concept, even with H, He, and D Ignitor will provide results that can justify, in themselves, the construction of the machine. For example, the unique feature of having an elongated cross section but no divertor, and a high Z first wall acting as an extended toroidal limiter can test an alternative, considerably simpler, solution for plasma facing components in a reactor. Perhaps even more important is the level of internal power density available in Ignitor. The experimental life of the Ignitor device will initially follow three stages, characterized mainly by different fuel gases: phase I in H and ^{4}He, phase II in D and phase III in D-T, where the use of T will allow to carry out the most ambitious part of the program. In this work we present an example of the variety of experiments and studies that can be carried out in each of the three phases.

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MHD simulations of disruption mitigation by high-pressure gas jet

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Abstract

During the present campaign, Alcator C-Mod will use a newly installed high-pressure gas-jet injection system to perform disruption mitigation studies. Similar experiments have already been performed on DIII-D[1], but the C-Mod experiments will test this mitigation strategy for plasmas having higher absolute pressure, thereby providing insight into its effectiveness for an ITER-like plasma. MHD simulations are performed to aid in understanding how the cold-front associated with the radiating impurities interacts with the equilibrium magnetic fields. Impurity radiation is not directly modeled. Instead, the temperature profile is perturbed as a function of time to produce an inward propagating cold-front. As the cold front passes various mode rational surfaces, instabilities are triggered. Eventually, a large stochastic region develops which expands ahead of the imposed cold front leading to rapid heat transport away from the core. Thus, the thermal quench does not require penetration of the neutral impurities to the core of the plasma. In addition to C-Mod simulations, one simulation of a DIII-D equilibrium is conducted and can be compared directly to results from the DIII-D studies.

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Low noise electromagnetic delta-f particle-in-cell simulation of electron Bernstein waves

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Abstract

In the PIC simulations of wave-particle interactions, one key problem is the noise of the particle-in-cell (PIC) method for a finite number of particles may obscure the physical process being modeled. For instance, in the PIC simulations of the electron Bernstein wave (EBW) implemented in VORPAL, a massive parallel, hybrid plasma modeling code, for the typical experimental parameters, the incident wave field is required to be larger than 10^6 v/m in order to obtain the distinct EBW field from the numerical noise even for 400 particles per cell. The corresponding incident power is about 5MW, which is larger than the typical experimental value. To overcome this difficulty, we implemented the delta-f method in VORPAL and found that much lower incident field (10^2 v/m) can be used in the delta-f simulations. The measured discrete spectrum agrees well with the linear dispersion relation for the EBW modes. The extraordinary waves excited in the plasma were found to be in good agreement with the linear theory. With increasing incident field, the nonlinear processes significantly affect wave propagation, mode-conversion, and electron heating.

The Neoclassical Radial Electric Field of a Collisional Tokamak

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Abstract

The neoclassical electric field in a tokamak is determined by the conservation of toroidal angular momentum. In the steady state in the absence of momentum sources and sinks, it is explicitly evaluated by the condition that radial flux of toroidal angular momentum vanish. Of course, for an isothermal plasma the viscosity must simplify to an expression that vanishes for a radial Maxwell-Boltzmann ion response. In the presence of ion temperature variation obtaining the electric field in terms of density and temperature gradients is far more complicated. For a collisional or Pfirsch-Schlüter short mean free path ordering in which the plasma flow is sub-sonic [1] we find that there are two limiting cases of interest [2]. The first is the simpler case of an extremely up-down asymmetric tokamak (for example, just inside the separatrix of a single null configuration) for which the lowest order gyroviscosity does not vanish and must be balanced by the leading order collisional viscosity in order to determine the radial electric field. The second case is the more complicated case of an up-down symmetric tokamak for which the gyroviscosity must be evaluated to higher order and balanced by the lowest order collisional viscosity to determine the radial electric field. For equal ion and electron temperatures our result agrees with the more recent large aspect ratio, concentric, circular flux surface expression found by Claassen and Gerhauser [1]. In general both contributions must be retained, and standard drift kinetics can not be used to obtain the results [4].

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Transport Studies in the Columbia Non-neutral Torus

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Abstract

The Columbia Non-neutral Torus (CNT)[1] is a newly operational stellarator using a simple, elegant coil set to generate very low-aspect ratio stellarator fields, for the purpose of confining non-neutral plasmas. We have initiated a study of the transport in this device, using numerical and analytic means. As indicated in earlier equilibrium studies and transport estimates[2,3], CNT plasmas should be in transport regimes rather different from those in conventional neutral plasmas:

-For "cold" nonneutral plasmas, the ambipolar potential Phi can be very large, $e\Phi/T >> 1$, so the ExB drift v_E dominates the grad-B drift v_B.

-For very cold plasmas, v_E can compete with the poloidal component of $v_{\|}$.

-For warmer plasmas, which have a more conventional value $e\Phi/T \sim 1$, Φ can vary appreciably on a flux surface ψ, so the radial component of v_E can compete with that from v_B.

-CNT lacks a strong separation of ripple and toroidal scale-lengths which fosters well-confined superbanana orbits in standard stellarator neoclassical theory. Nevertheless, electron superbananas in CNT are well confined in a pure electron plasma with a short Debye length, and the electron confinement is expected to be excellent under these conditions.

-Particles with much larger ρ/a than the electrons envisioned for CNT, such as ions or energetic electrons, have passing orbits displaying a "parallel stochastic mechanism" similar to that found[4,5] to exist in perturbed tokamaks. Of course, energy conservation limits the radial motion of ions with an energy that is low compared to the electric potential produced by the electrons.

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Triplication of Budden Resonance by a Sheared-Flow Layer

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Abstract

In order to stabilize or reduce turbulent transport in tokamaks, several groups have introduced a layer of toroidal or poloidal sheared flow. We examine the influence of such a layer on the process of linear wave resonance, also known as mode conversion. Because of the local Doppler shift caused by the flow, the dispersion relations of waves are modified, and a single Budden resonance may be replaced by a triple resonance. The occurrence of this resonance triplication depends on the layer's parameters: its location, maximum flow speed, and radial width. We study a standard one-dimensional slab model with cold-plasma response in the ion-gyrofrequency range, with the example of conversion of a magnetosonic wave to ion-hybrid waves. When triplication occurs, wave energy is converted at three locations instead of one. This possibility must be taken into account in designing conversion scenarios for heating or for current- or flow-drive.

Coalescence of Magnetic Islands in the High Lunquist Number, Hall MHD, Regime

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Abstarct

The coalescence of magnetic islands in the high Lunquist number, Hall MHD, regime is studied. Within the resistive MHD model the coalescence rate (reconnection rate) is known to be independent of Lunquist number over a range of Lunquist numbers. Biskamp [1] has shown that the coalescence rate will stall (sloshing) in the limit of high Lunquist number (S on the order of 10^5). This stalling has been associated with the onset of a secondary tearing mode [1]. We will demonstrate this stalling results from high magnetic pressure gradients, which result from thin current sheets. The high magnetic pressure shuts down the ion flow into the current sheet, which effectively limits the transport of fresh flux into the reconnection site. We then simulate the problem with a Hall MHD model. We demonstrate that when the current sheet scale length, δ_J, reaches "Hall MHD scales" (i.e. $\delta_J < d_i$, where d_i is the ion inertial length) prior to the onset of sloshing, sloshing will be avoided and island coalescence will proceed at a rate independent of Lunquist number. Note that d_i may be small for the intial conditions of the problem. Within the Hall MHD limit, electron flow can transport fresh flux into the reconnection site, and the electron flow is not sensitive to the build up of magnetic pressure in the current sheet.

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The Plasma Science and Innovation Center (PSI-Center)

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The Plasma Science and Innovation Center (PSI-Center) has recently formed and received funding. The principal goal of the PSI-Center is to achieve significantly improved predictive capability for smaller-scale devices. This will be accomplished through the refinement of existing computational tools by adding sufficient physics modeling, boundary conditions, and geometric capabilities to benchmark results against experimental data. The developments will emphasize the modeling needs of emerging concept (EC) experiments, but improved simulation capabilities for all innovative confinement concepts (ICC) are expected. A special emphasis will be placed on physics effects that may extend beyond the standard analysis applied to the mainline programs. The PSI-Center will initially concentrate on five focus areas that have been identified as being very important for various EC experiments. The key physics issues that have been identified are: 1) two fluid / Hall physics, 2) kinetic and FLR effects, 3) reconnection and relaxation physics, 4) transport, atomic physics and radiation, and 5) boundary conditions and geometry. All of these effects are also important in mainline fusion devices, but one or more tend to dominate in particular EC configurations. In some cases, important effects may result from high-frequency electron dynamics or kinetic effects that can not be calculated from first-principles in a practical manner during global simulations. Here, well benchmarked phenomenological modeling may be the best approach for some applications.

There are numerical simulation codes having some subset of these important features, but no existing code covers all of the special needs of innovative/emerging concepts. We plan to develop the needed features within existing codes to avoid the resource requirements and delays associated with developing completely new models. We will start with two codes: 1) NIMROD[1] which is a 3D code that is periodic in one dimension and employs finite elements in the other two dimensions; and 2) MH4D which employs a full 3D unstructured mesh.

While the entire EC community is invited to participate in this center, nine experimental programs will provide the initial database and test bed for the theoretical and computational efforts of the PSI-Center. These nine experiments are: 1) Caltech reconnection experiments, 2) FRX-L, 3) HIT-SI, 4) MBX, 5) PHD, 6) SSPX, 7) SSC, 8) TCS, and 9) ZAP. This set of experiments has many overlapping areas of physics that complement the PSI-Center's focus. Experimental data from dedicated run campaigns will be collected and compared to the numerical predictions generated by the computational tools developed by the Center.

We will discuss the physics issues that will be addressed by the center, and the methods that will be employed to study them.

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Nonlocal nonlinear electrostatic gyrofluid equations: a four-moment model

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Extending a previous single-temperature model[1], an electrostatic gyrofluid model that includes anisotropic temperatures ($T_{\|} \neq T_{\perp}$) and can treat general nonlinear situations is constructed. The model is based on a Lagrangian formulation of gyrofluid dynamics, which leads to an exact energy conservation law. Diamagnetic cancellations are inserted manually in such a way that energy conservation is preserved. Comparison with previous models[2] shows a very good agreement for zero-Larmor-radius terms in the gyrofluid equations of motion.

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IMPLEMENTATON OF ION GYRO-VISCOSITY IN THE NIMROD CODE

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We describe the implementation and validation of the ion gyro-viscous stress in the NIMROD extended MHD code. The ion gyro-viscosity is a non-dissipative finite Larmor radius (FLR) correction to the fluid plasma equations that is ignored as small in both the Hall and MHD parameter regimes. However, in the drift regime, which is relevant to modern tokamaks, it enters at the same order in the gyro-radius as other two-fluid effects, and therefore must be included in any two-fluid model of tokamak plasmas. In this regime, the velocity is often explicitly decomposed into $\mathbf{E} \times \mathbf{B}$ and diamagnetic drifts. In that case, and under certain restrictive conditions, the divergence of the gyro-viscous stress almost completely cancels the advection of the ion velocity by the diamagnetic drift (the so-called gyro-viscous cancellation), leading to a simplified set of equations. However, to attain a more widely applicable and less restrictive model, the equations can be written in terms of the total ion velocity, and the full gyro-viscous stress must be implemented. These new terms introduce dispersive waves that require special numerical treatment. These modes survive the gyro-viscous cancellation, and should be an issue even for numerical models that explicitly employ the drift ordered equations. Here we describe the implementation of the ion gyro-viscous stress in the NIMROD code, using high order finite elements. A semi-implicit time advance of the new dispersive terms removes the restrictive CFL time step limit, and allows the calculation to proceed on the MHD time scale. Details of the numerical algorithm and its validation are described, and initial results including the gyro-viscosity are given.

Global Invariants of Hydrodynamic Turbulence in the Pipe*

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Abstract

We apply new symbolic method [1] for the analyses of turbulent velocity fluctuations measured in water flow in a pipe [2]. The stationary flow of water occurs in a pipe 30cm diameter, 30m long and the flow recirculates. The flow Reynolds number is $R \approx 3 \cdot 10^5$ We compare turbulent velocity fluctuations measured simultaneously in the bulk of the water and near the wall of the pipe. There is practically no correlation between these two signals. These fluctuations look so different that one would assume that the nature of the turbulence at the wall and in the bulk of fluid is different.

On the other hand according to Lorenz-Ruelle-Takens theory [3,4] applied to this experiment the same chaotic attractor is driving fluctuations in the bulk of the water and near the walls of the pipe. The reason why fluctuations in the bulk of the water looks so different from fluctuations near the wall of the pipe is because the chaotic attractor is, figuratively speaking, is dressed very differently due to the boundary conditions at the pipe wall. Thus if we extract from the fluctuation data invariant characteristics they should be global invariants of turbulence.

We extract from fluctuation data cycles and their invariant properties using methods of symbolic dynamics [1]. We have found out that majority of the most stable cycles is the bulk of the water and near the wall are identical. This is a strong argument in support of LRT theory. On the other hand, the number of cycles of the same period is not the same. We do not have an explanation for this discrepancy.

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Hall effect on turbulence and relaxation process of flowing plasmas

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Abstract

The Hall effect on the nonlinear dynamics of a flowing plasma has been studied by comparing the magnetohydrodynamics (MHD) equations and the Hall MHD equations. The Hall effect, which is written by higher order derivative term, is known as one of the singular perturbations to the MHD equations. In the analysis of flowing plasma equilibrium, it is shown that a scale-hierarchy is created by cooperation of the plasm flow and the singular perturbation of the Hall effect, and the crossing of characteristics (the magnetic and flow fields) are discussed to compare with Parker's current sheet model in Ref. 1. In this study, the creation of microscopic scales by the Hall effect and its influence to the turbulence and relaxation process of macroscopic fields are investigated by numerical simulation. Numerical simulations of both MHD and Hall MHD systems show that the turbulence brings about dissipation of the magnetic and kinetic (flow) energies, and self-organization of large scale structures occurs. However, the perpendicular flow to the magnetic field (crossing of characteristics) is generated more effectively and the kinetic energy dissipates much faster in the Hall MHD system. The enhanced energy dissipation is primarily due to production of small scale fluctuations, which proves the creation of scale hierarchy by the singular perturbation of the Hall effect[2]. Furthermore, in the relaxation process, ruggedness of constants of motion may be important. The Hall MHD system has three constants of motion, the energy, the magnetic (electron) and ion helicities. The ion helicity consists of the magnetic, cross, and kinetic helicities. The kinetic helicity is known to be "fragile" with respect to the energy norm of the magnetic and flow fields[3]. Under an appropriate ordering of scales, the kinetic helicity can be suppressed, and the ion helicity translates as the cross helicity after subtracting the independent constant magnetic helicity. Conservation of the cross helicity is an essential condition to recover the macroscopic MHD picture from the Hall MHD framework.

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Transitions in Alfvén Eigenmode Spectrum in Advanced Scenarios on JET

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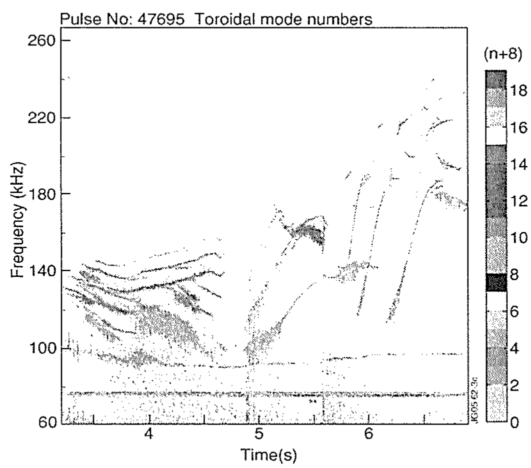
Abstract

In JET discharges with ICRF minority heating, the ICRF-accelerated ions excite two main types of Alfvén instabilities, Toroidal Alfvén Eigenmodes (TAEs) [1] and Alfvén cascade eigenmodes (ACs) [2-4], which dominate in plasmas with positive and reversed magnetic shear respectively. It is common for JET advanced scenarios with LHCD that transitions occur from AC-dominating Alfvén spectra to TAE-dominating ones as a non-monotonic $q(r)$-profile relaxes to a monotonic shape. Here, we investigate *opposite* transitions from TAE- to AC-dominating spectra in JET plasmas *without* LHCD.



Magnetic spectrogram showing TAEs and ACs in 2.6 T/2.5 MA JET discharge #47695.

Figure 1 displays an example of such opposite transition, where TAEs are observed at t < 4.6 sec, but AC are observed at t > 4.6 sec. It is shown that the opposite transitions in Alfvén spectrum are associated with formation of internal transport barriers (ITBs) that significantly increase the pressure-driven bootstrap current with a hollow profile. Conditions for obtaining the shear-reversed equilibrium that are determined by the ITB radius and pressure gradient are discussed.

Furthermore, we apply MHD spectroscopy based on an AC *envelope* for determining values of $q_{\min}$ in reversed shear plasmas.

This work was conducted under EFDA and partly funded by Euratom and the UK EPSRC.

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Two-Fluid Magnetic Islands in Toroidal Configurations*

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Abstract

Nonlinear simulation of toroidal magnetically confined plasmas using a two-fluid model in the M3D code has shown that electron fluid effects can change the behavior of magnetic islands compared to MHD. The parallel gradient of the electron pressure in the Ohm's law, $\nabla_{\|} p_e/en$, accelerates the growth of low-order magnetic islands when the helical component of the magnetic field is large and results in larger saturated island size. In stellarators, this can occur even in the ideal MHD configuration that is taken as the nominal "equilibrium" [1], while in tokamaks an island must first grow to a critical, nonlinear size [2,1]. Many other configurations also see enhanced reconnection. In a tokamak island, the critical "electron" pressure anisotropy can be driven by the parallel variation of the MHD pressure, i.e., taking the electron pressure in the Ohm's law term to be $p_e \equiv C_e p$ for a constant factor $0 < C_e < 1$ as the only non-MHD term. Numerical studies using a rapid parallel thermal equilibration of T_e as well as a perpendicular thermal conductivity show that the parallel variation of the two-fluid temperature and density differ from those of MHD both near the reconnection region and more globally over the island flux surfaces.

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Surfaces of Section Analysis of the Beam–Plasma System with Two Electromagnetic Waves

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Abstract

The problem of a beam-plasma system interacting with electromagnetic (laser) waves has been studied via a finite degree-of-freedom (DOF) model [1,2]. It has been shown through numerical simulations that if the electromagnetic waves satisfy a special matching condition, their energy can be transfered to the beam-plasma system provided that their amplitudes exceed a certain threshold. Using the "macroparticle" reduction [3], the system is further reduced to a one and a half DOF. The method of surfaces of section is applied to explain the threshold observed numerically. As the amplitudes of the electromagnetic waves are increased, the island of the initial condition undergoes initial deformation, corresponding to the region below threshold, and island breaking and chaos (phase space mixing), corresponding to the region above threshold. Above threshold the plasma wave driven by the electron beam can be further amplified through transfer of energy from the two electromagnetic waves. Applications of this phenomenon include high energy accelerators, features of laboratory and space plasmas, and laser-plasma interaction.

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Impact of Three-Dimensional Geometry on Ballooning Stability

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Abstract

The impact of ideal ballooning modes on β-limits for stellarators remains an open question. Theoretical calculations of global ballooning mode stability in stellarators have been done using the results of infinite-n ballooning theory and the ray tracing techniques introduced by Dewar and Glasser [1]. Cooper et al. [2] undertook a comparison of the Dewar-Glasser formalism and the results from the global TERPSICHORE code for a large-aspect ratio, ten-field period stellarator and found good agreement between the two methods for interchange type modes. More recent work using the Dewar and Glasser formalism has included testing ballooning stability in the LHD [3], Heliotron J [4], and NCSX [5] stellarators. In this work, ballooning stability is examined for a series of equilibria that transition from an axisymmetric case to a fully three-dimensional Quasi-Poloidal Stellarator (QPS) equilibrium [6]. The series of equilibria is calculated with a fixed rotational transform profile. Thus, even the axisymmetric case has stellarator shear and is completely stable to ballooning modes. As the degree of three-dimensionality is increased, localized, ballooning type modes are the first to become unstable. Indeed, near the first stability boundary, only localized ballooning modes are unstable even for the fully three dimensional QPS equilibrium. As β is increased well above the first stability boundary, interchange-type modes become unstable for the more three-dimensional equilibria. The possible impact of finite Larmor radius effects on ballooning stability is discussed.

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1D Hall-MHD Theory for the H-Mode pedestal: comparison with observations

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We have recently developed a theory for the H mode pedestal using the Hall-MHD system of equations. The equilibrium for the edge was determined by using the Double Beltrami conditions for the two generalized vorticities for the electron and ion fluids. The constraint of ballooning stability of the edge pressure profile leads to a unique prescription for all the edge parameters. The Hall-MHD model also predicts edge plasma currents and associated magnetic fields in both the toroidal and poloidal directions. Comparisons of our predictions with observations of the pedestal width and height scaling with some observations on JET and JT60-U will be presented. Also comparisons with the recent Lithium beam polarimetry measurements of the edge poloidal field and associated toroidal current on DIII-D with the predictions of the present model will be presented.

The Effect of parallel flow gradients on the threshold for L-H transitions.

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A recent theory of L-H transitions, based on the flow shear generation by finite beta drift waves, predicts a critical electron temperature for the onset of the transition in the edge region of tokamaks. Recent comparisons of this theory with observations of transition thresholds on USN and LSN on C-MOD have indicated a difference in the edge transition temperatures which are at variance with the theory. A clear indication is that for these two classes of discharges the parallel flow velocities are significantly different, which could account for the difference in the observed critical temperatures and hence the power thresholds. We have incorporated the effect of parallel flows in the edge region of tokamaks in our theory and will present results delineating the role of parallel flow and its gradients on the predicted critical temperature.

Influence of geometry on drift waves in tokamaks and stellarators*

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Abstract

There is a general consensus that unstable drift waves can produce a large amount of anomalous transport. These instabilities have been intensively investigated in tokamaks for the last few decades. Drift waves studies in stellarators have only received limited attention due to the complicated three-dimensional structure and the related high-resolution requirements for a numerical treatment. A computer code has been developed that calculates necessary magnetic field quantities of any magnetic confinement fusion devices using equilibria obtained from the VMEC code. The code solves the eigenvalue problem using the linear stability of simple iδ drift model, reactive ion temperature gradient (ITG) instability in the electrostatic limit using the ballooning mode formalism and applying WKB type boundary conditions. Linear stability of drift waves is investigated in a variety of stellarator configurations (W7-X, H1-NF, HSX) and the results are compared and contrasted with those of a numerical circular tokamak, ITER (International Thermonuclear Experimental Reactor) and JET (Joint European Torus) like equilibria and the analytical $\hat{s}$-α model equilibria. In case of the iδ model, generally, the high frequency modes are found to be strongly localized and most unstable while the low frequency modes are found weakly localized and less unstable. In the stellarators, the most unstable modes are found where the stabilizing effect of local magnetic shear is minimum or where the coupling between the local magnetic shear and geodesic curvature is strong. In contrast, this coupling is found to be weaker in tokamaks than in stellarators. In tokamak geometries, the existence of the high frequency modes and their frequencies and growth rates are found strongly dependent on the local shear of the magnetic field. The modes exist with their frequencies and growth rates inversely proportional to the magnitude of the shear, while, field line curvature has found less effective on these electron drift modes. The results of the JET-like equilibrium are also compared and contrasted with the results of a circular equilibrium with the same aspect ratio. However, in tokamaks with shaped cross section modes are found to be more localized than the modes in the circular equilibrium. As in the stellarators, this is found to be due to the variation in the strength of the local magnetic shear, which localizes the modes along the field lines and constraints them. In the case of the ITG model, as the magnitude of the local shear increases and bad curvature decreases the growth rate of ITG mode decreases as well and in the local good curvature region the modes become stable. However, in the stellarators the unstable modes found both in the good and in the bad curvature regions of the chosen magnetic surface.

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Search for Zonal Flow Associated with ITG Modes in CLM

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The basic physics transport experiments in the Columbia Linear Machine (CLM) have indicated inverse gyro-Bohm dependence of the ion thermal conductivity on the isotope mass. This paradox was explained by a unique 3-wave coupling of two ITG modes and an ion acoustic wave [1]. However, the competitive process of transport regulation via zonal flow [2] was not investigated.

A series of basic experiments to detect any generation of zonal flow is now reported. Towards this end we have carefully examined the fine structure of the power spectrum and found two side bands with a shifts of about 3 kHz. An interpretation of this in terms of frequency modulation (FM) of ITG mode by a zonal flow appears plausible. Detailed cross correlation studies of two axially separated probes (one capacitive probe, the other ring probe) reveal two distinct modes (both m=0): one with $k_{//}$ 0, $\omega/2\pi \sim$ 2 to 10 kHz ion acoustic wave, and the other with $k_{//} = 0$, $\omega/2\pi \leq 5$ kHz , possibly a zonal flow.

A theory using reductive perturbation method has been developed for self coupling of ITG mode in conjunction with the 3- wave coupling of two ITG radial harmonics and an ion acoustic mode. The results agree with the experimental values within a factor of 2.

The research was supported by U.S.Department of Energy Grant No. DE-FG02-98ER-54464.

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Conjectured Manipulation of the Zero Point Vacuum Energy Through Powerful Electric Discharges and its Possible Significance for CTR

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Abstract

Most recently it has been claimed that DD fusion reactions have been detected in sonoluminescence [1]. For this reaction a temperature of 10^8 °K is required, falling short by four orders of magnitude for what is predicted by accepted models of sonoluminescence [2]. Also unexpected nuclear reactions in powerful electric discharges have been observed by at least two groups [3,4]. To explain these reactions I make the conjecture that they result from a transient conversion of mechanical or electric energy into zero point vacuum energy inside a refractive medium with the change of the vacuum energy lowering the Coulomb barrier for nuclear reactions [5]. The transient release of zero point vacuum energy was conjectured by Schwinger[6] in an attempt to explain sonoluminescence, but this same may occur in powerful electric discharges, much more so than in the by comparison feeble sonoluminescence.

If ε is the dielectric constant of a medium in which the discharge takes place, the zero point energy squeezed out relative to it's environment, which can be a vacuum or a bubble embedded in a dielectric, is $u = (\hbar c / 2\pi^2)\int_0^{k_{max}} k^3 [1 - 1/\sqrt{\varepsilon}] dk$. For frequencies above the electron plasma frequency ω_p on has $\varepsilon = (1 + \omega_p^2 / c^2 k^2)^{-1}$ and hence $u = (\hbar \omega_p^2 / 8\pi c) k_{max}^2$, with $p = -u$ the pressure of the zero point vacuum energy. Setting $k_{max} \cong Z / r_B$, $r_B = \hbar^2 / mc^2$, one finds for iron wires that $p = -u = -10^{12}$ dyn/cm^2, sufficient to explain the observed disintegration of the wires into many small pieces [7]. With u the difference in the zero point energy in between the dielectric and it's surrounding, this means that a negative value of u implies a reduction in the zero point energy, and with it a reduction of the Coulomb force from $F = e^2 / r^2$ to $F' = e^2 / \varepsilon r^2$. In a bubble or void embedded in a medium with $\varepsilon < 1$ on has $F' < F$.

This suggests to enhance the nuclear fusion reaction rate by placing the fusion fuel in metallic capillars made up of high Z material. Choosing $Z \sim 90$, one finds a reduced Bohr radius equal to $r_B / Z = 6 \times 10^{-11}$ cm, about twice as large as the muon atom Bohr radius, reducing the width of the Coulomb barrier 100 fold, not 200 fold as for muon catalyzed fusion.

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Error-field Penetration Thresholds in a Two-Fluid Model

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A reduced nonlinear two-fluid model is used to investigate the response of a rotating tokamak plasma in which electron diamagnetic, ion diamagnetic, and Hall effects are significant to a static resonant error-field. The aim of this study is to determine the scaling of the critical error-field amplitude above which rotational shielding breaks down and significant magnetic reconnection is driven inside the plasma. Both analytic and numerical results are presented. This work was supported by the U.S. Dept. of Energy Contract No. DE-FC02-01ER-54652.

A gyrokinetic electron and fully kinetic ion plasma simulation model

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Abstract. A novel new kinetic simulation model has been developed to investigate dynamics in collisionless plasmas. In this model, the electrons are treated as gyrokinetic (GK) particles and ions are treated as fully kinetic (FK) particles. In the GK-electron and FK-ion (GKe/FKi) plasma simulation model, the rapid electron cyclotron motion is removed, while keeping finite electron Larmor radii, realistic electron-to-ion mass ratio, wave-particle interactions, and off-diagonal components of the electron pressure tensor. The model is particularly suitable for plasma dynamics with wave frequencies lower than the electron gyrofrequency, and for problems in which the wave modes ranging from Alfvén waves to lower-hybrid/whistler waves need to be handled on an equal footing. Using this model, the computation power can be significantly improved over that of the existing full-particle codes. The GKe/FKi model, furthermore, can also handle physics with realistic electron-to-ion mass ratio and dynamic processes on the global Alfvén time/spatial scales. With respect to the hybrid (i.e., FK ion and fluid electron) model, the GKe/FKi model has the advantage that important electron kinetic physics, such as wave-particle resonances and finite electron Larmor radius effects, are included. The simulation model has been successfully benchmarked for linear waves in uniform plasmas against analytic dispersion relation.

Application of Lattice Boltzmann Algorithms to Plasma Physics

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Abstract

The simulation of turbulent flows in complex geometry places great strain on computational algorithms designed for the direct solution of the Navier-Stokes and MHD equations. These algorithms require sophisticated schemes (high order finite elements or Newton-Krylov solvers) to resolve the nonlinear convective derivatives with second order accuracy and in a numerically stable manner. MHD has to handle even more nonlinear convective terms. The lattice Boltzmann (LB) approach attempts to circumvent these nonlinear convective terms by differencing a set of distribution functions on a minimal set of discrete kinetic velocity lattice vectors. Because of the ease of handling complex boundaries and its simple structure which permits highly efficient parallelization and vectorization, the LB method is becoming a competing tool for incompressible Navier-Stokes problems. However, in its application to plasma physics problems of current interest, LB methods are still in a more developmental phase. It is well known that the Achilles heel of any straightforward LB schemes is nonlinear numerical instability.

Here we report on some applications of LB to MHD : 3D MHD turbulence and Landau damping. In 3D MHD turbulence, we have achieved sustained timings of 22 TFlops on the Earth Simulator. As Landau damping is a wave-particle interaction phenomenon, it was considered outside the scope of macroscopic fluid equations. However, non-local closures, first introduced by Hammett & Perkins, have been able to recover Landau damping. Here we report on LB modeling of these nonlocal closures at the zeroth moment level and then discuss higher moment levels.

Entropic Lattice Boltzmann Methods for Turbulence

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Abstract

Lattice Boltzmann algorithms solve the nonlinear macroscopic conservation equations by embedding the problem into a higher dimensional phase space and then utilize a minimal subset of these extra degrees of freedom so that in the Chapman-Enskog long wavelength long time limit one recovers the original nonlinear set of equations. The non-local nonlinear convective derivatives of Navier-Stokes and MHD can now reproduced by a BGK collision operator with only local algebraic (macroscopic) nonlinearities. The resulting kinetic system is then solved on a discrete velocity lattice and entails (in its simplest form) collisional relaxation at each nodal site involving only on-site information followed by streaming of that information to neighboring lattice sites. The simplicity of the LB algorithm lends itself ideally to vectorization and parallelization [e.g., 22 Tflops for our 3D LB-MHD code on the Earth Simulator].

However, the Achilles' heel for the straightforward LB algorithm is numerical nonlinear instabilities: there are no constraints imposed to enforce non-negativity in the distribution functions. An entropic LB scheme enforces a discrete H-theorem onto the evolution of the distribution functions so that they non-negative. For Navier-Stokes turbulence, the entropic LB equation has the form [Karlin et. al., 2004]

$$f_j\left(\mathbf{x}+\mathbf{c}_j,t+1\right)=f_j(\mathbf{x},t)-\alpha(\mathbf{x},t)\,\beta\left[f_j(\mathbf{x},t)-f_j^{eq}(\mathbf{x},t)\right]$$

where $\mathbf{c}_j$ are the lattice velocity vectors, f_j^{eq} is an analytic (non-polynomial) function, and β is an arbitrary parameter determining the bare viscosity

$$\nu_0=\frac{1}{6}\left(\frac{1}{\beta}-1\right),\qquad 0<\beta<1$$

while the function $\alpha(\mathbf{x},t)$ is determined at each spatial node by a Newton-Raphson algorithm such that a discrete H-theorem is enforced : $H[\mathbf{f}]=H\left[\mathbf{f}+\alpha\left(\mathbf{f}^{eq}-\mathbf{f}\right)\right]$, where the discrete H-function is known analytically and has a weighted-Boltzmann form.

The entropic LB scheme permits, provided one has a sufficiently refined spatial grid, an unconditionally stable explicit algorithm for turbulence even **arbitrary** high Reynolds number [scheme is stable for $\beta \to 1$, i.e., for $\nu_0 \to 0$, $\mathrm{Re} \to \infty$].
Here we report on numerical solutions for 2D and 3D Navier-Stokes turbulence, and discuss the generalization of the entropic LB scheme to MHD.

Finite Ion Orbit Effects on Magnetic Islands in Toroidal Plasmas

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A kinetic theory for the interaction of an ion population with an isolated magnetic island in a tokamak plasma is presented. In this work, we examine islands whose characteristic widths are larger than the ion gyro radius but smaller than the ion banana width. In this regime, the energetic ion response to the island has a non-local feature due to the curvature and ∇B drifts. When solving the drift kinetic equation for the energetic ions, a change in coordinates is used to account for this behavior. A bounce averaging procedure is developed to describe the interaction of the ions with the electrostatic potential. Constraint relationships found from transport equations are used to determine the distribution function, which is treated in different velocity regions and rotation frequency values to find the contribution to the perpendicular (polarization) current. By considering the quasineutrality relation, the parallel current ($J_{//}$) in response to the ions is calculated. These currents are compared with some recent numerical results[1]. Using this current in the "dispersion relation" found from asymptotic matching, the island width evolution equation is determined. A pair of self-consistent equations for the islands' width, w, and its propagation frequency, ω, is to be derived. The results are to be compared with calculations valid for large island width so as to yield a description of magnetic island width evolution from sub-banana width to macroscopic scale lengths.

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

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Multigrid algorithm for high beta tokamak equilibria*

P.-A. Gourdain, R. Y. Neches, S. C. Cowley, and J.-N. Leboeuf

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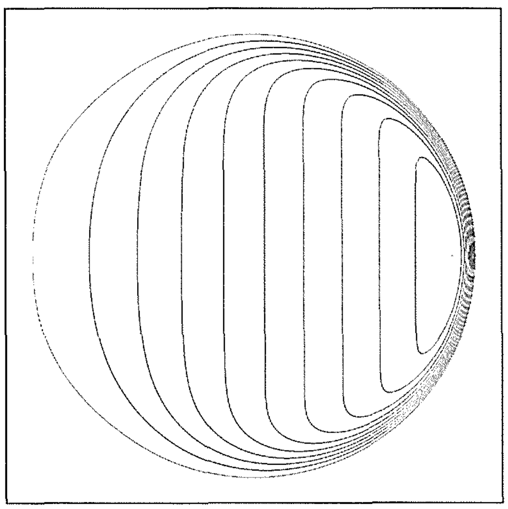
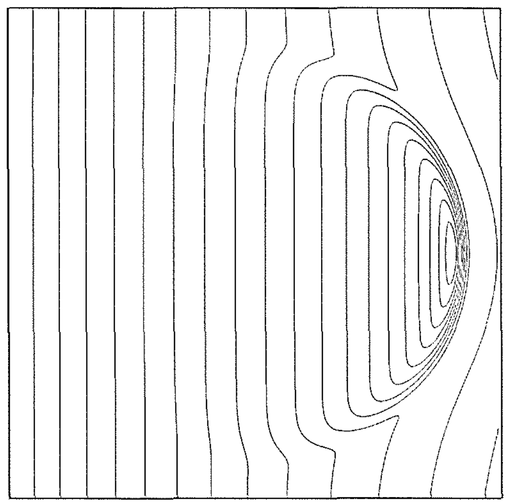
A free-boundary code to find efficiently high beta equilibrium solutions for tokamaks has been developed. The Code for Unity Beta Equilibria (CUBE) uses the multigrid method [1] to obtain accurate numerical solutions of the Grad-Shafranov equation at high values of plasma beta. It complements coarser solutions previously obtained using the contour dynamics method [2] which established the feasibility of such solutions. The highly resolved CUBE solutions are compared to the asymptotic theory of Cowley *et al.* [3] and asymptotic solutions of Hsu *et al.* [4]. The characteristic core and boundary layer regions are self-consistently recovered at plasma betas approaching unity. The properties of these high beta solutions with respect to, for example, magnetic axis shift and omnigeneity, are investigated in detail numerically with CUBE. Unity beta equilibria featuring shifts of more than 90% of the plasma minor radius have already been computed with a spatial resolution of one grid point per millimeter.



Flux surfaces for unity beta in the Electric Tokamak with a Shafranov shift of 90 % of the plasma minor radius.



|B| surfaces for unity beta in the Electric Tokamak with a Shafranov shift of 90 % of the plasma minor radius.

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*Work sponsored by DOE grants DE-FG02-04ER54737 and DE-FG02-04ER54740.

Time Development of Electron Cyclotron Emission in NSTX

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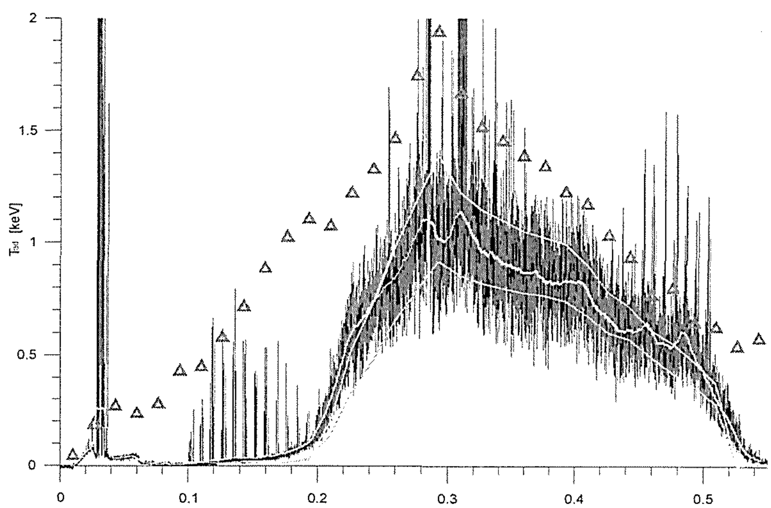
Abstract

One of the most important results deduced from ECE measurements on NSTX is the time development of the radiation plasma temperature. The ECE diagnostic on NSTX detects signals from both O- and X-polarizations. Since the outgoing O-mode at oblique incidence is approximately circularly polarized, the sum of these signals can be interpreted as a radiation temperature. We have performed simulations of the time development of ECE in the interval $0.09s < t < 0.6s$. The time evolution of the sum of the detected O- and X- signals is plotted along with the maximum temperature detected by Thomson scattering (this independent measurement for $0.1s < t < 0.5s$ corresponds well to the temperature at $R = 1.007\ m$) as well as the theoretical simulation of O- and X- signals for Gaussian beams corresponding to actual antenna orientation. The simulated intensity of ECE emission is determined from

$$I_{ECE} = const \int \iint \mathrm{d}S\, W_{Gauss}\, C_{EBW \int X \int O}\, \omega^2 T_{rad}^{eff}\, V_{relat}$$

where $C_{EBW-X-O}$ is the mode conversion efficiency and T_{rad}^{eff} is the effective radiation temperature from different rays (taking into account nonlocal reabsorption/emission).



red triangles: maximum temperature from Thomson scattering
black curves : time evolution of ECE signals from O and X channels – bursts are the consequences of interference with the reflectometer operating at the same frequency [16.5 GHz] – **yellow line**: running average
light blue curve: simulation radiation temperature for optimal beam orientation for maximal EBW-X-O
pink curve : simulation radiation temperature for experimental beam orientation.

Progress on PIXIE3D, a parallel, implicit, extended 3D MHD code

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Abstract

We report on the progress of PIXIE3D, a parallel, implicit, extended MHD 3D code. PIXIE3D features a novel finite-volume discretization,[1] suitable for general curvilinear 3D geometries that is: 1) conservative, 2) solenoidal in $\vec{B}$ and $\vec{J}$ to machine accuracy, 3) numerically non-dissipative, and 4) linearly and nonlinearly stable in the absence of physical dissipation.

PIXIE3D also features a fully implicit Jacobian-free Newton-Krylov solver. Newton-Krylov methods synergistically combine Newton's method for nonlinear convergence, and Krylov techniques to solve the associated Jacobian (linear) systems. Krylov methods can be preconditioned for efficiency. At the heart of PIXIE3D is a novel physics-based preconditioning strategy based on multigrid technology, which scales optimally with grid refinement and time step size. Such strategy extends the ideas put forth in previous 2D MHD work.[2,3] The "physics-based" concept exploits physics knowledge to derive well-conditioned (diagonally-dominant) approximations to the original system that are amenable to optimal multigrid solver technology.

The combination of scalable preconditioning and a Jacobian-free implementation make PIXIE3D "lightweight" both CPU-wise and memory-wise. We will present current serial performance results of PIXIE3D in 2D and 3D problems in various geometries. We will also report on the status of the parallel implementation of the physics-based concept using additive Schwartz methods, and future work.

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Application of a 'direct' δf PIC scheme to gyrokinetic ITG simulations in toroidal MHD equilibria

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The δf method implements a control-variates reduction of Monte-Carlo (statistical) noise in particle-in-cell (PIC) methods and has been widely applied to gyrokinetic simulations of microinstabilities such as the ion-temperature-gradient (ITG) and electron-temperature-gradient (ETG) mode.

δf may be calculated by integrating $\mathrm{d}f_0/\mathrm{d}t$ along characteristics or by a direct calculation $\delta f = f - f_0$, using the fact that f is, by definition, constant along the characteristics of the gyrokinetic equation. Traditionally the first method has been used. While the two methods are formally equivalent, it has been shown in cylindrical geometry that the direct method results in less noise and reduced computational effort [1].

In this work we will examine the issues involved in the application of the direct method to gyrokinetic simulation of ITGs in true toroidal MHD equilibria, with appropriate inclusion of zonal flows.

The key issues revolve around the error introduced in interpolating the (numerical) MHD equilibrium quantities and the nature of the corresponding gyrokinetic equilibrium.

Results of our simulations will be presented and conclusions drawn on the practical implementation of the direct method. Comparisons between the 'traditional' and 'direct' methods will be given.

We find that the direct method remains feasible using numerical MHD equilibria, but the implementation must be handled with care.

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2005 International Sherwood
Fusion Theory Conference
Apr 11, 2005 - Apr 13, 2005
Stateline, Nevada, USA

Enhanced Thermonuclear Yield Due to Low-Harmonic Relativistic Electron Bernstein Modes in Spherical Tokamak Plasmas*

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Abstract

A novel method for enhancement of the thermonuclear yield in Spherical Tokamaks (ST) is proposed. As opposed to conventional tokamaks, in the plasma environment of ST, the electron cyclotron frequency is lower than the electron plasma frequency, so that the propagation of electromagnetic, both O- and X-, modes to the interior is impeded by the cut-offs located at the edge area. This is not the case with the propagation of electrostatic Electron Bernstein modes.

Accordingly, in this model an external electron cyclotron waves, O- or X-mode, excite relativistic Electron Bernstein Mode[1] harmonics (EB harmonics) in the edge region of ST plasma. Nonlinear relativistic EB harmonics, in turn, propagate toward the central region of ST, whereby they are effectively absorbed in the electron cyclotron resonance region.

It is shown that an efficient control of nonlinear interaction is possible, leading to a favorable convective EB harmonics excitation. The scaling laws[2] for the thermonuclear yield, ratio of thermonuclear power to external power, for the case of excitation of EB harmonics, n(EB) + (n-1) (EB), n= 2,3 harmonic number, and for the excitation of n(EB) + (LH), LH lower hybrid mode, are obtained. The breakeven and multi-ion-species-plasma-ignition criteria are analyzed in terms of O- and X-Mode power.

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* Supported by Tesla Laboratories.

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Numerical study of the wave equation in the Lower Hybrid frequency in a toroidal plasma

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Abstract

The LH full wave equation in the electrostatic approximation and in a general magnetic field equilibrium, which is going beyond the usual WKB approximation (ray-tracing equations), has been numerically integrated when the magnetic equilibrium reduces to a system of circular and concentric magnetic surfaces. This work has been done in view of the comparison of the full numerical integration with the new analytical approach which treats the wave equation by a multiple spatial scale method based on the Poisson Summation formula [1]. In applying this formalism, in fact, the starting equation for the scalar potential in the cold plasma limit reduces to two nested one-dimensional equations: the first governs the wave structure along the magnetic field lines, while the second describes the slow radial dependence of the wave envelope, for which the usual WKB asymptotic technique is applied. This mixed WKB-full-wave approach can be entirely justified on the basis of spatial scale separation in the radial direction and, for waves that have parallel group velocity faster than in the perpendicular direction (e.g. the lower hybrid wave).
The numerical solution of the full 2D wave equation in a simpler Cartesian geometry (semi-infinite space) with outwards radiation conditions was treated by using standard numerical routines which integrate systems of ordinary differential equations [2]. In a more realistic toroidal geometry the solution has been obtained by using a spectral approach based on the Fourier analysis of the scalar potential in the periodic variables ϕ (poloidal angle) and ϕ (toroidal angle). The starting second order partial differential equation (PDE) for the scalar potential is replaced by a system of coupled ordinary differential equations along r (the radial variable). The solution of the set of coupled equations requires the use of non-standard numerical methods (shooting methods) owing to the difficulty to fix the correct boundary conditions and to avoid the consumption of a large amount of computational memory. The complete solution can be finally obtained by numerical methods based on the Fast Fourier Transform (FFT). Well-known characteristic behaviors of the lower-hybrid wave propagation, such as resonance cones of a Gaussian beam in a cold plasma, are studied as benchmarks of the numerical solution. A discussion of the full numerical solution when compared to the ray-tracing method previously hint is also presented.

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Pinch effects and stiffness of the Weiland model

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and the EFDA-JET contributors

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Abstract

The Weiland model[1] is usually considered non-stiff[2]. In order to measure the stiffness of this model its diffusivities were rewritten in the form of a gyro-Bohm critical gradient model (CGM)[3, 4]. The Weiland diffusivity in a CGM form becomes, $\chi = \chi^{gB}\chi_s(R/L_T - R/L_{T,th})^{\alpha}$, which yields a theoretical value of the stiffness number, χ_s, describing gyro-Bohm-like transport. A difference from earlier stiffness analysis is that the diffusivities have an $\alpha = 1/2$ dependence and not $\alpha = 1$. In the Weiland model this proportionality is not fixed, but varies with the plasma parameters. $\alpha = 1/2$ corresponds to the case when modes are well above the threshold.

Simulations of scans of applied electron or ion heating power, permitted calculation of the actual stiffness numbers of the Weiland model by determination of the slope of χ/χ^{gB} versus $(R/L_T - R/L_{T,th})^{1/2}$. The actual stiffness numbers exceed the theoretical ones and are significantly large, yielding evidence of stiffness of the Weiland model. There also seems to exist a correlation between the modes responsible for the drive of the diffusivities and the stiffness numbers.

At $R/L_T - R/L_{T,th} = 0$, the ambient transport ought to take on the value of the neoclassical transport. Nevertheless, when calculating the actual stiffness numbers, all the ambient diffusivities obtained by extrapolating χ to the threshold, turned out to be negative. Due to the variation of α in the Weiland model, discrepancies might be expected when extrapolating. Closer to the threshold an $\alpha = 3/2$ is more accurate, but this kind of fit to the data still reveals a negative ambient electron heat transport. It turns out that pinches can explain this kind of behaviour. As pinches render extrapolations on the form of $(R/L_T - R/L_{T,th})^{\alpha}$ inaccurate close to the threshold, the determination of the ambient transport becomes flawed. Hence, one has to be careful when using a CGM model close to the threshold.

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P1-46

The waves in Hall-MHD plasmas*

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Niigata University, Niigata 950-2181, Japan

Abstract

The three ideal MHD waves are followed as they transition under the increasing influence of a Hall current effect to the characteristic waves of the Hall-MHD model, which describes a two-fluid plasma with negligible electron mass. The relevant Hall parameter is $\lambda = (kd_i)^2$, where d_i is the ion skin depth and k is the wave number. The value $\lambda = 0$ corresponds to ideal MHD, while $\lambda \rightarrow \infty$ yields the characteristic surfaces in the Hall-MHD model.[1]

Unlike earlier work (e.g., Ref. 2) which only considered waves propagating in a constant state, we use geometric optics to obtain wave solutions for general equilibria. We produce not only a dispersion relation but also ray surfaces which approximate wave fronts resulting from a localized perturbation. We also solve for the eigenvectors which determine what information each wave carries. It is shown that all three MHD waves undergo great changes as λ becomes increasingly large. Most notably, the incompressible MHD shear Alfven wave becomes a compressible fluid dynamical wave with negligible perturbation of the electromagnetic field.

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*Work supported by USDOE Grant No. DE-FG02-86ER53223, by the Uchida Energy Science Foundation, and by the Basic Research Fund of Niigata University.

P1-47

Nonlinear stability of the LHD and the DIII-D

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Abstract

The NSTAB computer code applies the variational principle of ideal magnetohydrodynamics to calculate equilibrium and stability of toroidal plasmas without two-dimensional symmetry. Partial differential equations are solved in a conservation form that describes force balance correctly across islands and current sheets that are treated as discontinuities. The method has been applied to the LHD stellarator experiment in Japan and the DIII-D tokamak at General Atomics. Comparison with observations is favorable in both cases. Sometimes the solution of the equations turns out not to be unique, and there may exist bifurcated equilibria that are nonlinearly stable when other theories predict linear instability. The calculations are consistent with measurements of β as high as 4% in the LHD. Fully three-dimensional solutions for the DIII-D may serve to model NTM modes that have been observed.

This work has been supported by the U.S. Department of Energy Grant No. DE-FG02-86ER53223.

Nonlinear Dynamics of ELMs*

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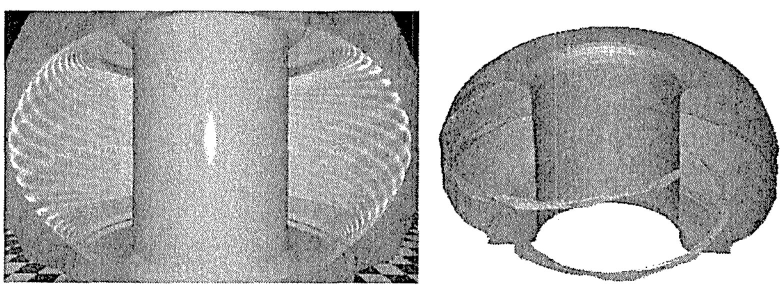
The peeling-ballooning model proposes intermediate wavelength MHD modes driven by the pressure gradient and current in the pedestal region as a mechanism for edge localized modes (ELMs) and constraints on the H-Mode pedestal.[1] The model has successfully explained onset conditions and a number of observed characteristics of many types of ELMs.[1,2] Recent studies have incorporated toroidal flow shear, revealing important effects on mode structure, and suggesting that mode growth strongly damps sheared flow in the edge, resulting in a collapse of the edge transport barrier during the ELM collapse. Nonlinear simulations of ELMs, employing 3D electromagnetic reduced-Braginskii equations, reveal the expected peeling-ballooning character of the modes in the linear phase, and explosive growth of one or many filaments during a fast nonlinear crash phase.[3] These filaments carry hot plasma from the pedestal region into the cold, open field line region, allowing local fast diffusion and secondary instabilities to remove energy from the core plasma via parallel transport along the filaments. We propose these two mechanisms, (1) temporary collapse of the edge transport barrier, and (2) radially propagating filaments acting as conduits, to explain the observed energy and particle losses during the ELM collapse. We explore the evolution of the magnetic field in the strongly nonlinear phase of the simulations, and consider modifications to nonlinear simulation codes to allow study of the full ELM crash.



(left) Calculated linear mode structure of an n=18 mode in DIII-D.
(right) Radially propagating filament during nonlinear phase of 3D simulation.

[1] P.B. Snyder, H.R. Wilson et al, Phys. Plasmas **9** (2002) 2037.
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[3] P.B. Snyder, H.R. Wilson and X.Q. Xu, to appear in Phys. Plasmas, May 2005.

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Computational Studies of Dynamo Suppression in the Reversed Field Pinch During PPCD

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Abstract

Laboratory experiments with Pulsed Poloidal Current Drive (PPCD) have shown reduction of the magnetic fluctuations that introduce stochasticity to magnetic field trajectories leading to anomalous energy transport in the RFP[1,2]. The applied inductive electric field alters the parallel current profile of standard RFP operation in a manner to improve the stability of core resonant tearing modes which are key to sustainment of nonlinear dynamo processes. These core resonant modes extract power from the mean magnetic field and transfer power via nonlinear interaction to modes resonant near the reversal surface[3].

We present results from a numerical study of the interaction between the mean field and tearing fluctuations during PPCD in the RFP using the 3D nonlinear nonideal MHD code NIMROD[4]. Simulations in cylindrical geometry with zero beta or finite pressure both demonstrate dynamo suppression observed during PPCD experiments. The simulations show a dramatic drop in magnetic fluctuation activity on a hybrid time between Alfvenic and resistive times.

Calculations of modal quasilinear power flux measure the interactive effects of tearing modes coupling to the PPCD modified mean fields. They show that the amount of energy extracted from the mean field by the core tearing modes is dramatically reduced. This reduction changes the core mode amplitudes and nonlinear power transferred to various resonances across the plasma minor radius. By comparison of the total modal growth rate to quasilinear and dissipative rates, we differentiate the degree to which nonlinear growth rates are affected by the action of PPCD.

Growth rate measurements demonstrate the linear stabilization of key tearing modes after the PPCD electric field is applied to the boundary. We present results from studies of the direct effect of PPCD on tearing eigenmodes using a linear stability analysis code. Analysis of terms in Ohm's Law show the ideal component of the PPCD electric field grows after initial penetration through the edge resistive layer. *Work supportedby US DOE

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One- and two-fluid computational studies of Field-Reversed Configuration (FRC) formation and stability

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C. Sovinec, N. Murphy – U. of Wisconsin

The NIMROD community macroscale simulation tool has been extended from a one-fluid to a two-fluid implicit plasma simulator. Calculations have addressed problems of FRC formation and stability. Using a one-fluid description, FRC formation by the merging of two opposite helicity spheromaks has been simulated in regimes of low to moderate Lundquist number S. The two-fluid model has simulated Hall effects on the prolate FRC internal tilt mode. Formation studies have been carried out with fixed boundary conditions (initial state contains two opposite helicity spheromaks) and are now being extended to allow helicity injection at the boundaries. The merging results show the formation of a FRC in the central region of reconnected flux at both low and moderate S. The two-fluid stability results are compared with similar NIMROD calculations with a one-fluid description, to earlier predictions based on a long-thin expansion and to other numerical work.

Plasma flow characteristics and flexibility studies of quasi-symmetric stellarators

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Abstract

Plasma flow generation and damping in stellarators is of significance to enhanced confinement regime access, impurity transport and magnetic island growth. Unlike the tokamak, where there is a strongly preferred direction (toroidal) for plasma flows, stellarators will generally posses finite flow components in both toroidal and poloidal directions. A fluid moments approach that provides a self-consistent method to evaluate both parallel and perpendicular neoclassical transport[1] for stellarators of arbitrary magnetic field structure has been applied to a variety of quasi-symmetric stellarator systems.[2] This has indicated that there is significant variation in the levels of parallel flow damping and flow anisotropy between configurations. Even in the absence of external momentum sources, the self-generated flows in stellarators can have sufficient levels of shear across flux surfaces to impact temperature-gradient driven modes. The three-dimensional nature of the stellarator equilibria also induces significant velocity shearing within magnetic flux surfaces that could impact ballooning and MHD instabilities.

The next generation of stellarators will incorporate substantial flexibility through control of currents in modular coil groups as well as toroidal and vertical coils. The Quasi-Poloidal Stellarator (QPS) achieves low effective ripple and approximate poloidal symmetry (in magnetic coordinates) through the use of a racetrack shaped magnetic axis and vertically elongated cross-sections in the regions of high toroidal curvature. Our studies have indicated this device can achieve a high degree of physics flexibility.[3] The important physics issues for QPS include flux surface fragility at low aspect ratio, plasma flow generation, and plasma/energetic particle confinement. Results of flexibility studies have shown that these physics targets can be varied significantly by using constrained optimizations that vary the coil currents within ranges that are defined by engineering considerations. Examples of this flexibility will be presented.

Acknowledgements - This work was supported by the U.S. Department of Energy under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

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Axial cavity for helicon waves in a nonuniform plasma

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Abstract

Plasma nonuniformity has a strong effect on the structure of helicon modes. In particular, a density gradient across the magnetic field supports a surface-type wave, localized in the strong gradient area [1]. This so-called radially-localized helicon mode has recently been observed experimentally in an axisymmetric plasma column [2]. The experimental results indicate that the plasma forms a cavity for the mode along the field lines, so that the wave transit time along the column is much shorter than the wave damping time. In this work, we present a mechanism for the wave trapping in the axial direction. A sharp drop in plasma density along the field lines causes a nearly complete reflection of the radially-localized helicon mode. This reflection is accompanied by an excitation of a conventional whistler. The axial wavelength of the excited whistler is much greater than that of the radially-localized wave. As a result, only a small portion of the energy is transferred to the whistler.

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Abstracts

Monday, April 11

Poster Session *P2*

at 3:30 pm

Plasma pressure effect on Alfvén cascade modes

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Abstract

Observations of Alfvén cascade modes reveal that these modes can exhibit spectral line bending at low frequencies, which is a significant deviation from the shear Alfvén wave dispersion relation. We find that this phenomenon is associated with finite plasma beta and geodesic curvature [1]. The geodesic curvature from toroidal geometry precludes shear Alfvén perturbations from being strictly incompressible, giving rise to low-frequency gap in the Alfvén continuum, as demonstrated numerically in Ref. [2]. In addition to the geodesic effect, there are two other pressure effects on shear Alfvén waves, which are convection in presence of an equilibrium pressure gradient and the toroidicity induced coupling between shear Alfvén waves and acoustic modes. Our analytical treatment of the problem enables parametric comparison of three mechanisms and identification of the dominant one. In contrast to the convective mechanism, the geodesic effect involves plasma compression, and the resulting characteristic frequency scales differently with plasma pressure. Moreover, we find that the convective contribution alone is unable to establish a low-frequency cascade mode, contrary to the erroneous statement of Ref. [3]. The key distinction between the geodesic compressibility and acoustic coupling is that geodesic compression occurs without plasma displacement along the magnetic field lines. As a result, the mode phase velocity is greater than the ion thermal velocity even in isothermal plasma, which allows the mode to avoid strong ion Landau damping.

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Discrete Alfvén Eigenmodes Destabilizeded by Energetic Particles in High-β Tokamaks

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Multiple branches of discrete Alfvén eigenmodes (termed αTAE) are observed in high-β second ballooning-mode stable toroidal plasmas due to the existence of multiple α-induced potential wells. Here, β is the ratio of plasma to magnetic pressures and α denotes the ballooning/interchange drive due to pressure gradient and curvature. In addition to the lowest-order quasi-marginally stable αTAE [*Hu and Chen*, 2004], the higher-order αTAEs experience small but finite Alfvén continuum damping through wave energy tunneling. Due to their trapped features, these high-n (toroidal wavenumber) eigenmodes exist independently of the toroidal Alfvén frequency gap, in contrast to the usual low-β TAE (toroidicity-induced Alfvén eigenmode) [*Cheng et al.*, 1985]. Both the quasi-marginally stable and the finitely damped αTAEs can be readily destabilized by energetic particles via wave-particle resonances. For negative magnetic shear, the αTAE can extend into the small-α regime and evolve into the low-β TAE. The detailed kinetic excitation mechanisms by both magnetically trapped and circulating energetic particles will be discussed.

Work supported by DOE and NSF.

MHD Equilibrium Reconstruction from Correlated Experimental Data

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Equilibrium reconstruction is an important tool for the real-time analysis of plasma physics experiments. For axisymmetric systems, the Grad-Shafranov equation relates the flux to the pressure and toroidal field. In equilibrium reconstruction, the inverse of this relationship is explored. The pressure and toroidal field are parameterized, and the best fit of these parameters to the experimental data is sought via the minimization of a cost function. The simplest choice for the cost function is a sum of squares of differences between observed and computed quantities, leading to a technique known as *ordinary least squares*. However, if the observations are correlated, as one would expect from the fluctuations of the edge magnetic field, such a cost function improperly weighs the residuals and produces inferior results. The optimal treatment, *generalized least squares*, includes the a priori covariance matrix of the data in the cost function and leads to a "best linear unbiased estimate" (BLUE). In the context of a simple numerical model, we compare the two approaches with respect to the fidelity of the fit in the regime of linear inverse theory, when the noise is relatively small. The presence of long-range correlations actually aids the fit of the BLUE, a feature much less pronounced or absent for the ordinary least squares treatment. Thus, the generalized least squares method produces significantly better results for measurements subjected to strong, long-range correlations. We also find that, in the absence of detailed pressure measurements, the parameterization contains near-degeneracies as the toroidal field and pressure terms exchange roles in the minimization.

Kinetic effects on resistive wall mode in tokamaks

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Abstract

The resistive wall mode (RWM) is an external kink driven unstable by the plasma pressure and the finite electrical resistivity of the surrounding metal wall. Since the RWM limits the maximum achievable plasma beta, it significantly reduces the power density in a tokamak reactor. It has been observed that the RWM can be suppressed by fast plasma rotation [1]. However, rotation alone is not expected to fully stabilize the RWM in ITER-like plasmas. It has been recently shown [2] that trapped-particle kinetic effects induced by the mode-trapped-particle interaction significantly damp or even fully stabilize the RWM in the slow plasma rotation regime for ITER-like plasmas. The resonant denominator has the form $\omega_D + \omega_E - i\nu_{eff} - \omega$, where ω_D, ω_E, ν_{eff} and ω are the magnetic drift, $E \times B$ drift, collision and mode frequencies. We have carried out the RWM stability analysis of ITER-like plasmas using a kinetic postprocessor of the PEST code including trapped and circulating particle kinetic effects. The kinetic postprocessor is based on the kinetic extension of the Haney-Freidberg's formula yielding the normalized RWM growth rate $\gamma\tau_w = -(\delta W_{MHD}^{\infty} + \delta W_K)/(\delta W_{MHD}^{b} + \delta W_K)$, where δW_{MHD}^{b} and δW_{MHD}^{∞} are the energies from fluid and vacuum with and without wall, δW_K is the kinetic energy, and γ and τ_w are the RWM growth rate and magnetic diffusion wall time. Since the growth rate of the resistive wall mode is small, the mode eigenfunction of marginally stable equilibria is used to calculate all the δW's. The mode eigenfunction at marginally stability is obtained from PEST by adjusting the wall position . The key assumption in the derivation of the dispersion relation is that mode eigenfunction is approximately insensitive to the wall position and kinetic effects. The kinetic postprocessor is also applied to the DIII-D equilibria and the the effects of trapped particles on the stability of the RWM in DIII-D is investigated. The authors thank Professor J.P. Freidberg for suggesting the use of ideal MHD codes to compute the RWM eigenfunction. This work was supported by US DOE Contracts DE-FG02-93ER54215 and DE-AC02-76CH03073.

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NIMROD Simulations of SSPX Spheromak Physics

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Abstract

The SSPX spheromak is formed and driven by a coaxial electrostatic gun that injects current and magnetic flux. The measured magnetic fluctuation amplitudes and core temperature tend to be anti-correlated, and both depend on the details of the current drive formation and sustainment pulses. The relative values of λ_{gun} (the ratio of the gun current to the gun magnetic flux) and λ_0 ($\lambda_0 = \mu_0 J_{\parallel}/B$) in the flux conserver have an important influence on the spheromak plasma performance. Here we report NIMROD simulations of SSPX extending earlier work, [1] in which we study the sensitivity of the spheromak behavior to variations in λ_{gun} relative to λ_0 during the sustainment phase of the current pulse. The NIMROD simulation results are in fairly good agreement with many features observed in SSPX and underscore the importance of controlling the current profile in order to mitigate magnetic fluctuation amplitudes and improve magnetic confinement. We also have added external circuit equations for the new 32 module capacitor bank being built for SSPX. The new capacitor bank will add considerable flexibility in shaping the injector current pulses and increase the peak injected currents substantially and hence the magnetic energy in the spheromak, which in turn is expected to lead to higher temperature plasmas. We report the results of new NIMROD simulations of SSPX including the new capacitor bank model.

This work is supported by the U.S. Department of Energy, Office of Fusion Energy Sciences, under Contract No. W-7405-ENG-48 at the University of California Lawrence Livermore National Laboratory and under grant FG02-01ER54661 at the University of Wisconsin Madison.

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Nonlinear electron cyclotron resonance heating in stellarators

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In a stellarator with helical ripple, the spatial extent of the local minima in the magnetic field can be of order of the resonant interaction region of applied ECRH waves due to short wavelength —B— variation. In this event, particles trapped in the helical ripples in stellarators bounce back and forth along the magnetic field line, and trapped particles get energy from the wave repeatedly. Quasi-linear theory is not valid in describing the wave-particle interaction when the turning points are very close to the resonance region or when particles stay in the resonance region. In this case, the particles stay in the resonance region long enough to make several energy excursions caused by relativistic nonlinear wave-particle interaction. When this is the case, the wave and particles are correlated and the stochastic process is not viable. In this work, nonlinear wave-particle interaction for deeply trapped particles is described quantitatively. Particles get net heating with collisions. For the case relevant to helically trapped electrons, the equivalent diffusion operator of a phase space is derived accounting the dominant nonlinear wave-particle interaction. * Research supported by U.S. DoE under grant no. DE-F02-99ER54546

Nonlinear Rayleigh-Taylor-Parker Instability: Direct MHD Simulations *

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Abstract

The line-tied Rayleigh-Taylor-Parker (RTP) instability may provide a prototype for a range of macroscopic phenomena such as ELMs and blobs in the SOL region of tokamaks, and substorm onset at the near-Earth magnetotail. However, the nonlinear stage of the RTP instability is not sufficiently well understood. An interesting theoretical prediction, based on reductive perturbation theory, is that the system will generically exhibit explosive growth or "detonation" [S. C. Cowley and M. Artun, Phys. Rep., 283, 185 (1997)]. In this study we present a series of 3D simulations of the nonlinear RTP based on the full ideal and compressible MHD equations. The simulations implement the so-called CWENO scheme which has been demonstrated to be robust in physical situations that require resolution of narrow, potentially discontinuous, small-scale structures. Our nonlinear simulations exhibit the characteristic finger pattern in the density and pressure profiles. Furthermore, shock-like coherent structures are found to form and dominate in the early nonlinear stage of the evolution, as the system evolves through a period of exponential growth from an initially unstable equilibrium. While the system shows a clear tendency to develop discontinuities, the solutions are bounded at all times and show no tendency to form finite-time singularities (or to "detonate"). The shock structure appears to be an intermediate asymptotic feature of the nonlinear development of the RTP instability, since its properties appear to be generic and insensitive to the initial conditions. The relevance of the nonlinear RTP instability to the problems of ELMs, blobs, and substorm onset will be discussed.

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Fully Implicit Solution of the Full 2-Fluid MHD equations in 2-dimensions using High-order Finite Elements with C^1 Continuity

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Abstract

It has been recognized for some time that it is necessary to go beyond the simple "resistive MHD" description of the plasma in order to get the correct quantitative results for the growth and saturation of global dissipative modes in a fusion device. The inclusion of a more complete "generalized Ohms law" and the off-diagonal terms in the ion pressure tensor introduce Whistler waves, Kinetic Alfven waves, and gyro-viscous waves, all of which are dispersive and require special numerical treatment. We have developed a new numerical approach to solving these Extended-MHD equations using a compact representation that is specifically designed to yield efficient high-order-of-accuracy, implicit solutions of a general formulation of the compressible Extended-MHD equations. The representation is based on a triangular finite element with fifth order accuracy that is constructed to have continuous derivatives across element boundaries, allowing its' use with systems of equations containing complex spatial derivative operators of up to 4th order. The final set of equations is solved using the parallel sparse direct solver, SuperLU, which makes linear solutions exceptionally efficient, since only a one-time LU decomposition is required. The magnetic and velocity fields are decomposed without loss of generality in a potential, stream function form. Subsets of the full set of 8 equations describing unreduced compressible Extended 2-fluid MHD yield (1) the two variable reduced MHD equations[1], and (2) the 4-field Fitzpatrick-Porcelli equations[2]. Applications are presented showing the effect of "two-fluid" terms, compressibility, and a background "guide field" on 2D magnetic reconnection. Equations for generalizing this to a full 3D solution are presented, along with an assessment of the computational requirements.

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Kinetic Simulation of Inertial-Electrostatic Confinement Experiments at Los Alamos National Laboratory

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Abstract

We discuss the application of the DEMOCRITUS simulation package to the simulation of experiments conducted at the Los Alamos Inertial-Electrostatic Confinement (IEC) device [1,2]. Recently considerable new experimental advances have been made [3], particularly with regards to the study of the stability of the electron population in the virtual cathode [4] and on proving experimentally the POP solutions predicted theoretically [5,6].

The momentous advance made experimentally requires a new simulation effort for explaining and interpreting some of the experimental finding, particularly in the area of the stability of the configurations obtained experimentally. To this end we have recently started a new effort to apply the existing DEMOCRITUS package [7] to the simulation of the IEC device at Los Alamos.

DEMOCRITUS is a 2D general geometry electrostatic PIC code. Three fundamental ingredients compose the package. First, we have a selection of different particle solvers including the explicit Boris algorithm, the implicit predictor-corrector scheme and a new fully implicit particle mover based on a Newton non-linear solver. Second, we use an adaptive grid with a general geometry discretization of the Poisson equation and we use a multigrid preconditioned Krylov solver for its solution [8]. Third, we use the immersed boundary method to handle complex geometric features (e.g. the presence of the grids to accelerate the particle in the IEC device) [9].

In the present poster we describe the method, we present a number of validation and verification results where we compare our simulation results with previous 1D simulations and with the experiment.

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Kinetic Reconnection in Force Free and Cusp Configurations

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Abstract

Great advances have been made in recent years in the study of the fundamental physics of reconnection. Using the GEM challenge [1] as a reference problem several groups have coordinated their efforts around the common goal of cracking the problem. A specific line of investigation that has spurred from the GEM challenge effort has been the study of the effect of a guide field on the physics of reconnection. Our previous work has investigated with kinetic PIC simulations the effect of the guide field on the physics of reconnection.
First, we have shown [2] that the off-diagonal terms of the pressure tensor remain the dominant cause of the decoupling of electrons and field lines in the innermost reconnection layer. However, as the guide field is increased the model for the role of the off diagonal terms changes and the electron inertia terms become more important [2]. Second, the decoupling of ions from the field lines in the outer reconnection layer changes nature as the guide field is increased: at small guide field values (or zero) the Hall physics allows the decoupling, but at higher guide field, the Kinetic Alfven Wave physics becomes the dominant mechanism [2]. Furthermore, particle acceleration changes as the guide field is increased [3].
These effects have been proven for the case of a Harris equilibrium with the addition of a guide field. In the present work we consider how these effects are conserved or modified in force free and cusp equilibria. We consider force free equilibria of the form:

$\mathbf{B}(z)=[B_0 \tanh(z/L), B_0/\cosh(z/L), 0]$.

Furthermore, we consider cusp configurations relevant for the VTF experiment [4] of the form:

$\mathbf{B}(x,y)=B_0 [x, -y, l_0]$.

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SINGLE AND MULTIPLE HELICITY STATES IN RFPS

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The transition from single-helicity (SH) to quasi-single-helicity (QSH) and from QSH to multiple helicity (MH) states is studied. For the cases studied, the QSH-MH transition is over a small range of Hartmann number H, but does not appear to have hysteresis. If a helical radial magnetic perturbation B_r of sufficient amplitude is applied at the boundary, QSH can exist for larger H, and hysteresis can appear. However, since QSH states have some chaotic field lines, the B_r at the boundary allows field lines from the interior to hit the wall. We have explored applying a helical *electric* field perturbation E_r (i.e. current j_r) at the boundary, and found that the QSH state can again occur for high H, without field lines hitting the wall. In a related study, we have investigated the hypothesis that SH states occur at low H because only a single helical mode (m, n), with $m = 1$, $n \sim R/a$, is linearly unstable for such resistive plasmas. For these studies, results from a linear resistive MHD eigenvalue code are compared with three-dimensional nonlinear simulations.

Simulation of 3D Kinetic Reconnection

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Abstract

3D kinetic simulations of reconnection are conducted using the implicit kinetic code CELESTE3D. We consider a number of configurations, from the classic Harris equilibrium to more complex bifurcated equilibriums [1], to 2D equilibriums with curved field lines [2]. We consider apply a number of diagnostic tools including Fourier mode analysis, Poincare plots and field line tracing.

The goal of our analysis is to address how reconnection onset can be achieved in 3D, and once reconnection starts how it evolves and affects the 3D magnetic topology. Two main issues will be addressed.

First, recent studies [3-4] based on Harris equilibriums investigated the process of reconnection onset due to the non-linear interaction of the lower-hybrid drift instability with the tearing instability. We consider how the different equilibriums described above and in particular how the presence of guiding and perpendicular fields modifies the mechanisms described in Ref. [3-4].

Second, we consider the topology of the magnetic field and consider the effects of the creation of an initial magnetic null point and its extension into an x-line [5].

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Volume preserving integrators for solenoidal fields on a grid

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A novel method of integrating solenoidal flows (magnetic fields) given on a grid is developed. In three dimensions, the method involves splitting the flow into two or possibly three flows that are two dimensional and area preserving, and can therefore be integrated by Crank-Nicolson or a modified form of leapfrog, both of which exactly conserve area. The method involves an interpolation scheme which ensures the solenoidal nature of the field throughout the domain (on and off the grid) by means of tri-cubic splines. Examples with realistic three-dimensional fields are shown. It is shown that the method is easily generalized to arbitrary curvilinear coordinates and also generalizes to higher dimensions. A method of integrating compressional three-dimensional time-dependent flows given on a grid is outlined.

Assessing the role of artificial diffusivity in the NIMROD simulations of the Livermore spheromak

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Abstract

Nonlinear simulations of the SSPX spheromak have used a large artificial diffusion term in the continuity equation to avoid complete evacuation of the gun region during the formation stage of the experiment (see, e.g., Ref. [1]). A question then arises as to what effect this term may have on the interpretation of the results. In this poster, we present a discussion of this issue based on exact solutions of several problems related to the plasma behavior in SSPX. In order to isolate the effect of artificial diffusivity, we "turn off" all other transport processes. The problems assessed are: flute instability in an axisymmetric magnetic field (as an example of pressure-driven modes); dispersion and damping of linear magnetohydrodynamic waves; properties of rarefaction waves and shock waves parallel to the magnetic field. Not surprisingly, the effects of a large diffusivity may be substantial in problems where compressibility effects are important. In particular, in the analysis of the flute instability, the diffusivity enters the problem only via non-paraxial terms. In certain range of perturbations spatial scales, overstable modes are present. On the other hand, at a very large diffusivity, one recovers a "classical" flute instability, although with a different adiabatic index. In sum, the effects of large diffusivity are more quantitative than qualitative - the instability does not change its fundamental nature. Conversely, we find that artificial diffusivity may have a substantial qualitative effect at the stage of spheromak formation in the "bubble-burst" mode, when violent supersonic motions create strong hydrodynamic flows, with shocks and rarefaction waves propagating along the deforming flux tubes. However, after the plasma "settles down," these motions essentially vanish. A remarkable similarity of NIMROD predictions and the actual features of the SSPX plasmas after the bubble-burst phase seems to agree with the general conclusions of our study. Repeating one of the computations from the end of the formation stage with the artificial diffusivity reduced by a factor of 10 results in an increase in peak temperature of 10 eV (about 10%). This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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The MHD dynamics of momentum transport and plasma flows

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Both in laboratory and astrophysical plasmas, there are situations in which momentum transport and flow phenomena can not be explained by classical processes. The magnetic fluctuations arising from the MHD instabilities in these plasmas are believed to have an important role in transporting toroidal momentum. The radial structure of the fluctuation-induced J x B forces can determine the physics of the momentum transport throughout the plasma. We investigate the three-dimensional nonlinear MHD dynamics of momentum transport in the Reversed Field Pinch (RFP). The three-dimensional nonlinear resistive MHD code DEBS, with an ad-hoc momentum source term added to the momentum equation, is employed. We first study momentum transport by a single tearing instability in the presence of the applied momentum source. The linear computations show that a single mode perturbation does not alter the flow profile and therefore can not transport momentum. However, we observe momentum transport by the perturbation of a single mode during the quasi-linear saturation. The linear computations are also compared with the analytical linear theory. The effect of both magnitude and shape of the plasma flow on the tearing instability is also examined. It is shown that plasma flow with high shear can enhance the linear growth rate or even drive a tearing mode unstable. We then examine the nonlinear dynamics of momentum transport when all the tearing fluctuations are present. It is shown that magnetic fluctuations can alter the flow profile through the nonlinear fluctuation-induced J x B term. The relatively high Lundquist-number computations show a strong correlation between the magnetic fluctuations and the flow profile relaxation.

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

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A self-consistent treatment of both a long wave-length tearing mode and electrostatic background micro-turbulence is developed with consideration of applications to the single helicity state of the RFP. Turbulent viscosities are derived for the case of homogeneous micro-turbulence as well as for micro-turbulence developing in a sheared magnetic field. A negative viscosity is found in both cases, motivating the possibility of generation of large scale flows via an inverse cascade of enstrophy. The electrostatic micro-turbulence is found to be largely decoupled from the long wavelength magnetic fluctuations, giving rise to a weak turbulent resistivity. The upshot of this result is that the tearing mode is replaced by a coupled magnetic island-convective cell system. The nonlinear evolution of this system is under analysis, with special emphasis on the effect of the finite size island on the background turbulence. Also, from this perspective, the meaning of a Hartmann Number criterion for access to the QSH state is unclear, since the turbulent viscosity (which likely exceeds the collisional viscosity), is in fact negative on large scales. The results of ongoing considerations of this issue will be reported.

Turbulence spreading modelling in temperature gradient driven turbulence

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Abstract:

In order to understand the mesoscale phenomena in turbulent tranport, spatial propagation of turbulence and its direct inverse process, namely the propagation and broadening of transport barriers should be understood[1]. In this presentation, a basic derivation of a simple nonlinear dynamical model of spreading of turbulence (ala k-epsilon models) will be presented, directed at this purpose. In the absence of local growth, the model predicts sub- diffusive spreading of turbulence. With local growth and saturation via nonlinear damping, ballistic propagation of turbulence intensity fronts is possible. Studies of turbulence jumping through gaps and penetrating marginal or stable regions will be presented. Theoretically, the transport model is derived starting from a reduced fluid system of equations and nonlinear energy flux term is computed via a particular form of renormalizable perturbation theory. It is possible to derive with a similar approach, a hierarchical shell model, which is in a way a discretized version of our transport model. The implications of addition of external "deterministic" (i.e. multiplicative) and "stochastic" (i.e. additive) noise to the initial model equations will also be considered.

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A Finite Volume Approach to Compressible MHD Simulations of High β Tokamak Plasmas

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Abstract

A new numerical approach based on the finite volume-spectral method is developed for nonlinear and compressible magnetohydrodynamics(MHD) simulations of high β tokamak plasmas. The finite volume method has an advantage over conventional finite difference methods for that it does not require a regularity for the grid structure. Furthermore, being based on the conservative form, it naturally satisfies the divergence free condition of magnetic field [1]. We have constructed two different numerical schemes to evaluate the accuracy of our codes. One is described in the conventional flux coordinate system. The radial direction is discretized using the finite volume method, while the periodic poloidal and toroidal directions are discretized using the pseudo-spectral method. In this approach, the high accuracy of resistive linear MHD instabilities is expected to be reproduced. The other numerical scheme consists of the quadratic finite volume mesh in the poloidal plane, on which the derivatives are estimated by the finite volume method for the direction parallel to the plane and by the psuedo-spectral method for perpendicular to the plane. The simulation results by these codes for the linear and nonlinear evolutions of resisitive instabilities are presented, and advantage and disadvantage of each code is discussed.

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Resistive Plasma Resistive Wall Modes

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Resistive plasma resistive wall modes (RPRWM) are similar to ideal plasma resistive wall modes (IPRWM). They can occur below the β threshold of ideal IWRWMs. Like IWRWMs, they are stabilized by toroidal rotation. Their linear growth rate scaling depends on both plasma resistivity η and the wall resistivity η_w. The growth rate γ has been verified both with M3D [1] in tokamaks and with the ETAW code [2] in RFPs to scale as $\gamma \sim \eta^{1/3}\eta_w^{4/9}$. It is possible to obtain this scaling theoretically [3], although the assumptions of the theory are more restrictive than in the simulations. The ideal mode dominates if $\eta_w > c_0\eta^{3/5}$, where c_0 depends on other parameters. This condition is marginal in some experiments and not easy to satisfy in numerical simulations.

Since the RPRWM is stabilized by toroidal rotation, like the IPRWM, it has probably not been detected in experiments. It might be an issue in slowly rotating plasmas.

Nonlinear simulations of RPRWMs in NSTX and ITER geometry have been carried out. The mode appears as a large amplitude external kink. The halo current asymmetry caused by the nonlinear modes tends to produce a toroidal peaking factor (TPF) less than 2. This behavior differs from disruptions caused by internal modes, which are more turbulent, and which tend to have TPF greater than 2.

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Determining the phase-velocity of magnetic islands in two-fluid plasmas

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The likely effect of neoclassical tearing modes on next-step tokamaks has yet to be determined with any degree of certainty, due to the many remaining unanswered questions in neoclassical tearing mode theory. Progress in this area is of vital importance to ITER. One of the major unknowns in neoclassical tearing mode theory relates to the (hopefully!) stabilizing effect of the ion polarization current. Both the sign and magnitude of this effect depend very sensitively on the island propagation velocity relative to the local velocities of the ion and electron fluids. Unfortunately, there is, as yet, no widely-accepted theory which predicts the propagation velocity of a nonlinear magnetic island in a two-fluid plasma. The development of such a theory is, therefore, of primary importance.

The physics which determines the phase-velocity of an isolated magnetic island, formed as the result of a nonlinear tearing instability, is investigated using a two-fluid model in slab geometry. It is found that the phase-velocity is determined by *momentum transport* across the magnetic flux-surfaces immediately surrounding the magnetic separatrix. Analytic predictions for the phase-velocity have been obtained in both the sub-sonic and sonic regimes. In the *sub-sonic* regime, which governs very wide magnetic islands, $k\,V_* \ll k_\parallel\,c_s$, where V_* the unperturbed local diamagnetic velocity, k is the island wave-number, $k_\parallel$ the parallel (to the magnetic field) wave-number calculated at the edge of the island, and c_s the local sound speed. In the *sonic* regime, which governs moderately wide islands, $k\,V_* \sim k_\parallel\,c_s$.

Extensive numerical simulations have been performed using a set of 2D, two-fluid, reduced-MHD equations. The results of these simulations are in excellent agreement with the analytic theory.

The theory described here predicts that, under normal circumstances, comparatively wide magnetic islands should propagate in the ion diamagnetic direction, and should experience a *stabilizing* effect due to the *ion polarization* current. This stabilizing effect may well control the threshold for the onset of neoclassical tearing modes in next-step tokamaks.

Hysteresis and the Onset of Fast Magnetic Reconnection

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Abstract

Magnetic reconnection is vastly different depending on the collisionality of the system in question. Collisionless (Hall-mediated) reconnection is fast, taking the form of Petschek's open outflow configuration. Collisional (resistive MHD) reconnection takes the Sweet-Parker form with a macroscopic current layer. The transition between these two states with varying resistivity may be important for understanding the onset of magnetic reconnection in physical systems such as solar eruptions and laboratory fusion experiments. We investigate the transition using basic theoretical arguments and two-fluid numerical simulations. We show that, for intermediate values of the resistivity, the reconnection is bistable, i.e., the two distinct reconnection configurations independently exist for the same parameters. The final configuration depends on the history of the system. We map the hysteresis curve and demonstrate that the transition from collisional to collisionless reconnection is catastrophic: below a critical resistivity the slow Sweet-Parker solution ceases to exist and fast reconnection abruptly onsets. We present a scaling analysis for the resistivities at which transitions occur, benchmark these scalings with simulations and compare the predictions to parameters in the solar corona and for a sawtooth crash.

Pseudospectral simulations of shear-flow-suppressed turbulent transport in the Helimak and Large Plasma Device experiments

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Nonlinear high-resolution electrostatic drift wave and Kelvin-Helmholtz simulations are performed for a plasma slab, periodic in one direction and satisfying Dirichlet boundary conditions in the other. The objective of this work is to investigate the effect of sheared $E \times B$ flows on the turbulence and corresponding transport in both the Helimak [1] and Large Plasma Device [2] experiments. Numerical results are then compared against experimental data. The code uses a hybrid Chebyshev-Fourier tau-collocation scheme for spatial discretization and an implicit-explicit finite difference scheme for the time evolution.

For small magnetic field pitch angles in the Helimak, turbulence is observed to increase to $\delta n/n \sim 50\%$, characteristic of large vortices and density blobs in a Rayleigh-Taylor plasma instability. When a negative radial bias voltage is turned on, it drives an axial $E \times B$ shear flow, and a transition to a state of reduced turbulence with $\delta n/n \sim 20\%$ is observed after a certain threshold of the bias potential. Simulations are aimed to predict this reduction in density fluctuations due to the sheared flow.

In the LAPD, two bias regimes are studied that result in weak and strong rotational sheared flows, dominated by drift wave and Kelvin-Helmholtz turbulence, respectively. In the drift wave regime there is a gentle sheared plasma rotation profile that suppresses the anomalous transport. In the strong shear or Kelvin-Helmholtz regime [3], linear instability theory gives mode numbers $m = 1$ to $m = 10$, corresponding to frequencies up to 100 kHz, which are linearly unstable. The vorticity turbulence undergoes an inverse cascade primarily involving low mode numbers $m = 2, 3, 4 \ldots$ with $20 - 50$ kHz fluctuations.

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Comparison of theoretical estimates of magnetic island width with numerical calculations in MHD equilibria

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Abstract

Magnetic islands play an important role in plasma confinement. In otherwise axi-symmetric devices, tearing modes may saturate at finite island width, and in non-axisymmetric devices magnetic islands are a generic feature of the three-dimensional equilibrium. Islands are typically associated with a local flattening of the pressure gradient. If the islands are sufficiently large so as to overlap, then regions of stochastic field lines will be produced. Islands and regions of chaotic fields lead to enhanced radial transport.

Analytical analyses of equilibrium island widths employ a small island assumption to calculate the self-consistent effect of the island on the current and pressure profiles, and treat the singular surface using a boundary layer technique. Assumptions of simplified geometry are often used. Analytic expressions for the island width depend on physical effects such as the resonant Pfirsch-Schlüter currents, the tearing mode stabilty parameter Δ', the resistive interchange stability parameters E,F and H of Glasser et al [1] and neoclassical bootstrap currents [2].

This presentation will compare analytical estimates of island widths developed by Hegna [3] with widths calculated using the 3D equiblibrium code PIES [4]. The following issues will be investigated: 1) code verfication at small island widths and simple geometry, where the analytical and numerical results should agree; 2) determine domain of validity of analytic approximation for the case with large islands and realistic geometry; and 3) generally further the understanding of the physics of island formation in relevant experiments.

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Conservation Properties of a Guiding-Center Fokker-Planck Collision Operator

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Abstract

The conservation properties of a guiding-center Fokker-Planck collision operator recently derived[1] by Lie-transform methods are investigated. Because the guiding-center Fokker-Planck collision operator is already in particle-conserving divergence form, the present work focuses on its momentum and energy conservation properties as well as its H-theorem property. Note that the guiding-center Fokker-Planck collision operator describes guiding-center collisions in a 4+1 phase space (energy-space coordinates + magnetic moment or pitch angle) in which the gyroangle information has been eliminated. Hence, the conservation properties are expressed in terms of local quantities (e.g., friction forces and energy dissipation rates) as well as dissipative gradients and fluxes.

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Gyroviscosity and (ion) perpendicular viscosity for plasma of arbitrary collisionality*

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Abstract

The drift kinetic equation [1], derived by R. D. Hazeltine for magnetized plasma of arbitrary collisionality, is widely believed to be exact through the second order in the expansion of small Larmor radius over a characteristic perpendicular length scale. We have discovered [2] that this equation is only exact through the first order. The reason is that Hazeltine used the incomplete expression for the gyrophase-dependent portion of distribution function to derive the equation for the gyrophase-averaged distribution function. Consequently, the second-order distribution function, as well as gyroviscosity and perpendicular viscosity derived by this approach, are incomplete. By slightly relaxing the Hazeltine's orderings, we can obtain a drift kinetic equation as well as the gyrophase-dependent portion of the distribution function that are accurate through the second order in the Larmor radius expansion. The formalism developed allows obtaining expressions for gyroviscosity and perpendicular viscosity for plasma of arbitrary collisionality in terms of few moments of the zeroth and first order (in the Larmor radius expansion) pieces of the gyrophase-averaged distribution function. In particular, for the short-mean-free-path plasma, the known expressions for the viscosity [3] can be recovered.

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Extended MHD stability analysis for transport modeling of ELMs

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Abstract

One of the key elements of the modeling of Edge-Localized Modes (ELMs) in tokamak plasmas is the triggering condition for ELM crashes. There is a consensus that ELMs can be triggered either by ballooning or peeling instabilities. The ELM triggering conditions have been recently studied in the ideal MHD limit [1, 2]. There are circumstances in which these conditions can be strongly modified by finite resistivity and viscosity. A set of equlibria applicable to the DIII-D geometry is generated with the TOQ and TEQ equilibrium codes and initial studies are carried out with the ideal MHD stability codes DCON, ELITE and BALOO. In this report, the extended MHD NIMROD code is used to study the effects of resistivity and viscosity on ELM triggering conditions for the cases that are close to the peeling-ballooning threshold. The modified peeling-ballooning threshold, which includes the effects of resistivity and viscosity, is implemented in the ASTRA code model for the H-mode pedestal and ELMs [3]. The model for the pedestal and ELMs is used in the ASTRA code to follow the time evolution of tokamak discharges from L-mode through the transition from L-mode to H-mode, with the formation of the H-mode pedestal, and, subsequently, to the triggering of ELMs. The model for the H-mode pedestal and for the triggering of ELMs predicts the height, width, and shape of the H-mode pedestal and the frequency and width of ELMs. Several systematic scans with plasma parameters, such as auxiliary heating power and elongation are presented. The new dependence for the ballooning threshold, derived from the MHD described above, is implemented in the ASTRA transport code. Results of integrated modeling of DIII-D like discharges are presented. The effects of the modified peeling-ballooning stability threshold on the ELM and pedestal parameters are discussed and the resulting dependences are compared with experimental observations.

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Magnetic Reconnection and Associated Transport of Plasma Thermal Energy*

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Abstract

The excitation of drift-tearing modes in the high-temperature regimes that are achieved in present day experiments is an important theoretical issue that remains to be resolved. The original theory of these modes [1] was carried out for collisional regimes where the effects of finite thermal conductivity are not important. A modern linearized theory [2] that includes the effects of a small but finite thermal conductivity shows that the structure of the mode is drastically changed relative to that of the regime with "adiabatic" electrons. When these effects become relevant, the threshold for the mode excitation, that is related to the gradients of the plasma current density and pressure, becomes difficult to overcome. This is consistent with a previous analysis that found the mode to become stable in the presence of a significant electron temperature gradient in collissionless regimes [3].

On the other hand, we have pointed out earlier that in problems involving singular perturbations, non-linear effects become important for relatively small amplitudes. Thus the limitations on the linear mode amplitude necessary for the validity of the linearized approximation are identified for the present case. Then, we assume that if the threshold is overcome initially, the stabilizing finite thermal conductivity terms can be reduced locally, for instance by the formation of small islands. Three possibilities have been explored: a local depression of the longitudinal electron thermal diffusion coefficient $D_{\|e}^{th}$, a local flattening of the electron temperature profile, and a combination of both. In all these cases the "threshold" from which the growth rate is evaluated can be reduced to the level ($\Delta'_{crit} \approx 0$) that is found in the highly collisional limit while the frequency of oscillation is of the order of the electron diamagnetic frequency and is higher than the relevant resistive growth rate.

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Harmonic Grid Generation for the Tokamak Edge Region

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Numerical simulation of magnetically confined plasmas is uniquely challenging because of its high degree of anisotropy. Parallel flows are typically orders of magnitude larger than transverse flows. Ratios of parallel to transverse thermal conductivities can be of order 10^{10} in realistic fusion plasmas. Ratios of fast to slow wave propagation speeds in the presence of two-fluid effects can be equally severe. Corruption of small transverse flows by large parallel flows due to discretization errors can destroy numerical accuracy.

A principal method for avoiding such corruption is the use of flux coordinate grids, in which at least one coordinate ψ approximately satisfies $\mathbf{B} \cdot \nabla\psi = 0$. In previous work, such a flux coordinate system is based on a static, axisymmetric equilibrium. If the simulation is followed far enough into the nonlinear regime, the magnetic field can evolve away from this initial configuration, causing the coordinate system to lose its field-aligned properties.

We have developed a method of harmonic grid generation to achieve alignment of the grid with the magnetic field. It generates a mapping of a rectangular grid in the logical domain to a simply-connected curvilinear grid with the desired properties in the computational domain. It uses a modified Beltrami equation, a generalization of Laplace's equation for curvilinear manifolds, in which the metric tensor $\mathbf{g}$ is chosen to provide the necessary grid properties for alignment as well as adaptation to the values or gradients of specified quantities. The method provides independence of initial representation and guarantees a well-posed grid. A variational approach allows the computation of a best fit for 3D magnetic fields which do not have nested flux surfaces.

An important application of this work is the development of an improved grid for simulation of the tokamak edge region, including the x-point on the separatrix, the pedestal region inside the separatrix, and the scrape-off layer and divertor outside the separatrix. Results will be presented for this application.

"Crystal" Magnetic Structure in Axisymmetric Plasma Accretion Disks*

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Abstract

The basic equilibrium conditions of an axisymmetric thin gaseous disk are well known [1]. The problem of formulating the equivalent conditions for a plasma disk where the electric and magnetic field configurations play an important role is, instead, considerably more complex. In particular, a characteristic set of coupled non-linear equations has to be identified and solved in physically relevant limits. For a gaseous disk, the vertical equilibrium condition can be separated from the radial condition, in the thin disk limit, and the vertical profile is determined once the temperature profile is prescribed. In the case of plasma disks, the vertical and the radial equilibrium conditions are intrinsically coupled when the toroidal current densities in the disk are significant.

The frozen-in law condition, for rotating plasmas with large electrical conductivities, leads to find that the relevant magnetic surfaces can exhibit a "crystal" structure of the poloidal magnetic field that involves a sequence of pairs of oppositely directed toroidal current filaments and have nul points (of the poloidal magnetic field). The corresponding plasma pressure is modulated radially with a period of the order of the height of the disk. The theory is carried out in the limit where the plasma pressure exceeds the magnetic field pressure ($\beta > 1$) as this lends itself to a complete non-linear analytic treatment. In view of dealing with the case where $\beta \sim 1$, that is of special importance in order to treat disks from which jets can emerge, the appropriate equations are derived and their symmetries are pointed out. The considered equilibria are related to the axisymmetric ballooning modes [2,3] which can fit within thin accretion disks and are marginally stable. The considered "crystal" configurations may be sustained by a form of non-linear coupling with mode packets of "similar" normal modes, which would exist in a relatively long cylinder [4] and have a slow but finite growth rate. These configurations are regarded as the initial states from which tridimensional modes [2] can be excited in the regions where the poloidal magnetic field is minimal and produce considerable angular momentum transport in view of explaining the accretion rates of significant astrophysical objects.

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The Columbus Concept within a Science Based Approach to Fusion Research*

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Abstract

Exploring the physics of meaningful fusion burning plasmas by a spectrum of complementary experiments is a keystone of the "Science First" approach to fusion research. The rationale for this approach is that the possible discovery of new phenomena and the understanding of known ones, in particular sawtooth oscillations, under fusion burning conditions will certainly contribute to define the characteristics of future fusion reactors. In this context, the role of the discovery of the delayed neutrons in the development of fission reactors is an important example to consider. Accordingly, we have progressed in the study of the Columbus experiment [2] that is designed to reach ignition conditions in D-T plasmas where the heating due to the produced α-particles compensates for all energy losses. Our intention is to incorporate the main engineering solutions adopted for Ignitor in the Columbus design and to take advantage of the results of the R&D effort that has been carried out already. Columbus is characterized by modestly increased linear dimensions ($R_0 \cong 1.5$ m is the plasma torus major radius, $a \cong 0.53$ m and $b \cong 0.98$ m are the minor radii) and by lower current densities in both the TF and PF magnets and within the plasma column. Like Ignitor, the machine is based on normal conducting, cryogenic magnet technologies and an optimized plasma confinement configuration which allow it to reach (real) ignition conditions by fusion reactions. The device concept takes advantage of the maturity of the Ignitor program, including the construction of full size prototypes of the main machine components, for the definition of its main elements. The linear increase in dimensions by a factor of 25/22 relative to Ignitor corresponds to an increase of the plasma column volume of about 45% and is guided by the criterion that the average poloidal filed which can be produced by the plasma current remains about equal to that of Ignitor for comparable values of the magnetic safety factor. The toroidal magnetic field is slightly decreased, by the factor 12.6/13 relative to Ignitor. The reference plasma current for Columbus is $I_p \cong 12.2$ MA that is the value that the ITER concept would produce for the same stability safety factor without, however, reaching ignition. Columbus is proposed for construction in the U.S. while Ignitor has been developed in Italy.

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Symbolic Signal Processing for Tokamak Turbulence*

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Abstract

Tokamaks plasma is turbulent. All physical quantities like density, electrostatic potential, magnetic field, ion and electron temperatures, etc., exhibit macroscopic fluctuations. These fluctuations play an important role in determining nonlinear stability of turbulent plasma. Experimental and computational physicists usually use two methods for the analysis of turbulent fluctuation data: cross-correlation function and Fourier transform methods which we found inadequate for the study of plasma turbulence: I. Correlation or cross-correlation functions are often used to find space and time scales of turbulence. We found that these scales are not very meaningful. There are many cases when there are no such correlations present and still there is strong dynamical coupling between signals. We developed a new symbolic method of studying such signals by computing mutual information [1]. II. The Fourier transform is a useful method for determining the coherent part of fluctuating signal (which corresponds to narrow peaks in the power spectrum) but it is not particularly informative for the analysis of the incoherent part of the signal (which corresponds to the broad portion of the power spectrum). This is so because the Fourier transform is not an invariant characteristic of the nonlinear dynamical processes of plasma turbulence. We have developed a new method of extracting from fluctuation data cycles and their invariant properties using symbolic dynamics [2]. These are global invariants of turbulence in the sense that different physical quantities measured in different locations exhibit the same invariants. Finally, we also developed a symbolic method to compute an overall nonlinear stability parameter similar to the maximum Lyapunov number using the time record of a single fluctuating variable instead of a full set of dynamical equations [3]. Many examples of application of the symbolic signal processing method for the analysis of experimental and computational turbulent fluctuation data will be presented. Our new signal processing methods could be used as a tool to study macroscopic stability in the center, bulk, edge, near SOL and for SOL regions of turbulent plasma.

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Consistency of the Accretion Theory of the Spontaneous Rotation Phenomenon with Recent Experiments*

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Abstract

The accretion theory [1] of the spontaneous rotation phenomenon has found further confirmation in the series of experiments carried out by the Alcator C-Mod [2] and DIII-D machines [3]. This theory has been the first to be based on having the source of angular momentum near the edge of the plasma column implying that a change of the edge configuration can affect the velocity of rotation. This feature is consistent with the Alcator C-Mod experiments producing lower and upper null poloidal field configurations that have found drastically different toroidal velocities. The intrinsic coupling between spontaneous rotation and thermal energy transport involved in the accretion theory is consistent with the observed relationship [2] between the change of rotation velocity from the L-confinement regime to the H-confinement regime and the scaling of the threshold to attain the H-regime. The DIII-D experiments with electron cyclotron heating have confirmed the existence of spontaneous rotation and shown the toroidal velocity to be proportional to $(T_e/T_i)W_{th}$ where W_{th} is the total thermal energy of the plasma column and the (T_e/T_i) is the electron to ion temperature ratio. This is consistent with the characteristics of the ion temperature gradient driven (ITG) modes whose excitation is involved within the accretion theory in order to carry angular momentum from the edge toward the center of the plasma column [1].

Recent relevant advances for the accretion theory are reported in this context.

*Sponsored in part by the US DOE and by the CNR of Italy

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Multimode Analysis of the Resistive Wall Mode Instability

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Abstract

The multimode analysis of the resistive wall mode instability (RWM) is discussed for a plasma that obeys the constraints of ideal magnetohydrodynamics (MHD). The full response of an ideal, non-rotating plasma to perturbations that evolve slowly compared to the Alfvén time is contained in the matrix for the effective plasma inductance, $\overleftrightarrow{\Lambda}$. We have computed $\overleftrightarrow{\Lambda}$ for a spectrum of plasma modes produced by Alan Glasser's DCON computer code[1]. This matrix can be used in a code that accurately calculates the effects of the external conductors, such as Jim Bialek's VALEN code[2], to obtain an essentially complete description of both plasma and the conducting structures. The full multimode representation of the plasma response to an external magnetic perturbation becomes important when (1) the plasma stability parameter of the least stable mode approaches unity, and/or (2) the absolute value of the plasma stability parameter of the second least stable mode is less than that of the first. The plasma stability parameter s of a mode is defined as the negative of the ratio of the energy that is required to produce the distribution of the normal magnetic field associated with that mode with the plasma, to the energy without the plasma. We compare the multimode representation and resulting plasma stability coefficients with the single mode approximation for the least stable plasma mode.

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Parsek: an Implicit Parallel Particle-in-Cell

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Abstract

Parsek is an object-oriented C++ framework for 3D parallel electromagnetic plasma simulation. Using the object oriented concepts of polymorphism and inheritance, Parsek can develop multiple models for both the particles and electromagnetic fields in a plasma. At the moment, the implicit moment Particle-in-Cell model for particles and the second-order formulation of Maxwell's equations for field have been implemented. The reason for the parallelization is performance. Many problems, such as 3D models of burning fusion plasmas, require weeks to simulate on a single-node workstation. The purpose of the present project includes portability and free distribution. The MPI library and GNU C++ compiler provide freely distributable tools for reaching this goal. The implicit moment method is used to handle effectively multiple time and length scales processes: the relevant time and length scales are resolved while effectively averaging over faster time scales (e.g., electron plasma frequency) and shorter length scales (e.g., Debye length). The practical consequence is the ability to handle realistic mass ratios and to simulate macroscopic systems while retaining a kinetic description of both ions and electrons. Using the algorithm Parsek implements, simulations impossible for other kinetic methods even on massively parallel computers have been possible on a single processor machine using the implicit PIC code CELESTE3D[1]. PARSEK amplifies the power of the implicit moment method using a full parallel version. PARSEK employs MPI blocking calls for grid and particle communication and a general three dimensional domain decomposition for the partition of physical space that subdivides the system into physical pieces and assigns the particles and cells in each physical part to a processor. In this work we will describe how PARSEK is structured and how to enable efficient parallelization when implicit numerical schemes are involved and present a report about the first results of the code and performance.

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Simulation of Turbulence and Blobs in Helimak and tokamak SOL *

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Abstract

We have extended the Krasheninnikov model for SOL transport[1] as described by D'Ippolito[2] by including additional temperature equations and accounting for temperature effects in the coefficients. We also include the thermal and electrical conductivity of the plasma which becomes more import as the field line length increases and/or the temperature drops. The relevant atomic processes for Helimak have also been included. The consequences of this model's predictions are significant and include: possible increase in wall sputtering and rapid inward transport of impurities due to blobs leading to thermal collapse for tungsten walls[3][4], increased transport in far SOL, and increased wall loading.

The Helimak [5] is a low temperature (≈ 10 ev) toroidal device that approximates an infinite cylinder with a helical magnetic field terminating on the top and bottom plates. The field line length can be adjusted over a wide range (10-1000 m). This device appears to be an accessible realization representing only the essential features of the plasma conditions described by the SOL model. Comparing predictions of this model with the experimental results tests the model validity and provides a basis for using the model in divertor design. The experiment shows fluctuation levels comparable with tokamak SOL and the discharge times are long enough to produce saturated, stationary turbulence. Experimental profiles display an in/out asymmetry qualitatively consistent with blobs. Simulations show reasonable agreement profiles and fluctuation characteristics. Details will be presented.

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Effect of external plasma on kink stability of line tied screw pinch

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In recent theoretical studies of the line tied screw pinch stability, the plasma was assumed to be isolated from the external conducting wall by a vacuum gap [1,2]. Following the reduced MHD approximation used in these papers, we consider a more general model where a central current channel is surrounded by a low density external plasma. Under the conditions of high conductivity, the outer plasma provides significant stabilizing response to the kink driven core modes. For this problem, we have calculated the marginal stability conditions [3]. We now report the complete solution of the eigenvalue problem in both periodic cylinder and line tied geometries. Within the scope of the model, the equilibrium current and plasma density are assumed to be step-like functions of radius. Deriving matching conditions for plasma radial velocities at jump points leads to coupled integral and differential equations in axial directions. Comparing solutions in line-tied and periodic cylinder cases we analyze: (1) the effect of the outer background plasma on kink stability, (2) the structure of alfvenic resonance in line-tied and periodic systems, and (3) importance of non-MHD sheath effects.
* Work supported by U.S.DoE and NSF

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Long mean-free-path collisional effects in the fluid description of magnetized plasmas*

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A very general, finite-Larmor-radius fluid formalism for collisionless magnetized plasmas has recently been developed[1]. It is based on perturbative solutions for the fluid moments of the Vlasov equation, including the complete third rank stress-flux tensor, with the only assumptions of small gyromotion periods and Larmor radii compared to any other time and length scales. Here, this theory is generalized with the inclusion of collisional effects. The goal is a model that would be applicable to arbitrary collisionality regimes, hence the traditional, short mean-free-path closure schemes are not useful. At low collisionality, the collisionless fluid equations get modified by adding the velocity moments of the collision operator part of the kinetic equation, but leaving everything else unchanged. An approximate representation of these collisional terms is obtained by evaluating the collision integrals with trial distribution functions which yield identically the fluid moments for which evolution equations are available. A truncated Hermite series representation of the trial distribution functions and the general Fokker-Planck form of the Coulomb collision operator are used, so that effects associated with the gyrophase-dependent part of the distribution functions are taken into account with optimal accuracy.

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Simulation Studies of Generalized Parallel Ion Stress Tensor in Slab Geometry

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Abstract

Numerical studies of generalized model of parallel ion stress tensor is executed in slab geometry using NIMROD [1] simulation tools. This work is premised primarily on analytical derivations of such tensor, which is an integral closure, previously presented by Held [2]. However, some application concepts are based on NIMROD simulations of wave damping using a local anisotropic stress recently implemented. The wave damping study is repeated with the integral closure. Generalized tensor is cast into geometrically correct form suitable for the study of relevant MHD phenomena in magnetized plasmas of arbitrary collisionality. Specifically, resistive MHD equations of plasma flow and temperature evolution in slab geometry [3] are closed with the generalized stress tensor. Simulations involve calculations of plasma quantities and profiles pertinent to the study of parallel flow and dynamics of magnetized plasmas. The plasma is modeled as that immersed in slab magnetic island(s), which may or may not exhibit field line stochasticity. This model of flow and temperature evolution is further reinforced by using the generalized parallel heat flow closure [4] in the energy conservation equation. Parallel flow damping in slab island geometry is closely monitored, and ratios of parallel to perpendicular viscosity at which flattening is observed are recorded. Implementation of this nonlocal form of stress tensor inherited many techniques and concepts from the implementation of the heat flow closure. Consequently, the local anisotropic stress is used as a semi-implicit operator in simulations. Future work comprises upgrading the analytic model of the stress tensor to exhibit enhanced time-dependence, and assessing the relative contributions of local and nonlocal stresses to stress-induced heating. Ultimately, this research would extend to the kinetic analysis of anomalous ion heating, Landau damping and magnetic reconnection.

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Hamiltonian and Lagrangian structure of some gyroviscous magnetofluid models

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Abstract

Magnetofluid theories, like MHD, can be expressed in terms of Eulerian (or spatial) variables, or in terms of Lagrangian (or material) variables. The former formulation generally exhibits a noncanonical Hamiltonian structure [1], while the latter is useful for deriving equations of motion using Hamilton's principle as applied to continuum theories [2]. Continuing the work of [3,4], we study the Hamiltonian and Lagrangian structure of several (generalized) gyroviscous magnetofluid models.

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The effects of plasma flow on ballooning instabilities in 3-D equilibria*

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Abstract

Plasma flows are known to influence a number of physical properties in toroidal confinement devices. In three-dimensional equilibria, the drives and damping properties of plasma flows have a different character than in tokamak equilibria [1]. Namely, neoclassical damping in both toroidal and poloidal directions and the presence of self-consistently generated ambipolar electric fields can result in flow components in both toroidal and poloidal directions. In this work, we formulate the problem of ideal MHD ballooning stability in three-dimensional equilibrium with arbitrary flows within the magnetic surface. In the absence of plasma flows, the nature of ballooning stability is qualitatively different in three-dimensional devices relative to axisymmetric configurations. A unique feature is the field-line dependence of the ballooning mode eigenvalues [2]. Using a conventional form for the ballooning mode eikonal in the presence of flows ($\xi \sim e^{iS/\epsilon}, \mathbf{B} \cdot \nabla S = 0, dS/dt = 0$) [3], a coupled set of partial differential equations for the perturbation amplitudes are derived. Analytic progress in determining solutions to these equations can by made in the limit of small flow.

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Pressure Anisotropy for Fluid Equation Closure in Long Mean Free Regimes for Tokamaks*

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Pressure anisotropy for the fluid momentum equation closure in the plateau regime for general toroidal plasmas is calculated in [K. C. Shaing, and D. A. Spong, Phys. Fluids B **2**, 1190 (1990)]. The calculation is based on the solution of the linear drift kinetic equation that is driven by the plasma flows instead of the plasma gradients. It is also emphasized that the perturbed plasma density, and perturbed pressure do not vanish. Thus, the complete Chapman-Enskog's program cannot be adopted in the long mean free path regimes, and only the asymptotic expansion procedure is applicable. This is because the perturbed particle distribution is localized in the velocity space, a well-known fact in the kinetic theory for toroidal plasmas. Note that even though the equilibrium is toroidally symmetric, the linear drift kinetic equation is not because the magnetohydrodynamic (MHD) perturbations break the symmetry. As emphasized in [K. C. Shaing, Phys. Plasma **11**, 5525 (2004)] that the equilibrium pressure anisotropy is applicable only at the mode rational surface where $m - nq = 0$ with m, the poloidal mode number, n, the toroidal mode number, and q, the safety factor. However, because one of the purposes for using pressure anisotropy in the theories is to study the toroidal mode coupling, and toroidally coupled side-band modes does not satisfy $m - nq = 0$. Thus, the toroidally asymmetric nature of the linear drift kinetic equation is important for calculating pressure anisotropy for MHD applications, such as NIMROD simulations. Here, we extend the pressure anisotropy calculations to the banana regime.

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Numerical modeling of the sawtooth crash in a small tokamak

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Abstract

We report on the results of a series of nonlinear numerical studies of the resistive internal kink instability in the CDX-U low aspect ratio tokamak, carried out using the M3D code[1]. The modest size and temperature of this device made it possible to simulate it using realistic values of those physical parameters (transport coefficients) that can be measured or inferred. A single-fluid, resistive MHD model was used for the study. The model proved adequate for predicting a linear growth rate of the n=1 instability, and for qualitatively reproducing key aspects of its nonlinear behavior. The linear study predicted that, in the absence of a large perpendicular thermal conductivity, all higher-n resistive ballooning modes were unstable, but that these could be stabilized by imposing the anomalously large thermal conductivity measured in the experiment, suggesting a self-stabilization mechanism. Features of the nonlinear evolution include a repeating cycle that consists of a relatively rapid crash causing stochasticization of the field lines and flattening of the temperature profile, followed by a slower recovery period in which flux surfaces heal and the profile is re-established. Estimates of the fractal dimension prove to be a convenient tool for characterizing the changing degree of stochasticity of the field. The time scales of the simulated sawtooth cycle do not agree closely with the experimental data, suggesting that a more sophisticated model of the plasma will need to be employed to make quantitatively accurate predictions. Accordingly, a two-fluid study of the instability using the same code is now underway. It may also be necessary to change the boundary conditions to more accurately reflect the fact that the current in the device is driven by an Ohmically induced loop voltage, and not by external sources.

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Nonlinear Toroidal Mode Coupling: a New Paradigm for Drift Wave Turbulence in Toroidal Plasmas*

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Abstract: Global gyrokinetic particle simulations and nonlinear gyrokinetic theory find that electron temperature gradient (ETG) instability saturates via nonlinear toroidal coupling. In such nonlinear interactions, wave energy at the unstable high toroidal- mode number domain cascades toward the stable lower toroidal- mode number domain via scatterings off the driven low- mode number quasi modes. During the saturation process, there is negligible zonal- flow dynamics, and the saturated electrostatic ETG turbulence maintains extended radial envelope structures. Both the fluctuation intensity and, as a consequence, the transport level are, thus, independent of the spatial extent of the radial envelope. The nonlinear toroidal coupling mechanism strictly requires the toroidal geometry and, as such, represents a new paradigm for the spectral cascade of plasma turbulence in toroidal systems. Implications of this nonlinear paradigm to the trapped- electron mode (TEM) turbulence will also be discussed.

* *Work support by DoE and NSF Grants.*

Reconstruction of soft X-ray emissivity from NSTX plasma

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February 25, 2005

A fast soft X-ray camera (64x64 pixels, up to 300 frames at the rate 500 frames/millisecond) giving a 2-D image of line integrated emissivity from the NSTX plasma is now operational and is capable of generating fast image of the large scale mode development in the plasma. A special numerical code BST was created for generating 3-D geometry of sight-lines based on equilibrium reconstruction and then for reconstructing both un- and perturbed (by the mode) emissivity profile.

SVD Analysis of the Mirnov Loop Data in Tokamaks*

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Abstract

A Singular Value Decomposition (SVD) method is being developed to calculate the plasma surface magnetic perturbations from measurements of the magnetic field at the tokamak vessel wall. Normally, the VACUUM code calculates the magnetic field at or near the surface of the vacuum vessel as a response matrix to the normal component of the perturbed magnetic field at the plasma surface. In inverting this relation, the SVD provides an effective way to deal with the different dimensionalities of the variables as well as the possible singular behavior of the response matrix. For model cases with 256 data points describing the plasma surface, as few as 64 observation loops (assuming that the Mirnov loops are situated near the vessel), are sufficient to accurately reproduce the plasma surface perturbation in DIII-D plasma modeled with the GATO/Vacuum codes. It is found that the Mirnov measurements must be extremely accurate since small errors at the shell position are amplified strongly by the modified Bessel function-like behavior between the plasma surface and the shell. A quantitative assessment of the bounds of the Mirnov errors necessary for acceptably accurate results at the plasma surface will be presented. A natural consequence of the analysis is that both the poloidal and toroidal components of the Mirnov loop measurements are now calibrated with respect to the plasma magnetic perturbation.

*Work supported by U. S. Department of Energy Contract No. DE-AC02-76-CH03073, and U. S. DoE grant No. DE-FG03-95ER54309 and DE-FG03-94ER54271.

On the statistical mechanics of two-dimensional turbulence

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Abstract

A statistical mechanical description is proposed for generic two-dimensional, anisotropic, inhomogeneous, inviscid fluid flow. Flows of plasma physics and geophysics are representative examples in that they are quasi two-dimensional and are characterized by mean zonal flows and the presence of coherent structures. Crucial requirements for equilibrium in statistical mechanics are statistical independence of small parts of a system (macro-cells) and additivity of invariants in macro-cells. Energy, an extensive quantity, should be additive and the interaction energy between a macro-cell and the rest of the system (reservoir) should be small. Previous attempts at applying statistical mechanics ideas to fluids have regarded the homogenous discrete (vortex) phase space volume as a macro-cell without explicitly considering statistical independence. The novel feature of the present study is a definition of continuous phase space hypersurfaces based on mean values of the stream function, which accounts for the anisotropic and inhomogeneous properties of the flow. Consequently, statistical quantities such as energy and entropy can be defined on each hypersurface and a corresponding canonical distribution is obtained that possesses a linear relation between potential vorticity and the stream function. The statistical mechanics approach given is general in nature, but here it is motivated by and applied to experiments in a rapidly rotating annulus. The canonical distribution on each macro-cell and the linear relation between potential vorticity and stream function is derived and compared with experiments.

Hamiltonian Hybrid Fluid–Kinetic Model of Low Temperature, Relativistic Plasmas

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Abstract

We present a hybrid fluid-kinetic model of low temperature, relativistic plasmas. The full kinetic description is retained in one phase-space direction (in our applications this direction is determined by the laser propagation) while moments, retained through second order, are taken in the remaining momentum directions. The corresponding equations of motion are obtained using the Hamiltonian formulation of the Maxwell–Vlasov system by preforming a reduction to the moment description in the usual way. This model makes no assumptions about the behaviour in the direction where the full kinetic description is retained and assumes small momentum spread ("temperature") in the directions over which moments are taken. This model inherits the Hamiltonian structure of the Maxwell–Vlasov system but it is necessary to assume a form for dependence of the distribution function on the moments in order to determine some high-order moments occurring in the bracket. We compare this model to the cold fluid, to our warm-fluid model[1] as well to a quasi-static Vlasov model.[2] We present applications relevant to on-going experimental studies of intense, short-pulse laser-plasma interactions.

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A Hybrid Chapman-Enskog/Moment-Approach for Deriving General Closures Relations *

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Abstract

The derivation of general closure relations for plasma fluid equations is complicated by the myriad of time and spatial scales present in magnetic fusion and astrophysical plasmas. These matters are further complicated by the fact that plasma collisionality, which is parameterized by spatially varying density and temperature, can vary significantly throughout the plasma. The nearly collisionless core plasma and collisional to moderately collisional edge plasma of modern magnetic fusion experiments are good examples of this added difficulty. Although much work concentrates on deriving closures applicable in the extreme regimes of collisionality, modern fluid simulation codes, which treat the macroscopic stability of the entire plasma, benefit from a single, unified closure scheme.

In this work, an approach to deriving general closures, which combines aspects of the Chapman-Enskog [1] and moment approaches [2], is set forth. The recast, Chapman-Enskog-like (CEL) drift kinetic equation has time, space and velocity derivatives acting on the kinetic distortion of the distribution function, F, which is to be determined. In past work [3, 4], time-dependence was ignored and simplified spatial (free-streaming) and collision (Lorentz, pitch-angle scattering) operators were inverted to solve for F. In this work, time-dependence is retained and Grad's moment approach, which expands the velocity-space dependence of F in a series of Laguerre polynomials times spherical harmonics, is used to approximate elements of the operator which are unamenable to inversion.

The remaining operator is inverted by integrating along time-dependent characteristics with the resultant closure moments expressed as coupled integral equations. This approach retains physics that has previously been ignored and expands the role of the closure moments as drives in the CEL drift kinetic equation. In the steady-state limit, it is shown that the closures reduce to previous expressions. Discussions regarding the physical accuracy and implementation of these time-dependent closures in plasma fluid codes are included.

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Analysis of Numerical Algorithms for Two-Fluid Multiscale Computation

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Abstract

Nonlinear plasma simulations including separate electron and ion dynamics have been performed using fluid, particle-in-cell, and hybrid approaches. However, relatively few computations have addressed two-fluid effects in application to global MHD-like behavior, because the range of time-scales is much greater than MHD alone. 'Extending' such numerical MHD modeling to consider electron-fluid effects can be made tractable by considering drift models (as done in Ref. [1], for example) or by applying implicit and semi-implicit techniques to numerically stabilize the fast waves of the extended system. Here, we consider von Neumann analysis of several possible schemes. Hall-MHD algorithms based on Ref. [2] are considered, and we find that while a predictor-corrector advance of magnetic field with a spatially fourth-order semi-implicit operator is numerically stable for electron MHD, the complete time-advance for Hall-MHD is numerically unstable, as observed in computations. However, a very similar algorithm with an explicit predictor step is numerically stable and has better accuracy. The accuracy is also compared with what results from a time-centered implicit algorithm. The information from these analyses has been used to improve the semi-implicit Hall advance in the NIMROD code [3]. Results computed with the original algorithm [4] and those from the revised versions are compared with findings from numerical analysis.

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Numerical Study of Hall Dynamo Effect Driven by Two-Fluid Tearing Instability

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Abstract

Dynamo effects from tearing instabilities in reversed-field pinches flatten the equilibrium current profile, and Hall effects may lead to important corrections to the standard MHD dynamo description. We present two-fluid simulations of generically relevant current-driven tearing instabilities in slab geometry, through the nonlinear saturation stage, to investigate dynamo effects. The simulations have been run with the NIMROD code [1] in the zero-β and large guide-field limits for computational simplicity as our first step toward more comprehensive dynamo calculations. The reported simulations use an unphysically small equilibrium scale length *L*, smaller than the ion skin depth c/ω_{pi}, in order to emphasize two-fluid effects. [As discussed in Ref. 2, the whistler mode is otherwise strongly coupled to the compressional Alfven wave at $k_{//}=0$ and β=0 through ion motion.] Nonlinear simulation results are compared with analytical quasilinear calculations [2], which show that the dynamo effect driven by the $<\vec{J}\times\vec{B}>$ Hall term is greater than the contribution from the MHD dynamo term, $<\vec{V}\times\vec{B}>$, in the narrow electron layer. The magnetic island growth rate in linear and nonlinear stages of the simulation with the Hall term are compared with resistive MHD results.

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Abstracts

Tuesday, April 12

Poster Session *P3*

at 7:30 pm

Divergent Subcritical Convection in Magnetized Plasma from Asymmetric Sourcing

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Asymmetric particle and heat sourcing in a plasma confined in a closed magnetic field line configuration results in convection cells, as is well-known. This phenomenon occurs even if the sourcing, on average, produces density and temperature profiles that are subcritical, i.e., stable to MHD interchange modes. Such subcritical convection is expected to be small compared to the convection from supercritical driving, for which the system is interchange unstable. The ratio of subcritical to supercritical convection is expected to scale as the inverse Reynolds numbers. We show that this ratio is, in fact, considerably larger. As marginal stability is approached, the subcritical convection grows from very small to almost the unstable convection size, i.e., of order unity. This effect may be similar to why a driven, damped harmonic oscillator increases in amplitude as resonance is approached. The divergent phenomenon is shown analytically and a numerical simulation is done to demonstrate this effect. It is also shown that transport from the subcritical convection can be substantial. Applications to neutral atmospheres and to the magnetized plasma Levitated Dipole experiment (LDX) will be discussed.

Resistive MHD Simulation of HIT-SI using MH4D

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The HIT-SI experiment at the University of Washington is a high beta spheromak with steady state AC current drive[1]. Helicity is injected by two half torus Reversed Field Pinches (RFP's) connected to the ends of a cylindrically symmetric flux conserver, rotated by 90 degrees from each other. The RFP's are driven with sinusoidally varying voltage and flux. Each side has its voltage and flux in phase, but is 90 degrees out of phase from the other side. The helicity injection rate, which is proportional to the voltage times the flux, goes like sin(wt)**2 on one side and cos(wt)**2 on the other, making the total injection rate constant in time.

This poster will report on progress to begin 3-D resistive MHD simulations of this experiment using the code MH4D[2]. It will use an unstructured tetrahedral mesh that was constructed to closely match the actual geometry of the experiment using the mesh generation code T3D[3]. Simulations will start from an initial RFP-like Taylor State in one injector and will follow the plasma dynamics as the injector flux reconnects to form closed internal flux. These initial simulations will attempt to answer two important questions: (1.) How high must the injector current to flux ratio be driven to initiate the reconnection process; and (2.) How high does the Lundquist number, S, have to be in order to get build up of closed internal flux.

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Improvements to the ISLAND Module for Computing Saturated Tearing Modes in Tokamaks

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Abstract

The ISLAND module in the National Transport Code Collaboration Module Library [1] is an implementation of a quasi-linear model to compute magnetic island widths driven by saturated neoclassical tearing modes. The module is indended to be used in axisymmetric toroidal plasmas with arbitrary aspect ratio, cross-sectional shape, and plasma beta [2]. An adaptive ODE solver is used in a shooting method to integrate a coupled system of ODEs for harmonics of the magnetic perturbation, which are derived from the three-dimensional scalar plasma pressure force balance equations. The presence of a magnetic island has the effect of locally flattening the pressure and current density profiles, which removes the singularity at each mode rational surface. Since the differential equations for different harmonics are coupled, all of the equations in the original version of the module were integrated from the magnetic axis through the magnetic islands to the outer boundary condition, and the island widths were adjusted until the solutions matched the required conditions at the outer boundary. Unfortunately, this procedure of integrating from the magnetic axis through narrow magnetic islands out to the plasma edge causes the adaptive ODE solver to labor and to take an excessive number of steps. In the new ISLAND module presented here, the following changes have been made in an effort to increase its speed and accuracy when computing the widths of multiple magnetic islands: The pair of ODEs for each harmonic is integrated from the outer boundary inward to the mode rational surface and from the magnetic axis outward to the mode rational surface. The harmonic mixing terms are computed using the previous iteration, which is stored and interpolated as needed. The value of Δ' for each helical harmonic can be computed using the new ISLAND module. The module has an option to vary the island widths until all of the solutions for the magnetic field perturbation harmonics and their first derivatives are continuous throughout the plasma.

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Constrained resonance: flux amplification in helicity injected spherical Tokamaks and current limiting mechanisms in RFPs

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In a Taylor-relaxed plasma, the magnetic field is described by a linear equation

$$\nabla \times \mathbf{B} = \lambda \mathbf{B}. \tag{1}$$

Without an externally imposed vacuum field, this is an eigen-problem with discrete eigenvalues. The vacuum magnetic field changes the characteristics of the equation into a linear driven problem, where resonance phenomenon arises naturally. In a doubly connected torus such as a spherical Tokamak or a reversed field pinch, the perturbations to the vacuum magnetic field are of two kinds. It can either be a vacuum poloidal field intercepting the wall ($\mathbf{B} \cdot \mathbf{n}|_{\partial\Omega} \neq 0$) like that in co-axial helicity injection current drive for a spherical Tokamak, or a pure vacuum toroidal flux (so $\mathbf{B} \cdot \mathbf{n}|_{\partial\Omega} = 0$) like that in the reversed field pinch experiment.

Conventional Jensen-Chu-Taylor theory concentrates on the eigenmodes of equation (1) that do not carry net toroidal flux, the so-called flux-free Chandrasekhar-Kendall (CK) modes. It predicts a resonance at the eigenvalues of the flux-free CK modes if the vacuum field is coupled to the modes. If the vacuum field is decoupled from the particular flux-free CK modes, a "mixed" Taylor state is obtained in which the net toroidal current saturates when the applied Volt-seconds becomes sufficiently large. In a RFP, this is known as the helical Taylor state. An axisymmetric equivalent is predicted for the multi-pinch experiment.

Our recent work has shown that the previously neglected flux-carrying CK modes are responsible for a resonance phenomenon that has important practical implications. These resonances are primarily responsible for flux amplification in spherical Tokamak current drive by co-axial helicity injection, and for providing robust current limiting mechanism in the RFP. Unlike Taylor's "mixed state," which is effectively an energy sink, the resonance poses energy barriers whose effect is carried over to partially relaxed plasmas with finite pressure and spatially varying λ profiles.

Due to finite net toroidal flux constraint in a doubly connected torus, this new class of resonance can no longer occur at the eigenvalues of the flux-carrying CK modes[1]. The constraint couples neighboring flux-carrying CK modes, which up shifts the resonance frequencies. Here we will give detailed analysis demonstrating the new constrained resonance; how it determines the flux amplification in an ST [2]; and how it provides current limiting discharges in a RFP. The importance of field errors to the resonances and quasi-single helicity state of the RFP will be explained. In addition, partially relaxed plasma states, where λ is a flux function, will be considered because of the importance to the resonance phenomenon[3]. The different fate of Taylor's "mixed state" and the resonances will be clarified.

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Hysteresis Effects in Edge Poloidal Flow Generation*

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Gas puffing at the edge of the TJ-II stellarator has been used to control the development of an edge poloidal velocity shear layer [1]. Recent experiments have been done to test for hysteresis in the development of the flow. In this work, a numerical transport model is used to examine for hysteresis in the development of an edge poloidal velocity shear layer due to a modeled gas puff. The transport model couples together density, ion temperature, electron temperature, poloidal flow, toroidal flow, radial electric field, and a fluctuation envelope equation which includes a shear-suppression factor [2]. The model has been modified to include a turbulence growth rate for resistive ballooning modes as well as ion temperature gradient modes. For the cases run with parameters consistent with these TJ-II experiments (only RF heating, no neutral beams), the resistive ballooning mode growth rate is dominant in the edge region. In this work, we present results from a series of cases using parameters that are typical of TJ-II discharges and ramps (both up and down) of an edge density source term used to model a gas puff. The impact of the ramp on the generation of edge poloidal velocity is discussed.

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

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Beam ion distribution function model and Alfvén Eigenmode stability*

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ABSTRACT

A good model for the energetic ion distribution function is critical in determining the stability of plasma cavity modes such as Alfvén Eigenmodes (AE). In this work an analytical model for the Neutral Beam Injection (NBI) generated fast ion distribution function is proposed. This model includes the collisional velocity drag and pitch angle scattering mechanisms. We employ image source/sink method for the pitch angle scattering diffusion, which shows good agreement with the Monte-Carlo simulations when the pitch angle width is small compared with the confinement regions in velocity space. Surprisingly, we find that for TAE modes the model distribution function increases (rather than decreases) the growth rate that is obtained from only the ω_* drive without the energy derivatives of the distribution function. This model is applied to the prediction of the instability of AEs in ITER taking into account a realistic beam ion distribution function. The excitation of high mode number AEs in DIII-D by tangentally injected beams is also discussed.

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Comparisons of resistive MHD and gyrokinetic simulations of the slab tearing mode instability

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The linear and nonlinear evolution of the collisionless and semi-collisional tearing mode[1] has been successfully simulated using the electromagnetic turbulence code GEM[2]. Recent results using GEM will be presented. One issue to address is that GEM sees an unstable odd-parity (k_z=0) mode for current layers wider than the ion gyroradius. The origin of this odd-parity mode is under investigation. Comparisons of GEM results with similar resistive MHD calculations using NIMROD will be made in slab geometry. The recent two-fluid capability in NIMROD will be used to gain further insight into the importance of kinetic effects and the validity of the two-fluid model for such problems.

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Electron Temperature Gradient Turbulence

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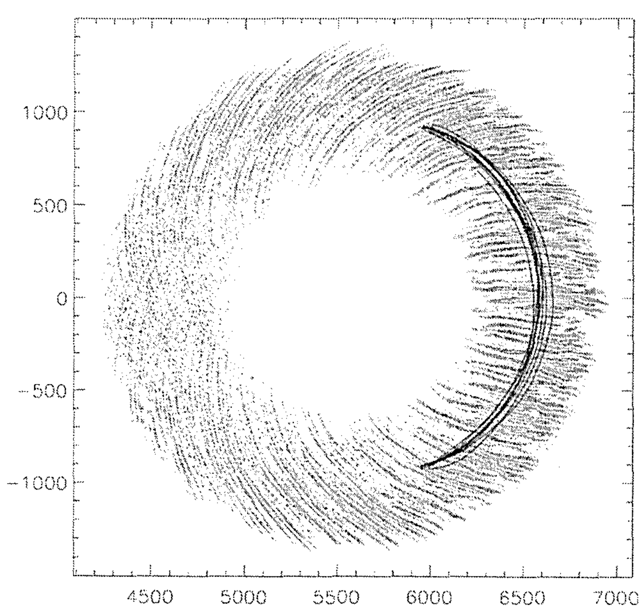
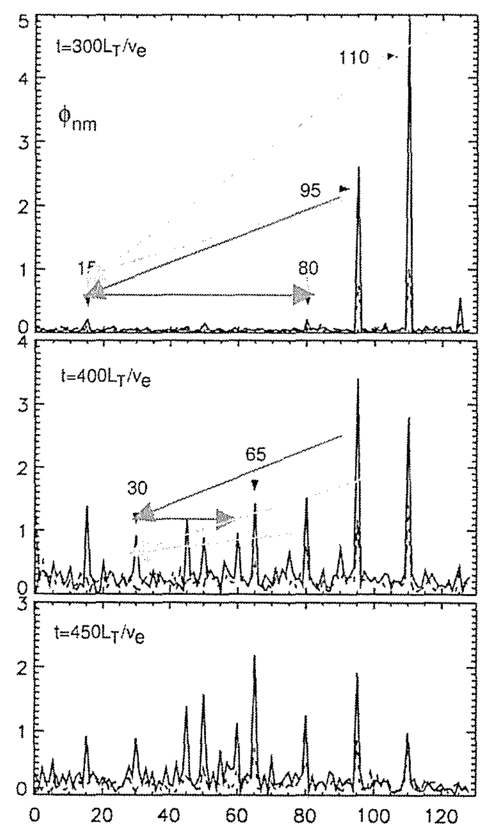
Global gyrokinetic particle simulation and nonlinear gyrokinetic theory find that electron temperature gradient (ETG) instability saturates via nonlinear toroidal coupling, which is a nonlocal interaction in the wavevector space that transfers energy successively from unstable modes to damped modes preferentially with lower toroidal mode numbers. The electrostatic ETG turbulence is dominated by nonlinearly generated radial streamers. The length of the streamers scales with the device size, which is longer than the distance between mode rational surfaces and electron radial excursions. Both fluctuation intensity and transport level are independent of the streamer length, and are much smaller than the mixing length estimates or experimental values. Extensive studies for numerical convergence in global gyrokinetic particle simulations will also be discussed. This work is supported by DOE SciDAC Center for Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas.





Meanders and non-standard reconnection/collision processes in the standard nontwist map

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As a simple, low-dimensional model for degenerate Hamiltonian systems, as used for describing magnetic field lines in tokamaks with reversed magnetic shear profiles, the standard nontwist map can be used to study phenomena encountered in such settings. Past studies of this map focused primarily on understanding the basic patterns of creation/annihilation of periodic orbit island chains, separatrix reconnection, and destruction of the main shearless curve.[1-3] Here, we address more complicated reconnection/collision scenarios and map out in which the parameter regions the various scenarios are found. The appearance of such non-standard scenarios is closely associated with the formation of meanders, i.e., invariant curves in phase space that are "folded-over". [4]

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Hybrid Kinetic-MHD Simulations of the Resistive Internal Kink

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Abstract

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

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

This poster will present the δf PIC implementation in NIMROD and some validation tests. In particular, a benchmark comparison of hot particle effects on ideal internal kink mode from the present implementation and M3D-K and NOVA-K. In agreement with the other two codes, hot particles in NIMROD shows a stabilization of the internal kink mode at low β_h fraction and the excitation of a fishbone mode as the β_h fraction is increased. We will also present preliminary results of hot particle effects on the resistive kink mode and possible implications for sawtooths.

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A fractional diffusion model of nonlocal heat transport

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Experimental and theoretical evidence suggests that transport in magnetically confined fusion plasmas deviates from the standard diffusion paradigm. Some examples include the confinement time scaling of L-mode plasmas, inward energy transport in off-axis heating experiments, and rapid pulse propagation phenomena. One of the main culprits for the failure of the standard diffusion paradigm is the locality assumption. In particular, Fick's law, one of the cornerstones of diffusion, assumes that the fluxes only depend on local quantities, i.e. the spatial gradient of the field(s). However, unless one invokes ad hoc, sometimes unphysical, complicated spatio-temporal and/or nonlinear dependences in the heat diffusivity, the above mention transport phenomena cannot be described in the context of the standard diffusion model.

The goal of this presentation is to show that fractional derivative operators are a natural, powerful tool to construct models of nonlocal transport in magnetically confined plasmas. Our motivation for using fractional derivatives stems from Ref.[1], where we proposed and tested a fractional diffusion model of tracers in 3-dimesional, pressure-gradient-driven plasma turbulence. In this model, fractional derivatives in space account for large displacements of tracers ("Levy flights") and fractional derivatives in time account for non-Markovian ("memory") effects caused by eddies that trap the tracers. An appealing feature of fractional models is that they exhibit self-similar non-Gaussian scaling and at a "microscopic" level describe generalized Brownian random walks without characteristic spatio-temporal scales.

To study heat transport, we present here an extension of the model in Ref.[1] that includes, in addition to the fractional operator describing anomalous transport, a regular Laplacian operator to account for the diffusion dominated transport in the core. Also, we incorporate in the model finite-size domain effects, boundary conditions, sources, spatially dependent diffusivities, and general asymmetric fractional operators. We present a numerical and analytical study of the model. In particular, we show that, consistent with experimental results of L-mode discharges, the energy confinement time τ_E scales as $\alpha_E \sim L^{\alpha}$ with $\alpha < 2$, where L is the system size and α is the order of the fractional derivative in space. Also, we show that the model exhibits inward energy transport with off-axis heating. and rapid pulse propagation.

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

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Abstract

Fast toroidal plasma flows are routinely induced by neutral beam injection in current tokamaks such as NSXT and DIII-D. Fast flow has also been observed in Alcator C-MOD without any external input of momentum. These equilibrium flows are beneficial to the overall plasma performance since they stabilize external modes such as the resistive wall mode and suppress turbulence when the flow shear is large enough. Flow and flow shear have also a significant influence on the stability and nonlinear evolution of the internal kink mode and ballooning modes. Theoretical results indicate that improvements in plasma stability usually occur regardless of the flow direction (toroidal or poloidal). While equilibria with both poloidal and toroidal arbitrary flows can now be generated with the U. Rochester code FLOW [1], the tools available to tackle the stability problem are quite limited. With the exception of the code MARS [2], none of the available stability codes includes the effects of finite flow. MARS includes only toroidal flow. With the goal of producing a tool capable of investigating MHD stability with arbitrary flow, we have undertaken the development of a new linear stability code, named FLOS. The code is based on a recent δW formulation in which the energy principle (including arbitrary flow) is reduced to an eigenvalue problem of the kind $(\omega\mathbf{A}\text{-}\mathbf{B})\mathbf{x}=0$. Such a formulation is attractive because it allows a straightforward implementation of the finite element method to determine the elements of **A** and **B.** In the present work, we discuss the progress toward the development of such a code for tokamak stability in the presence of macroscopic flow. The code is presently limited to the analysis of internal modes. The finite elements implementation is also discussed in detail, and benchmark problems are presented.

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Modeling of edge plasma turbulence in a spherical tokamak

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Abstract

We report on first results of modeling of edge plasmas in spherical tokamak geometry with the fluid turbulence code BOUT [1]. Compared to a conventional tokamak, in a spherical tokamak the magnetic field is relatively small, and the pitch angle B_p/B_t is large. This leads to important consequences that make modeling of edge plasma in a spherical tokamak a challenging problem: the numerical solution becomes very sensitive to the boundary conditions at the radial boundaries, and the time step is severely constrained by the electrostatic shear-Alfven modes [2]. Another specific feature of the spherical tokamak is the large mirror ratio, manifesting itself through pressure anisotropy, $p_{||} - p_{\perp}$. which may affect plasma flow shear.

Using numerical simulations with BOUT, we analyze the effects of the spherical tokamak geometry on fluctuations in the edge plasma upstream, and in the divertor region. We will present recent results of BOUT simulations for two spherical tokamaks, MAST and NSTX, and discuss them, comparing with typical simulations results for conventional tokamak geometry.

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Equilibrium Reconstruction in Stellarators: V3FIT.

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Abstract

Input parameters to an MHD equilibrium code include the radial pressure and current profiles. These input parameters are not directly measurable in an experiment. Equilibrium Reconstruction (ER) refers to the process of determining (or reconstructing) the input parameters (current and pressure profiles) by making observed diagnostic signals as consistent as possible with signals computed from the equilibrium. ER is an example of a broad class of procedures called data assimilation, or parameter estimation procedures.

The EFIT [1] code, the most widely used tool for axisymmetric equilibrium reconstruction, has proven invaluable for equilibrium control, and for comparisons with MHD stability and confinement predictions. The V3FIT code, currently under construction, will perform fast, accurate reconstruction for stellarators. To be most useful for experiments, the V3FIT code will need to a) run rapidly, b) be flexible, and c) be extensible. V3FIT is written in Fortran 95, and makes extensive use of the modern features (modules, derived types, and pointers) of the language.

The broad outline of the reconstruction algorithm is clear: a function minimization in the space of equilibrium parameters, with the function to be minimized being a measure of the mismatch between observed and model-derived diagnostic signals. However, for the ER to be rapid, the evolution of the equilibrium parameters toward their true values will need to be tightly coupled to the iterative equilibrium solution. There are many possible algorithms for this tight coupling between the equilibration and reconstruction iterations, and the best algorithm is not known. The code is being written in a structured, modular way, with clear and consistent data flow. Thus, modifying old algorithms and implementing and testing new algorithms will be easy. The modular code structure makes adding signal types (magnetic diagnostics[2] implemented, microwave interferometry and polarimetry in progress) and changing the equilibrium solver (currently VMEC[2]) straightforward.

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

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Ion heating by collisional damping of tearing modes in RFPs

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Abstract

Strong ion heating is observed in the reversed field pinch (RFP). During a sawtooth crash in the Madison Symmetric Torus (MST) RFP the ion temperature can spontaneously double in $\sim 100\,\mu$s. The heating may arise from tearing instabilities due to irreversible transfer of kinetic flow energy into heat caused by ion-ion collisions. The standard viscous stress tensor calculations are not applicable for high temperature plasmas because the ion-ion collision time ν_{ii}^{-1} is larger than the tearing mode growth time γ^{-1} and the characteristic time of sawtooth crashes. To treat this regime, we first employ a hot dielectric tensor in tearing mode theory. We applied the formalism to calculate the absorption rate of a wave in plasma, using tearing mode eigenfunctions. For the case of interest, $\nu_{ii} < \gamma << \omega_{ci}$, $v_{Ti} << \omega_{ci}/k_{\|}$ the ion-ion collisional corrections to the dielectric tensor are found from the Fokker-Plank kinetic equation by a perturbation method while the electron absorption is negligible [1]. We also developed more accurate numerical models. One solves the kinetic equation with Landau collision operator in a driven electric field. Another finds the time evolution of linear tearing mode with ions modeled by the kinetic equation with collisions. In the simplified analysis we used the mode amplitude found from comparison of experimentally measured amplitude of magnetic field fluctuation with calculated linear eigenmode components. On the time scale smaller than ν_{ii}^{-1} the experimentally observed ion temperature rise can be interpreted from this calculation by small-scale spatial velocity oscillations when signal is averaged over the volume with varying velocity. On the larger time scale the enhanced ion temperature relaxes to a more moderate value and the resulting temperature gain can be explained by ion-ion collisions. The heating rate is proportional to the square of the ion Larmor radius such that it is strong in low magnetic field configurations. A more accurate estimate of fluctuating electric field and velocity based on the numerical solution of nonlinear resistive MHD equations is performed. We found that velocity amplitude is comparable to the ion thermal velocity and that it is very localized near resonance surface. This supports the assumptions of the simplified analysis.

Work supported by U.S. Department of Energy and by the NSF Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas.

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Implementation of Field Error and Resistive Wall Boundary Conditions in Finite Element Codes

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Abstract

Current tokamak experiments depend critically on the boundary conditions of the magnetic fields for effective operation. While non-axisymmetric boundary conditions have been considered deleterious for plasma operation because of locked modes [1], recent experiments show they might be advantageous for ELM control [2]. Instabilities which can arise due to the finite resistivity of the wall have also emerged as a emerged as a problem for advanced tokamak operation [3]. Implementation of these boundary conditions into finite element codes requires a different formulation of the boundary conditions as compared to the finite difference codes in earlier work. Here, we review the proper formulation with particular attention paid to numerical accuracy of the method.

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Plasma Response to Waves in Arbitrary Magnetic Field Geometry

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Abstract

We examine the effect that complicated magnetic geometries and collisions have on the propagation and absorption of radio frequency waves in a plasma. This is accomplished by calculating a conductivity tensor for the plasma using the method of integration along characteristics. The geometric effects included are magnetic field curvature, perpendicular gradients, quadratic parallel gradients, and the full effect of linear parallel gradients. Previous theories treated only the lowest order effects of linear parallel gradients and treated collision in an arbitrary manner. The effects of these terms on the plasma response function are described in terms of the physics of the characteristic trajectories and the plasma distributions. Methods for calculating the relative importance of each effect are derived based on the plasma and magnetic parameters. One dimensional calculations of wave propagation and absorption in a tokamak are performed using the AORSA1D code. The result of these calculations demonstrate a clear change in power absorption due to the proper treatment of collisions and higher order effects of linear parallel gradients.

Nonlinear dynamics of sub-cyclotron motion [1]

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Abstract

The nonlinear dynamics of charged particle motion in a uniform magnetic field with a plane perpendicular electrostatic wave is examined for the case when the wave frequency ω is a subharmonic of the cyclotron frequency Ω. Recently it has been shown [1,2] that, even in this frequency range, significant stochastic heating can occur for a wave amplitude above a critical threshold value. Using a canonical Lie perturbation technique including terms up to third order, details of the orbits including the stability of fixed points, appearance and motion of fixed points with increasing perturbation parameter, separatrix width, and the transition to global stochasticity are investigated for the cases when $\omega = N/2$ and $\omega = N/3$ where N is an integer. At second order in the perturbation parameter an intrinsic secularity appears that is generic for all wave frequencies. Thus, the frequencies $\omega = N$ and $N/2$ are, in a sense, special. The case $\omega = N/3$, meanwhile, is shown to be more generic. The transition to the adiabatic limit ($\omega \ll \Omega$) will also be discussed.

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[1]C.C. is supported in part by an appointment to the U.S. Department of Energy Fusion Energy Post-doctoral Research Program administered by the Oak Ridge Institute for Science and Education. Z.M.S. is supported by the National Natural Science Foundation of China, National Basic Research Project "non-linear Science" in China and National Hi-Tech Inertial Confinement Fusion Committee of China. L.C. is supported in part by U.S. Department of Energy and National Science Foundation grants.

Spectral Elements for two-dimensional resistive MHD

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Abstract

We have developed spectral element discretizations for the vorticity-flux and vorticity-current form of two-dimensional viscous resistive incompressible MHD. In the time-stepping we treat the diffusive terms implicitly and all other terms explicitly. We have implemented these methods both on a regular mesh of rectangular elements and on a collection of isoparametrically mapped rectangular elements. Our methods are flexible and permit us computations with a few elements of high or very high degree or many elements of moderate or low degree.

In the regular case we have implemented fast solvers and used the resulting fast algorithm to quickly explore different algorithmic possibilities and different examples. In particular we have tested different discretiziations for the Poisson brackets, in which we integrate the terms in the Poisson bracket with Gaussian Quadrature of variable order in different formulations. We have also tested different filters and algorithmic approaches to stabilize the computation for a wider range of parameters.

We also present an initial implementation of a spectral element discretization with higher order continuity across the element interfaces. We have developed a globally C1-continuous element and will show numerical results for several examples. In the regular case, this discretization allows fast solvers in a very similar way as the C0-continuous elements.

For more geometric flexibility we developed a version of our code that works with isoparametrically mapped rectangular elements. Using the special structure of the spectral element discretization, the matrix vector products can still be implemented fast and the solvers can be sped up by a Schur complement approach. We will present its flexibility and performance in a number of examples.

We have tested our methods mostly on the tilting mode and tearing mode examples. We will present results from the time integrations and convergence studies for derived quantities such as growth rates.

Our implementations serve to study different higher-order spectral element discretizations for the type of problems treated by the M3D program packages, and to design and test promising candidates for possible further inclusion into these codes.

Simulation of Sub-critical Turbulence by Shear Flows

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It is found that a transition from a laminar to a turbulent state can occur in some flows that are stable according to Rayleigh criterion. In order to find the possible mechanism of the transition, we study the dynamics of Spatial Fourier Harmonics (SFH). The linear dynamics of harmonics shows that there can be transient energy growth, while the non-linear interaction can change this transient behavior leading to the sub-critical transition to turbulence. We investigate the nonlinear effect in the simplest case of a sheared flow whose dynamics is governed by the two dimensional Euler equation in the stream function formulation:

$$\left[\frac{\partial}{\partial t} + U_0(y)\frac{\partial}{\partial x}\right]\Delta\psi + [\psi, \Delta\psi] = 0, \tag{1}$$

Here $U_0(y) = (Ay, 0)$ is the basic flow velocity with constant shear A along the y-axis and ψ is the stream function associated to the perturbation. Two initial conditions are studied: (1) the symmetric Gauss function and (2) the elliptical Gauss function in $\mathrm{r} = (x, y)$ plane

The result of the nonlinear simulation for the first initial condition shows that the energy of the vortex with negative vorticity increases or decreases depending upon the vortex size and amplitude, while the one of positive vorticity increases, saturates and oscillates rapidly. We will use numerical simulations to investigate the degree of energy amplification depending on the vortex size and amplitude. For the second type of initial condition, we investigate how the nonlinear dynamics acts in each case of positive and negative vorticity. The nonlinear dynamics rotates the vortex in the opposite direction in wave-number space. The interplay between shear and nonlinear interaction prevents the vortex from decaying away and let it grow for a longer time.

We will discuss the asymptotic growth of the transient as the possible mechanism for the sub-critical transition to turbulence in plasma and geophysical fluid.

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Nonlinear Plasma Simulation Studies using M3D*

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The multilevel physics, parallel processing plasma simulation code, M3D [1,2] is used to study toroidal plasma discharges. M3D currently has physics levels of MHD, two-fluids [3], and hybrid gyrokinetic-particle/fluid models.[4] It uses unstructured meshes [5], and the parallel processing structure utilizes MPI and the PETSc framework[6], with good parallel scaling up to 1000s of processors.

NSTX discharges can have strong toroidal shear flow approaching 0.3 of the Alfven velocity. Nonlinear M3D simulations show that the strong toroidal flow coupled with ion diamagnetic effect, ω^*i, can give arise to a saturated state of the m=1 internal kink mode. This may explain saturated sawtooth modes often seen in the experiment.

A long standing puzzle in tokamak research is that some experimental measurements show that the central q value does not rise above one, after a sawtooth crash [7], while theory and simulation typically show q_0 rise above one after a crash. One attempt for the explanation uses localized reconnection picture.[8] M3D simulation of sawtooth crashes in TEXTOR geometry shows that the localization effect of reconnection is rather small. Nevertheless, we exaggerated the localization numerically to find that the main effect of the localization is to make the field lines stochastic, as can be expected from a theoretical reasoning. Whether such stochasticity can give rise to a sawtooth thermal crash with relatively small change of the current profile so that q_0 can stay substantially below one is currently being studied.

* Work supported by US DoE Contracts DE-AC02-76-CH0-3073, DE-FG02-91ER54109, and DE-FG02-86ER53223.

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On the fully implicit field solver in the Particle-In-Cell code VORPAL

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Abstract

The Yee algorithm, which is traditionally used to evolve the EM field in PIC (Particle-In-Cell) codes, is fully explicit. To keep the Yee field advance numerically stable the time step must thus meet the Courant condition: $\Delta t < \Delta x/c$ (where Δx is the cell size and c is the speed of light). In many cases the physics of interest occur on much slower time scales and the Courant condition imposes an unnecessarily strict limit on the time step.

To remove the Courant limit on the time step we have implemented a fully implicit field solver in the PIC code VORPAL [1]. Our implicit field solver is based on the algorithm suggested by Bowers [2]. The Bowers scheme uses modified versions of Faraday's and Ampere's laws where damping is directly included in the curl terms. After Crank-Nicholson time discretization the level of damping corresponds directly to the degree of implicitness. I.e., as the damping parameter is increased, the discretized equations go from fully explicit to fully implicit. The spatial discretization is done on the Yee mesh and just like the Yee algorithm the implicit scheme is second order in both space and time.

The coefficient matrix is very sparse (with a 5-point stencil in 3D) and can be inverted by an iterative solver. We have used Sandia's parallel iterative solver library Aztec and have gotten convergence for Courant numbers as large as 2000 with the Conjugate-Gradient Squared method.

Performance benchmarks will be presented in addition to some preliminary results with the new implicit solver applied to coupling of electron Bernstein waves.

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Alfven wave dynamics in gyrokinetic particle simulations

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The effect of electromagnetic perturbations in gyrokinetic particle simulation is investigated employing a fluid-kinetic hybrid electron model.[1] At a critical β value, we expect excitations of new branches of electromagnetic modes, that are the Alfvenic ion temperature gradient mode (AITG)[2] and the kinetic ballooning mode (KBM).[3] Based on a small parameter expansion by the square-root of the electron-ion mass ratio, the hybrid model solves the adiabatic response in the lowest order and solves the kinetic response in the higher orders. We take two steps in verifying the Alfven wave dynamics; (1) in the limit of massless electrons, (2) in the case with kinetic electrons including the response of perturbed magnetic field lines. This work is supported by Department of Energy (DOE) Cooperative Agreement No. DE-FC02-03ER54695 (UCI), DOE Contract No. DE-AC02-76CH03073 (PPPL).

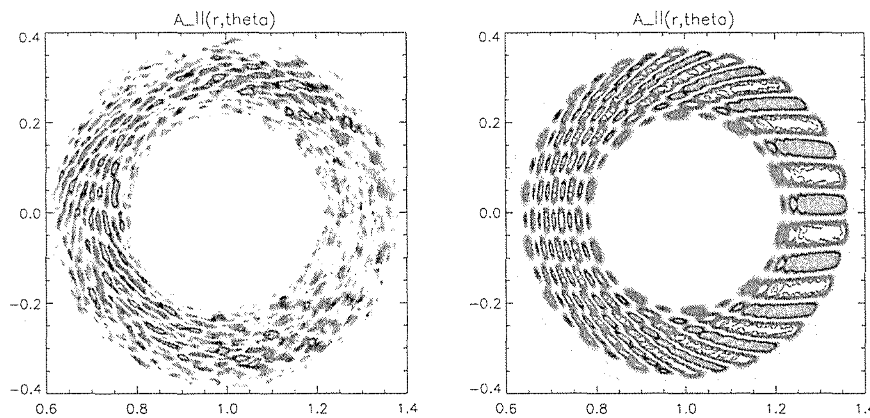

Figure 1: (**Left**) Evolution of $A_{\|}$ accompanied by a linear ITG instability. (**Right**) Perturbing magnetic field lines at t=0. Odd parity modes chosen for $A_{\|}$.

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Numerical study of the conducting shell and NBI stabilization of the MHD modes in the FRC [1]

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Abstract

Stability properties of an FRC configuration with parameters typical for the proposed MRX-FRC experiment have been studied using the hybrid version of the 3D simulation code HYM. Effects of the close-fitting conducting shell and the energetic beam ions on stability properties of the MHD modes with toroidal mode numbers n=1-4 have been investigated. A full-orbit kinetic description is used for both the thermal and the beam ions, and the electrons are treated as a cold fluid. Conducting-shell stabilization of the low-n modes is found to be stronger than had been previously found in MHD plasmas [1] due to the change in the linear mode structure caused by thermal ion kinetic effects. With conducting-shell stabilization, the n=2 co-interchange mode becomes the most unstable mode, but it can be effectively stabilized by neutral beam injection (NBI). Hybrid simulations show that the NBI stabilization is more effective for broader beams (larger beam ion temperature), and for the FRCs with elongation order of one. For this case, the low-n modes (n=1 and n=2) are stabilized completely for the typical beam ion parameters.

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Key Physics Involved In Paleoclassical Transport Model

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The *key hypothesis of the paleoclassical model* of electron heat transport [1,2] is that electron guiding centers diffuse with the poloidal magnetic flux (ψ), field lines in current-carrying toroidal plasmas. To understand this, consider $\mathbf{F} = m\mathbf{a}$ for electrons with a Lorentz force: $m_e \, d\mathbf{v}/dt = q_e(-\partial\mathbf{A}/\partial t + \mathbf{v}\times\mathbf{B})$, in which the scalar potential part of $\mathbf{E}$ is neglected. Using $\mathbf{A} = \psi_t \boldsymbol{\nabla}\theta - \psi\boldsymbol{\nabla}\zeta$, the $R^2\boldsymbol{\nabla}\zeta$ component of this equation yields $m_e R^2 \dot{\zeta} = q_e \, d\psi/dt$. Neglecting plasma resistivity, this equation can be integrated over time to yield the constancy of the canonical toroidal angular momentum $p_\zeta \equiv m_e R^2\dot{\zeta} - q_e\psi$.

When plasma resistivity is present a number of things happen: the poloidal magnetic field $\mathbf{B}_p \equiv \boldsymbol{\nabla}\zeta\times\boldsymbol{\nabla}\psi$ becomes a dissipative (i.e., non-conservative) electromagnetic field component (with a poloidal flux source S_ψ from the inductive transformer flux change or a non-inductive current source balanced by resistivity-induced magnetic flux diffusion in equilibrium), $d\psi/dt$ obeys a diffusion equation ($d\psi/dt = D_\eta \Delta^+\psi - S_\psi$ [2]), one can't simply integrate over time, and p_ζ is not a conserved quantity — at least not on the resistive diffusion time scale. On the electron gyromotion time scale p_ζ is conserved and $\psi(x,t) = \psi(x_g) + \delta\psi \sin(-\omega_{ce}t + \varphi_0)$ in which x is a local radial variable and $\delta\psi \sim \varrho_e \, d\psi/d\varrho << \psi(x_g)$. The small amount of poloidal flux $\delta\psi$ traversed by the radial component of electron gyromotion is governed (on the magnetic diffusion time scale) by a diffusion equation and diffuses radially [2]: $d\delta\psi/dt = D_\eta \, \partial^2\delta\psi/\partial x^2$, which yields a diffusive radially spreading of $\langle(\Delta x_\psi)^2\rangle/\Delta t = 2D_\eta$. In an electron gyroperiod $\Delta t \equiv 2\pi/\omega_{ce}$ this causes the electron guiding center to diffuse by $\langle(\Delta x_g)^2\rangle/\Delta t = 2D_\eta$ in which $D_\eta = \eta_\parallel^{\rm nc}/\mu_0$ is the magnetic field diffusivity induced by the neoclassical parallel resistivity. Thus, electron guiding centers diffuse with the poloidal magnetic flux — or at least the small amount of it that electrons sample in their gyromotion. Hence, the ψ position of the electron guiding centers becomes a "stochastic" (diffusing) variable in a drift-kinetic theory.

Diffusing electron guiding centers are accounted for in the paleoclassical model by adding a Fokker-Planck term [3] to the right of the electron drift-kinetic equation. The flux-surface-average of this term neglecting ψ transient effects (i.e., assuming $d\psi/dt = 0$) is [2] $\langle\mathcal{D}\{f\}\rangle \simeq (1/V')(\partial^2/\partial\rho^2)[V' D_\eta f(\rho)]$, in which ρ is a radial toroidal flux coordinate, V is the volume of a flux surface and $V' \equiv \partial V/\partial\rho$. The modified drift-kinetic equation (MDKE) yields both the usual neoclassical and paleoclassical transport fluxes. For long collision lengths the lowest order distribution function components are Maxwellianized and T_e equilibrated along field lines taking account of the toroidal, poloidal, and (near medium order rational surfaces) helical periodicities of axisymmetric toroidal plasmas [1,2]. The net paleoclassical heat flux results from the energy average of $\langle\mathcal{D}\{f_{\rm Max}\}\rangle$. It produces poloidal, toroidal, and helical periodicity contributions [1,2] in the usual sheared magnetic fields.

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Status of Continuum Edge Gyrokinetic Code Physics Development*

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We are developing an edge gyro-kinetic continuum simulation code to study the boundary plasma over a region extending from inside the H-mode pedestal across the separatrix to the divertor plates. A 4-D $(\psi, \theta, \epsilon, \mu)$ version of this code is presently being implemented, en route to a full 5-D version. A set of gyrokinetic equations[1] are discretized on computational grid which incorporates X-point divertor geometry. The present implementation is a Method of Lines approach where the phase-space derivatives are discretized with finite differences and implicit backwards differencing formulas are used to advance the system in time. A fourth order upwinding algorithm is used for particle cross-field drifts, parallel streaming, and acceleration. Boundary conditions at conducting material surfaces are implemented on the plasma side of the sheath. The Poisson-like equation is solved using GMRES with multi-grid preconditioner from HYPRE. A nonlinear Fokker-Planck collision operator from STELLA[2] in $(v_{\|}, v_{\perp})$ has been streamlined and integrated into the gyro-kinetic package using the same implicit Newton-Krylov solver and interpolating F and $dF/dt|_{coll}$ to/from (ϵ, μ) space.

Initially a hybrid model will be used: The ion dynamics is solved by the gyro-kinetic equation, the electron's contributions to the neoclassical transport mainly comes from the generalized Ohm's law. The Poisson equation is replaced by a gyro-kinetic vorticity density equation. However, for the calculation of bootstrap current, the electron drift kinetic equation will be solved.

We present the most recent progress from the code. With our 4D code we will compute the ion thermal flux, ion parallel velocity, self-consistent electric field, and geo-acoustic oscillations, which we will then be able to compare with standard neoclassical theory; and we will study the transition from collisional to collisionless end-loss. A validation plan will be presented, which will include a comparison of our 4D code with other kinetic neoclassical codes (such as GTC_neo[3] and XGC[4]) and experiments.

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Towards an Efficient Field Solve for Edge-Plasma Simulations*

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Abstract

We explore the numerical efficacy of multi-grid preconditioning methods in solving the plasma field equations in the edge of a tokamak with a single-null X-point divertor geometry.

The edge plasma region is divided into several zones (Inner/outer private flux region, Scrape-off-layer, Core region etc.), each represented by a logical rectangular grid with certain connectivity; the overall geometry is therefore represented by a semi-structured grid. Through the use of HYPRE, a high performance preconditioner library, we show that multi-grid method is an effective way of solving field equations in the above edge geometry. It can be used either as an independent solver or a preconditioner to the Newton-Krylov iteration methods. In particular, the algebraic multi-grid method, capable of effective coarsening for both the structured and unstructured parts, is shown to be superior to its geometric counterpart. For a model field diffusion equation solved by GMRES on one million grid points, the residual decreases by seven orders of magnitude after less than ten iterations with algebraic multi-grid preconditioning. However, with a geometric multi-grid preconditioner, which is based on structured grid, the number of iterations could reach hundreds for the same level of convergence. The CPU time for the former is about two orders of magnitude less than the latter. The algebraic method is also shown to be robust with respect to the anisotropy of diffusion coefficients and the stencil asymmetry typically induced by the inclusion of convection terms. Preliminary results of the solution to a Possion-like equation in a single-null X-point geometry with realistic grid size will be presented, along with the discussion of its parallel scalability.

We expect the algebraic multi-grid preconditioning will be an efficient algorithm for field solve both in fluid and kinetic edge-plasma simulations.

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Time Dependent Plasma Viscosity and Poloidal Flow Damping with Orbit Squeezing in Tokamaks*

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In the vicinity of a magnetic island, and in the zonal flow, the radial extent of the radial electric field layer is about the width of the ion poloidal gyro-radius in tokamaks. Thus, the effects of the orbit squeezing become important in these situations and in other applications such as in the edge region of the high confinement mode (H-mode) plasmas as well. A time dependent plasma viscosity with the effects of the orbit squeezing included is calculated. The calculation is performed by solving linear drift kinetic equation with plasma flows instead of gradients as the driving terms [K. C. Shaing, and D. A. Spong, Phys. Fluids B **2**, 1190 (1990)] in the time domain without using either Fourier or Laplace transform to examine if the initial condition of the perturbed particle distribution function contributes to the plasma viscosity. It is found that the initial condition does not contribute to the plasma viscosity in the high frequency limit. The poloidal flow damping rate in tokamaks is found to reduce from 0.675 ν_{ii}/ε obtained in [C. T. Hsu, *et al.*, Phys. Plasmas **1**, 132 (1994)] to approximately 0.675 $\nu_{ii}/(\varepsilon|S_,|)$, when the effects of orbit squeezing are taken into account. Here, ν_{ii} is the ion-ion collision frequency, ε is the inverse aspect ratio, and S is the orbit-squeezing factor. Thus, the plasma confinement can be improved when the effects of the orbit squeezing are included. It is important to include the effects of orbit squeezing in turbulence simulations.

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Discrete Particle Noise in PIC Simulations of Plasma Microturbulence

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A powerful method of code verification is cross-benchmarking results between codes addressing the same problem using different numerical techniques. Such cross-benchmarking can uncover both inadvertent errors the source code and inherent limitations in the underlying numerical method employed. A major source of controversy in cross-benchmarking exercises between gyrokinetic particle-in-cell (PIC) and continuum simulations of plasma microturbulence has been the role of discrete particle noise. Previous comparisons[1] between gyrokinetic PIC and continuum simulations of ITG turbulence showed that the fluctuation spectra from the PIC and continuum codes were essentially identical. While there were significant (~30%) differences in the fluctuation intensity and the resulting heat transport among codes, such difference could not be attributed solely to the integration technique (PIC vs. continuum). However, more recent comparisons between PIC[2,3] and continuum[4] gyrokinetic simulations of ETG turbulence show substantial (about a factor of 4) differences in the heat transport. These differences can be attributed to the integration technique, leading to a renewed interest in the role of discrete particle noise in PIC simulations of microturublence. A renormalized estimate of the dielectric shielding provides an estimate of the potential fluctuation spectrum associated with a given level of discrete particle noise,

$$S_{noise}(\vec{k}_\perp) = \sum_{k_z} \frac{w_{rms}^2 S_{filt}^2(\vec{k})\Gamma_0(k_\perp \rho)}{N_{tot}\left[2-\Gamma_0(k_\perp\rho)\right]\left[2-(1-S_{filt}(\vec{k}))\Gamma_0(k_\perp\rho)\right]}$$

where w_{rms} is the rms particle weight, S_{filter} represents finite-size particles and filtering, and N_{tot} is the total number of particles. Using this estimate we find that the noise level in PIC simulations of ITG turbulence is small compared to the turbulent spectrum [see Fig. 1(a)]. Making the same comparison for ETG turbulence we find that the late-time fluctuation spectrum is dominated by discrete particle noise [see Fig. 1(b)]. Hence, we conclude that differences in the transport observed in PIC and continuum simulations of ETG turbulence are likely due to discrete particle noise — an inherent limitation in the PIC technique.

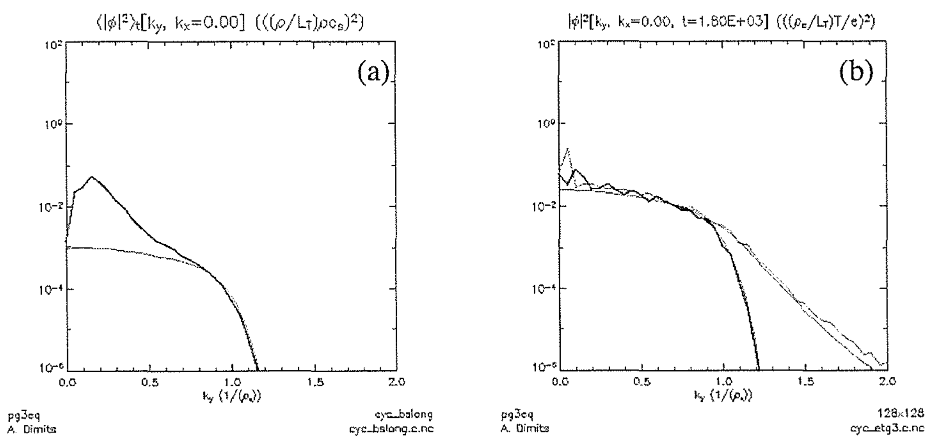

Figure 1. (a) Observed fluctuation spectrum from a PIC simulation of ITG turbulence (black curve) together with estimated noise level (red curve). (b) Observed fluctuation spectrum from a PIC simulation of ETG turbulence at k_x=*0* (black curve) and k_y=*0* (red curve) together with the estimated noise levels (blue and green curves, respectively).

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Calculation of Parallel Heat Flow in Chaotic Magnetic Fields*

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Abstract

This work compares the heat flow parallel to the magnetic field from calculations using local† and non-local‡ forms for the closure in the plasma temperature equation. Calculations were made with the high-order finite element plasma fluid code NIMROD§ in slab geometry with regions of magnetic field-line chaos resulting from two overlapping magnetic field perturbations. Details of the numerical implementation of the integral form for $\vec{q}_{\|}$ will be presented along with various magnetic field diagnostics and a review on the tools used to obtain them.

On-axis temperature versus collisionality calculated using both local and non-local closures is compared for fields with different amounts of chaos (parameterized by an island overlap criterion and by Lyapunov exponents). Special attention is given to regions in the magnetic field where the two forms for $\vec{q}_{\|}$ differ most. An effective radial thermal diffusivity derived from the calculated heat flow is also compared between the two models.

Calculation of $\vec{q}_{\|}$ at each point in the computational domain for realistic temperatures using the non-local form of the closure involves integrating long distances in each direction along the magnetic field-line. The initial implementation of this closure in the NIMROD code used a fast ODE integrator but was prohibitively costly in cpu-time. Subsequent development has yielded a nonclassical quadrature scheme coupled with linear fitting to simultaneously calculate the closure at all grid points in the periodic direction with a single field line integration. The large resulting speed up, which depends on collisionality, is remarkable.

Magnetic field diagnostic tools recently coupled to NIMROD were used in this work and results will be presented. Although these calculations were made in slab geometry, care was taken to choose magnetic flux functions which generate realistic islands so that results from this study might yield insight into more complicated simulations or experiments.

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Gyrokinetic Particle-In-Cell Calculations of Ion Temperature Gradient Driven Turbulence with Parallel Nonlinearity and Strong Flow Corrections*

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Abstract

Nonlinear gyrokinetic calculations have been performed with the three-dimensional, global, toroidal, particle-in-cell, delta-f, UCAN code[1] to study the effects of parallel nonlinearity and strong (externally imposed) flow corrections on ion temperature gradient driven turbulence. These calculations are electrostatic and adiabatic electrons are used. An equilibrium ion temperature gradient only is imposed, along with a generic parabolic q-profile appropriate to a large aspect ratio tokamak. The strong flow corrections derived by T. S. Hahm[2] have been added to the usual orbit and weight equations used in the UCAN code. The parallel nonlinearity[3] has been reactivated as well in the same equations. To examine the effect of strong flow corrections, the calculations have been performed with fluctuations-generated flows or zonal flows arbitrarily set to zero but with externally imposed sheared flows obeying a variety of profiles more or less localized in radius and with various flow magnitudes. The calculations show that the strong flow corrections have a qualitative effect on the saturation level of the fluctuations and on the steady-state heat flux even at the highest flow magnitudes used. The calculations with the re-activated parallel nonlinearity have been performed with no externally imposed flow but with fluctuations-generated or zonal flows allowed to self-consistently evolve. The parallel nonlinearity makes a quantitative difference in the saturation level of the fluctuations and in the saturated flux, as reported by Villard and colleagues[3]. This difference does however appear to diminish as the system size is increased at fixed ion gyroradius. Results of convergence studies with increasing system size and with varying degrees of self-similarity in profiles and parameters will be presented.

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Non-Maxwellian ion distribution function in the steep gradient region of tokamak plasma edge

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Gradient scale length of plasma density and temperature in the edge pedestal can be comparable or smaller than the banana orbit width of thermal ions. In the present-day large size tokamaks and future fusion reactors including ITER, the ion orbits in the H-mode pedestal can execute a significant radial excursion orbits before experiencing orbit-breaking Coulomb collisions. Under such circumstances, a local thermal equilibrium may not be possible for ions, but only a global steady state distribution function may be meaningful. A similar situation can occur for a relatively hot ion distribution function in a small tokamak, as reported from an ATC experiment.[1] We use the XGC (X-point incouded Guiding Center[2]) code to study the property of ion distribution function in a quiescent pedestal plasma with steep density and temperature gradients. The ion distribution function is not only non-Maxwellian, but also anisotropic. It is shown that the non-Maxwellian property of the ion distribution function is also greatly influenced by the orbit squeeze and expansion from radial electric field shear. The asymmetric parallel temperature profiles observed in ATC tokamak will be compared with our numerical simulation result. The velocity space hole from to the X-point effect in a diverted tokamak plasma edge[3], will also be discussed as another important feature of non-Maxwellian ion distribution.

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Nonlinear Upshift of the Critical Density Gradient for TEM Turbulence and the Role of Collisions

D. R. Ernst, K. Zeller and W. Dorland[†]

Plasma Science and Fusion Center, Mass. Inst. of Technology, Cambridge, MA, USA
[†]*Department of Physics, Univ. of Maryland, College Park, MD, USA*

Gyrokinetic simulations of trapped electron mode (TEM) turbulence, using the GS2 flux-tube nonlinear code, have revealed a nonlinearly quasi-stable range of density gradients lying above the threshold for linear growth.[1] The density gradient is the sole driving factor for the TEM under study. The onset of TEM turbulence was found to ultimately limit the density gradient in the C-Mod internal transport barrier. The associated turbulent particle and energy fluxes remain suppressed until the TEM linear stability threshold is exceeded by a finite margin, typically 25%. Analogous to the Dimits shift of the critical ion *temperature gradient* for toroidal ITG turbulence,[2,3] intrinsically generated zonal flows result in self-quenching of the primary modes. In contrast with the ITG case, in which finite ion collisionality eliminated the upshift through zonal flow damping,[4] this new TEM nonlinear upshift persists in the presence of realistic ion-ion and electron-ion collisions.

Using a simplified test case similar to the Cyclone Base Case, but with zero temperature gradient and finite collisionality, we have carried out more detailed studies of the role of zonal flows and collisions in the TEM upshift.[5] Within the nonlinearly quasi-stable range of density gradients, nearly periodic bursts occur. Very near the nonlinear critical density gradient, the bursts are so widely separated in time that only a single burst is observed. As the bursts self-quench in the TEM case, most of the energy in the primary modes is passed to the zonal flows, via what appears to be secondary instability.[6] Whether the TEM nonlinear upshift lies in range of weaker zonal flows that are stable to tertiary instability[6] remains to be determined.

If the electron-ion and ion-ion collision frequencies are kept consistent, it is clear that the role of collisionality in TEM turbulence is more complex than in ITG turbulence. In the previously studied ITG case with adiabatic electrons, the sole effect of ion-ion collisions was to slowly damp zonal flows.[4,7] For the pure TEM studied here, which is driven both by resonant and non-resonant effects, electron-ion collisions are linearly damping. This damping competes with collisional zonal flow damping to determine the interval between bursts of particle flux, and the average level of transport. Although neglected in previous work, the parametric dependence of the growth rate of the primary modes influences the period between bursts. Accordingly, with stronger density gradients, the regular bursts transition to more intermittent behavior. Well above marginal stability, we find the temperature scaling of TEM turbulent particle transport to be primarily gyro-Bohm (for small ρ_*), with a relatively weak departure due to collisionality effects.

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Ion Temperature Gradient Turbulence in Shaped Plasmas

W.X. Wang[1], S. Ethier[1], T.S. Hahm[1], W.W. Lee[1], J.L.V. Lewandowski[1], Z. Lin[2], J. Manickam[1], G. Rewoldt[1], W.M. Tang[1]

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[2] *University of California, Irvine, CA*

Abstract

The capability of simulating plasma turbulence in a shaped tokamak geometry has been developed for a global gyrokinetic particle code (GTC). It directly reads experimental plasma profiles and uses the corresponding numerical equilibrium. To validate this general geometry simulation capability cross benchmarks with original GTC code have been carried out using a model circular geometry with cyclone parameters. Linear benchmark shows good agreement in both real frequency and growth rate for ion temperature gradient (ITG) modes. In the nonlinear ITG benchmark performed with retained velocity space nonlinearity, good agreement is obtained for the steady-state level of turbulence fluctuations, zonal flow and heat flux over whole simulation domain. It is also shown that the zonal flow has a global scale length of minor radius and that no particle flux is produced in the electrostatic turbulence with adiabatic electrons. Nonlinear ITG simulations, using DIIID-size shaped plasmas as test bed, are conducted to investigate turbulence penetration over a transport barrier with strong $\mathbf{E} \times \mathbf{B}$ shear flow, from a linearly unstable outer region to a stable inner region. The nonlinear simulations are also extended to study the turbulence and transport properties of shear reversal plasma.

Work supported by U.S. DOE.

Gyrokinetic PIC Study of Shaping Effects on ITG Turbulence*

V. K. Decyk[1], J.-N. Leboeuf[1], A. Dimits[2], and D. Shumaker[2]

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[2] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.

The general geometry PG3EQ_NC module in the massively parallel SUMMIT gyrokinetic PIC framework has been developed to study the impact of equilibrium effects such as shaping and finite plasma beta on ITG turbulence in tokamak geometry. This is done at first in the electrostatic approximation and with adiabatic electrons. Features of the PG3EQ_NC module include the quasi-ballooning representation local to a flux surface but almost field-aligned, which it shares with its circular geometry PG3EQ counterpart [1]. They also encompass magnetic and plasma profiles from Miller equilibria [2] or from experimental equilibria via an interface to EFIT data [3]. Successful tests of the general geometry and circular geometry implementations of PG3EQ in the limiting case of a model circular equilibrium will be reported. Progress in the incorporation of Miller equilibria and effects of shaping on ITG turbulence in that context will be discussed. The use of experimental equilibria will be highlighted in the so-called Cyclone base case [4] and the effects of shaping and finite beta will be presented and contrasted with their circularized counterparts. Initial results of the application of the PG3EQ_NC module to an advanced tokamak discharge in DIII-D will be reported as available.

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*This work is performed for USDoE by Univ. California LLNL under contract W-7405-ENG-48 and by UCLA under grant DE-FG02-04ER54617.

Field Reversed Configuration for Direct Fusion Propulsion

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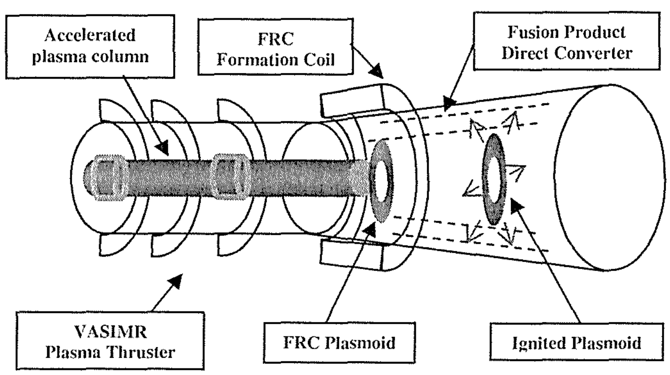
The Field Reversed Configuration (FRC) is an attractive concept for plasma propulsion because its intrinsically high plasma *beta* and the formation of magnetically detached plasmoids.

Direct FRC fusion-propulsion schemes (that is, besides the basic concept of a reactor producing electricity to power a thruster) have been previously discussed (*e.g.* [1]), with the plasma exhaust accelerated directly from the fusion core or collected from the FRC scrape-off layer and channeled through a magnetic nozzle

This study analyzes a different scheme (see figure) where the FRC is formed in the final stage of a plasma thruster, like the *VASIMR* engine [2]. The plasma detachment in the nozzle is then induced in a controlled way, through the formation of a sequence of FRC plasmoids. In case the FRC is able to sustain fusion conditions, the energy of the fusion products can be collected in the nozzle, while the plasmoid is leaving the rocket (ideally via direct conversion from neutron-free reactions) with transit time in the nozzle longer than the ignited FRC life time. Only the fusion products that are escaping radially the detached plasma (plasmoid) are interacting with the rocket and are not expected to produce appreciable net back-thrust.



The case of a sub-critical (without fusion yield) FRC is also interesting for the possibility of increasing the overall nozzle performance via a controlled detachment and of implementing plasmoid pre-acceleration schemes.

A preliminary assessment of the feasibility of this concept is presented along with results from a simulation study initiated with the *NIMROD* code (MHD/two-fluid) [3] to reproduce the plasma detachment in the *VASIMR* magnetic nozzle and to compare with the induced detachment obtained through FRC plasmoid formation.

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[3] http://www.nimrodteam.org

Hot Electron Instability in a Dipole Confined Plasma

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In a plasma with an energetic electron species present in a cold background plasma two interacting collective modes, an MHD-like mode and a hot electron interchange mode may be present [1]. The stability of interchange modes in a z-pinch, including a core and hot electron species has recently been recently studied by Krasheninnikova and Catto [2]. Using the dispersion relation derived in this reference we show that when necessary conditions are satisfied the two modes may be present or absent in a closed-field line magnetic confinement geometry such as a hard core z-pinch or a dipole. When the modes are unstable at low beta a re stabilization is observed for both modes for a sufficiently high hot electron beta value.

In the LDX experiment electron cyclotron resonance heating is utilized to produce plasmas with beta values of up to 7% [3]. Initial experimental ECRH results will be discussed and compared with theoretical predictions.

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Supported by US DoE

Gyrokinetic Simulations of ITG and ETG Turbulence*

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Abstract

In our earlier analysis [1] of the flux-surface averaged contributions to the zonal-flow shear in nonlinear gyrokinetic simulations of toroidal ion-temperature-gradient driven turbulence, it was found that zonal-flow energy in ITG turbulence is generated primarily through the Reynolds' stress and dissipated by transit-time damping (through coupling to geodesic acoustic modes). Here, we examine whether a spatially local determination of the flow-shear contributions, which is more analogous to what could be probed with experimental diagnostics, can provide similar information on the zonal-flow balances.

Results will be presented from an ongoing study of electron-temperature-gradient driven (ETG) turbulence and transport using δf-PIC nonlinear gyrokinetic simulations. The simulations typically show evolution through streamer-dominated states in which χ_e/χ_{eGB} is very large (of order 20-60), before settling down to states with much lower values of χ_e. The late-time low-χ_e states are streamer free, with potential spectra and χ_e levels consistent with the noise dominated regime of a model for the interaction of δf-PIC noise and turbulence recently developed by Hammett (see G. Hammett et al., this meeting). Explorations varying numerical parameters (system size, particle size, and simulation particle number density) are underway to attempt both to make contact with other reported gyrokinetic ETG simulation results (for which there is a wide range of transport levels), and to check consistency of the scaling of the late-time potential fluctuations and transport with Hammet's model.

*Work performed for USDoE by Univ. California LLNL under contract W-7405-ENG-48.
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Presented at the 2005 International Sherwood Fusion Theory Conference Stateline, Nevada, April 11-13, 2005.

Computational Aspects of Modeling ITER AT Time Dependent and Time Independent Configurations*

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Abstract

Predictive modeling of future tokamak burning plasma devices such as ITER is becoming more refined on a continual basis due to the increased understanding of the physical processes that govern energy and particle transport. However, as the modeling effort becomes more sophisticated, the amount of computational effort also increases and it becomes more difficult to generate and verify the results. The best theoretical predictions of ITER AT behavior includes a host of computationally intensive methods and codes, all of which must act in unison in order to achieve the desired goal of essentially 100% noninductive current operation. For example, it is important to include stiff turbulent transport models, MHD equilibrium calculations, Monte Carlo fast ion deposition and slowing down, as well as ECH, fast wave and lower hybrid heating and current drive effects. The nonlinear interaction of these computational models generally results in severe restrictions in the time step used to advance the transport equations. This problem is particularly acute for ITER AT discharges where current relaxation times are much longer than the usual transport analysis which spans a few energy confinement times. Furthermore, reversed shear discharges, used in many AT scenarios are observed to introduce a sensitivity and associated uncertainty in the current profiles which may require additional computations due to the uncertainty in the modeling of turbulent growth rates and flux surface shape evolution. At General Atomics all of these effects are brought together under the control of the ONETWO transport code. We had to develop special solution methods, including adaptive grid techniques, as well as variations in the approach to steady state which can not be done in the standard time stepping manner due to the long times involved. Using globally convergent, fully implicit, nonlinear numerical solution methods for the coupled transport equations we are able to generate time-evolved solutions which bring the kinetic profiles into a near steady state. Subsequently the current density with its current drive sources is determined by forcing the toroidal electric field into a flat, spatially independent form, which yields a steady-state ohmic current profile based on the previously determined kinetic profiles. This process can be iterated and results in the desired, time independent, steady state AT scenario. The problems encountered, the solution methods, and the incorporation of parallel computing methods using both OpenMP and MPI are discussed within the contest of a transport code, using ONETWO as an example.

*This was work supported by the U.S. Department of Energy under DE-FC02-04ER54698 and DE-AC05-00OR22725.

Modeling Plasma Effects of Edge Resonant Magnetic Perturbations on Divertor Tokamaks

R.A. Moyer,[1] T.E. Evans,[2] M.J. Schaffer,[2] A. Runov,[3] R. Schneider,[3] S. Kasilov,[4] P.B. Snyder,[2] S. Kruger,[5] and D.P. Brennan[6]

[1]University of California, San Diego, California, USA
[2]General Atomics, San Diego, California, USA
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[5]Tech X Corporation, Boulder, Colorado, USA
[6]Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

The ability to control pedestal and ELM behavior in high performance H-mode plasmas substantially improves the viability of next-step burning plasma devices such as ITER. Small (1 part in 5000) magnetic perturbations from external coils have been used in DIII-D to suppress large Type I ELMs without degrading core confinement [Evans, *et al*., Phys. Rev. Lett. **92** (2004) 235003-1]. Extrapolating this approach to next-step devices requires an improved ability to self-consistently model the plasma response to the edge magnetic perturbations. This task requires three components: 1) 3D equilibrium reconstruction, 2) plasma transport in the perturbed equilibrium, and 3) MHD stability in the resulting pedestal plasma. We have initiated an international collaboration to develop improved computational tools based on existing codes for this purpose As a first step, we have calculated the effect of the applied fields on the equilibrium by adding the perturbing field to an axisymmetric solution to the Grad-Shafranov equation (from EFIT) using the field line integration code TRIP3D [Evans, *et al*., Phys. Plasmas **9** (2002) 4957]. Scaling studies for inner wall limited and diverted plasmas (upper and lower single null and double null) demonstrate that, in the absence of a significant plasma "healing" or error field amplification response, the edge of a poloidally divertor tokamak is inherently more sensitive to formation of stochastic field regions than a limiter tokamak (in which most previous stochastic boundary experiments have been performed). This is due to the high magnetic shear associated with the divertor X-points, which provides many closely spaced resonant surfaces which can lead to stochasticity. This approach has been used to design configurations of the flexible DIII-D coil set (6 external and 12 internal coil segments) which maximize the resonant field amplitude on the pedestal rational surfaces and is being used to assess various options for external coils in JET and ITER. We compare the results from this modeling with experimental data, and present our plans for incorporating the plasma response using e.g. existing 3D equilibrium reconstruction tools such as VMEC and PIES. These equilibria will be used in the Monte Carlo heat transport code E3D to model the plasma transport for validation with measured electron temperature and heat flux profiles. Preliminary ELM linear stability modeling with the ELITE code [Snyder, *et al*., Nucl. Fusion **44**, 320 (2004)] assuming axisymmetry of the measured profiles in the perturbed state suggests that the enhanced radial transport due to perturbation increases the time for the pedestal profile to reach the marginally stable point, but that the same n=25–30 modes become linearly unstable shortly before a surviving ELM event. On the longer term, we plan to use the free boundary MHD stability code NIMROD to investigate how the 3D plasma response alters the pedestal stability properties.

*This work supported in part by US DOE under DE-FG02-04ER54758, DE-FG02-05ER54809, DE-FC02-04ER54698, and DE-FG03-95ER54309.

Post Deadline

Abstracts

Tuesday, April 12

Poster Session *P3*

at 7:30 pm

Simulations of carbon sputtering and plasma-sheath chemistry interactions at fusion reactor divertor plates *

L. A. Zepeda-Ruiz, J. Marian, G. Gilmer, C. Mundy, E. Bringa, T. D. Rognlien
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Livermore, CA 94550

Abstract

The interaction of edge plasma with material surfaces raises key issues for the viability of ITER and future fusion reactors, including heat-flux limits, net material erosion, and impurity production. A fundamental numerical model of such interactions is presented that is center on the use of Molecular Dynamics (MD) simulations to determine material sputtering yields. After exposure of the graphite divertor plate to the plasma in a fusion device, an amorphous C/H layer forms. This layer contains 20-30 atomic percent deuterium/tritium bonded to the carbon. Subsequent D/T impingement on this layer produces a variety of hydrocarbons that are sputtered back into the sheath region. We present molecular dynamics (MD) simulations of D/T impacts on amorphous carbon layer as a function of ion energy and orientation. In particular, energies are varied between 20 and 120 eV to transition from chemical to physical sputtering. These results are used to quantify yield, hydrocarbon composition and eventual plasma contamination. In addition, we present the temporal evolution of the chemical-reaction kinetics for a simple H plasma in the sheath region of the divertor. The connection between the amorphous layer, sheath region and main plasma region, is made by setting appropriate boundary conditions to the sheath chemistry calculations. The plasma region dictates electron and ion temperatures, pressure, and flow velocities together with the relative mass fractions for the ionic species. For its part, the MD results are used to estimate the source term for the contaminating reactants (C and C_xH_y) in the sheath and presheath regions.

* This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

The general expression of the gyroviscous force *

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Under the only assumption of a small gyromotion period and Larmor radius compared to any other time and length scales, and to lowest significant order in $\delta = \rho/L$, the general form of the gyroviscous stress tensor is given in Ref.[1]. This expression is valid for arbitrary collisionality, is applicable to either fast (i.e. $\partial/\partial t \sim \delta\Omega_c$, $u \sim v_{th}$) or slow (i.e. $\partial/\partial t \sim \delta^2\Omega_c$, $u \sim \delta v_{th}$) dynamics, and does not require the distribution function to be close to a Maxwellian. It contains as special limits the Braginskii[2] form valid for high collisionality and fast dynamics, the Macmahon[3] form valid for arbitrary collisionality and fast dynamics, the Mikhailowskii-Tsypin[4] form valid for high collisionality and slow dynamics, and a slow dynamics form "hopefully valid" for arbitrary collisionality derived by pretending that, even at low collisionality, the leading order distribution function could be a Maxwellian[5] or just isotropic[1]. The divergence of this stress tensor (gyroviscous force) is evaluated in exact, coordinate-free vector form, retaining arbitrary magnetic geometry, parallel gradients, β, parallel flow and compressibility. Considering in particular the contribution from Braginskii's part, the final form of the momentum equation after the "gyroviscous cancellation" and the "effective modification of the pressures by the parallel vorticity", is precisely established.

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Coupled BOUT/UEDGE study of edge-plasma turbulence on the transport timescale*

L.L. LoDestro, T.D. Rognlien, M.V. Umansky, and X.Q. Xu

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Abstract

The simulation of plasma profile evolution on the transport timescale with particle and energy fluxes provided by state-of-the-art turbulence codes is critical for the prediction and optimization of MFE plasmas. However, the computational intensiveness of the turbulence codes together with the disparity in the turbulence and transport timescales at present prevents the useful straightforward exercise of the turbulence codes on long timescales: this problem remains one of the formidable multi-scale challenges for MFE plasmas. In the edge region of a tokamak plasma, self-consistency of the profiles with the driven turbulence is particularly important for the capture of the complex interplay of effects involved in pedestal formation and structure. Also, analysis of the fluxes to material surfaces can bring in very long timescales: the characteristic timescales of the turbulence are of the order $\sim 10^{-5} - 10^{-4}$s; that of recycling (among the longer scales) is of the order $\sim 10^{-2} - 10^{-1}$s. To approach these problems, we apply a relaxed iteration method [1] to couple the 3D edge turbulence code BOUT [2] and the 2D axisymmetric edge transport code UEDGE [3]. Initial results [4], in an L-mode plasma, exhibited large poloidal variations, with the ion flux to the main-chamber walls exceeding that to the divertor plates. Here we report new simulations and progress in our coupling algorithm technique. The UEDGE and BOUT infrastructures have been upgraded to ennable coupling via the Python framework; and the coupling is being extended to additional fields.

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

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Recent Advances in the Ignitor Program*

F. Bombarda[1], B. Coppi[2], and the Ignitor Project Group
[1]ENEA, Frascati, Italy
[2]MIT, Cambridge, MA

Abstract

There have been significant advances both in understanding the plasma physics regimes that the experiments by Ignitor are expected to cover and in finalizing the design of the Ignitor machine. A realistic form of control of the plasma temperature in view of the "thermonuclear instability" onset as ignition is approached has been simulated by the JETTO 1+1/2 D transport code. It consists in coordinating the value of the plasma density that influences strongly the plasma resistivity, and the ICRH system that is employed to keep the plasma slightly "subcritical" but yet with high values of Q [1].

The development of the two-stage, four barrel fast pellet injector for Ignitor is being carried out in the framework of a collaboration between ENEA at Frascati and Oak Ridge National Laboratories (Fusion Energy Division). According to our preliminary simulations, 3-4 km/s will be adequate to reach the inner part of the plasma column and thus provide the means for a fine control of the density profile in Ignitor, particularly during the critical phase of the initial current and temperature rise. The compact size of the Ignitor machine favors the injection from the low field side, for which very positive results have been obtained on the FTU machine [2], in terms of density profile peaking and good energy confinement. A key component for this device, the fast valve, has been successfully developed in Italy, while most of the other components have been procured at ORNL and are being assembled. The new fast valve considerably reduces the requirements on the expansion volumes necessary to prevent the propulsion gas to reach the plasma chamber and is a necessary component to reach the desired pellet speeds [3].

The Ignitor design is characterized by the absence of a separate divertor volume. The plasma chamber is covered by a first wall of molybdenum tiles acting as an extended limiter that follows very closely the plasma shape. The available 2D simulation codes are not able to treat this configuration because of the singularity at the tangency point between LCFS and first wall. Therefore more flexible numerical schemes are being explored for a proper treatment of the Ignitor configuration [4]. In the meantime, simple calculations show that a large fraction of the power available during a high performance discharge in Ignitor can be radiated. The remaining fraction is assumed to be deposited on the first wall by convective/conductive mechanisms, and the resulting thermal loads on the tiles are estimated. Also the case of heat loads due to possible 3D asymmetries in the machine is considered by simple geometrical modelling.

Among the progresses in the machine design, we cite a new configuration of the plasma chamber and a solution for the first wall (Molybdenum tiles and tile carriers), the optimization and simplification of the entire poloidal field system, the completed construction of the second generation prototypes of the toroidal magnet plates, and the definition of the power supply system.

*Sponsored in part by ENEA of Italy and by the US Department of Energy.

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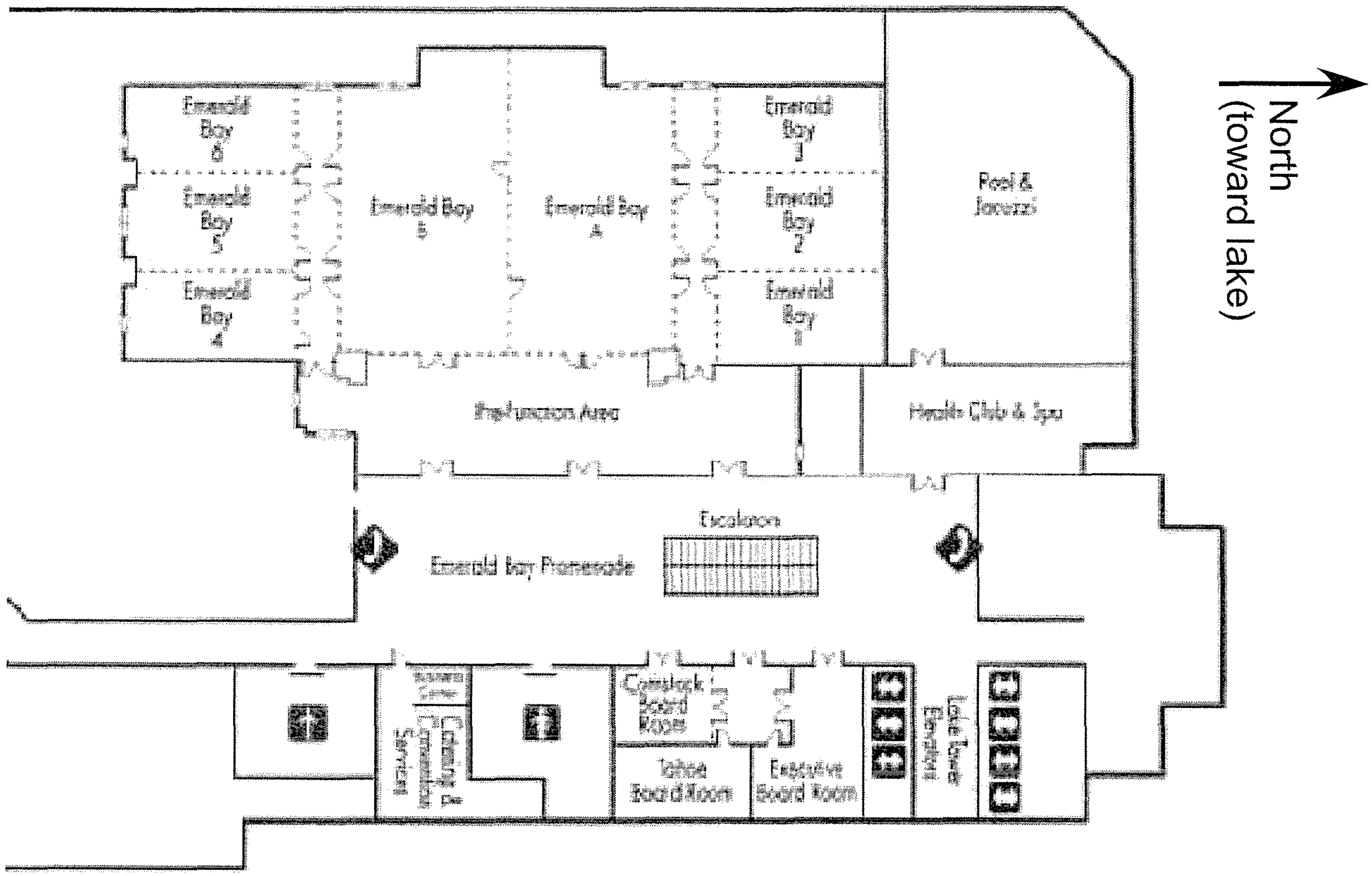

All sessions will be held in the Emerald Bay rooms.
Computer access is in the Executive Board room.

Monday, April 11

Oral Session O1 – Chair: Gary Staebler

8:20 – 8:30 Welcome and meeting arrangements – T.D. Rognlien, LLNL

8:30 – 9:30 Review paper: *Photonic band gap materials: engineering the fundamental properties of light*, Sajeev John, Univ. Toronto

9:30 – 10:00 *Natural velocity of magnetic islands*, F.L. Waelbroeck, IFS, Univ. Texas

Poster Session P1

10:00 – 12:00 Posters with coffee

12:00 – 1:30 Lunch

Oral Session O2 – Chair: Carl Sovinec

1:30 – 2:00 *Gyrokinetic simulations of ion and impurity transport*, C. Estrada-Mila, Univ. Calif., San Diego

2:00 – 2:30 *Intermittent transport and scaling of the scrape-off-layer width in tokamaks*, A.Y. Aydemir, IFS, Univ. Texas

2:30 – 3:00 *Gyrokinetic δf simulation of the collisionless and semicollisional tearing mode instability*, W. Wan, Univ. Colorado

3:00 – 3:30 *Equation free projective integration: A novel scheme for modeling multiscale processes in plasmas*, M.A. Shay, Univ. Maryland

Poster Session P2

3:30 – 5:30 Posters with coffee

Special Session/Discussion on Cluster Architecture – Chair: Vincent Chan

5:30 – **7:30** Presentations by C. Bolton, V. Decyk, E Valeo, J. Candy, and D. Ernst

Tuesday, April 12

Oral Session O3 – Chair: Peter Catto

8:30 – 9:30 Review paper: *Scrape-off layer flows, magnetic topology, and the flow boundary conditions imposed at the separatrix in a tokamak plasma*, B. LaBombard, MIT

9:30 – 10:00 *Particle noise induced diffusion and its effects on ETG simulations*, G.W. Hammett, PPPL

10:00 – 10:30 Coffee break

Oral Session O4 – Chair: Steve Jardin

10:30 – 11:00 *Rotation, error field, and wall thickness effects on resistive wall modes in ITER*, L.J. Zheng, IFS, Univ. Texas

11:00 – 11:30 *Nonlinear dynamics of energetic particle-driven fishbone instability in tokamak plasmas*, G.Y. Fu, PPPL

11:30 – 12:00 *Modelling nonperturbative frequency sweeping*, R.G.L. Vann, Univ. Warwick

12:00 – 12:30 *Nonlinear evolution of edge localized modes*, D.P. Brennan, MIT, General Atomics

12:30 – 5:30 Open time

5:30 – 7:00 Conference dinner

Harveys Hotel, Conference Level

Poster Session P3

7:30 – 9:30 Poster Session 3

Wednesday, April 13

Oral Session O5 – Chair: John Cary

8:30 – 9:30 Review paper: *Unique MHD properties of spherical torus plasmas*, J. Menard, PPPL

9:30 – 10:00 *Self-organized temperature redistribution during sawtooth oscillation on TEXTOR*, H. Park, PPPL

10:00 – 10:30 Coffee break

Oral Session O6 – Chair: Tom Rognlien

10:30 – 11:00 *Gyrokinetic simulations of Z-pinch*, P. Ricci, Dartmouth College

11:00 – 11:30 *On the possibility of the sheath-driven, finite-beta modes localized near the divertor plate*, R.H. Cohen, LLNL

11:30 – 12:00 *Time and space dependent parallel viscous force*, A.L. Garcia–Perciante, Univ. Wisc.

12:00 Conference adjourned