

# **Proceedings of the 2008 International Sherwood Fusion Theory Conference**

**March 30 - April 2, 2008, Boulder, Colorado.**

	Monday March 31, 2008	Tuesday April 1, 2008 <i>John Greene Memorial Session</i>	Wednesday April 2, 2008
8:30 AM	<b>Session 1A: Ballroom (Rogers, Chair)</b> 8:25 AM – John Cary <i>Opening Remarks</i>  <a href="#">George McKee</a> <i>Modern Measurement Capabilities &amp; Analysis Techniques for Validation of Turbulence Simulations</i>	<b>Session 2A: Ballroom (Chan, Chair)</b> 8:30 AM - V. Chan <i>Biography of John Greene</i>  8:40 AM - <a href="#">John Johnson</a> <i>On John M. Greene's MHD Equilibrium and Stability Work</i>	<b>Session 3A: Ballroom (Tang, Chair)</b> <a href="#">Steve Cowley</a> <i>Explosive Instability in Plasmas</i>
9:00 AM			
9:30 AM	Break	9:20 AM - <a href="#">Phil Morrison</a> <i>"Oh, that."</i>	Break
10:00 AM	<b>Session 1B (Posters)</b>	Break	<b>Session 3B: Ballroom (Belova, Chair)</b> <a href="#">Boris Breizman</a> <i>Nonlinear Consequences of Weakly Driven Energetic Particle Instabilities</i>
10:30 AM		<b>Session 2B: Ballroom (Turnbull, Chair)</b> <a href="#">Alan Glasser</a> <i>Scalable Parallel Computation for Extended MHD Modeling of Fusion Plasmas</i>	
11:00 AM		<a href="#">Ming Chu</a> <i>Modeling of Resistive Wall Mode with Full Kinetic Damping</i>	<a href="#">Anthony Webster</a> <i>The Ideal Magnetohydrodynamic Peeling Mode Instability</i>
11:30 AM		<a href="#">Hong Qin</a> <i>Variational Symplectic Integrator for the Guiding Center Motion of Charged Particles for Long Time Simulations in General Magnetic Fields</i>	<a href="#">Nikolai Gorelenkov</a> <i>Low frequency eigenmodes due to Alfvén acoustic coupling in toroidal fusion plasma</i>
12:00 PM	Lunch	<a href="#">Jong-kyu Park</a> • <i>Tokamak Plasma Response to External Magnetic Perturbation</i>	
12:30 PM		Afternoon Break	
1:00 PM			
1:30 PM			
2:00 PM	<a href="#">X Q Xu</a> <i>TEMPEST simulations of the neoclassical radial electric field</i>		
2:30 PM	<a href="#">Felix Parra</a> • <i>Limitations of gyrokinetics on transport time scales</i>		
3:00 PM	<a href="#">Jianying Lang</a> • <i>Zonal Flow &amp; Zonal Density Saturation Mechanisms for Trapped Electron Mode Turbulence</i>		
3:30 PM	<a href="#">Prashant Valanju</a> <i>High Power Density Experiment(HPDX) Next Step device in the age of ITER</i>		
4:00 PM	<b>Session 1D (Posters)</b> <i>Refreshments and alcohol will be served.</i>	<b>Session 2C (Posters)</b> <i>Refreshments and alcohol will be served.</i>	
4:30 PM			
5:00 PM			
5:30 PM			
6:00 PM		<b>Session 2D: Ballroom</b> Awards Banquet <i>Dinner and alcohol will be served.</i>	
6:30 PM			
8:30 PM			

# List of Oral Presentations

1. **Emily Belli:** *Drift-Kinetic Simulations of Neoclassical Transport*
2. **Boris Breizman:** *Nonlinear Consequences of Weakly Driven Energetic Particle Instabilities*
3. **Ming Chu:** *Modeling of Resistive Wall Mode with Full Kinetic Damping*
4. **Steven Cowley:** *Explosive Instability in Plasmas*
5. **Alan Glasser :** *Scalable Parallel Computation for Extended MHD Modeling of Fusion Plasmas*
6. **Nikolai Gorelenkov:** *Low frequency eigenmodes due to Alfvén acoustic coupling in toroidal fusion plasma*
7. **John Johnson:** *On John M. Greene's MHD Equilibrium and Stability Work*
8. **Prashant Valanju:** *High Power Density Experiment (HPDX) - Next Step device in the age of ITER*
9. **Jianying Lang:** *Zonal Flow and Zonal Density Saturation Mechanisms for Trapped Electron Mode Turbulence*
10. **George McKee:** *Modern Measurement Capabilities and Analysis Techniques for Validation of Turbulence Simulations*
11. **Philip J Morrison:** *"Oh, that."*
12. **Jong-kyu Park:** *Tokamak Plasma Response to External Magnetic Perturbation*
13. **Felix Parra:** *Limitations of gyrokinetics on transport time scales*
14. **Hong Qin:** *Variational Symplectic Integrator for the Guiding Center Motion of Charged Particles for Long Time Simulations in General Magnetic Fields*
15. **Andrei Simakov:** *A comprehensive analytical model for 2D magnetic reconnection in resistive, Hall, and electron MHD*
16. **Anthony Webster:** *The Ideal Magnetohydrodynamic Peeling Mode Instability*
17. **Xueqiao Xu:** *TEMPEST simulations of the neoclassical radial electric field*

A special John Greene Memorial Session was held on Tuesday, April 1. The session consisted of a biography of John M. Greene presented by Vincent Chan and the two presentations #7 and #11 (see above).

# Poster Session 1B

1. **Svetlana Shasharina:** *Visualization Schema for Fusion Simulation Data*
2. **Shinji Tokuda:** *Conjugate Variable Method in Hamilton-Lie Perturbation Theory Applied to Plasma Physics*
3. **Leonid Zakharov:** *Locked kink mode  $m/n=1/1$  during vertical disruption events*
4. **Peter Catto:** *Electrostatic turbulence in tokamaks on transport time scales*
5. **Grigory Kagan:** *Arbitrary poloidal gyroradius effects in tokamak pedestals and transport barriers*
6. **Jae-Min Kwon:** *Delta-f and full-f hybrid particle in cell scheme for the neoclassical simulation of tokamak plasmas*
7. **Alessandro Cardinali:** *Hamiltonian Perturbation Theory in the Study of Lower Hybrid Wave Propagation in Ionized Gas*
8. **Diego Del-Castillo-Negrete:** *Singular value decomposition and wavelet methods for noise reduction in particle-based transport calculations*
9. **Ping Zhu:** *Nonlinear Ballooning Instability of an H-mode Pedestal*
10. **Dalton Schnack:** *The Absence of Complete FLR Stabilization in Extended MHD*
11. **Eugene Tracy:** *A new improved normal form for linear conversion*
12. **Mark Adams:** *Toward Optimal Multigrid Algebraic Solvers In Magnetohydrodynamics Simulations of Fusion Plasmas*
13. **Ryoji Takahashi:** *The kinetic effects of energetic particles on resistive MHD stability*
14. **Scott Baalrud:** *Enhanced Electron Scattering due to the Ion Acoustic Instability*
15. **Todd Krause:** *Natural selection: pruning the Darwin approximation*
16. **Andrew S Richardson:** *Ray tracing simulation of ICRF mode conversion in Alcator C-Mod*
17. **Wendell Horton:** *The Microtearing Modes and Drift Wave Turbulence*
18. **Motoki Nakata:** *Vortex Structures in ETG*
19. **Bruce Cohen:** *Hybrid Simulation of Plasmas Including Coulomb Collisions*
20. **H R Strauss:** *MHD Simulation of Resonant Magnetic Perturbations and Resistive Wall Effects*
21. **Ronald Waltz:** *Numerical Experiments on the Drift Wave-Zonal Flow Paradigm for Nonlinear Saturation*
22. **Ihor Holod:** *Gyrokinetic PIC simulations of toroidal momentum transport in tokamak*
23. **Parvez Guzdar:** *Low-dimensional and 2D simulations of magnetic fluctuations in MCX*

24. **Federico Halpern:** *Summary of recent advances in the Weiland drift wave model for anomalous transport in tokamaks*
25. **Tariq Rafiq:** *Analytical and numerical studies of drift resistive and inertial ballooning modes in general toroidal geometry*
26. **Fatima Ebrahimi:** *Momentum transport from magnetic fluctuations in laboratory and astrophysical plasmas*
27. **Joshua Breslau:** *The CDX Sawtooth Benchmark for 3D Nonlinear MHD*
28. **Roddy Vann:** *Modelling observations of mode polarisation from MAST*
29. **Linjin Zheng:** *Linear gyrokinetics and kinetic investigation of resistive wall mode stability in ITER*
30. **Roman Kolesnikov:** *Electromagnetic high frequency gyrokinetic particle-in-cell simulation in magnetically-confined plasmas*
31. **Sterling Smith:** *A numerical approach to obtain the linear stability spectrum of ideal MHD with arbitrary equilibrium flows and a free boundary*
32. **Sumire Kobayashi:** *Plasma Turbulence and Transport in a Ring Dipole System*
33. **Eliezer Hameiri:** *A fluid-dynamical analog of a two-fluid plasma*
34. **Jane Pratt:** *Drift-Wave Eigenmodes and Spectral Gaps in Tandem Mirrors*
35. **Takahide Okabe:** *A particle code for the mixing efficacy problem of advection-diffusion models with sources and sinks*
36. **Bruno Coppi:** *Thermo-rotational Instability in Plasma Disks Around Compact Astrophysical Objects*
37. **Jesus Ramos:** *Finite-Larmor-Radius Kinetic Theory of a Magnetized Plasma in the Macroscopic Flow Reference Frame*
38. **Matt Landreman:** *Confinement regime transition: Spontaneous rotation reversal and collisionality of the plasma edge*
39. **Yong Xiao:** *Characteristic time scales in microturbulences*
40. **Alexander Pletzer:** *The FACETS Core Solver*
41. **Jean C Perez:** *Shear-flow-driven Alfvénic fluctuations in the Large Plasma Device*
42. **Ker-Chung Shaing:** *Critical Toroidal Rotation Profile for Resistive Wall Modes in Tokamaks*
43. **Dmitri Ryutov:** *Basic properties of a snowflake divertor*
44. **Johan Carlsson:** *Simulations of lower-hybrid coupling in the Madison Symmetric Torus*
45. **John R Cary:** *Simulations of nonlinear dynamics of electron Bernstein waves*
46. **Kurt Tummel:** *Non-fluid Micro-Reconnecting Modes and Relevant Experimental Observations*

47. **Gian Luca Delzanno:** *A robust, efficient equidistribution 2D grid generation method based on Monge-Kantorovich optimization*
48. **Wenlu Zhang:** *Transport of Energetic Particles by Microturbulence in Magnetized Plasmas*
49. **Zhihong Lin:** *Gyrokinetic simulation of energetic particle turbulence and transport*
50. **Yasutaro Nishimura:** *Roles of shear Alfvén wave on micro-turbulence transport in global gyrokinetic particle simulation*
51. **Linda Sugiyama:** *Guiding Center Models for 3D Plasmas*
52. **Andrew Ware:** *Neoclassical Viscosities and Anomalous Flows in Stellarators*

# Poster Session 1D

1. **Cristel Chandre:** *Reduction of radial transport and application to test particle dynamics*
2. **Friedwardt Winterberg:** *Thermonuclear Dynamo inside an Alfvén Black Hole*
3. **James Howard:** *Global Dynamics of Single Ion Motion in a Model Field-Reversed Configuration*
4. **Charlson Kim:** *Impact of velocity space distribution on hybrid kinetic MHD simulation of the (1,1) mode*
5. **Roscoe White:** *Chaotic Transport in a Reversed Field Pinch*
6. **V Alexander Stefan:** *Thermonuclear Yield Due to the Relativistic Electron Bernstein Modes in Spherical Tokamak Plasmas*
7. **Harry Mynick:** *Anisotropic pressure for calculations of shielding*
8. **Stuart Hudson:** *Temperature gradients are supported by cantori in chaotic fields*
9. **Roman Smirnov:** *Tokamak dust transport and distributions in edge plasmas*
10. **Paolo Ricci:** *High- and low-confinement modes in simple magnetized toroidal plasmas*
11. **Ryan White:** *Exact integral identities for the Sinh-Poisson equation*
12. **Antoine Cerfon:** *MHD Compressibility Stabilization in a Z-Pinch; Fact or Fiction*
13. **Dr Ghanshyam:** *Interpretation of filamentation of intense electromagnetic waves in inhomogeneous plasma: relativistic nonlinearity*
14. **Gerrit Kramer:** *Field Ripple Induced Alpha Particle Losses in ITER*
15. **Yanli Xiao:** *A study of full-wave and ray-tracing methods for a simple model of multi-dimensional mode conversion*
16. **David Russell:** *Saturation mechanisms in reduced simulations of boundary turbulence*
17. **George Vahala:** *Unitary Mesoscopic PetaScale Computational Models for Nonlinear Physics-excitation of Kelvin waves in vortex reconnection*
18. **Min Soe:** *Large Eddy Simulations (LES) of MHD using Lattice Boltzmann Methods*
19. **Gregory Rewoldt:** *Global gyrokinetic calculations for experimental cases*
20. **Alex Arefiev:** *Ambipolar Acceleration of Ions in a Magnetic Nozzle*
21. **Philip J Morrison:** *Hamiltonian formulation and analysis of a collisionless fluid reconnection model*
22. **Dylan Brennan:** *Flow Shear Effects on Resistive MHD Instabilities in Tokamaks*
23. **Alain Brizard:** *Recirculation effects in multiple linear conversion*
24. **Thomas Fouquet:** *Progress on TGYRO: the steady-state gyrokinetic transport code*
25. **Philip Snyder:** *Understanding and Predicting the H-Mode Pedestal Height*

26. **Alexander Pigarov:** *Modeling of hydrogen inventory and plasma-wall coupling*
27. **Renato Gatto:** *A model of electron transport from self-consistent action-angle transport theory*
28. **Francesca Bombarda:** *Plasma Position Control Strategies for Ignitor*
29. **Hiroaki Ohtani:** *Energy release in Magnetic Reconnection with Chaos Diffusion*
30. **John Wright:** *Full-Wave Electromagnetic Field Simulations of Lower Hybrid Wave Propagation in ITER Relevant Regimes*
31. **Richard Fitzpatrick:** *A Toroidal Shell Model for Shaped Tokamak Plasmas*
32. **Bonita Squires:** *Preliminary Calculations for the Study of Ballooning Mode Growth in the Early to Intermediate Nonlinear Regime*
33. **Donald Spong:** *Development and application of the moments method transport analysis to plasma flows in 3D configurations*
34. **John Loverich:** *Hierarchical Fluid Models and Plasma Simulation*
35. **Eisung Yoon:** *A new non-random scheme for nonlinear collision operation in a particle code*
36. **Bruno Coppi:** *New Approaches to Ignition and Developments for Fusion Energy Sources*
37. **Carl Sovinec:** *Preconditioning the Implicit Hall Advance in NIMROD*
38. **Srinath Vadlamani:** *Investigations of Multigrid implementation of precondition within the extended MHD NIMROD code*
39. **Rajaraman Ganesh:** *Effects of Profile Relaxation on ITG Drift Turbulence Simulations*
40. **Ammar Hakim:** *First Results From Coupled Core-Edge Simulations Using the FACETS Code*
41. **Christopher Carey:** *MHD kink instability driven by differential rotation and kink stabilization by azimuthal rotation*
42. **Jacob King:** *Numerical Studies of Two Fluid Tearing Modes in Slab and Cylindrical Geometries*
43. **Scott Parker:** *GEM Simulation of Energetic Particles Driven Modes*
44. **Jesse Pino:** *Global Magnetorotational Instability with Density Gradients*
45. **Seung-Hoe Ku:** *Surprising new physics from Full-f particle simulation of ITG turbulence in a tokamak geometry*
46. **Jianhua Cheng:** *Nonlinear Dynamics of Ions Confined in an rf Potential Well*
47. **Chris Crabtree:** *"Fluid" Theory of Micro-Reconnecting Modes*
48. **Vladimir Svidzinski:** *Kinetic effects in RFP plasma*
49. **Xinzheng Liu:** *Finite Ion Orbit Effects on Magnetic Islands in Toroidal Plasmas*

50. **Kyle Gustafson:** *Non-diffusive transport in  $E \times B$  zonal flows finite Larmor radius effects and fractional diffusion modeling*

51. **Xianzhu Tang:** *A multi-disciplinary approach to plasma/wall interaction*

52. **Erin Mondloch:** *Ray tracing of Ideal Ballooning Modes in Boozer Coordinates*

## Poster Session 2C

1. **Loren Steinhauer:** *Computation of flowing multi-fluid equilibria with finite-Larmor-radius corrections*
2. **Nathaniel Ferraro:** *New results in Equilibrium and Stability of Two-Fluid Plasmas*
3. **Bastiaan Braams:** *Reaction dynamics and spectroscopy of hydrocarbons in edge plasma*
4. **Ambrogio Fasoli:** *Analysis of fluctuations, turbulence, and related transport in the TORPEX simple magnetized toroidal plasma*
5. **Luca Guazzotto:** *New capabilities of the equilibrium code FLOW*
6. **Cihan Akcay:** *Mimetic Operator-Based Matlab Equilibrium Solver for Non-Uniform Quadrilateral Grids*
7. **Alexander Wurm:** *Breakup of invariant tori in the extended standard nontwist map*
8. **James Myra:** *Linear Analysis Tools for Edge and SOL Plasmas*
9. **Vladimir Mirnov:** *On Possibility of Fizeau Interferometry In High Temperature Magnetized Plasma*
10. **Gary Staebler:** *Theory of Electron-ion Collisions in Trapped Gyro-Landau Fluid Models*
11. **James D Callen:** *Toroidal Flow In Tokamak Plasmas*
12. **Andrew Cole:** *Smoothed neoclassical toroidal viscosity induced by field errors in tokamaks*
13. **Daniel D'Ippolito:** *Effect of intermittent transport on rf-specific impurities*
14. **Nikhil Chakrabarti:** *Parametric Excitation of GAMs by finite beta drift waves*
15. **Travis Austin:** *Simulating at the Ion Cyclotron Time Scale Using the Linear Delta-f Particle-In-Cell Method*
16. **Chris McDevitt:** *Transport of Parallel Momentum by Waves and Particles in Collisionless Electromagnetic Turbulence*
17. **Stephen Jardin:** *Two-Fluid Nonlinear Magnetic Reconnection in the Presence of an Arbitrary Guide Field*
18. **Andris Dimits:** *Gyrokinetic Models for Edge Plasmas*
19. **Ronald Cohen:** *Edge plasma flows in kinetic simulations of a single-null divertor tokamak*
20. **Kowsik Bodi:** *Formulation and implementation of a velocity-dependent anomalous radial transport model for kinetic codes*
21. **Eric Held:** *A mixed finite-element method for anisotropic thermal conduction*
22. **Juhyung Kim:** *Uniformly sheared ExB effect on ETG fluid dynamics*
23. **Jeong-Young Ji:** *A systematic derivation of general closures for electron-ion plasmas*
24. **Guoyong Fu:** *Energetic Particle-induced Geodesic Acoustic Mode*

25. **Jason TenBarge:** *Behavior of Fluid Modes for Arbitrary Relativistic Temperatures*
26. **Chris Hegna:** *Local 3-D MHD equilibria with magnetic islands*
27. **B D Dudson:** *Ideal-MHD ELM simulations with the BOUT++ code*
28. **Scott Kruger:** *Modeling of the Plasma Response to Resonant Magnetic*
29. **Masaru Irie:** *"The Local Cold Bundage" emerged from the injected pellets and its effects on MHD instabilities in tokamaks*
30. **Sergei Sharapov:** *MHD Spectroscopy of Transport Transitions on JET*
31. **Yang Chen:** *Particle-in-Cell simulation of kinetic phenomena with Vlasov ions and drift kinetic electrons*
32. **Paola Rebusco:** *Excitation of Spiral Modes from Plasma Accretion Disks Around Black Holes and Quasi Periodic Oscillations*
33. **Robert Budny:** *Predictions of H-mode and Hybrid plasma performance in ITER*
34. **Mark Schlutt:** *Analytic and computational investigation of the effect of finite parallel heat transport on the formation of magnetic islands in three-dimensional plasma equilibrium*
35. **Alan Turnbull:** *Ideal MHD Spectrum of the ARIES Compact Stellarator Configuration*
36. **Valerie Izzo:** *Resonant Field Amplification and Rotational Screening in DIII-D RMP Simulations*
37. **Varun Tangri:** *Electrostatic Ion Temperature Gradient Modes in the Reversed Field Pinch Geometry*
38. **Adam Bayliss:** *A quantitative comparison of DC helicity injection in the HIT-II spherical tokamak and 3-D MHD simulation*
39. **Ravi Samtaney:** *Adaptive Mesh Simulations of Pellet Injection using a Level-Set Approach with Cartesian Grids*
40. **Thomas Jenkins:** *Modeling of RF/MHD coupling using NIMROD and GENRAY*
41. **Darin Ernst:** *Nonlinear Upshift of the TEM Critical Density Gradient and the Role of Zonal Flows in TEM Saturation*
42. **David Smithe:** *Solution to the divergence preservation difficulty in the Alternating Direction Implicit (ADI) method for electromagnetic particle-in-cell simulation of plasmas*
43. **Nong Xiang:** *Nonlinear wave couplings in an inhomogeneous plasma*
44. **Yi-Min Huang:** *Resistive Tearing Instability in a Line-tied Configuration*
45. **John Finn:** *The effect of line-tying on tearing modes*
46. **Ilon Joseph:** *Rotational Shielding of Resonant Magnetic Perturbations from an H-mode Pedestal*
47. **Francois Waelbroeck:** *Formation of the velocity shear layer in the edge of a diverted tokamak*
48. **Elena Belova:** *Simulation studies of FRC with rotating magnetic field current drive*

49. **Weixing Wang:** *Couplings between toroidal momentum and heat transport in tokamaks*

50. **Neil Pomphrey:** *Analysis Methods for Trim Coils in NCSX*

51. **Yansong Wang:** *An Analytic Study of the Perpendicularly Propagating Electromagnetic Drift Instabilities in the Magnetic Reconnection Experiment*

# **Abstracts of Oral Presentations**

## Drift-Kinetic Simulations of Neoclassical Transport\*

E.A. Belli and J. Candy

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A new  $\delta f$  Eulerian kinetic code NEO-GK has been developed for numerical studies of neoclassical transport. NEO-GK serves a dual role: in addition to its practical value as a tool for high-accuracy neoclassical calculations, NEO-GK also functions as a stepping-stone (together with our nonlinear GK code GYRO) toward a full-F gyrokinetic code which integrates neoclassical transport and microturbulence. NEO-GK is based on a hierarchy of equations derived by expanding the fundamental drift-kinetic equation in powers of  $\rho_*$ , the ratio of the ion gyroradius to the system size. Thus, unlike NCLASS [1], NEO-GK represents a first-principles calculation of the neoclassical transport coefficients (particle flux, heat flux, bootstrap current, poloidal rotation, etc.) directly from the particle distribution function. NEO-GK extends previous numerical studies by including the self-consistent coupling of electrons and multiple ion species and the calculation of the first-order electrostatic potential via coupling with the Poisson equation. Fully general geometry is included, using either a full numerical equilibrium or the Miller local parameterized equilibrium model [2].

For benchmarking, comparisons of the second-order transport coefficients with various analytical theories are presented. Three model collision operators are compared in NEO-GK: the full Hirshman-Sigmar operator [3], which includes pitch-angle scattering dynamics and energy diffusion, and the reduced Hirshman-Sigmar operator [4] and the Connor model [5], both of which consist of just the sum of pitch angle scattering and momentum-restoring terms. For all three models, the ambipolar relation  $\sum_s Z_s \Gamma_s = 0$ , which can only be maintained with complete cross-species collisional coupling, is confirmed. With the full Hirshman-Sigmar collision operator, we confirm that the widely used Chang-Hinton analytical model [6] overestimates the ion energy flux in the intermediate aspect ratio regime. Agreement with the more accurate Taguchi banana regime model [7] is shown for validation. The reduced Hirshman-Sigmar operator and the Connor model are found to consistently underestimate the ion energy flux in all collisionality regimes. Through comparisons with simulations using an adiabatic electron model, the effects of kinetic electron dynamics on the ion transport coefficients are specifically identified. The effects of heavy impurity ions are also explored and limitations of multi-species collisionally-interpolated analytical theories are discussed. Furthermore, parameterized studies of the effects of shaping are performed using the Miller model. Results using DIII-D experimental profiles are also presented.

Finally, finite orbit width effects are studied via solution of the third and fourth-order drift-kinetic equations. Neoclassical transport near the magnetic axis is explored and the implications of non-local transport on the validity of the  $\delta f$  formulation are discussed.

- [1] W.A. Houlberg, *et al.*, Phys. Plasmas **4**, 3230 (1997).
- [2] R.L. Miller, *et al.*, Phys. Plasmas **5**, 973 (1998).
- [3] S.H. Hirshman and D.J. Sigmar, Phys. Fluids **19**, 1532 (1976).
- [4] D.J. Sigmar, S.H. Hirshman, and J.F. Clarke, Phys. Fluids **19**, 656 (1976).
- [5] J.W. Connor, Plasma Phys. **15**, 765 (1973).
- [6] C.S. Chang and F.L. Hinton, Phys. Fluids **25**, 1493 (1982).
- [7] M. Taguchi, Plasma Phys. Control. Fusion **30**, 1897 (1988).

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# **Nonlinear Consequences of Weakly Driven Energetic Particle Instabilities**

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## **Abstract**

The build-up of the energetic particle population in fusion plasmas is typically slow compared to the growth times of energetic-particle-driven instabilities. This feature draws special attention to nonlinear studies of unstable waves in the near-threshold regimes. The goal is to characterize the long-time behavior of the weakly dissipative waves and resonant particles in the presence of particle sources and sinks. This system exhibits an intricate nonlinear dynamics ranging from benign saturation of unstable modes to explosive growth of nonlinear phase space structures and avalanche-type events. The list of intriguing nonlinear effects also includes frequency-chirping phenomena.

This talk presents a first-principle theoretical approach to the nonlinear description of near-threshold instabilities, aimed at understanding a variety of experimental data from JET, MAST, DIII-D, C-Mod, NSTX and TFTR. The theory interprets the pitchfork splitting effect, observations of Alfvén Cascades, rapid frequency chirping in Alfvén modes and fishbones, anomalous losses of fast ions. The most recent progress refers to the role of transient perturbations (quasimodes) and geodesic acoustic effects in the observed spectrum of Alfvén Cascades and to the MHD-mechanism of frequency downshift during the decay of the fishbone pulse.

The talk blends recent results into a broader discussion of how the present theory responds to the experimental challenges and what kind of theoretical and computational advances could potentially resolve some of the critical outstanding issues.

Work supported by the U.S. DOE Contract No. DE-FG03-96ER-54346

# **Modeling of Resistive Wall Mode with Full Kinetic Damping \***

M.S. Chu<sup>1</sup> and Y.Q. Liu<sup>2</sup>

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Magnetohydrodynamic (MHD) stability of the plasma depends critically on the frequency and wave length of the perturbation. Future tokamaks are expected to operate in regimes where the external macro-scale perturbations have much lower frequencies than the intrinsic dynamical time scales of the particles [1]. This situation calls for a detailed re-examination of the assumptions on previous models of the response of the plasma to MHD perturbations [2]. We have developed a full drift kinetic version of MARS-F based on the kinetic formulation of MHD response [3]. The kinetic integrals are evaluated in a general toroidal geometry with flow, and self-consistently incorporated into the MHD formulation. In particular, the energy and momentum flux across the plasma surface is expressed in terms of the MHD perturbations. The new code has been tested on a Soloviev analytic equilibrium. It is observed that most of the kinetic damping comes from the particle precession drift resonances, from particles with nearly vanishing drift frequency. The RWM eigenmode structure is modified by the new kinetic terms. These kinetic terms may provide strong stabilization for high-pressure plasmas, such as those from DIII-D. Implication on the stability and plasma response [4] relevant for the resistive wall mode, with its time scale dramatically slowly by the external resistive wall, is discussed.

[1] B. Hu, R. Betti and J. Manickam, *Phys. Plasmas* **12**, 057301 (2005).

[2] A. Bondeson and M.S. Chu, *Phys. Plasmas* **3**, 3013 (1996).

[3] T.M. Antonsen, Jr. and Y.C. Lee, *Phys. Fluids* **25**, 132 (1982).

[4] Y.Q. Liu, et al., *Phys. Plasmas* **7**, 2681 (2000).

\*Work supported in part by the U.S. Department of Energy under DE-FG03-95ER54309.

# Explosive Instability in Plasmas

Steven C. Cowley

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Some of the most dramatic events in nature are large scale disruptions of plasmas such as tokamak disruptions, solar flares, magnetospheric substorms and Edge Localized Modes. For all these examples the speed of disruption suggests that an explosive mechanism is responsible. I will discuss the fundamental nature of explosive growth and the issues for fusion plasmas. As an example I will outline a particular mechanism for the explosive release of energy in a plasma [1] via filamentary eruptions. I will also show experimental evidence [2] for its role in Edge Localized Modes. The size and connectivity of the filament and the mechanisms for releasing stored plasma energy will be discussed. At the heart of these mechanisms lie near singularity formation. These may include the formation of contact discontinuities and current sheets [3]

## References

- [1] S. C. Cowley and M. Artun, Phys. Rep. **283**, 185 (1997), H.R. Wilson, and S.C. Cowley, Phys. Rev. Lett., **92**, 175006(2004) and B.H. Fong, S.C. Cowley, and O.A. Hurricane, Phys. Rev. Lett., **82**, 4651 (1999).
- [2] A. Kirk, et. al., Phys. Rev. Lett., **92**, 245002(2004) and A W Leonard, et. al. Plasma Phys. Control. Fusion 48 No 5A (May 2006)
- [3] P. Zhu, C. C. Hegna, and C. R. Sovinec Phys. Plasmas **13**, 102307 (2006) and B.H. Fong Ph.D. Thesis Princeton (1999).

# Scalable Parallel Computation for Extended MHD Modeling of Fusion Plasmas

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A principal contribution of John Greene to plasma physics and magnetic fusion energy research is an understanding of the computational implications of the huge range of length and time scales in ideal and resistive MHD. His achievements include the efficient computation of the ideal MHD spectrum in the pioneering PEST code [1], as well as deep theoretical understanding of the role and behavior of the singular layer in linear resistive instabilities [2].

Today's version of this challenge is the need for scalable parallel computation for the nonlinear extended MHD modeling of fusion plasmas. Macroscopic modeling codes such as NIMROD and M3D have become major contributors to our understanding of Tokamaks and Innovative Confinement Concepts [3, 4]. The demands of multiple length scales lead to the need for high-order spatial representation and adaptive grids [5]. The demands of multiple time scales lead to the need for implicit time steps and the resulting requirement for efficient parallel solution of large, sparse linear systems.

Parallel solution of a linear system is called scalable if simultaneously doubling the number of dependent variables and the number of processors results in little or no increase in the computation time to solution. This property is essential for the efficient use of current and future generations of parallel supercomputers, with  $10^4 - 10^5$  processors and petaflop speeds. Two approaches have been found to have this property for parabolic systems: multigrid methods [6] and domain decomposition methods [7].

Since extended MHD is primarily a hyperbolic rather than a parabolic system, dominated by the effects of ideal or two-fluid MHD waves, additional steps must be taken to parabolize the linear system to be solved by such a method. Such physics-based preconditioning methods have been pioneered by Luis Chacón, using finite volumes for spatial discretization, multigrid methods for solution of the preconditioning equations, and matrix-free Newton-Krylov methods for the accurate solution of the full nonlinear preconditioned equations [8].

The work described here is an extension of these methods to high-order spectral element methods for spatial discretization. Multigrid methods, appropriate for low-order spatial discretization, are replaced by the FETI-DP method of domain decomposition for high-order spectral elements. Application of physics-based preconditioning to a flux-source representation of the physics equations is discussed. The full set of preconditioned equations is solved by matrix-free Newton-Krylov iteration. The resulting scalability will be demonstrated for ideal and Hall MHD waves and for 2D magnetic reconnection.

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## Low frequency eigenmodes due to Alfvén acoustic coupling in toroidal fusion plasma\*

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Investigating the interaction of energetic ions with MHD modes is important not only for planning future self-sustained burning plasmas but it is an area where ideal MHD and kinetic theories are put to the test with great accuracy. We report on a theory and observations of a new class of global MHD solutions resulting from coupling of two Alfvén and acoustic fundamental MHD oscillations due to geodesic curvature. These modes predicted theoretically and numerically and called Beta-induced Alfvén-Acoustic Eigenmodes (BAAEs) have been recently observed in both low beta JET and high beta NSTX plasmas. They are capable of inducing strong radial transport of beam ions in NSTX especially in the presence together with multiple TAE instabilities.

Acoustic branch coupling also upshift the reversed shear Alfvén eigenmodes (RSAEs) eigenfrequency due to the finite pressure. We present a theory which explains the upshift of RSAE frequency due to finite pressure gradient. It is applied to NSTX observations at medium to high plasma beta. Experimental results supported by the ideal MHD code NOVA simulations clearly separate the effects of the plasma pressure and pressure gradient. We observe that the upshift of the RSAE frequency depends on mode number and is sensitive to the  $q$ -profile, which is in agreement with theoretical and numerical results. The upshift in frequency helps to understand observable “suppression” of RSAEs at high beta. Sweeping frequency RSAEs are seen to inflict the enhanced beam ion losses.

By understanding the range of BAAE and RSAE frequency excitation we are able to extend the use of so-called MHD spectroscopy to high beta plasma and by using frequency observations in new regimes to determine  $q_{min}$ . We have found that MSE measurements of  $q$ -profile in NSTX agree with the  $q_{min}$  values inferred from the BAAE and RSAE theories. Such observations would be a very important tool for diagnosing  $q$ -profile and other plasma parameters in ITER, CTF and other burning plasma experiments.

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On John M. Greene's MHD Equilibrium and Stability Work  
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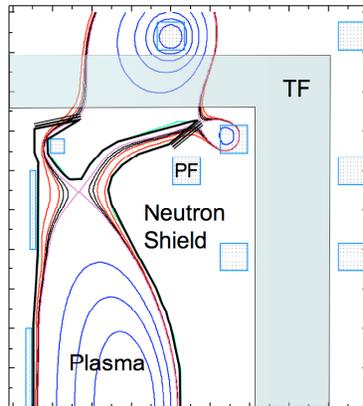
Katherine Weimer and I had the privilege of collaborating with John Greene on most of his MHD work. Here, I want to illustrate the breadth of his efforts by commenting on our incorporation of curvature effects into stellarator equilibrium models, Hamada Coordinates, the Mercier Criterion, resistive instabilities, and the PEST code. An illustration of how John kept our interactions exciting was the morning he walked into my office to say: "I know the answer; can you help me formulate the question?"

## High Power Density Experiment (HPDX) - A Next Step Device in the Age of ITER

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A next generation high (reactor-level) power density machine (HPDX), capable of demonstrating  $Q_{XT}$  ( $= Q_{\text{Exothermic}} = \text{fusion power} / \text{total electrical input}$ )  $> 1$ , is explored. (JET and NIF achieve  $Q_{XT} \sim 1/10$ ). We give a solution for the extreme challenge of simultaneously maintaining  $\beta \sim 6$  times ITER and power density  $\sim 10$  times ITER and  $Q_{XT} > 1$ . The device will run in the advanced tokamak mode,  $R=2.2\text{m}$ ,  $A=2.5$ ,  $\kappa=2.7$ . Density peaking and enhanced elongation will be exploited to maximize beta for a given beta normal. Because HPDX is conceived as a prelude to a fusion reactor, its primary function is to demonstrate that appropriate conditions needed for the simultaneous occurrence of high beta, good confinement, stability (including thermal stability for a self-heated plasma), proper heat exhaust etc. can be created using only those methods that are likely to be pertinent under actual reactor.

A critical challenge of the beta optimized HPDX is the enormous heat load that will be incident on the divertor; the problem is further accentuated by density peaking. A radically new magnetic geometry that tends to isolate the divertor from the main plasma, the SuperX divertor (SXD), has been invented to solve this problem: its working is demonstrated by both 1D and 2D edge codes.



Example of a Super X Divertor at large R and with line length  $\sim 5\text{-}10$  x standard divertor.

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# Zonal Flow and Zonal Density Saturation Mechanisms for Trapped Electron Mode Turbulence

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## Abstract

Mode coupling theory and gyrokinetic turbulence simulation are used to study the nonlinear saturation mechanisms of collisionless trapped electron mode (CTEM) turbulence [1, 2]. Turbulence simulations show that the importance of zonal flow is parameter sensitive, but is well characterized by the ExB shearing rate formula. The importance of zonal flow is found to be sensitive to temperature ratio, magnetic shear and electron temperature gradient. For parameter regimes where zonal flow is unimportant, zonal density (a purely radial density perturbation) is generated and is found to be the dominant saturation mechanism. In fact, CTEM turbulence saturates at physically reasonable levels with or without zonal flow. This is in stark contrast to ion temperature gradient driven turbulence where the zonal flow has an order of magnitude effect on the saturation level. A toroidal mode coupling theory is developed that agrees well with simulation in the initial nonlinear saturation phase (before fully developed turbulence ensues). The theory predicts nonlinear generation of the zonal density and then the feedback and nonlinear saturation of the unstable mode. Inverse energy cascade is also observed in CTEM turbulence and reported here. Further exploration on the magnetic fluctuation effect will be discussed. Finally, we have utilized GEM to investigate the Toroidal Alfvén Eigenmode (TAE) in tokamak plasmas. Here, we present numerical results showing the gap and continuum frequencies and compare directly with the eigenfrequency obtained from an eigenmode calculation.

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# Modern Measurement Capabilities and Analysis Techniques for Validation of Turbulence Simulations

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Fluctuation diagnostics deployed at magnetic fusion experiments have advanced significantly in their breadth and depth and now measure turbulence characteristics in multiple plasma fields over a wide range of wavenumbers. The corresponding development of comprehensive nonlinear simulations of turbulence and transport is now allowing for quantitative comparisons of various turbulence properties between measurement and simulation, a crucial task required to validate simulations and ultimately to develop a predictive capability for turbulent transport. Specialized diagnostics have been developed to probe fluctuations in density, temperature, electrostatic potential, velocity and magnetic field, as well as to examine a wide range of wavenumbers from the ion gyroradius scale to electron scales. Quantities that can be compared include fluctuation amplitudes, wavenumber and frequency spectra, and spatial and temporal correlations. The corresponding development of advanced analysis techniques applied to multipoint, spatially resolved fluctuation measurements allows for extraction of critical characteristics such as zonal flow fields as well as the nonlinear dynamics of turbulence, including internal energy transfer. Detailed comparisons between measurements and simulation require "synthetic diagnostics" that model diagnostic measurement physics and performance to facilitate these direct, quantitative tests. Validation exercises also require the execution of focused experiments that systematically vary critical parameters to insure proper scaling behavior. Initial efforts to perform validation exercises and thereby test and challenge simulations will be presented.

## “Oh, that.”

P. J. Morrison

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John Greene produced important research in a many areas. His work was characteristically original, of great depth and clarity, concise, mathematically clean, and broadly applicable. In this talk I will highlight some of his research, including: BGK modes, exact nonlinear solutions of the Vlasov-Poisson system; the inverse scattering transform, a method of solution for the KdV equation (and others) via a remarkable transformation; Greene’s residue criterion, which describes e.g. how magnetic surfaces break; and other work on Hamiltonian systems.

# Tokamak Plasma Response to External Magnetic Perturbation

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Tokamak plasmas are sensitive to external magnetic perturbations as small as  $|\delta B|/B \approx 10^{-4}$  can be important. An asymmetric external magnetic perturbation changes the plasma equilibrium, and the asymmetry of the equilibrium current contributes to the perturbed magnetic field  $\delta\vec{B}$ . The linear Ideal Perturbed Equilibrium Code (IPEC) finds the perturbed non-axisymmetric tokamak equilibrium with the same  $p$  and  $q$  profiles. Often the magnetic field strength is changed little at fixed points in space, but the wobble of the magnetic surfaces causes a large variation in the field strength that perturbs the action  $J = \oint v_{\parallel} d\ell$  and, therefore, the particle drift motion.

The non-axisymmetry of the equilibrium currents tends to give:

(1) Strong poloidal coupling - The magnetic perturbation tends to be locally close to resonant with the magnetic field lines because that gives the largest distortion in the equilibrium plasma currents.

(2) Amplification of the external perturbation - The perturbed magnetic field can either be amplified or shielded by the perturbed plasma current, but the most important perturbations are those that are amplified by the non-axisymmetric distortions of the equilibrium plasma currents. Nevertheless, the plasma must shield the perturbation if the toroidal torque between an external magnetic perturbation and the plasma,  $\int \vec{x} \times (\vec{j} \times \vec{B}) d^3x$  is sufficiently strong. Maxwell's equations imply this torque is given by an expression, which is approximately  $(n/\mu_0) \oint (\delta\vec{B}^x \cdot \hat{n})(\delta\vec{B}^p \cdot \hat{n}) da \sin(n\varphi_p)$ , where  $n$  is the toroidal mode number,  $\delta\vec{B}^x \cdot \hat{n}$  is the perturbation due to external coil currents,  $\delta\vec{B}^p \cdot \hat{n}$  the perturbation due to the plasma response, and  $\varphi_p$  is the phase difference between them.

The IPEC code has (1) resolved paradoxes in error field correction on NSTX and DIII-D (Phys. Rev. Lett. **99** 195003), (2) shown that ELM control coils in ITER could be designed to greatly reduce asymmetries in the central plasma while producing a strong perturbation at the plasma edge, (3) found that NSTX experiments on rotating error fields indicate strong plasma shielding due to the Maxwell limit on the torque.

## Limitations of gyrokinetics on transport time scales

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### ORAL PRESENTATION

Gyrokinetic models are widely used in simulations of tokamak drift wave turbulence. However, these models are only valid on time scales of the order of the saturation time of the turbulence and are unable to predict and evolve the equilibrium profiles of density, temperature and electric field. Calculating these profiles requires the extension of gyrokinetics to transport time scales. We are developing a self-consistent electrostatic model to calculate the distribution functions of both ions and electrons and the electrostatic potential for wavelengths that go from the size of the tokamak to smaller than the ion Larmor radius. A set of gyrokinetic variables is defined so that the gyrophase dependent part of the distribution is absorbed into the gyrokinetic variables by extending the linear treatment of Lee, Myra and Catto [1] to retain the usual nonlinear gyrokinetic modifications [2]. Using this procedure we find a nonlinear full  $f$  gyrokinetic equation correct to first order in a gyroradius over global scale length expansion. The electrostatic potential must be found to insure quasineutrality. In  $\mathcal{O}$  models, the gyrokinetic quasineutrality equation is normally used for this purpose. However, intrinsic ambipolarity requires that the ion distribution function be known at least to second order in gyroradius over characteristic length to calculate the long wavelength, axisymmetric components of the electrostatic potential self-consistently. Using the example of a steady-state  $\theta$ -pinch, we prove that the quasineutrality equation fails to provide the axisymmetric piece of the potential even with a distribution function correct to second order. We also show that second order accuracy is enough if a moment description is used instead of the quasineutrality equation. These results demonstrate that the gyrokinetic quasineutrality equation is not the most effective procedure to find the electrostatic potential if the long wavelength components are to be retained in the analysis.

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# Variational Symplectic Integrator for the Guiding Center Motion of Charged Particles for Long Time Simulations in General Magnetic Fields

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A variational symplectic integrator for the guiding center motion of charged particles in general magnetic fields is developed for long time simulation studies of magnetized plasmas [1]. Instead of discretizing the differential equations of the guiding center motion, the action of the guiding center motion is discretized and minimized to obtain the iteration rules for advancing the dynamics. Standard integrators only guarantee the error to be small in each time-step. The errors at different time-steps often accumulate coherently, and result in a large error over a large number of time-steps. The variational symplectic integrator conserves exactly a discrete Lagrangian symplectic structure, and has better numerical properties over long integration time, compared with standard integrators, such as the standard and variable time-step 4th order Runge-Kutta methods. The symplectic integrator conserves the symplectic structure exactly, and guarantees that the energy error is bounded by a small number for all the time-steps. To construct the symplectic algorithm, it is necessary to adopt the variational approach because standard symplectic integrators are only valid for canonical Hamiltonian systems, and the guiding-center dynamics in general magnetic field does not possess a (global) canonical symplectic structure. Numerical examples with more than 25 million time-steps are given to demonstrate the superiority of the variational symplectic integrator. This significant improvement in long term simulation capability of gyrokinetics is a direct, otherwise-impossible result of the geometric formulation of the gyrokinetic theory using the modern language of differential geometry [2, 3].

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# A comprehensive analytical model for 2D magnetic reconnection in resistive, Hall, and electron magnetohydrodynamics\*

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Magnetic reconnection – the topological rearrangement of magnetic fields immersed in highly electrically conductive plasma and the accompanying magnetic energy release – usually happens on very fast time scales and is of fundamental importance for both laboratory and naturally occurring plasmas. While computational evidence exists [1] of fast (e.g. dissipation independent) reconnection rates, there is no fundamental comprehensive analytical model that is able to explain them. In this work, we propose such a quantitative model (à la Sweet-Parker). The model describes the magnetic field dissipation region for 2D steady-state (e.g. at or around the time of maximum reconnection rate) magnetic reconnection without a guide field. It takes into account plasma resistivity, electron viscosity (hyper-resistivity), and electron inertia. It recovers the Sweet-Parker results for small ion inertial length scales [2], the electron MHD results in the limit of ion inertial length scales larger than other relevant scales [3], and is valid everywhere in between [4]. The model gives predictions for the dissipation region aspect ratio, the incoming and outgoing plasma flows magnitudes, the ratio of created to dissipated magnetic fields, and the reconnection rate as a function of dissipation and inertial parameters. It has been benchmarked (and is in excellent agreement) with more than thirty-five non-linear simulations of magnetic coalescence problem with resistivity, hyper-resistivity, and ion inertial length scale varying over many orders of magnitude each. It confirms a number of long-standing empirical results and resolves several outstanding controversies (e.g. whether only the open X-point or also the elongated dissipation regions are allowed in Hall MHD reconnection). The model can be straightforwardly expanded to include effects of ion viscosity, guide field, and so on.

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# The Ideal Magnetohydrodynamic Peeling Mode Instability

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The rapid deposition of energy by Edge Localised Modes (ELMs) onto plasma facing components poses a threat to the performance of large Tokamaks such as ITER and DEMO. The trigger for ELMs is believed to be the ideal Magnetohydrodynamic Peeling-Ballooning instability, but recent numerical calculations have suggested that a plasma equilibrium with an X-point - as is found in all modern Tokamaks - is stable to the Peeling mode. This is surprising, because previous analytical calculations (G. Laval, R. Pellat, J. S. Soule, *Phys Fluids*, **17**, 835, (1974)), found the Peeling mode to be unstable in cylindrical plasmas with arbitrary cross-sectional shape. However the analytical calculation only applies to a Tokamak plasma in a cylindrical approximation. To avoid these shortcomings Webster & Gimblett[1], re-examined the assumptions made in cylindrical geometry calculations, and generalised the calculation to a Tokamak at marginal stability. The resulting equations solely describe the Peeling mode, and are not complicated by coupling to the ballooning mode, for example.

It was found that: (i) at marginal stability a radial plasma displacement induces a skin current that is parallel and proportional to both the equilibrium edge current and the amplitude of the radial plasma displacement. (ii) the boundary condition relating the plasma displacement to the vacuum field's perturbation is identical to requiring equality of the normal components of the perturbed plasma and vacuum magnetic field, evaluated at the equilibrium plasma position. (iii) marginal stability of the Peeling mode at high toroidal mode number is identical to solving  $\delta W_S + \delta W_V = 0$ , where  $\delta W_S$ ,  $\delta W_V$ , and  $\delta W_F$  are the surface, vacuum, and plasma contribution to the energy principle's  $\delta W = \delta W_F + \delta W_S + \delta W_V$ . (iv) suggested defining the Peeling mode as one for which  $\delta W_F$  may be neglected, with (in)stability determined by the sign of  $\delta W_S + \delta W_V$ . (v) for the trial function used by Laval et al, Peeling mode (in)stability is determined by a single parameter  $\Delta'$  that involves the poloidal average of the normalised jump in the radial derivative of the perturbed magnetic field's normal component. The calculation of  $\Delta'$  in such a way as to capture the effect of the X-point, without the need for a discretisation of space as required by most numerical methods, is the subject of the remainder of this contribution.

For potentials satisfying Laplace's equation in systems that are approximately 2-dimensional, conformal transformations are often used to calculate fields in complicated geometries. However the usual requirement for the field's normal component to be zero on the boundary is unnecessarily restrictive, as may be seen by calculating how the boundary conditions transform. Similarly it is possible to calculate how other quantities transform as we map between the two systems, to obtain analytic expressions for  $\Delta'$  and the vacuum energy  $\delta W_V$ , in terms of a sum of Fourier coefficients. The Fourier coefficients are given in terms of an integral involving the straight field line angle. The equilibrium vacuum field (for a shaped cross section) may be calculated also, and used to obtain an analytic expression for the straight field line angle at the plasma-vacuum boundary. Subsequently the Fourier coefficients and their sum may be calculated, and it is found that at high toroidal mode number, a perturbation from a single Fourier mode in straight field line coordinates (Laval et al's trial function), has the vacuum energy  $\delta W_V$  and  $\Delta'$  the same as for a circular cross section, with  $\delta W_V \simeq 2\pi^2 \Delta^2 \frac{|\xi_m|^2}{R} m$  and  $\Delta' = -2m$ . Further applications, and consequences for the stability of the Peeling mode are discussed.

[1] 34th EPS Conference on Plasma Phys. Warsaw, 2-6 July 2007 ECA Vol 31F, P-4.088

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# TEMPEST simulations of the neoclassical radial electric field\*

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We present gyrokinetic neoclassical simulations of tokamak plasmas with self-consistent two-dimensional electric field using a fully nonlinear (full-f) continuum code TEMPEST. A set of gyrokinetic equations are discretized on a five dimensional computational grid in phase space. 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. The fully nonlinear Boltzmann model is used for electrons. The neoclassical electric field is obtained for the first time by solving gyrokinetic Poisson equation with self-consistent poloidal variation. Alternatively the neoclassical electric field can be evaluated according to the radial Ampere's law averaged over a closed-flux surface  $4\pi\langle\mathbf{J}\cdot\nabla\psi\rangle+\partial\langle\mathbf{E}\cdot\nabla\psi\rangle\partial t=0$  where  $\psi$  is the poloidal magnetic flux,  $\langle\cdots\rangle$  represents the flux surface average, and  $\mathbf{J}$  is the sum of all the current in the plasma, including the classical polarization current, gyroviscosity current, and the ion guiding-center current (the electron current is typically neglected in tokamak geometry, because it is smaller than the ion current by a factor of a mass ratio  $m_e/m_i$ ) [1-3]. The steady-state neoclassical radial electric field  $E_\psi$  on a magnetic surface is obtained from the condition  $\langle j_\psi\rangle=0$ . However, this method is incomplete in the sense that the poloidal electric field cannot be solved simultaneously in a consistent way. This is an unsatisfactory situation since the potential varies significantly in the edge plasma around the X-point and in the divertor leg region due to contact with divertor plates. The gyrokinetic Poisson equation is seldom used because the small coefficient in front of Poisson operator associated with the gyroradius makes the equation singular when  $\rho_i\ll L_P\ll L_B$ . Here,  $L_P=|\nabla(\ln P)|^{-1}$  is the characteristic gradient scale length for the plasma profile,  $L_B=|\nabla(\ln B)|^{-1}$  the characteristic length for the magnetic field, and  $\rho_i=v_{Thi}/\Omega_{ci}$  the ion gyroradius. For this reason, no single code exists to simulate both neoclassical transport and turbulence. However, there are efforts being undertaken to try to solve this dilemma [4,5]. In this work, we develop a method to efficiently solve the gyrokinetic Poisson equation to remove the singularity and to correctly yield the neoclassical radial electric field. We prove here the mathematical equivalence of the two approaches for solving neoclassical electric field in the large-aspect-ratio limit. With our TEMPEST code we compute radial particle and heat flux, the dynamics of relaxation of poloidal rotation, including Geodesic-Acoustic Mode (GAM), its radial propagation, collisional decay and the development of neoclassical electric field, which we compare with neoclassical theory with a Lorentz collision model. The present work provides a numerical scheme and a new capability for self-consistently studying important aspects of neoclassical transport, rotations and turbulence in toroidal magnetic fusion devices.

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# **Abstracts of Poster Presentations**

# **Toward Optimal Multigrid Algebraic Solvers In Magnetohydrodynamics Simulations of Fusion Plasmas**

Mark Adams

Magnetohydrodynamic simulations of tokamak fusion plasmas exhibit a large separation of temporal scales. To overcome the temporal stiffness associated with the fast compressive and Alfvén waves in single-fluid resistive MHD, we consider the development of optimal implicit algorithms. We strive to achieve "textbook" multigrid efficiency in which the set of nonlinear equations is solved to discretization accuracy at each time step, with a cost equivalent to a few (less than 10) residual calculations (or work units). We present results from a few canonical MHD problems: magnetic reconnection in 2D and in the presence of a strong guide field.

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## **MIMETIC OPERATOR-BASED *MATLAB* EQUILIBRIUM SOLVER FOR NON-UNIFORM QUADRILATERAL GRIDS.**

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We present the outline, construction and results of a Grad-Shafranov solver written in *MATLAB* that uses mimetic operators to produce equilibria for NIMROD-based grids. Our Grad-Shafranov code is user-friendly, transparent and compact thanks to *MATLAB*'s suitability for vector arithmetic and linear algebra manipulations. It produces equilibria for linear lambda profiles, configurations with external flux and FRCs. It is second-order accurate in space and has good convergence. Test cases include a Taylor state spheromak, linear lambda equilibrium with current profiles varying from hollow to peaked and a FRC equilibrium. All these cases were initially performed on uniform quadrilateral grids. The Taylor state results show very good agreement with the analytical Taylor profiles with 0.02% error for a 51x51 grid and 0.005% error for a 101x101 grid. The linear lambda solver is compared to the triangular-finite area linear lambda solver and it too has very closely matching solutions. The FRC algorithm is found to be very flexible in producing FRC equilibria, and can generate equilibria with very high elongations with profiles varying from racetrack to elliptical.

# **Ambipolar acceleration of ions in a magnetic nozzle**

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## Abstract

Generation of supersonic plasma jets usually requires a nozzle with a magnetic mirror configuration. The incoming flow becomes sonic at the mirror throat, after which the acceleration continues in the diverging part of the nozzle. The magnetic nozzle converts electron thermal energy into kinetic energy of ion motion along the magnetic field lines. As the plasma density drops downstream and the electron mean free path increases, the electron motion becomes collisionless. An interesting feature of this kinetic regime is that the magnetic mirror limits direct access of the incoming electrons to certain areas of phase space in the downstream flow. In plasma confinement systems, such as mirror machines, the otherwise inaccessible trajectories can be repopulated due to Coulomb collisions. In this work, we address a different (purely collisionless) mechanism of electron trapping that is relevant to space applications such as plasma thrusters. In contrast to confinement systems, the ambipolar potential in an expanding plume ejected by a thruster is necessarily time-dependent. Its profile involves a rarefaction wave at the leading edge. The rarefaction wave accommodates a part of the total potential drop needed to keep electrons and ions together. While travelling through the rarefaction wave, electrons lose a part of their kinetic energy associated with the motion along the field. As a result, electrons can become trapped downstream from the magnetic mirror. The trapped electrons cool down, filling up the areas of phase space that would be otherwise inaccessible. The cooling is essentially adiabatic because the electron motion is much faster than the time evolution of the electrostatic potential. In this work, we present a rigorous adiabatic description of the trapped electron population. We also examine the impact of the adiabatic cooling on the profile of the ambipolar potential and the ensuing ion acceleration. This problem can be formulated for an arbitrary distribution function of incoming electrons. However, in order to make the problem tractable analytically, we consider an incoming “water-bag” electron distribution.

# Simulating at the Ion Cyclotron Time Scale Using the Linear $\delta f$ Particle-In-Cell Method

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The particle-in-cell (PIC) method has been a vital tool for investigating particle behavior in warm plasmas, but the noise so often associated with the PIC method makes it unattractive to many. In recent years, the  $\delta f$  particle-in-cell method has been introduced as an attractive low-noise alternative. The  $\delta f$  method eliminates the unperturbed noise associated with the PIC method by solving for the perturbed distribution,  $\delta f$ , where distribution function  $f = f_0 + \delta f$  and  $f_0$  is known. Evolution of  $\delta f$  takes place via the standard Lorentz force and evolving particle weights.

We are currently employing the linear  $\delta f$  method in simulations at the ion cyclotron time scale to examine various wave phenomena associated with rf wave launching. We avoid the fast time scales associated with the electrons by employing a linear implicit plasma dielectric model that removes all particle noise due to electrons but still permits the incorporation of electron effects on the rf waves. We will present benchmark results for the combined linear  $\delta f$  and plasma dielectric method, and introduce recent work that adds complex weights to the linear  $\delta f$  method to permit toroidal harmonics in simulations. We will also describe the ability of this method to capture true particle orbits, in addition to non-Maxwellian and finite banana effects.

# ENHANCED ELECTRON SCATTERING DUE TO THE ION ACOUSTIC INSTABILITY \*

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Ion acoustic instabilities cause growth of the thermal fluctuations in plasmas with cold ions relative to electrons ( $T_e \gg T_i$ ) when  $u > c_s / \sqrt{1 + k^2 \lambda_D^2}$  where  $u$  is the ion fluid speed relative to electrons,  $c_s$  the ion sound speed,  $k$  the wavenumber of the excited mode and  $\lambda_D$  the electron Debye length. When the ion fluid speed satisfies this condition a spectrum of unstable wavenumbers grows exponentially from the otherwise damped modes. The growth rate of unstable wavenumbers is peaked near  $k\lambda_D = 1$  with shorter wavelengths (larger  $k$ ) also being unstable. These convective instabilities propagate along the direction of ion flow with a growth rate depending on the non adiabatic electron response and produce a long range collective response for discrete particles. We derive a Lenard-Balescu type collision operator that accounts for the ion acoustic convective instabilities whereby interactions between electrons and the excited waves leads to enhanced “thermal” fluctuations and electron scattering relative to the conventional Coulomb level<sup>1</sup>.

The presheath region of an ion sheath, present near the boundary of nearly all plasmas, is considered as a particular example of the theory to demonstrate enhanced electron transport ubiquitous in low temperature plasmas. Enhanced scattering by the convective instabilities near plasma boundaries may lead to population of the otherwise truncated tail of the Maxwellian electron velocity distribution near an ion sheath. Population of this high-energy tail, which cannot be explained by classical Coulomb scattering, is one of the oldest open questions in plasma physics. The first measurements date back to 1925 by Irving Langmuir<sup>2</sup> and this phenomenon was named “Langmuir’s paradox” by Gabor in 1955<sup>3</sup>.

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# A quantitative comparison of DC helicity injection in the HIT-II spherical tokamak and 3-D MHD simulation\*

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Current drive via DC helicity injection has been accomplished using a voltage applied across a poloidal magnetic field known as coaxial helicity injection (CHI) as used in HIT-II and NSTX. MHD calculations using the NIMROD code have been performed to study CHI in the HIT-II spherical tokamak. Numerical studies of CHI in a realistic geometry with  $\beta = 0$  reproduce the “bubble-burst” formation and subsequent relaxation of the parallel current density through the excitation and saturation of a line-tied kink-mode (characterized in HIT-II by amplification of poloidal flux). The computed strength of saturated fluctuations and magnitude of amplified poloidal flux are in quantitative agreement with data obtained in the HIT-II experiment. Computational scans of poloidal flux and toroidal field strength in weakly-driven cases with little or no current relaxation agree quantitatively with published HIT-II results, showing linear dependence of the toroidal plasma current on the vacuum poloidal flux, and independence of toroidal plasma current on the vacuum toroidal field strength (or rod current) [A.J. Redd et al. *Phys. Plasmas* **14**, 112511 (2007)]. However, a 30% margin of error between the measured injected current and the simulations exists. This discrepancy is likely due to dissipative parameters. Results from  $\beta \neq 0$  simulations with evolution of anisotropic thermal transport will also be presented. These simulations permit a detailed description of the 3-D saturated state exhibited by the helicity-injected driven plasma.

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## **Simulation studies of FRC with rotating magnetic field current drive\***

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The HYM code has been modified to include the effects of rotating magnetic field (RMF) current drive. Initial 3D two-fluid and hybrid simulations have been performed for even-parity and odd-parity RMF and different FRC parameters. Simulations show that the RMF pushes the plasma radially inward, resulting in a reduced plasma density outside separatrix. Dependence of RMF penetration on plasma parameters and RMF amplitude and polarity is investigated. Lower plasma density and larger RMF amplitudes result in faster RMF field penetration, in agreement with previous studies [R. Milroy, *Phys. Plasmas* **8**, 2804 (2001)]. Effects of the applied RMF field on particle confinement have been studied using 3D test particle simulations. Simulations of stationary RMFs show that for relatively large ion Larmor radius ( $S^* < 20$ ), there is very little difference between even- and odd-parity RMFs in terms of the ion losses. The rate of particle losses is larger in larger FRCs, and increases with the RMF amplitude. In contrast, high-frequency RMF can reduce ion losses provided  $\omega_{\text{rmf}} \gg \omega_{\text{ci}}$ , and the RMF is of even-parity. The improved particle confinement is related to ponderomotive forces due to the rapidly oscillating, inhomogeneous electromagnetic field. It is also found that high-frequency, odd-parity RMFs force particles away from the midplane toward the FRC ends.

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## **Formulation and implementation of a velocity-dependent anomalous radial transport model for kinetic codes\***

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The representation of radial plasma transport driven by plasma turbulence in magnetic fusion devices often takes the form of anomalous diffusion and convection coefficients for fluid transport codes. Continuum kinetic edge codes [such as the (2d,2v) transport version of TEMPEST and also EGK] compute the collisional transport directly, but there is a need to model the anomalous transport from turbulence for long-time transport simulations. For kinetic codes, an anomalous transport model must be treated carefully. In particular, using only spatial diffusion coefficients, even with, the velocity-space variation, typically leads to effective off-diagonal transport coefficients for the moments (e.g., density, momentum, and energy), which makes comparison to simpler fluid transport models (e.g., UEDGE) problematic. However, it is shown that when convective transport is also allowed, a set of diagonal coefficients can be constructed. The model includes velocity-dependent convection and diffusion coefficients expressed as a Hermite polynomials in velocity. The specification of the Hermite coefficients can be set, e.g., by specifying the ratio of particle and energy transport as in fluid transport codes. Such a model is presented and results are shown for its implementation in the TEMPEST gyrokinetic edge code. TEMPEST simulations are presented showing the separate control of particle and energy anomalous transport, and comparisons are made with neoclassical transport also included.

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## Plasma Position Control Strategies for Ignitor\*

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The ignition experiment Ignitor will produce, in high performance discharges, a neutron flux at the first wall comparable to that expected in future power producing reactors ( $10^{15}$  n/cm<sup>2</sup>/s). As a consequence, traditional magnetic diagnostics may fail due to a sensible, although reversible, degradation of the inorganic insulators surrounding the conductors that are positioned in the shade of the Mo first wall tiles. The measurements of some fundamental plasma parameters, such as current and position, by means of electromagnetic diagnostics can thus become problematic. The Ignitor project is trying to solve these problems with an R&D program aimed at the development of effective and affordable devices for electromagnetic diagnostics with higher damage threshold, while at the same time exploring alternative, or rather supplementary methods for plasma position measurements. One of these is based on the diffraction and detection of soft X-ray radiation emitted near the top or bottom of the plasma column, where the distance of the LCMS from the wall, in Ignitor, is only few millimeters. A cylindrical diffracting element placed inside the horizontal port can focus a spectrally resolved profile on a space resolving detector placed outside the vessel [1]. With this arrangement, the detector is removed from the direct view of the plasma, and the front-end electronics can be more easily protected. According to our estimates, with a proper choice of focal lengths and positioning of the diffracting element and detector, it should be possible to detect plasma movements with sufficient time resolution to be used for real-time feedback control of the vertical plasma position. The main features of this novel diagnostic approach are presented, and the strategy for its interfacing with the control system is outlined. The vertical position and shape controller for Ignitor has been designed on the basis of the CREATE\_L linearized plasma response model [2]. The possible degradation of the electromagnetic diagnostic system has already been taken into account, but the inclusion of a new and different type of signal has yet to be explored.

\*Sponsored in part by ENEA of Italy and by the U.S. D.O.E.

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## Reaction dynamics and spectroscopy of hydrocarbons in edge plasma

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Small hydrocarbons, especially methane, ethene ( $C_2H_4$ ), and their break-down products, are a common pollutant in tokamak edge plasma, and it is very important to understand the dynamics of these hydrocarbons, their reactions with plasma D/T, and the tritium codeposition on the tokamak vessel wall. Our OFES project concerns the ab initio calculation of reaction cross-sections for collisions between these hydrocarbons and “hydrogen”, all neutral or charged, and also computational spectroscopy of the hydrocarbons.

Our work contains a unique approach to the construction of potential energy and dipole moment surfaces (PES and DMS), which are parameterized representations of the energy and dipole moment of the system as a function of the nuclear configuration fitted to ab initio electronic structure calculations. The approach relies on computational invariant theory and the MAGMA computer algebra system as an aid to develop representations for the potential energy and dipole moment surfaces that are fully invariant under permutations of like nuclei. We express the potential energy surface in terms of internuclear distances using basis functions that are manifestly invariant; we tend to use polynomials in Morse-like variables, functions  $y_{i,j} = \exp(-\alpha r_{i,j})$  of the internuclear distances, and have combined that with use of a many-body expansion. The potential energy surface is then used for molecular dynamics calculations in order to simulate reactions, and for use with the MULTIMODE [Joel M. Bowman, Stuart Carter and Xinchuan Huang, *Int. Rev. Phys. Chem.* 22 (2003) 533–549] code to calculate rovibrational spectra.

At present the construction of the potential energy surfaces for the entire methane and ethane families, neutral and charged, is well advanced, and we have carried out detailed spectroscopic simulations of the ions  $C_2H_3^+$  [A. R. Sharma, J. Wu, B. J. Braams, S. Carter, R. Schneider, B. Shepler and J. M. Bowman, *J. Chem. Phys.* 125 (2006) #224306] and  $C_2H_5^+$  [manuscript in preparation]. This and ongoing work on reaction dynamics will be presented at the meeting.

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# Flow Shear Effects on Resistive MHD Instabilities in Tokamaks

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## Abstract

Recent advances have occurred in both theoretical analyses of non-Ideal MHD instabilities and experimental equilibrium reconstructions in tokamak discharges. These advances have made it possible to accurately test the theory of toroidal equilibrium flow effects on resistive MHD stability against experimental observations. Stability analyses are presented using equilibria based on reconstructions from experiments on the DIII-D tokamak showing resistive tearing/interchange instabilities onset in the presence of equilibrium flow. The effects of sub-sonic flow on the onset are detailed in the analyses, where both the inner layer physics and the coupling between surfaces can be affected in the linear dispersion relation. Including the flow in the equilibrium solutions is crucial in initial value computations, but does not significantly affect the outer region solutions for the instabilities, which are computed using the PEST-III code. Flow shear provides free energy to the instability in the inner layer in the experimental regime, while differential flow between neighboring rational surfaces can have a damping influence by decoupling their outer region solutions. At low flow the dominant effect is the damping of coupling between surfaces, while at high flow the inner layer effects dominate. Simulations of the nonlinearly coupled onset and evolution of these instabilities using the NIMROD code are combined with reduced analytic analyses and linear computational results to gain an intuitive understanding of the physics behind these competing influences and experimental observations.

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## The CDX Sawtooth Benchmark for 3D Nonlinear MHD

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The sawtooth instability [1] is a basic dynamic of inductive tokamak discharges, making accurate prediction of the sawtooth cycle a fundamental test for nonlinear MHD codes. The sawtooth cycle in the CDX-U tokamak [2], chosen because its small size and low temperature allow simulation using actual device parameters, has become an important benchmark for the comparison of M3D [3] and NIMROD [4]. Initial tests were conducted using a number of simplifying assumptions, such as the use of volumetric heating and current drive and a very large constant perpendicular heat conductivity. Comparisons showed impressive agreement between the two codes both on the linear instability of the  $m=1, n=1$  mode that gives rise to the sawtooth crash, and on the details of nonlinear cyclical sawtooth behavior. However, both codes significantly underpredicted the sawtooth period, giving a value of approximately 200  $\mu\text{s}$  as compared to 500  $\mu\text{s}$  measured in the experiment, indicating the need for greater fidelity to experimental conditions in the simulations. A second generation of CDX sawtooth benchmarks has been developed based on an analytically specified equilibrium with a more realistic self-consistent heat transport profile. Improvements in the model include the use of a loop voltage and ohmic heating, along with resistivity and viscosity profiles that evolve to track changes in the plasma temperature. Results from this benchmark are significantly closer to experimental values.

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## **Recirculation effects in multiple linear conversion**

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We construct a conceptual model, which focuses on the topology of intersecting rays in phase space, in order to investigate how linear conversion from a primary wave (e.g., magnetosonic) to a secondary wave (e.g., ion-hybrid) is modified by the presence of a tertiary wave (e.g., minority-ion Bernstein). We show that such a one-dimensional multiple-conversion model may exhibit energy recirculation. Using modular eikonal methods, we calculate transmission, reflection, and conversion coefficients for this model. Analytical results (confirmed numerically) show that all these coefficients exhibit interference effects, which depend on an interference phase, calculated from the coupling constants and the area enclosed by the intersecting rays. We consider the cases where the tertiary wave may have positive or negative energy. In both cases, the secondary-wave conversion is affected by the presence of the tertiary wave. In particular, when the tertiary-wave energy is negative (i.e., when the wave is supported by an inverted population of energetic particles), the secondary-wave conversion coefficient may exceed 100 %.

## Predictions of H-mode and Hybrid plasma performance in ITER

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Time-dependent integrated predictive modeling is carried out using the PTRANSP code [1] to predict fusion power and parameters such as alpha particle density and pressure in ITER plasmas. Auxiliary heating by neutral beam injection and ion-cyclotron heating of He<sup>3</sup> minority ions are modeled, and the GLF23 transport model is used in the prediction of the evolution of plasma temperature profiles. Effects of beam steering, beam torque, plasma rotation, beam current drive, pedestal temperatures, sawtooth oscillations, magnetic diffusion, and accumulation of He ash are treated self-consistently.

Variations in assumptions associated with physics uncertainties lead to ranges of predictions for DT fusion power for standard base-line H-mode DT plasmas (with  $I_p=15$  MA,  $B_{TF}=5.3$  T, and Greenwald fraction=0.86) in the range 150-450 MW. Predictions for Hybrid DT plasmas (with  $I_p=12$  MA,  $B_{TF}=5.3$  T, and Greenwald fraction=0.70) and for alternative plasmas such as more optimistic "Scenario 1" H-mode plasmas with density close to the Greenwald limit are considered, as well as reduced  $B_{TF}$  plasmas. One result is that if  $B_{TF}$  is reduced 20%,  $P_{DT}$  and  $Q_{DT}$  will be lower by about a factor of two (scaling as  $B^{3.5}$ ).

Predictions of beam and alpha parameters such as  $-R\nabla(\beta_{beam})$  and  $-R\nabla(\beta_\alpha)$  are presented. Examples of the predictions are that with 33 MW of negative-ion neutral beam injection at 1 MeV  $-R\nabla(\beta_{beam})$  dominates  $-R\nabla(\beta_\alpha)$  in the core region, and thus will be important for driving instabilities. Also steering of the negative ion neutral beam injection has a strong effect on the fast ion drive. Another prediction is that sawtooth crashes in H-mode plasmas will shift the peaks of  $n_{beam}$  and  $n_\alpha$  past the half radius.

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<sup>1</sup>Predictions of H-mode performance in ITER, R.V. Budny, R.Andre, G.Bateman, F.Halpern, C.E.Kessel, and A.Kritz, submitted

# Toroidal Flow In Tokamak Plasmas\*

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Many effects influence toroidal flow evolution in tokamak plasmas. Momentum sources and radial transport due to axisymmetric neoclassical, paleoclassical and anomalous processes are usually considered. In addition, the toroidal flow can be affected by field errors. Small, non-axisymmetric field errors in tokamaks arise from coil irregularities, active control coils and collective plasma magnetic distortions (e.g., NTMs, RWMs). Resonant field errors (FEs) cause localized electromagnetic torques near rational surfaces in flowing plasmas. Toroidal flow inhibits penetration of resonant field errors into the plasma by producing a shielding effect at the rational surface. Sufficiently large resonant FEs can lock the plasma to the wall leading to magnetic islands and reduced confinement or disruptions. Non-resonant field errors cause magnetic pumping (TTMP), ripple-trapping and radial drifts of bananas, and lead to radial nonambipolar particle fluxes and toroidal flow damping over the entire plasma. Many of these processes can also produce momentum pinch and intrinsic flow effects.

This paper presents a coherent and comprehensive picture of all these effects within a fluid moment context. Effects on successively longer time scales are considered sequentially: on the compressional Alfvén time scale the ion radial force balance yields  $\Omega_t \equiv \mathbf{V}_i \cdot \nabla \zeta = -[d\Phi/d\psi + (1/n_i e_i)(dp_i/d\psi) - q \mathbf{V}_i \cdot \nabla \theta]$ ; on the sound wave time scale pressure becomes constant along a field line and flows within a flux surface become incompressible; and then on the ion collision time scale the poloidal ion flow ( $\mathbf{V}_i \cdot \nabla \theta$ ) is damped to a diamagnetic-type value dependent on the ion temperature gradient. Finally there are many second order (in the small gyroradius expansion) radial particle transport fluxes:  $\mathbf{E} \times \mathbf{B}$ ; classical; Pfirsch-Schlüter; banana-plateau; parallel nonaxisymmetric (i.e.,  $\partial|\mathbf{B}|/\partial\zeta \neq 0$ ) neoclassical toroidal viscosity (NTV) flow damping effects due to TTMP [1,2], ripple trapping [3] and banana-drifts [4];  $\tilde{\mathbf{J}} \times \tilde{\mathbf{B}}$  toroidal torques on resonant surfaces [5] combined with NTV effects [6]; polarization flows; fluctuation-induced; and from sources. The nonambipolar components of the particle fluxes cause radial currents in the plasma. Setting the flux-surface-average of the total radial current (i.e.,  $\langle \mathbf{J} \cdot \nabla \psi_0 \rangle$ ) to zero yields [2,7] the transport-time-scale toroidal flow evolution equation ( $\mathbf{e}_\zeta \equiv R^2 \nabla \zeta$ ):

$$\underbrace{m_i n_i \langle R^2 \rangle \frac{\partial \Omega_t}{\partial t}}_{\text{inertia}} = - \underbrace{\langle \mathbf{e}_\zeta \cdot \nabla \cdot \vec{\pi}_{\parallel i} \rangle}_{\text{due to } \tilde{B}} - \underbrace{\langle \mathbf{e}_\zeta \cdot \nabla \cdot \vec{\pi}_{\perp i} \rangle}_{\text{cl, neo, paleo}} + \underbrace{\langle \mathbf{e}_\zeta \cdot \tilde{\mathbf{J}} \times \tilde{\mathbf{B}} \rangle}_{\text{res. FEs}} - \underbrace{\frac{1}{V'} \frac{\partial}{\partial \psi_0} V' \Pi_\zeta}_{\text{fluctuations}} + \underbrace{\langle \mathbf{e}_\zeta \cdot \sum_s \mathbf{S}_s \rangle}_{\text{sources}}.$$

The derivation of this equation and its various components will be presented and discussed.

\*Research supported by U.S. DoE grants DE-FG02-86ER53218 and DE-FG02-92ER54139.

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## Hamiltonian Perturbation Theory in the Study of Lower Hybrid Wave Propagation in Ionized Gas

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The application of Lower Hybrid heating and current drive to next generation tokamaks, mainly devoted to burning plasma physics studies, is crucial for the plasma profiles control and internal transport barrier formation. For correct modeling of the plasma wave interaction, a wave equation, valid for the lower hybrid range of frequencies (cold plasma and electrostatic approximation), has been derived and asymptotically solved (WKB expansion) up to the second order in the expansion parameter [1]. This approach allows the electric field reconstruction inside the plasma and a critical analysis of the wave propagation in the vicinity of caustics and cut-offs. In this work, starting from the Hamiltonian character of the WKB non-linear-partial-differential equation (Hamilton-Jacobi equation) for the wave-phase surface, we analytically solve the Hamilton-Jacobi equation in 2D geometry (in a general tokamak plasma equilibrium) by means of the “Hamiltonian perturbative theory”, considering the toroidal geometry as a perturbation of the straight cylindrical geometry and expanding the equation in terms of the inverse aspect ratio  $\epsilon$ . The essence of this technique is to expand the generating function  $S$  (that in our case is the phase surface or the Eikonal) in powers of the small parameter  $\epsilon$ , and then determine  $S_n$  recursively by solving a chain of partial differential equations, that in general can be solved by quadrature.

With this method, we can avoid a direct numerical (or analytical) integration of the ray equation system (Hamilton equations), and obtain an analytical expression for the generating function (phase surface) at any order of the expansion. An extension of the analysis to the cold electromagnetic equation (in presence of both slow and fast modes) will be also presented in order to study the solution behavior in the mode conversion regime.

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## **MHD kink instability driven by differential rotation and kink stabilization by azimuthal rotation**

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Large-scale, highly collimated energetic plasma outflows are observed in some active galactic nuclei. Recent observations of these extragalactic outflows suggest that some of these jets maintain a large scale helical magnetic structure with an asymmetry about their central axis [1]. The kink instability is known to create similar magnetic structures in laboratory plasmas. Thus, extragalactic jets may resemble a screw pinch topology and be susceptible to the current driven kink instability. We investigate the launching and stability of extragalactic jets through magnetohydrodynamic (MHD) simulations of jet evolution. In these simulations a small scale equilibrium magnetic corona is twisted by a differentially rotating accretion disk. Two-dimensional calculations show the formation of a collimated outflow. Three-dimensional calculations show that the outflow is unstable to the  $m=1$  kink instability, and that the growth rate of the kink decreases as the rotation rate of the accretion disk increases. Thus, the kink instability is stabilized for high rotation rates of the accretion disk. This stabilization is shown to be a result of the azimuthal rotation of the jet.

The stabilizing effect of azimuthal rotation on the kink instability is investigated through a normal mode analysis of a cylindrical plasma. A MHD equilibrium is considered with general magnetic field, pressure, and mass density profiles, and solid body rotation in the azimuthal direction. Applying the normal mode analysis to this equilibrium results in an eigenvalue problem for the growth rates of the unstable modes. This eigenvalue problem is solved using a shooting method. The eigenvalues and corresponding eigenmodes are examined as the rotation rate of the plasma is varied.

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# Simulations of lower-hybrid coupling in the Madison Symmetric Torus

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Simulations of Lower Hybrid (LH) coupling in the Madison Symmetric Torus (MST) Reversed Field Pinch (RFP) will be presented. Due to the special requirements of the RFP configuration (tight-fitting conducting shell in which only minimal portholes can be tolerated), a novel interdigital line slow-wave launch structure is used, mounted below the mid plane on the inboard side. The unusual configuration made it necessary to modify the main RF coupling code, RANT3D/AORSA1D-H, which was primarily developed for tokamak simulations. To complement the RANT3D/AORSA1D-H results, more first-principles simulations were performed with the VORPAL code. Preliminary results will be presented.

# Simulations of nonlinear dynamics of electron Bernstein waves

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## **Abstract**

Nonlinear simulations of electron Bernstein waves (EBW) are carried out using the VORPAL Computational Framework (C. Nieter and J. R. Cary, *J. Comp. Phys.*, 2004). Parametric decays of the incident EBW waves into other EBW waves are observed for sufficiently large amplitude (consistent with experimental values) and sufficiently large frequency. With inclusion of ion dynamics, decay into an EBW at a lower frequency and a low frequency ion wave is seen to occur. A theoretical model is presented and compared with simulation results. These nonlinear processes can affect the propagation of the incident wave and the power deposition profile.

POSTER

## **Electrostatic turbulence in tokamaks on transport time scales**

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### **Abstract**

Simulating electrostatic turbulence in tokamaks on transport time scales requires retaining and evolving a complete turbulence modified neoclassical transport description, including all the axisymmetric neoclassical and zonal flow radial electric field effects, as well as the turbulent transport normally associated with drift instabilities. Neoclassical electric field effects are particularly difficult to retain since they require evaluating the ion distribution function to higher order in gyroradius over background scale length than standard gyrokinetic treatments. In fact, in the long wavelength limit typical gyrokinetic descriptions only self-consistently evaluate the leading order gyroradius correction to a Maxwellian. In the axisymmetric limit, however, any kinetic description must be intrinsically ambipolar, making neoclassical heat and particle transport independent of the long wavelength axisymmetric radial electric field. To insure intrinsic ambipolarity and remove the need for a higher order gyrokinetic distribution function, a hybrid gyrokinetic-fluid treatment is formulated that employs moments of the full Fokker-Planck equation. The resulting hybrid description is able to model all electrostatic turbulence effects with wavelengths much longer than an electron Larmor radius, such as the ion temperature gradient (ITG) and trapped electron modes (TEM).

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# MHD Compressibility Stabilization in a Z-Pinch Fact or Fiction

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## Abstract

Ideal MHD theory shows that in a cylindrical Z-pinch, the  $m=0$  interchange mode is stabilized for sufficiently gradual plasma pressure profiles. Since plasma compressibility is found to be the stabilizing effect, this result is highly dependent on the ideal MHD equation of state, which is unreliable for fusion grade plasmas.

We investigate the validity of the ideal MHD result using a hybrid Vlasov-fluid model, which is more appropriate for the low collisionality regimes expected in fusion plasmas. The analysis is based on an extension of the model presented in [1]. The ions, assumed to be collision free on the MHD time scale, are treated with the Vlasov equation, while the electrons, assumed to be collision dominated on this time scale, are treated with a warm fluid equation. We first derive several general properties of the model applicable to static equilibria in an arbitrary 3-D geometry. We find strong similarities between the properties of the ideal MHD model and the hybrid model. In particular, the equilibrium equations turn out to be identical. At marginal stability, the potential energy integrals differ only by the plasma compressibility term, which, remarkably, is completely absent in the Vlasov-fluid model. Carrying out a detailed linear stability analysis for the special case of the  $m=0$  mode in a cylindrical Z-pinch geometry, we show explicitly that the absence of plasma compressibility leads to the conclusion that the mode can not be stabilized for any pressure profile. From the dispersion relation, we find that the instability is driven by the resonant ions.

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## **Parametric excitation of GAMs by finite beta drift waves<sup>\*</sup>**

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Linear geodesic acoustic modes (GAMs) are primarily electrostatic. As has been shown recently, these modes can be excited nonlinearly by coupling to electron drift waves<sup>a</sup>. We extend our earlier calculations, in which a GAM was excited by resonant coupling to two electrostatic drift waves, to include finite beta effects. The electromagnetic drift waves can excite GAMs with a zonal field. This field in fact introduces a threshold condition for the excitation of the nonlinear electromagnetic GAM. The most significant finite beta effect occurs in the edge region of toroidal plasmas, where the steep density gradients can make the magnitude of the drift frequency become comparable to the shear Alfvén frequency.

<sup>a</sup>N. Chakrabarti et al. Phys. Plasmas **14**, 052308 (2007)

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**Title** : Reduction of radial transport and application to test particle dynamics

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**Abstract** : We consider the transport of charged test-particles for edge tokamak plasmas. Due to the interaction with the turbulent electric potential obtained by numerical codes of interchange instability, such particles undergo a drift which enhances transport. The radial transport of such particles is responsible for the loss of confinement in toroidal devices. It is therefore of great importance to design control strategies aiming at reducing it. We show how a control strategy based on a global reduction of transport can be also applied to a reduction of radial transport. An appropriate modification of the electric potential associated with a small additional amount of energy is able to reduce transport along one spatial direction.

# Particle-in-Cell simulation of kinetic phenomena with Vlasov ions and drift kinetic electrons

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**Abstract.** Kinetic simulations of low-frequency kinetic processes in fusion plasmas are mostly based on the gyrokinetic model for ions, which is based on a number of assumptions (the gyrokinetic ordering). These assumptions are not always satisfied. In the plasma edge or internal transport barriers, the scale length of the equilibrium density and temperature profiles are not much larger than the ion Larmor radius, and there is often present a strong  $\mathbf{E} \times \mathbf{B}$  flow comparable to the ion thermal speed. In such a situation the ion gyrokinetic model presently used in turbulence codes needs to be extended. The theoretical formulation of a more accurate gyrokinetic model is itself nontrivial. Even if an accurate model is found, numerical implementation of it could be very challenging, based on past experience of developing gyrokinetic algorithms.

Numerically, the main constraint on efficient simulation is due to the fast electron motion along the magnetic field line. This motion is not eliminated in the gyrokinetic model. In practice we found that for small devices such as NSTX a time step of  $\Omega_i \Delta t = 0.2$  has to be used for stability. With a time step slightly smaller it is possible to follow the ion gyro-motion accurately. The Vlasov ion/drift kinetic electron model we propose to explore is based on these considerations.

The field equations of this model are the Faraday's equation and the Ampere's equation without the displacement current. We have implemented this model in a 3-D shearless slab. Similar Vlasov ion model (but with fluid or Vlasov electrons) has been tested in 1-D or 2-D geometry previously to produce the Alfvén waves, ion sound waves and the whistler waves accurately (D. Barnes, J. Cheng and S. E. Parker, to appear in *Physics of Plasmas*). In 3-D test simulations of waves with  $k_{\perp} \rho_i \leq 1$  it is found that the time step is severely limited by the high frequency compressional Alfvén waves. We will report on techniques to eliminate this wave and benchmark the simulation with the dispersion relations for the other branches of low-frequency waves, namely the shear Alfvén wave, the ion sound wave and drift waves.

# Nonlinear Dynamics of Ions Confined in an rf Potential Well

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The dynamics of charged particles confined in a radio frequency (rf) quadrupole potential well has been studied intensively in both theories and experiments [1–4]. Recently, the Paul trap has been investigated as a potential candidate for realistic quantum computation [5]. In an rf potential well, ions undergo a liquid to solid transition as they are laser cooled. Also, under certain parameter (the trap size, magnitude and frequency of the rf potential, etc) regimes, the trapped ions absorb energy from the external rf potential, and are rf heated, causing loss of confinement of the ions. Many simulations have been carried out to study the rf heating and liquid to solid phase transition of the trapped ions [1–4]. However, most of the models are implemented with only a single ion species. We have developed a code to study the dynamics of a few ions of multiple species including ion micromotion in an rf potential well. The effect of laser cooling will be simulated within the code. We will explore the configuration of the confined ions and come up with parameter regimes where rf heating is absent. Additionally, we simulate how collisions between trapped ions and the background gas at room temperature affect confinement of the ions from first principles. This poster presents some preliminary simulation results.

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# Edge plasma flows in kinetic simulations of a single-null divertor tokamak\*

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The ion distribution function in the H-mode pedestal region and scrape-off layer has the potential of having a substantial non-Maxwellian character resulting from large banana orbits, steep gradients in temperature and density, and neutral-ion charge-exchange. Because of the shape of banana orbits and because the sense of progression about a banana depends on the sign of the magnetic field components, kinetic effects can produce asymmetries in the toroidal and poloidal mean flows, and these asymmetries change with reversal of field components. An assessment of the magnitude and character of such flows is made using the 4D (2r,2v) version of the TEMPEST continuum gyrokinetic code that utilizes a collision model (Coulomb or Lorentz) to calculate the ion distribution in a single-null tokamak geometry throughout the pedestal/scrape-off-layer regions. The ion distribution function, mean density, parallel velocity, and energy radial profiles are shown at various radial and poloidal locations. The collisions cause neoclassical energy transport through the pedestal that is then lost to the divertor plates along the open field lines outside the separatrix. The resulting heat flux profiles at the inner and outer divertor plates are presented and discussed, including asymmetries that depend on the B-field direction. Also examined is the effect a radial electric field exhibiting a deep well just inside the separatrix, which reduces the width of the banana orbits by the well-known squeezing effect.

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## Hybrid Simulation of Plasmas Including Coulomb Collisions\*

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Kinetic simulation of collective phenomena including Coulomb collisions in inhomogeneous plasma presents significant multi-scale challenges. When the ratio of the collisional mean-free-path of an ion or electron species to the local scale length of the plasma properties or the electromagnetic fields varies from very much greater than unity (kinetic limit) to very much smaller than unity (fluid limit) over a domain of interest, a unified simulation approach becomes difficult using standard methods; and a brute-force, first-principles approach is typically impractical. This paper reports progress on the development of a kinetic-fluid hybrid technique for plasma simulation including Coulomb collisions, which allows the algorithm to adapt the balance of fluid and kinetic representations based on the local relative collisionality.<sup>1,2</sup> Specific applications are presented in which we quantitatively assess the performance and accuracy of the algorithm.<sup>1,2</sup> We also present considerations of the error properties of the collision algorithm and some insights concerning the different properties of pairwise collision algorithms, *e.g.*, Takizuka and Abe,<sup>3</sup> or Nanbu<sup>4</sup> algorithms, and grid-based, Langevin-equation algorithms, *e.g.*, Rognlien and Cutler,<sup>5</sup> and Manheimer, Lampe and Joyce.<sup>6</sup>

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# Smoothed neoclassical toroidal viscosity induced by field errors in tokamaks\*

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Nonaxisymmetric resonant magnetic perturbations—whose wave vector  $\vec{k}$  satisfies  $\vec{k} \cdot \vec{B} = 0$  on a surface inside the plasma—have long been known to cause localized electromagnetic braking forces on their respective surfaces. However, magnetic perturbations irregardless of their resonance property can also affect the plasma rotation through their modification to  $|B|$ . Variations along a field line induce nonambipolar radial transport and produce a global toroidal force on the plasma, known as neoclassical toroidal viscosity [NTV]. In general, this nonambipolar radial transport stems from TTMP [1, 2], ripple trapping [3], and radial drifts of ion banana orbits [4].

The flux-surface-average toroidal viscous force is related to the nonambipolar radial flux for species  $a$  via  $\Gamma_a = 1/(e_a \chi' \psi') \langle \vec{B}_t \cdot \vec{\nabla} \cdot \vec{\pi}_{\parallel a} \rangle$ . Here  $\chi' = \vec{B} \cdot \vec{\nabla} \Theta$ ,  $\psi' = \vec{B} \cdot \vec{\nabla} \zeta$ ,  $\Theta$  ( $\zeta$ ) is the “poloidal” (“toroidal”) angle in Hamada coordinates,  $\vec{B}_t = \psi' \vec{\nabla} V \times \vec{\nabla} \Theta$  is the toroidal magnetic field, and  $V$  is the volume enclosed by a flux surface. Previously calculated NTV results [4] for the low-collisionality “ $\nu$ ” and “ $1/\nu$ ” regimes were evaluated *separately* utilizing a relevant small parameter (in each case) to expand the drift kinetic equation and calculate the radial particle flux for each species  $a$ :

$$\Gamma_a \equiv \langle n_a \vec{V}_a \cdot \vec{\nabla} V \rangle = \frac{1}{4\pi^2} \iint d\Theta d\zeta \int d^3v \left( \vec{v}_{d,a} \cdot \vec{\nabla} V \right) f_a. \quad (1)$$

Low-collisionality in this context is distinguished by  $\nu_{\text{eff},a} < \omega_{b,a}$ , where  $\nu_{\text{eff},a}$  is the effective collision frequency for species  $a$ , and  $\omega_{b,a}$  their bounce frequency. The radial drift velocity is given by  $\vec{v}_{d,a}$ , and  $f_a$  is the perturbed distribution function. This paper seeks to simplify these previous results and provide a *single* particle flux (or toroidal viscous force) valid for both low-collisionality regimes. Provided pitch-angle scattering dominates over collisional energy exchange, the energy component of phase space can be decoupled into independent regions ( $E > E_c$  for  $\nu$  regime,  $E < E_c$  for  $1/\nu$  regime, with  $E_c$  determined by  $\nu_i(E_c) = \epsilon\omega_E$ ) within which the perturbed distribution function can be calculated similar to [4]. A smoothed radial particle flux may then be constructed by summing the partial contributions owing to  $\nu$  and  $1/\nu$  banana drift effects respectively:

$$\Gamma_a = \frac{1}{4\pi^2} \iint d\Theta d\zeta \left[ \int_{E_c}^{\infty} d^3v \left( \vec{v}_{d,a} \cdot \vec{\nabla} V \right) f_{\nu,a} + \int_{E'_c}^{E_c} d^3v \left( \vec{v}_{d,a} \cdot \vec{\nabla} V \right) f_{1/\nu,a} \right]. \quad (2)$$

This particular technique was first employed by Tsang and Callen [5] to smooth the transition between the axisymmetric banana, plateau, and Pfirsch-Schlüter regimes. The details of this derivation with the final result calculated in terms of the equilibrium flows and an ion-temperature-gradient-determined “intrinsic” flow will be presented.

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## **New Approaches to Ignition and Developments for Fusion Energy Sources\***

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A series of experiments carried out by the helical LHD facility in Japan has led to produce well confined plasmas with peak densities  $n_0 \approx 10^{21} \text{ m}^{-3}$  that were obtained previously only by high magnetic field compact devices, starting with Alcator A. These plasmas are characterized by the high degree of plasma purity that is necessary in order to reach ignition conditions and are associated with an optimal path in the relevant  $(n, T)$  parameter space in order to reach these conditions. In fact, this path is one of the bases of the Ignitor program [1] and has been adopted by the LHD team and the NCSX team (Princeton) to envision power producing conceptual reactors named HDR (Helical Demo-Reactor) and ARIES-CS (Compact Stellarator), respectively, that operate with plasma densities and temperatures equal to those chosen as the objective of Ignitor. It is evident that the helical configuration resolves in principle the problem of producing the poloidal field without the need of a stationary current drive system, yet to be invented, capable of operating efficiently in plasmas close to ignition condition. Thus Ignitor can provide the needed knowledge of the relevant burning plasmas also for this approach in the near term and with an affordable project.

Another effort initiated at Cambridge University (U.K.) is directed at envisioning compact axisymmetric devices for the practical exploitation of fusion by introducing novel concepts some of which have been investigated within the Ignitor program (such as disposable components, battery of devices functioning in parallel, etc.). An important development resulting from our interaction with the Cambridge group is the adoption of a new superconducting material (magnesium diboride) for the largest poloidal field coils of Ignitor that, like all the magnets of Ignitor, is cooled by He gas. These coils require 15 K while the copper coils start at 30 K. The rapid developments concerning this material and the expected progress in improving its properties make it possible to envision its adoption for other important coils producing higher magnetic fields and open new options in the design of new significant experimental devices.

In view of extending the operation of Ignitor to H-regimes where ignition conditions can be attained, a series of double X-point configurations have been analyzed and a pair of optimal configurations has been identified. These refer to maximum toroidal fields  $B_T \approx 13 \text{ T}$  on axis, and a toroidal current of 9 MA when the X-points lay on the first wall or of 10 MA when the X-points lay on

the outer surface of the plasma chamber but still relatively close to the edge of the plasma column. The relevant magnetic safety factors are in the range  $3.45 \lesssim q_{95} \lesssim 4$ .

\*Sponsored in part ENEA of Italy and by the U.S. Department of Energy.

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# Thermo-rotational Instability in Plasma Disks Around Compact Astrophysical Objects\*

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Differentially rotating plasma disks, around compact objects [1,2], that are imbedded in a “seed” magnetic field are shown to develop vertically localized ballooning modes that are driven by the combined radial gradient of the rotation frequency and the vertical gradients of the plasma density and temperature. When the electron mean free path is shorter than the disk height and the relevant thermal conductivity can be neglected, the vertical particle flows produced by of these modes have the effect to drive the density and temperature profiles [3] toward the “adiabatic condition” where  $\eta_T \equiv (d \ln T/dz)/(d \ln n/dz) = 2/3$ . Here  $T$  is the plasma temperature and  $n$  the particle density. The faster growth rates correspond to steeper temperature profiles ( $\eta_T > 2/3$ ) such as those produced by an internal (e.g. viscous) heating process. On the other hand, the well known M.R.I. (magneto-rotational) instability [4] that is driven by the radial gradient of the rotational frequency and has maximum growth rate that is close to the local plasma rotation frequency in a cylindrical geometry is severely penalized by having to fit into a thin disk [5]. In the end, ballooning modes excited for various values of  $\eta_T$  can lead to the evolution of the disk into a different current carrying configuration such as a sequence of plasma rings [6].

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# Fluid Theory of Micro-Reconnecting Modes<sup>1</sup>

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## Abstract

Collisionless Micro-Reconnecting Modes (MRM) are electromagnetic instabilities with scale distances perpendicular to the confining magnetic field of the order of the electron skin depth ( $k_{\perp}d_e \sim 1$ ) which are not confined by electron gyroradius effects ( $k_{\perp}\rho_{te} < 1$ ) and are relevant to toroidally confined plasmas. Through the development of quadratic forms, numerical procedures and asymptotic analysis [1] we examine in detail the fluid theory of these modes. These modes are driven by the electron temperature gradient and are strongly influenced by density gradients. The parallel component of the perturbed magnetic vector potential ( $\hat{A}_{\parallel}$ ) is an even function of the radial variable about a resonant surface leading to the formation of microscopic magnetic islands. We suggest that MRM are a candidate to explain the  $d_e$  scale turbulence observed in recent Princeton experiments [2]. In the (fluid) limit ( $\omega > k_{\parallel}v_{te}$ ) and when the temperature gradient is greater than the density gradient these modes satisfy  $k_{\perp}d_e > 1$  with growth rates of the order of  $\gamma \sim c_{se}/L_s(2k_y d_e/\beta_e)^{1/3}(T_i/T_e)^{1/3}(r_{Te}^2/L_s^2)^{1/3}$  where  $c_{se} = (T_i/m_e)^{1/2}$  is the “electron sound” velocity,  $\beta_e$  is the ratio of electron pressure to magnetic field pressure,  $L_s$  is the scale length of the shear of the magnetic field, and  $r_{Te}$  is the temperature gradient scale-length. In the quasi-linear limit these modes produce an increased perpendicular thermal conductivity, which is relevant to the excitation of meso-scale drift-tearing instabilities [1,3].

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# **Singular value decomposition and wavelet methods for noise reduction in particle-based transport calculations**

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A major limitation of particle-based transport calculations is the intrinsic noise caused by limited statistical sampling with finite number of particles. Thus, a key element for the success of these calculations is the development of efficient denoising methods. In this contribution we explore the use of two denoising techniques: Singular Value Decomposition (SVD) and Wavelet Decomposition (WD). The specific problem of interest is the reconstruction of smooth (denoised) particle distribution functions from discrete particle data obtained from Monte Carlo simulations.

The SVD denoising at a fixed time is based on a low-rank truncation of the decomposition of a coarse-grained representation of the particle distribution function. For time-dependent denoising we discuss the use of generalized low rank approximation methods. The WD denoising is based on the thresholding of empirical wavelet coefficients [Donoho et al., 1996].

As a first step we consider particle data obtained from a 2-D Monte Carlo simulation of plasma collisional relaxation including energy and pitch angle scattering. We present detailed numerical results comparing the reconstruction of the particle distribution function using SVD and WD denoising techniques.

We also discuss the application of these methods to transport in magnetically confined plasmas in toroidal geometry. In this case, the particle data is obtained from a delta-f particle code that follows the guiding center orbits in a prescribed equilibrium magnetic field and incorporates collisions using a Monte Carlo operator.

# A robust, efficient equidistribution 2D grid generation method based on Monge-Kantorovich optimization

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A new cell-area equidistribution method for two-dimensional grid adaptation, based on Monge-Kantorovich optimization (or Monge-Kantorovich optimal transport), is presented. The method is based on a rigorous variational principle, in which the  $L_2$  norm of the grid displacement is minimized, constrained *locally* to produce a prescribed positive-definite cell volume distribution. The procedure involves solving the Monge-Ampère equation: a single, nonlinear, elliptic scalar equation with no free parameters. Existence and uniqueness of solutions of the Monge-Ampère equation have been proved. Once a well-resolved solution is found, the adapted grid cannot be folded. We show that for sufficiently small grid displacement, this method also minimizes the  $L_2$  norm of the grid-cell distortion, measured by the trace of the metric tensor. We solve the Monge-Ampère equation numerically with a Jacobian-Free Newton-Krylov method. The ellipticity property of the Monge-Ampère equation allows multigrid preconditioning techniques to be used effectively, delivering a scalable algorithm under grid refinement. Several challenging test cases demonstrate that this method produces optimal grids in which the constraint is satisfied numerically to truncation error. We also compare this method to the well known deformation method [2] and show that our new method produces far better quality grids.

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## Gyrokinetic Models for Edge Plasmas

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We consider issues involved in gyrokinetic modeling for charged-particle species in magnetic fusion edge plasmas. A simple reduction from a full electromagnetic gyrokinetic-ion-based model, which may be a useful in many cases, is the use of *electrostatic* gyrokinetic ions and electromagnetic drift kinetic electrons. This choice removes the ions from Ampere's Law and from the magnetic field energy, and therefore removes any the need for any gyroaveraging operations in Ampere's Law and in the magnetic-field portion of the energy conservation relation. Several additional important issues are addressed: 1) The gyrokinetic Vlasov equations should be in conservation form to facilitate a conservative discretization. 2) High-order magnetic inhomogeneity terms, which have been retained in some edge-relevant gyrokinetic treatments, are not necessary. This results in very substantial simplifications in the expression of both the single-particle energy and the system (kinetic + field) energy conservation relation. This, in turn, is valuable for the production of a useable energy conservation simulation diagnostic. 3) We examine the gyrokinetic Poisson equation for the case when the perturbations are neither small-amplitude nor long-wavelength. In this case, the operator involved depends on the actual time-dependent distribution function, and (the matrix resulting from the discretization of the operator kernel) must be calculated frequently or at each time step. A finite-element formulation provides a straightforward route for discretizing the gyrokinetic Poisson kernel. However, there is still considerable expense involved in calculating this kernel. This expense may be mitigated somewhat by using approximate forms, which are under investigation. 4) For the system to have the correct energy conservation properties, the use of a time-dependent kernel in the gyrokinetic Poisson equation dictates that suitable higher order terms must be retained in the particle equations of motion (characteristics). These higher order terms provide their own significant implementation challenges and computational expense. 5) We build on the theoretical formulations of large-amplitude gyrokinetic Coulomb collision operators (when linearization does not apply) to develop an operator suitable for numerical implementation.

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## Effect of intermittent transport on rf-specific impurities\*

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Experiments and computer simulations show that the turbulent transport across the SOL is mediated by coherent objects called “blobs,” which are localized enhancements of plasma in the 2D (radial, poloidal) plane (e.g. see the review paper in Ref. 1). Thus, the SOL density and temperature are spatially and temporally intermittent. The effect of this intermittency on nonlinear (e.g. typical atomic physics) processes is not yet understood. For a nonlinear function  $f$ , intermittency ensures that  $\langle f(Q) \rangle \neq f(\langle Q \rangle)$ , where  $Q$  is any quantity and  $\langle \rangle$  denotes a time average, so that a usual transport code treatment may underestimate the effect.<sup>1</sup> The present work addresses the effect of intermittency in the context of an important practical application: *impurity sputtering (and self-sputtering) by ions accelerated in rf sheath potentials* on surfaces near ICRF antennas.<sup>2</sup> Rf-enhanced electron losses during ICRF heating can lead to kV sheath potentials in the vicinity of the antennas; the ion acceleration in these potentials gives large sputtering yields and the possibility of self-sputtering for high-Z materials.<sup>2</sup> For ITER, if the ICRF antennas are recessed in the wall, this leads to the possibility of self-sputtering avalanche at the first wall, which would clearly impact the desirability of using a high-Z coating. From a theoretical point of view, this problem is also an interesting example of an rf-turbulence interaction in which intermittency plays an important role. We will describe a simple ballistic model for the mutual interaction of a periodic train of blobs with the neutral pulses created by blob-induced sputtering of a high-Z wall. A condition for self-sputtering avalanche will be given under certain simplifying assumptions, and its dependence on blob, sheath, and wall parameters will be described.

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# Ideal-MHD ELM simulations with the BOUT++ code

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BOUT++ is a C++ framework for writing plasma fluid simulations with an arbitrary number of equations in 3D curvilinear coordinates. It has been developed from the original 3D 2-fluid boundary turbulence code BOUT. Though designed to simulate tokamak edge plasmas, the methods used are general and almost any metric tensor can be specified, allowing the code to be used to simulate (for example) plasmas in slab, sheared slab, and cylindrical coordinates. BOUT++ automates the common tasks needed for simulation codes, separating the complicated (and error-prone) details such as differential geometry, parallel communication, and file input/output from the user-specified equations to be solved. Thus the equations being solved are made clear, and can be easily changed with only minimal knowledge of the inner workings of the code. Benchmarking has been performed for linear and non-linear fluid and MHD test problems, including the Orszag-Tang vortex and comparisons to the BOUT code which will be presented.

The aim of this work is to develop non-linear ELM simulations in order to understand particle and energy loss mechanisms. As a step towards this, we will report linear ideal-MHD ELM simulations which have been compared to results from ELITE. A t-file formatted grid from a MHD equilibrium code, TOQ, has been converted into an input for BOUT++, and linear ELM simulations have been performed using a reduced ideal MHD model which includes both pressure and current drives. Instead of employing the surface terms which drive peeling modes at the interface between plasma and vacuum, we use a real parallel current profile peaked inside the pedestal due to the bootstrap current driven by steep pressure gradient. Agreement between the calculated growth rates and those from ELITE is within a factor of 2 over the range of mode-numbers analyzed. The diamagnetic stabilization has been observed in the BOUT++ simulations as toroidal mode number  $n$  increases. Several issues are still under investigation, for example at high mode-number, ELITE finds the growth-rate declining, whereas BOUT++ results showed them to be increasing in the absence of diamagnetic terms.

# Momentum transport from magnetic fluctuations in laboratory and astrophysical plasmas

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## Abstract

In both laboratory and astrophysical plasmas, toroidal angular momentum can be rapidly transported in the radial direction. The leading explanation of momentum transport is stresses from MHD instabilities. Here we investigate momentum transport from current-driven and flow-driven instabilities. We have recently performed a theoretical and computational study of momentum transport from current-driven reconnection (from tearing modes) in the presence of shear flow in a reversed field pinch (RFP)[1]. We have established that Maxwell and Reynolds stresses from tearing instabilities can transport momentum rapidly in the RFP. It has been shown that a single tearing mode can transport momentum, but the transport is enhanced by nonlinear mode coupling. In disk geometry, we also perform nonlinear MHD computations both for turbulence generated by tearing modes and by flow-driven Magneto-Rotational Instability (MRI). Computations show that in an MRI stable disk configuration, tearing modes can grow and cause transport of momentum. The effects of disk thickness and flow magnitude in momentum transport from tearing and MRI instabilities will be shown. We also discuss more general fundamental differences between current-driven and flow-driven instabilities, such as momentum transport properties and nonlinear mode saturation. The saturation mechanism of flow-driven instability as a quasilinear effect will be addressed in detail. In nonlinear computation with fixed Keplerian flow, we find a causal relationship between the magnetic field amplification and the saturation of MRI mode. Using quasilinear theory, we also calculate fluctuation-induced dynamo term, which causes the vertical field to increase.

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## Nonlinear Upshift of the TEM Critical Density Gradient and the Role of Zonal Flows in TEM Saturation

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Initial nonlinear simulations of TEM turbulence<sup>1</sup> with GS2 found a nonlinear upshift of the TEM critical density gradient, similar to the Dimits shift of critical ion temperature gradient in ITG turbulence. We have since shown the upshift increases strongly with collisionality,<sup>2</sup> consistent with the strong damping of TEMs by detrapping, and the relatively weak collisional damping of zonal flows. The role of secondary instability<sup>3</sup> is evident in the creation of zonal flow dominated states in the upshift regime. During single bursts of particle flux, the growth rate of the potential is approximately proportional to the amplitude of the dominant primary mode. We are now investigating the parameter space of the upshift.

In contrast with our TEM work, which has focused on density gradient driven cases with  $T_i = T_e$  and significant collisionality, a second study,<sup>4</sup> with strong electron temperature gradients and  $T_e = 3T_i$ , found that zonal flows have little effect on the turbulent saturation level. We have carried out a series of nonlinear simulations in both regimes, based on Cyclone parameters, to address this apparent discrepancy.<sup>5</sup> We found that the presence of the electron temperature gradient drives fine scale spatial structure, which reduces the effect of zonal flows relative to our original case. A simultaneous study<sup>6</sup> has also linked the importance of zonal flows to the electron temperature gradient.

Toward understanding this empirical result, we have investigated the radial-poloidal spatial anisotropy of the saturated turbulence as a function of the driving temperature and density gradients. We have also developed a linear stability diagram, based on 2,000 simulations, which shows the electron temperature gradient drives primarily shorter wavelength modes. TEM turbulence driven by the electron temperature gradient appears to somewhat resemble ETG turbulence, where at short wavelengths, the ions are more adiabatic, and secondary growth rates are reduced.<sup>7</sup> Thus, even though an initial zonal flow would be almost completely undamped<sup>8</sup> for the  $k_{\perp}\rho_i > 1$  typical of temperature gradient driven TEMs, zonal flows are not strongly driven.

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## **Analysis of fluctuations, turbulence and related transport in the TORPEX simple magnetized toroidal plasma**

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The basic plasma device TORPEX provides a unique testbed for benchmarking numerical codes for tokamak scrape-off layer simulations with experimental results. In the TORPEX geometry, a vertical magnetic field, superposed on a toroidal magnetic field, creates helicoidal magnetic field lines, with both ends terminating on the torus vessel. As in the scrape-off layer of fusion devices, the turbulence driven by magnetic field curvature and plasma gradients cause the plasma to diffuse in the radial direction, while simultaneously being lost along the field line. The configuration provides more detailed diagnostics and wider parameter scans than are usually possible in major confinement devices, facilitating the experimental study of low frequency instabilities and the related turbulence and cross-field transport.

In TORPEX, full spatio-temporal imaging of the electrostatic fluctuations is performed, using a multiple probe array or via conditional sampling of data obtained from movable probes; thus, high-resolution measurements of plasma parameters and wave fields throughout the plasma cross-section are obtained. Electrostatic drift and interchange instabilities are characterized in terms of their driving mechanisms, their dispersion relation, and their development into turbulence. Measurements of density fluctuation time series across the plasma cross-section in a variety of plasma conditions reveal universal aspects such as a quadratic relation between skewness and kurtosis. Blobs are observed to carry plasma from the high to the low-field side of the machine. The blob generation and ejection are related to a strongly sheared  $\mathbf{E} \times \mathbf{B}$  flow. The blob effect on cross-field transport is investigated in details. Future research lines, such as active control of drift and interchange instabilities using tunable antennas, optical turbulence imaging, and the study of the interaction of supra-thermal ions with turbulence, will also be discussed.

# New results in Equilibrium and Stability of Two-Fluid Plasmas

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A new two-fluid computational tool for calculating equilibrium, stability, and reconnection processes in high-temperature magnetized plasmas has been extended to include equilibrium and 3D linear stability of toroidal plasmas. M3D- $C^1$  [1] is based on high-order, compact finite elements with  $C^1$  continuity on an unstructured adaptive grid. The split-implicit time advance is shown to be closely related to the ideal MHD energy principle, and allows time steps several orders of magnitude in excess of the Courant condition based on the Alfvén or whistler waves. We present new results of accurate axisymmetric free-boundary stationary states of a comprehensive two-fluid plasma model including flow, gyroviscosity, and nonuniform, anisotropic thermal conduction. These solutions are true steady-states on all time scales. Results for both large aspect-ratio, circular cross-section configurations, and realistic NSTX and ITER geometries are presented. Spontaneous rotation is observed to occur in the absence of external angular momentum injection, in accordance with theoretical predictions [2, 3]. These stationary states form the equilibrium configuration for subsequent newly enabled free-boundary linear stability calculations. Normal modes are calculated by integrating the linearized 3D two-fluid equations. The full model consists of 8 scalar variables. Nontrivial, energy conserving, subsets of the full equations exist including (1) 2-variable reduced MHD which is a toroidal generalization of the Strauss equations[4] and a 4-variable reduced model which is a toroidal generalization of [5]. Future capabilities discussed include a resistive wall and a scalable full 3D nonlinear time evolution.

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## The effect of line-tying on tearing modes

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The study of MHD linear stability with line-tying has been the subject of intense research in the solar physics community for several decades, in an attempt to understand the dynamics of solar flares and the related mechanisms of energy release (see the review paper [1]). In the astrophysical context, line-tying of flux tubes to an accretion disk is considered an important effect. Moreover, recent experiments on two cylindrical devices [2-3] have brought even further interest on this subject. It is important to notice, however, that applications to solar physics or to laboratory experiments span a wide range of values of the Lundquist number  $S$  (proportional to the inverse of plasma resistivity),  $S > 10^{10}$  in the solar corona while  $S \sim 50$  for the experiments.

In this presentation, we will therefore analyze the effect of plasma resistivity on line-tied modes in cylindrical geometry and discuss the existence of tearing modes in line-tied plasmas [4-6]. We will show that  $m=1$  and  $m=2$  modes can be unstable as tearing modes (characterized by the growth rate scaling as a fractional power of resistivity) in a line-tied plasma only if the length  $L$  of the plasma column is very long and the equilibrium magnetic field has a large amount of magnetic shear [4]. When the cylinder length is shortened (but line-tying does not completely stabilize the modes), the scaling of the growth rate changes from tearing to pure resistive diffusion (i. e. growth rate proportional to plasma resistivity). The pure resistive scaling was already obtained in Refs. [5-6]. These results are consistent with the following interpretation: for  $L \rightarrow \infty$ , the modes have a tearing width characteristic of tearing, leading to characteristic tearing mode growth. As  $L$  decreases, the modes develop a *geometric width*, and the pure resistive scaling occurs if  $L$  is small enough that the geometric width exceeds the tearing width.

We will also present new results on the effect of plasma pressure and different axial boundary conditions at one end of the plasma column (ranging from line-tied to free, with the other end line-tied) [3] on the stability of the system.

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# A Toroidal Shell Model for Shaped Tokamak Plasmas

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The toroidal shell model of Freidberg & Haas[1] is generalized to tokamak plasmas with shaped cross-sections. The model assumes a constant pressure, zero current plasma, bounded by a toroidal current sheet. The inverse-aspect ratio,  $\epsilon$ , is much less than unity. However, the ratio  $\beta/\epsilon$  is of order unity.

The model allows the physics of pressure driven external modes, such as vertical instabilities, external kink modes, and resistive wall modes, to be examined in a framework which is much more realistic than cylindrical calculations, but much less complicated than full numerical simulations. Many example applications of the model will be provided.

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# Progress on TGYRO: the steady-state gyrokinetic transport code

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## Abstract

We report on the status and development of a prototype steady-state gyrokinetic transport code, TGYRO. This prototype is being developed as part of a SciDAC-funded project (partner to the larger FACETS project) to develop software to integrate micro-scale gyrokinetic turbulence simulations into a framework for practical multi-scale simulation of a burning plasma core. It is our intention to aggressively pursue the International Thermonuclear Experimental Reactor (ITER) as an eventual simulation target after a period of code validation.

Currently, the TGYRO code has two operational modes:

1. **global**: a feedback scheme is applied to a single global GYRO simulation for which target fluxes are specified. The temperature and density profiles are then adjusted dynamically until the GYRO fluxes match the target fluxes;
2. **local**: in the spirit of traditional local transport codes, the flux is calculated independently at points along the minor radius, and profiles are adjusted in order to satisfy steady-state power balance. At each radius, one can run call a nonlinear gyrokinetic simulations (GYRO) [1], an advanced gyrofluid model (TGLF) [2] or simple transport model (IFS-PPPL).

There is a unified software interface to control both of these operational modes which resembles closely the more well-known GYRO user interface. The global feedback scheme is currently being beta tested by selected GYRO users, whereas the local scheme is still under development. In this presentation we will focus on details of the local scheme only.

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## **Energetic Particle-induced Geodesic Acoustic Mode**

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We report a new Energetic Particle-induced Acoustic Modes (to be called EGAM) discovered [1,2] in the recent numerical simulations using the particle/MHD hybrid code M3D [3]. The new mode was found to be excited by energetic particles with free energy associated with anisotropic particle distribution function. The mode had a global radial structure peaked at the center of plasma and had a frequency inside the GAM frequency continuum. An integral differential equation is derived for EGAM including the non-perturbative effects of energetic particles. Analysis shows that energetic particles can either enhance or reduce the EGAM frequency depending on details of particle distribution such as particle energy and pitch angle distribution. In the limit of isotropic distribution and large energetic particle temperature, the energetic particle pressure reduces the GAM frequency unlike the thermal species. Furthermore, the effects of finite orbit width of the energetic particles determine the radial mode structure of the global EGAM. Details of the analytic dispersion relation for EGAM and numerical simulations will be presented.

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# Effects of Profile Relaxation on ITG Drift Turbulence Simulations

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It is commonly believed in the magnetic fusion community that ion temperature gradient (ITG) drift modes are very sensitive to small changes, i.e., very stiff to local temperature and density gradients. Therefore, it has been widely suspected that global gyrokinetic simulations using the  $\delta f$  scheme [1] suffer from profile relaxation in the nonlinear stages of the simulation, unless an energy source is added in the simulation. This relaxation is believed to be responsible for the low levels of ion thermal diffusivity observed in these simulations. To shed some light on this question, we have used the global gyrokinetic code, GTC, in toroidal geometry [2, 3] to test the sensitivity of the profile modification caused by self-consistent energy diffusion. By monitoring the actual profile relaxation during the course of the simulation, we will show that this type of relaxation has negligible effects on the steady state transport for the ions. Instead, the new results seem to indicate that the turbulence properties in the steady state are mostly determined by the linear (initial) profiles rather than the nonlinearly modified ones and, in the nonlinear state, the free energy source in these simulations becomes inaccessible to the particles due to the existence of turbulence. In the present study, all the simulations have included both the nonlinearly-generated zonal flows and the parallel velocity-space nonlinearity, which were shown to be the essential ingredients for global steady state turbulent transport [4]. We intent to check the validity of these results using the full-F version of the new GTS code in more realistic geometry [5].

The work is supported by DoE contract DE-AC02-76-CHO3037, the SciDAC GPS Project (FY05-07) and the OASCR MMRE MultiScale Gyrokinetics Project (FY06-08).

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# A model of electron transport from self-consistent action-angle transport theory<sup>1</sup>

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An explicit electron transport model is derived from a version of the action-angle collision operator that includes both a diffusion term and a friction term in action-space <sup>2</sup>. By adopting the adiabatic invariants of the unperturbed particle motion and their conjugate angles as phase-space coordinates, the theory describes the degradation of the plasma confinement as a result of the breaking of the invariants by wave-particle resonances. The friction term, missing in the quasilinear approach, describes the back-reaction of the particles on the fluctuations, giving to the model that property of self-consistency that is often crucial in predicting correct transport rates. With regard to the fluctuation spectrum, the theory is structurally similar to quasilinear theory in that it does not determine the spectrum, but rather accepts whatever spectrum one believes to correctly describe a particular transport mechanism. This provides a common framework to view the effects on transport of perturbations of very short wavelength, which give rise to collisional transport, or of longer wavelengths in the turbulent range.

After giving an overview of the general formalism, we specialize to passing electrons in tokamaks and study their transport induced by magnetic turbulence. We perform all the mathematical steps required to translate the random-walk in action space into more familiar radial transport, obtaining the complete set of transport equations <sup>3</sup>. The resulting model shows several interesting features, regarding particle and energy pinches, turbulent heating and current density transport. We conclude by outlining planned future directions.

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# Interpretation of filamentation of intense electromagnetic waves in inhomogeneous plasma: relativistic nonlinearity

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## **Abstract**

A relativistically intense electromagnetic wave propagating through inhomogeneous plasma is susceptible to filamentation instability. The nonlinearity responsible for this instability arises through the relativistic oscillation of the mass of electrons in the field of the pump wave. When the equilibrium is perturbed by a electromagnetic perturbation, a further reduction in the plasma frequency occurs in the regions of high field intensity due to the relativistic mass increase of the electrons in presence of the pump wave and perturbation. For a linear density profile the amplitude of the filament varies with  $z$  as an Airy's function. Growth rate increases with the transverse wave vector of the perturbation.

## **New capabilities of the equilibrium code FLOW**

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Plasma rotation is ubiquitous in magnetic-confinement experiments. Toroidal rotation is routinely observed in tokamak experiments, either induced by means of neutral beams (e.g. in NSTX and DIII-D) or appearing spontaneously (e.g. in Alcator C-Mod, JET and Tore Supra). It is well known that equilibria in the presence of macroscopic plasma rotation can be considerably different from static equilibria, if the rotation becomes comparable to some plasma characteristic speed. For a few years now, the code FLOW [1] has been successfully used to study the effect of plasma rotation on the equilibrium of different magnetic confinement configurations. Active work is now in progress in view of the inclusion of FLOW as a module of the European Integrated Tokamak Modeling (ITM), aimed at building a comprehensive numerical framework for ITER simulations. We also report on the latest work on the code, including a benchmark with the CHEASE code for tokamak equilibria deduced from eqdsk type files, and the implementation in FLOW of several diagnostics (namely, trapped particle fraction and bootstrap current evaluation), highlighting the additional physics that can now be studied with the code. Finally, we describe the extension of FLOW to the study of Reversed Field Pinch configuration.

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## **Non-diffusive transport in $\mathbf{E} \times \mathbf{B}$ zonal flows: finite Larmor radius effects and fractional diffusion modeling**

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Experimental, numerical, and analytical studies in fusion plasmas have pointed out the importance of non-diffusive transport, i.e. transport processes that deviate from the standard diffusive paradigm. Experimental examples include the observation that cold pulse perturbations in tokamaks and stellarators travel much faster than expected on the basis of diffusive time scales, see e.g. Ref.[1]. Also, studies of  $\mathbf{E} \times \mathbf{B}$  test particle transport in plasma turbulence have shown clear evidence of non-diffusive behavior [2].

On the other hand, zonal flows attract considerable interest due to their presumed role in suppressing and regulating turbulent transport. Thus, a problem of interest is the study of the role of zonal flows in non-diffusive transport. Early results in Ref.[3] showed that large displacements induced by zonal flows result in super-diffusive transport in plasma and fluid systems. However, with few exceptions, e.g. Ref.[4,5], most studies of non-diffusive test particle transport in  $\mathbf{E} \times \mathbf{B}$  zonal flows have neglected finite Larmor radius (FLR) effects. Including these effects is critical, for example, because the Larmor radii of fusion alpha particles are significantly larger than the radii of thermal ions.

Here we present a detailed study of FLR effects on non-diffusive transport in the context of a Hamiltonian model describing chaotic test-particle transport by a special case of Hasegawa-Mima drift waves in zonal flows [6]. The FLR effects are included through the gyro-averaged equations of motion. We focus on the statistical properties of particles that alternate chaotically between being trapped in eddies and being advected by the zonal flow. It is shown that the transport of this group of particles is super-diffusive for a wide range of Larmor radii. Also, it is observed that the probability distribution function (pdf) of particle displacements is strongly non-Gaussian and exhibits anomalous self-similar scaling. Therefore, a diffusive model (with an effective diffusivity) cannot describe particle transport in this case.

As an alternative, we present an effective macroscopic transport model based on fractional diffusion operators. These are non-local (integro-differential) operators that allow a generalization of the Fourier-Ficks prescription (the cornerstone of the diffusion model) incorporating anomalous scaling along with non-Gaussian and non-Markovian (memory) effects [2]. It is shown that the fractional diffusion model reproduces the shape and space-time scaling properties of the non-Gaussian pdf of particle displacements.

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## **Low-dimensional and 2D simulations of magnetic fluctuations in MCX\***

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Recently magnetic fluctuations in the Maryland Centrifugal eXperiment (MCX) plasma have been measured by an azimuthal array of sixteen coils in the edge region of the plasma. A detailed analysis of these fluctuations indicates that there is primarily a convection of the low azimuthal mode number (dominantly  $m=2$ ) fluctuations by the azimuthally rotating plasma. However the frequency spectrum of this mode is broad and is almost of the same order as the frequency. Furthermore bicoherence studies indicate a dominant interaction between these modes and a low frequency  $m=0$  mode. We utilize a 2D (radial and azimuthal) MHD code to investigate the dynamics of the primary interchange instability which can be unstable in a rotating mirror geometry. For very low sheared rotation there is a broad spectrum (in  $m$ ) of unstable modes. However as the sheared rotation is increased the high mode numbers become stabilized and the spectrum is dominated by low mode numbers. We will present detailed comparisons of spatio-temporal dynamics of our simulations with the data from the sixteen probes. We will also present results from a low-dimensional model which captures the observed spatio-temporal features of the observations.

\* Work supported by DOE

# First Results From Coupled Core-Edge Simulations Using the FACETS Code

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We present results from the first coupled core-edge simulations in the FACETS framework. The FACETS core solver component is capable of using different flux models, for example, simple analytical models and the GLF23 and MMM95 models. Different solver strategies and time-stepping schemes can be selected at run time. The core solver uses a worker-manager design pattern to achieve good parallel scaling. To solve for the edge transport UEDGE is incorporated into the FACETS edge component. UEDGE solves the two-dimensional transport equations for electrons, ions and neutrals in the tokamak edge. Present version of UEDGE incorporated into FACETS is serial, but efforts are underway to make the code parallel. For coupled simulations FACETS uses a parallel-composition design pattern in which the core and edge solvers are run on different processor sets simultaneously. Algorithms to coupled the core edge boundaries are incorporated into updaters which control the transfer of data between the core and edge and also monitor and control convergence of the coupled solution. Several coupling strategies are incorporated into FACETS. The simplest scheme uses explicit coupling in which conserved variables and their fluxes are exchanged across the core-edge boundary at each time-step. No effort is made to ensure convergence. This scheme works well if the time-steps are limited by the explicit stability limit of each component, but is computationally very intensive. To improve convergence and allow for larger time steps a Picard (functional) iteration scheme is also implemented. This scheme allows for much larger time-steps, better convergence control and is computationally more efficient than explicit coupling. However, it still imposes an upper limit on the coupled time-step. To overcome this a Newton-solver is implemented. Results with these coupling schemes are presented. Parallel scaling of the coupled core-edge component in FACETS are also presented.

## Summary of recent advances in the Weiland drift wave model for anomalous transport in tokamaks

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An outline is presented of the recent advances in the prediction of transport computed by the Weiland drift wave model [1]. This model describes the collective behavior of ion temperature gradient (ITG), trapped electron (TEM), and magnetohydrodynamic (MHD) modes that drive anomalous transport in tokamaks. The advances in the model include an improved description of the effects of finite beta, low and negative magnetic shear, and plasma elongation. The effects on ITG modes resulting from the magnetic field gradient and magnetic field curvature drifts are derived using an appropriate equilibrium. In the ballooning approximation, the extension along the magnetic field lines of the Gaussian eigenfunction used to represent the drift modes depends on the effective magnetic shear. The parametric dependence with respect to temperature gradient, density gradient, magnetic shear, collisionality, elongation, and plasma beta is determined for transport channels such as ion thermal transport, electron thermal transport, toroidal momentum transport, and particle transport. The diffusivities computed using the new model are compared to the diffusivities computed using a previous version of the Weiland model [2]. It is shown that the models yield similar levels of transport at low beta and high magnetic shear. However, the new model provides more sophisticated high beta and low magnetic shear effects, which are due to the refinement of the description of the drift mode eigenfunction relative to the previous model. In particular, it is found in the new model that ITG modes can be suppressed by low and reversed magnetic shear, and that the transition between ITG modes and MHD modes occurs at relatively high beta, with the beta threshold being sensitive to the effects of magnetic shear and elongation.

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F.D. Halpern *et al.*, *Phys. Plasmas* **15**, 012304 (2008).

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# A FLUID-DYNAMICAL ANALOG OF A TWO-FLUID PLASMA\*

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## Abstract

Following our work on the variational formulation of rotating two-fluid equilibrium states, we work out the analogous case of an unmagnetized classical fluid. The case of a compressible and non-isentropic fluid is intriguing because it is typically not considered by fluid dynamiscists who mostly deal with incompressible fluids or with equations of state of the form  $p = p(\rho)$ , but not when  $p$  also depends on the entropy. In such a case, the vorticity is not strictly carried by the fluid, but nevertheless there are still surfaces in which its toroidal and poloidal fluxes are conserved, a notion more familiar in plasma physics than in fluid dynamics.

In carrying out this work it is necessary to find all independent constants of the motion, which are used as constraints in a variational principle. It is also necessary to distinguish between toroidal and cylindrical equilibria, since the number of constants of the motion is not the same for both. We are able to show in each case that we have indeed accounted for all the constants. This formulation allows the simple consideration of stability, which will also be discussed.

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# Local 3-D MHD equilibria with magnetic islands\*

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## Abstract

A number of authors have used the notion of local solutions to the MHD equilibrium equations to study the independent effects of variations in plasma shaping and profiles on linear instabilities [1-3]. In this work, we extend our previous studies of local 3-D equilibria [3] by allowing for the presence of a single helicity magnetic island chain in the formulation. The goal is to generate a tool to study the effects of magnetic island topology on high- $k$  MHD and microinstabilities. A resistive MHD model is employed to describe the self-consistent island magnetic fields, currents and plasma profiles. The profiles are determined to within two free functions of the helical magnetic flux that either be freely prescribed (as in Grad-Shafranov theory) or determined consistent with local transport processes. The resulting equilibrium quantities that can then be used to construct the various geometric quantities of interest that are relevant to stability calculations. Of particular importance are the magnetic field line curvature ( $\vec{\kappa} = \hat{\mathbf{b}} \cdot \nabla \hat{\mathbf{b}}$ ) and local shear  $s = \hat{\mathbf{b}} \times \hat{\mathbf{n}} \cdot \nabla \times (\hat{\mathbf{b}} \times \hat{\mathbf{n}})$  where  $\hat{\mathbf{b}}$  is the unit tangent vector to the magnetic field and  $\hat{\mathbf{n}}$  is the unit normal vector to the magnetic surface. Helical currents flowing in the island vicinity modify the local shear properties in accordance with the identity  $s = \mu_o^{-1} J_{\parallel} / B - 2\tau_n$  where  $\tau_n = -\hat{\mathbf{n}} \cdot (\hat{\mathbf{b}} \cdot \nabla)(\hat{\mathbf{b}} \times \hat{\mathbf{n}})$  is the normal torsion. As an application, we address the linear stability properties of resistive ballooning modes near an equilibrium magnetic island.

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# A mixed finite-element method for anisotropic thermal conduction <sup>\*</sup>

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## Abstract

The highly anisotropic nature of heat transport in high-temperature, magnetized plasmas yields stiff systems of algebraic equations upon spatial discretization. The application of high-order, 2-D finite elements in the NIMROD code [1] has had substantial success in representing this anisotropy with parallel to perpendicular conductivity ratios,  $\kappa_{\parallel}/\kappa_{\perp} \geq 10^{10}$ . These results hold even when the grid is not aligned with the magnetic field. Recent work, however, indicates that stochastic magnetic fields further tax the spatial representation, requiring prohibitively high-order 2-D polynomials and extensive Fourier expansions in the third dimension for spatial convergence. In this work, we present a mixed finite-element method which solves simultaneously for temperature,  $T$ , and an auxiliary scalar which is related to the large parallel heat flux,  $q_{\parallel}$ . While this approach leads to larger and potentially more ill-conditioned systems, it can improve spatial accuracy by converting second-order derivatives to first order and by reducing the order of nonlinearities in the parallel conduction term. Furthermore, finite-element research [2] in the fields of fluids and elasticity suggests that averaging  $\kappa_{\parallel}^{-1}$ , as opposed  $\kappa_{\parallel} (\sim T^{5/2})$ , can further improve spatial accuracy when  $\kappa_{\parallel}$  is temperature dependent. Comparisons of spatial accuracy and computational efficiency between the  $T$ -only and the mixed finite-element ( $T$  plus  $q_{\parallel}$ ) methods are presented for stochastic magnetic fields in slab and toroidal geometry. The development and application of 3-D preconditioners for iterative solutions to the resultant stiff equations of the mixed finite-element method are also discussed.

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## **Gyrokinetic PIC simulations of toroidal momentum transport in tokamak**

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The simulation of toroidal angular momentum transport has been carried out using global toroidal gyrokinetic particle-in-cell code (GTC). The turbulence driven redistribution of momentum is observed, resulting with a peaked momentum profile in the central region of the radial domain. Cases with constant (rigid body rotation) and sheared angular velocity are considered. The momentum flux evolution shows the presence of both diagonal and off-diagonal components. The various driving terms of generalized momentum transport equation are identified and compared.

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# The Microtearing Modes and Drift Wave Turbulence

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Microtearing modes are driven by combinations of the electron temperature gradient and the plasma current density gradient, and thus may add to the anomalous electron thermal flux in current carrying plasmas. The problem has a long history in fusion research where generally the earlier results such as Connor et al. in PPCF (1990) find that the passing electron response and a stabilizing MHD response from  $\Delta'$  overcome the destabilization from the trapped electrons. They conclude that a typical tokamak system is unlikely to have unstable microtearing modes.

There is experimental and gyrokinetic simulation evidence suggesting the presence of microtearing modes perhaps coupled to the ETG modes. Without the temperature gradient we benchmark a gyrofluid code with simulations [Horton et al. PoP, 012902 (2007)] showing coherent structures and dramatic magnetic energy releases to the electron pressure from sheared magnetic fields - positive  $\Delta'$ . Then we add the electron temperature balance equation to have three PDE's that give the ETG turbulence in the limit of vanishing current gradients. We show the changes in the form of the plasma turbulence and the anomalous transport coefficients as we vary the parameters of the system. The electron inertia and the parallel electron pressure gradients are kept as key forces in the plasma turbulence. The conversion of reversed magnetic field energy to electron flow and thermal energy is monitored in the turbulence.

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# Global Dynamics of Single Ion Motion in a Model Field-Reversed Configuration

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## Abstract

We analyze single ion motion in a model field-reversed configuration. A two-dimensional effective potential is derived and shown to possess a potential trough as well as isolated critical points. Sufficient conditions for Lyapunov stability are derived for these equilibria and shown to allow large populations of energetically trapped orbits, which can be regular or chaotic. Among these the classical guiding center orbits gyrating about closed field lines form a small minority. Indeed, for moderate field elongation the great majority of trapped orbits appear to be chaotic, with significant populations of regular orbits librating about stable periodic orbits. For larger conserved angular momentum the potential trough disappears and ions are energetically trapped in a larger convex potential well. The dynamics in this regime is very sensitive to elongation, with large resonances and chaotic regions for particular integer values of the inverse elongation. These theoretical results are well confirmed by numerical orbits, Poincaré sections, and Lyapunov exponents. The abundance of periodic orbits and paucity of guiding center orbits suggests that the frequency of the imposed rotating magnetic field in RMP experiments should be chosen close to the libration frequencies of the dominant periodic orbits rather than the cyclotron frequency.

# Resistive Tearing Instability in a Line-tied Configuration

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The effects of line-tying on magnetohydrodynamic instabilities are an important issue for astrophysical plasmas, such as the solar corona or astrophysical jets. Recently, several laboratory experiments aimed at studying line-tying effects have been initiated. This work studies the effect of line-tying on the resistive tearing instability in the slab geometry. A strong guide field perpendicular to the conducting boundary is assumed, therefore the system is described by the well-known reduced MHD equations. A spectral eigenvalue code solving the linear stability has been developed. Relevant issues such as how the growth rate depends on the system length  $L$  and how it scales with respect to the resistivity  $\eta$  will be addressed.

# Temperature gradients are supported by cantori in chaotic fields

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(Dated: January 29, 2008)

With the tantalizing prospect that localized regions of chaotic field can effectively be used to suppress ideal instabilities, as shown by the resonant magnetic perturbation (RMP) experiments on DIII-D [1], it becomes necessary to understand the impact of chaotic fields on confinement. Using a model of heat transport for illustration, we show that chaotic fields can support significant temperature gradients. Despite the fact that flux (KAM) surfaces may be destroyed by applied error fields, the remnants of the KAM surfaces, the cantori [2], present extremely effective barriers to field-line transport, and thus present effective barriers to any transport process that is dominantly parallel to the field. Coordinates adapted to the structure of the chaotic magnetic field, which we call chaotic coordinates [3], can be used to reduce the representation of the temperature from generally a function of three-dimensional space to the much simpler form  $T(s)$ , where  $s$  labels that chaotic coordinates surfaces. In chaotic coordinates, the temperature profile will generally be a smoothed devil's staircase.

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**"The Local Cold Bundage" emerged from the injected pellets  
and  
its effects on MHD instabilities in tokamaks**

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**The fusion reactor experiment should allow bulk densities close to the Greenwald value with retaining a high energy confinement. So far only pellet injection technique are said to meet this requirement.**

**However we should remember that this technique inherently forms extra-natural plasmoid with few orders of magnitude higher local density and lower temperature zone surrounding the pellet " SOLID ! HYDROGEN ".**

**In this presentation we would like to discuss the formation and expansion process of "the Local Cold Bandage" dressed around the rational surfaces emerging from the extremely high density plasmoid as the driving particle reservoir. This will cause unique MHD instabilities in reactor level tokamaks.**

## **Resonant Field Amplification and Rotational Screening in DIII-D RMP Simulations\***

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The application of resonant magnetic perturbations (RMP) to DIII-D plasmas at low collisionality has achieved ELM suppression, primarily due to a pedestal density reduction. NIMROD RMP simulations investigate the mechanism of enhanced particle transport. The simulations are initiated with realistic vacuum fields from the DIII-D I-coils, C-Coils and measured intrinsic error fields added to an EFIT reconstructed DIII-D equilibrium. The plasma responds to the applied fields while the boundary conditions maintain effectively constant coil currents. A non-rotating plasma amplifies the resonant components of the applied fields by factors of 2-5, which is theoretically predicted for marginally tearing stable plasmas. The poloidal velocity forms  $E \times B$  convection cells crossing the separatrix, which push particles into the vacuum region and reduce the pedestal density. Low toroidal rotation at the separatrix reduces the resonant field amplitudes, but does not strongly affect the particle pump-out. At higher separatrix rotation, the poloidal  $E \times B$  velocity is reduced by half, while the enhanced particle transport is entirely eliminated. The anticipated resonant field amplification in ITER and DIII-D are assessed with NIMROD dimensionless parameter scaling studies in conjunction with analytic error field theory.

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# Two-Fluid Nonlinear Magnetic Reconnection in the Presence of an Arbitrary Guide Field

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Many studies of 2-fluid (2F) magnetic reconnection have been performed by the space physics community to study the fundamental processes associated with solar flares and the earth's magnetopause. For two-dimensional studies, it has become standard to refer to the reconnecting magnetic field in the plane of the simulation as the “reconnecting field”, and the magnetic field in the direction of symmetry as the “guide field”. Early studies were performed without any guide field [1], but more recent work has included guide fields [2]. As the guide field is increased to values much greater than the reconnecting field, we better approximate the geometry and conditions applicable to reconnection in tokamak fusion experiments. Conventional tokamak experiments normally operate in what we call the “standard tokamak” regime:  $\delta \ll \rho_s \ll d_i$ ,  $\beta \ll 1 \sim \beta_p$ . Here,  $\delta = LS^{-1/2} \sim (L\eta)^{1/2}$  is the Sweet-Parker reconnection thickness,  $L$  is a typical equilibrium scale length,  $\eta$  is the plasma resistivity,  $S$  is the Lundquist number,  $\rho_s = c_s / \Omega_i = \sqrt{\beta} d_i$  is the ion Larmor radius,  $c_s = (T/M_i)^{1/2}$  is the ion sound speed,  $\Omega_{ci} = eB/M_i c$  is the ion cyclotron frequency  $d_i = c/\omega_{pi}$  is the ion skin depth,  $\omega_{pi}$  is the ion plasma frequency, and  $\beta$  and  $\beta_p$  are the plasma pressure normalized to the toroidal and poloidal magnetic field pressures, respectively. Our study seeks to clarify the following: (1) Under what conditions can we expect to see fast reconnection in the standard tokamak regime, (2) How does the reconnection rate scale with the parameters  $\delta$ ,  $\rho_s$ ,  $d_i$ ,  $\beta$ , and  $\beta_p$ , (3) What is the effect of density evolution on fast reconnection, and (4) How valid are reduced MHD equations in these regimes? We find that for small enough resistivity, reconnection rates are independent of the value of the resistivity but increase with  $d_i$ . However, all calculations require an effective hyper-resistivity  $H$  proportional to  $d_i$  in order to resolve the singularity at the x-point. The peak reconnection rate increases with decreasing  $H$ , but asymptotes to a value independent of  $H$ . The reconnection rate decreases with increasing guide field. If we include density evolution in the simulations, the decrease of the reconnection rate with the guide field strength is even more dramatic. This is partly explained by compressibility. Density depletes in the reconnection region for the small guide field case, increasing the local  $d_i$ , but not nearly as much when the guide field is increased. Increasing  $\beta$  increases the reconnection rate some but not greatly. These studies were done in 2D slab geometry with a complete 8-field 2F model. In order to relate to some previous studies, we have repeated some of the calculations with the reduced 4-field model. We find that the 4-field model does a fairly good job at reproducing the evolution at high guide field strengths, but is not as good at low field strengths. This work was supported by USDOE Contract no. DE-AC020-76-CH3073 and by the SciDAC Center for Extended MHD Modeling (CEMM)

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# Modeling of RF/MHD coupling using NIMROD and GENRAY

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We summarize recent theoretical and numerical work relevant to the development of a self-consistent framework for the inclusion of RF effects in fluid simulations. Specifically, we consider the stabilization of resistive tearing modes in tokamak (DIII–D–like) geometry by electron cyclotron current drive (ECCD), reporting on our efforts to self-consistently include the effects of the RF-induced current in the NIMROD code [C. R. Sovinec et al., *J. Comp. Phys.* 195, 355 (2004)]. Previous investigations [T. G. Jenkins et al., *Bull. Am. Phys. Soc.* 52, 131 (2007)], in which an ad hoc (non-self-consistent) model for this RF-induced current was used, have demonstrated that the nonlinearly saturated magnetic islands which arise from tearing modes can be markedly decreased in width by the RF. We generalize the model used previously to include nonaxisymmetric RF perturbations, investigating both the behavior of the magnetic islands as the ad hoc RF amplitude is modulated in time and the equilibration of the RF-induced currents over the plasma flux surfaces. Additionally, we present initial results obtained by the use of a more accurate physical model for the RF, in which the GENRAY and CQL3D codes are used to obtain accurate physical descriptions of RF propagation and deposition in the plasma.

This work was conducted as part of the SWIM project (online at [www.cswim.org](http://www.cswim.org)) and is funded by the U. S. Department of Energy.

# A systematic derivation of general closures for electron-ion plasmas\*

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## Abstract

A systematic approach for writing any number of moment equations is formulated for electron-ion plasmas. The distribution functions for electrons and ions are expanded in terms of orthogonal polynomials of random velocity variables in contrast to total velocity variables. The moments of the streaming part of the kinetic equation are explicitly written with simple formulas and a tractable version of the exact linearized Coulomb collision integrals is presented for like-species. The electron-ion and ion-electron operators that conserve momentum and energy are also calculated with a small-mass ratio approximation. In addition, a formalism for obtaining general closures from the moment equations is discussed for arbitrary collisionality. Parallel and perpendicular moment equations can be computed directly from the full moment equations and the parallel moment equations reduce to those developed from the drift kinetic equation in a strong magnetic field. Since the expressions for parallel and perpendicular moments are in coordinate-free geometric form, they can be used in any magnetic field configurations such as nested flux surface geometry and stochastic magnetic fields. A general method for solving the equations for any high order moments is explained. For plasmas with high collisionality in a strong magnetic field, the solutions provide the Braginskii closures with correction terms which are due to a more accurate treatment of collision operators and the streaming part. These corrections are important when estimating the valid range of Braginskii closures. The higher order moment solutions also provide a natural way to close more accurately the collisional friction and heating terms in the five fluid moment equations. The same method can be applied to finding general (integral) closures for arbitrary collisionality.

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### **Rotational shielding of resonant magnetic perturbations from an H-mode pedestal\***

I. Joseph, V.A. Izzo, R.A. Moyer, *UCSD*, T.E. Evans, T.H. Osborne, M.J. Schaffer, *General Atomics*, A.H. Boozer, M.S. Chance, J.E. Menard J.-K. Park, *PPPL*, M.F. Heyn, I.B. Ivanov, S.V. Kasilov, *EURATOM-ÖAW, ITP Graz, Austria*, A.M. Runov, R. Schneider, *MPI-Greifswald* – The application of resonant magnetic perturbations (RMPs) to an H-mode plasma can suppress edge localized modes by reducing the edge pressure gradient below the Type-I peeling-ballooning MHD stability threshold. An important paradox in the description of this process is that the RMPs produce large particle transport, but little thermal transport. Although the applied fields produce a stochastic band of overlapping islands in the infinitely resistive vacuum limit, the perturbations are predicted to be strongly modified by the near-ideal response of a collisionless plasma. Unless the perturbation induces large enough Lorentz braking forces at the resonant surfaces to overcome the force of viscous friction in the bulk plasma, a thin boundary layer of current will flow near the rational surface that will act to screen out the applied field. In single fluid theory, the plasma core, where the resistivity is small and large  $E \times B$  rotation predominates, is predicted to lie in the inertial limit where no actual reconnection can take place. Calculations using the NIMROD code show qualitative agreement with core screening, but the dimensionless parameters of the simulation lie in the visco-resistive limit and allow some amount of reconnection. Order unity resonant field amplification was observed in the simulation, demonstrating that such estimates can only be correct to order of magnitude. In theory, electron diamagnetic rotation is large enough to flow counter to the ions near the plasma edge in the standard DIII-D ELM suppression scenario, and this requires a two-fluid description of the plasma response. In fact, the width of the resonant current channel is predicted to become smaller than an ion gyroradius, requiring kinetic analysis. While two-fluid theory would predict a large torque on the ions, a kinetic model in a cylindrical plasma demonstrates that the electrons experience most of the torque. As the Lorentz force acts to brake the electron flow, the electrons accelerate the ions through the electric field. In fact, Carbon-VI impurity ions are observed to spin up during RMP application in a narrow region near the plasma edge. A phenomenological model of the magnetic plasma response has been developed by discarding the poorly known details of the non-ideal physics involved in the reconnection process. The Ideal Perturbed Equilibrium Code (IPEC) is used to describe the ideal MHD plasma interior and the VACUUM code is used to describe the resistive stochastic exterior. This two state model allows the boundary between the ideal and stochastic regions to be placed at an arbitrary point within the separatrix and can accurately account for resonant field amplification.

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# Arbitrary poloidal gyroradius effects in tokamak pedestals and transport barriers

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## Abstract

A technique is developed and applied for analyzing pedestal and internal transport barrier (ITB) regions in a tokamak by formulating a special version of gyrokinetics. In contrast to typical gyrokinetic treatments, canonical angular momentum is taken as the gyrokinetic radial variable rather than the radial guiding center location. Such an approach allows strong radial plasma gradients to be conveniently treated, while retaining zonal flow and neoclassical (including orbit squeezing) behavior and the effects of turbulence. The new, nonlinear gyrokinetic variables are constructed to higher order than is typically the case by generalizing the linear procedure of Lee, Myra and Catto [1]. The nonlinear gyrokinetic equation obtained is capable of handling such problems as collisional zonal flow damping with radial wavelengths comparable to the ion poloidal gyroradius, as well as zonal flow and neoclassical transport in the pedestal or ITB.

Our choice of gyrokinetic variables allows the toroidally rotating Maxwellian solution of the isothermal tokamak limit of to be recovered [2]. More importantly, we prove that a physically acceptable solution for the lowest order ion distribution function in the banana regime anywhere in a tokamak (and, in particular, in the pedestal) must be nearly this same isothermal Maxwellian solution. That is, the ion temperature variation scale length must be much greater than the poloidal ion gyroradius. Therefore, in the banana regime, the background radial ion temperature profile cannot have a pedestal similar to that of plasma density. This statement is what allows us to write the nonlinear gyrokinetic equation in a relatively compact form. More importantly, it has a direct consequence. Namely, it suggests that it will be difficult to sustain the strong background ion temperature variation needed to obtain an ion temperature at the top of the pedestal in the 2-4 keV range as assumed in ITER [3]. In addition, the absence of strong ion temperature variation implies an enhancement of the bootstrap current in the pedestal.

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# Impact of velocity space distribution on hybrid kinetic MHD simulation of the $(1, 1)$ mode

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Numeric studies of the impact of the velocity space distribution on the stabilization of  $(1, 1)$  internal kink mode and excitation of the fishbone mode are performed with a hybrid kinetic MHD model. These simulations extend the physics capabilities of NIMROD[C. R. Sovinec et al., “Nonlinear magnetohydrodynamics simulation using high-order finite elements”, JCP **195**, (2004)]—a three dimensional extended magnetohydrodynamic (MHD) code—to include the kinetic effects of an energetic minority ion species. Kinetic effects are captured by a modification of the usual magnetohydrodynamic (MHD) momentum equation to include a pressure tensor calculated from the  $\delta f$  particle-in-cell (PIC) method[S. E. Parker and W. W. Lee, “A fully nonlinear characteristic method for gyrokinetic simulation”, PFB 5, (1993)]. The particles are advanced in the self-consistent NIMROD fields. We outline the implementation and present simulation results of energetic minority ion stabilization of the  $(1, 1)$  internal kink mode and excitation of the fishbone mode. A benchmark of the linear growth rate and real frequency is shown to agree well with another code. Finally, the impact of the details of the velocity space distribution is examined; particularly extending the velocity space cutoff of the simulation particles and the impact of passing versus trapped particles. These details strongly impact the stabilization and excitation of the  $(1, 1)$  mode.

# Uniformly sheared $E \times B$ effect on ETG fluid dynamics

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Effect of linearly sheared  $E \times B$  flow on turbulence is investigated in Electron Temperature Gradient(ETG) fluid model (Horton et al. Nucl. Fusion 45, 2005) at nonlinear stages. The linear dynamics is well known to stabilize drift-wave and ETG modes in general. But our previous work (J. Kim et al. PoP 2007) showed that nonlinear dynamics can extract energy from the sheared flow into the vortex structures selectively. The fluid simulation based on the pseudospectral method and so-called shearing box method (Rogallo, 1982) enables us to investigate the nonlinear dynamics in sheared flow at a growth rate  $\gamma \gtrsim \omega_E$ . We analyze vorticity distribution functions and explain how the symmetry breaking by  $E \times B$  shear leads to the skewness of the distribution. Kelvin-Helmholtz driven drift wave is shown to have the positively skewed vorticity distribution function as the background vorticity (J. C. Perez et al. PoP 2006).

And we present the electrostatic and electromagnetic heat flux scalings based on the fluid simulation with the broad range of the parameter scan. The ETG gyroBohm scaling  $\rho_e v_{te}/L_{Te}$  is modified in details and we will revisit our previous analysis (S. Kaye et al, Nuclear Fusion, 2007 and Elina et al., draft).

# Numerical Studies of Two Fluid Tearing Modes in Slab and Cylindrical Geometries\*

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The NIMROD code is used to run two-fluid computations that are relevant to magnetic relaxation in RFPs and other magnetically confined configurations. Linear two-fluid tearing-mode computations in slab geometry are benchmarked with analytical results [1] in different large guide field regimes. Scans of beta (sound gyroradius) and the tearing stability parameter are presented. Growth rates agree with the two-fluid slab analytics to within a half percent in the limit of small resistive layer width for a 120x14 bicubic finite element mesh with mesh packing around the rational surface. With the two-fluid model, the growth rate is 2.5 times larger than the MHD model at large sound gyroradius, and the two-fluid model converges to the MHD growth rate in the small gyroradius limit. Recent computations include a pressure profile to consider drift-tearing behavior. Nonlinear tearing results without drift are characterized with respect to current-profile relaxation. The Hall dynamo, the Rutherford stage, and the onset of saturation are investigated.

Cylindrical cases with parameters relevant to the Madison Symmetric Torus RFP are compared to existing analytics and are used to investigate two-fluid effects that distinguish results from the resistive MHD model. The two-fluid modifications of the mode structure are explained with qualitative theoretical reasoning. Mode rotation, introduced by the two fluid effects in cylindrical geometry, is seen when the sound gyroradius is larger than the resistive layer. An estimation of the resolution requirements for multi-helicity nonlinear computations is also presented.

\*Supported by the U.S. Dept. of Energy.

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# Plasma Turbulence and Transport in a Ring Dipole System

Sumire Kobayashi

Gyrokinetic GS2 simulations of plasma turbulence and particle and heat transport in a dipole magnetic field geometry created by a ring current are presented. These simulations are relevant to the levitated dipole experiment (LDX) at MIT, and also have potential applications to magnetospheric dipole fields. In addition to ideal interchange and ballooning modes, a non-MHD mode known as the entropy mode is present in this system. The entropy mode has a scale length smaller than ideal modes (eg,  $k_{\perp} \rho_i \sim 1$ ) but comparable growth rates. Considering parameter regimes that are ideally stable, we explore the physics of turbulent transport generated by a entropy mode, finding enormous variation in the nonlinear dynamics as a function of the density and temperature gradients and the plasma collisionality. This variation is explained in part by the damping and stability properties of spontaneously formed zonal flows in the system.

## Electromagnetic high frequency gyrokinetic particle-in-cell simulation in magnetically-confined plasmas.

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

Using the gyrocenter-gauge kinetic theory, we developed an electromagnetic version of the high frequency gyrokinetic algorithm [1, 2] for particle-in-cell (PIC) simulation of plasma heating and current drive with RF waves. Gyrokinetic formalism enables separation of gyrocenter and gyrophase motions of a particle in a magnetic field. From this point of view, a particle may be viewed as a combination of a slow gyrocenter and a quickly changing Kruskal ring. The efficiency of the algorithm is due to the fact that the simulation particles are advanced along the slow gyrocenter orbits, while the Kruskal rings capture fast gyrophase physics. The nonlinear dynamics of RF waves is described by the Kruskal rings based on first principles physics. Self-consistent simulation is performed by solving Faraday's and Ampere's laws using Yee's algorithm together with the locally implicit method [3]. We performed a number of simulations of electromagnetic wave propagation in hot inhomogeneous plasmas using new nonlinear delta-f PIC algorithm. Comparisons with a direct Lorentz-force approach are presented. This work is supported by the MSG project (U.S. DoE ASCR Multiscale Mathematics Research and Education Program).

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# Field ripple induced Alpha Particle losses in ITER\*

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(Dated: January 30, 2008)

## Abstract

Alpha particles in ITER should be confined well during the burn phase and not lost due to the effects of magnetic field ripple. The toroidal field ripple in ITER is small, 0.2% or less, but the insertion of three test blanket modules (TMB) increases the field ripple. In this presentation we show that for two standard ITER scenarios the alpha particle losses are small when no TBMs are present but that significant hot spots appear when TBMs are inserted, especially during low current high  $q$  operation. For this study we have used the full Lorenz orbit SPIRAL code to calculate the alpha particle loss distribution at the plasma boundary and the guiding center ORBIT code<sup>a</sup> to estimate the total losses.

\* Work supported by DoE contract No. DE-FG03-94ER54271.

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# Natural selection: pruning the Darwin approximation

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There are two basic approaches to the Darwin system, the order- $(v/c)^2$  approximation to the relativistic interaction of classical charged particles. The first solves the Maxwell equations in Coulomb gauge and then approximates the vector potential to remove retardation effects. The second approach approximates the Coulomb gauge equations themselves, then solves these exactly for the vector potential. A priori these need not result in the same approximation. Here the equivalence of these two approaches is investigated and a unified framework provided in which to view the Darwin approximation. Darwin's original treatment is variational in nature, but subsequent applications of his ideas in the context of Vlasov theory are not. We present here action principles for the Darwin approximation in the Vlasov context, and this serves as a consistency check on the use of the approximation in this setting.

**Modeling of the Plasma Response to Resonant Magnetic Perturbations with the NIMROD Code** S.E. KRUGER, Tech-X Corporation, D.D. SCHNACK, UW-Madison, E.D. HELD, USU, T.E. EVANS, General Atomics, R.A. MOYER, UCSD — Resonant magnetic perturbations (RMPs) have successfully been used to control ELMs in the DIII-D tokamak.<sup>1</sup> In these experiments, internal coils are used to tailor the mode amplitude spectrum at the separatrix with the goal of affecting transport at the edge. Intuitively, inducing islands at the separatrix would cause a stochastic edge and enhanced electron temperature transport; however, experimental evidence shows that temperature gradients are relatively unchanged, while the density gradient is substantially reduced. Modeling of these experiments by initial-value extended magnetohydrodynamics codes is attractive because the essential features; magnetic reconnection, parallel and perpendicular transport, and ELM stability; have all been independently studied with these codes. Here we show results of modeling just the the field error penetration problem. We extend the numerical simulations of Fitzpatrick<sup>2</sup> to three-dimensional geometry, two-fluid physics, and anisotropic viscosity.

<sup>1</sup>R. A. Moyer, T. E. Evans, T. H. Osborne, et al., *Phys. Plasmas* **12** (2005) 056119

<sup>2</sup>Fitzpatrick, *Physics of Plasmas*, **10** (2003) 1782

# Surprising new physics from Full-f particle simulation of ITG turbulence in a tokamak geometry<sup>1,2</sup>

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Kinetic ITG (ion temperature gradient) turbulence has been considered to be one of the main sources of anomalous transport in tokamak plasmas. Most of the known properties of the ITG turbulence have been obtained from delta-f gyrokinetic simulation technique, which assumes given background plasma. The marker particles then represent the turbulent perturbations driven by the ion temperature gradient, according to the delta-f gyrokinetic equation. The ordering approximations used in reducing the delta-f equation from a full-f equation include questionable terms, such as the velocity space nonlinearity term, which has been a cause controversy in the last several years. The growing weight in the delta-f simulation has been another source of controversy.

We report a new gyrokinetic ITG simulation result from a full-f gyrokinetic code XGC1, using adiabatic electrons. In the physics sense, a full-f gyrokinetic code is simpler and can overcome many of the delta-f problems. In the computational sense, however, a full-f simulation is more difficult to realize. A full-f code can include the interaction of the turbulence with the background plasma self-consistently. A full-f code does not order out the v-space nonlinearity term. In XGC1, the combination of background  $E_r$  and the zonal  $E_r$  together dynamically balances the radial pressure from the plasma as the plasma temperature relaxes with the turbulence transport. XGC1 in full-f mode finds that the ion heat conductivity is smaller than that from the XGC1 delta-f mode due to the turbulence interaction with the background plasma. This may bring the ion heat conductivity closer to the experimental values than what has been known from many delta-f simulations. In fact, the immediate generation of the background  $E \times B$  shearing acts on the ITG even in the linear stage, before the action by zonal flows begin, completely changing the turbulence dynamics paradigm. Careful comparison of the new results with the known delta-f ITG results in the cyclone geometry will be presented, followed by predictions in the real tokamak geometry. Application to the edge plasma will also be discussed.

<sup>1</sup>In collaboration with H. Weitzner, L. Greengard, NYU, and the SciDAC FSP Prototype Center for Plasma Edge Simulation team

<sup>2</sup>Work supported by US DOE OFES and OASCR.

## **Delta-f and full-f hybrid particle in cell scheme for the neoclassical simulation of tokamak plasmas**

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Although the delta-f simulation method is extensively used as one of the essential tools for the kinetic simulation of the core plasmas with mild gradient in tokamak geometry, its application in the steep gradient region is limited for various numerical problems. On the other hand, the full-f simulation scheme provides a way to deal with the steep gradient plasmas though its application in the mild gradient region requires more simulation particles compared to the delta-f method. In this work, we develop a hybrid particle in cell scheme combining both the delta-f method for the core and the full-f method for the edge to cover whole tokamak plasma. Unlike tracking a full-f particle weight which is constant along the particle's trajectory, the delta-f method requires information of the perturbed particle's weight against a certain assumed distribution function. Therefore, a way to determine the perturbed weights of particles moving from the full-f region to the delta-f region is needed. In this work, a 4D simulation grid is setup in the overlapping region of the delta-f and the full-f simulation domain and delta-f weights of the particles in this region are computed using the least square fitting method on this grid. We demonstrate that essential neoclassical phenomena of both the core and the edge plasma with steep pedestal like profiles can be simulated within a single simulation framework. Statistical issues in joining the two domains with different simulation methods will be also discussed.

# Confinement Regime Transition: Spontaneous Rotation Reversal and Collisionality of the Plasma Edge\*

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The main observations that are consistent with the accretion theory [1] of the spontaneous rotation phenomenon include: i) the reversal of the direction of rotation in the transition from the L- to the H confinement; ii) the propagation of angular momentum from the outer edge toward the center of the plasma column during the L-H transition; iii) the strong effects of the magnetic field topology of the outermost magnetic surfaces and of the edge plasma regimes on the magnitude and direction of the spontaneous rotation; and iv) the intrinsic connection between spontaneous rotation and the plasma transport properties. The change from co- to counter-current rotation in the transition from L- to H-regime confinement is associated with the reversal of the phase velocity of modes, at the edge of the plasma column, that eject angular momentum from it. In the H-regime the collisional ballooning mode, which is driven by the combined effects of the plasma pressure gradient and of magnetic curvature and has a toroidal phase velocity in the direction of the electron diamagnetic velocity, is considered to be prevalent. The mode phase velocity changes its sign when the edge collisionality increases and the local pressure gradient decreases in connection with the H→L transition. The condition for the reversal of the phase velocity is related to the effect of the transverse viscosity affecting the relevant poloidal flows. In fact, this effect led [2] to the first experimental identification of (collisional) drift modes by a (linear) Q-machine, where the transition marked the switch-off and on of modes with different mode numbers in regimes where the collisional (ion-ion) viscosity was important. On the other hand, since in current toroidal plasma experiments the ion gyroradius is much smaller than in Q-machine experiments, an anomalous ion viscosity for poloidal flows has to be considered to justify the transition when the relevant plasma parameters are taken into account. An alternative to this option is that a collisional impurity driven mode [3], that has a phase velocity in the ion diamagnetic velocity direction, becomes prevalent over the plasma pressure gradient driven ballooning mode.

\*Sponsored in part by the US D.O.E. and the N.S.F.

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# Gyrokinetic simulation of energetic particle turbulence and transport

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The fully self-consistent simulation of energetic particle turbulence and transport In a burning plasma such as ITER must incorporate three new physics elements: kinetic effects of thermal particles at the thermal ion gyroradius  $\rho_i$  (*micro* scale), nonlinear interactions of a large number of the shear Alfvén wave (SAW) modes at the energetic particle gyroradius  $\rho_{EP}$  (*meso* scale), and *meso-micro* cross-scale couplings of the microturbulence and SAW turbulence. The large dynamical ranges of spatial-temporal processes further require global simulation codes that are efficient in utilizing massively parallel computers at the petascale level and beyond. Therefore, the studies of energetic particle physics in ITER burning plasmas call for a paradigm shift to the gyrokinetic turbulence approach. In this paper, the rationale and the progress of the gyrokinetic simulation of energetic particle turbulence and transport will be summarized. In particular, the gyrokinetic simulation of the global Alfvénic waves driven by the energetic particles has been performed using the GTC code. In the simulation, continuum damping of the shear Alfvén wave is demonstrated and a frequency gap due to the toroidal effects is generated. In the presence of the energetic particles, the excitation of the toroidal Alfvén eigenmode (TAE) is observed. The range of the most unstable toroidal modes is identified in a size scan from the existing tokamak to the ITER.

Work supported by SciDAC GSEP Center, DOE cooperative agreement DE-FC02-08ER54976.

# 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 high aspect ratio tokamak plasma is presented. We examine islands whose characteristic widths are larger than the ion gyro radius but comparable to the ion banana width for a thermal particle. In this regime, the trapped ions do not respond to the island electrostatic potential and helical magnetic geometry to lowest order due to the banana drifts. When solving the drift kinetic equation for ions, a change in coordinates is used to account for this behavior. A bounce averaging procedure is developed to separate out and solve the lower order distribution function. A two-fluid model is used to determine the electrons response. An iteration procedure is introduced to calculate the potential, which is shown to be a combination of functions of the helical flux surfaces and the topologically toroidal flux surfaces. The contribution to the perturbed current is composed of the helical flux surface-averaged bootstrap current and parallel current that arises in response to the kinetic ions. The parallel current ( $J_{||}$ ) is calculated and used in a modified Rutherford equation, and the island width evolution equation is determined. A pair of self-consistent equations for the island width,  $w$ , and its rotation frequency,  $\omega$ , is to be derived. The results are to be compared with calculations for large island width so as to yield a description of magnetic island width evolution from sub-banana width to macroscopic scale lengths.

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# Hierarchical Fluid Models and Plasma Simulation

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A variety of plasma fluid models exist for modeling plasma dynamics. In this talk we outline our efforts in modeling fast high energy density plasmas including Z-Pinches and FRCs. At the highest level the fluid models take into account gyroviscous effects through the 10 moment model. Addition of collisions thermalizes the distribution to produce a Two-Fluid model. Neglect of ion inertia result in the well known Hall MHD system which is used to model ion demagnetization effects. Finally, dropping the Hall term in Ohms law results in the ideal MHD system. It's easy to show theoretically where each fluid plasma model is valid, though it's interesting to observe the effect of each term in nonlinear simulations. Simulations of plasma dynamics phenomena will be performed across regimes. This simulation help illustrate the effects that are neglected when reduced models are used and also illustrate regimes where higher fidelity models are computational overkill. The results presented are a compilation of work performed by the authors over the years with new results presented that demonstrate a new fluid plasma modeling tool developed at Tech-X.

# Transport of Parallel Momentum by Waves and Particles in Collisionless Electromagnetic Turbulence

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Recent experimental results [1,2] indicate that the phenomenology of momentum transport bifurcations (MTB) and the buildup of spontaneous rotation is much richer than initially thought [3]. We present a new theoretical approach which accounts for these new developments and also makes novel concrete predictions. A mean field calculation of the resonant particle momentum flux coupled to an energy-momentum conserving wave kinetic equation (for quasi-particles) relates the resonant particle momentum, wave momentum (usually neglected in transport modelling), and refractive force. Thus, spontaneous rotation in a region can occur either by wave or resonant particle momentum in/out flow to/from that region.

In this work we distinguish two cases from the general theory of gyrokinetic modes developed. The first case considered corresponds to drift wave turbulence in the low beta limit. Since away from marginality, the resonant particle contribution is usually small, we concentrate primarily on transport induced by radial fluxes of wave momentum. This component is calculated from the wave kinetic equation via a procedure analogous to a Chapman-Enskog expansion [4], as in radiation hydrodynamics. We find that both intensity gradients in the wave population, as well as electric field shearing are capable of driving a net radial flux of parallel momentum, the latter entering as a product with a factor of  $\partial V_{gr}/\partial k_r$ , and thus explicitly dependent on the mode phase velocity. This introduces two distinct classes of MTBs: strong  $\mathbf{E} \times \mathbf{B}$  shearing introduced via a transport bifurcation, or a flip in the mode propagation direction.

The second case considered is that of kinetic shear Alfvén waves (KSAW). Here we find that dispersion due to finite Larmor radius corrections, coupled with the mean profile gradients, allow for a radial flux of KSAW momentum. A net imbalance in the parallel propagating KSAW populations (i.e. unequal Elsasser populations  $N_+$ ,  $N_-$ ), can thus induce a net radial transport of parallel momentum carried by waves. Since KSAWs are generated by mode conversion of TAEs on small scales, this suggests a novel momentum transport channel for future burning plasmas.

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# On Possibility of Fizeau Interferometry In High Temperature Magnetized Plasma \*

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The phase velocity of electromagnetic waves propagating through a substance depends on whether they propagate in a moving or stationary medium. This well-known Fizeau effect was proposed for interferometric measurement of electron current density in plasma [1]. Indeed, in the case of a high frequency electromagnetic wave, the plasma dielectric response is dominated by the electrons. Correspondingly, the velocity of the medium is associated with the electron flow velocity so that the Fizeau measurement of this characteristic can be linked with the electron current circulating in plasma.

In the case of cold unmagnetized electrons, the plasma refraction index  $N^2 = 1 - X$  depends on the wave frequency  $\omega$  via the factor  $X = \omega_{pe}^2/\omega^2$ . Due to specific  $\omega^{-2}$  scaling, the phase velocity of the wave turns out to be insensitive to the electron flow velocity [2]. Any deviation from this scaling may result in phase velocity dependence on the electron flow velocity. The purpose of our study is to analyze all possible mechanisms that can make the Fizeau effect measurable. We evaluate the phase difference caused by the Fizeau effect and relate it to the experimental high-resolution, vertically viewing far-infrared polarimeter-interferometer system that is currently used on the Madison symmetric torus (MST) reversed field pinch (RFP). More specifically, the calculations include the effect of motion of the plasma-vacuum interface, corrections caused by electron gyrorotation, and the influence of the finite electron temperature on dispersive properties of the wave.

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# Ray tracing of Ideal Ballooning Modes in Boozer Coordinates

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## Abstract

We report on initial efforts to examine ray tracing for ideal ballooning modes in stellarators using results from the Boozer coordinate based COBRA stability code. Previously [1], we have examined ray tracing of ideal ballooning modes in VMEC [2] coordinates using the COBRAVMEC stability code [3]. These calculations use stellarator coordinates,  $(\iota, \theta, \zeta)$ , where  $\iota$  is the rotational transform and  $\theta$  and  $\zeta$  are the VMEC poloidal and toroidal angles, respectively. The ray tracing techniques introduced by Dewar and Glasser [4] require solution of the ballooning eigenvalue,  $\lambda$ , over a range of parameters. In stellarator coordinates, these parameters are  $\lambda = \lambda(\iota, \alpha_S, \zeta_k)$  where  $\alpha_S = \theta - \iota\zeta$  is a field-line label and  $\zeta_k = k_t/k_\alpha$  is the ballooning parameter in these coordinates. In order to make comparisons with previous work, we seek solutions using tokamak coordinates,  $\lambda = \lambda(q, \alpha, \theta_k)$ , where  $q = 1/\iota$ ,  $\alpha = q\theta - \zeta$  is a field-line label, and  $\theta_k = k_q/k_\alpha$  is the ballooning parameter in tokamak coordinates. This is not possible with VMEC coordinates because VMEC coordinates are not straight-field line coordinates. Since most stellarators have a dominant toroidal magnetic field, the VMEC toroidal angle is a single-valued coordinate along a field a line while the poloidal angle is not. Thus, it becomes necessary to solve the ideal ballooning in straight-field line coordinates such as Boozer coordinates,  $(\iota, \theta_B, \zeta_B)$ . We discuss modifications of the COBRA code and initial results in applying it to two stellarator configurations: the Helically Symmetric Experiment [5] and the Quasi-Poloidal Stellarator [6].

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# Hamiltonian formulation and analysis of a collisionless fluid reconnection model

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The Hamiltonian formulation of a plasma four-field fluid model that describes collisionless reconnection is presented. The formulation is noncanonical with a corresponding Lie-Poisson bracket. The bracket is used to obtain new independent families of invariants, so-called Casimir invariants, three of which are directly related to Lagrangian invariants of the system. The Casimirs are used to obtain a variational principle for equilibrium equations that are a generalization of the Grad-Shafranov equation to include flow. Dipole and homogeneous equilibria are constructed. The linear dynamics of the latter is treated in detail in a Hamiltonian context: canonically conjugate variables are obtained; the dispersion relation is analyzed and exact thresholds for spectral stability are obtained; the canonical transformation to normal form is described; an unambiguous definition of negative energy modes is given; and thresholds sufficient for energy-Casimir stability are obtained. The Hamiltonian formulation also is used to obtain an expression for the collisionless conductivity and it is further used to describe the linear growth and nonlinear saturation of the collisionless tearing mode.

## **Anisotropic pressure for calculations of shielding**

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A nonaxisymmetric magnetic perturbation in a tokamak produces corresponding currents and transport<sup>1,2</sup>, which modify the plasma equilibrium<sup>3</sup>, and can result in plasma shielding of the perturbation<sup>1</sup>, up to some threshold level. In Ref.1, the contribution to this effect from Coriolis terms in a slab was studied. In the present work, we obtain analytic expressions for the contribution from the pressure anisotropy in a tokamak produced by the perturbation. Flux-surface averaging these expressions gives rise to earlier results<sup>4,5,2</sup> for “banana-drift” radial currents. The unaveraged expressions obtained here are needed to compute the perturbed currents, magnetic field, and shielding threshold from this effect, and may be used in a perturbed mhd equilibrium code, such as the IPEC code<sup>6</sup> now under development.

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# Linear Analysis Tools for Edge and SOL Plasmas\*

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The edge and scrape-off-layer region of a tokamak plasma is subject to well known ideal and resistive instabilities that are driven by various curvature- and sheath- related mechanisms. While the boundary plasma is typically strongly turbulent in experiments, it is useful to have computational tools that can analyze the linear eigenmode structure, predict quantitative trends in growth rates and elucidate the underlying drive mechanisms. Furthermore, measurement of the linear growth rate of unstable modes emerging from a known, established equilibrium configuration provides one of the few quantitative ways of rigorously benchmarking plasma turbulence codes with each other and with a universal standard. Because the tokamak edge physics community is becoming increasingly reliant on large-scale-simulation, rigorous verification and validation (V&V) of edge codes is critical.

In this paper, we describe a suite of codes that can describe linearized, nonlocal (e.g. separatrix-spanning) modes in axisymmetric (realistic divertor), toroidal geometry. The suite consists of (i) the BOUT 3D fluid turbulence code, here run with the nonlinear terms turned off, and (ii) a new linear eigenvalue code for the boundary plasma, 2DX, under development. Results of several benchmark comparisons are given for these codes, with each other and with analytical results. These results extend earlier verification studies for BOUT<sup>1</sup>, provide verification of 2DX and are a step towards the creation of accepted verification standards for edge turbulence codes.

Additionally, the 2DX code structure and development is discussed. A method, and sample results for including kinetic physics models are presented, together with future development plans, and potential applications such as edge MHD with two-fluid or kinetic effects and quasilinear fluxes.

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# Vortex Structures and Transport Reduction in Gyrokinetic Simulations of Slab Electron Temperature Gradient Turbulence

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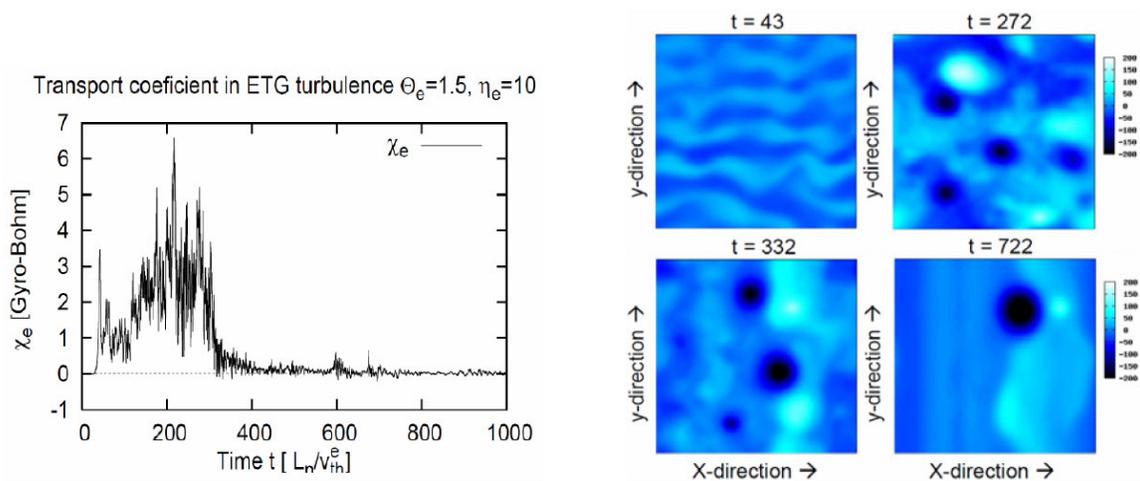
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The electron temperature gradient (ETG) turbulence is considered as one of the possible candidates causing the anomalous electron heat transport in a core region of magnetic fusion plasmas. Although the ETG mode with the adiabatic ion response is isomorphic to the ion temperature gradient (ITG) mode, the nonlinear evolution of the ETG instability is totally different from the ITG turbulence that is largely affected by the self-generated zonal flows, and is still an open question.

In this study we have carried out gyrokinetic Vlasov simulations of the ETG turbulence in a two-dimensional slab geometry, and have found spontaneous transition of the ETG turbulence accompanied with significant reduction of the electron heat flux. In the early nonlinear phase of the ETG instability, potential fluctuations observed in a wide wavenumber range cause a high-level heat transport. Then, we see the transition from high to low transport levels, where the turbulent heat flux is decreased about an order of magnitude. A coherent potential structure with large amplitude is formed by merging of vortices, and survives long time after the transition. For a certain parameter range near the marginal stability of the ETG mode, we have also found a regular flow pattern with ranging vortices in the nonlinear saturation phase of the instability. More detailed results of the ETG simulations will be reported at the conference.



Time-history of the electron heat flux (left) and color contours of the electrostatic potential resulted from the gyrokinetic Vlasov simulations of the slab ETG turbulence.

# Roles of shear Alfvén wave on micro-turbulence transport in global gyrokinetic particle simulation

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Anomalous particle and heat transport in magnetized fusion plasma in the electrostatic limits have been studied extensively by three dimensional gyrokinetic turbulence simulations. In the presence of magnetic perturbations, there exist new branches of modes, for example, toroidicity induced Alfvén eigenmodes (TAEs), Alfvénic ion temperature gradient (AITG) modes, and kinetic ballooning modes (KBM), that can play important roles in plasma turbulence and transport. The fluid-kinetic electron hybrid model [1] for simulations of the electromagnetic turbulence in global tokamak plasmas [2] is extended to treat zonal flows and zonal fields in the toroidal geometry for fusion applications. The full torus electromagnetic gyrokinetic particle simulations [3] using the hybrid model with kinetic electrons in the presence of magnetic shear is presented. Formation of the zonal flows, the zonal fields, and the transport regulation mechanism are investigated. Furthermore, the gyrokinetic simulation of the global Alfvénic waves driven by the energetic particles has been performed using the GTC code. In the simulation, continuum damping of the shear Alfvén wave is demonstrated and a frequency gap due to the toroidal effects is generated. In the presence of the energetic particles, the excitation of TAE is observed. The range of the most unstable toroidal modes is identified in a size scan from the existing tokamak to the ITER. This work is supported by DOE SciDAC centers GPS-TTBP and GSEP, DOE cooperative agreement DE-FC02-08ER54976.

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# Energy release in Magnetic Reconnection with Chaos Diffusion

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## Abstract

New results are presented for the energy inflow and conversion from magnetic energy to kinetic energy and thermal energy. As a guide we use the two components Harris sheet-like simulation of Horton et al. PoP 2007 where approximately 50% of the reversed field magnetic energy ends up in the electron thermal energy and the electron parallel flow energy in the exhaust fans. For this classical reconnection geometry we have developed a PIC code called PASMO (PARTicle Simulation code for Magnetic reconnection in Open systems). The simulations show the influence of both in the incoming and outgoing boundary conditions on the rate of reconnection. The conditions for the internal modes in the space physics plasmas and the tokamak are discussed. The simulations can study both of cases without or with a guide field. The base case for fast reconnection is without guide field and with plasma compression. In the case without a guide field the particle orbits become chaotic and the role of the divergence of the off-diagonal momentum stress tensor is shown to be of critical importance in the hydrodynamical description of the kinetic processes of energy conversion. Outgoing velocity distributions are shown in detail along with their fluid moments up to and including the heat fluxes. In the case with a guide field, the quadrupole structure of magnetic field is not clearly presented because the guide field cancels the opposite component of quadrupole magnetic field, and the spatial structure of current sheet becomes longer and asymmetric. The pressure tensor is generated due to this asymmetry, and accelerates the electron toward downstream.

Work supported by Grant-in-Aids for Scientific Research (No. 18340188) and for Young Scientists (B) (No. 19740346) from the Japan Society for the Promotion of Science (JSPS), and the Research Cooperation Program on “Hierarchy and Holism in Natural Sciences 2” at National Institutes of Natural Sciences, and the Department of Energy and the National Science Foundation grant ATM 200502484.

# A particle code for the mixing efficacy problem of advection-diffusion models with sources and sinks

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The mixing efficacy or stirring effectiveness of a flow can be quantified in terms of the suppression of concentration variance of a passive scalar sustained by steady sources and sinks. The mixing efficacy defined this way is the ratio of the scalar variance mixed by molecular diffusion alone to the (statistically steady state) variance in the presence of stirring. This measure of the effectiveness of the stirring is naturally related to the enhancement factor of the equivalent eddy diffusivity over molecular diffusion. This mixing efficacy naturally depends on the Peclet number, but it was recently noted that the maximum possible mixing efficacy at a given Peclet number depends as well on the structure of the sources and sinks. That is, in general it does not make sense to talk about the mixing effectiveness or eddy diffusion of a flow without also specifying the source-sink structure of whatever is being stirred. We present the results of particle-based numerical simulations quantitatively confirming the source-sink dependence of the mixing efficacy as a function of Peclet number for a model flow.

# GEM Simulation of Energetic Particles Driven Modes

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## Abstract

The GEM code [1, 2], with kinetic electrons and electromagnetic perturbations implemented for equilibria of shaped magnetic flux surfaces, can in principle be used to study energetic particles driven MHD modes such as the Toroidicity-Induced Alfvén Eigenmodes. Using a low- $n$  global TAE as a test case [3], the GEM simulation does indeed show the existence of a global discrete eigenmode. However, the observed frequency ( $0.35\Omega_A$ ) is below the expected TAE frequency ( $0.5\Omega_A$ ). We suspect that the discrepancy is caused by the nonzero parallel electric field in GEM, which is likely amplified due to the reduced proton-to-electron mass ratio ( $m_p/m_e = 500$ ) used in GEM simulations of MHD scale modes. We are currently studying the same problem with a hybrid model with gyrokinetic ions and massless fluid electrons, implemented in GEM. The fluid electron model consists of the electron continuity equation, parallel Ohm's law and a closure equation for the electron temperature. This model can be reduced to the exact MHD eigenmode equation when electron pressure is neglected in the Ohm's law, making a direct comparison with MHD results possible. GEM shows the existence of the low- $n$  global TAE eigenmode. Additionally, the transient high frequency continuum mode branches are observed and the low- $n$  global eigenmode is within the gap. Work is underway, to benchmark the gap and continuum frequencies with an eigenmode analysis. Including an energetic particle species results in a different mode with different mode characteristics, which appear to be an Energetic-Particle-Driven (EPM) mode. In this presentation we will further characterize the observed eigenmodes - with fluid electrons and with energetic particles - and attempt to resolve the discrepancy between observations and theoretical predictions.

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# Shear-flow-driven Alfvénic fluctuations in the Large Plasma Device

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The generation of Alfvénic fluctuations in the presence of sheared flows is investigated through theory, simulation and experimental data from the Large Plasma Device (LAPD). The LAPD is an 18 m long, 1 m diameter cylindrical vacuum chamber surrounded by a number of magnetic field coils properly positioned to create a fairly uniform axial magnetic field with  $\delta B/B < 0.5\%$ . Previous work have been devoted to the study of electrostatic fluctuations driven by a combination of Kelvin-Helmholtz and Drift Wave instabilities. Sheared rotation is achieved in the LAPD by  $\mathbf{E} \times \mathbf{B}$  flows, created by a localized radial electric field at the edge of the cylindrical plasma column. In this work we report new measurements and analysis of the magnetic fluctuation data, in the sheared rotation experiments, that shows Alfvénic-like behaviour. Linear and nonlinear two-fluid simulations are presented that establish the relation of the magnetic fluctuations with the KH and DW instabilities associated to the flow and density inhomogeneities. Comparisons between the experiments and the simulations are discussed.

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# Modeling of hydrogen inventory and plasma-wall coupling

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Sophisticated integrated modeling tools are needed for assessment, prediction, and control of plasma transport, power load handling, wall erosion and re-deposition processes, migration of eroded material, and tritium retention and transport in wall material in ITER and future magnetic fusion reactors. However, so far there is very limited experience in the coupled plasma-wall modeling. For these reasons, the main focus of our work is on the study of synergetic effects in the coupling of particle and energy transport processes in plasma and wall regions.

In this work we are using newly developed transport code - the Wall and Plasma-Surface Interaction (**WallPSI**) - to calculate the wall temperature, erosion rates, and concentration of absorbed, mobile and trapped particle species in the wall material. The code incorporates new approach in modeling of stimulated release of hydrogen, chemical erosion and RES processes, and saturated wall condition based on the surface directed stimulated convection in the implantation region. We also developed the 1-D plasma transport code Edge1D (which mimics the radial plasma transport in tokamaks by solving equations: for plasma and neutral densities and for electron, ion and neutral temperatures) and performed coupling of WallPSI and Edge1D codes.

As a first step, we simulated with WallPSI the hydrogen transport in the wall impacted by plasma at high and low wall temperatures and for various materials (C, Be, W). Wall saturation time, wall pumping efficiency, mobile and trapped hydrogen inventories, and permeation properties for different materials and plasma conditions will be reported and the role of stimulated convection in wall saturation and in dynamics of chemical erosion will be highlighted.

Next, as has been recently shown in [1], interactions of plasma with hydrogen-saturated wall can cause thermal instabilities resulting in massive release of gas from walls. Improved analytical models describing the plasma-wall coupling instabilities will be presented. In more detailed studies of plasma-wall coupling and featured instabilities, we use WallPSI coupled to Edge1D. Modeling shows that without external stabilizing loop (e.g. gas puffing/pumping) the plasma evolution can end up with plasma-wall instability resulting in either formation of MARFE or high-temperature low-recycling edge plasma.

Finally, we note that the **WallPSI** module is used in ongoing SciDAC project on Framework Application for Core-Edge Transport Simulations (FACETS). Initially this work includes coupling of core transport codes, 2-D edge-plasma multi-fluid transport code UEDGE, and WallPSI. Recent report on the progress toward integrated modeling can be found in [2].

This work was supported by U.S. Department of Energy under grants DE-FG02-04ER54739 and DE-FC02-07ER54908 at University of California, San Diego.

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# Global Magnetorotational Instability with Density Gradients

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## Abstract

The magnetorotational instability (MRI) is an important mechanism for the transfer of angular momentum in rotating astrophysical systems such as accretion disks. The standard MRI dispersion relation is drawn from a local analysis, but can be misleading when the radial wavelength is comparable to the equilibrium scale size. We examine global incompressible perturbations of a differentially rotating MHD plasma with radial density gradients. If the equilibrium magnetic field is either purely axial or purely toroidal, axisymmetric modes can be found as global radial eigenvalues of an effective potential. We show that the standard Keplerian profile including the origin is mathematically ill-posed, and thus any solution will depend strongly on the inner boundary. A class of unstable ‘cavity’ modes are found to be localized by the form of the rotation and density profiles, with reduced dependence on boundary conditions. These results are extended to non-axisymmetric perturbations and to helical equilibrium field profiles. Consequences for the nonlinear regime are also investigated.

## The FACETS Core Solver

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Started in 2007, the SciDAC project for the development of a Framework Application for Core Edge Transport Simulation (FACETS) aims at producing tokamak core-to-wall transport simulations on massively parallel architectures. FACETS integrates the best software components available from the fusion and applied mathematics communities. Here, we report on the progress of developing a parallel, implicit, PETSc based solver for advancing the electron/ion densities and temperatures in the plasma core. Owing to electron/ion temperature gradient driven turbulent fluxes, the equations are both highly stiff and nonlinear. Developing numerical methods that are sufficiently robust to cope with the core equations remains a numerical challenge, which we are addressing by using adaptive time stepping and a V path multigrid approach. Leveraging on the flexibility of the FACETS infrastructure, which allows one to assemble a solver at run time, we evaluate different time stepping schemes (backwards Euler, time centered and modified Crank-Nicholson) by comparing their stability, accuracy, and their overall performance. Initial benchmark results against the ASTRA code using fluxes from the transport model GLF23, as well as scaling results in the number of processors are shown. \_\_\_\_\_

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## Analysis Methods for Trim Coils in NCSX

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The traditional approach for designing trim coils for nulling magnetic perturbations that drive islands on low order rational surfaces employs a perturbation analysis that does not take into account the modification to the plasma equilibrium by the applied fields. A comparison of theory and experiment by Park et al<sup>1</sup> has shown that omitting the perturbed plasma currents from the analysis can be problematic. In this poster we present analysis of three response matrices which impact trim coil design in NCSX – a matrix  $D$  which measures the plasma response (calculated by VMEC) to field error distributions of normal magnetic field on the plasma boundary, a matrix  $B$  that is determined by normal fields produced on the plasma surface by equally likely displacements of the currents in the primary equilibrium coil set due to construction errors, and a matrix  $T$  that gives the normal field distribution that can be produced on the plasma surface by currents in a candidate trim coil set. Our analysis, essentially a least squares minimization of the displaced plasma boundary, relies naturally on the eigen-analysis of the three response matrices. The analysis is complementary to recent perturbed equilibrium studies by C. Nuehrenberg (private communication) using the CAS3D stability code.

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Work sponsored by DOE grants DE-AC02-76CH03073 and DE-FG02-03ERS496

# Drift-Wave Eigenmodes and Spectral Gaps in Tandem Mirrors

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## Abstract

By producing high energy confinement times (70 – 90 ms) as well as radial-loss times that dominate the Pastukhov end-loss time ( $> 100$  ms), the GAMMA-10 tandem mirror system has demonstrated that the combination of electrostatic and mirror confinement can successfully insulate electrons from thermal end-losses. Scaling laws derived in [J. Pratt and W. Horton, Phys. Plasmas (13), 2006] provide a key prediction that there is a qualitatively different drift wave turbulence in the tandem mirror geometry than in a corresponding size toroidal device. Recent experimental results show that sheared radial electric fields  $E_r$  in the GAMMA-10 tandem mirror suppress low frequency drift wave fluctuations. Using a discrete representation we calculate the kinetic Alfvén eigenmodes in the modeled GAMMA-10 and in a multiple magnetic mirror array formed by the Large Plasma Device (LAPD). We analyze the possibility of spectral gaps in the frequency spectrum of Alfvén waves and ballooning modes due to the multiple mirror cells in these machines. Eigenmodes that reside in the gaps are easily destabilized [Yang Zhang, W. W. Heidbrink, H. Boehmer et al. Phys. Plasmas (15), 2008]; thus spectral gaps are of interest for confinement. We also find a rich spectrum of stable drift-Alfvén modes that can resonate with alpha particles and hot ions.

Work supported by the Department of Energy Grant DE-FG02-04ER5474. We thank H. L. Berk, R. F. Post, and T. K. Fowler for useful comments on the tandem mirror confinement problem.

# Analytical and numerical studies of drift resistive and inertial ballooning modes in general toroidal geometry

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A linear stability theory of non-ideal MHD ballooning modes is investigated using a two fluid model for arbitrary three-dimensional electron-ion plasmas. Resistive-inertia ballooning mode (RIBM) eigenvalues and eigenfunctions are calculated for a variety of equilibria including axisymmetric shifted circular geometry ( $\hat{s}$ - $\alpha$  model) and for three dimensional configurations of interest relevant to the Helically Symmetric Stellarator (HSX). For typical HSX parameters, characteristic growth rates exceed the electron collision frequency. In this regime, electron inertia effects dominate plasma resistivity and produce an instability whose growth rate scales with the electromagnetic skin depth. However, the resistive and inertia effects become unimportant as the plasma  $\beta$  is increased close to the transition to an ideal mode. Analytic calculations of RIBM stability using a two scale analysis are presented. This work generalizes previous calculations used for axisymmetric  $\hat{s}$ - $\alpha$  equilibria [1] to general three-dimensional geometry. Both analytic and numerical results show that in the absence of drift effects RIBM modes are purely growing and persist in regimes where ideal MHD ballooning modes are stable. It is found that the magnitudes of the linear growth rates are not sensitive to the magnetic configuration in HSX plasmas. This result indicates that the level of anomalous transport in a quasi-helically symmetric (QHS) configuration is comparable to the corresponding transport in a configuration whose symmetry is spoiled by adding mirror terms to the magnetic spectrum (Mirror). This is consistent with experimental observations on HSX. The common stability properties in the QHS and Mirror configurations are due to a similar structure of the curvature and local magnetic shear.

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**Finite-Larmor-Radius Kinetic Theory of a Magnetized Plasma  
in the Macroscopic Flow Reference Frame\***

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Closure of the fluid moment equations for collisionless or low-collisionality magnetized plasmas requires at some point the kinetic evaluation of some components of the Chew-Goldberger-Low (CGL) pressure and/or heat-flux tensors, the so-called parallel closure problem. Since the CGL variables are moments of the gyrophase-averaged distribution function, the kinetic information needed for the parallel closures in a finite but small Larmor radius analysis can be obtained from a drift-kinetic equation. Moreover, since the CGL moments are defined relative to the macroscopic flow velocity and in order to allow for the fast flows that are becoming increasingly important in plasma research, it is most advantageous to express the drift-kinetic equation in the reference frame of the local macroscopic flow velocity. This work derives the drift-kinetic equation for a collisionless plasma in the macroscopic flow reference frame, under the assumption of fast (i.e. sonic) time scales and flow velocities with first-order finite-Larmor-radius corrections:  $\partial/\partial t = O(\delta\Omega_{cl}) + O(\delta^2\Omega_{cl})$  and  $u = O(v_{thl}) + O(\delta v_{thl})$  where  $\delta \sim \rho_l/L$ . The use of the full macroscopic velocity differs from recent related analyses<sup>1,2</sup> that use the more conventional electric drift velocity to define the moving frame. Also, no simplifications are made with regard the temporal or spatial variation of the magnetic field, and the electric field is eliminated algebraically using the exact momentum conservation equation. Consistent with a collisionless regime, far-from-Maxwellian distribution functions with large pressure anisotropies and parallel heat fluxes are allowed. Despite its generality, the resulting equation is remarkably compact. Its velocity moments are shown to reproduce exactly the known finite-Larmor-radius fluid evolution equations for the CGL variables<sup>3</sup>, including the higher-order and higher-moment terms.

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## **Excitation of Spiral Modes from Plasma Accretion Disks Around Black Holes and Quasi Periodic Oscillations\***

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Coherent non-axisymmetric plasma collective modes that can be excited in accretion structures (“disks”), for instance under the combined effects of differential rotation and of density and temperature vertical gradients [1], around black holes are proposed as being at the origin of the observed QPO’s (quasi periodic oscillations) from X-ray sources. These modes (of the spiral type), have discrete frequencies that are multiples ( $m_\phi$ ) of the “disk” rotation frequency at the radius where the mode amplitudes are maximum and have relatively short radial wavelengths. The rational ratios (e.g. 3/2) of the double-peaked frequency spectra of the observed radiation are interpreted as the result of the natural non-linear decay into the lowest harmonics of the excited spiral modes. The enhanced rate of radiation emission associated with QPO’s is attributed to these non-axisymmetric structures. The  $m_\phi = 1$  harmonic is considered to be heavily weighted by its decay into axisymmetric ( $m_\phi = 0$ ) modes and to have a relatively small amplitude.

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

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## Global gyrokinetic calculations for experimental cases

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The GEM (gyrokinetic electromagnetic) code[1] is a global particle-in-cell code with relatively complete physics, including non-circular cross section via the Miller MHD equilibrium, multiple ion species, electron collisions, and perpendicular and parallel equilibrium flows, and now can access experimentally-derived profile information from the TRANSP system. A coarse-graining procedure for the electrons has recently been implemented to limit particle weight growth [2].

For a DIII-D case with moderate ion temperatures and moderate rotation, a nonlinear GEM calculation for the core region ( $0.1 < r/a < 0.8$ ) yields maximum ion heat fluxes comparable to experimental values, for the experimental levels of equilibrium flow. Sensitivity of the fluxes to changes in flow and in density and temperature gradients will be discussed. Also, an NSTX case known from flux-tube calculations to be linearly unstable to microtearing modes will be considered in a global nonlinear GEM simulation.

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## **High- and low-confinement modes in simple magnetized toroidal plasmas**

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Global fluid simulations of interchange turbulence are presented for a simple magnetized toroidal plasma, in which a vertical magnetic field superposed on a toroidal magnetic field creates helicoidal field lines with both ends terminating on the torus vessel. We consider  $\beta \ll 1$  plasma, with  $T_i \ll T_e$ , and we study the dynamics of density, electron temperature, and potential. The simulations show the presence of two turbulent regimes characterized by low and high confinement properties. We evaluate analytically the properties of the low confinement regime, obtaining expressions for the plasma gradients and for the density and heat fluxes that agree well with the simulation results. By increasing the plasma source strength or reducing the vertical magnetic field, a transition to a high confinement regime occurs, in which a strong velocity shear limits the perpendicular transport, the peak density and temperature increase and their gradients steepen up. We present an analytic estimate of the L-H transition condition that agrees well with the simulation results.

# Ray tracing simulation of ICRF mode conversion in Alcator C-Mod

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Mode conversion between magnetosonic and ion Bernstein or ion cyclotron waves has been studied as a tool for heating and current drive in tokamak plasmas. Magnetosonic fast waves with frequencies in the ion cyclotron range of frequencies (ICRF) are launched into a multi-ion species plasma, and undergo mode conversion in the ion-ion hybrid resonance layer. This phenomenon has been studied both experimentally and numerically for the Alcator C-Mod tokamak [1–4]. In addition to the full-wave simulations reported in [3, 4], there has been recent work to develop a ray tracing code (RAYCON) which treats mode conversions as a ray splitting [5]. In this poster, we report preliminary work on using the RAYCON code of Juan et al. to model ICRF mode conversion for Alcator C-Mod. The ray tracing results will be compared to the full wave simulations of Wright et al., in order to benchmark the RAYCON code. The goal of this work is to demonstrate that the new ray splitting algorithms implemented in RAYCON can give useful results, even in the presence of mode conversion, which would cause traditional ray tracing algorithms to break down.

This research was supported in part by an appointment to the U.S. Department of Energy Fusion Energy Postdoctoral Research Program administered by the Oak Ridge Institute for Science and Education.

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## **Saturation mechanisms in reduced simulations of boundary turbulence**

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An important goal of turbulence research is the identification of the physical mechanisms that saturate linear instabilities in the tokamak edge region, as these dynamical processes serve as "control valves" in regulating strong-turbulent particle and energy transport from the edge into the scrape-off layer (SOL). Commonly identified saturation mechanisms include wave-breaking and zonal-flow shear stabilization.<sup>1</sup> We use our SOLT code<sup>2</sup> to simulate the turbulent evolution of vorticity, density, temperature and zonal fluid momentum, in the two dimensions orthogonal to the magnetic field in the outboard midplane region of a tokamak. In the simulation plane, the edge region supports the electron drift wave instability and curvature-driven instabilities, while sheath losses and the grad-Te instability are isolated in the SOL. Charge separation by the curvature and grad-B drifts enables blob transport<sup>3,4</sup> of density, temperature and vorticity (charge) from the edge into the SOL. A zonally-averaged momentum conservation law is used to advance the (bi-directional) zonal flow.<sup>2</sup> We artificially damp the zonal flow evolution to compete shear flow stabilization and wave-breaking. Absent this damping, the free evolution of zonal flow tends to minimize the particle flux into the SOL, the blobs are of the isolated "mushroom" variety, and the turbulence is intermittent. With increasing damping, and decreasing zonal-flow shear, particle flux into the SOL increases, and the blobs become quasi-periodic pulsating streamers. Exceptions to this scenario will be noted, e.g., as a function of sheath location.

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## Basic properties of a snowflake divertor

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The snowflake divertor [1] exploits a tokamak geometry in which the poloidal magnetic field null approaches second order; the name stems from the characteristic hexagonal, snowflake-like, shape of the separatrix for an exact second-order null.

The proximity of the poloidal field structure to that of a second-order null substantially modifies edge magnetic properties compared to the standard X-point geometry; this, in turn, affects the edge plasma behavior. Modifications include: 1) The flux expansion near the null-point becomes 2-3 times larger. 2) The connection length between the equatorial plane and divertor plate significantly increases. 3) Magnetic shear just inside the separatrix becomes much larger. 4) In the open-field-line region, the squeezing of the flux-tubes near the null-point increases, thereby causing stronger decoupling of the plasma turbulence in the divertor legs and in the main SOL [2]. We provide detailed characterization of these geometrical features of a snowflake divertor for a simple coil geometry and assess their impact on the edge plasma.

In particular, larger flux expansion opens up new possibilities for the reduction of the peak heat flux on the divertor plates. Stronger squeezing of flux-tubes near the X-point has a dramatic effect on the dynamics of non-diffusive (“blob”) transport. The blobs are now harder to form, and, once formed, they move slower than in the standard X-point geometry. A similar strong effect of the flux-tube squeezing is the modification of sheath-driven instabilities in common and private flux regions [2]. For the snowflake, unstable modes should localize much closer to the divertor plates. The increased shear causes a significant radial squeezing of neoclassical orbits that pass close to the null point. This squeezing may reduce the effect of the neoclassical transport near the X-point. On the other hand, some special orbits become quite different compared to the standard X-point case.

We also analyze the sensitivity of the divertor configuration to variations of the toroidal plasma current and conclude that the snowflake configuration is robust if the current in the divertor coils is a few percent higher than the current corresponding to an exact second-order null (so-called “snowflake-plus” configuration). Importantly, the required PF coils can be placed a considerable distance outside the vacuum chamber.

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# Adaptive Mesh Simulations of Pellet Injection using a Level-Set Approach with Cartesian Grids

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Abstract

We have developed an adaptive mesh refinement (AMR) Magnetohydrodynamic (MHD) code to simulate pellet injection into tokamaks, an inherently three-dimensional phenomenon requiring fine resolution of the physics in the vicinity of the pellet. We will present fully three-dimensional AMR simulation results of pellet injection into a tokama. The main emphasis of the poster is to describe a new algorithmic advance to the AMR-MHD code: namely the utilization of a signed-distance function level-set approach along with a rectilinear grid in the radial and axial directions. Finite volume methods for tokamak MHD simulations require a mapping in the poloidal plane to conform with the shaped cross-section of the plasma (as in Ref. [1]). The level-set approach has the advantage that the differential operators are well-behaved as opposed to the mapped grid method wherein the mesh metric terms can impose severe accuracy constraints, and furthermore require special treatment near grid singularities (e.g. the magnetic axis). The disadvantage of the level-set based approach is that the mesh is not aligned with flux surfaces and treatment of boundary conditions is non-trivial. The level-set utilized in the simulations is a signed distance function.

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<sup>1</sup> R. Samtaney et al. Adaptive mesh simulations of multi-physics processes during pellet injection into tokamaks. Journal of Physics Conference Series, Volume 78,01062, 2007.

# **Analytic and computational investigation of the effect of finite parallel heat transport on the formation of magnetic islands in three-dimensional plasma equilibrium.\***

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A resistive MHD model and boundary layer analysis is used to investigate the formation of pressure-induced magnetic islands in three-dimensional stellarator equilibrium. In this work we revisit previous analytic island calculations<sup>1</sup>, allowing for the influence of finite parallel heat transport. Using a boundary layer analysis, an equation for the equilibrium island width is derived. We find that finite parallel heat transport can greatly affect the impact of resistive interchange and bootstrap current contributions to magnetic island formation. However, the resonant Pfirsch-Schlüter currents driven by resonant components in  $1/B^2$  are largely unaffected by transport processes.

In high temperature stellarators, parallel heat transport takes on an integral form.<sup>2</sup> To make further progress employing a more realistic heat transport operator, an integral closure for the parallel heat transport is computationally employed through NIMROD. To apply this code to a full, general 3-D problem, a vacuum equilibrium helical magnetic field is loaded into the geometry of a straight stellarator (no toroidal curvature). Future plans include heating this configuration and perturbing the magnetic field to trigger the formation of magnetic islands, and examining the effect of finite parallel heat transport on the island formation and saturation processes.

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# The Absence of Complete FLR Stabilization in Extended MHD \*

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## Abstract

It is well known that the kinetic effects due to finite Larmor radius (FLR) are able to stabilize the pure interchange mode in a weakly unstable plasma under gravity [1]. The dominant FLR stabilization effects on the interchange instability can be retained by taking into account the ion gyroviscosity or the generalized Ohm's law in an extended MHD model [2,3]. However, recent simulations and theoretical calculations indicate that the complete FLR stabilization of the pure interchange mode may not be attainable by the ion gyroviscosity or the two-fluid effect alone in the framework of extended MHD [4,5]. For a class of plasma equilibria in certain finite- $\beta$  or non-isentropic regimes, the critical wavenumber for the complete FLR stabilization tends toward infinity, and the FLR stabilization effects are eliminated.

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## Critical Toroidal Rotation Profile for Resistive Wall Modes in Tokamaks

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We develop a three-mode model including the effects of the toroidal coupling to describe resistive wall modes in tokamaks. The determinant of a 6x6 matrix for the dispersion relation is derived. The toroidal rotation speed at each rational surface and the mode frequency appear in the dispersion relation. In between rational surfaces, the magnetic axis, and the plasma boundary, the toroidal rotation profile is calculated using toroidal momentum diffusion equation with plasma rotation speed at the rational surfaces, at the magnetic axis, and at the plasma boundary as the boundary conditions in each region. These coupled equations uniquely determine a critical toroidal plasma rotation profile for the resistive wall modes described by the model. The model is especially useful in determining the critical rotation profile when the toroidal rotation speed is externally controlled. From the results of this model, it is noted that the toroidal rotation profile is more important than the rotation speed at a given radius in determining the stability of the resistive wall modes in tokamaks.

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# MHD Spectroscopy of Transport Transitions on JET

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Depending on auxiliary power, magnetic configuration, and impurities, plasmas in Joint European Torus (JET) exhibit L-H or H-L transitions at the plasma edge and formation of Internal Transport Barriers (ITB) in the plasma core. MHD spectroscopy of  $q_{\min}(t)$  in discharges with reversed magnetic shear has been earlier developed based on detecting fast ion-driven Alfvén cascade (AC) eigenmodes [1], and this technique serves well for identifying ITB formation times on JET [2] and on DIII-D [3]. In the present work, a possibility of MHD spectroscopy of L-H transitions and ITB formation is demonstrated based on measurements of magnetic turbulence, which is shown to change abruptly together with the transport transitions. It is found that the best way to identify the abrupt changes in the turbulence is to analyse the spectrogram of the *phase shift* in the magnetic signals measured by toroidally separated magnetic pick-up coils. These phase spectrograms often shows a sudden change of the sign in the wave propagation velocity during L-H transitions even when the amplitude of the perturbations remains nearly constant.

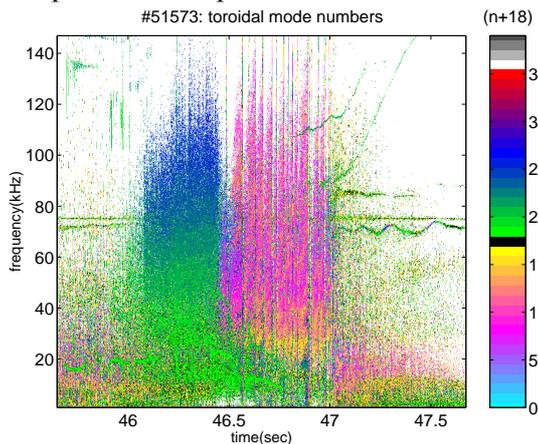


Figure 1. Phase magnetic spectrogram showing toroidal mode numbers of a broadband magnetic turbulence in 2.6 T/2.3 MA JET discharge #51573.

Figure 1 displays an example of the magnetic turbulence transitions, where the modes propagating in the ion diamagnetic direction (green-blue) build up at the ITB formation at  $t = 46$  sec. When L-H transition happens at the plasma edge at  $t=46.5$  sec, an abrupt change in the sign of the mode propagation is observed – the modes propagate in the electron drift direction (pink colour) in H-mode. This observation supports prediction of the turbulence propagation sign in Ref.[4]. Toroidal mode numbers, mode frequencies, and Doppler shift effects associated with plasma rotation, are assessed and the experimental data is interpreted. Importance of measurements detecting the sign of propagation for electrostatic turbulence is discussed.

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

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## Visualization Schema for Fusion Simulation Data

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### Abstract

Large fusion simulation projects like CEMM,<sup>1</sup> SWIM,<sup>2</sup> and FACETS<sup>3</sup> store data using very different formatting conventions, even if they use a standard file format such as HDF5.<sup>4</sup> This makes visualization and comparison of different codes problematic, requiring individual readers for each code and visualization tool. In this poster we present the Visualization Schema, which reflects the visualization essence of the fusion simulation data and allows visualization tools to view multiples types of data in a uniform way. The schema is described by an XML schema and a specification document for the HDF5 data markup. It is accompanied by a C++ API that uses XML files or the markup to read HDF5 data. Based on this API, a plugin for the VisIt<sup>5</sup> visualization package is implemented. This plugin now supports the NIMROD,<sup>6</sup> M3D,<sup>7</sup> VORPAL<sup>8</sup> and prototypical FACETS data. Examples of XML instances for NIMROD and M3D, HDF5 markups for VORPAL and FACETS, and sample visualizations using the plugin, will be also presented in the poster.

The work is supported by a DOE/SBIR grant DE-FG03-02ER84101 and Tech-X Corporation.

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<sup>1</sup> CEMM: <http://w3.pppl.gov/cemm/>.

<sup>2</sup> SWIM: <http://swim.org>.

<sup>3</sup> FACETS: <https://facets.txcorp.com/facets>.

<sup>4</sup> HDF5: <http://hdf.ncsa.uiuc.edu/HDF5/>.

<sup>5</sup> VisIt: <http://www.llnl.gov/visit>.

<sup>6</sup> NIMROD: <http://www.nimrodteam.org/>.

<sup>7</sup> M3D: <http://w3.pppl.gov/~jchen/>.

<sup>8</sup> VORPAL: <http://www-beams.colorado.edu/vorpal/>.

## **Tokamak dust transport and distributions in edge plasmas\***

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Dust in tokamaks has been recognized as a potentially important issue for safety and performance of future fusion reactors. It is known that microscopic dust particles are highly reactive and mobile that imposes risk of environmental hazard during tokamak maintenance or an accidental loss of vacuum event. In addition accumulation and migration of dust in the fusion chamber may impair diagnostic instruments and contaminate fusion plasmas with dust material. Studies of dust collected from interior of tokamaks reveal that the dust is composed mainly of the divertor plate and the first wall materials, can have irregular, flake like or spherical shapes, and sizes in submicrometer to several micrometer range. Possible mechanisms of dust production in tokamaks include sputtering, flaking, and brittle destruction of plasma contacting surfaces as well as condensation of impurities in cold plasma regions. In this study we investigate behavior of dust in edge plasmas of tokamaks including dust dynamics, spatial distributions, dust-plasma and dust-wall interactions using numerical modeling with the Dust Transport in Tokamaks (DUSTT) and the structural analysis LS-DYNA codes. The DUSTT code solves coupled equations of dust motion, charging, ablation and heat balance in the tokamak plasmas allowing to simulate trajectories of individual dust particles as well as dust distributions using Monte-Carlo statistical averaging over large number of simulated dust trajectories. The simulated dust trajectories are compared with measured ones using fast CCD cameras in NSTX tokamak and qualitative agreement in the dust dynamics is demonstrated. The dust transport simulations show that dust particles in present fusion devices can penetrate deeply in the edge plasma toward separatrix. The simulated amount of dust material crossing the separatrix is consistent with dust injection experiments on DIII-D tokamak. It is shown also that most of the penetrating material is originated in the divertor region and is carried by big dust particles in the size distribution of injected dust particles. The DUSTT modeling show that dust particles in tokamaks can acquire speed up to a few hundred meters per second that in toroidal geometry of a tokamak leads to intensive dust-wall collisions. Simulations of the collisions with the LS-DYNA code for different impact speeds and combinations of the dust and the wall materials demonstrate that the accelerated dust of high mass density can cause significant damage to the wall and possibly lead to an avalanche-like mechanism of dust production in tokamaks.

\*This work is performed in part under auspices of US DOE by UCSD grant No. DE-FG02-04ER54852.

# A numerical approach to obtain the linear stability spectrum of ideal MHD with arbitrary equilibrium flows and a free boundary\*

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The ideal MHD linear stability normal modes and frequencies for a circular cylindrical plasma having an arbitrary equilibrium flow,  $\mathbf{V}$ , are calculated using a Galerkin finite element approach. The linearized equations to be solved are

$$\begin{aligned}\omega\rho\xi &= \rho\mathbf{u} - i\rho\mathbf{V} \cdot \nabla\xi \\ \omega\rho\mathbf{u} &= -\tilde{\mathbf{J}} \times \mathbf{B} - \mathbf{J} \times \tilde{\mathbf{B}} + \nabla\tilde{p} - \nabla \cdot [\xi(\rho\mathbf{V} \cdot \nabla\mathbf{V})] - i\rho\mathbf{V} \cdot \nabla\mathbf{u},\end{aligned}$$

where  $\omega$ ,  $\xi$ , and  $\mathbf{u}$  are unknown,  $\tilde{\mathbf{J}}$ ,  $\tilde{\mathbf{B}}$ , and  $\tilde{p}$  are perturbed quantities that can be expressed in terms of  $\xi$ , and the equilibrium quantities satisfy

$$\rho\mathbf{V} \cdot \nabla\mathbf{V} = \mathbf{J} \times \mathbf{B} - \nabla p.$$

By introducing  $\mathbf{u}$ ,  $\omega$  only appears linearly in the linearized set of equations, and, after utilizing a finite element expansion for each of the components of  $\xi$  and  $\mathbf{u}$ , the problem takes the form of a generalized eigenvalue problem

$$\omega\mathbf{A} \cdot \mathbf{x} = \mathbf{B} \cdot \mathbf{x}.$$

The finite elements used are a cubic bspline finite element for the radial components of  $\xi$  and  $\mathbf{u}$ , and the derivative of a cubic bspline for the other two components. This choice of elements both avoids spectral pollution and gives desirable convergence properties. Comparisons of the calculated normal modes and frequencies to analytic results and to other numerical studies are presented for the cases of 1) A wall at the plasma boundary, 2) A conducting wall at a finite distance from the boundary, 3) No wall, and 4) A resistive wall at a finite distance from the boundary. The boundary conditions for each are implemented by first relating the value of  $\xi$  at the plasma boundary to the perturbed magnetic fields in the vacuum and in the wall, then relating the value of  $\xi$  at the plasma surface to terms that arise from an integration by parts of the Galerkin approach.

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# Solution to the divergence preservation difficulty in the Alternating Direction Implicit (ADI) method for electromagnetic particle-in-cell simulation of plasmas

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The recent advances in alternating direct implicit (ADI) methods<sup>[1]</sup> promise important new capability for time domain plasma simulations, namely the elimination of numerical stability limits on the time step. But the utility of these methods in plasma simulations where charge and current are dominant effects, such as in electromagnetic particle-in-cell (EMPIC) computations, has been uncertain, as the methods introduced so far do not have the property of divergence preservation. This property is related to charge conservation and self-consistency, and is critical for accurate and robust EMPIC simulation. This paper contains a complete study of the ADI methods in the presence of charge and current sources. It has now been shown that there are four significantly distinct ADI cases, with four more related by duality. Of those, only one preserves divergence and, thus, is guaranteed to be stable in the presence of moving charged particles.<sup>[2]</sup> We have performed simulations using the VORPAL<sup>[3]</sup> software framework and verified this property. Specifically, of the other three cases, two are verified unstable, as expected, and one remains stable, despite the lack of divergence preservation. This other stable algorithm is shown to be related to the divergence preserving case by a similarity transformation, effectively providing the complement of the divergence preserving field in the finite-difference energy quantity. The advantage of the ADI algorithm is that it allows exact implicit solutions, using only simple tri-diagonal matrix inversion, which have the same operation ordering as explicit methods. However, tri-diagonal solvers are not known to scale effectively for domain-decomposition-type parallel computation. Here, we also report on progress in improving ADI scaling to large scale computing using a novel concurrent divide-and-conquer technique.

This work was supported by the Department of Energy under grants DE-FG02-07ER84732, DE-FG02-04ER41317, DE-FC02-07ER41499, and PPPL subcontract S-006288-F.

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# Understanding and Predicting the H-Mode Pedestal Height\*

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The pressure at the top of the edge transport barrier (or “pedestal height”) strongly impacts fusion performance. Predicting the pedestal height in future devices such as ITER remains an important challenge for plasma theory. While uncertainties remain, MHD stability calculations, accounting for diamagnetic stabilization, have been largely successful in predicting the observed pedestal height, when the barrier width is taken as an input (e.g. [1-2]). Such peeling-ballooning stability studies typically find that the predicted pedestal height ( $\beta_{\text{Nped}}$ ) scales roughly with the 3/4 power of the pedestal width [2], a relation that can be understood to result from the balance of relatively local ballooning modes and non-local peeling-ballooning and kink-peeling modes. This strong correlation between the stability-constrained height and the width, along with significant measurement uncertainty in the width, have complicated prior efforts to discern the dependencies of the width on observed parameters. Here, we employ the peeling-ballooning stability calculations as a constraint, accounting for the strong correlation of the width and height, and allowing study of the dependencies of the width itself. In a large set of DIII-D data, as well as a set of power scans [3], we find a relatively simple scaling for the pedestal width, similar to the  $\beta_{\text{pped}}$  scaling observed in [4]. Employing this working model of the pedestal width, along with peeling-ballooning stability calculations using the ELITE code, we are able to predict the pedestal height in both past and future experiments. Here we explore the physics underlying the pedestal width, in an attempt to put this aspect of the successful working model on a more firm theoretical basis.

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## Large Eddy Simulations (LES) of MHD using Lattice Boltzmann Methods

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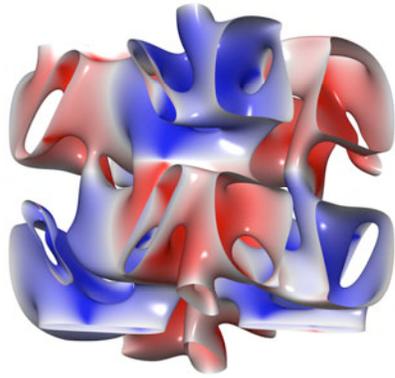
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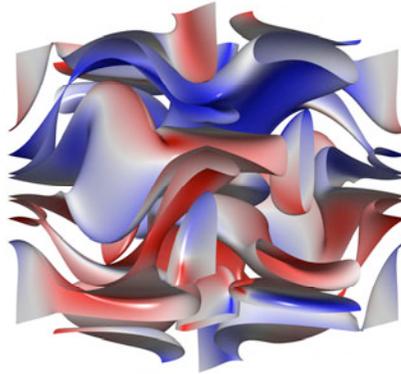
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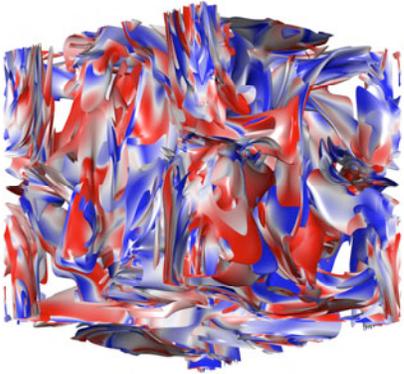
3D free-decaying MHD turbulence is simulated using Lattice Boltzmann (LB) methods on a spatial grid of  $1800^3$ -grid for low and high magnetic Prandtl numbers.  $\nabla \cdot \mathbf{B} = 0$  is automatically satisfied to machine accuracy. Isosurfaces of vorticity and current show the persistence of many large scale structures for long times – in contrast to the vorticity isosurfaces of Navier-Stokes Turbulence. The lattice Boltzmann code scales perfectly with processors – tested up to 9000 cores on an SGI-Altix.



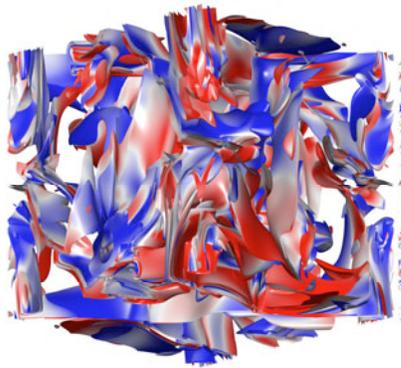
t = 0 vorticity



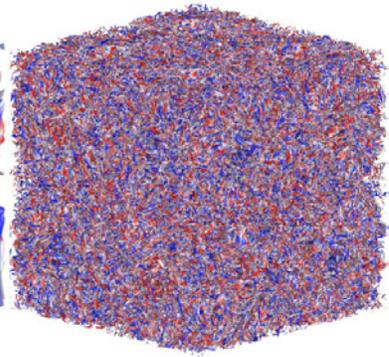
current



t = 50K vorticity



current



Navier-Stokes vorticity

We contrast these DNS simulations with LES-LB simulations in which the eddy transport coefficients can be determined purely from local moments of LB – thus not spoiling the parallelization of the LES-LB codes.

## Preconditioning the Implicit Hall Advance in NIMROD\*

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The two-fluid algorithm in the NIMROD code is being applied to study two-fluid macroscopic dynamics in spheromaks, tokamaks, RFPs, FRCs, reconnection experiments, and several idealized problems. Among these, the two-dimensional applications (two-fluid reconnection in the MRX experiment [1], spin-up in FRCs [2], and idealized problems) are the ones that have progressed farthest. This is a consequence of numerical linear algebra. The stiffness of macroscopic dynamics in magnetized plasmas is significantly greater in two-fluid models than in MHD due to communication through dispersive normal modes, the whistler wave in particular.

The matrices for the NIMROD time-advance are solved by Krylov-space methods. The iterations converge rapidly only when an approximate inverse, the preconditioner, is incorporated. With a two-dimensional finite-element mesh and finite Fourier series for the third coordinate, solving a set of matrices that drop coupling among different Fourier components has proven to be an effective preconditioner for many three-dimensional MHD computations. In addition, the SuperLU library [3] provides an efficient means of finding the approximate inverses. Unlike MHD, however, convergence of the Krylov iterations for the two-fluid magnetic advance in NIMROD's implicit leapfrog [4] is sensitive to small perturbations (less than 1%) when using typical time-steps that are of order the global Alfvén time. The perturbations lead to coupling among Fourier components that is not represented in the present preconditioning scheme.

Here, we consider numerical observations and implications for improving the preconditioner. For example, the  $\partial\mathbf{J}/\partial t$  part of electron inertia is a symmetric contribution that limits the phase speed of the whistler branch. When included in our two-fluid computations, convergence properties improve, regardless of whether electron inertia is important for the physics of interest. Also, polynomial methods provide a straightforward way to incorporate Fourier-component coupling, and Krylov iterations decrease significantly when they are used. However, the additional work is comparable to additional iterations, and there is little if any gain in overall computational performance. Parallel scaling is considered in a companion presentation. [5]

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## Development and application of the moments method transport analysis to plasma flows in 3D configurations

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Neoclassically driven  $E_r$ /flow shearing in stellarators is of importance due the possibility that certain configurations can enhance these effects and provide more direct access to enhanced confinement regimes. Conversely, for the case of tokamaks with three-dimensional shaping, there is a concern that too much edge ripple from TF coils, ELM suppression coils, etc. can damp flows, suppress  $E_r$  shearing and make H-mode access more difficult. A moments method transport analysis (PENTA code) that can address such questions<sup>1</sup> has been developed for non-axisymmetric systems This method is based on the momentum conserving, self-consistent ambipolar transport formulation of Sugama, et al.<sup>2</sup> and has been applied to general three-dimensional configurations, ranging from conventional stellarators to rippled tokamaks.<sup>3</sup> For devices with strong three-dimensional shaping, the electric field is predominantly driven by ambipolar transport, but moderated by flow damping effects. For devices such as rippled tokamaks, with weak three-dimensional shaping, the electric field is more strongly driven by the damping of external parallel flows (e.g., from NBI). Small symmetry breaking effects (present even in quasi-symmetric systems) remove the dependency between viscosities that characterizes perfectly symmetric systems and lead to nonlinear dependencies of the viscosities and stress tensor components on the electric field; these allow multiple, bifurcated electric field solutions. These differences can lead to plasma flows with strong directional variations and shearing rates within flux surfaces as well as the more conventional velocity shearing across flux surfaces. We have applied this model to a range of configurations and find that among stellarator systems particularly strong  $E_r$  shearing is present for QP (quasi-poloidal) symmetry, which approximately minimizes the damping of  $E \times B$  driven flows, allowing the development of regions with large  $E_r$  shearing. These can be to some extent moderated by other effects, such as anomalous momentum damping, that lead to a diffusive spreading in the electric field profile. A code has recently been developed to evaluate these diffusive spreading effects.

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# Preliminary Calculations for the Study of Ballooning Mode Growth in the Early to Intermediate Nonlinear Regime.

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## Abstract

Recent progress has been made in analytically describing the various stages of nonlinear ballooning mode growth in a general confinement configuration [1]. The intermediate nonlinear regime becomes relevant when the plasma filament length across the magnetic flux surface becomes comparable to the mode width in the same direction. This is particularly significant for tokamaks operating in H-mode in which the pedestal region is known to give rise to ballooning instabilities. The nonlinear ballooning mode model may eventually be able to quantify the precursor and precollapse phase of edge localized modes (ELMs) in both simulation and experiment. In this work we outline a two-pronged approach to analyze the intermediate nonlinear regime of ballooning mode growth. The first is an initial value computational model that solves the reduced analytic nonlinear equations derived in [1]. These results will be compared to solutions of the primitive MHD equations using NIMROD simulations of the same nonlinear regime. The idea is to provide a computational model that describes the transition between early to intermediate nonlinear mode growth and characterizes the relevant physics of each regime. Initially we are studying the linear stability properties of a class of tokamak equilibria with the eventual goal of using experimentally relevant EFIT data. We present linear calculations and convergence studies using NIMROD to map out stability regions of various toroidal equilibria. The equilibria are generated using the TOQ equilibrium code to provide a range of current, pressure, and  $q$  profiles. The linear results from NIMROD will be used to determine which TOQ equilibria will be useful for future nonlinear ballooning-mode simulations and studies.

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# Theory of Electron-ion Collisions in Trapped Gyro-Landau Fluid Models\*

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Including electron-ion collisions in a system of trapped gyro-Landau fluid equations [1] is complicated by the need to resolve the boundary between trapped and passing particles. The interaction between the Landau damping of the circulating particles and the averaging away of this damping by the trapped particles plays a crucial role in determining the gradient of the electron distribution function at the trapped passing boundary. It is this boundary gradient that determines the collisional damping of the trapped electron density moment. A hierarchy of trapped gyro-Landau fluid models with increasing number of velocity moments are explored to understand the role of the Landau and curvature drift resonances in determining the trapped electron density damping. It is found that both resonance terms can damp the density moment through coupling to higher velocity moments but that the Landau resonance has by far the strongest coupling strength. The 4-moment Hammet-Perkins Landau resonance closure scheme [2] is extended to an arbitrary higher moment system. This allows a high accuracy solution of the electron distribution function covering the trapped and passing regions continuously. The least damped eigenmode is found to be localized to the trapped region by the Landau damping outside this region of velocity space. The density moment of the gradient of the distribution function at the trapped-passing boundary can be computed and shown to be the primary damping of the trapped particle density. A model for this boundary term can be fit to the high moment solution and used in a low moment trapped gyro-Landau fluid system to accurately reproduce the linear drift-wave growth rate reduction due to electron-ion collisions.

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## **Thermonuclear Yield Due to the Relativistic Electron Bernstein Modes in Spherical Tokamak Plasmas\***

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Abstract

A model for an efficient control of anomalous absorption in Spherical Tokamaks (ST) is proposed. In this model an external electron cyclotron waves, O- or X-mode, excite relativistic Electron Bernstein Mode<sup>1</sup> harmonics (EB harmonics) at 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 harmonic resonance region.

The scaling laws for the thermonuclear yield, ratio of the thermonuclear power to the external power, for the case of excitation of EB harmonics,  $n(\text{EB}) + (n-1) (\text{EB})$ ,  $n= 2 \dots 6$  harmonic number, are obtained. The plasma-ignition criterion is analyzed in terms of O- and X-Mode power.

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## Computation of flowing multi-fluid equilibria with finite-Larmor-radius corrections\*

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The system of equations for axisymmetric multi-fluid equilibria is composed of a second-order partial differential equation and an algebraic “Bernoulli” equation for each species [1,2]. The former reflects the “radial” force balance and the latter mechanical energy conservation along streamlines. The species include the electron fluid and one or more ion fluids. Additional ion components may represent other ion species (e.g. fusion ash or an injected “beam” component) or a superthermal component of the primary ion species.

Multi-fluid equilibria exhibit distinct characteristic surfaces for each species. Thus the confinement surface (flow separatrix) for an ion species may lie outside the magnetic separatrix (confinement surface for massless electrons). This contrasts sharply with single-fluid equilibria which have only one set of characteristic surfaces. It should be noted that the multi-fluid paradigm is more general and more accurate than the single-fluid. Multi-fluid equilibria are characterized by three “arbitrary” surface functions for each species, representing the poloidal flow, enthalpy, and entropy. By comparison, static equilibria (Grad-Shafranov) have only two. In general, multi-fluid equilibria have nonuniform density and pressure on characteristic surfaces.

The solution method best suited for two-dimensional, multi-fluid equilibria is iterative. The successive-overrelaxation method is used to update the magnetic flux function. A Newton method is used to update the density and toroidal flow for each ion species. At present a practical solution for two-fluid equilibria is in hand. Coded in Visual Basic in an Excel platform, it computes essentially instantaneously on a personal computer. Equilibrium examples for field reversed configurations will be presented, although the algorithm works equally well for spherical tokamaks and other axisymmetric equilibria.

It is anticipated that a three-fluid version of the algorithm and computed examples will be available for presentation. Further, it is hope to add the Braginskii gyroviscosity, which is a fluid-based model of kinetic “finite-Larmor-radius” effects. The gyroviscous correction is important in the steep gradient region near the separatrix of FRCs and possibly spherical tokamaks.

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# MHD Simulation of Resonant Magnetic Perturbations and Resistive Wall Effects

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Resonant magnetic perturbations (RMP) have been found effective in suppressing ELMs in the DIII-D experiment. [1] The experimental temperature profile is found to be less affected by the RMP than the density profile. Simulations with the M3D code [2] indicate that plasma rotation has an essential effect on the RMP. For low rotation, the magnetic field is stochastic in the outer part of the plasma. As expected, the temperature is strongly affected, while the density is modified only slightly. At higher rotation speed, the stochastic layer is thinner. The temperature can maintain a gradient across this layer, an effect which has been observed in stellarators. The density is affected by the greater rotation and experiences enhanced loss. Resistive wall boundary conditions tend to lessen the the effect of the RMP.

The resistive wall boundary conditions have been recently benchmarked by a comparison of M3D and MARS linear resistive wall mode (RWM) simulations in ITER with a double wall. The region between the ITER first wall and the outer wall is modeled in M3D as a dense, highly resistive region. The comparison between M3D and MARS is reasonably good. Nonlinear M3D RWM simulations are in progress.

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# Guiding Center Models for 3D Plasmas

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Guiding center (GC) models of charged particle dynamics in magnetized plasmas combine a fast gyration around the magnetic field lines with a smoother, gyration-averaged trajectory, separated in terms of a small gyroradius parameter,  $\epsilon = \rho_i/L < 1$ . To model effects occurring within a gyro-orbit, the gyro-motion is described in terms of an explicit gyro-angle, defined in terms of local orthogonal coordinate axes tied to the magnetic field at each point in space, at the particle's guiding center. In a 2D slab with straight uniform magnetic field lines, guiding center expansions are exact to all orders in  $\epsilon$ . For general 3D fields, this is not the case. 3D guiding center models have assumed[1,2] that the local, pointwise-defined coordinate systems can be specified in such a way that the spatial gradients of the coordinate axes exist and are consistently defined over the plasma. A new analysis for 3D fields shows that exact expansions exist only under stringent conditions that are not generally satisfied by magnetically confined plasmas. Plasmas with nonzero magnetic torsion  $\mathbf{b} \cdot \nabla \times \mathbf{b} \neq 0$ , where  $\mathbf{b} \equiv \mathbf{B}/B$  is a unit vector, equivalent to finite parallel current, may possess practically useful GC expansions, nonuniform in phase space, to first order in  $\epsilon$ , or to higher order if they satisfy a 2D restriction such as toroidal axisymmetry. Neglecting the fast MHD waves, the compressional and shear Alfvén waves, also introduces 3D geometric approximations.

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

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# Kinetic effects in RFP plasma

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## Abstract

Strong tearing mode activity is present at sawtooth crashes in the Madison Symmetric Torus reversed field pinch (RFP). It is believed that tearing modes are responsible for strong ion heating and change in plasma flow profile at the crash. Our results based on both linear and nonlinear resistive MHD models showed that the spatial scale of velocity, electric field and current profiles in the tearing mode near resonance surface is comparable to ion gyroradius. The ion gyroradius is relatively large in RFPs because of smaller equilibrium magnetic field. In these conditions both two fluid and kinetic effects can be significant. We study ion kinetic effects on tearing modes in RFP plasmas. We consider RFP-like equilibrium in plane geometry and solve for linear eigenmodes in resistive MHD, two fluid and fully kinetic models. In the first two models we solve an eigenvalue problem, in the last we use particle in cell code VPIC and follow linear time evolution of the fastest growing mode. Also we examine nonlinear effects in tearing modes by running 2-D nonlinear time evolution in plane geometry in resistive MHD and PIC models. We analyze how the scale of plasma flow and flow amplitude in the mode are effected by the finite ion gyroradius effect, to what plasma component (ions or electrons) the magnetic energy of initially unstable equilibrium is transferred. Results of this analysis will be presented.

# The kinetic effects of energetic particles on resistive MHD stability

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## Abstract

Recent experiments have shown JET discharges to be stable for values of  $\beta_N/4\ell_i$  as a function of  $\rho^*$  far exceeding where JT-60U, DIII-D, and Asdex-G are unstable. It is conjectured that kinetic effects of high energy particles can play a crucial role in the stability of the 2/1 tearing mode in JET, where the energetic particle  $\beta$  has the highest fraction. Using model equilibria based on experimental reconstructions, the non-ideal MHD linear stability and nonlinear evolution of cases unstable to the 2/1 mode is investigated including a delta-f PIC model for the energetic particles coupled to the MHD solution using the NIMROD code. The energetic particles have a significant effect on the stability of the 2/1 mode. Furthermore, implications for ITER are discussed based on extrapolated results.

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## A multi-disciplinary approach to plasma/wall interaction

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A multi-disciplinary team from LANL consisting of plasma physicists, materials scientists, and chemists, is being assembled to address the complex physics and chemistry underlying plasma/wall interaction in fusion reactor conditions. Although the capabilities that we will develop are applicable to a variety of plasma conditions and choice of wall materials, the initial focus will be on the potential of liquid lithium first wall in enabling a flat temperature profile burning plasma. Our approach integrates experiment, theory, and modeling, and simultaneously addresses the coupled materials and plasma issues.

There are abundant experimental evidence that support the choice of lithium as the first wall material. Large (TFTR) and small (CDX-U) tokamaks with solid lithium wall coating have seen dramatic improvement in plasma confinement correlated with low recycling and reduced edge plasma density. Current representative plasma-based lithium wall studies include the Lithium Tokamak Experiment (lithium-covered stainless steel wall; \$M T~10-100 eV experiment) and the National Spherical Torus Experiment (permanent lithium evaporator over carbon tile; \$100M T~keV experiment) at Princeton.

Our aim is to leapfrog the plasma-based lithium wall studies into the burning plasma regime (T=10-15 keV) using high power density ion beams, thus provides crucial data for the feasibility of the low recycling wall/flat temperature/high confinement path to fusion energy. Bombarding lithium wall sample with 10-15 keV H, D and 3.5 MeV He ion flux at power load of hundreds of kW/m<sup>2</sup> at LANL's Ion Beam Materials Laboratory is an existing experimental capability.

A number of processes contribute to "recycling" at the wall, for example, physical and chemical sputtering, reflection, out-gassing of H<sub>2</sub>, D<sub>2</sub>, He via surface recombination, evaporation at elevated temperature under ion irradiation. Most of these processes have strong temperature dependence, which itself is set by transport in liquid lithium with implanted H,D, and He. The thermal and H,D,He transport is complicated by the precipitation of lithium hydrate and lithium deuteride in a liquid lithium solution and the electronic excitation by high energy ion bombardment. Although our experimental measurements are primarily targeted at net "recycling" coefficient, a primary objective of our research is to develop predictive multiscale modeling capability to understand the underlying physics and chemistry. This is critical for guiding the design and optimization of an eventual fusion reactor first wall. In this poster, we will outline the various physical/chemical processes of interest and uncertainty, and present a multi-scale modeling approach to quantify them.

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# Electrostatic Ion Temperature Gradient Modes in the Reversed Field Pinch Geometry

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## Abstract

In this work, the linear stability of ion temperature gradient (ITG) modes in a typical RFP regime has been investigated. The low safety factor and negative shear regime typical of reversed field pinch plasmas (RFP), poses a sparsely investigated but interesting regime.

There is renewed interest in electrostatic fluctuations in the RFP because recently it has been found that global tearing modes, which normally dominate core transport in the RFP, are largely stabilized when current profile is externally controlled. This may allow small-scale modes to become a significant factor of RFP confinement.

Drift modes, resistive g-modes and rippling modes are too weak to explain observations. We investigate the possibility that the linearly unstable slab and toroidal ion temperature gradient (ITG) modes might be responsible for transport in these scenarios.

In this work, we examine the linear stability of ITG modes using GYRO in a typical RFP flux tube. To assess and understand the results, we make comparisons with fluid models, gyrokinetic theory and prior analytical calculations. We evaluate the growth rate and its parametric scaling with various parameters, which reveal several intriguing results. Higher ion temperature for example, is not always de-stabilizing and the shear scaling differs considerably from simple slab theory. Finally, using mixing length arguments, we determine if this instability is relevant to the small-scale RFP turbulence.

# Behavior of Fluid Modes for Arbitrary Relativistic Temperatures

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A new covariant fluid model for magnetized plasmas, incorporating anisotropy in both temperature and heat flow, is used to study the behavior of various fluid modes as the plasma temperature varies from moderate to ultra-relativistic values. General dispersion relations have been derived, as functions of  $z = mc^2/kT$ , providing analytic results for asymptotic limits of the linearized model. The model employed is a significant improvement over previous covariant fluid models (Hazeltine and Mahajan (2002)). In particular, it allows for independent transport of parallel and perpendicular thermal energy; it is shown that models which ignore this distinction give unphysical results. Furthermore, it is shown that distinct, fully covariant models that coincide at non-relativistic temperatures can diverge from each other as the temperature becomes relativistic. In particular, certain covariant descriptions that agree with well-known non-relativistic fluid equations at moderate temperatures yield unphysical results in the relativistic limit.

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# Conjugate Variable Method in Hamilton-Lie Perturbation Theory Applied to Plasma Physics

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The conjugate variable method, which is an essential ingredient in the path-integral formalism of classical statistical dynamics, is used in order to apply the Hamilton-Lie perturbation theory to a system of ordinary differential equations that does not have the Hamilton dynamic structure. The method endows the system with the Hamilton dynamic structure by doubling the independent variables; hence the canonical Hamilton-Lie perturbation theory becomes applicable to the system. The method is applied to two classical problems in plasma physics, a non-linear oscillator that can explode and the guiding center motion of a charged particle in a magnetic field, to demonstrate the effectiveness and to study the property of the conjugate variable method. It is also discussed to apply the present method to eigenvalue problems in MHD stability analysis.

## A new improved normal form for linear conversion

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We consider the resonant interaction of two linear waves in nonuniform plasma and derive an improved normal form that can be used in ray tracing algorithms. We assume that, away from the conversion itself, the waves are well described by WKB (ray tracing) methods. In ray phase space, conversion occurs when a ray of one wave type intersects the dispersion manifold of the other wave type, thereby exciting a converted ray. In this work, we always consider rays associated with the *uncoupled* waves, a precise definition of which is one of the contributions of this work. We define the uncoupled wave operators as those operators whose symbols appear on the diagonal of the 2x2 coupled wave equation when we cast the dispersion matrix into normal form [1]. In the normal form representation, the diagonals Poisson-commute with the off-diagonals. Hence, if we use the diagonals as ray Hamiltonians, the off-diagonals are ray invariants and have a natural physical interpretation as the coupling strength between the two modes. The outgoing amplitudes and phases of the transmitted and converted rays can be computed in terms of the coupling strength. Requiring that the diagonals Poisson-commute with the off-diagonals determines the polarizations up to a phase; hence this choice of normal form uniquely defines what we mean by the uncoupled wave operators. Here we show how to find the local polarization basis of the uncoupled waves *while following a ray*. These polarizations evolve adiabatically, while those associated with the eigenvalues of the dispersion matrix lose their adiabatic character in the conversion region. This is done for a generic conversion with no assumption other than smoothness of the entries of the dispersion matrix. In prior work, it was shown that it is always possible to locally cast the original NxN matrix operator governing the wave evolution into a local 2x2 form which governs the two resonant wave types [2]. Here, we consider the problem of how to incorporate the normal form definition given above into a ray tracing algorithm. This is done by introducing a variational principle for the coupled evolution of rays and polarization vectors for the two interacting wave types. We show how to incorporate the normal form constraint into the ray variational principle using Lie group methods, and provide a complete description of how to derive the evolution equations for the ray-polarization system.

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# Non-fluid Micro-Reconnecting Modes and Relevant Experimental Observations<sup>1</sup>

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## Abstract

The class of modes whose natural transverse (to the magnetic field) scale distance is  $d_e = c/\omega_{pe}$  that (i) do not depend on the effects of finite electron gyroradius for their radial localization, (ii) produce adjacent strings of magnetic islands, and (iii) are driven by the transverse electron temperature gradient, are not described by the fluid approximation but require a phase space description for the electron population dynamics [1]. This means that  $\omega \sim k_{\parallel} v_{te}$  and  $k_{\perp} d_e \sim 1$ ,  $\omega$  being the mode complex frequency that is of the order of  $k_{\perp} c T_e / (e B r_{Te})$ ,  $k_{\parallel}$  and  $k_{\perp}$  are the longitudinal and transverse mode numbers, and  $1/r_{Te} \equiv -(\mathrm{d} \log T_e / \mathrm{d} r)$ . The implied ordering,  $\beta_e \sim 2r_{Te}^2 / L_s^2$  where  $\beta_e$  is the ratio of electron thermal energy density to the magnetic energy density and  $L_s$  is the scale distance of the magnetic shear, is regarded as relevant to current experiments. We consider these modes to be the most natural candidates for those observed with the Princeton NSTX device [2]. The electromagnetic drift-kinetic equation is adopted for the electrons and leads to a second order differential (dispersion) equation with complex inhomogeneous coefficients. These modes can produce an effective transverse thermal diffusion that is of the order of  $(d_e / r_{Te}) c T_e / (e B)$  and reduce the longitudinal electron thermal conductivity, an effect [3] that allows the excitation of mesoscopic drift tearing modes in high temperature regimes.

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## Ideal MHD Spectrum of the ARIES Compact Stellarator Configuration\*

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Ideal MHD stability calculations for variations of a compact stellarator equilibrium show a complex spectrum of ideal instabilities. The ARIES compact stellarator reactor design [1] is a three period stellarator with a major radius of 7.75 m,  $B_0 = 5.7$  T, and an aspect ratio of 4.5, optimized with engineering coil constraints for magnetic well and alpha particle confinement. A reference equilibrium is computed from the VMEC code [2] and variations with  $\beta$  and rotational transform,  $\iota$ , were studied to determine the sensitivity of the stability using the TERPSICHORE code [3]. At  $\beta = 4.06\%$ , the equilibrium is slightly unstable with a conformal wall at 2.05 times the minor plasma radius to a “symmetry-preserving” (coupled toroidal mode numbers with  $n = 3k$ ,  $k = \pm 1, \pm 2, \dots$ ), predominantly  $m/n = 9/6$  mode peaked at the edge, and a symmetry breaking ( $n \neq 3k$ ) global  $3/2$  mode. The growth rates are small indicating proximity to the  $\beta$  limit. At higher  $\beta$ , several modes become unstable and for  $\beta = 8.2\%$  there are three external and two internal symmetry breaking modes, and one unstable symmetry-preserving mode. A scan over conformal wall position showed that the symmetry-preserving mode and the first three symmetry-breaking modes are stabilized by a closer wall. The remaining symmetry-breaking  $2/1$  and  $4/2$  modes are still unstable with a wall on the plasma but have very low growth rates. The sensitivity to the presence of the  $\iota = 2/3$  surface at the edge of the plasma in the reference equilibrium was also investigated. With the  $2/3$  surface removed at constant  $\beta$ , the equilibrium is marginally unstable to an  $m/n = 13/5$  mode peaked in the core. On increasing  $\iota$  so that the  $\iota = 2/3$  surface moves deeper into the plasma, the  $3/2$  mode is destabilized. This mode requires a conformal wall within 1.1 times the average plasma minor radius for stability. In summary, while the reference design with  $\beta = 6.5\%$  is above the calculated limit, given the resilience of stellarators to weakly unstable modes this seems reasonable; LHD and W7-AS results indicate that this level of internal instability is tolerated in stellarators. Alternatively, an increase in major radius to 8.25 m would lower  $\beta$  to  $\sim 4\%$  with only a small penalty.

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# Investigations of Multigrid implementation of precondition within the extended MHD NIMROD code.

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Considerable effort has been put forth in efforts to simulate Edge Localized Modes (ELMs) with nonlinear extended magnetohydrodynamic codes in order to understand the effects of ELMs on plasma confinement properties[8]. These simulations have led to new numerical challenges. The disparate time scales demand implicit treatment, but the required operators for the two-fluid physics leads to non-symmetric matrices. The broad linear spectrum means greater resolution is required, further increasing the condition number of the matrices. Thus, an effective preconditioner is necessary. SuperLU, a direct linear solver, has proven to be an effective preconditioner for NIMROD's three-dimensional matrices[7]. Because the majority of the simulation time is spent in matrix solves, effective use of computational resources requires effective linear solves. Multigrid methods, while more than 30 years old [2, 3], are currently regarded as the most efficient solvers [5] for a wide variety of problems. For elliptic problems, they have been shown to be the fastest algorithms. Multigrid methods are *scalable* (or *optimal*) because they can solve a linear system with  $N$  unknowns with  $O(N)$  operations. In addition to this favorable scaling, the fundamental idea of operating at different scales can also be exploited to minimize the computations and work well for parallel computing [4]. The result of such an efficient algorithm is the ability to solve a larger problem on proportionally more processors in nearly the same amount of time. We currently implement the multigrid linear solver *hypre* via an interface to the PETSc numerical suite, which also can interface Super LU. We will present processor scaling results comparing SuperLU and *hypre* as preconditioners for the (2, 1) tearing mode benchmark case [6] and recent ELM milestone case [1].

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## Unitary Mesoscopic PetaScale Computational Models for Nonlinear Physics - excitation of Kelvin waves in vortex reconnection

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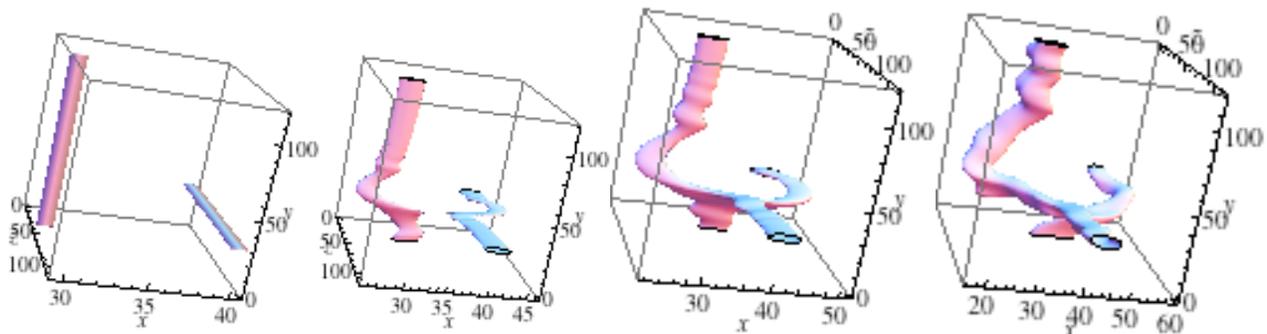
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Lattice models of Nonlinear Physics have proven to be an ideal mesoscopic computational tool. In particular, lattice Boltzmann schemes for fluid and MHD turbulence are viewed as ideal candidates for petascale computations. The basic algorithm involves streaming and BGK collisional relaxation –to be augmented by a discrete H-theorem that provides numerical stability for arbitrary small transport coefficients. This entropic lattice Boltzmann algorithm has been exploited for fluid turbulence and work is in progress to generate such an algorithm for MHD.

An alternate lattice mesoscopic representation involves qubits at each spatial node of the lattice. Unlike lattice Boltzmann schemes, these qubits are locally entangled by unitary collision operators and the post collision probabilities are then streamed to the neighboring nodes by unitary streaming operators. This streaming spreads the quantum entanglement throughout the lattice. While these unitary algorithms can be run on quantum computers, they are also ideally parallelized on classical computers.

Here we present a unitary model of the 3D Gross-Pitaevskii (GP) equation, an equation that describes the ground state wavefunction of a BEC state. The GP equation, which is related to the nonlinear Schrodinger equation, is a conservative system. Nevertheless vortex reconnection occurs without the presence of viscosity or resistivity. Moreover Kelvin waves are emitted during the reconnection and propagate along the vortex tubes. What is surprising is that these simulations require only 2 qubits/spatial node – even for 3D algorithms. We are extending these ideas to determine unitary representations for 3D MHD turbulence.



Figures: Two quantized vortices with initial perpendicular orientation, reconnect even without viscosity or resistivity and then break apart with the emission of Kelvin waves.

## Modelling observations of mode polarisation from MAST

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The Mega-Amp Spherical Tokamak [1] is equipped with “OMAHA” Mirnov coils that enable the measurement of radial, vertical and toroidal perturbations (denoted below by subscripts  $r$ ,  $z$ ,  $t$ , respectively) at each probe’s location. We can write the perturbation at a particular frequency  $\omega$  as follows ( $\{\delta B_j \geq 0, \theta_j\}$  and  $\psi$  are constants):

$$\delta \mathbf{B} = \sum_{j \in \{r, z, t\}} \mathbf{e}_j \delta B_j \cos(\omega t + \theta_j) = \delta \mathbf{B}_{\text{major}} \cos(\omega t + \psi) + \delta \mathbf{B}_{\text{minor}} \sin(\omega t + \psi)$$

The orientation of the mode is characterised by the angle made by the major and minor axis vectors  $\delta \mathbf{B}_{\text{major}}$  and  $\delta \mathbf{B}_{\text{minor}}$  with the equilibrium field  $\mathbf{B}_0$ . The mode’s polarisation is given by the ratio of the axis lengths  $R = |\delta \mathbf{B}_{\text{minor}}| / |\delta \mathbf{B}_{\text{major}}|$ :  $R = 1$  implies circular polarisation;  $R = 0$  implies plane polarisation. The sign of  $\hat{e}_\phi \cdot (\delta \mathbf{B}_{\text{major}} \times \delta \mathbf{B}_{\text{minor}})$  determines whether the mode is left- or right-polarised with respect to the toroidal direction.

Observations which indicate that measurements of orientation and polarisation empirically distinguish various families of modes will be presented. We will then describe ongoing work to model these observations in terms of eigenmode calculations and discuss whether the modelling and experimental observations are consistent.

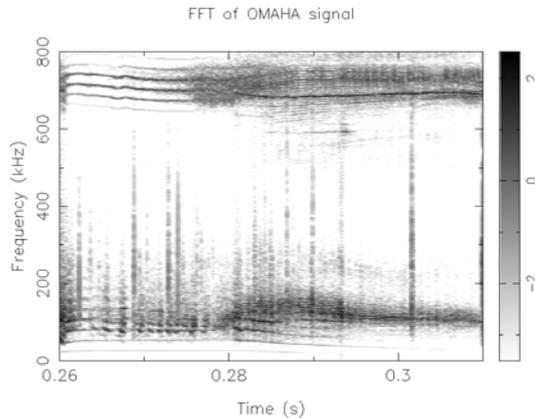


Fig: Spectrum of magnetic perturbations in NBI-heated MAST shot 18690 showing one group of modes at 100 kHz and another group at 700 kHz.

Mode type	TAEs	CAEs
Frequency (kHz)	(65, 145)	> 600
Major angle (rads)	> 1.0	< 0.7
Minor angle (rads)	> 1.0	> 1.0
Axis length ratio	(0.4, 0.8)	(0.2, 0.5)
Mode number	$0 < n < 8$	$ n  > 5$

Table: The two mode families robustly fall into one of two categories, provisionally identified as TAEs and CAEs on the basis of the modes’ orientation.

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# Formation of the velocity shear layer in the edge of a diverted tokamak

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The edge of diverted tokamaks typically exhibit strong flows. These flows are believed to play a key role in the transition to the H mode of confinement. In the H mode, the flows are especially large and appear to govern both the width of the pedestal and its stability.[1]

In the present work we consider the effects of the edge geometry on transport and on plasma rotation. We focus in particular on the null lines associated with a divertor. The presence of the null lines causes strong poloidal variations in the diffusion of particles and momentum. The resulting pressure variations within flux surfaces causes a poloidal torque. The consequent plasma rotation is known as the Stringer spinup.[2] Strauss has shown that the spinup increases with pressure diffusivity but is opposed by sound wave propagation.[3]

We restrict attention to the inner part of the plasma edge where parallel equilibration is faster than perpendicular transport. This makes it possible to reduce the fluid conservation laws to a set of one-dimensional equations for the pressure, parallel velocity, electric field, and current. These 1-D transport equations determine the profile functions that enter into the the Grad-Shafranov equilibrium equation. They depend on the geometry through coefficients representing averages over the flux-surfaces of geometrical quantities such as the poloidal field amplitude and the field-line curvature. Our model includes the terms in the ion viscous stress tensor that are known to give rise to the Stringer spin-up. Integrating the transport equations analytically results in a set of coupled equations for the fluxes that specify the electric field as well as its effect on the fluxes of particles and parallel momentum. Using an analytic model for the equilibrium,[4] we investigate the behavior of the solution of these equations in the approach to the separatrix where the conditions for their applicability break down.

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# Numerical Experiments on the Drift Wave-Zonal Flow Paradigm for Nonlinear Saturation\*

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The ITG-adiabatic electron (-ae) gyro-landau-fluid simulations of the early 90's [1,2] established that the ExB shear from toroidally symmetric ( $n=0$ ) "radial modes" provide the dominant nonlinear saturation mechanism for drift wave turbulence. This is loosely referred to as the "drift wave-zonal flow paradigm" for nonlinear saturation [3]. Actually the radial modes (labeled by a radial wave number  $k_x \neq 0$ ) have several components: a residual or zero frequency "zonal flow" part and an oscillatory "geodesic acoustic mode" (GAM) part. The ExB residual flow is nearly in balance with the ion pressure diamagnetic flow [4], hence radial modes have little net fluid flow. The time average residual flow shears result in equilibrium "profile corrugations" near low order rational surfaces [5]. The zonal flows are weakly damped only by ion-ion collisions (which we ignore) and the GAM's are strongly Landau damped only at low to moderate  $q$ . At high- $q$  the Hinton-Rosenbluth residual flow [6] vanish and only the GAM's remain. Curiously none of the rich physics of radial modes has been used in nonlinear saturation models which refer only to the linear growth rates of the [ $n > 0$ ,  $k_x = 0$ ] transport producing modes. What is the difference between the residual zonal flow saturation in the low- $q$  (core) and GAM saturation in the high- $q$  (edge)? Do the mechanisms and "paradigm" apply equally well to TEM and ETG turbulence?

To explore these and other questions, we have done "numerical experiments" with GYRO by modifying components of the nonlinear coupling convolution and modifying the linear physics of the radial modes *while keeping the linear physics of the finite- $n$  modes unchanged*. In the latter we modify the " $q$ " in the radial modes to trade off the zonal flows versus the GAMs, modify the " $1/R$ " curvature in the radial modes to vary the GAM frequency, as well as the turn off the radial mode Landau damping. We find: (1) the [ $n_1 \neq 0$ ,  $n_2 = 0$ ,  $n = n_1$ ] *nonlinear coupling triads* account for nearly all of the nonlinear saturation; (2) the ExB shear ( $\delta\phi -$ ) components of the radial modes nonlinearly stabilize while the diamagnetic ( $\delta f -$ ) components nonlinearly destabilize; (3) transport increases as the zonal flow residuals and GAM damping decrease; (4) transport decreases as the GAM frequency decreases; and (5) the transport is largely unchanged without GAM Landau damping. From contour plots of the time-average nonlinear transfer function [ $T(\vec{k}) = -2\gamma_k E(\vec{k})$  with  $\sum_k T(\vec{k}) = 0$ ], we determine if (6) the radial modes  $k_y = 0$ ,  $k_x \neq 0$  provide a small net sink of turbulent energy  $E(\vec{k})$  from GAM Landau damping. Finally contrary to previous work, we find all these mechanisms and "the paradigm" are universal: Conclusions (1-5) hold equally well for ITG-ae, ITG/TEM, and purely TEM transport; and (1-2) appear to hold for ETG transport.

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# **An Analytic Study of the Perpendicularly Propagating Electromagnetic Drift Instabilities in the Magnetic Reconnection Experiment**

Yansong Wang

A local linear theory is proposed for a perpendicularly propagating drift instability driven by relative drifts between electrons and ions. The theory takes into account local cross-field current, pressure gradients and modest collisions as in the MRX. The unstable waves have very small group velocities in the direction of pressure gradient, but have a large phase velocity equal to the relative drift velocity between electrons and ions in the direction of cross-field current. By taking into account the electron-ion collisions and applying the theory in the Harris sheet, we establish this instability could be excited in the center of the Harris sheet and will have enough e-foldings before it propagates out of the unstable region.

## Couplings between toroidal momentum and heat transport in tokamaks

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Global gyrokinetic simulations have been carried out to investigate turbulence driven momentum and energy transport for realistic experimental parameters. For neoclassical transport, it is found that the effective toroidal momentum diffusivity is much smaller than the ion heat diffusivity, i.e.,  $\chi_\phi/\chi_i \sim 0.1 - 0.01$  due to no banana orbit enhancement, as is also expected from neoclassical theory. Our turbulence simulations verify that there exists strong coupling between ion momentum and heat transport for ion temperature gradient (ITG) driven turbulence, and the effective  $\chi_\phi/\chi_i$  is on the order of unity. This is in a broad agreement with experimental observations in conventional tokamaks where low-k fluctuations are believed to be responsible for a high level of plasma transport. On the other hand, NSTX H-mode plasmas obtain a different regime where the toroidal momentum transport appears to show more close connection with the anomalous electron heat transport. Ongoing simulations are focusing on investigating trapped electron mode (TEM) driven heat and momentum transport and their relationship in NSTX plasmas. Various numerical experiments are performed to identify the role of residual stress and pinch effect in the momentum transport. We also found that residual turbulence may survive the dissipation of a strong mean **EXB** flow shear and drive a finite momentum flux. This finding may offer a possible explanation to recent experimental observation that the toroidal momentum transport remains highly anomalous, even while the ion heat flux is reduced to a neoclassical level. Work supported by U.S. DOE Contract DE-AC02-76-CH03073 and the SciDAC GPS-TTBP project.

## Neoclassical Viscosities and Anomalous Flows in Stellarators\*

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We discuss initial work to use neoclassical viscosities calculated with the PENTA code [1,2] in a transport model that includes Reynolds stress generation of flows [2]. The PENTA code uses a drift kinetic equation solver to calculate neoclassical viscosities and flows in general three-dimensional geometries over a range of collisionalities. The predicted neoclassical viscosities predicted by PENTA can be flux-surfaced average and applied in a 1-D transport model that includes anomalous flow generation. This combination of codes can be used to test the impact of stellarator geometry on anomalous flow generation.

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# Chaotic transport in a Reversed Field Pinch <sup>1</sup>

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## Abstract

Particle transport in a toroidal plasma confinement device can be non-diffusive when magnetic chaos is present but the system is not too far above stochastic threshold. In some conditions a phenomenological fit to the results gives a diffusion constant and also a convective inward pinch velocity.<sup>2</sup> The combination of diffusion and pinch is actually an expression of the subdiffusive and nonlocal nature of the transport, brought about by the existence of a spectrum of long distance Levy flights.<sup>3</sup> The effect is illustrated by numerical modelling of the magnetic structure<sup>4</sup> and associated particle transport in conditions relevant for the reversed-field pinch experiment at the Consorzio RFX.<sup>5</sup> A nonlocal transport model using the Montroll equation<sup>6</sup> with a kernel derived from the guiding center simulations is constructed. A two fluid model is used, representing the densities of trapped and passing particles, since only passing particles probe the stochastic field to any distance, and trapped particle motion is diffusive.

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# Exact integral identities for the Sinh-Poisson equation

Ryan White

An integral identity which must be satisfied by any solution to the Sinh-Poisson equation is derived. The derivation is based on a famous analysis [G. H. Derrick, *Journal of Mathematical Physics* 5, 1252 (1964)] which demonstrates the impossibility of local solutions (solitons) to a wide class of nonlinear field equations. The method of proof employs a scale variation of the action integral that yields an integral identity which is inconsistent with energy conservation. The method used to derive the integral identity is very general and can be immediately applied to any differential equation derivable from an action principle. However, the scale change used is not compatible with a finite boundary. Therefore the present work employs a distinct but related variation that is sufficiently general to be used on any compact boundary and still allows for the derivation of a nontrivial integral relation. This technique is applied to the Sinh-Poisson equation which governs the equilibrium electrostatic potential for a fully-ionized plasma. We consider both a square and circular boundary and derive an integral relation which must hold for arbitrary boundary data.

# **Thermonuclear Dynamo inside an Alfvén Black Hole**

Friedwardt Winterberg

As in an acoustic black hole where the fluid is moving faster than the speed of sound and where the sound waves are swept along, in an Alfvén black hole the plasma is moving faster than the Alfvén velocity, with the Alfvén waves swept along and eliminated as the cause of the magneto hydrodynamic instabilities. To realize an Alfvén black hole, it is proposed to bring a plasma into rapid rotation by radially arranged lumped parameter transmission lines intersecting the plasma under an oblique angle. The rotating plasma slides frictionless over magnetic mirror fields directed towards the rotating plasma, with the mirror fields generated by magnetic solenoids positioned at the end of each transmission line. It is then shown that, with this configuration one can realize a thermonuclear dynamo, which also can serve as the analogue of a magnetar.

# Full-Wave Electromagnetic Field Simulations of Lower Hybrid Wave Propagation in ITER Relevant Regimes\*

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Lower hybrid (LH) waves have the attractive property of damping strongly via electron Landau resonance on relatively fast tail electrons at  $(2.5 - 3) \times v_{te}$ , where  $v_{te} = (2T_e/m_e)^{1/2}$  is the electron thermal speed. Consequently these waves are well-suited to driving current in the plasma periphery where the electron temperature is lower, making lower hybrid current drive (LHCD) a promising technique for off-axis ( $r/a \geq 0.60$ ) current profile control in reactor grade plasmas. It is therefore important to develop a predictive capability in this area. Advanced simulation codes in this area such as CQL3D-GENRAY [1], treat wave propagation in the geometrical optics limit using toroidal ray tracing, which is known to neglect important effects on the wave spectrum, due to focusing and diffraction [2]. In order to accurately assess these effects we have developed a version of the TORIC full-wave electromagnetic field solver valid in the lower hybrid range of frequencies (LHRF) [3, 4].

At the density and magnetic field, characteristic of present day devices such as the Alcator C-Mod and the ITER devices [ $B_0 \approx 5$  T,  $n_e \approx 1 \times 10^{20} \text{ m}^{-3}$ ], the perpendicular wavelengths of propagating LH waves (a few mm) impose challenging demands on the numerical resolution requirements of full-wave spectral solvers such as TORIC. Therefore, the resulting calculations can only be carried out on mid-size to massive computing clusters. The new LH full-wave solver TORIC-LH solves for the propagation of slow and fast waves in the LHRF with an electric field boundary condition at the wall chosen to couple the electrostatic LH slow wave [3, 4]. A parallel matrix inversion algorithm was adapted [4] to this solver and has been tested successfully.

Results will be shown for parameters typical of LHRF experiments on the Alcator C-Mod device that demonstrate significant spectral broadening of the injected wavenumber spectrum due to diffraction effects, resulting in more off-axis electron absorption than found with conventional ray tracing treatment. We will also discuss results related to coupled Fokker-Planck and full-wave calculations in which a nonthermal electron distribution function is used in the full-wave solver.

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# Breakup of invariant tori in the extended standard nontwist map

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## Abstract

Recently, the magnetic field line structure of reversed magnetic shear tokamaks has been modeled by an area-preserving nontwist map that includes non-integrable perturbations describing ergodic magnetic limiters.[1] An expansion around the equilibrium shearless curve (corresponding to the main transport barrier in the model) showed that map is locally equivalent to the standard nontwist map with an additional perturbation due to the limiter.[2] For this *extended* standard map we investigate the details of the breakup of invariant tori with winding number of the inverse golden mean using Greene's residue criterion.

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# Nonlinear wave couplings in an inhomogeneous plasma

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## Abstract

The nonlinear dynamics of electrostatic waves near the ion gyro-frequency and lower hybrid frequency in an inhomogeneous plasma is simulated via both the  $\delta f$  and full particle-in-cell (PIC) simulations using the VORPAL Computational Framework (C. Nieter and J. R. Cary, *J. Comp. Phys.*, 2004). Linear mode transform from an electron plasma to an ion Bernstein wave (IBW) is observed. In addition, the nonlinear wave couplings between different waves are also studied. It is shown that due to the self-interaction of the incident wave, the second harmonic mode can be generated, and a significant portion of the wave energy could be transferred from the fundamental higher harmonic modes. The deposition profile may be significantly affected by this nonlinear process.

# A study of full-wave and ray-tracing methods for a simple model of multi-dimensional mode conversion

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Mode conversion can occur in a nonuniform plasma when two waves of different character are locally resonant. Jaun et al. have recently developed a numerical ray-tracing algorithm for realistic tokamak models that accounts for the ray splitting that occurs at conversions [1,2]. Here we report on our efforts to carry out a direct comparison of ray-based and full-wave methods by considering a simple model consisting of a pair of coupled wave equations in two spatial dimensions. We did this for two different models. The first model is taken to be two coupled wave equations in two spatial dimensions of the form

$$\begin{pmatrix} \hat{D}_1 & \eta \\ \eta & \hat{D}_2 \end{pmatrix} \begin{pmatrix} \psi_1(x,y;t) \\ \psi_2(x,y;t) \end{pmatrix} = 0, \quad \hat{D}_k = \partial_t^2 - \nabla \cdot c_k^2(x,y) \nabla, \quad (k=1,2),$$

with spatially dependent wave speeds,  $c_1(x,y)$  and  $c_2(x,y)$ . These wave speeds are distinct for almost all  $(x,y)$  space, and are equal only along a line where conversion occurs. We launch a WKB-type wave packet in channel 1 and study its effect upon channel 2. In the second model, the wave in channel 1 has  $\hat{D}_1$  in the same form as above, but channel 2 is now a simple model for minority-ion gyroresonance  $\hat{D}_2 = i\partial_t - \Omega(x,y)$ , where  $\Omega$  is the local gyrofrequency of the minority species. For harmonic solutions in one spatial dimension, this can be shown to be equivalent to the Budden model [3]. In both of our models, outgoing WKB boundary conditions are used. From the full-wave output, we compute the initial energy density as a function of position and consider its evolution along a family of rays, including the ray splitting associated with conversion. These full-wave results will then be compared to the ray-based predictions.

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# Characteristic time scales in microturbulences

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Most of existing transport models are based on some form of quasilinear theory (QLT), the validity of which depends on the ordering of several characteristic time scales of the turbulence. In particular, the Chirikov stochasticity parameter  $S > 1$  and the turbulence Kubo number  $K < 1$  are required for the validity of QLT. We report a verification of the quasilinear transport model through global gyrokinetic particle simulation using the gyrokinetic toroidal code (GTC). Relevant kinetic and fluid time scales which enter  $K$  and  $S$  are systematically examined in a comparative study of turbulence driven by electron temperature gradient (ETG) instability, ion temperature gradient (ITG) instability, and collisionless trapped electron mode (CTEM) instability. Transport processes for both active and passive species are studied. The simulation results provide the foundation for the ordering of time scales in the transport models and clarify the validity regimes of the quasilinear transport models.

GTC simulation found that ETG transport is proportional to the local fluctuation intensity, and phase-space island overlap leads to a diffusive process with a time scale comparable to the parallel wave-particle decorrelation time, determined by the fluctuation spectral width in  $k$ -parallel. This kinetic time scale is much shorter than the fluid time scale of eddy mixing, due to the fast transit velocity of the electrons, and so it is this time scale which enters the effective Kubo number. Quasilinear calculation of the electron heat conductivity matches very well with the simulation value.

The kinetic parallel spectral transit time scale is also shorter than the fluid time scale in the GTC simulation of ITG turbulence indicating that the ion transport is also regulated by parallel wave-particle decorrelation. Nonlinear simulations indicate that electron thermal transport in the ITG turbulence is driven by nonresonant interactions. The separation of transport mechanisms and levels between the active species (ions) and the passive species (electrons) is clearly demonstrated in the ITG turbulence.

It is instructive to contrast the instability drive and transport process in ITG and ETG turbulence to that of the CTEM turbulence. The detuning of the precessional resonance is much weaker than that in ITG and ETG. GTC simulation indicates that the kinetic resonance de-tuning and fluid mixing time scales in CTEM turbulence are comparable. Both electrons and ions can be active species in CTEM turbulence; however, the transport mechanisms are different.

$[\frac{L_{ne}}{v_i}]$	$\tau_{wp} = \frac{4\chi}{3\delta v_r^2}$	$\tau_{\parallel} = \frac{1}{\Delta k_{\parallel} v_i}$	$\tau_{\perp}$	$\tau_{eddy}$	$\tau_{rb}$	$\tau_{au}$	$\frac{1}{\gamma}$
<i>ITG(A)</i>	1.7	1.8	2.0	4.9	21	7.2	9.1
<i>ETG</i>	1.3	1.7	2.5	13.4	139	110	11
<i>TEM</i>	2.4	N/A	14.4	4.85	57	5.9	4.0

Table 1: Time scales in ITG, ETG and CTEM turbulences

# A new non-random scheme for nonlinear collision operation in a particle code<sup>1,2</sup>

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The importance of the kinetic simulation is ever increasing in understanding plasma turbulence, transport and equilibrium at the first principles level. The Lagrangian particle-in-cell technique is one of two major methods for kinetic studies, together with the Eulerian continuum technique. The conventional Monte Carlo collision schemes, successfully used in many particle codes for decades, possess some incurable shortcomings. The random particle noise generated by Monte Carlo collisions severely limits the size of the electron simulation time step [1] and prohibits the use of an advanced nonlocal particle push techniques. Optimization of the computing time can be limited by this shortcoming. In addition, a Monte Carlo collision operation does not limit the weight growth in a delta-f particle code, while a physical collision operation should. This shortcoming may impose a limit in the total simulation time length. Problems associated with these phenomena have caused controversy in the interpretation of the particle simulation results and have been in hot debate for several years.

In this work, a new method to implement the nonlinear Coulomb collision process in a particle code is presented, which can resolve the above shortcomings. The new method is deterministic. It does not use the Monte Carlo random scattering. Gyrophase angle is neglected, assuming a strong magnetic field. The new method uses a particle-in-cell technique in the two dimensional velocity space ( $v$ -space), 1) by scattering the particle information to the  $v$ -space grid, 2) by solving the non-linear Fokker-Planck collision operation on  $v$ -space grids using a constant volume method, and 3) by gathering the collision information back to the particles to diffuse the particle weights accordingly. Near-by physical cells are combined to promote the weight smoothing in real space, too. Even though the main purpose of the present work is to improve the Coulomb collision technique in a particle-in-cell kinetic code, the Fokker-Planck operation part can be used in a continuum kinetic simulation code. Other Fokker-Planck operation scheme, such as Hinton's recent Langevin approach [submitted to Phys. Plasmas], can also be adopted to replace the Fokker-Planck operation part in the present new scheme. This scheme is more economical than a conventional binary nonlinear Monte Carlo collision scheme, with a more accurate conservation property. Verification of the new collision operation scheme will be presented, by reproducing the well-known neoclassical transport phenomena in a particle-in-cell tokamak code.

<sup>1</sup>In collaboration with G. Park, S. Ku, C.S. Chang, H. Weitzner, L. Greengard, NYU; and T. Lao, D. Keyes, Columbia University

<sup>2</sup>Work supported by US DOE

# Locked kink mode $m/n = 1/1$ during vertical disruption events<sup>1</sup>

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The locked (for 10-20 msec) kink mode  $m/n = 1/1$ , observed during vertical disruption events on JET when the safety factor  $q \simeq 1.5$  is far above the Kruskal-Shafranov limit, represents one of the most puzzling MHD phenomenon. Recently significance of understanding of this mode became obvious due to prediction of large sideways forces on the vacuum vessel if JET vertical disruptions were scaled to ITER.

Here, theory of the locked  $m/n = 1/1$  kink mode is given. It is shown that the electrical contact of the plasma with the in-vessel conducting surfaces can change the stability conditions of the plasma. As a result, the stable according the conventional idealized theory plasma becomes unstable if it can share the surface currents, excited by the kink mode, with the conducting surfaces. This explains the existence of the kink mode at  $q > 1$ . Also, the theory determines the amplitude of the sideways forces on the in-vessel components due to  $m/n = 1/1$  kink mode as well as the means of their mitigation.

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# Transport of Energetic Particles by Microturbulence in Magnetized Plasmas

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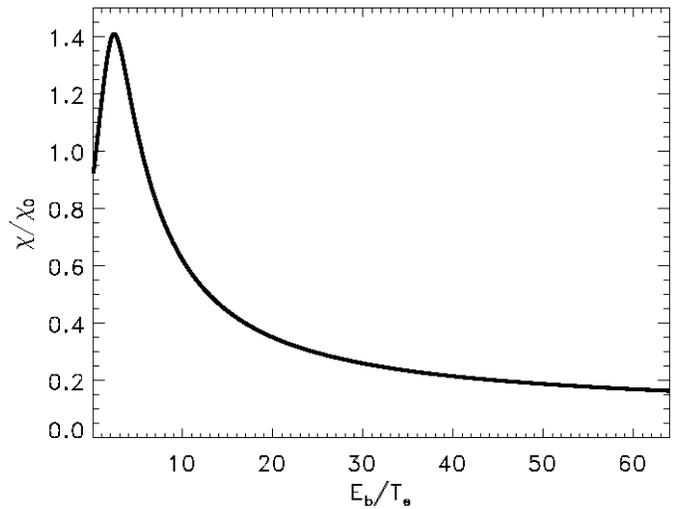
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The confinement of energetic particles (NBI beam ions, RF heating tails,  $\alpha$ -particles etc) is a critical issue in the burning plasmas such as ITER. Theoretical and experimental studies<sup>1</sup> have indicated that energetic particles do not suffer a large transport due to the microturbulence excited by the thermal particles. However, a recent experiment<sup>2</sup> shown some evidences of possible re-distribution of NBI beam ions due to the microturbulence. This leads to current debates in the theory and simulation of the energetic particle transport by the microturbulence.

To resolve this apparent discrepancy<sup>1,2</sup>, we study the effects of the microscopic ion temperature gradient (ITG) turbulence on the energetic particle transport in large scale simulations using the global gyrokinetic toroidal code (GTC). The ion radial spreads as functions of energy and pitch angle are measured in the steady state ITG turbulence. The probability density function of the radial excursion is found to be very close to a Gaussian, indicating a diffusive transport from a random walk process. The radial diffusivity as a function of energy and pitch angle can then be calculated using the random walk model. We find that the diffusivity decreases drastically for high energy particle due to the averaging effects of the large gyroradius and banana width, and the fast decorrelation of the energetic particles with the waves. By performing the integration in the phase space, we can calculate the diffusivity of a passive species with any distribution function. The NBI beam ions satisfy a slow-down distribution function parameterized by the born energy ( $E_b$ ) and the electron temperature ( $T_e$ ). Shown in Fig. 1 is the NBI beam ion diffusivity calculated from GTC simulations of the ITG turbulence. It shows that the NBI beam ion diffusivity decreases rapidly for  $E_b/T_e < 20$  and more gradually for  $E_b/T_e > 20$  to a very low level. This result may explain the differences between the older experiments<sup>1</sup> with a higher energy of energetic particles and the newer experiment<sup>2</sup> with a lower energy of energetic particles.

**Fig. 1** NBI beam ion diffusivity normalized by the turbulence heat conductivity  $\chi_0$  as a function of the born energy ( $E_b$ ) and the electron temperature ( $T_e$ ).



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# Linear gyrokinetics and kinetic investigation of resistive wall mode stability in ITER

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## Abstract

We outline our newly derived gyrokinetic theory<sup>1</sup> and discuss its impact on kinetic investigations of the stability of MHD modes, especially the resistive wall mode in ITER. With a sufficiently high order equilibrium distribution function and with the gyrophase-dependent part of the perturbed distribution function included, our formalism contains the following new features as compared to the conventional gyrokinetic theory: (1) the  $\mathbf{J}_0 \times \delta\mathbf{B}$  effect in the perpendicular momentum equation is retained self-consistently; (2) additional source terms in the gyrophase-averaged gyrokinetic equation are brought back, so that the MHD parallel equation of motion can be retrieved in the proper limit; and (3) additional FLR effects are recovered. The success in recovering full MHD with our newly derived gyrokinetic theory now allows the possibility to study MHD modes in a self-consistent kinetic manner. We develop the kinetic adaptive eigenvalue shooting code AEGIS-K for tokamak configurations, with our newly developed gyrokinetic theory incorporated. Besides the feature of full kinetic treatment, the adaptive nature of the AEGIS-K code enables us to investigate the coupling of the shear-Alfvén resonance (or continuum damping) and the wave-particle resonance. Preliminary numerical results for resistive wall mode stability in ITER will be presented.

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# Nonlinear Ballooning Instability of an H-mode Pedestal \*

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## Abstract

In this work, we extend the MHD theory for nonlinear ballooning instability in the intermediate nonlinear regime [1] to the edge pedestal region of an H-mode tokamak, taking into account two characteristic features of that region. First, the H-mode edge pedestal region is characterized by its narrow radial width defined by a relatively small radial gradient scale length of the pressure profile. The relative smallness of the pedestal width introduces a new spatial scale to the dynamics of ballooning mode, the effects of which could become significant in the regime where the pedestal width approaches the scale of ballooning mode width across flux surfaces. Second, the magnetic configuration of the H-mode edge pedestal region is also unique in its spatial proximity to the separatrix in diverted tokamaks. In the vicinity of the separatrix, magnetic field lines tend to linger longer near the X-point, which effectively reduces the local magnetic shear and could enhance the linear ballooning instability [2]. Recent MHD simulations of edge localized modes also indicate the localization of nonlinear filamentary structures in the outer, bad curvature region near X-point [3]. This work extends our previous analytic theory [1] by incorporating effects of these two features on the nonlinear growth and structure of ballooning instability in the edge pedestal region.

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