# 1998
# International Sherwood Fusion Theory Conference

March 23–25, 1998
Atlanta, Georgia

Hosted By
Auburn University

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# 1998
# International
# Sherwood Fusion Theory Conference

## March 23–25, 1998
## The Radisson Hotel, Courtland and International Boulevard
## Atlanta, Georgia

*Hosted by*

**Auburn University**

**United States Department of Energy**
**Office of Fusion Energy Sciences**

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## GENERAL INFORMATION

In all, 156 papers were submitted, 118 of these electronically. Of these, 13 were selected for oral presentation out of 26 requests. In addition, there are 3 review papers. Several ancillary meetings are scheduled as well.

## MEETING PROGRAM

- The **review papers** (1A01, 2A01, 3A01) will be presented in the Capitol Ballroom, North at 8:30 a.m. Monday through Wednesday.
- The **oral papers** will be presented in the Capitol Ballroom, North as follows: On Monday from 9:30 a.m. to 12:00 p.m. (1B), on Tuesday from 9:30 a.m. to 10:30 a.m. (2B) and 7:30 p.m. to 9:30 p.m. (2D), and on Wednesday from 9:30 a.m. to 10:30 a.m. (3B).
- All **poster sessions** will be presented in two-hour sessions in the Capitol Ballroom, Center and South. They will be on Monday starting at 2:00 p.m. (1C) and 4:00 p.m. (1D), on Tuesday starting at 10:30 a.m. (2C), and on Wednesday starting at 10:30 a.m. (3C).
- **Poster boards** will be available for the review and oral speakers at the poster session which follows their presentations.

## IMPORTANT INFORMATION

- **Registration** will be held in the Convention Rotunda Lobby on Sunday evening from 6:00 p.m. to 9:00 p.m., on Monday morning from 7:30 a.m. to 12:30 p.m., on Monday afternoon from 1:15 p.m. to 6:00 p.m., Tuesday from 8:00 a.m. to 12:30 p.m. and 7:30 p.m. to 9:30 p.m., and on Wednesday from 8:00 a.m. to 12:30 p.m.
- A complimentary **Reception** of light appetizers with a cash bar will be held on Sunday evening from 6:00 p.m. to 9:00 p.m. in the Augusta Suite.
- A complimentary **Companions' Breakfast** will take place Monday morning at 9:00 a.m. in the Atlanta Ballroom.
- **Coffee** will be served 9:15 a.m. – 11:00 a.m. Monday through Wednesday in the Convention Rotunda Lobby.
- **Beverages** will be served in the Convention Rotunda Lobby beginning at 3:00 p.m. on Monday and 8:00 p.m. on Tuesday.
- A **Buffet Dinner** will be served on Tuesday evening in the Capitol Ballroom, South beginning at 6:15 p.m., preceded by a cash bar at 6:00 p.m.

## ANCILLARY MEETINGS

- The **MHD Working Group** will meet Sunday afternoon, March 22, 2:00 p.m. to 6:00 p.m. in the Atlanta Ballroom, I.
- The **Innovative Confinement Concepts Community** will meet Monday evening, March 23, 5:30 p.m. to 7:00 p.m. in the Atlanta Ballroom, I.
- The **Nonlinear MHD and Extended-MHD Workshop** will meet Wednesday afternoon, March 25, and Thursday, March 26.
- **Future Sherwood** meetings: *Sherwood 99*, will be held March 22–24, 1999, in Atlanta as an imbedded topical conference in the APS centennial meeting. *Sherwood 2000*, hosted by UCLA, will meet in Los Angeles.

The Radisson Hotel, Courtland and International Boulevard
Atlanta, Georgia
March 23-25, 1998

# Registration Schedule

| | | |
|---|---|---|
| **Sunday** | 6:00 p.m. – 9:00 p.m. | Convention Rotunda Lobby |
| **Monday** | 7:30 a.m. – 12:30 p.m. | Convention Rotunda Lobby |
| | 1:15 p.m. – 6:00 p.m. | Convention Rotunda Lobby |
| **Tuesday** | 8:00 a.m. – 12:30 p.m. | Convention Rotunda Lobby |
| | 7:30 p.m. – 9:30 p.m. | Convention Rotunda Lobby |
| **Wednesday** | 8:00 a.m. – 12:30 p.m. | Convention Rotunda Lobby |

# Presentations Schedule

**Review and Oral Presentations:** Capitol Ballroom, North
**Poster Presentations:** Capitol Ballroom, Center and South

**Monday**

| | | | |
|---|---|---|---|
| 8:20 a.m. – 8:30 a.m. | Welcome | J.D. Hanson, *Local Arrangements Chair* | |
| 8:30 a.m. – 9:30 a.m. | 1A | Review Paper | **D. Rind** |
| 9:30 a.m. – 12:00 noon | 1B | Oral Session | (5 30–minute talks) |
| | | *Lunch break* | |
| 2:00 p.m. – 4:00 p.m. | 1C | Poster Session | |
| 4:00 p.m. – 6:00 p.m. | 1D | Poster Session | |

**Tuesday**

| | | | |
|---|---|---|---|
| 8:30 a.m. – 9:30 a.m. | 2A | Review Paper | **P. Thomas** |
| 9:30 a.m. – 10:30 a.m. | 2B | Oral Session | (2 30–minute talks) |
| 10:30 a.m. – 12:30 p.m. | 2C | Poster Session | |
| | | *Free afternoon* | |
| 7:30 p.m. – 9:30 p.m. | 2D | Oral Session | (4 30–minute talks) |

**Wednesday**

| | | | |
|---|---|---|---|
| 8:30 a.m. – 9:30 a.m. | 3A | Review Paper | **J. Borovsky** |
| 9:30 a.m. – 10:30 a.m. | 3B | Oral Session | (2 30–minute talks) |
| 10:30 a.m. – 12:30 p.m. | 3C | Poster Session | |

**Coffee**: 9:15 a.m. – 11:00 a.m. Monday through Wednesday in the Convention Rotunda Lobby.
**Beverages**: 3:00 p.m. – 5:00 p.m. Monday and 8:00 p.m. – 9:00 p.m. Tuesday in the Convention Rotunda Lobby.

# Oral Presentations

## Monday Morning

| | | |
|---|---|---|
| Welcome | | |
| 8:20 a.m. | | J. D. Hanson, *Local Arrangements Chair* |
| **Review Paper** | 1A | P. Catto Presiding |
| 8:30 a.m. | | David Rind, *Global Warming: Where Are We Now?* |
| **Oral Session** | 1B | S. Hirshman Presiding |
| 9:30 a.m. | | A. Thyagaraja, *Ideal MHD has Four Continua - Proof of Grad's Conjecture* |
| 10:00 a.m. | | F.L. Hinton, *Damping of Poloidal Flow Driven by Turbulence in Tokamaks* |
| 10:30 a.m. | | Abhay K. Ram, *Heating or Cooling of Ions by Two Lower Hybrid Waves* |
| 11:00 a.m. | | Christiane Marliani, *Adaptive Mesh Computations for Current Sheets* |
| 11:30 a.m. | | Allan Reiman, *Physics Design of a Compact Stellarator* |

## Tuesday Morning

| | | |
|---|---|---|
| **Review Paper** | 2A | C. Hegna Presiding |
| 8:30 a.m. | | Paul R. Thomas, *DT Experiments in the JET Tokamak* |
| **Oral Session** | 2B | A. Glasser Presiding |
| 9:30 a.m. | | C.S. Chang, *Generation of Plasma Rotation by ICRH in a Tokamak* |
| 10:00 a.m. | | Richard Fitzpatrick, *Bifurcated states of a rotating tokamak plasma in the presence of a static error-field* |

## Tuesday Evening

| | | |
|---|---|---|
| **Oral Session** | 2D | L. Chen Presiding |
| 7:30 p.m. | | J. Fleischer, *Compressible Alfven Turbulence in One Dimension* |
| 8:00 p.m. | | J.A. Tataronis, *Nonlinear Electron Acceleration by RF and Random Fields* |
| 8:30 p.m. | | J. Candy, *Nonlinear Simulation of Kinetic Instabilities in Tokamaks* |
| 9:00 p.m. | | Z. Lin, *Gyrokinetic Simulations in General Geometry* |

## Wednesday Morning

| | | |
|---|---|---|
| **Review Paper** | 3A | A. Glasser Presiding |
| 8:30 a.m. | | Joseph E. Borovsky, *The Earth's Magnetosphere at High Reynolds Number* |
| **Oral Session** | 3B | C. Hegna Presiding |
| 9:30 a.m. | | F. Zonca, *Existence of ion temperature gradient driven shear Alfvén instabilities in tokamaks* |
| 10:00 a.m. | | H. Qin, *Gyrokinetic Theory and Computational Methods for Electromagnetic Modes in Tokamaks* |

# Conference Presentations

## Sherwood '98

The Radisson Hotel, Courtland and International Boulevard,
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March 23-25, 1998

## Monday Morning

**Welcome:** 8:20 a.m. — J. D. Hanson, *Local Arrangements Chair*

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1A **Review Paper** Capitol Ballroom, North, 8:30 a.m. – 9:30 a.m.
P. Catto Presiding

1A01 David Rind, *Global Warming: Where Are We Now?*

**Coffee:** 9:15 a.m.–11:00 a.m. — Convention Rotunda Lobby

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1B **Oral Presentations** Capitol Ballroom, North, 9:30 a.m. – 12:00 noon
S. Hirshman Presiding

1B01 *Ideal MHD has Four Continua - Proof of Grad's Conjecture*
A. Thyagaraja, C.N. Lashmore-Davies and R.A. Cairns

1B02 *Damping of Poloidal Flow Driven by Turbulence in Tokamaks*
F.L. Hinton and M.N. Rosenbluth

1B03 *Heating or Cooling of Ions by Two Lower Hybrid Waves*
Abhay K. Ram and Abraham Bers

1B04 *Adaptive Mesh Computations for Current Sheets*
Christiane Marliani

1B05 *Physics Design of a Compact Stellarator*
Allan Reiman, Long-poe Ku, Don Monticello and the QAS Design Team

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**Lunch Break:** 12:00 noon – 2:00 p.m.

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## Monday Afternoon

**Beverages:** 3:00 p.m.–5:00 p.m. — Convention Rotunda Lobby

1C **Poster Presentations** Capitol Ballroom, Center and South, 2:00 p.m. – 4:00 p.m.

Posters from sessions 1A and 1B

1C01 *Transport Studies of Quasi-Axisymmetric Stellarators*
Harry E. Mynick

Posters, Monday 2:00 p.m. to 4:00 p.m.

1C02 *Rapid Computing with TERPSICHORE and CAS3D MHD Stability Codes for a Quasi-axial Stellarator*
M.H. Redi, D.A. Monticello, G.Y. Fu, M.C. Zarnstorff, C. Nuehrenberg and W.A. Cooper

1C03 *External Kink Stability in Quasi-axisymmetric Stellarators*
G.Y. Fu, M. Hughes, C. Kessel, L.P. Ku, D. Monticello, M. Redi, A. Reiman and A. Cooper

1C04 *Electromagnetic Gyrofluid Simulation of Turbulence and Transport*
Philip Snyder, Greg Hammett and Michael Beer

1C05 *The Dynamics of Small-Scale Turbulence Driven Flows*
Michael A. Beer and G.W. Hammett

1C06 *Comparing gyro-Landau-fluid and particle simulations*
G.W. Hammett, M.A. Beer and W. Dorland

1C07 *Ion Cyclotron Instability Near the Magnetic Field Well*
M.V. Gorelenkova and N.N. Gorelenkov

1C08 *Glasser-Green-Johnson effect and neoclassical tearing mode stability*
Leonid E. Zakharov

1C09 *Object-Oriented MHD*
A.Y. Aydemir, K.C. Shaing, W.H. Miner and J.C. Wiley

1C10 *Novel Hybrid Magnetic Fusion Devices*
A.K. Sen

1C11 *Non Ideal Effects in High-$\eta$ TAE Stability Study Using 2-D HINST Code*
N.N. Gorelenkov, C.Z. Cheng, G.Y. Fu and W. Tang

1C12 *Lattice Boltzmann Simulation of Rayleigh Benard and 3D Shear Flows*
George Vahala, Darren Wah, Pavol Pavlo and Linda Vahala

1C13 *Higher-Order Isotropic Velocity Grids in Lattice Boltzmann Simulations*
Pavol Pavlo, George Vahala and Linda Vahala

1C14 *Analysis of the m=2 tearing mode stabilization by lower hybrid current drive on FTU*
A. Cardinali

1C15 *Systematic Studies of Wake Fields in Plasma Channels*
B.A. Shadwick, C.B. Schroeder and J.S. Wurtele

1C16 *Enhanced Instability of the Parallel Velocity Shear Instability due to Magnetic Shear Reversal*
Daniel McCarthy and Slade Maurer

1C17 *Validation of NIMROD with the Soloviev Equilibrium*
Alfonso Tarditi and Dalton Schnack

1C18 *Energy Confinement Time for Ignition-Relevant Tokamak Plasmas During Electron Cyclotron Heating*
V. Stefan

Posters, Monday 2:00 p.m. to 4:00 p.m.

1C19 *Enhancement of Ideal MHD Wall Stabilized ß Limits from Profile and Cross-Section Optimization*
A.D. Turnbull, T.S. Taylor, L.L. Lao, R.L. Miller, M.S. Chance and B.J. Lee

1C20 *Competition of high-n ballooning modes and the parallel heat transport in the nonlinear stage of internal disruption*
Y. Nishimura, C.C. Hegna and J.D. Callen

1C21 *Interpretation of Pitchfork Splitting Effect*
B.N. Brieizman, M.S. Pekker, A. Fasoli, D.N. Borba and R.F. Heeter

1C22 *Calculation of Feedback Stabilization of Tokamak Wall Modes*
Allen H. Boozer

1C23 *Current Profile Control and MHD Stability Studies of Reverse Shear Plasmas in Alcator C-Mod*
P.T. Bonoli, M. Porkolab, J.J. Ramos, S.J. Wukitch and Y. Takase

1C24 *Neoclassical Profiles and Advanced Tokamak Operation*
William Dorland, Michael Kotschenreuther and Q.P. Liu

1C25 *Tokamaks Without Turbulent Transport*
M. Kotschenreuther, Bill Dorland and Q.P. Liu

1C26 *Theoretical Model for the Plasma Rotation Paradox*
B. Coppi and G. Penn

1C27 *Progress on the GA/LLNL Project to Merge and Modernize ONETWO and CORSICA*
H.E. St. John, T.B. Yang and R. Cohen

1C28 *Transport Equations in Axisymmetric Toroidal Plasmas with Large Mean Flows*
W. Horton and H. Sugama

1C29 *A Distributed Field Line Following Code as an Example of Client-Server Programming with an Embedded Scripting Language*
J.C. Wiley and T.Y. Brian Yang

1C30 *Seed Magnetic Island Formation due to Geometrically Coupled Magnetic Perturbations*
C.C. Hegna and J.D. Callen

1C31 *Chaos in Trapped Particle Orbits*
Roscoe White

1C32 *Effect of Convection on the H-mode Temperature Pedestal*
D.A. D'Ippolito, J.R. Myra, V.P. Bhatnagar and J.J. Jacquinot

1C33 *Optimizing Stability of Small Aspect Ratio Toroidal Hybrids*
A.S. Ware, D.B. Batchelor, B.A. Carreras, S.P. Hirshman, V.E. Lynch and D.A. Spong

1C34 *Collisionless, Non-Ideal Ballooning Modes*
Robert G. Kleva and Parvez N. Guzdar

1C35 *Strong X-ray Generation and Coulomb Ion Explosion from Cluster - Laser Interaction*
T. Tajima, M. Downer and Y. Kishimoto

1C36 *Confinement Studies of Low Aspect Ratio, Omnigenous Stellarators*
D.A. Spong, S.P. Hirshman, D.B. Batchelor, B.A. Carreras and V.E. Lynch

1D **Poster Presentations** Capitol Ballroom, Center and South, 4:00 p.m. – 6:00 p.m.

1D01 *Stability of a Levitated Dipole*
J. Kesner

1D02 *Stability analysis of Alfven eigenmodes in JET deuterium-tritium plasmas and ITER*
D. Borba, A. Fasoli, R. Heeter, W. Kerner and S. Sharapov

1D03 *Low Collisionality Transport in Low Bp/Bt Tokamaks*
K. Imre, C.S. Chang and H. Weitzner

1D04 *Double Beltrami Flows - Diamagnetic Structures*
S.M. Mahajan

1D05 *Gyrofluid Simulation of Alfvén waves in the Magnetosphere*
Samuel Jones and Scott Parker

1D06 *Runaway Electron Production in DIII-D Experiments Calculated with the CQL3D/KPRAD Fokker-Planck/Radiation Model*
R.W. Harvey, V.S. Chan, S.C. Chiu, T.E. Evans, M.N. Rosenbluth and D.G. Whyte

1D07 *Multispecies Kinetic Model of Detached Plasmas*
Alla Batishcheva and Oleg Batishchev

1D08 *Nonlinear Theory of Internal Kink Modes Destabilized by Fast Ions*
F. Porcelli, J. Candy, H.L. Berk and B.N. Breizman

1D09 *Stability and Transport in Wall-Confined Spheromaks*
T.K. Fowler, D.D. Hua and L.D. Pearlstein

1D10 *Stability of detached divertor operation*
S.I. Krasheninnikov

1D11 *Growth of An Ideal MHD Mode Driven Slowly Through Its Instability Threshold: Application To Disruption Precursors*
J.D. Callen, C.C. Hegna, E.J. Strait and A.D. Turnbull

1D12 *In-Out Asymmetry of Particle and Heat Fluxes on Divertor Plates Produced by Electric Drifts*
R.H. Cohen and D.D. Ryutov

1D13 *Electric Fields near a Tokamak Separatrix and Their Effect on Edge Profiles*
T.D. Rognlien, D.D. Ryutov and N. Mattor

1D14 *Raised Nonlinear Thresholds and Numerical Convergence in Gyrokinetic Simulations of Ion-Temperature-Gradient Turbulence in Tokamaks*
A.M. Dimits, D.E. Shumaker , W.M. Nevins , B.I. Cohen and S.E. Parker

1D15 *Temporal Response of Theoretical Transport Models to Modulated Heat Sources and Cold Edge Pulses in Transient Experiments*
J.E. Kinsey, R.E. Waltz, J.C. DeBoo, H.E. St. John, D.P. Schissel and E. Fredrickson

Posters, Monday 4:00 p.m. to 6:00 p.m.

1D16 *Magnetic Island Structure with Sheared Flow and Viscosity*
C. Ren, M.S. Chu and J.D. Callen

1D17 *The Effect of Neutral Diffusion on Ion Parallel Flow*
Tunde Fulop, Peter J. Catto and Per Helander

1D18 *Thermal Instabilities in the Edge Transport Barrier & the L/H Transition*
W.M. Stacey

1D19 *Adaptive Unstructured Grid Approach to SOL Modeling*
Oleg Batishchev, Alla Batishcheva and Dieter Sigmar

1D20 *Effect of Rotation Shear on MHD Modes in Tokamaks with Low Magnetic Shear*
M.S. Chu, L. Chen and L.J. Zheng

1D21 *Variational Principles for Rotating Plasmas and Classical Fluids*
Eliezer Hameiri

1D22 *UEDGE Simulation of Steady State Detached Plasmas*
M.E. Rensink and T.D. Rognlien

1D23 *Stability analysis of the magnetohydrodynamic modes around a q-minimum*
L.J. Zheng, L. Chen and M. Chu

1D24 *Zonal Flows and the Physics of Shear Suppression*
P.H. Diamond, J. Fleischer and F.L. Hinton

1D25 *A Split-Weight Scheme for the Electron Dynamics in Tokamak Plasmas*
Igor Manuilskiy, Wei-li Lee, Harry Mynick and Scott Parker

1D26 *On the Nonlinear Stability of Ion-Acoustic Waves*
Nikhil Padhye and P.J. Morrison

1D27 *Effects of orbit distortion on classical transport*
R.D. Hazeltine, K.C. Shaing and A.Y. Aydemir

1D28 *Oscillatory Processes in Models of Internal Transport Barrier Formation*
D. Lopez-Bruna, D.E. Newman, B.A. Carreras and P.H. Diamond

1D29 *Extreme Limit of the Spherical Stellarator Approach*
Paul E. Moroz

1D30 *Correcting Field Errors in Tokamaks*
James D. Hanson

1D31 *High Mode Number MHD Stability at the Edge of a Tokamak*
R.L. Miller, J.W. Connor, R.J. Hastie, L.L. Lao, T.S. Osborne, T.S. Taylor and H.R. Wilson

1D32 *An Efficient Algorithm for the Wall Electric Field Diffusion Problem During Fast Current Quenches*
P.B. Parks, D.E. Post, S. Putvinskij, H.A. Scott and D.A. Humphreys

1D33 *Expectations for the NSTX High Harmonic Fast Wave System*
M.D. Carter

1D34 *Diocotron Instabilities of Nonneutral Plasmas*
John M. Finn and Daniel C. Barnes

Posters, Monday 4:00 p.m. to 6:00 p.m.

1D35 *Improved Edge Models for Coupled Core/SOL/Divertor Simulations of Tokamak Plasmas*
J. Mandrekas and W.M. Stacey

1D36 *Kinetic Modelling of Drift Alfvén Turbulence*
Frank Jenko and Bruce Scott

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## Tuesday Morning

2A **Review Paper** Capitol Ballroom, North, 8:30 a.m. – 9:30 a.m.
C. Hegna Presiding

2A01 Paul R. Thomas, *DT Experiments in the JET Tokamak*

**Coffee:** 9:15 a.m.–11:00 a.m. — Convention Rotunda Lobby

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2B **Oral Presentations** Capitol Ballroom, North, 9:30 a.m. – 10:30 am
A. Glasser Presiding

2B01 *Generation of Plasma Rotation by ICRH in a Tokamak*
C.S. Chang, S. Zweben , R. White , C. Phillips and J. deGrassie

2B02 *Bifurcated states of a rotating tokamak plasma in the presence of a static error-field*
Richard Fitzpatrick

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2C **Poster Presentations** Capitol Ballroom, Center and South, 10:30 a.m. – 12:30 p.m.

Posters from sessions 2A and 2B

2C01 *Symbolic Analysis of Turbulent Plasma Fluctuations*
M Lehrman, A.B. Rechester and M.A. Meir

2C02 *Higher-Order Effects in Mode Conversion Theory*
D.G. Swanson

2C03 *Inertial damping and active rotation control of tearing fluctuations in a tokamak*
D. Maurer, C. Cates, M.E. Mauel, D. Nadle, G.A. Navratil, E. Taylor, W.A. Reass and G.A. Wurden

2C04 *An Implicit Bounce-Averaged Fokker-Planck (BAFP) Code to Model Spherical Inertial Electrostatic Confinement (IEC) Fusion Systems*
L. Chacon, D.C. Barnes and D.A. Knoll

2C05 *Conditions for Observing Neoclassical Ion Temperature Gradient Screening of Impurities in Tokamaks*
W.A. Houlberg, M.R. Wade, L.R. Baylor, K.C. Shaing and P.C. Efthimion

2C06 *Efficient C++ library for Differential Algebra*
Svetlana Shasharina and John Cary

Posters, Tuesday 10:30 a.m. to 12:30 p.m.

2C07 *Single Integral Expressions for Electron Cyclotron Damping, Relativistically and with an Arbitrary Distribution Function*
I.P. Shkarofsky

2C08 *Fokker-Planck Modeling of Transient Effects in the Edge Plasma of TdeV*
M. Shoucri, I.P. Shkarofsky, G. Pacher, R. Decoste, O. Batishchev and A. Batishcheva

2C09 *Investigation of Inner Layer Models Using Resistive Energy Principle Approach*
S.A. Galkin, J.M. Greene, A.D. Turnbull, A. Pletzer, M.S. Chu and R.L. Miller

2C10 *Identification, Triggering and Control of Large Events in a SOC system*
H. Chen, D.E. Newman and B.A. Carreras

2C11 *Optimization Study of Slow Wave Current Drive in the MST Reversed-Field Pinch*
E. Uchimoto, R.W. Harvey, A.P. Smirnov, C.B. Forest, S.C. Prager, J.S. Sarff and M.R. Stoneking

2C12 *The Effect of Shear Flow on Neoclassical Tearing Modes*
S.E. Kruger, C.C. Hegna and J.D. Callen

2C13 *Particle Canonical Variables in Toroidal Geometry --- Arbitrary Choice of Magnetic Flux Coordinates*
H. Vernon Wong

2C14 *Finite Orbit Width and Larmor Radius Effects in Fast Particle Instability of Low-$\eta$ TAE*
C.Z. Cheng, N.N. Gorelenkov and M.V. Gorelenkova

2C15 *Mode Conversion and Coupling to Electron Bernstein Waves in NSTX*
Steven D. Schultz, Abraham Bers and Abhay K. Ram

2C16 *A Distributed Parallel Algorithm for a Class of Weak Turbulence Problems*
B. Demsky and J. Candy

2C17 *Transport in Edge Plasmas*
Peter J. Catto, P. Helander, J.W. Connor and R.D. Hazeltine

2C18 *Evolution of Density Pulses in the Presence of Static Magnetic Islands*
E.H. Held, J.D. Callen and C.C. Hegna

2C19 *Nonlinear Instability in Collisionless Trapped Electron Turbulence*
Derek Baver, Paul W. Terry and Eduardo Fernandez

2C20 *Sheath over a divertor plate with small-scale surface imperfections*
D.D. Ryutov and R.H. Cohen

2C21 *Improved H-mode with Neon Injection in the DIII-D Tokamak*
G.M. Staebler, G.L. Jackson, W.P. West, S.L. Allen, R.J. Croebner, M.J. Schaffer and D.G. Whyte

2C22 *The dissipative Budden problem with spatially non-uniform damping*
E.R. Tracy, A.N. Kaufman, J.J. Morehead and A.J. Brizard

2C23 *Unifying Role of Radial Electric Field Shear in Supershot Scalings with Isotopic Mass, Heating Power, and Edge Recycling*
D.R. Ernst, B. Coppi, M. Porkolab and S.D. Scott

Posters, Tuesday 10:30 a.m. to 12:30 p.m.

2C24 *Numerical Simulation Magnetic Reconnection in the MRX Experiment*
D.D. Schnack and A. Tarditi

2C25 *Convergence Properties of a 3D non-linear gyrokinetic $\delta f$ code in magnetic coordinates*
T.M. Tran, K. Appert, M. Fivaz and J. Vaclavik

2C26 *Effect of phase-shifts on feedback stabilization schemes for the control of the resistive shell mode in tokamaks*
Edmund P. Yu and Richard Fitzpatrick

2C27 *Comparison of Flux Tube and Global Gyrokinetic Simulations*
Charlson Kim and Scott Parker

2C28 *Study of Resistive Wall Mode in Tokamak Plasma: Implications to Feedback Stabilization*
Dae-Young Lee

2C29 *Progress on Iterative Coupling of Uedge/Monte-Carlo Simulations*
L.L. LoDestro, M.E. Rensink and T.D. Rognlien

2C30 *Stability of Tearing Modes for Finite Mercier Index*
F.L. Waelbroeck and J.M. Greene

2C31 *Theory of Enhanced Reversed Shear Mode+*
K.C. Shaing, A.Y. Aydemir, W.A. Houlberg and M.C. Zarnstorff

2C32 *Simulation of Alpha-driven Toroidicity-Induced Alfven Eigenmodes in TFTR*
Yang Chen, Roscoe White, Guoyong Fu and Raffi Nazikian

2C33 *$\delta f$ Simulations of Neoclassical Transport in Stellarator*
W.M. Tang, H.E. Mynick, Z. Lin and R.B. White

2C34 *Excitation of Contained Modes by Energetic Particles*
G. Penn, B. Coppi and C. Riconda

2C35 *Theory of Simulation Thermostats*
John A. Krommes

2C36 *E X B shear suppression of turbulence by time-dependent Er*
T.S. Hahm

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**Lunch Break**: 12:30 p.m. – 2:00 p.m.

## Tuesday Afternoon

Free afternoon: no formal conference agenda

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## Tuesday Evening

*Evening Buffet Dinner*
Capitol Ballroom, South
6:15 p.m. – 7:30 p.m.
*Cash Bar from 6:00 p.m.*

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## Tuesday Evening

**Beverages:** 8:00 p.m.–9:00 p.m. — Convention Rotunda Lobby

2D **Oral Presentations** Capitol Ballroom, North, 7:30 p.m. – 9:30 p.m.
L. Chen Presiding

2D01 *Compressible Alfven Turbulence in One Dimension*
J. Fleischer and P.H. Diamond

2D02 *Nonlinear Electron Acceleration by RF and Random Fields*
J.A. Tataronis and V. Petrzílka

2D03 *Nonlinear Simulation of Kinetic Instabilities in Tokamaks*
J. Candy

2D04 *Gyrokinetic Simulations in General Geometry*
Z. Lin, W.W. Lee, W.M. Tang and R.B. White

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## Wednesday Morning

3A **Review Paper** Lakeshore Room, 8:30 a.m. – 9:30 a.m.
A. Glasser Presiding

3A01 Joseph E. Borovsky, *The Earth's Magnetosphere at High Reynolds Number*

**Coffee:** 9:15 a.m.–11:00 a.m. — Convention Rotunda Lobby

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3B **Oral Presentations** Capitol Ballroom, North, 9:30 a.m. – 10:30 a.m.
C. Hegna Presiding

3B01 *Existence of ion temperature gradient driven shear Alfvén instabilities in tokamaks*
F. Zonca, L. Chen, J.Q. Dong and R.A. Santoro

3B02 *Gyrokinetic Theory and Computational Methods for Electromagnetic Modes in Tokamaks*
H. Qin, W.M. Tang and G. Rewoldt

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3C **Poster Presentations** Capitol Ballroom, Center and South, 10:30 a.m. – 12:30 p.m.

Posters from sessions 2D, 3A and 3B

3C01 *Multidimensional theory of wave emission in a mode conversion region*
Yu Krasniak, E.R. Tracy and A.N. Kaufman

3C02 *Statistical model of the test particle transport in chaotic magnetic fields*
Attila Montvai

Posters, Wednesday 10:30 a.m. to 12:30 p.m.

3C03 *The Role of Flows in the Formation and Control of Internal Transport Barriers*
D.E. Newman, B.A. Carreras, D. Lopez-Bruna and P.H. Diamond

3C04 *Fokker-Plank Modeling of Ion Temperature Gradient Instability*
S.V. Novakovski, J.F. Drake, C.S. Liu and R.Z. Sagdeev

3C05 *Stabilization of the m=2/n=1 neoclassical tearing mode in ITER using a continuous localized current drive*
A. Pletzer and F. Perkins

3C06 *Hole-Clump Dynamics with Collisions*
D. Eremin, H.L. Berk, B.N. Breizman and J. Candy

3C07 *Two-point Boundary Value and Cauchy Formulations in an Axisymmetrical MHD Equilibrium Problem*
Calin Vlad Atanasiu and Alexey A. Subbotin

3C08 *A Newton Method For The 3D MHD Equilibrium Equations*
Hilary Oliver, Allan Reiman and Don Monticello

3C09 *Recent Results on Simulation of Turbulence in Boundary Plasmas*
X.Q. Xu, R.H. Cohen, G.D. Porter, J.R. Myra, D.A. D'Ippolito and R. Moyer

3C10 *Theory and Modeling of SOL and Edge Turbulence*
J.R. Myra, D.A. D'Ippolito, X.Q. Xu, R.H. Cohen, G.D. Porter and R. Moyer

3C11 *Coils for Prescribed 3D Finite-ß Equilibria*
Peter Merkel

3C12 *Structure of Parallel-Velocity-Shear Driven Mode in Toroidal Plasmas*
J.Q. Dong, W.B. Xu and W. Horton

3C13 *Theory of Low-n External Kinks in High-ß Toroidal Plasmas*
Riccardo Betti and Evengi Fedutenko

3C14 *Generalized Force-Free Equilibria*
Parvez N. Guzdar and Swadesh M. Mahajan

3C15 *Transport of Angular Momentum in Hot Accretion Disks and in Laboratory Plasmas*
Paolo S. Coppi and Bruno Coppi

3C16 *Edge Bootstrap Current and High li Advanced Tokamak Operational Mode*
Y.R. Lin-Liu, M.S. Chu, R.L. Miller, A. D. Turnbull and T. S. Taylor

3C17 *Weakly nonlinear dynamics of marginally stable plasmas*
Diego del-Castillo-Negrete

3C18 *Theory and Interpretation of Internal Modes in Alcator C-Mod*
Francesca Bombarda, Bruno Coppi, Ambrogio Fasoli, Stephano Migliuolo, Joseph Snipes, Wolfgang Kerner and Guido Huysmans

3C19 *NIMROD: An Overview of Code Status, Validation, and First Research Topics*
C.R. Sovinec, T.A. Gianakon, S.J. Plimpton, A.G. Tarditi and the NIMROD Team

3C20 *The Application of NIMROD to Tearing Modes*
A.H. Glasser, S.E. Kruger, J.-N. Leboeuf, M.S. Chu and the NIMROD Team

Posters, Wednesday 10:30 a.m. to 12:30 p.m.

3C21 *Two Tokamak Applications of NIMROD: Ballooning Modes and Secondary Island Generation by Mode Coupling*
T.A. Gianakon, C.R. Sovinec, A.H. Glasser, M. Chu and the NIMROD Team

3C22 *The Los Alamos Intense Neutron Source and the Periodically Oscillating Plasma Sphere (POPS)*
R.A. Nebel and D.C. Barnes

3C23 Global Toroidal Gyrokinetic Particle Simulation of Turbulent Transport in a Diverted Tokamak Plasma
R.D. Sydora, O. Hurricane, V.K. Decyk, S.C. Cowley and J.M. Dawson

3C24 Improving The Multi-Mode Transport Model
Arnold H. Kritz, Glenn Bateman, Aaron J. Redd, Gregory Rewoldt, Jan Weiland, Jon Kinsey and Bruce Scott

3C25 *Axisymmetric ideal magnetohydrodynamic equilibria with incompressible flows*
H. Tasso and G.N. Throumoulopoulos

3C26 *Gyrokinetic Stability and Plasma Flux Surface Shape*
R.E. Waltz and R.L. Miller

3C27 *The M3D Project for Plamsa Simulation Studies*
W. Park, E.V. Belova, G.Y. Fu, H.R. Strauss and L.E. Sugiyama

3C28 *Rotation in Toroidal Plasmas*
L.E. Sugiyama and W. Park

3C29 *MHD Simulations of Pellet Injection and Disruptions using the MH3D++ Code*
H.R. Strauss and W. Park

3C30 *3D Hybrid Simulations with Gyrokinetic Particle Ions and Fluid Electrons*
E.V. Belova, W. Park, G.Y. Fu, H.R. Strauss and L.E. Sugiyama

3C31 *On the Fluctuation Spectrum of a Vlasov Plasma*
P.J. Morrison and B.A. Shadwick

3C32 *Discontinuity Model for Transport Barrier Formation in Reversed Shear Tokamaks*
Y. Kishimoto, Y. Koide, W. Horton, T. Tajima and J.-Y. Kim

3C33 *Effects of Non-Circular Plasma Geometry on Finite-$\beta$ Kinetic Ballooning and Trapped-Electron-$\eta i$ Modes*
Aaron J. Redd, Arnold H. Kritz, Glenn Bateman and Gregory Rewoldt

3C34 *Invariants in Lie-Poisson Systems*
Jean-Luc Thiffeault and Philip J. Morrison

3C35 *Full Plasma Cross Section Landau Fluid Calculations of Ion Temperature Gradient Driven Turbulence in Tokamaks*
J.-N. Leboeuf, V.E. Lynch, B.A. Carreras, J.D. Alvarez and L. Garcia

# Abstracts

Arranged in presentation order, including
review papers, oral presentations, and poster presentations.

# Global Warming: Where Are We Now?

David Rind
*NASA / Goddard Institute for Space Studies*

What is our present state of knowledge concerning whether climate is warming, whether that warming is due to man's influence, and what this implies about the future? These are the questions addressed in this talk. Climate does appear to have warmed over the past century, and this last year appears to have been the warmest in recorded history. In fact, since 1866, the 13 warmest years have all occurred since 1980, and this is despite the two biggest volcanoes of the century (El Chichon, and Mt. Pinatubo) having gone off in the last 15 years. We have good records of how trace gases have varied over that time, so one would think we would now know the climate sensitivity (temperature change in response to radiative forcing change). Unfortunately, key components of the puzzle are still missing. We are not sure what other forcings have occurred during the past 100 years, such as solar variability or tropospheric aerosol change. We're also not sure of how much heat the ocean takes up, which governs the rate at which climate should have changed. The numerical models employed to represent the climate system result in a range of climate sensitivities, most of which imply dire conditions for the next century; however, key physical processes are still in question, and could diminish or amplify the likely response. The uncertainties are particularly onerous because the climate system appears to react with a long time-scale, so to have a significant impact on the future requires action far in advance of any firm scientific conviction. If we guess wrong our quality of life will suffer needlessly, in either the present or the future.

# Ideal MHD has Four Continua – Proof of Grad's Conjecture

**A. Thyagaraja**, C.N. Lashmore-Davies

UKAEA, Fusion, Culham Science Centre, Abingdon,
Oxfordshire, OX14 3DB, UK.
(UKAEA/Euratom Fusion Association),

R.A. Cairns

School of Mathematical and Computational Sciences,
University of St. Andrews, St. Andrews, Fife, KY16 9SS, UK.

**ABSTRACT**

The continuous spectrum of ideal magnetohydrodynamics in a cylindrical screw pinch is investigated. Contrary to many claims in the literature in the last twenty five years, it is rigorously proved that there are in fact *four* continua, the two new ones being those associated with the 'fast' and 'slow' magnetosonic waves, in addition to the previously described shear Alfvén and sound continua. This result confirms the truth of the conjectures of Grad (Proc. Natl. Acad. Sci. USA, **70**, 3277 (1973)) which were disputed by Appert, Gruber and Vaclavik (Phys. Fluids, **17**, 1471 (1974)) and by Goedbloed (Phys. Fluids, **18**, 1258 (1975)). It is found that the theorem of Appert *et al* to the effect that at the fast and slow wave resonances, all solutions of the Hain-Lüst equation governing the radial plasma displacement are regular is indeed correct. However, their further conclusion that this implies the existence of only two continua is at variance with both the physics and the mathematical properties of the *complete system* of ideal magnetohydrodynamic (MHD) equations governing the problem. Whereas the shear Alfvén and sound continua arise from the singularities of the Hain-Lüst equation, the magnetosonic continua result from the singularities of the resolvent operator associated with the non radial displacements. Two independent proofs of the existence theorem in question are given: the first via the solution of the Cauchy initial-value problem for the ideal MHD system using Laplace transforms (similar to Landau's approach to the Vlasov equation) and the second, by the explicit construction of the corresponding Case-Van Kampen continuum eigenfunctions. The generalized eigenfunctions for all the four continua are constructed in terms of the fundamental Frobenius solutions of the Hain-Lüst equation and their singularity structures are highlighted. Both nondegenerate and degenerate (ie 'overlapping') continua are discussed. Together with the full set of discrete eigenfunctions (if any), these solutions are complete in the Hilbert space of displacements. The two new, magnetosonic continua have potentially important consequences for plasma heating and turbulence. These are very briefly indicated, as are some generalizations of the approach adopted.

**Acknowledgements**: This work was supported jointly by the UK Dept. of Trade and Industry, Euratom and the UK Engineering and Physical Sciences Research Council, Grant GR/K 58937.

# Damping of Poloidal Flow Driven by Turbulence in Tokamaks

F.L. Hinton and M.N. Rosenbluth†

*General Atomics*
*San Diego, California*

Plasma turbulence generates, through mode coupling and finite gyroradius and banana width effects, fluctuating radial currents which have an axisymmetric component. The sheared poloidal flows driven by these currents are important in saturating the modes responsible for transport. We have considered an important aspect of this problem, the kinetic linear plasma response to such currents, treating them as a known source. The driven flows are not damped by collisionless processes, such as transit time damping, although they are attenuated by plasma polarization. When the source currents are assumed to be random and statistically stationary, the mean square E×B flow is found to increase linearly with time, for times longer than a few ion transit times. By solving the gyrokinetic equation and quasineutrality as an initial value problem, the flow is found to asymptote to a nonzero value. This was confirmed by gyrokinetic simulation, while gyrofluid models incorrectly predict a total collisionless decay of the flow because present gyrofluid closures have no trapped ion bounce averaging. We have proposed [1] that this gyrofluid over-damping may lead to overestimation of turbulent diffusion by gyrofluid codes.

When ion-ion collisions are included in the solution of the drift kinetic equation, the poloidal flow is found to decay to zero, although not exponentially in time. In particular, the decay is faster than exponential for short times, because collisions have an effect first in a boundary layer, while it is slower than exponential for long times because it is dominated by more energetic ions with small collision rates. The decay time, defined by an integral over the time history of the flow, is found to be $\tau_d = 1.5\,\tau_{ii}\,\varepsilon$, where $\tau_{ii}$ is the bulk ion-ion collision time, and $\varepsilon$ is the inverse aspect ratio. Plasma polarization plays an important role in the dynamics. To second order in the ion banana width, the E×B flow is again found to asymptote to a non-zero value at large times, determined by the plasma polarization, which is modified by collisions.

This is a report of research partially sponsored by the U.S. Department of Energy under Grant No. DE-FG03-95ER54309.

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†ITER JCT, San Diego, California.

[1] M.N. Rosenbluth and F.L. Hinton, to be published in Phys. Rev. Lett.

# Heating or Cooling of Ions by Two Lower Hybrid Waves*

Abhay K. Ram, Abraham Bers
*Plasma Science and Fusion Center, M.I.T., Cambridge, MA*

For low-energy ions in a magnetic field **B**, a new phenomenon of *nonlinear coherent* energization is found to take place when ions interact with two, colinear, perpendicularly (to **B**) propagating lower hybrid waves that are separated in frequency by an integer multiple ($\leq 3$) of the ion-cyclotron frequency, and for an appropriate choice of the wavelengths[1, 2, 3]. These low-energy ions would not gain any net energy in the presence of one wave and, consequently, the nonlinear coherent energization can access a larger region of the ion phase space – not just the tail of the ion distribution function. Ideally the higher frequency wave should have the shorter wavelength. In this case, the low-energy ions can be heated into the chaotic phase space where heating occurs even more rapidly. If we assume that the two waves have the same electric field amplitude, the heating is found to be independent of the amplitude, but the heating rate is proportional to the square of the amplitude. The nonlinear coherent mechanism can also be used to decelerate ions and thus extract their energies as may be of interest in the removal of energy from fusion $\alpha$-particles. Since the frequency and wavelength spectra of lower hybrid waves can be externally controlled in tokamak experiments, it should be possible to either heat low-energy ions or remove energy from energetic ions of a particular species, and from a pre-determined region of phase space. Detailed analytical and numerical results on the ion dynamics in a spectrum of waves will be presented.

## References

[1] A.K. Ram, A. Bers, and D. Benisti, to be published in *J. Geophys. Res.* (1998).
[2] A.K. Ram, A. Bers, and D. Benisti, to be published in the Proceedings of the 2nd Europhysical Topical Conference on RF Heating and Current Drive of Fusion Devices, Brussels, Belgium (1998).
[3] D. Benisti, A.K. Ram, and A. Bers, submitted to *Phys. Rev. Lett.* and *Phys. Plasmas* (1998).

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# Adaptive Mesh Computations for Current Sheets

Christiane Marliani
*Courant Institute of Mathematical Sciences, New York University*

The formation of current sheets is investigated in the framework of two-dimensional incompressible magnetohydrodynamics. Using Elsässer variables $\mathbf{z}^{\pm} = \mathbf{u} \pm \mathbf{B}$, the equations take the symmetric form

$$\partial_t \mathbf{z}^{\pm} + \mathbf{z}^{\mp} \cdot \nabla \mathbf{z}^{\pm} = \mu_+ \Delta \mathbf{z}^{\pm} + \mu_- \Delta \mathbf{z}^{\mp} - \nabla p \ , \ \ \nabla \cdot \mathbf{z}^{\pm} = 0$$

where $\mu_{\pm} = (\nu \pm \eta)/2$ and $\nu$ is the viscosity, $\eta$ the resistivity and $p$ the sum of ordinary and magnetic pressure.

In order to follow the evolution of thinner and thinner current sheets which are found in the ideal case ($\nu = \eta = 0$), adaptive mesh refinement techniques are used [1]. Finer levels are generated where steep gradients are forming and discarded if they are not needed anymore. The hierarchichal grid structure is automatically adapted to ensure sufficient resolution over the whole integrational domain.

Starting with an initial resolution of $256^2$ grid points after 6 or 7 levels of refinement by a factor two the local resolution achieved in these runs corresponds to $16384^2$ or $32768^2$ grid points on an ordinary mesh.

I discuss simulations for different initial conditions. After a short transitional period current sheets are forming. Depending on the symmetry of the initial conditions one finds either simple or more complicated sheet structures. In both cases the absolute maxima of the current density and the vorticity in the sheet structures are found to grow exponentially in time [2] whereas the thickness of the sheets is shrinking exponentially. The self-similar evolution is in agreement with a simple scaling ansatz for the stream functions by Sulem *et al.* [4].

In two dimensions it is possible to formulate the dynamic equations for scalar quantities. Taking the $z$-component of the curl of the above equations for the ideal case yields

$$\partial_t \omega^{\pm} + \mathbf{z}^{\mp} \cdot \nabla \omega^{\pm} = \mathbf{e}_z \cdot \sum_i \nabla z_i^{\pm} \times \nabla z_i^{\mp}$$

with $\omega^{\pm} = [\nabla \times \mathbf{z}^{\pm}]_z$ meaning the sum and difference of vorticity $\omega$ and current density $j$ and with $z_i^{\pm}$ the $i$-th component of the vector $\mathbf{z}^{\pm}$. The observed exponential growth of current density and vorticity is explained by a depletion of the nonlinear production term $\mathbf{e}_z \cdot \sum_i \nabla z_i^{\pm} \times \nabla z_i^{\mp}$ due to the geometric properties of the deformation matrices in the vicinity of the current density's extrema.

In addition, I show results for the coalescence instability (compare [3]) obtained with the same adaptive mesh refinement technique. Simulations for the ideal case *and* the case of small, non-vanishing resistivity $\eta \neq 0$ are discussed.

## References

[1] H. Friedel, R. Grauer, and C. Marliani. *J. Comput. Phys.*, 134:190–198, 1997.
[2] R. Grauer and C. Marliani. *submitted to Phys. Plasmas*, 1997.
[3] D. W. Longcope and H. R. Strauss. *Phys. Fluids B*, 5(8):2858–2869, 1993.
[4] P. L. Sulem, U. Frisch, A. Pouquet, and M. Meneguzzi. *J. Plasma Phys.*, 33:191–198, 1985.

# Physics Design of a Compact Stellarator*

Allan Reiman, Long-poe Ku, Don Monticello
*Princeton Plasma Physics Laboratory, Princeton, NJ*

and the QAS Design Team

We have been pursuing the design of a compact stellarator with good neoclassical transport and MHD stability properties. For this purpose, we have focused on quasi-axisymmetric (QA) configurations[1]. This presentation will give an overview of our design effort, focusing particularly on the issue of ballooning stability. Neoclassical transport calculations for the design study will be described at this meeting by H. Mynick. Global MHD stability calculations will be described by G. Y. Fu and M. Redi.

A critical problem that we have faced in designing an attractive QA configuration is the ballooning $\beta$ limit, which tends to be an issue for stellarators except at high aspect ratio. We have solved this problem by incorporating large axisymmetric ($n = 0$) components of ellipticity and triangularity in the shape of the outer boundary, using Aries tokamak stability studies[2] as a guide in choosing a stabilizing shape. For $R/a \approx 3$, our configurations typically have ballooning $\beta$ limits in the 6% to 7% range, with one configuration found to be ballooning stable at $\beta = 11\%$.

Because of the nature or their drift trajectories, their low aspect ratio, and a bootstrap current comparable in magnitude to that of tokamaks, QA stellarators tend to look like stellarator - advanced tokamak hybrids. Relative to advanced tokamaks, they have the advantage that the external transform can suppress disruptions, and reduces or eliminates the need for rf current drive. Furthermore, the control over the $q$ profile allows us to construct configurations with monotonically decreasing $q$ profile (not possible in reverse shear tokamaks, which always have a shear reversal layer that causes stability problems), and to obtain levels of shear at the edge not obtainable in tokamaks. The edge shear is stabilizing for external kink modes, and has allowed us to construct configurations which are stable to external kinks at $\beta = 7\%$, with the conducting wall far from the plasma (at $2a$). This result will be discussed in the presentation of G.Y. Fu.

## References

[1] J. Nuehrenberg, W. Lotz, and S. Gori, in *Theory of Fusion Plasmas*, E. Sindoni, F. Troyon and J. Vaclavik eds., SIF, Bologna, 1994.
[2] S. Jardin, C. Kessel, C. Bathke, D. Ehst, T. Mau, F. Najmabadi, and T. Petrie, Fusion Engineering and Design, **38**, 27 (1997).

*Work supported in part by U.S. Department of Energy Contract No. DE-AC02-76-CH03073.

# Transport Studies of Quasi-Axisymmetric Stellarators

Harry E. Mynick
*PPPL*

The Stellarator Group at PPPL is investigating the properties of quasi–axisymmetric (QA) stellarators, toward developing an attractive configuration of this type. Here, the transport characteristics in some QA stellarators we have studied will be presented, beginning with the MHH2 concept[1], which was our starting point, and moving to a family of the QAS type[2], obtained by perturbing from an ARIES equilibrium. These have much lower aspect ratio ($A \equiv R/\bar{a} \simeq 2.1$, in comparison with $A \simeq 4.5$ for MHH2), and often much improved stability characteristics. We have found a 2 field–period configuration (QAS2) having an average ballooning $\beta_{bal} \simeq 6.8$ %, and neoclassical transport only slightly greater than that for a fully axisymmetric configuration, and far below the anomalous rates which might be expected on the basis of empirical scaling laws. 4 and 8 field–period configurations have also been examined, also having $\beta_{bal}$ in the range 6.5–7.0 %, and which have enhanced shear $\iota'$, in an effort to enhance stability to external kinks and neoclassical tearing, but at the expense of somewhat higher ripple. These have transport levels comparable to those of MHH2, and thus require further reduction of ripple (by perhaps a factor 2–3) to make neoclassical loss subdominant to our empirical estimate of anomalous loss. Efforts are underway to further optimize all 3 of these QAS variants.

## References

[1] P.R. Garabedian, *Phys. Plasmas* **3**, 2483 (1996).
[2] A. Reiman, R. Goldston, L-p Ku, D. Monticello, H. Mynick, G. H. Neilson, M. Zarnstorff, I. Zatz, W. A. Cooper, A. Boozer, *8th International Toki Conference on Plasma Physics and Controlled Nuclear Fusion*, (September, 1997).

# Rapid Computing with TERPSICHORE and CAS3D MHD Stability Codes for a Quasi-axial Stellarator

M. H. Redi, D. A. Monticello, G. Y. Fu, M. C. Zarnstorff
*Princeton Plasma Physics Laboratory*

C. Nuehrenberg
*IPP, Greifswald, Germany*

W. A. Coooper
*CRPP-PPB, Lausanne, Switzerland*

The potentially attractive quasi-axially symmetric stellarator concept[1] proposes to combine the best features of stellarators and tokamaks. As high fusion power tokamak experiments are often terminated by mhd-driven disruptions at high beta, it is important to investigate mhd stability for such a design.

The TERPSICHORE[2] and CAS3D[3] code suites have been modified to run efficiently within the U. S. NERSC CRAY computer scheduling system which delays or forbids execution of very large computer codes. For a low number of flux surfaces (48), the mapping codes in each suite were near or above 80MW in size, but relatively straightforward ways were found to reduce the number and size of arrays computed. Thus, the executable size could be reduced by a factor of 2-10, without sacrificing rapid cpu time. This makes possible inclusion of ballooning mode analysis with TERPSICHORE within a stellarator design optimizer (see paper by Reiman, this conference) and use of CAS3D for evaluation of the stability of short and long wavelength mhd.

A two period quasi-axial stellarator with 20% external transform was examined for mhd stability with the CAS3D stability analysis code. This case was later optimized for ballooning and Mercier stability and for good particle transport (see paper by Mynick, this conference). A global mode analysis for the three-dimensional plasma configuration characterized by low aspect ratio was carried out with the fixed boundary version of CAS3D for beta up to 6.73%. At 6.73% beta and 48 flux surfaces with a nonmonotonic, low shear profile, the largest amplitude Fourier components of the most unstable eigenmode were found to be localized within the inner half radius. As beta is reduced to 6.0% this mode is stabilized. As the mesh size is reduced the growth rate is found to decrease quadratically. At 6.73% beta, some lower growth rate modes near the plasma edge are found to be due to numerical error, as the mesh size is reduced. With a higher number of flux surfaces (129 vs. 48), the most unstable mode at 6.73% beta was located near 0.25r/a and at 6.5% beta was located near 0.6r/a. Changes in the instability composition and radial structure as beta and mesh size are varied will be shown. Very high toroidal mode number simulations show increased growth rates and narrowed radial extent for this mode as expected.

Comparisons with TERPSICHORE and progress in applying the free boundary version of the CAS3D code to this and other cases will be discussed.

## References

[1] J. Nuehrenberg, W. Lotz, and S. Gori, in *Theory of Fusion Plasmas*, E. Sindoni, F. Troyon and J. Vaclavik eds., SIF, Bologna, 1994. P. Garabedian, Phys. Plas. **3**, 2483 (1996).
[2] W. A. Cooper, et al., Phys. Plas. **3**, 275 (1996).
[3] C. Schwab, Phys. Plasmas **3**, 2401 (1996).

# External Kink Stability in Quasi-axisymmetric Stellarators

G. Y. Fu, M. Hughes, C. Kessel, L. P. Ku, D. Monticello, M. Redi, A. Reiman
*Princeton University, Princeton, NJ 08543*

A. Cooper
*CRPP, Lausanne, Switzerland*

Quasi-axisymmetric stellarators (QAS) offer great potential for magnetic fusion reactors with high beta, steady state operation and good confinement. One of key issues for QAS is the stability of external kink mode driven by pressure-induced bootstrap current. Recently, high-beta ballooning-stable QAS have been obtained by adding appropriate three dimensional modification to the plasma boundary of an optimized tokamak equilibrium[1]. In this work, the stability of low-n external kink modes in QAS is assessed using a 3D free boundary MHD stability code Terpsichore[2]. It is found the kink stability is strongly dependent on rotational transform profile, especially the value of rotational transform and magnetic shear near the plasma edge. The effects of edge magnetic shear are strongly stabilizing. By choosing appropriate externally generated transform, kink stable QAS with large shear are found at beta value up to 7%. In contrast, the equivalent tokamak equilibria (at fixed $\iota(a)$) have lower beta limits around 4% for external kink mode without conducting wall. Detailed numerical results of parameter dependence on magnetic shear, edge iota value, and beta will be presented.

## References

[1] A. Reiman et al., this conference.
[2] W. A. Cooper et al., Phys. Plasmas **3**, 275 (1996).

# Electromagnetic Gyrofluid Simulation of Turbulence and Transport*

Philip Snyder, Greg Hammett, Michael Beer
*Princeton Plasma Physics Laboratory*

An electromagnetic gyrofluid model is developed for studying turbulent processes in magnetized plasmas. This work extends earlier electrostatic gyrofluid simulations to include the perturbed parallel magnetic potential ($\delta A_{||}$) and non-adiabatic passing electron dynamics. A new set of electron fluid equations is derived from the drift kinetic equation, initially in the zero electron mass limit to avoid introducing the fast electron thermal time scale into the simulations. The simulation does not yet include electron collisions, $\delta B_{||}$, or electron heat flux due to magnetic perturbations, but the electron equations do include the effects of electron temperature and density gradients, electron $\mathbf{E} \times \mathbf{B}$ motion, and the parallel electron currents which, along with parallel ion currents, give rise to the parallel magnetic potential. This improved model of both linear and nonlinear electron dynamics, as well as the inclusion of shear Alfvén wave coupling, extends the validity of our model into finite-$\beta$ regimes, and should improve assessments of transport due to the toroidal ion temperature gradient (ITG) mode. Linear benchmarks and preliminary nonlinear results will be presented. Initial indications are that electromagnetic effects may reduce heat transport associated with the toroidal ITG mode.

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# The Dynamics of Small-Scale Turbulence Driven Flows*

Michael A. Beer, G. W. Hammett
*PPPL*

The dynamics of small-scale fluctuation driven flows are of great interest for micro-instability driven turbulence, since nonlinear toroidal simulations have shown that these flows play an important role in the regulation of the turbulence and transport levels. In particular, the damping of these poloidal flows is a sensitive control of the transport levels. The gyrofluid damping of these flows was shown to be accurate for times shorter than a bounce time [1]. Since the decorrelation times of the turbulence are generally shorter than a bounce time, our original hypothesis was that this description was adequate. Recent work [2] pointed out possible problems with this hypothesis, emphasizing the existence of a linearly undamped component of the flow which could build up in time and lower the final turbulence level.

The existence of linear collisionless poloidal flow damping is sensitive to initial conditions. If the distribution function at $t = 0$ is Maxwellian, as seems likely for $\mathbf{E} \times \mathbf{B}$ nonlinearly driven flows, most of the flow damps away (due to collisionless Landau damping) at a rate $\sim v_t/qR$. The residual flow correctly calculated in [2] is a non-Maxwellian component of the flow which is not collisionlessly damped. In our original gyrofluid treatment [1], we included collisionless damping terms which were appropriate (and essential) to capture the fast collisionless damping of the damped components, but which do not accommodate the linearly undamped components. While gyrofluid and gyrokinetic results agree on the initial collisionless damping, the standard closures used in the gyrofluid equations fail to describe the residual non-zero potential at times longer than several bounce times.

Although this residual component of the flow is undamped linearly, it can still be damped nonlinearly by the turbulence itself, i.e., by turbulent viscosity. Thus the nonlinear drive of the poloidal flows can, at least in some cases, be balanced by the nonlinear damping of these flows and a steady state balance can be reached. We have tested this by modifying the gyrofluid closures in such a way that a weak linear instability is actually introduced into a component of the poloidal flow, and find that it is still possible to still reach a saturated state where the nonlinear damping balances this weak linear drive.

The size of the residual undamped flow scales with $r/R$ [2]. Gyrofluid and particle simulations show similar scalings with $r/R$, at least far from marginal stability, also suggesting that nonlinear damping of the poloidal flows is providing a sufficient sink. However, there are indications that the situation may be different closer to marginal stability, where the ratio of nonlinear damping to drive may differ and particle simulations [3] have seen the poloidal flow rise to large levels and shut off the turbulence. While this may be a robust result, there is also a possibility that the system has multiple equilibrium points, leading to bifurcations and/or intermittent behavior dependent on initial conditions. These issues are still being investigated.

## References

[1] Beer, M. A., Ph. D. thesis, Princeton University (1995).
[2] Rosenbluth, M. N. and Hinton, F. L., Phys. Rev. Lett. **80**, 724 (1998).
[3] A. M. Dimits, private communication (1997).

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# Comparing gyro-Landau-fluid and particle simulations*

G. W. Hammett, M. A. Beer
*PPPL*
W. Dorland
*Univ. Maryland*
et al.

We will review past and ongoing comparisons of gyro-Landau-fluid simulations with kinetic/particle simulations, and discuss some of the issues involved, some of which are still being investigated. Previous comparisons between gyrofluid and gyrokinetic particle simulations in 3-D slab geometry[1] found fairly good agreement in $\chi$ (within 10% in a scan of $L_n/L_s$), though there were 40% differences in the saturation level of $\Phi_{RMS}$. An idealized 3-mode coupling problem has also been studied, and we will show kinetic simulations that show how the introduction of a small amount of collisions can cause the kinetic turbulence level to rise to be closer to the gyrofluid result.

Comparisons in toroidal geometry are ongoing[2], but generally show a larger discrepancy in $\chi$ (a factor of $\sim 2-3$) than in slab geometry, with larger differences near marginal stability and better agreement far from marginal stability. The particle simulations see a nonlinear upshift in the effective critical temperature gradient. This may be due to a component of poloidal flow which is linearly not damped except for collisions[3], but which can be damped nonlinearly by turbulent viscosity (for more on this topic, see the paper by Beer et.al., this conference). Several noise tests have been successfully completed[2]; particle noise does not appear to be a problem. In one case with no magnetic shear ($\hat{s} = 0$) where the gyrofluid $\chi$ had previously been 1.5 times larger than the gyrokinetic $\chi$, we have since found that the gyrofluid resolution had been inadequate and increasing the resolution brings the gyrofluid $\chi$ into good agreement with the particle results. However, in another case with magnetic shear, no significant change in the gyrofluid $\chi$ has been seen as the resolution has been increased. Further tests of resolution issues should be carried out by trying sub-grid turbulence models and/or an algorithm by Dimits for giving more uniform resolution in a field-line following grid. We will continue investigation of alternative closures, such as nonlinear modifications or toroidal modifications to include Pfirsch-Schluter heat fluxes to better describe poloidal flow dynamics. The gyrofluid/particle comparisons to date have been done in the adiabatic electron, electrostatic, collisionless, single-ion species limit. Electromagnetic effects can sometimes have a stabilizing influence on ITG turbulence. On the other hand, adding trapped electrons is usually destabilizing, and may push the fluctuations into a stronger turbulence regime or provide additional decorrelation mechanisms. These might be regimes where gyro-Landau-fluid closures may work better. Likewise, the addition of collisions or multiple ion species may improve comparisons. A sensitivity study of predicted temperatures and $Q$ to various assumptions about $\chi$, pedestal temperature, etc. will be shown.

## References

[1] S. E. Parker, W. Dorland, R. A. Santoro, et.al., Phys. Plasmas **1**, 1461 (1994). W. Dorland, Princeton Univ. Ph.D. Dissertation (1993).
[2] A. Dimits, M.A. Beer, S.E. Parker, W. Dorland, et.al., manuscript in preparation.
[3] M.N. Rosenbluth, F.L. Hinton, Phys. Rev. Lett. **80**, 724 (1998).

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# ION CYCLOTRON INSTABILITY NEAR THE MAGNETIC FIELD WELL*

M.V. Gorelenkova, N.N. Gorelenkov†

*Troitsk Institute for Innovative and Fusion Research, Troitsk, Russia, 142092*

Low aspect ratio tokamaks, such as NSTX (National Spherical Torus Experiment), have relatively low toroidal magnetic field, which can be exceeded by its poloidal component. Also, the plasma beta is believed to be significant, which make it possible to create such an equilibrium, where the magnetic field will have local minimum close to the magnetic axis. Under these conditions the local Alfvén velocity will have local minimum as well, which may result into the existence of the Alfvén eigenmodes. Then, the heuristic equation for the localized eigenmodes of the magnetosonic (or fast Alfvén, compressional Alfvén ) wave is $k^2 = w^2/v_A^2$, where $v_A$ is the Alfvén velocity, $k$ is the mode wavevector. It can be derived more rigorously [N. N. Gorelenkov, C. Z. Cheng, Nucl.Fusion **35** (1995) 1743] and can be reduced to the form

$$\left(\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial}{\partial r}r - V(r)\right) E_\theta(r) = 0,$$

where the potential well $V(r)$ is formed at $r_0 = r_{B_{min}}$ and is given by

$$V(r) = -\frac{\omega^2}{v_A^2(r_0)}\frac{1}{1 + r^2/\Delta^2},$$

$\Delta$ is a potential well width, and $E_\theta$ is the poloidal component of the perturbed electric field. As such eigenmodes can be excited through the local cyclotron resonance, just their eigenfrequency could provide the information about the absolute value of the magnetic field as well as the depth of the magnetic well, which enters the analysis through the quantization condition. The dispersion relation is obtained and presented. The estimates for the growth rates of the magnetosonic eigenmodes is presented.

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†Present address: Princeton Plasma Physics Laboratory, P. O. Box 451, Princeton, NJ 08543-0451

# Glasser-Green-Johnson effect and neoclassical tearing mode stability

Leonid E. Zakharov
*PPPL, Princeton University*

Stabilization of neoclassical tearing modes is considered as one of the top priority problems for tokamaks. While the ordinary tearing modes have typical value of the tearing stability parameter $r\Delta' \simeq 1$, the neoclassical values of $r\Delta'$ may be at least an order of magnitude larger (e.g, about 30 in TFTR). At this level of $\Delta'$ any active stabilization of neoclassical tearing modes is problematic.

Here, we evaluated the role of Glasser-Green-Johnson (GGJ) effect on neoclassical tearing mode stability. While this effect has been taken into account earlier in comparison between theory and experiments on TFTR[1], there is an opinion that at small island width, when the plasma pressure is not flattened inside the island and does not follow the magnetic field lines, the GGJ effect is quenched in the same way as the neoclassical driving mechanism. We extended the theory of incomplete equilibrium[2] to the case of plasma with magnetic islands and found that the GGJ effect is not sensitive to the pressure perturbation inside the island and it remains inverse proportional to the island width. Moreover, the numerical factor in front of GGJ contribution into $\Delta'$ is twice bigger without pressure perturbation (for small islands) than for flattened pressure inside the island.

Thus, GGJ effect may give significant enhancement in the threshold for excitation of neoclassical tearing modes. This makes realistic (although still very difficult) under-threshold detection of the neoclassical mode and its complete feedback stabilization.

## References

[1] N. N. Gorelenkov, *et al*, Phys. Plasmas, 3, 3379, (1996).
[2] L. Zakharov, G. Pereverzev,Sov. J. Plasma Physics, 14, 75 (1988).

# Object-Oriented MHD

A. Y. Aydemir, K. C. Shaing, W. H. Miner, J. C. Wiley*
*Institute for Fusion Studies*
*The University of Texas*
*Austin, TX 78712*

Our nonlinear MHD code **CTD** is being rewritten using object-oriented methods for a massively parallel environment. The extra effort involved in a complete overhaul of the code, rather than a mere upgrade and port to a new platform, is expected to pay off in terms of efficiency, flexibility, and ease of use. With the techniques employed, we envision being able to switch among various physics models and geometries, as well as the lower level numerical algorithms, in a trivial fashion. Our early applications will be in resistive MHD, continuing our earlier work on the vertical displacement events in shaped tokamaks. Later on, we expect to incorporate a correct treatment of various neoclassical effects for studying linear and nonlinear stability in the next generation of tokamaks.

*Fusion Research Center

ABSTRACT

# NOVEL HYBRID MAGNETIC FUSION DEVICES

A.K. Sen
Columbia University

## "Pinch-Tormac": A New Fusion Device

The concept is a semi-closed device based on linear theta pinches. Specifically, we propose a racetrack configuration whose linear segments are theta pinches and whose curved segments are Tormac like sectors. This new fusion device can naturally be called "Pinch-Tormac." The Tormac sectors consist of quadrupole line cusps superposed on the curved solenoidal magnetic field of the theta pinch coils. The reason the device appears semi-closed is that only a small population of particles which are in the sheath separating the closed and open field lines regions, "see" the open field lines of the cusp fields and this occurs only at the curved ends of the device. Therefore, the loss rate in this device is much smaller than that in a regular Tormac and vastly smaller than that in an open ended theta pinch. Also as hot high $\beta$ plasma is produced by theta pinches, the most uncertain problem auxiliary heating in a regular Tormac is automatically avoided. Therefore, a Pinch-Tormac promises to be a far more attractive fusion device than either a standard theta pinch or standard Tormac. As a linear theta pinch is neutrally MHD stable, the only potential for instability exists in the curved ends. However, the plasma in the Tormac sectors is in absolute minimum B and hence enjoys at least MHD stability in principle. We show that for high $\beta$ fusion-type parameters and a device length of approximately 100 m, one can obtain $n\tau_{conf} \sim 10^{15}$ cm$^{-3}$ sec., indicating fusion feasibility.

## "Stellarator-Pinch": A Hybrid Fusion Device

This scheme is analogous to the "Pinch-Tormac" device discussed above in terms of the overall race-track configuration consisting of two theta pinches connected via stabilized toroidal sectors. The difference in this case is the use of stellarator halves for the toroidal sectors. As a stellarator has much better particle confinement properties than that of a tormac, one can dispense with the requirement of very long lengths of theta pinches in the "Pinch-Tormac" configuration. The primary purpose of theta pinch sectors of modest lengths will be to provide a technologically convenient and efficient method of plasma heating in a stellarator, which remains a difficult issue. In view of the very high densities and moderately high temperatures available from theta pinches, one can envision a modest size closed device with $n\tau_{conf} \sim 2.4 \times 10^{14}$ cm$^{-3}$ sec which indicates fusion feasibility.

# NON IDEAL EFFECTS IN HIGH-$n$ TAE STABILITY STUDY USING 2-D HINST CODE*

N.N. Gorelenkov, C.Z. Cheng, G.Y. Fu, W. Tang
*Princeton Plasma Physics Laboratory, P. O. Box 451, Princeton, NJ 08543-0451*

A high-$n$ stability code, HINST, has been developed to study the stability of TAE's (Toroidicity induced Alfvén Eigenmodes) in large tokamaks such as ITER where the spectrum of unstable TAE's is shifted toward the medium to high-$n$ modes. The code is based on the poloidal ballooning and radial Fourier transformations. HINST solves the $2D$ eigenmode problem by expanding the eigenfunctions in terms of orthogonal basis functions. The eigenmode problem is reduced to a system of coupled $1D$ equations, which is solved numerically. The numerical method allows to include nonperturbatively non-ideal effects such as full ion finite Larmor radius and drift orbit width effects, trapped electron collisional damping, continuum and radiative dampings, etc. Present version of HINST uses simplified $s - \alpha$ equilibrium with circular magnetic surfaces. Fast particles are assumed to have zero drift orbit radial width, and Maxwellian distribution function. FLR effects for all ion species are retained. The 2D numerical results are benchmarked for medium-$n$ modes with the NOVA results[1] for large and moderate aspect ratio and low-$\beta$ tokamak equilibrium. In addition to TAE HINST can also compute the stability of kinetic branches like RTAE (Resonance TAE) and KTAE. The results show that TAEs and RTAEs can be driven unstable by alpha particles in a model ITER-like equilibrium with $n = 10 - 50$. The growth rate for the most unstable mode is within the range $0.3 - 1\%$ of the real frequency. The most unstable modes are localized near $r/a \simeq 0.5$ and have a radial mode width $\Delta r/a \simeq 0.1 - 0.2$.

## References

[1] C. Z. Cheng, Phys. Reports **211** (1992) 1.

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# Lattice Boltzmann Simulation of Rayleigh Benard and 3D Shear Flows

George Vahala, Darren Wah
*Department of Physics, William & Mary, Williamsburg, VA 23187*

Pavol Pavlo
*Institute of Plasma Physics, Czech Academy*

Linda Vahala
*Department of ECE, Old Dominion University, Norfolk, VA 23529*

To apply lattice Boltzmann methods (LBM) to divertor plasmas, one must be able to handle boundary conditions. For proper spatial resolution, this will require non-uniform spatial grids. However, with our introduction of higher isotropy velocity lattices, there is now a natural un-coupling of the space and velocity grids. We continue to employ Lagrangian streaming since it does not introduce any numerical diffusion or dissipation (but we are running at marginal stability with CFL = 1) - and invoke second order interpolation schemes to connect back to the non-uniform spatial grid. It is verified that these interpolation schemes do not adversely affect the simulation values of the transport coefficients.

As a preliminary to introducing sources and sinks into the macroscopic conservation laws, as needed for divertor simulations, we here considered LBM for Rayleigh-Benard convection (2D) as well as 3D free-shear turbulence.

# Higher Order Isotropic Velocity Grids in Lattice Boltzmann Simulations

Pavol Pavlo
*Institute of Plasma Physics, Czech Academy*

George Vahala
*Department of Physics, William & Mary, Williamsburg, VA 23187*

Linda Vahala
*Department of ECE, Old Dominion University, Norfolk, VA 23529*

Lattice Boltzmann methods (LBM) can play a major role in solving systems, particularly those whose evolution involves nonlinear advection terms. Depending on the collisionality regime, LBM can be viewed as a maximally discretized molecular dynamics - an optimzed mesoscopic description between the full molecular dynamics and the macroscopic conservation laws. Only a few attempts have been made to simluate macroscopic systems that are closed at the second moment (energy) level because inherent numerical instabilities severely limit the accessible parameter regimes.

In conventional LBM, Lagrangian schemes are employed with the underlying discrete symmetry of the chosen lattice such that the intended physics is not marred in the continuum limit. Typically this has resulted in the spatial and velocity lattices being intrinsically coupled, and with the need to be space-filling, this restricted the lattice geometry in 2D to be either a composite square grid or a hexagonal grid or the projection of a 4D FCHC grid onto 3D.

Here we propose to uncouple the spatial and velocity grids. This allows us to employ higher isotropy velocity grids that need no longer be space-filling. The use of these higher iostropy grids yields much enhanced numerical stability - both in 2D and in 3D. In particular, an octagoanl velocity grid is employed in 2D and its generalization to a 53-bit model in 3D.

The use of LBM to represent neutrals in the gas blanket divertor will also be considered.

# Analysis of the m=2 tearing mode stabilization by lower hybrid current drive on FTU

A. Cardinali

*Associazione Euratom-ENEA sulla Fusione*

Stabilization of the m=2 tearing mode by localized deposition of the lower hybrid wave at 8 GHz on the island interior is analysed for FTU tokamak plasma, where, in some discharges, a double tearing mode develops and leads to a sudden disruption. An accurate calculation of the parameters required to the stabilization of the mode has been derived by means of a numerical code which includes the wave dynamics and the solution of the Fokker-Planck equation. The deposition layer of the wave power and the amount of current generated inside the island are determined accurately and used in the calculation of the non-linear saturation of the island width [1]. Useful informations on the lower hybrid wave parallel wavenumber spectrum to be launched in view of the tearing mode stabilization can be obtained and used in planning the experimental scenarii. The combined effects of the electron cyclotron and lower hybrid waves on the mode stabilization are also described.

## References

[1] S. Bernabei *et al.*, to be published on Nuclear Fusion (1998).

# Systematic Studies of Wake Fields in Plasma Channels*

B. A. Shadwick, C. B. Schroeder, J. S. Wurtele
*Physics Department, UC Berkeley and Center for Beam Physics, LBNL.*

We examine wake fields produced by an intense, short laser pulse propagating in a plasma channel which has an arbitrary density profile. As accelerating structures, not only do plasma channels have many desirable features, they are also becoming experimentally realizable. As part of an overall research program to analyze plasma channels as accelerating structures, a new fluid simulation code has been developed with the primary purpose of producing fast tools to explore parameter space for both theoretical investigation of accelerator performance as well as the modeling and design of experiments. This code has flexible physics content, for example, the laser either be fully resolved temporally or treated as ponderomotive force. An important feature, from the accelerator design point of view, is capability to study of beam propagation dynamics. We present preliminary results consisting of a detailed analysis of the transverse structure of the wake for a wide range of experimentally accessible channel profiles and characteristics of the corresponding accelerated beam.

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# Enhanced Instability of the Parallel Velocity Shear Instability due to Magnetic Shear Reversal

Daniel McCarthy, Slade Maurer
*Southeastern Louisiana University*

The three-dimensional dynamics of the electrostatic parallel velocity shear ($v'_{||}$) instability in a sheared magnetic slab has been studied numerically. Previous numerical studies of this mode [1] showed that the fluctuation levels of this mode were extremely large ($\sim 50\%$) which was recently verified experimentally [2]. Another interesting feature of the mode was that it is 'tilted' with respect to the magnetic field i.e. has wave vectors in both the $y$ and $z$ directions, where the orientation of the tilting depends upon the sign of the parallel velocity gradient. For the situation when there is a peaked velocity profile, there will be an opposite tilting of the modes on either side of the profile. In other words the mode will have its own effective shear. What we find in this work is that if the magnetic shear is oriented so as to increase the tilting of the mode, there is a reduction in both the fluctuation levels and momentum transport. However, if the magnetic shear is oriented so as to reduce the relative tilting, the fluctuation levels an

## References

[1] D. R. McCarthy, A. E. Booth, J. F. Drake, and P. N. Guzdar Phys. Plasmas **4** 300 (1997).
[2] J. Willig, R. L. Merlino, and N. D'Angelo, Bull Am. Phys. Soc **42** 1890 (1997).
[3] P. J. Catto, M. N. Rosenbluth, and C. S. Liu, Phys. Fluids **16**, 1719 (1973).

# VALIDATION OF NIMROD WITH THE SOLOVIEV EQUILIBRIUM

Alfonso Tarditi and Dalton Schnack
Science Applications International Corp.
San Diego, CA 92121
and
The NIMROD Team

NIMROD is a new three-dimensional fluid code designed for the analysis of advanced fusion experiments. In addition to ideal and resistive MHD, NIMROD contains a two-fluid model including Hall effects and electron inertia. These equations are solved with a highly accurate semi-implicit algorithm that effectively decouples the computational time step from the fastest time scales in the problem. The grid can be decomposed into a collection of rectangular and triangular blocks. This allows arbitrary cross-sectional poloidal geometry to be easily represented. The grid is aligned with the flux surfaces inside the separatrix providing an accurate representation of the anisotropies inherent in strongly magnetized plasmas. Spatial approximation is by finite elements. The numerical dispersion relation is free from spectral pollution.

NIMROD is undergoing an extensive validation campaign. As part of this program, we have compared the linear growth rate of internal kink modes in the Soloviev equilibrium[1] with previously published numerical results[2]. Convergence studies as functions of spatial and temporal resolution, and physical dissipation have been performed. Good agreement has been obtained. The results of these studies are presented.

1. L. S. Soloviev, Sov. Phys.-JETP 26, 400 (1968).
2. D. Berger, L. C. Bernard, R. Gruber, and F. Troyon, J. App. Math. and Physics (ZAMP) 31, 114 (1980).

# Energy Confinement Time for Ignition-Relevant Tokamak Plasmas During Electron Cyclotron Heating*

V. Stefan
Tesla Laboratories, Inc.
La Jolla, CA 92038-2946

The scaling laws for the advanced tokamak energy confinement time are evaluated. Plasma is assumed to be of low coollisionality with equilibrated electron and ion temperatures. The characteristics of rf field, in electron cyclotron range of frequencies, are chosen to be: f~110 GHz, pulse length $\tau_p$~2-10s, and P=1-10MW. In this power range the sideband turbulence strongly affects the energy confinement time $\tau_E \sim (3/2)\, n_e T_e / Q$ where Q is the local plasma turbulent heating rate. The following scaling laws are obtained:

$$\tau_E \sim P_{rf}^{-3/2} \;, \quad \gamma > \gamma_{EB} \;, \quad P_r \geq 1\text{MW} \;,$$

$$\tau_E \sim P_{rf}^{-2/3} \;, \quad \gamma >> \gamma_{EB} \;, \quad P_{rf} \leq 10\text{MW} \;,$$

where $\gamma$ is the secondary parametric growth rate[1] for the electron Bernstein mode (EB) decay and $\gamma_{EB}$ linear (collisional) damping rate of EB mode. The scaling (1) and (2) are essentially different from scalings usually obtained for sideband turbulence free plasma[2].

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* Supported by Tesla Labs, Inc..

[1] In these calculations, modes with noncollisional damping are not taken into account.

[2] For example Freidberg et.al., found $\tau_E \sim P_{rf}^{-1}$. J.P. Freidberg, S.P. Harrakainen, and D.J. Sigmar, Sherwood Theory Conference (1983).

# Enhancement of Ideal MHD Wall Stabilized $\beta$ Limits from Profile and Cross-Section Optimization

A.D. Turnbull, T.S. Taylor, L.L. Lao, R.L. Miller,
M.S. Chance,† and B.J. Lee‡

*General Atomics*
*San Diego, California*

Stability calculations for strongly shaped equilibria predict large improvements in the ideal MHD $\beta$ limit from Negative Central Shear (NCS) with elevated $q_{min}$ if stabilization from a nearby conducting wall is taken into account [1,2]. Experiments in TFTR and DIII–D, however, are apparently limited by ideal instabilities at significantly lower $\beta$ values and have so far failed to realize the anticipated gains from wall stabilization. Systematic stability calculations will be reported which shed some light on this apparent discrepancy. With a moderately placed wall, the gain in the ideal $\beta$ limit from stabilization by the wall is shown to be strongly dependent on the cross section and the details of the current density and pressure profiles. There is a synergistic relationship between the gains due to optimization of the cross-section and the gains from profile optimization; the gain resulting from optimization of one without the other is relatively moderate but simultaneous optimization of both the profiles and cross section shaping yields much larger increases in the $\beta$ limit. The reasons for this lie in the details of the coupling of the plasma with the wall. However, the essence of the synergism is that increased $\beta$ improves the coupling to the wall so that higher $\beta$ limits achievable from optimization of the cross section yield even further improvements. This synergism is demonstrated in detail for a variety of cross sections and pressure profiles with L–mode type edge conditions in which $p'$ vanishes at the edge. Preliminary results on the effect of optimization of the edge current density and finite edge pressure gradient are also discussed.

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†Princeton Plasma Physics Laboratory, Princeton, New Jersey.
‡Korea Basic Science Institute, Taejeon, Korea.

[1] A.D. Turnbull *et al.*, Phys. Rev. Lett. **74** (1995) 718.
[2] C. Kessel *et al.*, Phys. Rev. Lett. **72** (1994) 1212.

# Competition of high-n ballooning modes and the parallel heat transport in the nonlinear stage of internal disruption

Y.Nishimura, C.C.Hegna, and J.D.Callen

*University of Wisconsin-Madison*

The topological paradox of the tokamak sawtooth is that the central q-value remains below unity after the temperature crash, regardless of the plasma temperature or the Lundquist number range[1, 2, 3], as long as they are high enough. It is suggested by an MHD simulation that the free energy couples geometrically from the $m/n = 1/1$ to higher $n$ mode numbers; the $m/n = 1/1$ magnetic island evolution gives rise to convection of the pressure inside the inversion radius and builds up a steep pressure gradient across the island separatrix or the Y-ribbon, and thereby triggers ballooning instabilities below the threshold for the axisymmetric equilibrium. Also indicated was the strong coupling of the 1/1 mode to the 2/1 and the 0/1 modes, which is indicative of dispersion of the current free energy inside $q = 1$ surface. This mode coupling feature is prominent in higher $\beta$ calculations. The computational results shown here are for a case with the maximum toroidal

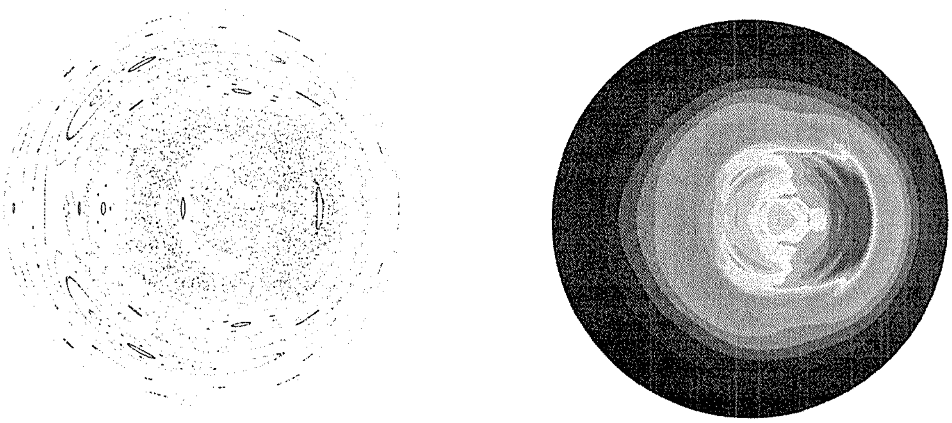

Figure 1: (a) Poincaré mappings of magnetic field line trajectories in a poloidal cross section, and (b) Pressure contours. To the right is the bad curvature side.

number $n = 4$. The q-profile has been taken from a peaked current profile ($q_0 = 0.81$) and the averaged toroidal $\beta$ of 1.5%. Global stochastization of the magnetic field lines and concomitant heat transport along the field lines are investigated self-consistently. Further simulation and analysis with higher-n numbers will be presented. For the completeness of the work, the compressible version of the FAR code[4] is employed to investigate the effects of pressure relaxation by the sound wave.

## References

[1] T. H. Osborne, R. N. Dexter, and S. C. Prager, Phys. Rev. Lett **49**, 734 (1982).
[2] H.Soltwish et al., Plasma Phys. Controlled Fusion, **37**, 667 (1995).
[3] Y. Nagayama et al., Phys. Plasmas, **3**, 1647 (1996).
[4] L. A. Charlton et al., J. Comp. Phys. **86**, 270 (1990).

# Interpretation of Pitchfork Splitting Effect

B. N. Breizman, M. S. Pekker
*Institute for Fusion Studies, The University of Texas at Austin, Austin TX 78712*

A. Fasoli*
*Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge MA 02139*

D. N. Borba, R. F. Heeter
*JET Joint Undertaking, Abingdon OX14 3EA, United Kingdom*

Recent observations of toroidal Alfvén eigenmodes driven by energetic ions in JET have revealed an unusual phenomenon: the mode spectrum exhibits pitchfork splitting (a transition from a single spectral line to several closely-spaced spectral components) [1]. This paper offers a first-principle theoretical interpretation of pitchfork splitting.

Our analysis of the experimental data is based on a nonlinear theory of near-threshold regimes for kinetic instabilities [2]. The evolution of the system in these regimes is governed by resonant wave-particle interaction and collisional relaxation of the particles, which is strongly enhanced near the resonance. The competition between the two mechanisms gives a rich family of nonlinear scenarios that we use to explain the mode saturation level and bifurcations that cause pitchfork splitting. The proposed model relates the positions and the amplitudes of the spectral components to the values of the instability growth rate and the effective collision frequency of the resonant particles. This may develop into a useful diagnostic tool.

## References

[1] A. Fasoli, *et. al.,* Plasma Phys. and Control. Fusion **39** 287 (1997).
[2] H.L. Berk, B.N. Breizman and M.S. Pekker, Plasma Phys. Reports. **23** 778 (1997).

*also at JET Joint Undertaking, Abingdon OX14 3EA, United Kingdom

# Calculation of Feedback Stabilization of Tokamak Wall Modes*

Allen H. Boozer
*Columbia University*

Standard and spherical tokamaks require a conducting wall to obtain high beta equilibria that can be maintained largely by the bootstrap effect. A conducting wall does not fully stabilize a non-rotating plasma but slows the growth by several orders of magnitude to a rate proportional to the resistivity of the wall. Suggestions have been made for the feedback stabilization of the slowly growing wall mode, but a number of issues of implementation remain. A major limitation on computational studies of feedback is the plasma model. Here we describe a plasma model that is exact within the approximation of linear ideal MHD. The effect of the plasma region on the external magnetic field is given by the normal component of the perturbed field $b(\theta,\phi,t) = \mathcal{J}\mathbf{b}\cdot\nabla r$ at the location of the unperturbed plasma boundary with $(r,\theta,\phi)$ any toroidal coordinates with Jacobian $\mathcal{J}$. The component $b(\theta,\phi,t)$ can be written as a sum of normal modes, $b = \sum \Phi_i(t) f_i(\theta,\phi)$ with $\Phi_i$ having units of magnetic flux. The change in the energy in the region occupied by the plasma and a surrounding vacuum is $\delta W = \sum w_i {\Phi_i}^2/2$ with $w_i$ an eigenvalue. The flux in a mode is given by $\Phi_i = \int f_i \mathbf{b}\cdot d\mathbf{a}$. The normal field, $\Phi_i(t) f_i(\theta,\phi)$ could be produced by a surface current, $\mathbf{K} = \nabla r \times \nabla\kappa$ with $\kappa(\theta,\phi) = \sum I_i(t) h_i(\theta,\phi)$, at the plasma boundary. The flux $\Phi_i$ and the current $I_i$ are proportional, so $\Phi_i = L_i I_i$ defines the inductance for each mode. A sink must exist for the potential energy released by an instability. The most convenient sink is a surface current, which has the spatial distribution $h_i(\theta,\phi)$ and a distinct amplitude $I_i^d$, that is dissipated through Ohm's law, $d\Phi_i/dt = -R_i^d I_i^d$. Including the flux due to external currents, $\Phi_i^x = \int f_i \mathbf{b}_\mathrm{x}\cdot d\mathbf{a}$, the flux $\Phi_i = L_i I_i + \Phi_i^x$ with $I_i = I_i^p + I_i^d$. The perturbed plasma current $I_i^p$ is produced by the plasma distortion caused by the normal field with $L_i I_i^p = \sum_j(\delta_{ij} + s_i\lambda_{ij})\Phi_j$. The matrix ${\lambda_{ij}}^{-1} = \int f_i h_j d\theta d\phi$, and the dimensionless stability constants, $s_i = -L_i w_i$, are proportional to the eigenvalues of $\delta W$. The simplest approximation is to retain a single mode and let the flux due to the wall be $\Phi_x = M I_w$. The wall current is given by $d\Phi_w/dt = -R_w I_w$ with the flux penetrating the wall $\Phi_w = L_w I_w + M I$. The coupling between the wall and the plasma is given by $c = M^2/L_w L$. Wall modes exist if $0 < s < c/(1-c)$ with the approximate growth rate $\gamma_w = (s/c)R_w/L$, and an ideal mode exists for larger $s$ with the approximate growth rate $\gamma_I = sR_d/L$. That is, the time constant of the resistive shell, $L/R_d$, is chosen to simulate the ideal mode. The implementation of this model in an electromagnetic code will be described.

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# Current Profile Control and MHD Stability Studies of Reverse Shear Plasmas in Alcator C-Mod *

P.T. Bonoli, M. Porkolab, J.J. Ramos, S.J. Wukitch
*MIT Plasma Science and Fusion Center, Cambridge, MA 02139*

Y. Takase
*Tokyo University, Tokyo, Japan*

A simulation model has been developed which calculates self-consistent MHD equlibria in the presence of noninductive current densities due to neutral beam injection, driven lower hybrid waves, fast ICRF waves, and bootstrap effects.[1] This model has been combined with an ideal MHD stability code (JSOLVER / PEST-II)[2] and used to study access to high-$\beta$, reversed shear plasmas in the Alcator C-Mod tokamak.[3]

A sequence of C-Mod equilibria has been analyzed, representing the evolution of a discharge from low $\beta_N \simeq 1$ up to the $\beta$-limit ($\beta_N \simeq 3.5$) and beyond. Here we define $\beta_N = \beta_t/(I_p/aB)$ (%-m-T / MA). It has been found that lower hybrid current drive (LHCD) can be used to provide a sufficient level of off-axis current profile control for maintaining reversed shear current profiles with $q(\psi) > 2$. In addition, the fraction of bootstrap current in these discharges increases from $f_{bs} = I_{bs}/I_p \simeq 0.4 - 0.8$ as the plasma $\beta$ increases. Ideal MHD stability analysis of these C-Mod equlibria indicates the $\beta$-limit is set by the onset of the $n = 1$ external kink mode with a conducting shell placed at $r_w = \infty$. A source of on-axis seed current density is provided by ICRF fast wave current drive. The effects of plasma shaping ($\kappa$, $\delta$), plasma configuration (double null versus single null), and current profile control on the $\beta$-limit will be discussed.

Recently an advanced code for ICRF heating (TORIC) has been combined with a calculation of driven current due to mode converted ion Bernstein waves (IBW). This model has been used to investigate localized current profile control via mode conversion current drive (MCCD) in Alcator C-Mod. Results will be presented which demonstrate the possiblity of significant current profile modification both on-axis and off-axis in C-Mod.

## References

[1] R.S. Devoto, D.T. Blackfield, M.E. Fenstermacher, P.T. Bonoli, M. Porkolab, and G. Tinios, Nuclear Fusion **32**, 773 (1992).
[2] R.C. Grimm, R.L. Dewar, and J. Manickam J. Comp. Physics **49**, 94 (1983).
[3] P.T. Bonoli, M. Porkolab, J.J. Ramos, W. Nevins, and C. Kessel, Plasma Phys. Controlled Fusion **39**, 223 (1997).

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# Neoclassical Profiles and Advanced Tokamak Operation

William Dorland
*Institute for Plasma Research, Univ. of Maryland*

Michael Kotschenreuther, Q. P. Liu
*Institute for Fusion Studies, Univ. of Texas*

We report on the compatibility of neoclassical transport with MHD stability and steady-state, high-$\beta$ tokamak operation. To date, we have identified steady-state configurations with less than 1% externally supplied current, volume averaged $\beta$ ¿ 50%, and excellent microstability properties, although we have considered only pure DT plasmas. We are extending the calculations to include impurity and helium ash transport to probe the resilience of these findings. In any case, it appears that NSTX will provide a good test of theoretical predictions which favor a compact (R $\sim$ 1 meter), low-aspect ratio, low power ($\sim$ 30 MW) ignition experiment. A complete description of the codes and physics assumptions/models will be presented, along with predictions for NSTX.

# TOKAMAKS WITHOUT TURBULENT TRANSPORT

M. Kotschenreuther, Bill Dorland and Q. P. Liu

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

Recent experimental and theoretical results indicate that it is possible to suppress turbulence when the velocity shear $\gamma_E$ is of the order of $\gamma_{linear}$ (we use $\gamma_E$ defined by Hahm and Burrell). Here we present comprehensive electromagnetic gyrokinetic micro-instability calculations in numerically generated MHD equilibria to determine when this criterion can be satisfied with no driven toroidal flow (as is relevant to reactors). For aspect ratio A of 3 and 1.4, increasingly hollow current profiles are increasingly more favorable, since $\gamma_{linear}$ decreases and $\gamma_E$ increases. Broad, MHD stable pressure profiles with high bootstrap fraction (>95%) and high $\beta$ can strongly satisfy the criterion if $\rho_*$ is not *too small.* For example, for A=1.4 and $\langle\beta\rangle >$ 50%, $\gamma_E$ exceeds $\gamma_{linear}$ by an order of magnitude for all ITG and drift modes for $\rho_*=1/50$, a value comparable to proposed volume neutron sources. For A=1.4, this allows ignition for transport somewhat worse than neoclassical transport (see the poster by B. Dorland). High k microtearing modes may nonetheless be unstable in the center, but this is not expected to greatly affect global confinement.

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# Theoretical Model for the Plasma Rotation Paradox*

B. Coppi, G. Penn
*Massachusetts Institute of Technology, Cambridge MA 02139*

Significant plasma rotation has been observed to be produced in toroidal plasmas subject to ICRF heating in the absence of any evident direct angular momentum inputs[1]. The plasma rotates in the direction of the plasma current, with toroidal velocities at the magnetic axis ranging from $10^4$ to $10^5$ m/s in experiments on the Alcator C-Mod machine. The onset of this rotation and its decay after ICRF has been turned off are characterized by similar time scales on the order of 50-100 ms, much faster than expected from classical momentum transport. A process to induce this rotation with balanced ICRF inputs is proposed that is related to the excitation of a special class of magnetosonic modes at frequencies of the order of the ion cyclotron frequency and above. These modes are radially confined only if they have a poloidal phase velocity in the ion cyclotron direction, resulting in a correlated direction for the toroidal phase velocity. These radially confined modes, termed "contained modes"[2], will deposit their angular momentum on the plasma as they damp out. In contrast, modes having the opposite phase velocity can be expected to travel to the plasma edge and convert into radiation which will then be absorbed by the enclosing wall. The resulting torque on the plasma is in the same direction as the toroidal current, with an opposing torque applied to the experimental apparatus rather than to the plasma. We find that this mechanism is consistent with the observed magnitude and direction of the plasma rotation given the total power injected by ICRF of 3.5 MW. A relevant issue is the transport of angular momentum from the rather peripheral region where contained modes are localized to the magnetic axis; for this a "secondary instability" (electrostatic mode) capable of producing radial momentum transport is considered.

## References

[1] J. E. Rice, M. J. Greenwald, I. H. Hutchinson, E. S. Marmar, Y. Takase, S. M. Wolfe, F. Bombarda, "Observations of Central Toroidal Rotation in ICRF Heated Alcator C-Mod Plasmas", MIT report PSFC/JA-97-4, submitted to *Nucl. Fusion*.
[2] B. Coppi, G. Penn, C. Riconda, *Ann. Physics* **261** (1997) 117.

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# Progress on the GA/LLNL Project to Merge and Modernize ONETWO and CORSICA

H.E. St. John, T.B. Yang,† and R. Cohen†

*General Atomics*
*San Diego, California*

As part of the effort at General Atomics (GA) and Lawrence Livermore National Laboratory (LLNL) to improve all aspects of modeling and experimental data analysis related to DIII–D, and in preparation for participation in the National Transport Code (NTC) Initiative, GA and LLNL have started a collaboration to merge the capabilities of the CORSCIA and ONETWO transport codes into a flexible, user-friendly code. The initial goal is to provide a programmable (steerable) front end for ONETWO and a graphical user interface which will generate the most common front-end scripts for either ONETWO or CORSICA (which is already steerable). This paper presents our progress on the GUI development and an automatic wrapper generation tool for the programmable front end, and gives illustrations of ONETWO operation with the programmable environment and GUI. In the longer term, the objectives of this collaboration will be met through the NTC, which will collect modules from throughout the community and develop a flexible framework which will facilitate their interconnection in traditional (*e.g.*, to recreate ONETWO) or novel ways.

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†Lawrence Livermore National Laboratory, Livermore, California.

# Transport Equations in Axisymmetric Toroidal Plasmas with Large Mean Flows

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

H. Sugama
*National Institute for Fusion Science, Toki 509-5292, Japan*

The tokamak with large toroidal mass flows is a complex dynamical system with the features of multiscale turbulence, bifurcations and noncompositional transport. By noncompositional is meant that neither the neoclassical transport nor the ITG-trapped electron transport models alone provide adequate descriptions of the toroidal plasma transport. Thus, we continue our research of a unified description of neoclassical and turbulent transport in the presence of large mean flows. We also derive the nonlinear electromagnetic gyrokinetic equation for plasmas with large mean flows and general geometries, which is in agreement with a form given by Brizard [1] and is different from other works in toroidal geometry. Based on the drift and gyrokinetic equations, we derive the balance equations for particle, thermal energy, and toroidal momentum containing the sum of the collisional neoclassical and electromagnetic turbulent fluxes. A comparison is made of the anomalous momentum transport fluxes given by the Reynolds stress between the forms that arise in the slab, the cylinder and the axisymmetric torus. The comparison clarifies the differences between earlier specialized treatments of turbulent momentum transport. With the standard short wavelength drift wave amplitude ordering, the surface averaged fast parallel momentum equations are not directly modified by the fluctuations giving the usual determination of the first order radial electric field in terms of the toroidal velocity and temperature gradients. The temperature and toroidal velocity are governed by the coupled transport equations. While the transport matrix is complicated and fully nondiagonal,the fluxes exhibit the Onsager symmetries required for thermodynamics consistient with the second law. In the limit of vanishing fluctuations the system reduces to the collisional neoclassical transport in a torus.

## References

[1] A. Brizard, Phys. Plasmas **2**, 459 (1995).

# A Distributed Field Line Following Code as an Example of Client-Server Programming with an Embedded Scripting Language

J. C. Wiley*
*Fusion Research Center, The University of Texas at Austin*

T.-Y. Brian Yang
*Lawrence Livermore National Laboratory, University of California*

Recently, members of this community have been discussing technologies to make scientific codes easier to use and maintain. Inevitably these discussions include languages other that FORTRAN. Here we examine the use of a number of these languages and technologies in a code to calculate field lines and heavy ion trajectories in fields generated by user designed and positioned coils.

The user interface is written in Java. Java is a relatively easy to learn language and provides a platform independent user interface API. We also use Java Bean technology to permit users to assemble a coil structure from component coil sets. Java Beans also allows us to explore the properties of introspection and serialization. Introspection allows programs to discover component interfaces at run time. Here we use Java Bean components to define various elements of the program including coil types and various coil and field line viewers. The serialization property provides a mechanism for the user to save the state of program including the customized elements on the users machine. The question of where and how state information is retained is important in client-server and distributed applications.

Communication between the client and server is defined in terms of CORBA (Common Object Request Broker Architecture) IDL (Interface Definition Language). CORBA-IDL is language neutral so that the same description can automatically generate both Java and C++ skeletons and stubs. CORBA defines a platform-independent interprocess-communication standard which when combined with Java provides a rich, robust, and portable computational environment.

The server is written in C++ which provides for perhaps higher computational efficiency than Java using currently available compilers. C++ also provides certain features such as operator overloading which some feel is important to define rich class libraries. One interesting feature that we are exploring with this code is including an embedded Python interpreter in several classes. This allows a user to include a Python script as part of a Java Bean component. This script can be executed by a Python interpreter embedded in the corresponding C++ class. This is a slightly different use of a scripting language to provide the user with a rich yet restricted interaction with compiled code.

While each of the computational elements explored in this code provides interesting and useful features, it is yet to be determined whether the overall versatility is worth the complexity in both the software elements and the computational skills needed to exploit them. We also need to extend the model to include legacy FORTRAN modules.

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# Seed Magnetic Island Formation due to Geometrically Coupled Magnetic Perturbations*

C. C. Hegna, J. D. Callen
*University of Wisconsin, Madison, WI 53706-1687*

The presence of a seed magnetic island is necessary to excite the destabilization mechanisms associated with neoclassical bootstrap currents in toroidal confinement devices. A possible source for the seed island is that produced from the combination of geometric coupling and the magnetic signal of another MHD event (e. g., toroidal coupling and a m=2/n=2 magnetic signal from a sawtooth yields a magnetic signal that is resonant at q = 3/2). Seed island formation produced by an external magnetic source constitutes an example of forced reconnection. In this work, we model this by calculating the response of tearing stable resonant magnetic surface to a temporally growing magnetic perturbation. For a sufficiently fast growing source, the seed island dynamics is governed by a non-constant-psi phase. In this regime, the induced width is a decreasing function of Lundquist number for a given strength in the external source. The effects of differential rotation between the two magnetic signals will also be discussed.

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# Chaos in Trapped Particle Orbits*

Roscoe White
*Plasma Physics Lab, Princeton University*

In magnetic fusion devices the long time confinement of high energy particles, whether 3.5 Mev alpha particle fusion products or other ions introduced for heating purposes, is essential to the attainment of a self sustaining nuclear burn. It has been well established that the motion of such particles, with energies much higher than the typical 10 Kev background plasma, is neoclassical[1]. That is, small scale fluctuations present in plasmas and thought to be responsible for the anomalous thermal flux to the plasma edge, do not influence the orbits. Thus their motion is that of charged test particles in a given magnetic field. Nevertheless, predicting the degree of alpha particle confinement in a given device with high accuracy requires many hours of computing time, even using algorithms in which the rapid gyro motion has been eliminated. An analytic expression is obtained for the threshold for stochastic transport of high energy trapped particles in a tokamak due to toroidal field ripple. The result permits rapid evaluation of energetic particle loss in general equilibria[2]. The approach to chaos has two limiting cases, island overlap from neighboring precession resonances and the overlap of bounce resonance webs extending from resonant surfaces.

## References

[1] S. J. Zweben et. al., *Plasma Physics and Controlled fusion*, 39, A275, 1997
[2] R. B. White, R. J. Goldston, M.H. Redi and R. V. Budny, *Plasma Physics* 3, 3043, 1996

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# Effect of Convection on the H-mode Temperature Pedestal *

D. A. D'Ippolito, J. R. Myra
*Lodestar Research Corporation, Boulder, Colorado 80301*

V. P. Bhatnagar, J. J. Jacquinot
*JET Joint Undertaking, Abingdon, U.K.*

Recently it has been observed on JET that the Edge Localized Modes (ELMs) in ICRF heated discharges have smaller amplitudes and a higher repetition rate than those occurring during NBI heating [1]. For the ICRF ELMs, the perturbation of the edge parameters is typically 2 - 5 times smaller than that with beams although the confinement enhancement factor is similar. Importantly, the peak heat load to the JET divertor during ELMy H-modes is reduced during ICRF, and the extrapolation to ITER power handling requirements is more favorable. The physical origin of these differences is not yet understood.

One possible explanation is that the interaction of the ICRF antennas with the plasma edge causes a cooling of the edge temperature pedestal, an increase in the resistivity, and a change in the character of the underlying MHD modes. As a first step in developing a model, we examine here the edge cooling by analyzing the linear and nonlinear energy balance problem in the presence of externally-driven convection. A (zero-frequency) perturbation of the edge electrostatic potential $\phi$ is postulated, which is produced by the penetration of antenna-driven convective cells [2, 3] into the resistive edge plasma. A linear analysis of the coupled vorticity and energy equations in a two-field $(\phi, T)$ model yields the spatial penetration of the potential and temperature perturbations. The nonlinear interaction of these perturbations gives rise to additional terms in the heat diffusion equation which can affect the edge temperature if the convection is strong enough. An analytic solution of a model problem will be discussed to illustrate the magnitude and parametric dependence of the resulting cooling. Numerical solution of the full equations is also in progress. Some ideas on the relation of the edge cooling to the ELM data and plans for future work will also be discussed.

## References

[1] V. P. Bhatnagar, et al., *Proceedings of the 24th EPS Conference on Controlled Fusion and Plasma Physics*, Berchtesgaden, Germany, Vol. **I**, p. 77 (1997).
[2] The JET Team, presented by J. Jacquinot, Plasma Phys. Controlled Fusion **33**, 1657 (1991).
[3] D. A. D'Ippolito, J. R. Myra, J. Jacquinot and M. Bures, Phys. Fluids B **5**, 3603 (1993).

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# Optimizing Stability of Small Aspect Ratio Toroidal Hybrids

A. S. Ware
*University of Montana*

D. B. Batchelor, B. A. Carreras, S. P. Hirshman, V. E. Lynch, D. A. Spong
*Oak Ridge National Laboratory*

Small aspect ratio toroidal hybrid (SMARTH) devices have many attractive features for a fusion power system. SMARTH configurations are a hybrid between a stellarator and a tokamak: the poloidal field is provided by both external modulated coils as well as plasma current. These configurations have an axisymmetric diverted region, high volume utilization, an absence of low order resonances near the edge and a magnetic well throughout the plasma volume. Initial studies of these devices focused on configurations with a simple set of modulated circular toroidal field coils[1] but the particle confinement for these configurations proved to be poor. An optimization method using the second order adiabatic invariant $J^*$ has been developed and implemented[2]. The optimized configurations come close to satisfying a criteria for omnigeneity[3]. Thermal transport can be improved by a factor of 20-30 to within a factor of 3-4 of an equivalent tokamak while maintaining a low aspect ratio $A \sim 3$.

The $\beta$ limits for these devices are set by ideal ballooning modes. The configurations optimized for improved particle confinement have stability thresholds of $\beta \leq 6\%$. The primary region of instability for the optimized configurations is at the outer edge. In this same region the force balance calculated by the VMEC 3D equilibrium code also breaks down. An improved calculation of the force balance is being implemented in VMEC 3D in order to determine whether or not these configurations are stable. Direct calculation of the ballooning stability for these configurations is computationally intensive due to the large number of Boozer modes required to describe the flux surfaces. A test function method has been developed which quickly and accurately determines the stability of the entire plasma volume. The computational time using this method is decreased by a factor of 60[4]. This has made it possible to begin the development of an optimization method which contains a stability criteria as well as a particle confinement criterion. We will report on progress to include a stability criteria in further confinement optimization studies.

## References

[1] B. A. Carreras, V. E. Lynch, and A. S. Ware, ORNL/TM-13252, 1996.
[2] D. A. Spong, et al., *Phys. Rev. Lett.*, in press.
[3] J. R. Cary and S. G. Shasharina, *Phys. Rev. Lett.* **78**, 674 (1997).
[4] S. P. Hirshman, et al., *Bull. Amer. Phys. Soc.* **42**, 1912 (1997); A. S. Ware, et al., *Bull. Amer. Phys. Soc.* **42**, 1912 (1997).

# Collisionless, Non-Ideal Ballooning Modes

Robert G. Kleva, Parvez N. Guzdar
*University of Maryland*

The loss of energy during disruptions in tokamaks at high $\beta$ is extremely rapid. Analyses of tokamak stability at high $\beta$ are usually based on the ideal MHD equations. However, even when a tokamak plasma is stable in the ideal MHD approximation, the plasma is still unstable when the effect of collisions is included in the analysis. But the time scale over which the energy is lost in a $\beta$ limit disruption is very short, usually much shorter than an electron-ion collision time based on the peak temperature. Therefore, it is unlikely that collisions play a role in $\beta$ limit disruptions. But even if a plasma is effectively collisionless, that does not mean that the plasma is ideal. The finite, non-zero electron mass may play a role in stability.

Using our toroidal MHD code, we study the stability of high $\beta$ tokamak plasmas, including the effect of the electron mass in Ohm's law. The effect of the electron mass is characterized by a parameter, the skin depth $d_e = c/\omega_{pe}$ where $\omega_{pe}$ is the electron plasma frequency. We find that ballooning modes are unstable due to the non-zero electron mass, even if the plasma resistivity $\eta$ is zero. The growth rate of the ballooning mode is proportional to $d_e$. The growth rate decreases as $\beta$ decreases, but the mode remains unstable.

# "Strong X-ray Generation and Coulomb Ion Explosion from Cluster - Laser Interaction"

**T. Tajima and M. Downer**

**Department of Physics**
**The University of Texas at Austin, Austin, Texas 78712 USA**

**and**

**Y. Kishimoto**

**Naka Fusion Research Establishment, JAERI**
**Naka, Ibaraki 310-0195 Japan**

ABSTRACT

The optical properties of clustered materials have attracted interest. Here, we investigate both linear and nonlinear optical properties when a laser is irradiated onto cluster material and/or cluster plasma. It is shown in the linear regime that unlike a gas plasma or an electron plasma in a metal, a cluster plasma permits propagation of electromagnetic waves below the plasma cutoff. Their phase velocity becomes below the speed of light, though close to it. This results from the induction of the polarization on the cluster surface. This new optical mode, "cluster mode", is confirmed via numerical simulation. With an increase of laser field, the linear polarization no longer applies and the laser field begins to strongly interact with the cluster, leading to a strong absorption of laser energy by electrons. Such high energy electrons stochastically interact with cluster ions, depicting a meandering orbit, thereby emitting a copious amount of soft x-ray. Furthermore, such a strong interaction gives rise to a Coulomb explosion of cluster ions, producing high energy ions.

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# Confinement Studies of Low Aspect Ratio, Omnigenous Stellarators*

D. A. Spong, S. P. Hirshman, D. B. Batchelor, B. A. Carreras, V. E. Lynch
*ORNL*

Transport optimized stellarators based on the concept of bounce-averaged omnigeneity (no net drift away from a flux surface) have opened up a new region of the stellarator design space which potentially offers flexibility[1] to achieve a wider range of physics requirements than previously possible. We have developed an optimization procedure[2, 3] based on the VMEC stellarator equilibrium algorithm which allows exploration of this design space using a variety of weighted physics goals. The r.m.s sum of deviations of these physics goals ¿from their targets is minimized by varying the shape of the outer magnetic flux surface and the plasma current profile. External to this automated search we also vary the targeted aspect ratio, the number of field periods, the form of the iota profile, the plasma beta, and the maximum level of internal plasma current in searching for interesting configurations. In addition, the weights assigned to the different targets and the initial guess are chosen by the user to emphasize/de-emphasize certain characteristics. This process has led to a range of configurations which achieve the best compromise among the chosen set of physics targets. Since these devices generally do not attain precise bounce-averaged omnigeneity, comparisons are made between them using a number of confinement evaluation tools. These include: plotting contours of $B_{\text{min}}$ (deeply trapped particle), $B_{\text{max}}$ (regions of trapped/passing transition) , and the second adiabatic invariant J. In addition, we use Monte Carlo techniques to evaluate thermal transport and follow ensembles of collisionless particles to evaluate energetic particle confinement. Our recent design explorations have focused on a lowered number of field periods (2—4) and have considered both tokamak- and stellarator-like iota profiles. It is expected that by keeping the number of field periods low, not as many magnetic coils will be required and that a higher coil-to-plasma spacing can be maintained. Stellarator-like iota profiles (increasing towards the edge) may require less plasma current to maintain and lessen the equilibrium flux surface shift with finite beta. Tokamak-like iota profiles (decreasing towards the edge) allow axisymmetric divertors and remove low order islands from the plasma edge. We find that low field period optimized configurations have very good thermal and energetic particle confinement properties. Results for these devices will be presented both for near-term experimental devices as well as for the reactor regime.

## References

[1] J. R. Cary, S. G. Shasharina, Phys. Rev. Lett. 78, 674 (1997).
[2] S. P. Hirshman, D. A. Spong, J. C. Whitson, D. B. Batchelor, B. A. Carreras, V. E. Lynch, J. A. Rome, "Transport Optimization and MHD Stability of a Small Aspect Ratio Toroidal Hybrid Stellarator," to be published in Phys. Rev. Lett., 1998.
[3] D. A. Spong=DD, S. P. Hirshman, J. C. Whitson, D.B. Batchelor, B.A. Carreras, V. E. Lynch, and J. A. Rome,"$J^*$ Optimization of Small Aspect Ratio Stellarator/Tokamak Hybrid Devices" to be published in Phys. Plasmas, 1998.

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# Stability of a Levitated Dipole *

J. Kesner

*MIT Plasma Fusion Center*
*Cambridge, Mass 02139*

A levitated magnetic dipole has uniquely good properties for the confinement of a fusing plasma [1]. In particular it can be stable to both gross MHD electrostatic drift frequency modes and does not suffer neo-classical degradation of confinement. Additionally it is inherently steady state, requires no current drive and permits a large expansion of the SOL flux. MHD modes are stabilized by compressibility which derives from the expansion of the magnetic flux.

The stability of low beta electrostatic modes in a magnetic dipole field has been examined [2] when the distribution function is to lowest order Maxwellian. In this study we obtain the dispersion relation from the drift kinetic equation and solve for marginal stability by means of a Nyquist analysis. The use of the Nyquist criterion permits us to accurately obtain marginal stability conditions with a minimum of simplifications. In particular it permits us to include FLR and temperature/density profile effects, wave-particle resonances, collisionality and parallel dynamics. It is shown using a Nyquist analysis that for sufficiently gentle density and temperature gradients the configuration would be expected to be stable to interchange modes. Furthermore it is shown that when it is stable to the interchange mode it is also stable to the dissipative trapped ion, collisionless trapped particle modes and modes driven by parallel dynamics such as the "universal" instability.

These results are applicable to any magnetic configuration for which the curvature drift frequency sufficiently exceeds the diamagnetic drift frequency and in particular the compressibility generated corrections can become important in tokamak drift wave theory for low aspect ratio Tokamaks.

# References

[1] A. Hasegawa, L. Chen and M. Mauel, Nuclear Fus. **30**, (1990) 2405.
[2] J. Kesner, Phys Plasmas 4 (1997) 419.

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# Stability analysis of Alfvén eigenmodes in JET deuterium-tritium plasmas and ITER

D. Borba*, A. Fasoli †, R. Heeter ‡, W. Kerner, S. Sharapov
*JET Joint Undertaking, Abingdon OX14 3EA , U.K.*

The study of Alfvén eigenmodes (AE) in JET during the DTE1 campaign has covered three main areas: the excitation of intrinsically stable low-n AEs using the saddle coil antennas[1], excitation of AE by the energetic ions produced by auxiliary heating, and excitation of AE by the fusion born alpha particles.

In the high performance hot-ion H-mode DT experiments on JET, with fusion powers up to 16.1 MW and central $\beta_0 \approx 0.7\%$ (discharge # 42976), no observable AE activity was found on the external magnetic diagnostics. The absence of alpha particle driven AE is in agreement with CASTOR-K[2] stability calculations. The stability is due to the global nature of the eigenfunctions in high beta and the additional damping provided by the high energy (E=160 KeV) tritium beams.

In the optimised shear DT experiments AE were found to be always unstable due to the presence of a large high energy tail generated by the high ion cyclotronic resonant heating (ICRH). This ICRH heating is required to obtain the internal transport barrier. The most favourable scenario for the observation of alpha particle effects on AE is created by suddenly switching off the auxiliary heating (ICRH+NBI)[3]. AE activity is observed around 500ms into the afterglow phase of some of these discharges. Stability calculations performed by the CASTOR-K model show that a few hundreds of milliseconds into the afterglow phase of these discharges the drive from the slowing down alpha particles can overcome the various damping mechanisms. However, the presence of a slowing down tail of ICRH generated energetic ions provides an additional drive, which can be comparable to the alpha particle drive. The quantification of the contribution of the ICRH tail to the destabilization of the AE is difficult due to the uncertainties in the ICRH-drive calculations. Thus, no clear evidence of alpha particle driven AE has been observed in JET.

The stability of Alfvén eigenmodes in ITER plasmas is analysed using the CASTOR-K model. The calculations show that the model can compute stability boundaries of Alfvén eigenmodes in ITER. High toroidal mode number calculations require large numerical resolution, but sufficient convergence can be obtained for the mode numbers of interest $10 < n < 30$. The destabilization of AE in ITER is determined mainly by the competition between the alpha particle drive and the ion Landau damping from deuterium ions. Core localized modes with toroidal mode numbers in the range of $10 < n < 20$ are the most unstable AE in ITER. However, these AE are stabilised by the ion Landau damping at high densities. The results indicate stability or marginal stability for relevant plasma parameters obtained from the ITER reference scenario.

## References

[1] A. Fasoli et al, Plasma Phys. Control. Fusion 39 , B 287 (1997)
[2] D.Borba et al, Proc. Joint Varenna-Lausanne Intl. Workshop p267 (1996)
[3] R.V. Budny et al, Nuclear Fusion 32, 429 (1992)

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*Associação Euratom/IST, Av Rovisco pais 1096, Lisbon, Portugal
†MIT PSFC; 190 Albany St. Cambridge, MA 02139
‡Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton NJ 08543, USA

## Low Collisionality Transport in Low $B_P/B_T$ Tokamaks*

K. Imre, C.S. Chang, and H. Weitzner
Courant Institute of Mathematical Sciences,
New York University, New York, NY

Low collisionality methods are applied to study transport in a tokamak with low $B_P/B_T$ and ion flows comparable with the ion sound speed. The currents are determined and the equations which characterize the number density and temperature are also given. The electron-ion temperature difference is related to the profiles and ion flow velocity. There is only one heat flow relation for the combined electron-ion fluid; this relation depends largely on ion quantities. For explicit results a model collision operator is used.

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1D04

# Double Beltrami Flows — Diamagnetic Structures*

S. M. Mahajan
*Institute for Fusion Studies, The University of Texas at Austin*

It is shown that a two magneto fluid description allows equilibrium states with a rich variety of magnetic field and velocity field configurations. Included in this list are the magnetic fields which are pressure-confining purely diamagnetic (increasing away from the center), and the fields which can show short wave length structure. There are two length scales associated with the equilibrium configuration; the length scales are determined by the value of the invariants: the total magnetic helicity and the total generalized helicity. The importance of these disparate length scales in fusion and astrophysical plasmas is discussed.

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# Gyrofluid Simulation of Alfvén waves in the Magnetosphere

Samuel Jones and Scott Parker
*Department of Physics, University of Colorado, Boulder*

We are using a linear one-dimensional gyrofluid model of magnetospheric Alfvén waves. Our interest is in how equilibium pressure and magnetic field nonuniformities along a magnetic field line will affect shear Alfvén waves. We are especially interested in electron inertia and other kinetic effects which may allow for a finite parallel electric field and associated auroral electron acceleration[1]. Our model includes the following aspects: reflecting boundary conditions to represent the ionosphere - magnetosphere boundary, dipole variation of the magnetic field and hence the β and Alfvén speed along the field line, and finite electron inertia.

An important result so far of this simulation is that it predicts that significant pulses of non-zero electric field at the magnetosphere-ionosphere boundary will be generated from relatively small initial wave perturbations in the electron density. Estimates of the energy of the resulting accelerated electrons will be given. We will also discuss progress on including more a more complete ion gyrofluid model[2] and tracer particle electrons for more detailed kinetic predictions of the electron acceleration.

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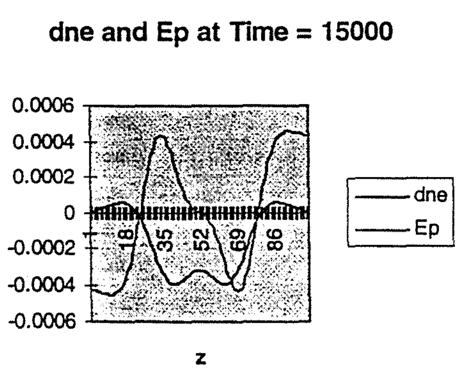
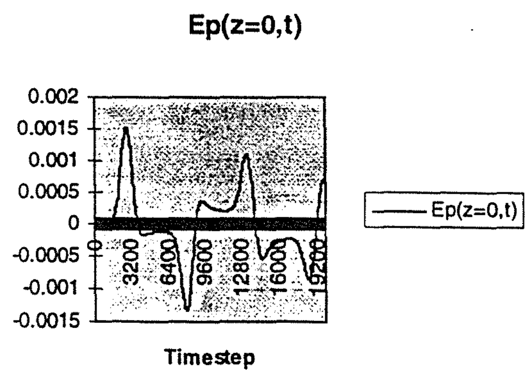
## References

[1] "On the kinetic dispersion relation for shear Alfvén waves," R.L. Lysak and W. Lotko, J. Geophys. Res., **101**, 5058 (1996)

[2] "Toriodal gyrofluid equations for simulations of tokamak turbulence," M.A. Beer and G.W. Hammett, Phys. Plasmas **3**, 4046 (1996)




Shown above is a snapshot of the parallel electric field and the perturbed density of an Alfvén standing wave. Also shown is the resulting parallel electric field at the left boundary vs. time.

# Runaway Electron Production in DIII-D Experiments Calculated with the CQL3D/KPRAD Fokker-Planck/Radiation Model

R.W. Harvey,* V.S. Chan, S.C. Chiu,◊ T.E. Evans,
M.N. Rosenbluth,† and D.G. Whyte‡

*General Atomics*
*San Diego, California*

Rapid temperature drops in tokamaks due to impurity pellet injection or disruptions, can lead to a massive generation of runaway electrons. This is caused by the large induced electric fields which keep the plasma current constant on time scales short compared to the resistive time. The CQL3D bounce-averaged Fokker-Planck (FP) code [1] provides a ready means for calculation of the 2D-in-momentum-space distribution of runaway electrons generated at each flux surface in such time-varying plasmas. In addition to the nonlinear, relativistic, Coulomb collision FP operator, we have implemented a ''knock-on'' collision model giving exponential ''avalanche'' of runaways [2], a constant current algorithm and a loss function to model transport physics. For modeling runaway generation in DIII–D due to impurity pellet injection, CQL3D uses $n_e(t)$, $T_e(t)$, and $Z_{eff}(t)$ profiles obtained with the KPRAD [3] pellet ablation, ionization, and radiation code. The principle calculated results for high-$Z$ pellet injection in DIII–D are:

(1) Complete conversion of the plasma current to runaways occurs if losses are neglected.

(2) The residual tail electrons remaining after the rapid temperature drop lead to a prompt population of ''hot tail electrons'' which either provides complete, prompt conversion (''hot tail runaway''), or provides a large seed which quickly avalanches to full conversion.

(3) When magnetic fluctuation losses are included using experimentally measured levels arising during pellet injection [$\delta B / B = 1\%$] [4], the runaway electrons are lost before full conversion of plasma to runaway current. This is in accord with the experimental results and shows the importance of transport losses in the model.

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*CompX, Del Mar, California. ◊Sunrise R&M, Inc., San Diego, California.
†ITER JTC, San Diego, California. ‡University of California, San Diego, California.

[1] R.W. Harvey and M.G. McCoy, in Proc. of IAEA TCM on Advances in Simulation and Modeling of Thermonuclear Plasmas, Montréal, 1992, p. 527, IAEA, Vienna (1993); G.D. Kerbel and M.G. McCoy, Phys. Fluids **28**, 3629 (1985).

[2] R. Jayakamar *et al.*, Phys. Lett. **A172**, 447 (1993); M.N. Rosenbluth *et al.*, IAEA-CN-64/FP-26, Montréal (1996); S.C. Chiu, Int. Sherwood Theory Conf. 1997.

[3] D.G. Whyte *et al.*, EPS, 1997.

[4] T.E. Evans, General Atomics, personal communications, 1997.

# Multispecies Kinetic Model of Detached Plasmas *

Alla Batishcheva
*MIT Plasma Science and Fusion Center, Cambridge, MA 02139*

Oleg Batishchev
*Lodestar Research Corporation, Boulder, CO 80301 / MIT PSFC*

Kinetic effects may play an important role in the scrape-off layer plasmas as was shown by many authors [1, 2, 3]. Unfortunately this analysis has been limited to a single plasma species (except for a few PIC models). Other species were taken as a fixed background, and collisions with them were linearized. However, this might be insufficient. For instance, momentum and energy exchange between plasma species can be important, and must be treated self-consistently. Elastic and inelastic collisions with neutrals may distort distribution functions as well. If neutral density rises, then neutral-neutral collisions become important, and must be taken into consideration. The goal of current work is to build a comprehensive kinetic model of collisionaly coupled plasma and neutral particles, which takes into account most important elementary processes in the edge plasma. To solve a set of kinetic equations we are using finite-difference approach [4], which in a contrast to discrete particles and Monte-Carlo methods [5, 6] has no statistical noise. This feature is crucial for important suprathermal tail resolution. Neutral recycling, presheath, and electric field effects are also treated self-consistently. We apply our model to study detachment for the realistic conditions of experimental machines.

## References

[1] R.H.Cohen and T.D.Rognlien., *Contrib. Plasma Phys.* **34**, 198 (1994).
[2] S.I.Krasheninnikov, *Contrib. Plasma Phys.* **34**, 151 (1994).
[3] O.Batishchev, *Contrib. Plasma Phys.* **36**, in print (1998).
[4] A.A.Batishcheva et al., *Phys. Plasmas* **3**, 1634 (1996).
[5] R.J.Procassini et al., *Nucl. Fusion* **30**, 2329 (1990).
[6] O.V.Batishchev et al., *Phys. Plasmas* **3**, 3386 (1996).

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# Nonlinear Theory of Internal Kink Modes Destabilized by Fast Ions

F. Porcelli
*INFM and Dipartimento di Energetica, Politecnico di Torino, 10129 Torino, Italy*

J. Candy, H. L. Berk, B. N. Breizman
*Institute for Fusion Studies, The University of Texas at Austin, Austin TX 78712*

Oscillation bursts of MHD activity associated with a global plasma mode driven unstable by energetic ions (fishbone oscillations) are regularly observed in toroidal plasmas. Experimental observations [1] and linear stability investigations [2] indicate that the unstable mode is an internal kink (with toroidal $n = 1$ and dominant poloidal $m = 1$ mode numbers). The mode interacts resonantly with trapped energetic ions which satisfy $\omega_{\rm Dh} \sim \omega$, where $\omega$ is the mode frequency and $\omega_{\rm Dh}$ is the toroidal precession frequency. In experiments where the fast ion orbit width is a significant fraction of the minor radius, the instability may eject a significant fraction energetic poulation. Therefore, this instability is of concern for the efficient operation of beam heated and/or burning plasmas.

In this paper, we present a theoretical description of the nonlinear phase of fishbone oscillations. Our analysis includes the nonlinear fast particle dynamics but neglects fluid nonlinearities, and thus it should be considered as the first step towards a complete nonlinear theory of the fishbone instability. In the present context, the mode saturates and damps as a consequence of the nonlinear trapping of fast ions in the potential well of the perturbing wave field. In particular, we provide: (i) a general solution of the linear initial value problem – indicating that diamagnetic frequency effects lead to an *algebraic* rather than an exponential decay of the plasma displacement in time [3]; (ii) a description of the behavior close to the marginal stability threshold; (iii) the self-consistent dynamical picture of frequency chirping; (iv) a numerical code [4] to compute the time evolution of the fast ion population in tokamak geometry; and (v) a prediction of anomalous fast ion transport and loss for realistic plasma parameters.

## References

[1] K. McGuire, *et. al.* Phys. Rev. Lett. **50** 891 (1983); M.F.F. Nave, *et. al.* Nucl. Fusion **31** 697 (1991).
[2] L. Chen, R. White and M.N. Rosenbluth, Phys. Rev. Lett. **52** 1122 (1984); B. Coppi, S. Migliuolo and F. Porcelli, Phys. Fluids **31** 1630 (1988).
[3] B.N. Breizman, J. Candy, F. Porcelli and H.L. Berk, to be published in Phys. Plasmas.
[4] J. Candy, F. Porcelli, B.N. Breizman and H.L. Berk, Proc. 24th EPS Conf. Berchtesgaden, Vol 21A III 1189 (1997).

# Stability and Transport in Wall-Confined Spheromaks

T. K. Fowler, D. D. Hua
*University of California, Berkeley*

L. D. Pearlstein
*Lawrence Livermore National Laboratory*

The calculation of El-Nadi and Rosenbluth [1] for drift-waves in very high beta plasmas with zero pressure gradient is revisited for large but finite beta. Results are applied to high-beta wall-confined spheromaks, for which the equilibrium is the lowest Taylor state at zero pressure gradient – stable to all MHD modes, both ideal and resistive. It is shown that, within limits, even if confinement deteriorates as beta increases, wall confinement leads to interesting compact fusion reactors based on spheromaks.

## References

[1] A. El-Nadi and M. N. Rosenbluth, Phys. Fluids **16**, 2036 (1973)

# Stability of detached divertor operation*

S. I. Krasheninnikov

MIT, Plasma Science and Fusion Center, Cambridge, MA 02139, USA

Experimental observations show that impurity radiation, hydrogen ionization, and plasma recombination regions "jump" towards the X-point after detachment occurs. It may indicate that the location of these regions is unstable. Here we consider physical picture of detached divertor plasma instability driven by hydrogen radiation and hydrogen plasma ionization-recombination processes.

To sustain the SOL plasma by recycling processes in the divertor it is necessary to have a non-zero power into recycling region $Q_H$ (notice that due to hydrogen radiation the ionization of each hydrogen atom "costs" $E_{ion} \gtrsim 30$ eV). We argue that due to the effects of plasma recombination, to sustain the plasma with given upstream plasma pressure, $P_{up}$, the power $q_H$ must be larger than some critical value, $(Q_H)_{crit} > 0$. The main physical arguments for that can be explained as follows. To sustain energy balance, the neutral flux into relatively hot ionization region, $\Gamma_N$, must satisfy inequality $Q_H > E_{ion}\Gamma_N$. Therefore when $Q_H$ reduces $\Gamma_N$ must be reduced to sustain a steady-state condition. However, $\Gamma_N$ is determined by the neutral pressure (which continuously increases with $Q_H \to 0$), location of the neutral source and diffusive neutral transport (governed by neutral-ion collisions) through a cold plasma region, "plasma buffer", separating neutral source and ionization fronts. Therefore, to reduce neutral transport through the "plasma buffer" it is necessary to increase either the width of the buffer, $\Delta_b$, or the plasma density, $n_b$, in the buffer. However, in both these cases three-body recombination rate in cold "plasma buffer" strongly increases. Therefore, an increase of $\Delta_b$ and/or $n_b$ will cause not a reduction of $\Gamma_N$ but a shift of recombination source of the neutrals upstream which in return will lead to upstream plasma cooling and pushes the ionization-recombination fronts even further upstream. As a result, plasma recycling only can be sustained in steady state condition for $Q_H \geq (Q_H)_{crit}$ due to finite neutral source provided by plasma recombination and energy loss due to hydrogen radiation and ionization.

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# Growth Of An Ideal MHD Mode Driven Slowly Through Its Instability Threshold: Application To Disruption Precursors*

J. D. Callen, C. C. Hegna
*University of Wisconsin, Madison, WI 53706-1687*

E. J. Strait, A. D. Turnbull
*General Atomics, San Diego, CA 92186-5608*

The growth rate of an ideal MHD mode in a high temperature plasma that is driven slowly [$\gamma_h \equiv (1/\beta)(d\beta/dt) \sim \text{sec}^{-1} \ll \hat{\gamma}_{MHD} \sim \mu\text{sec}^{-1}$] through its instability threshold in pressure gradient is shown to grow temporally as $\gamma(t) = \hat{\gamma}_{MHD}(\gamma_h t)^{1/2}$, for $t \geq 0$. Here, $\hat{\gamma}_{MHD}$ is an incremental growth rate for a global, interchange-like ideal MHD mode in a plasma as the instability threshold is exceeded: $\gamma^2 = \hat{\gamma}^2_{MHD}(\beta/\beta_c - 1)$. Such growth leads to an MHD perturbation $\tilde{\xi}$ that grows as $\exp[(t/\tau)^{3/2}]$ with $\tau \sim \hat{\gamma}^{-2/3}_{MHD}\gamma_h{}^{-1/3} \sim$ 100s of $\mu$sec. Note that the characteristic time $\tau$ is both significantly slower than the ideal MHD instability growth time ($\hat{\gamma}^{-1}_{MHD}$) and much shorter than the heating time ($\gamma_h{}^{-1}$) — it is a geometric mean of these times.

While internal, kink-like ideal MHD modes induced by current-gradient free energy tend to saturate nonlinearly at small amplitudes[1] and then are converted into slowly growing resistive-kink or tearing modes, interchange-like modes grow linearly to much larger amplitudes[2] before inducing current sheets that nonlinearly modify their growth. Further, it has been shown by Coppi[3] that when resistivity effects are added to an ideal MHD marginal stability eigenmode, the largest the mode growth rate can be is a factor of $S^{1/3}$ smaller than $\hat{\gamma}_{MHD}$. Hence, it is much smaller than $\gamma(\tau)$ as long as $S \gg \hat{\gamma}_{MHD}/\gamma_h$, in which $S$ is the Lundquist number. Thus, in high temperature tokamak plasmas where these conditions are satisfied, after an initial complicated resistive to ideal MHD transition phase (in a time $\sim \tau$), a driven global, interchange-like ideal MHD mode can be expected to grow linearly according to the model indicated in the preceding paragraph from a small initial perturbation level to a macroscopic scale size before it becomes nonlinear. Thereafter, it presumably leads to dramatic, macroscopic redistributions of the plasma pressure which can be expected to result in a catastrophic disruption.

This simple, driven ideal MHD instability model explains[4] the growth ($\sim \exp[(t/\tau)^{3/2}]$ with $\tau \sim 400$ $\mu$sec in accord with $\hat{\gamma}_{MHD} \sim 1.5 \times 10^5$/sec and $\gamma_h \sim 1.5$/sec) of major disruption precursors in DIII-D negative central shear (NCS) plasmas[5].

## References

[1] M. N. Rosenbluth, R. Y. Dagazian and P. H. Rutherford, Phys. Fluids **16**, 1894 (1973).
[2] A. D. Beklemishev, Phys. Fluids B **3**, 1425 (1991).
[3] B. Coppi, "On The Stability of Hydrodynamic Systems With Dissipation," in **Propagation and Instabilities In Plasmas**, W. I. Futterman, Editor (7th Lockheed Symposium on Magnetohydrodynamics) (Stanford Univ. Press, Stanford, Calif., 1963), p. 70.
[4] J. D. Callen, C. C. Hegna, E. J. Strait, A. D. Turnbull, "Growth Of An Ideal MHD Mode Driven Slowly Through Its Instability Threshold," GA Report currently in preparation.
[5] M. S. Chu et al., Phys. Rev. Lett. **77**, 2710 (1996).

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# In-Out Asymmetry of Particle and Heat Fluxes on Divertor Plates Produced by Electric Drifts *

R. H. Cohen, D. D. Ryutov
*Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

The radial electric field in the open field line region just outside the separatrix is usually directed outward and causes poloidal drifts whose direction correlates with the direction of the toroidal magnetic field. This circumstance may serve as a lead in attempts to relate the direction of the toroidal magnetic field to the in-out asymmetries of i) the heat fluxes; ii)temperature and density distributions. We provide a general classification of the plasma flows on the open field lines, taking into account various spatial distributions of particle and heat sources, the momentum transfer from the plasma to neutral gas (by the ionization and charge exchange), and the possible presence of several linked "nozzles" along the fluxtube. We conclude that, in regimes with considerable recycling, it is possible to explain experimentally observed correlations. We specify conditions under which a sonic transition in the plasma flow along the field lines occurs inside the plasma (at a distance from the wall), at the wall, or does not occur at all. This allows one to formulate proper hydrodynamic boundary conditions at the divertor plates, suitable for the use in numerical simulations.

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# Electric Fields near a Tokamak Separatrix and Their Effect on Edge Profiles*

T.D. Rognlien, D.D. Ryutov, N. Mattor
*Lawrence Livermore National Laboratory, Livermore, CA 94551 USA*

The equilibrium electric field in the vicinity of a tokamak separatrix is partly controlled by ion viscosity which is generally believed to be determined by turbulent processes. There are several different formulations of the resulting electric field equation. [1, 2, 3] We discuss the differences in these models and show how they have been implemented into the UEDGE 2-D transport code. Simulation results are given for the electric field profiles in both slab geometry and in the full toroidal geometry of single-null divertor tokamaks with an emphasis on the structure near the separatrix. The effect of the $\mathbf{E} \times \mathbf{B}$ poloidal and radial drifts on the profiles of plasma density and temperatures are illustrated and explained based on these flows. We discuss the depth to which the poloidal variations penetrate into the core region and thus influence profiles in the so-called pedestal region. Profiles in the pedestal region, especially that of the electric field, are believed important in helping control the L-H transition for core confinement through shear in the poloidal $\mathbf{E} \times \mathbf{B}$ flow. In the scrape-off layer, the parallel electron current also adds to asymmetries in such systems by convection of electron energy. It is reemphasized that the diamagnetic drifts in the plasma equations yield no net transport of particles, momentum, or energy in the plasma volume.

## References

[1] F.L. Hinton and Y.-B. Kim, Nucl. Fusion **34**, 899 (1994).
[2] N. Mattor, private communication (1995).
[3] T.D. Rognlien and D.D. Ryutov, Contrib. Plasma Phys., to be pub. (1998).

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# Raised Nonlinear Thresholds and Numerical Convergence in Gyrokinetic Simulations of Ion-Temperature-Gradient Turbulence in Tokamaks[1]

**A.M. Dimits, D.E. Shumaker, W.M. Nevins and B.I. Cohen**
Lawrence Livermore National Laboratory
and
**S.E. Parker**, University of Colorado, Boulder

Nonlinear gyrokinetic simulation of tokamak ion-temperature-gradient (ITG) turbulence[2] is of particular current interest, since it provides a means to test the first-principles basis of the gyrofluid simulations which underly the IFS-PPPL transport model.[3] Based on the IFS-PPPL model, it has been predicted that the proposed ITER tokamak reactor will not reach ignition.[4]

Recent gyrokinetic simulations of an ITER-relevant DIII-D discharge have been found to give values of the ion thermal diffusivity $\chi_i$ lower than gyrofluid simulations[5] by a factor sufficient to have a significant impact on predictions of ITER performance.

We have extensively investigated the convergence with respect to particle number of these simulations by varying the number of simulation particles used from $5\times10^5$ to $67\times10^6$ (corresponding to 1–128 particles per computational cell). Above a nonlinear threshold temperature gradient, good convergence of $\chi_i$ with respect to particle number is achieved with 2 or more particles per cell. This result is further supported by "scrambling tests,"[6] which give an indirect measure of the ratio of the noise due to particle discreteness to the physical fluctuations. The methodology and results from these tests will be presented.

We have found a new phenomenon in gyrokinetic simulation temperature-gradient scans. The gyrokinetic thermal diffusivity $\chi_i$ is observed to go to zero below a value of the temperature gradient significantly larger than the linear instability threshold. We find that as many as 64 particles per cell may be needed to achieve convergence for these values of the temperature. The dependence of the separation between the nonlinear and linear thresholds on the local aspect ratio as well as direct code diagnostics suggest that time-independent sheared flux-surface-averaged $\boldsymbol{E} \times \boldsymbol{B}$ flows play a key stabilizing role in this phenomenon. The generality and robustness of this phenomenon are under investigation.

Further convergence tests with respect to simulation system size and spatial resolution have also been completed and will be reported. Progress in increasing the physics content of our gyrokinetic simulations will also be discussed.

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[2]A.M. Dimits *et al.*, PRL **77**, 71 (1996).

[3]M. Kotschenreuther *et al.*, Phys. Plasmas **2**, 2381 (1995).

[4]"Turbulence May Sink Titanic Reactor," J. Glanz, Science **274**, (Dec. 6, 1996).

[5]M.A. Beer, 1997, private communication.

[6]M. Kotschenreuther, W. Dorland and G. Hammett, 1995–1997, private communications.

# Temporal Response of Theoretical Transport Models to Modulated Heat Sources and Cold Edge Pulses in Transient Experiments

J.E. Kinsey,† R.E. Waltz, J.C. DeBoo, H.E. St. John,
D.P. Schissel, and E. Fredrickson‡

*General Atomics*
*San Diego, California*

Motivated by the results from the ITER Profile Database which did not significantly distinguish between various tokamak transport models using steady-state data, we have extended the model testing exercise to include transient experiments to aid in assessing various transport models. Here, we compare the results from the IFS/PPPL, GLF23, Multi-mode, and Itoh-Itoh-Fukuyama models. A unique feature of the ion temperature gradient mode that we are particularly interested in testing, is the presence of a critical gradient. Specific properties including nearness to marginality and electron-ion temperature ratio affecting the temporal behavior of the thermal transport are considered. Data from recent DIII–D modulated ECH experiments and from previous cold pulse experiments on other tokamaks is examined in order to characterize the model predicted temporal response in time-dependent simulations. Both the magnitude and phase of the response of the predicted temperature profiles relative to the modulated heat source are compared to the measured plasma response to characterize each model. These results are supplemented with similar comparisons to ohmically heated discharges from TEXT, TFTR, and JET exhibiting a rapid radial response following a cold edge pulse produced by trace impurity injection.

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†General Atomics sponsored ORISE Postdoctoral Fellow.
‡Princeton Plasma Physics Laboratory, Princeton, New Jersey.

# Magnetic Island Structure with Sheared Flow and Viscosity

C. Ren
*University of Wisconsin-Madison*

M. S. Chu
*General Atomics*

J. D. Callen
*University of Wisconsin-Madison*

In a magnetic fusion device like a tokamak, plasma is confined by nested magnetic surfaces. However, resistive instabilities, such as tearing modes, can change the equilibrium by reconnecting the magnetic field lines and forming the so-called magnetic islands, therefore degrading the confinement. The island structure can be observed from the electron temperature fluctuation profile measured by the Electron Cyclotron Emission (ECE) diagnostic [1]. It is found [2] that, in addition to the $\pi$-phase jump across the rational surface, the phase of the ECE fluctuations gradually changes radially in the island region. This motivates us here to study possible effects of sheared flow on the island structure.

In this paper, we study the steady state of a magnetic island in the presence of sheared flow and viscosity. More specifically, the momentum equation

$$\rho(\mathbf{v}\cdot\nabla)\mathbf{v} = \mathbf{J}\times\mathbf{B} - \nabla p + \nu\nabla^2\mathbf{v} + \mathbf{S}$$

is solved along with ideal Ohm's law in a two dimensional slab geometry. Here, S is a momentum source and $\mathbf{B} = B_z(\psi)\mathbf{z} + \mathbf{z}\times\nabla\psi$. The free functions $\mathbf{S}$, $B_z(\psi)$ and $h(\psi) = p+\frac{1}{2}\rho v^2$ are chosen to yield an equation, similar to the Grad-Shafranov equation, which can describe a steady state magnetic island, with proper boundary conditions. The numerical island solution will be studied for its structure deformation due to the sheared flow and viscosity. The result will be compared to the measured phase change in the ECE electron temperature fluctuation profile.

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## References

[1] C. Ren *et al.*, Physics of Plasmas **5**, 450 (1998).
[2] C. Ren *et al.*, Bull. Amer. Phys. Soc. **42**, 1974 (1997).

# The Effect of Neutral Diffusion on Ion Parallel Flow

Tünde Fülöp
*Department of Electromagnetics, Chalmers University of Technology, Göteborg, Sweden*

Peter J. Catto
*Massachusetts Institute of Technology, Plasma Science and Fusion Center, and Lodestar Research Corporation, Boulder, CO*

Per Helander
*UKAEA Fusion, Culham Science Centre (UKAEA/Euratom Association)*

Bulk ion flow can be modified by ion-neutral interactions in the edge region of tokamaks where neutral atoms are abundant. In this region, the standard neoclassical expression for the ion flow is not consistent with the experimental observations [1]. Previous work in the plateau regime suggests that the discrepancy is caused mainly by momentum loss due to ion-neutral charge exchange [2]. In this work, we show that in the absence of neutral diffusion ion-neutral charge exchange cannot affect the neoclassical transport of the ions significantly if the neutral mean-free path is short and the neutral density is low compared to the plasma density. However, we also demonstrate that in the plateau regime the inclusion of neutral diffusion can substantially modify parallel ion flow inside the separatrix as determined by the flux-surface averaged momentum constraint.

## References

[1] W. L. Rowan et al., Phys. Fluids B **5**, 2485 (1993)
[2] P. M. Valanju et al., Phys. Fluids B **4**, 2675 (1992)

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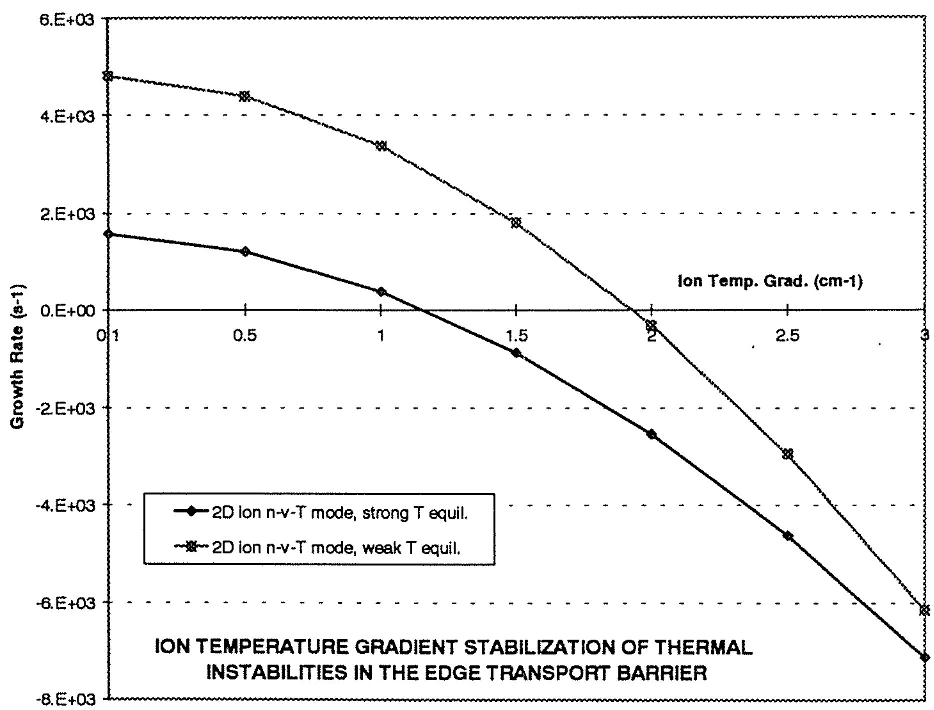
# Thermal Instabilities in the Edge Transport Barrier & the L/H Transition

W. M. Stacey
*Fusion Research Center, Georgia Institute of Technology*

Multi-fluid thermal stability analyses of the plasma edge transport barrier predict the existence of 2D radial-perpendicular, edge localized thermal n-v-T instabilities in the experimentally observed range $\sim 1 < k_r < \sim 20$ cm$^{-1}$ driven by atomic physics cooling mechanisms coupled with a positive temperature dependence of the radial thermal diffusivity in the plasma edge. In particular, recycling neutral densities in the range $10^{10}$ - $10^{11}$ cm$^{-3}$ are shown to be sufficient to drive such instabilities for typical tokamak edge parameters. Estimated turbulent transport rates associated with such instabilities are in the range $\sim 10^3 < D, \chi < \sim 10^4$ cm$^2$/s for representative neutral densities in this range; which is the magnitude of L-mode transport in the tokamak plasma edge. These thermal instabilities are stabilized by a sufficiently large radial ion temperature gradient of the order $L_T^{-1} \sim 1$ cm$^{-1}$ (which is the order of experimentally observed edge gradients), as illustrated in the following figure, computed for $k_r = 5$ cm$^{-1}$, T = 150 eV, $\chi_r = 10^3$ cm$^2$/s, $n_{carbon} = 5\text{x}10^{12}$ cm$^{-3}$, $n_0 = 5\text{x}10^{10}$ cm$^{-3}$.




It has been widely observed that tokamak confinement degrades for edge neutral densities greater than about $10^{11}$ cm$^{-3}$. If these thermal instabilities in the transport barrier govern L-mode transport in the plasma edge, then the L/H transition would take place when the conductive heat flux through the transport barrier becomes sufficiently large that the ion temperature gradient exceeds the threshold ion temperature gradient required for the stabilization of thermal instabilities in the transport barrier. Taking this as a working hypothesis, the observed phenomena associated with the L/H transition and the parameter scaling of the L/H power threshold can be explained.

# Adaptive Unstructured Grid Approach to SOL Modeling *

Oleg Batishchev
*Lodestar Research Corporation, Boulder, CO 80301 / MIT PSFC*

Alla Batishcheva, Dieter Sigmar
*MIT Plasma Science and Fusion Center, Cambridge, MA 02139*

Accurate modeling of scrape-off layer plasmas requires guaranteed resolution of sharp plasma gradients. These gradients are associated with ionization, radiation and recombination fronts, observed in both experiments and numerical simulations [1, 2]. These fronts may have a complicated shape, and may reveal a bifurcated behavior [3]. This combined with the necessity to take into account geometrical features, like vertical plates, bypasses, etc. makes most presently existing codes limited under modern demands. The first limitation comes from the fact that meshes are usually structured. The second comes from the widely used practice of manual grid adaption to the solution, which requires a lot of user effort. We overcome these problems by developing moving, unstructured, grids, which automatically adjust themselves to the local plasmas gradients [4]. A new discretization scheme combines flexibility of finite elements method with conservation properties of finite volumes method. Besides managing sharp gradients, it is capable of dealing with large anisotropy of plasmas transport coefficients. We illustrate the effectiveness of our method on a set of model SOL-related problems.

## References

[1] G.D.Porter et al., *Phys. Plasmas* **3**, 1967 (1996).
[2] D.Knoll et al., *Phys. Plasmas* **3**, 3358 (1996).
[3] S.I.Krasheninnikov, *Phys. Plasmas* **4**, 3741 (1997).
[4] O.Batishchev et al., *Contrib. Plasma Phys.* **36**, in press (1998).

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# Effect of Rotation Shear on MHD Modes in Tokamaks with Low Magnetic Shear

M.S. Chu, L. Chen,† and L.J. Zheng†

*General Atomics*
*San Diego, California*

In tokamaks with low magnetic shear, the Alfvén wave can be substantially modified by the variation of the toroidal rotation velocity across the plasma surface. First, the location of Alfvén resonance of the MHD mode within the plasma is modified by the rotation shear. The location is determined by both the overall mode structure and the local rotation shear, and the region which provides instability drive to the MHD mode can be enlarged or reduced. Second, the Alfvén wave restoring force is substantially weakened over a low shear region, when the shearing rate of the rotation frequency matches with the shearing rate of the local Alfvén frequency. Because the plasma rotation frequency is usually much smaller than the Alfvén frequency, substantial modifications of the Alfvén stability only occur in weak magnetic shear tokamak plasmas driven by strong tangential neutral beam injection.

The effect of rotation shear on MHD modes in a reversed shear tokamak is examined. It is found that (I) rotation shear has a stabilizing effect on the finite beta double kink [1] localized between two mode resonant surfaces; and (II) the flow shear has a destabilizing effect on MHD modes localized within the central reversed shear region. Following the analysis provided in Ref. 1, these effects are extracted analytically. Numerical results from the MARS code confirm this analytic expectation. This will also be presented.

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†University of California, Irvine, California

[1] C.G. Gimblett, R.J. Hastie, and T.C. Hender, Phys. Plasmas **3**, 3369 (1996).

# Variational Principles for Rotating Plasmas and Classical Fluids*

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

Two variational principles for MHD equilibria with flow, and without any symmetry, were recently published.[1,2] Both minimize the energy subject to a set of constraints including a new constant of the motion which generalizes the conservation of angular momentum in axisymmetric flow. One work[1] shows conservation only for incompressible plasmas, the other[2] derives the constant of the motion more generally, but only formally, from Noether's theorem without a clear view of its meaning. We have actually discovered this conservation law much earlier,[3] and showed it to have the meaning of conservation of circulation along some special curves.

We show here that, without imposing some symmetry, the energy cannot be a minimum for flows not parallel to the magnetic field. An equilibrium state with a more general flow field is merely a stationary point of the energy. This result is consistent with the existence Floquet-type ballooning modes since Floquet modes are typically not controlled by Lyapunov (energy) integrals. The variational principle may nevertheless be useful as a starting point for further manipulation. For example, it can be manipulated to obtain an analog of Grad's principle of minimizing $\int(\frac{1}{2}\mathbf{B}^2 - p)d^3\mathbf{r}$ instead of the energy for static equilibria. So far, however, we have not found a functional with a true minimum.

This work has an analog for classical fluids. The additional conserved quantity is again fluid circulation along special curves, and it enables the formulation of a variational principle both for tokamak-like configurations and for swirling "tea cups". (The number of constraints in these configurations is not the same.) Interestingly, this formulation was not known for non-isentropic fluids for which the equation of state is more general than $p = p(\rho)$.

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[1]V.A. Vladimirov and H.K. Moffatt, J. Fluid Mech. **283**, 125 (1995).
[2]V.I. Ilgisonis and V.P. Pastukhov, Plasma Phys. Reports **22**, 208 (1996).
[3]E. Hameiri, J. Math. Phys. **22**, 2080 (1981), Sec. III.

# UEDGE Simulation of Steady State Detached Plasmas*

M. E. Rensink, T. D. Rognlien
*Lawrence Livermore National Laboratory*

To minimize the heat load on divertor plates it is desirable to operate with detached plasmas, but there is some evidence from both experiment and simulations [1] that a fully detached plasma evolves in time to an x-point MARFE with degraded core confinement. In this report we compare steady-state results from the UEDGE plasma model coupled to two different models for the neutrals: a reduced Navier-Stokes fluid model [2] and a Monte Carlo model [3]. For a system with net particle throughput, e.g., due to fueling in the core and pumping in the divertor, we find steady-state fully-detached plasmas with both fluid and Monte Carlo neutrals models. Some differences in the results from the two models may be attributed to molecules. The degree of detachment or position of the ionization front along the divertor leg is controlled by the input power, core plasma density and pumping parameters. For a closed system with no net particle flux at the boundaries, it is also possible to find steady-state fully-detached plasmas if we constrain the total particle inventory rather than the core plasma density. With the Monte Carlo neutrals model it is not possible to fix the total particle inventory, so only the fluid neutrals model can find steady-state fully-detached plasmas for a closed system.

## References

[1] G.D. Porter et al., Phys. Plasmas 3 (1996) 1967.
[2] F. Wising et al., Contr. Plasma Phys 36 (1996) 136.
[3] D. Reiter, J. Nucl. Mat 196-198 (1992) 80.

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# Stability analysis of the magnetohydrodynamic modes around a q-minimum

L. J. Zheng, L. Chen
*Department of Physics and Astronomy, University of California - Irvine, Irvine, CA 92697*

M. Chu
*General Atomics, San Diego, CA 92186-5608*

In tokamak reversed shear discharges, the safety factor $q(r)$ is non-monotonic and exhibits an off-axis minimum, $q_{\rm min}$. At $q_{\rm min}$, the magnetic shear $q'$ is small, but $q''$ is usually of order unity. In this situation, it is pointed out that the MHD modes around the $q_{\rm min}$ are radially localized. By exploiting this feature of mode structure, a localized mode theory is developed. An eigenmode equation with two singular layers is obtained by the flux surface averaging. Numerical analysis is carried out to solve the resultant eigenmode equation and obtain the stability condition. Results thus obtained is compared to that from the previous theory of Gimblett et. al. [Phys. Plasmas, 3, 3369 (1996)], who assumed mode structure with a top-hat trial function.

# Zonal Flows and the Physics of Shear Suppression

P. H. Diamond, J. Fleischer
*University of California at San Diego, La Jolla, CA 92093*

F. L. Hinton
*General Atomics, San Diego, CA 92186*

The ongoing debate about ITER has sparked interest in so-called "radial modes", which are simply zonal flows with $n = 0, k_r$ finite. These zonal flow layers are the tokamak analogue of the wind belts of Jupiter. In particular, the predicted saturation levels for ITG modes appears to be sensitive to the dynamics of zonal flows. Moreover, these *zonal flows constitute fluctuating shear flows, which are distinct from the mean sheared flow*. Despite the fact that zonal flows have been observed in simulations for some time now, they remain poorly understood and their potential implications are somewhat unappreciated in the M.F.E. theory community.

Here, we report on recent progress in understanding the basic physics of zonal flow layers and their interaction with drift waves. Regarding suppression, we consider the simple paradigm of a drift wave propagating in an ensemble of randomly phased zonal flows with finite spectral width and autocorrelation time. Straight-forward application of standard eikonal methods allows the calculation of the mean-square radial wave number, which increases until dissipative coupling becomes strong enough to quench turbulence. This in turn, yields a *mean-square shear suppression criterion*, in terms of the zonal flow spectral intensity. The physical process here is random refraction, not eddy decorrelation. Also, the mean-square shear can be large even if the mean shear is negligible. Indeed, we show that the inequality $\langle (V')^2 \rangle > \langle V' \rangle^2$ is satisfied for several model systems. Regarding generation, we consider the modulational stabili! ty of an $n = 0$ zonal flow in the presence of finite-$n$ drift wave turbulence. Note that this is a special case of the time-honored problem of convective cell generation. Here, zonal flow generation results form modulations of the net *charge* flux, i.e. the local *difference* between the electron and ion particle fluxes, hereafter referred to as the differential flux. Note that treating the electron dynamics as adiabatic is invalid, here. As with the mean flow, modulation of the differential flux may then be related to modulations of the wave energy density flux, via a Poynting theorem. Finally, the spectral transport equation is used to compute the modulations. Instability results from the resonance between zonal flow phase velocity and drift wave group velocity. The drift wave spectral structure required for zonal flow growth will be discussed. We conclude with an introduction of a *spectral* predator-prey model for zonal flow - drift wave interaction.

# A Split-Weight Scheme for the Electron Dynamics in Tokamak Plasmas*

Igor Manuilskiy, Wei-li Lee, Harry Mynick, Scott Parker†
*Princeton Plasma Physics Laboratory*

A split-weight scheme for the electron dynamics in tokamak plasmas has been developed. The scheme, which is intended to replace the commonly used simulation models of the bounce-averaged response for the trapped particles and the adiabatic response for the passing particles, accurately follows the electron orbit and, in the meantime, correctly describes their interactions with the waves associated with the perturbed potentials. The approach used in the present work is closely related to the $\delta f$ gyrokinetic simulation scheme [1], except that the all-important electron inertia is kept intact without significant time step reduction in the simulation. It is applicable for the entire electron population and is equally suitable for describing electrostatic and electromagnetic fluctuations.

Specifically, in the present approach, $\delta f$ is split into an adiabatic part and a non-adiabatic part. Since the majority of the electrons exhibit adiabatic response for low-frequency modes, this procedure makes the gyrokinetic Poisson's equation well-behaved for $(k_\perp \rho_s)^2 << 1$ modes. The procedure to follow the non-adiabatic part is as follows. The weight equation for the electrons [1],

$$dw/dt = -\kappa \partial\phi/\partial\theta + v_{\|} \partial\phi/\partial x_{\|}$$

can also be written as

$$dw_{na}/dt = d(w - \phi)/dt = -\kappa \partial\phi/\partial\theta - \partial\phi/\partial t,$$

where $\kappa$ represents spatial inhomogeneity and $\phi$ is the perturbed potential. There are two alternative schemes exploiting this approach. The first one resembles the cut-off scheme described by Dimits and Lee [2]. However, it represents a significant improvement, since the fraction of the non-adiabatic electrons is dynamically determined. The criterion of $\omega << k_{\|} v_{\|}$ can be used to determine the adiabaticity of the particular electron under consideration. Alternatively, one can follow dynamically only the non-adiabatic part; each electron will be partly adiabatic, partly non-adiabatic. Then only the latter will contribute to the charge density.

The details of the scheme and its extension to finite-$\beta$ plasmas as well as its implementation in the GTC code [3] will be presented.

## References

[1] S.Parker and W.W.Lee, Phys. Fluids B, **5**, 77 (1993).
[2] A.Dimits and W.W.Lee, J. of Comput. Physics, **107**, 309 (1993).
[3] Z.Lin, W.W.Lee, W.M.Tang and R.B.White, Bull. Am. Phys. Soc., **42**, 1985 (1997).

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†also at Colorado University

# On the Nonlinear Stability of Ion-Acoustic Waves

Nikhil Padhye, P. J. Morrison
*Department of Physics and Institute for Fusion Studies, The University of Texas at Austin, Austin, TX 78712.*

Nonlinear stability of ion-acoustic waves in the KdV limit has been established in earlier works [1, 2]. Here we study Lyapunov stability of the full fluid system; not the equation governing KdV solitons. The equilibrium is shown to be a critical point of a free energy functional, but negative energy modes are shown to persist at short wavelengths. These are suggestive of a short wavelength instability. The difference between the KdV limit and the general case is also pointed out. We investigate the effect of ionic pressure, obeying an adiabatic law with $\gamma = 3$, on the stability of ion-acoustic waves, and find that it is not enough to suppress the negative energy modes at short wavelengths. In the process of studying stability, we find explicit solitary and periodic wave solutions to the ion-acoustic equations with pressure, which may be new. Solitary wave solutions are found to exist at Mach numbers much higher than the upper cutoff of 1.58 for the case without pressure.

## References

[1] T. B. Benjamin, Proc. R. Soc. Lond. A, **328** (1972) pp. 153–183
[2] J. L. Bona, Proc. R. Soc. Lond. A, **344** (1975) pp. 363–374; see also J. L. Bona and A. Soyeur, J. Nonlinear Sc., **4** (1994) pp. 449–470

# Effects of orbit distortion on classical transport

R. D. Hazeltine, K. C. Shaing and A. Y. Aydemir

Institute for Fusion Studies

It is well known that electrostatic fields in tokamaks can vary on relatively short scale-lengths, approaching the ion banana width. The resulting "squeezed" ion orbits are associated with significantly reduced neoclassical transport. It is shown here that an analogous process occurs, for steeper field variation, at the level of particle gyration: potentials varying on a scale comparable to the ion gyroradius distort gyroorbits and thus modify classical transport. The gyro-distortion can take one of three forms, depending upon the sign and size of the electric field shear; reduction in orbit width occurs only in a potential well. In this case, and assuming that the ion density and temperature vary slowly on the scale of the shrunken orbit, we compute the classical ion heat flux. It is shown that this flux is reduced by a factor of $S^{-2}$, where

$$S \equiv 1 - \frac{c\Phi''(r)}{B\Omega}.$$

The sharp potential variation required for large $S$ might result from steep electron temperature gradients near the separatrix of a spherical tokamak (with comparable poloidal and toroidal field components) or RFP.

# Oscillatory Processes in Models of Internal Transport Barrier Formation*

D. Lopez-Bruna, D. E. Newman, B. A. Carreras
*Oak Ridge National Laboratory*

P. H. Diamond
*University of California, San Diego*

The process of transition to an enhanced confinement regime via the formation of a transport barrier is accompanied by a still not well understood dynamical activity, like dithering and fluctuation level bursts. An explanation may come from the competing rules of the drive for the turbulence and the turbulence suppression mechanisms (usually via the electric field shearing rate) near the barrier. These mechanisms conform to a flux function such that the flux of escaping particles and heat does not depend monotonically on the gradients of the system (e.g., the pressure gradient). This means that, when a critical gradient is reached locally, the system self-regulates to a new stable regime for which the flux through the corresponding flux surface (transport barrier) is smaller than it was before the critical condition is met. This kind of flux function by itself implies the phase transition nature of the process and the propagation of the transport barrier[1]. However, depending on the actual realization of the transition model other features can be found and the route to transition may admit a number of "side" dynamics. In this work we identify and discuss the oscillatory or bursty behavior inherent to a particular realization of the transition model [2], which comes from the transition mechanisms themselves but, nevertheless, goes beyond the simple creation and propagation of a transport barrier.

## References

[1] V. B. Lebedev, P. H. Diamond, Phys. Plasmas **4**, 1087-1096 (1997).
[2] D. E. Newman et al., Dynamics and Control of Internal Transport Barriers in Reversed Shear Discharges. To be published in Phys. Plasmas (1998).

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# EXTREME LIMIT OF THE SPHERICAL STELLARATOR APPROACH

Paul E. Moroz

Department of Engineering Physics
University of Wisconsin, Madison, WI 53706, USA

New results are presented for a relatively novel fusion concept, the Spherical Stellarator (SS) [1-7], with the focus given to its extreme limit called Extreme-Low-Aspect-Ratio Stellarators (ELARS) [8-9].

Stellarators are intrinsically the steady-state devices and thus have a number of advantages over many other fusion concepts. However, stellarators normally feature large aspect ratios, $A \approx 7$-$10$ (the lowest-A stellarators ever built have $A \approx 5$). This leads to very large and expensive reactors. Also, stellarators normally feature rather low $\beta$ limits which makes an inefficient reactor. The SS configurations (called so in analogy with the Spherical Tokamaks) offer significant improvements. The main characteristics of the SS: very low plasma aspect ratio stellarator device, $A \leq 3.5$, positive plasma current (increasing the vacuum rotational transform), high $\beta$ limits (well above 1-5% typical for traditional stellarators), improved particle transport, and simplicity of the coils. In a large and high-$\beta$ SS device, the required plasma current is fully supported by the bootstrap effect [2-3] and thus does not need any current drive technique.

The ELARS configurations correspond to the extreme low-aspect-ratio limit of the SS. This is an advanced concept from many points of view: it is very compact and relatively inexpensive to construct and operate, it has modular coil design so any component can be replaced, it is capable of confining the high $\beta$ plasmas in a steady-state fashion with improved transport characteristics. This report represents the theoretical analysis of this type of fusion configurations. Important ELARS configurations with the helical center post have been discovered and called the Helical Post Stellarators (HPS) [8-9]. The main advanced features included in the definition of the HPS class of stellarators are the following: (a) extremely low plasma aspect ratio, $A \leq 1.5$, (b) simple coil system featuring a helical center post, (c) extremely high $\beta$ limits assisted by a positive plasma current (in a large HPS, it is the bootstrap current), and (d) improved particle transport characteristics close to that in an equivalent tokamak. The helical post can be a single helix, or may consist of a few helices. Present report includes new results on SS and ELARS and demonstrates their advanced characteristics for controlled fusion.

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**References.**

[1] P. E. Moroz, Phys. Rev. Lett. **77**, 651 (1996).
[2] P. E. Moroz, Phys. Plasmas **3**, 3055 (1996).
[3] P. E. Moroz et al., Fus. Tech. **30**, 1347 (1996).
[4] P. E. Moroz, Stellarator News **48**, 2 (1996).
[5] P. E. Moroz, Plasma Phys. Contr. Fus. **39**, 1841 (1997).
[6] P. E. Moroz, Plasma Phys. Rep. **23**, 502 (1997).
[7] P. E. Moroz, Nucl. Fusion **37**, 1045 (1997).
[8] P. E. Moroz, Stellarator News **54**, 6 (1997).
[9] P. E. Moroz, IAEA Tech. Comm. Meet. on Innov. Approach. Fus. Energy, Pleasanton, USA (Oct. 1997).

# Correcting Field Errors in Tokamaks*

James D. Hanson
*Physics Department, Auburn University, Auburn, AL 36849 USA*

By design, tokamaks are axisymmetric. In reality, the externally imposed magnetic field is not quite axisymmetric, due to current coil feeds, misalignments of toroidal field coils, shifts and tilts of poloidal field coils, shape distortions of coils, etc. As tokamaks have grown larger and hotter, the deleterious effects of these non-axisymmetries have become more apparent. The most important are the tearing modes associated with the resonant magnetic perturbations which generate magnetic islands. The observed tearing modes are suppressed by high plasma rotation, degrade the plasma confinement, and are often precursors to disruptions. The problems caused by the magnetic field non-axisymmetries are expected to be more significant in large next-generation tokamaks, due to the low plasma rotation frequency.

Non-axisymmetric correction coils can be highly effective at canceling the low order magnetic islands generated by magnetic field errors. In computing the magnetic island sizes and toroidal phases, the use of a straight-cylinder approximation can cause substantial error. An arbitrary phase n=1 error can be corrected at a single resonant surface with one set of four correction coils. Correcting higher n harmonics requires more coils toroidally. Correcting errors at more than one rational surface requires more correction coil sets.

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# High Mode Number MHD Stability at the Edge of a Tokamak

R.L. Miller, J.W. Connor,† R.J. Hastie,† L.L. Lao, T.S. Osborne, T.S. Taylor, and H.R. Wilson†

*General Atomics*
*San Diego, California*

A new 2D MHD code is being constructed to calculate the high-$n$ ballooning/ peeling stability near the edge of a tokamak plasma. It will treat finite aspect ratio and non-circular geometry including effects of a separatrix boundary. Recently Connor, Hastie, and Wilson [1] [CHW] developed a high-mode-number peeling/ballooning mode model at the tokamak edge in which a critical role is played by the edge current density. The bootstrap current density, with its dependence upon pressure gradient and collisionality, must be an important element of any realistic edge stability calculation. When bootstrap current effects are included, the CHW model suggests a power threshold for L–H transitions and provides a plausible explanation for an ELM cycle. In contrast to the present work, the CHW model was cast in a large aspect ratio circular geometry.

The effect of a plasma separatrix is studied using the local equilibrium model of Bishop [2] and numerical equilibria for direct comparison with experiment. In limited plasmas, the most restrictive mode is one with the resonant surface just outside the plasma boundary. A separatrix introduces two new effects: every resonant surface occurs inside the plasma boundary and even at high toroidal mode number $n$ the variation of q across the mode width cannot be neglected. A 2D eigenvalue code determines the marginal edge current density for high mode numbers. The radial coordinate is discretized with extensive packing of mesh points about rational surfaces while the poloidal variable is decomposed into Fourier modes with special treatment near the separatrix. The code is constructed in such a way that additional physics effects such as rotation may be added and additional terms can be added to accurately treat intermediate mode numbers. Initial results will be presented for the pressure gradient and edge current density stability boundaries for a range of shapes and pedestal widths.

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†UKAEA, Culham Laboratory, Abingdon, Oxfordshire, United Kingdom.

[1] J.W. Connor, R.J. Hastie, and H.R. Wilson, UKAEA FUS 383 November 1997, submitted to Physics of Plasmas

[2] C.M. Bishop, P. Kirby, J.W. Connor, R.J. Hastie, and J.B. Taylor, Nucl. Fusion **24**, 1579 (1984).

# An Efficient Algorithm for the Wall Electric Field Diffusion Problem During Fast Current Quenches

P.B. Parks, D.E. Post,† S. Putvinskij,† H.A. Scott,‡ and D.A. Humphreys

*General Atomics*
*San Diego, California*

During fast current quenches in tokamak discharges the toroidal electric field at the plasma surface $E_1$ is an important boundary condition as it affects both the rate of the current quench and production of prompt or secondary runaway electrons. The surface boundary condition is influenced by thickness $\Delta$ and resistivity $\eta$ of the vessel wall. If the characteristic skin time of the wall $\tau_{\text{skin}} \sim \Delta^2 \mu_0 / \eta$ is much shorter than the decay time $\tau_{\text{p}}$ of the plasma current $I_{\text{p}}$, then all field quantities within the wall may be assumed to be uniform. Hence, the surface field is given by $E_1(t) = \eta I_{\text{wall}}(t) / (2\pi a \Delta)$, in which the wall current is dictated by

$$\frac{dI_{\text{wall}}}{dt} + \frac{I_{\text{wall}}}{\tau_{\text{wall}}} = -\frac{dI_{\text{p}}}{dt} \ , \tag{1}$$

with $\tau_{\text{wall}} \sim \mu_0 a \Delta / \eta$ being the characteristic time for external flux decay, and $a$ the plasma minor radius. This boundary condition, involving the plasma current at each time step in the plasma current density evolution equation, was used in the KIP code, a (1-D) straight-cylinder plasma model for study of killer pellet shutdown scenarios with runaways in ITER [1].

However , the realistic situation is that $\tau_{\text{skin}} \geq \tau_{\text{p}}$ and thus the problem of diffusion of the fields into the wall must be solved self-consistently with the plasma evolution making the fully soaked in wall model, Eq. (1), inaccurate. The new approach described here involves three coupled integro-differential equations for $I_{\text{wall}}(t)$ and the electric fields on the inner and outer wall surfaces: $E_1(t)$ and $E_2(t)$, respectively. The equations are reduced to two coupled Volterra-type integral equations relating $I_{\text{wall}}(t)$ and $E_1(t)$ to the plasma current $I_{\text{p}}(t)$ which replace Eq. (1). In this way the essential skin effect during the fast current quench is captured. The numerical algorithm uses a stepwise procedure [2] which allows one to express each discretized variable in terms of earlier values, and thus avoid iterations. Initial results will be presented and compared with previous killer pellet shutdown solutions.

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†ITER JTC, San Diego, California.
‡Lawrence Livermore National Laboratory, Livermore, California.

[1] S. Putvinskij *et al.*, J. Nucl. Mater. **241-243**, 316 (1997).
[2] W.L. Mocarsky, J. Inst. Math. Appl. **8**, 235 (1971).

# Expectation for the NSTX High Harmonic Fast Wave System*

M. D. Carter
*ORNL*

Non-inductive current drive is required during plasma initiation and for current sustainment in the National Spherical Torus Experiment (NSTX)†. Radio frequency (RF) waves launched from a phased antenna array have been chosen as the primary external method for driving these currents in the initial phases of this experiment. Waves in the high harmonic fast wave (HHFW) frequency range are expected to allow the current carrying electrons to absorb most of the RF power while reducing the power delivered to the ions. A specific frequency of 30 MHz has been chosen for NSTX because of practical considerations pertaining to the size of the device as well as the cost and availability of the required 6 MW of RF power.

High values of stored plasma kinetic energy relative to the magnetic field energy ($\beta$) are expected in NSTX. These parameters are obtained by driving a large toroidal current (1 MA) in a device with a relatively low toroidal magnetic field (0.3 T). The full RF power is needed to both heat the plasma and efficiently drive current early in the discharge when the poloidal component of the magnetic field is negligible and $\beta$ is low. The RF power and efficient current drive must also be maintained throughout the shot as the plasma $\beta$ and current rise to their full values, at which time the toroidal and poloidal components of the magnetic field at the antenna location become comparable. Thus, the HHFW antenna system is required to deliver high power levels over a wide range of plasma geometries and parameters.

The somewhat limited experience with HHFWs in traditional tokamak experiments has shown that HHFWs can be used successfully. However, RF experience in the unique and rapidly varying plasma regimes expected for the NSTX is almost non-existent. Therefore, the physics of HHFWs and the design of an antenna system for NSTX have relied heavily on numerical models.

The NSTX antenna design has required the calculation of the plasma radiation spectrum for a broad range of antenna and plasma geometries. Two coupled three-dimensional computer models have been used, and the modeling results have directly influenced the antenna design. Early modeling work performed a general survey of the expected plasma parameters to give a target for the basic antenna geometry and its phasing requirements. It was found that these targets were sensitive to the plasma equilibrium, so consistent free-boundary equilibria had to be used. Traditional methods of toroidally phasing the antenna array as well as new methods with poloidal phasing were studied to optimize the current drive efficiency and plasma power coupling. As the antenna design matured, engineering and practical constraints were included so that the models could provide a check of the consistency of the design with the physics requirements. Detailed modeling of preliminary designs determined the sensitivity of the overall antenna performance to details such as the orientation of the antenna in the device and to RF circuit requirements.

A review of the design process and performance expectations for the preliminary antenna design will be presented. Possibilities for using the HHFW system to control current and heating profiles in the plasma core will also be presented.

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†http://www-local.pppl.gov/nstxhome/index.shtml

# Diocotron Instabilities of Nonneutral Plasmas

John M. Finn
*LANL*

Daniel C. Barnes
*LANL*

The diocotron instability in a one dimensional $n = n(r)$ nonneutral single species plasma, for example in a Penning-Malmberg trap, is an instability driven by the presence of a hollow density profile. It is well known that the $l = 1, k = 0$ mode is exponentially stable (i.e. does not have an exponentially growing mode) regardless of the hollowness of the profile[1], although there can be weak power law growth associated with phase mixing of modes at an endpoint of the continuum[2]. On the other hand, the UCSD experiment shows robust exponential growth, with $\gamma/\omega$ of order a few percent, and very large amplitude nonlinear saturation[3]. We have studied the effects of finite length on the $l = 1$ mode. Specifically, we have included the effect of axial compressional due to the radial variation of the length $L = L(r)$ and the perturbation of the length $\delta L$. We obtained the profile of $L(r)$ by a two dimensional electrostatic equilibrium code, which shows $dL/dr < 0$. For reasonable experimental parameters we obtain a growth rate and mode structure in agreement with the experiment. We will discuss the dependence of the results on the length of the plasma, and comparisons of these factors with the experiments.

## References

[1] R. Levy, *Phys. Fluids 8*, 1288 (1965).
[2] R. Smith and M. N. Rosenbluth, *Phys. Rev. Lett. 64*, 649 (1990).
[3] C. F. Driscoll, *Phys. Rev. Lett. 64*, 645 (1990).

# Improved Edge Models for Coupled Core/SOL/Divertor Simulations of Tokamak Plasmas

J. Mandrekas, W. M. Stacey
*Fusion Research Center, Georgia Institute of Technology*

Conditions at the edge region of a tokamak plasma are critical in determining the overall performance of the system, as well as the feasibility of operating scenarios that rely on radiative losses from injected impurities and atomic processes to exhaust a large fraction of the heating power [1], [2]. Due to the strong interaction between the core and the SOL/divertor regions through the separatrix (neutral influx from the SOL into the core, power and energy fluxes from the core to the SOL/divertor), a simultaneous modeling of both regions is necessary. However, most analyses treat only one region (the core or the edge) in detail while employing either arbitrary boundary conditions or very simple physical models for the other. A few attempts have been recently made to perform self-consistent core-edge simulations by coupling $1\frac{1}{2}$D core transport codes to 2D edge fluid codes [3], but the resulting code systems are rather cumbersome and computationally expensive, therefore discouraging the performance of the large number of simulations that are necessary to test new operating concepts and analyze the effect of various uncertainties.

We have developed a new SOL/divertor model for coupling with core transport codes to provide a more self-consistent calculation of the core/SOL/divertor problem. The model includes a multi-region 2D neutral transport calculation based on an adaptation of the Transmission/Escape Probability (TEP) method [4], and an improved "2-point" divertor model with atomic physics and impurity radiation effects. The model includes momentum loss through charge exchange (CX) and elastic scattering with cold neutrals and due to volume recombination, as well as energy loss terms due to ionization, recombination and CX effects, while the impurity radiation calculation includes options for finite residence time and CX recombination effects. The combined neutrals/plasma model is comprehensive but numerically fast and imposes little computational burden on the $1\frac{1}{2}$D core transport code. The model will be coupled to our $1\frac{1}{2}$D core transport code GTWHIST. Preliminary results of coupled core/SOL/divertor simulations will be presented.

## References

[1] D. Post, et al, *Phys. Plasmas* **4** (1997) 2631.
[2] J. Mandrekas, W.M. Stacey, F.A. Kelly, *Nucl. Fusion* **37** (1997) 1015.
[3] L. L. Taroni, *Contributions in Plasma Physics* to be published, 1998.
[4] W.M. Stacey, J. Mandrekas, *Nucl. Fusion* **34** (1994) 1385.

# Kinetic Modelling of Drift Alfvén Turbulence

Frank Jenko, Bruce Scott
*Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany*

The parallel dynamics of passing electrons is in general electromagnetic and at most weakly collisional in the steep gradient zone of tokamak H mode plasmas, i.e. $\beta > m_e/M_i$ and $\nu_e < k_{||}v_{te}$ respectively. Therefore one needs to retain the effect of electron Landau damping in computations of the turbulent transport associated with drift Alfvén waves. We present simulation results from an electromagnetic turbulence model with drift-kinetic electrons and a Lorentz collision operator in three-dimensional sheared slab geometry. Transport scalings with various plasma parameters such as $\beta$ and $q$ as well as diagnostics examining the nonlinear mode structure will be shown. Computational benchmarks between this kinetic system and a corresponding transcollisional Landau-fluid model in the strongly collisional as well as the collisionless regime are now in progress and will be reported. Preliminary results indicate that understanding the role of magnetic flutter might turn out to be very important for electromagnetic systems. Whereas flutter doesn't contribute much to the cross-field transport directly, it might still have an impact on the dynamic equilibrium of the turbulence and thus indirectly change the observed $E \times B$ transport level. All these efforts are essential for the construction of more comprehensive transport models for the edge region, $r/a > 0.8$, of a tokamak.

# DT Experiments in the JET Tokamak

Paul R Thomas
*JET Joint Undertaking*

During the summer of 1997, JET conducted a campaign of experiments using DT fuel which produced a total of 675 MJ of fusion energy. Hot ion H-modes produced peak fusion powers of up to 16MW and, using a lower power variant, provided a clear demonstration of alpha particle heating. Internal transport barriers were created using the Optimised Shear (OS) regime but the operating range was more restrictive than in pure D plasmas because of a lower H-mode threshold. Full exploitation of OS plasmas must await further development and the next DT campaign.

The DT experiments in JET were the first to be carried out in the geometry of ITER. So, in addition to high yield transient plasmas, considerable emphasis was placed on mapping out the properties of long pulse ELMy H-modes, which are the baseline ITER scenario. Experiments were dedicated to the study of the isotopic effects on the H-mode threshold and energy confinement scaling, DT relevant ion cyclotron heating (ICRH) schemes were evaluated and alpha particle driven instabilities were looked for. Whilst the H-mode threshold power was shown to be inversely proportional to the mean ion mass, the energy confinement scaling shows no mass dependence. In addition to hydrogen minority ICRH, the deuterium minority in tritium, the second harmonic tritium and helium-3 minority schemes were all shown to be effective and had heating efficiencies in line with theoretical expectations. Whilst ICRH driven TAE instabilities have been seen in JET, there is no sign of them being driven by alpha particles in JET.

Of comparable importance to the experimental results was the operational experience of tritium handling, mixture control and repairs to tritiated systems. This shows that it is possible to operate safely with DT fuel, using a closed system for exhaust gas reprocessing, and that atmospheric releases can be kept to very low levels. Furthermore, the exchange of divertor target tiles using remote handling, which is presently under way, is another important demonstration of ITER and reactor technology.

## Generation of Plasma Rotation by ICRH in a Tokamak

C.S. Chang[1], S. Zweben[2], R. White[2], C. Phillips,[2] and J. deGrassie[3]
Courant Institute of Mathematical Sciences,
New York University, New York, NY

Inventing a way to generate plasma rotation by a controllable, external method can have a significant impact on the success of magnetic fusion program. Strongly sheared rotation can enhance plasma confinement. Strong rotation can also stabilize resistive wall mode, which can be a difficult problem to solve in a fusion reactor.

In the present work, a method of generating plasma rotation in a tokamak by ion cyclotron resonance heating is presented. ICRH induces radial electrical current of resonant ions, by forcing their guiding center orbits drift radially. A radial electric field $E_r$ develops and the plasma responds immediately with return current $j_r$ through orthogonal conductivity relation with $E_r$ to keep itself quasi-neutral. The resulting $j_r \times B$ force then can modify the plasma rotation. It is found that the fast wave power used in the present-day tokamak experiments can be strong enough to generate strong toroidal torque, if the conditions are right, which is comparable to that from unbalanced neutral beam injection. Comparison with experimental observation in TFTR, D-IIID, and ALCATOR C-MOD will be presented.

[1]Also at KAIST.
[2]PPPL, Princeton University.
[3]General Atomics.

# Bifurcated states of a rotating tokamak plasma in the presence of a static error-field*

Richard Fitzpatrick
*Institute for Fusion Studies, UT Austin*

The bifurcated states of a rotating tokamak plasma in the presence of a static, resonant, error-field are found to be strongly analogous to the bifurcated states of a conventional induction motor. The two plasma states are the "unreconnected" state, in which the plasma rotates and error-field driven magnetic reconnection is suppressed, and the "fully reconnected" state, in which the plasma rotation at the rational surface is arrested and driven magnetic reconnection proceeds without hindrance.

Recently, we have developed a *fully comprehensive* theory of the important "unreconnected" to "fully reconnected" bifurcation, which allows for a *nonlinear* response of the plasma in the vicinity of the rational surface to the external error-field. This theory unifies and extends all previous theories of error-field induced mode locking. [1, 2, 3, 4]

The response regime of a rotating tokamak plasma in the vicinity of the rational surface to a static, resonant, error-field is determined by *three* parameters: the normalized plasma viscosity, $P$, the normalized plasma rotation, $Q_0$, and the normalized plasma resistivity, $R$. There are *eleven* distinguishable response regimes. The extents of these regimes are calculated in $P$-$Q_0$-$R$ space. In addition, an expression for the critical error-field amplitude required to trigger a bifurcation from the "unreconnected" to the "fully reconnected" state is obtained in each regime.

For $R \ll 1$, the plasma response is determined by *linear* layer physics, [1, 2] whereas for $R \gg 1$ the plasma response is *nonlinear* (*i.e.*, depending on either Rutherford island physics, or Sweet-Parker layer physics [4]). As $Q_0$ increases, resistivity becomes progressively less important until, eventually, a regime is reached in which there is effectively zero driven magnetic reconnection, [3] and the plasma response is determined by the physics of wave absorption at Alfvén resonances. [1, 5]

The appropriate response regime for low density, ohmically heated, tokamak plasmas is found to be the nonlinear *constant-*$\psi$ regime for small tokamaks, and the linear *constant-*$\psi$ regime for large tokamaks. The critical error-field amplitude required to trigger error-field driven magnetic reconnection in such plasmas is found to be a rapidly decreasing function of machine size, indicating that particular care may be needed to be taken to reduce resonant error-fields in a reactor-sized tokamak. In NBI heated plasmas it is possible to access more exotic plasma response regimes.

## References

[1] R. Fitzpatrick, in *Theory of Fusion Plasmas*, Proc. Joint Varenna-Lausanne Int. Wksp., Varenna 1992, p. 147.
[2] R. Fitzpatrick, Nucl. Fusion **33**, 1049 (1993).
[3] O.A. Hurricane, T.H. Jensen, and A.B. Hassam, Phys. Plasmas **2**, 1976 (1995).
[4] X. Wang, and A. Bhattacharjee, Phys. Plasmas **4**, 748 (1997).
[5] X. Wang, A. Bhattacharjee, Z.W. Ma, C. Ren, C.C. Hegna, and J.D. Callen, *Structure and dynamics of current sheets at Alfvén resonances in a differentially rotating plasma*, to appear in Physics of Plasmas.

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# Symbolic Analysis of Turbulent Plasma Fluctuations*

M. Lehrman and A.B. Rechester
Institute of Nonlinear Science Applications
14 West Street
Sharon, MA 02067

M.A. Meir
Fusion Research Center
The University of Texas at Austin

A new signal processing method [1] has been applied for the analysis of electron temperature and density fluctuations and plasma potential fluctuations measured with Langmuir probes on Texas Experimental Tokamak [2]. All three fluctuations have been measured simultaneously at two different locations. We have also analyzed turbulent density fluctuations in the main core of TFTR plasmas measured with microwave reflectometry at several different locations. [3] We have computed usual cross-correlation functions and non-linear information correlation function for all different pairs of time series. We have also computed usual power spectrum and symbolic power spectrum. Our results are demonstrating that the symbolic method can be a valuable tool for the analysis of turbulent plasma data.

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[1.] M. Lehrman, A.B. Rechester and R.B. White, "Symbolic Analysis of Chaotic Signals and Turbulent Fluctuations". Phys. Rev. Letter 78, 54 (1997)

[2.] M.A. Meier, G.A. Halloch, and R.D. Bengtson, "Measurement of Turbulent Plasma by the Time-Domain Triple-Probe Method". Paper presented at the third workshop on Electrical Probes in Magnetized Plasmas, Berlin, Germany - September 22-25, 1997, Fusion Research Center, the University of Texas at Austin, report FRCR #500

[3.] E. Mazzucato and R. Nazikian, Phys. Rev. Lett. 71, 1840 (1993)

# Higher-Order Effects in Mode Conversion Theory*

D. G. Swanson
*Physics Department, Auburn University, AL 36849*

Since most derivations of the mode conversion – tunneling equation for either ion or electron cyclotron harmonics depend on finite Larmor orbit expansions, some have questioned the validity of the truncation of the Bessel series because the argument of the Bessel function may not always be small. The argument is generally of the form $\lambda = \frac{1}{2}k^2\rho^2$, and for some energetic species, this may approach unity. It is shown in this paper that in the derivation of the appropriate tunneling equation, the smallness parameter is actually $\beta = 2\mu_0 nkT/B_0^2$ for the resonant species, and since this is small for all species, the higher order terms are of little consequence. In order to verify this result, a particular example is given where the next higher-order term is kept, raising the order of the tunneling equation from the familiar fourth-order equation to a sixth-order equation which is solved using the GSS[1] method. In the characterization of the dispersion relation, two things are observed: (1) the tunneling layer thickness is changed only imperceptably, and (2) another mode conversion layer is added at some distance from the primary tunneling layer, leading to a major change in the dispersion relation far from the resonance. It is shown analytically for an ion harmonic case that the tunneling factor is increased by a factor of $1 + 9\beta/16$, which is small. Making no truncation in the Bessel series leads to a dispersion relation that still has nearly imperceptable changes near the resonance, but shows significant curvature of the dispersion relation far from the resonance. Since the principal results from mode conversion theory are the transmission, reflection and conversion coefficients, and these are determined from effects near the resonance, there is no problem with the validity of mode conversion due to truncation effects. If one wants to follow the trajectory of a mode-converted branch, however, the ray-tracing code may need to keep either many terms in the expansion or use the Bessel functions directly.

## References

[1] D. J. D. Gambier and J. P. M. Schmitt, Phys. Fluids **26**; D. J. Gambier and D. G. Swanson, Phys. Fluids **28**, 145 (1985).

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# Inertial damping and active rotation control of tearing fluctuations in a tokamak*

D. Maurer, C. Cates, M. E. Mauel, D. Nadle, G. A. Navratil, E. Taylor
*Columbia University*

W. A. Reass, G. A. Wurden
*Los Alamos National Laboratory*

Active tearing mode control experiments on the HBT-EP[1] tokamak point to the importance of inertial damping in the amplitude dynamics of $m/n=2/1$ magnetic islands.[2] Resonant magnetic perturbations (RMPs) generated by a compact saddle coil set impose either two-phase rotating or single-phase oscillating drive fields on the plasma surface. Using these drive fields, fast frequency and amplitude modulations are induced in pre-existing *2/1* tearing fluctuations. It is conjectured that the observed amplitude damping is due to ion polarization currents induced by rapid mode frequency changes. Theoretical estimates of the ion polarization current contribution to the Rutherford equation are compared to the experimentally observed amplitude damping. The observed damping effect allowed the implementation of an asynchronous control technique based upon an idea of Kurita *et al.*[3] Applying a frequency modulated (FM) drive perturbation that alternates between frequencies above and below the natural mode frequency maintains inertial damping of tearing activity. The FM drive modulates the mode frequency while not allowing the pre-existing fluctuation time to lock to the applied drive field and grow in amplitude. This technique, when applied to disruptive discharges, decreased core thermal and particle loss by controlling the *2/1* island size. In addition, rotation control of naturally occurring modes ($f = 7$ *kHz*) has been achieved over the frequency range *3 -15 kHz*, with an applied field of the order of the poloidal field fluctuation at the edge of the plasma. This active *stirring* of the plasma[4] is observed to induce local toroidal ion flow changes of *2 - 5 km/s* near the position of the $q=2$ surface. These ion fluid velocity changes are approximately *20 percent* of the induced mode frequency change.

## References

[1] M. K. V. Sankar, E. Eisner, A. Garofalo,*et al*, J. Fusion Energy 12, 303 (1993).
[2] G. A. Navratil, C. Cates, M. E. Mauel, D. Maurer,*et al.*, submitted to Physics of Plasmas.
[3] G. Kurita, T. Tuda, M. Azumi, and T. Takeda, Nuc. Fusion **32**, 1899 (1992).
[4] T. H. Jensen and A. W. Leonard, Phys. Fluids B **3** (12), 3422, (1991).

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# AN IMPLICIT BOUNCE-AVERAGED FOKKER-PLANCK (BAFP) CODE TO MODEL SPHERICAL INERTIAL ELECTROSTATIC CONFINEMENT (IEC) FUSION SYSTEMS

L. Chacón
*U. of Illinois at Urbana-Champaign*

D. C. Barnes, D. A. Knoll
*Los Alamos National Laboratory*

The IEC fusion concept takes advantage of the potential well generated by an inner spherical cathode (physical or virtual), biased negatively to several kV with respect to a concentric outer grounded boundary, to focus ions inwards and form a dense central core where fusion may occur. However, defocusing of the ion beams due to ion-ion collisions may prevent a satisfactory energy balance in the system [1]. Hence, determining the actual degree of ion defocusing is crucial to ascertain the energetic capabilities of this approach.

BAFP is a fully implicit code developed to address this issue for a Penning IEC Fusion system [2] (PFX), in which ion confinement is provided by an electron cloud (virtual cathode), which in turn is confined by a Penning trap. In BAFP, electrons are assumed Maxwellian. Ions are injected into the system with a radial beam-like distribution. Ion-ion collisions are handled by the fully nonlinear Fokker-Planck collision operator, with the Rosenbluth potentials numerically evaluated from the numerically-determined distribution function. For realistic parameters, the collision frequency is very small compared to the bounce frequency, $\nu_{col} \ll \nu_{bounce}$. A bounce-average of the operator, carried to first order in $\nu_{col}/\nu_{bounce}$, removes the shortest time scale of the problem. The solution procedure is simplified by the introduction of independent variables which removes the convection and field transport terms. The radial electrostatic potential profile is obtained self-consistently by solving Poisson's equation every time step. Multiple potential wells can be handled. BAFP does not include the effects of either ion-electron or electron-electron collisions.

Efficient time advance requires implicit time differencing. For this, the Fokker-Planck collision operator is linearized and discretized so that its intrinsic conservation properties (particles and energy) are preserved [3, 4]. The linear system of equations obtained is solved using a preconditioned GMRES iterative procedure [5].

BAFP simulations will pursue three main objectives: 1) prove the convergence of the ion distribution to a Maxwellian in the absence of ion sources or sinks; 2) find the conditions for the existence of focused ion beams in steady-state, and 3) calculate the energy gain in such situations. Results of code tests will be presented.

## References

[1] W. M. Nevins, *Phys. Plasmas*, **2** (10), 3804-3819, (1995)
[2] D. C. Barnes, T. N. Tiouririne, L. Turner, R. A. Nebel, *Proc. International Sherwood Fusion Theory Conference*, Dallas, TX, 2C28 (1994).
[3] E. M. Epperlein, *J. Comp. Phys.*, **112**, 291-297 (1994)
[4] J. S. Chang, G. Cooper, *J. Comp. Phys.*, **6**, 1-16 (1970)
[5] Y. Saad, M. Schultz, *SIAM J. Scientific and Stat. Comp.*, **7**, 856-869 (1986)

# Conditions for Observing Neoclassical Ion Temperature Gradient Screening of Impurities in Tokamaks*

W. A. Houlberg, M. R. Wade, L. R. Baylor
*Oak Ridge National Laboratory*

K. C. Shaing
*Institute for Fusion Studies*

P. C. Efthimion
*Princeton Plasma Physics Laboratory*

For several decades it has been known theoretically that Coulomb collisions between unlike ions can generate a strong component of the particle flux driven by the ion temperature gradient ($T_i'$). For higher charge and mass impurities in the low collisionality (banana) regime this flux is down the $T_i$ gradient and called 'temperature screening' while at higher collisionalities (Pfirsch-Schlüter regime) it can be up the $T_i$ gradient. We use transport coefficients calculated by the multiple species neoclassical transport code NCLASS [1] to show that the neoclassical $T_i'$ driven particle flux can be an important contributor to impurity transport behavior in many of the improved confinement regimes in tokamaks. In TFTR reverse shear plasmas where turbulence is completely suppressed in the core, the diffusivity of minority species is in agreement with NCLASS calculations.[2] However, strong peaking of the deuterium density generates an inward component of the minority species particle fluxes that tends to mask $T_i'$ contributions. On the other hand, in DIII-D VH modes the flat density gradient allows the $T_i'$ contribution to be an identifiable contributor to impurity transport even though turbulence is not completely suppressed and may be several times as large as the neoclassical diffusivity.[3] We show this by comparing carbon and neon behavior. The radiative improved (RI) mode observed in TEXTOR and many other experiments may also be a case where neoclassical $T_i'$ driven particle fluxes are important. In the RI, as with other modes, the impurity behavior can be quite complex with $T_i'$ driving impurities inward at the edge (if the collisionality is high enough) and outward in the core (if the main ion density profile is flat enough). If planned experiments and analyses continue to confirm the neoclassical contributions it should be possible to design more attractive fusion systems that take advantage of expelling helium ash from the core and maintaining a higher-Z radiative boundary to distribute the thermal load through radiation.

## References

[1] W. A. Houlberg, K. C. Shaing, S. P. Hirshman, M. C. Zarnstorff, *Phys. Plasmas* **4** (1997) 3230.
[2] P. C. Efthimion, et al., "Observation of Particle Transport Barriers in Reverse Shear Plasmas on the Tokamak Fusion Test Reactor," *Phys. Plasmas*, to be published.
[3] M. R. Wade, W. A. Houlberg, L. R. Baylor, "Evidence of Neoclassical Impurity Transport in DIII-D," 1998 TTF Meeting, Atlanta.

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# Efficient C++ library for Differential Algebra

Svetlana Shasharina
*University of Colorado*

John Cary
*University of Colorado*

We created a protype of C++ library for Differential Algebra, which uses Expression Templates combined with the garbage collection tiling methods for multiplication. Preliminary results show that all operations are more than 10 times faster than in existing C++ codes.

# Single Integral Expressions for Electron Cyclotron Damping, Relativistically and with an Arbitrary Distribution Function*

I.P. Shkarofsky

*Centre canadien de fusion magnétique, Varennes, Québec, J3X1S1, and MPB Technologies Ltd., Pointe Claire, Québec, H9R1E9, Canada*

The relativistic expressions for the dielectric tensor elements can be expressed as a double integral over both parallel and perpendicular momentum. The anti-hermitean parts can be integrated over a delta function for either one of these two momentum, leaving a single integral over the other momentum variable. We review these expressions for either integration option, and compare them with statements in the literature. We explicitly give the limits on the remaining integral, for all positive or negative values of the parallel refractive index, whose magnitude can be less or greater than one. This single integral form can be applied to electron cyclotron harmonic damping for any distorted electron momentum distribution function. As an example, we recover the results for a Maxwellian distribution. We also provide approximate results when the distribution function can be taken as a Maxwellian only in the perpendicular momentum direction. A computer program will be written for a distribution function subjected to distortion by both electron cyclotron and lower hybrid waves.

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# Fokker-Planck Modeling of Transient Effects in the Edge Plasma of TdeV*

M. Shoucri, I.P. Shkarofsky, G. Pacher, R. Décoste
*Centre canadien de fusion magnétique, Varennes, Québec, J3X1S1, Canada*

O. Batishchev, A. Batishcheva
*MIT Plasma Fusion Center, Cambridge, Mass., 02139, USA*

A kinetic approach is desirable to investigate fast transient processes, such as heating and cooling bursts caused by edge localized modes (ELMs), propagating into a tokamak scrape-off layer (SOL) plasma. A fluid plasma treatment may not be applicable, since the assumption of high collisionality fails and the plasma particles may be unable to relax completely to a Maxwellian, thereby affecting the transport properties[1]. Here we apply kinetic modeling of plasma transport to ELM propagation in the SOL of TdeV. The numerics use the time-dependent 1D-2V Fokker-Planck code, ALLA. Data taken from TdeV is used to model the energy and particle flux sources entering the SOL plasma from the core.

## References

[1] A. A. Batishcheva et al., Phys. Plasmas, **3**, 1634 (1996).

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# Investigation of Inner Layer Models Using Resistive Energy Principle Approach

S.A. Galkin,† J.M. Greene, A.D. Turnbull, A. Pletzer,‡
M.S. Chu, and R.L. Miller

*General Atomics*
*San Diego, California*

We apply the recently developed linear MHD eigenvalue TWIST-R code to study resistive MHD plasma stability using a variety of different inner layer models. The TWIST-R code is based on the fully toroidal resistive energy principle [1]. The code uses two projections of the plasma displacement (radial and tangential) [2] and can treat 2D toroidal plasma configurations surrounded by a vacuum region and an ideal conducting wall. Different inner layer models, either analytical or numerical, can be easily incorporated in the code, including models which couple different projections of the displacement, plasma rotation near resonance surfaces, etc. The code solves a nonlinear eigenvalue problem and the full structure of the resistive (and ideal) eigenfunctions simultaneously with corresponding eigenvalues can be obtained numerically.

Benchmark calculations were carried out between the TWIST-R code and the published benchmark case with the MARS and PEST-3 codes [3]. The benchmark comparison with PEST-3 code against pressureless and finite pressure plasma configurations was done using the classic Glasser-Greene-Johnson (GGJ) inner layer model [4]. We also compare the Greene and Miller inner layer model behavior [5] with the GGJ model. The inner layer ideal parity solutions and their effects on the sensitivity of dispersion relations were studied and the influence of the plasma parameters such as pressure, plasma shape, etc., on resistive modes is also discussed.

The immediate future plans include exploring of inner layer effects with compressibility, plasma rotation, magnetic well and the role of the ideal parity solutions.

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†Keldysh Institute of Applied Mathematics, Moscow, Russia.
‡ITER JTC, San Diego, California.

[1] M.S. Chu, R.L. Dewar, J.M. Greene, and A. Pletzer, Phys. Fluids B **5**, 1593 (1993).
[2] S.A. Galkin, V.V. Drozdov, and A.A. Martynov, Preprint KIAM **N52** (1991).
[3] A. Bondeson, G. Vlad, and H. Lütjens, Phys. Fluids B **4**, 1889 (1992).
[4] A.H. Glasser, J.M. Greene, and J.L. Johnson, Phys. Fluids **18**, 875 (1975).
[5] J.M. Greene and R.L. Miller, Phys. Plasmas **2**, 1236 (1995).

# Identification, Triggering and Control of Large Events in a SOC system*

H. Chen, D. E. Newman, B. A. Carreras
*Oak Ridge National Laboratory*

The concept of Self-Organized Criticality (SOC) has been advanced as a paradigm for turbulent transport in magnetically confined plasmas [1, 2]. In SOC systems transport is usually dominated by large events (i.e., avalanches in a sandpile). Therefore, in order to control the transport one needs to control the large events. Because SOC systems are intrinsically very resilient to perturbations a study of different types of perturbations has been made to determine which types can trigger or prevent these large transport events. Computational experiments with a sandpile model of SOC dynamics suggests some modification of the transport dynamics is possible with periodic perturbations of the internal sources and critical gradients. Triggering of large events can be achieved with bursty low frequency perturbations while high frequency small perturbations may be used to inhibit large events. Within a "noisy" turbulence data set there is often a particular signal of interest such as the "transport" events. While standard filtering techniques can sometimes be used to isolate this signal it is often difficult to reliably differentiate the parts of the signal. In order to observe these events in an intrinsically noisy system a variety of statistical tests is presented.

## References

[1] P. H. Diamond and T. S. Hahm, Phys. Plasmas **2**, 3640 (1995).
[2] D. E. Newman, B. A. Carreras, P. H. Diamond and T. S. Hahm, Phys. Plasmas **3**, 1858 (1996).

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# Optimization Study of Slow Wave Current Drive in the MST Reversed-Field Pinch*

E. Uchimoto,[a] R. W. Harvey,[b] A. P. Smirnov,[c] C. B. Forest, S. C. Prager,
J. S. Sarff, and M. R. Stoneking[d]
*Department of Physics, University of Wisconsin-Madison*

An advanced reversed-field pinch (RFP) in which large-amplitude resistive tearing modes are suppressed by current profile control techniques has significantly improved the prospect of the RFP for a future fusion reactor. Theoretically, we have shown that lower hybrid current drive (LHCD) is an effective means of modifying the current profile in the outer region of the RFP and improving the plasma confinement characteristics.[1),2)] Experimentally, pulsed poloidal current drive (PPCD) has led to a five-fold increase in the energy confinement time of the MST RFP.[3)] These results strongly motivate us to conduct a LHCD experiment, which is non-transient and potentially more controllable than PPCD.

To optimize the design of the LHCD experiment to be implemented in the Madison Symmetric Torus (MST), we have conducted an extensive parameter survey using our new computer code package for RF heating and current drive in the RFP. This code package consists of MSTEQ (Grad-Shafranov solver), GENRAY (generalized ray tracing code), and CQL3D (3-D, relativistic, bounce-averaged, quasi-linear, Fokker-Planck code), and each code is written for or adapted to the RFP topology including toroidal effects. We have shown that a judicious choice of wave frequency, parallel refractive index, wave spectrum, and antenna location will produce an auxiliary parallel current which is well localized in position ($r \sim 0.65a$) and sufficiently high in efficiency (0.6 MA/1 MW). We have also shown that penetration can be increased significantly by RF-induced transparency, the process in which quasi-linear velocity space diffusion flattens the electron distribution and reduces the Landau damping. This opens up the possibility of using slow waves for core current drive and heating of the RFP.

To avoid the ion-Landau damping even in a high current discharge (~ 600 kA) and to make good use of available resources from past tokamak experiments, we are focusing on the use of slow waves in the frequency range of 800 MHz. For profile control and transport reduction, a good candidate is found to be the slow wave of $\langle n_{\|} \rangle \sim 7.5$ launched from the region near the inboard side of the MST RFP. This choice is attractive in that current drive efficiency will be adequate and the driven current profile ideally positioned for a range of RF power. For core current drive and heating, an outboard launch is shown to be more effective assuming sufficient RF-induced transparency.

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a) Dept. of Physics & Astronomy, University of Montana, Missoula, MT 59812. b) CompX, Del Mar, CA 92014.
c) Moscow State University, Moscow, Russia. d) Dept. of Physics, Lawrence University, Appleton, WI 54912.

1) E. Uchimoto, *et al.*, Phys. Plasmas **1**, 3517 (1994).
2) E. Uchimoto, *et al.*, Proceedings of the 1997 Sherwood Theory Conf. (April 28-30, 1997; Madison), paper 1C13.
3) J. S. Sarff, N. E. Lanier, S. C. Prager, and M. R. Stoneking, Phys. Rev. Letters **78**, 62 (1997).

# The Effect of Shear Flow on Neoclassical Tearing Modes*

S. E. Kruger, C. C. Hegna, J. D. Callen
*University of Wisconsin, Madison, WI 53706-1687*

Neoclassical effects can destabilize tearing-type instabilities even when resistive MHD theory predicts stability[1]. These neoclassical tearing modes are predicted to be problematic for ITER[2] since they may lead to a beta limit below that required for ignition. Although theory has successfully been used to describe experimental observations, [3] several questions remain. In this work, the problem of shear flow effects on neoclassical tearing modes is formulated and preliminary numerical results are presented. The equations used are reduced from the full MHD equations by a unique multiple-time scale expansion[4] that allows a more natural introduction of neoclassical effects than traditional high aspect ratio expansions. This work generalizes previous neoclassical tearing mode studies to include the effects of shear flow which have been previously studied using resistive MHD theory[5].

## References

[1] C. C. Hegna and J. D. Callen, Phys. Fluids **4**, 4072 (1992).
[2] O. Sauter et al., Phys. Plasmas **4**, 1654 (1997).
[3] Z. Chang et al., Phys. Rev. Letters **74**, 4663 (1995).
[4] S. E. Kruger, C. C. Hegna, J. D. Callen, "Reduced MHD Equations for Low Aspect Ratio Devices", CPTC Report.
[5] L. Ofman, X.L. Chen, P. J. Morrison, and R. S. Steinolfson, Phys. Fluids B **3**, 1364 (1991) *and references therein*; M. Persson and A. Bondeson, Nuclear Fusion **29**, 989 (1989) *and references therein.*

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# PARTICLE CANONICAL VARIABLES IN TOROIDAL GEOMETRY ---- ARBITRARY CHOICE OF MAGNETIC FLUX COORDINATES

H. Vernon Wong
Institute for Fusion Studies,The University of Texas at Austin

It is convenient to describe toroidal equilibria with nested flux surfaces in terms of Boozer flux coordinates. The angular covariant components of the magnetic field are flux functions, and the generalised poloidal and toroidal angles are approximate particle canonical variables which facilitate the discussion of guiding center motion. In some equilibria however the representation of the magnetic field requires a summatiion over many fourier harmonics of the Boozer poloidal angle, and the use of another set of flux coordinates which minimises the number of required Fourier components may be more appropriate. In general, the angular coordiantes are not exact particle canonical variables ( unless the angles are chosen so that the flux covariant component of the magnetic field is zero). It is therefore of some interest to define particle canonical variables for guiding center motion in terms of an arbitrary choice of magnetic flux coordinates. We start with the Hamiltonian in cartesian coordinates and we introduce a generating function involving the flux coordinates to transform to new canonical variables. The generating function is chosen so that the particle motion is separated into the three time scales characteristic of charged particle motion in a strong magnetic field [1]. The particle guiding center canonical variables and Hamiltonian are then derived by carrying out a Larmor radius expansion. We will also discuss the modifications required to include the presence of large equilibrium electrostatic fields.

(1) C.S.Gardner, Phys.Rev. 115, 791 (1959)

# Finite Orbit Width and Larmor Radius Effects in Fast Particle Instability of Low-$n$ TAE. *

C.Z. Cheng, N.N. Gorelenkov
*Princeton Plasma Physics Laboratory, P. O. Box 451, Princeton, NJ 08543-0451*

M.V. Gorelenkova
*Troitsk Institute for Innovative and Fusion Research, Troitsk, Russia, 142092*

The effects of finite drift orbit width (FOW) and Larmor radius (FLR) of fast particles on the stability of low-n TAE are studied. The formulation is based on the solution of the low frequency ($\omega \ll \omega_c$, where $\omega_c$ is the cyclotron frequency) gyro-kinetic equation. A quadratic form has been derived in terms of invariant variables: energy $\mathcal{E}$, magnetic moment $\mu$, and toroidal angular momentum $P_\varphi$. The growth rate is computed perturbatively by averaging over the fast particle drift orbit. These new computational capability has been incorporated into the NOVA-K code [C. Z. Cheng, Phys. Reports **211** (1992) 1]. In the previous version of NOVA-K code the calculation of FOW effects were based on small radial orbit width approximation [G. Y. Fu and C. Z. Cheng, Phys. Fluids, **4** (1992) 3722]. The new NOVA-K version has been benchmarked. It is shown that both FOW and FLR effects are typically stabilizing: the TAE growth rate can be reduced by as much as a factor of 2 for TFTR supershots. However, under certain conditions FOW effects may enhance TAE growth rates. Here, we also present calculations for NSTX (National Spherical Tokamak Experiment) – a low aspect ratio tokamak. The toroidicity (and noncircularity) induced Alfvén gaps in NSTX, the existance of TAEs and their stability in the presence of fast particles are investigated.

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# Mode Conversion and Coupling to Electron Bernstein Waves in NSTX*

Steven D. Schultz, Abraham Bers, Abhay K. Ram
*Plasma Science and Fusion Center, M.I.T., Cambridge, MA*

In NSTX, and in similar high-$\beta$ tokamaks, the extraordinary (X) mode and the ordinary (O) mode, in the electron cyclotron range of frequencies (ECRF), are cutoff near the plasma edge. In such cases, a possible means of delivering ECRF power into the plasma core is by electron Bernstein waves (EBW). The EBWs can be excited by mode-conversion of an externally launched X-mode[1, 2]. Analytically, this process is similar to the mode conversion of a fast Alfvén wave to an ion-Bernstein wave [3], and can, in principle, lead to 100% power mode converted, i.e. the entire power on the X-mode can be converted to EBWs. We have been studying the mode-conversion process as a resonance absorption (at the upper-hybrid resonance) in the cold plasma description of the wave propagation, and as a kinetic phenomenon where the EBW is explicitly included in the mode-conversion description. A comparison of the mode-conversion efficiency shows that the two techniques yield essentially the same results over a certain range of parameters. In this range the upper-hybrid resonance (UHR) lies between $f_{ce}$ and $2f_{ce}$, where $f_{ce}$ is the electron-cyclotron frequency. When the UHR lies above $2f_{ce}$, the two techniques again give similar results for the power mode converted, but the kinetic description is required for properly interpretating the energy flow. A detailed theoretical and numerical description of the mode-conversion process will be discussed. In the high-$\beta$ tokamaks, the mode conversion process takes place near the edge of the plasma. This raises the possibility of direct excitation of EBWs in the plasma. Analyses of this direct coupling will be presented.

## References

[1] K.C. Wu, A.K. Ram, A. Bers, and S.D. Schultz, in *Proceedings of the 12th Topical Conference on RF Power in Plasmas*, AIP, New York, 1997, pp. 207-210.
[2] A. Bers, A.K. Ram, and S.D. Schultz, to be published in the Proceedings of the 2nd Europhysical Topical Conference on RF Heating and Current Drive of Fusion Devices, Brussels, Belgium (1998).
[3] A.K. Ram, A. Bers, S.D. Schultz, and V. Fuchs, *Phys. Plasmas* **3**, 1976 (1996).

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# A Distributed Parallel Algorithm for a Class of Weak Turbulence Problems

B. Demsky
*Department of Physics, The University of Texas at Austin, Austin TX 78712*

J. Candy
*Institute for Fusion Studies, The University of Texas at Austin, Austin TX 78712*

Software to enable the parallelization of specific, previously-existing particle codes (for the bump-on tail [1], TAE [2] and fishbone [3] instabilities) has been developed. The computation is managed by a central server, executing Java code [for multithread capability], that distributes the workload in an asymmetric manner to a collection of N clients (workstations of nonspecific platform). Each client performs a fraction of the computation using an identical code written in C++. For sufficiently large particle number (more than 10,000 per node for Pentium Pro class machines), the performance scales linearly with total collective system FLOPS (floating point operations per second). That is, doubling the number of available FLOPS doubles the number of particles which can be evolved per second. The efficiency of the distributed time-stepping algorithm relies on the rather special nature of the energetic particle nonlinearity. We show detailed simulation results for a novel problem: the spontaneous formation of phase space holes and clumps in a weakly unstable 2-D plasma [4].

## References

[1] J. Candy, J. Comput. Phys. **129** 160 (1996).
[2] J. Candy, D.N. Borba, G. Huysmans, W. Kerner and H.L. Berk, Phys. Plasmas **4** 2597 (1997).
[3] J. Candy, F. Porcelli, B.N. Breizman and H.L. Berk, Proc. 24th EPS Conf. Berchtesgaden, Vol 21A III 1189 (1997).
[4] H.L. Berk, B.N. Breizman and N.V. Petviashvili, Phys. Lett. A **234** 213 (1997).

# Transport in Edge Plasmas*

Peter J. Catto[a,b], P. Helander[c], J. W. Connor[c], and R. D. Hazeltine[d]
[a]Plasma Science and Fusion Center, Massachusetts Institute of Technology
[b]Lodestar Research Corporation, Boulder, Colorado
[c]UKAEA Fusion, Culham Science Centre, (UKAEA/Euratom Assoc.)
[d]Institute for Fusion Studies, The University of Texas at Austin

The edge plasma of a tokamak is affected by atomic physics processes and can have density and temperature variations along the magnetic field which strongly modify edge transport. We present a closed system of equations in the Pfirsch-Schlüter regime which can be solved for the radial and poloidal variation of the plasma density, electron and ion temperatures, and the electrostatic potential in the presence of poloidally asymmetric neutrals and an energy radiation sink. The viscosity and heat flux associated with the neutrals can be important if their density is high, in which case the neutral viscosity alters the electric field in the edge plasma. The parallel gradient in the electron temperature that arises in the presence of localized radiation sinks drives a flow of particles and heat across the field. This transport mechanism is particularly strong if a Marfe is formed since the electron temperature then varies substantially over the flux surface. Since the Pfirsch-Schlüter return current must pass through the Marfe, which is very cold and dense, a large poloidal electric field arises, with strong concommitant $E \times B$ convection. These fluxes can be directed either inwards or outwards. Moreover, whenever magnetic field lines do not form closed flux surfaces, but instead connect to material walls, additional convective modifications to conventional collisional transport arise.

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# Evolution of Density Pulses in the Presence of Static Magnetic Islands *

E. H. Held, J. D. Callen, C. C. Hegna
*University of Wisconsin-Madison*

A fundamental problem for bootstrap current-driven magnetic islands involves the dynamics and profile properties of pressure. Electron temperature flattening inside islands above the threshold width perturbs the bootstrap current and drives neoclassical tearing modes in Δ'-stable plasmas. Although temperature flattening inside the island separatrix has been observed[1], it is uncertain the degree to which the density profile shows a similar flattening above a critical island width. Because the radial density gradient can play an important role in the evolution of the bootstrap current and hence the stability of neoclassical tearing modes, it is fitting to study the dynamics and profile properties specific to density. This entails understanding the relevant processes and time scales for density equilibration parallel and perpendicular to magnetic field lines in the presence of static magnetic islands.

Although common, the treatment of parallel equilibration as a classical diffusive process may fail to incorporate the kinetic effects of free-streaming electrons in sufficiently collisionless plasmas. In addition, the parallel equilibration of particles involves the propagation of sound waves along field lines. As a paradigm for understanding density equilibration, we determine the evolution of particle pulses in the presence of a magnetic island by analytically solving the parallel momentum and continuity equations over multiple time scales. We assume that changes in the magnetic structure occur on a much slower time scale compared to particle equilibration. The competition between parallel and perpendicular time and length scales is displayed by the critical island width above which parallel transport dominates, $W_c = 4(r_s R_o/nsc_s)^{1/2}(\nu_c D_\perp)^{1/4}$, where $r_s$ is the radius of the resonant surface, $R_o$ is the major radius, $n$ is the toroidal mode number, $s$ is the shear length, $c_s$ is the sound speed, $\nu_c^{-1}$ is the normalizing time scale and $D_\perp$ is the perpendicular diffusion coefficient. At small island width ($W \ll W_c$), perpendicular diffusion dominates and magnetic island effects enter as first order corrections. This implies that density perturbations spread out predominately in the radial direction with only a small equilibration along field lines (i.e., in the flux surface). Inside an island of large width ($W \gg W_c$), however, rapid parallel processes quickly smooth out density perturbations around a flux surface with only a limited amount of perpendicular diffusion. This is the case except in the narrow region surrounding the separatrix, where singular field line behavior (i.e., zero rotational transform at the X-points) requires a boundary layer analysis near and far from the X-points. Based on the solutions at large and small island width, we discuss the feasibility of pellet injection near a magnetic island to control the radial density gradient and hence the bootstrap current so as to decrease the drive for neoclassical tearing modes.

## References

[1] Chang, Z., et al. Nuclear Fusion **34** (1994) 1309.

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# Nonlinear Instability in Collisionless Trapped Electron Turbulence*

Derek Baver, Paul W. Terry
*University of Wisconsin-Madison*

Eduardo Fernandez
*Center for Turbulence Research, Stanford University*

Collisionless trapped electron mode (CTEM) turbulence is believed to play a role in the fluctuations producing core transport in hot tokamak plasmas, particularly in the long wavelength regime. Saturation of long wavelength CTEM is strongly affected by the turbulent advection of the electron density, or electron nonlinearity. The behavior of this nonlinearity is quite different in the collisionless limit than in the dissipative limit, and is not well understood. Here, we adopt a simple fluid model of CTEM in order to focus on the important nonlinear physics associated with the electron nonlinearity. We find that this nonlinearity leads to nonlinear instability, causing both an anomalous input of energy and an anomalous damping, relative to the linear growth rate.

The origin of nonlinear instability is two-fold. First, as with all fluctuations involving the nonadiabatic electron density, the dispersion (both linear and nonlinear) has at least two branches. At infinitesimal amplitude, one yields the linear growth rate and the other is typically damped. The electron nonlinearity, which dominates long wavelength dynamics in the collisionless regime, is found to be quite efficient at exciting any branch that is damped. Unless the damping rate greatly exceeds the nonlinear transfer rate the damped branch reaches finite amplitude and dissipates energy, changing energy balances, saturation levels, and spectra. Second, the electron nonlinearity directly affects the correlation of density and potential, the quantity that governs energy input (instability). Analytic calculations based on an iterative inversion of the nonlinear electron propagator suggest that the electron nonlinearity leads to nonlinear instability, and this is born out by measurement of the nonlinear energy input rate in numerical simulations. These two mechanisms appear to work in different parts of the spectrum, with the anomalous damping operative at low k and the nonlinear instability at high k. In contrast to the dissipative regime, they produce a noticeable modification of the density spectrum, so that it no longer follows the shape of the potential spectrum.

These effects are assessed by looking at the spectra of the linear and nonlinear growth rates, the density-potential correlation, and saturated spectra. To quantify the effect of nonlinear transfer of energy to the damped branch we vary the ratio of the transfer to damping rate, thus manipulating the amplitude of the damped branch in saturation. These results are discussed in relation to techniques for modeling transport that rely the linear growth rate (e.g., mixing length estimates, shear suppression thresholds, quasilinear transport calculations, and bispectral deconvolution techniques to inferring growth rates).

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# Sheath over a divertor plate with small-scale surface imperfections *

D. D. Ryutov, R. H. Cohen

*Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

The surface of the divertor plate typically has fine "topographic" structure determined by the intrinsic properties of the material (like the grainy structure of graphite), and by erosion processes. The characteristic size of the surface imperfections may vary over a broad range. In this paper we consider the case where these structures have a scale height much less than the ion gyroradius but much greater than the electron gyroradius.

The magnetic field intersects the divertor plate at a shallow angle $\alpha \ll 1$. We show that the presence of fine surface structures, together with the smallness of $\alpha$, gives rise to many interesting new phenomena in the sheath (the case of smooth waviness of the surface was considered in Ref. [1], while the case of a coarsely grained surface, where the scale of the non-uniformities exceeds the ion gyroradius was considered in Ref. [2]).

It is shown that the fraction of the surface "wetted" by the plasma electrons is much less than that "wetted" by the plasma ions. The relation between statistical properties of the electron current density distribution over the surface and statistics of the surface imperfections is found. The importance of the "shadowed" areas inaccessible to electrons (behind the spikes on the surface) is emphasized. In particular, these shadows may lead to development of the fine potential structures that are translated along the field lines into the bulk of the plasma and cause additional plasma transport. It is demonstrated that, at $\alpha \ll 1$, secondary electron emission for a rough surface may be considerably larger than for a flat surface.

## References

[1] R.H. Cohen and D.D. Ryutov. Nucl. Fusion **37**, 621 (1997).
[2] R.H. Cohen and D.D. Ryutov, Submitted to Phys. Plasmas.

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# Improved H-mode with Neon Injection in the DIII–D Tokamak

G.M. Staebler, G.L. Jackson, W.P. West, S.L. Allen,† R.J. Groebner,
M.J. Schaffer, and D.G. Whyte‡

*General Atomics*
*San Diego, California*

DIII–D discharges with neon injection into an ELMing H–mode have been observed to make a transition to an L–mode with improved energy confinement 1.3-2.0 times the pre-neon L–mode phase. We follow the JFT-2M nomenclature [1] and call these IL–modes. Some of the IL–modes discharges make a transition back into an H–mode edge. The energy confinement during the ELM free phase is up to three times L–mode. This improved mode is called IH–mode. Power balance analysis of an IL–mode shows that the electron and ion thermal diffusivities are reduced in the core. The suppressed central transport of the IL–mode remains after the edge transport barrier forms in the IH-mode phase. Direct measurements of the fully stripped neon $10^+$ density profile is made with a calibrated charge exchange recombination (CER) system. The neon $10^+$ fraction is always less than 1% (normalized to the electron density). The radial electric field can also be computed from the CER measurements on DIII–D. The shear in the E×B velocity is found to exceed the maximum growth rate of the ion temperature gradient (ITG) mode in the core region, a condition for the suppression of turbulent transport. This agrees with the reduced power balance thermal diffusivities near the magnetic axis. In the outer half of the plasma the high wavenumber electron temperature gradient mode (ETG) is the dominant instability. The neon linear response is found to be stabilizing to the ETG modes. The electron thermal transport is observed to have an inverse correlation with the neon concentration in agreement with the ETG growth rate trend.

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†Lawrence Livermore National Laboratory, Livermore, California.
‡University of California, San Diego, California.

# The dissipative Budden problem with spatially non-uniform damping *

E. R. Tracy
*Physics Department, College of Wm. & Mary, Williamsburg, VA 23187-8795*

A. N. Kaufman, J. J. Morehead, A. J. Brizard
*Lawrence Berkeley National Laboratory, Berkeley, CA 94720*

In a two-ion-species plasma in a nonuniform magnetic field, the ion-hybrid mode can be generated by linear conversion from an incident magnetosonic wave. This hybrid wave, which could be useful for current drive and shaping, for heating, or for alpha-channeling, may be strongly damped by gyroresonance with fusion alphas in a DT plasma. In earlier work [1], we have obtained an analytic solution of the governing wave equations, using a slab model, and treating the gyroresonant damping as spatially uniform, which is a reasonable model for an alpha distribution which is isotropic and monoenergetic, appropriate for neonatal alphas. We showed that, for expected parameters in a fusion plasma, the hybrid mode is extinguished by damping, resulting in zero reflection of the incident magnetosonic wave. In the present work, we study the consequences of a more realistic spatial nonuniformity of the damping coefficient, resulting from a slowing-down distribution of the alphas. We show that, as expected, only the spatial region near the conversion layer is effective in damping the hybrid mode. We demonstrate that the reflection coefficient is a sensitive diagnostic for the magnitude of the hybrid damping.

## References

[1] A. N. Kaufman, J. J. Morehead, A. J. Brizard & E. R. Tracy, in *12th Topical Conference on Radio Frequency Power in Plasmas*, P. M. Ryan and T. Intrator, eds., AIP Conference Proceedings 403.

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# Unifying Role of Radial Electric Field Shear in Supershot Scalings with Isotopic Mass, Heating Power, and Edge Recycling

D. R. Ernst, B. Coppi,* M. Porkolab,* S. D. Scott
*Princeton University Plasma Physics Laboratory*
*P.O. Box 451, MS34, Princeton, NJ 08543 USA*

A model describing toroidal ITG modes with radial electric field shear is developed and tested with an in-depth analysis of TFTR data[1, 2]. The model departs from previous work primarily through the use of a neoclassical radial electric field $E_r$, which is calculated self-consistently, together with the ion temperature profile. Large notch features in the measured toroidal velocity profiles of impurity ions are consistently explained by the same neoclassical calculation[1, 2] which provides $E_r$. Improved analytical expressions for the neoclassical velocities reproduce more accurate numerical results while making possible efficient nonlinear transport simulations.

Enhanced confinement regimes, e.g., the H-Mode, VH-Mode, ERS, NCS, and High-$\beta_P$ Mode, are generally attained through sharp transitions from regimes of poorer confinement. The TFTR supershot, on the other hand, departs continuously from the L-Mode regime. This transitionless improvement contributes to a high degree of reproducibility and a prolonged steady state. At the same time, supershot plasmas exhibit favorable scaling with ion temperature and isotopic mass, and have a strong dependence of core confinement on edge recycling typical of other enhanced confinement regimes.

Turbulence suppression by radial electric field shear is shown to play a unifying role in the enhanced confinement trends of supershot plasmas. While unimportant at the lowest heating powers, this effect doubles the core ion temperature at moderately high heating powers. First, the confinement trends are described through the expedient criterion that the radial electric field shearing rate and maximum linear growth rate of the toroidal ion temperature gradient (ITG) instability are approximately equal in the core. The latter is evaluated for the relevant scenario where the ion temperature is much greater than the electron temperature and its gradient is relatively strong. This criterion is formulated analytically and integrated inward from the half-radius, reproducing the ion temperature profile without relying on estimates of the nonlinear saturation of turbulence. Second, nonlinear calculations that simultaneously evaluate the radial electric field, ion temperature, and turbulent saturation of toroidal ITG modes are carried out. These extend the model of Ref. [3] using an approximation based on toroidal gyrofluid simulations[4], together with a neoclassical radial electric field.

The ion temperature profiles of over sixty TFTR supershot experiments are reproduced by the model, encompassing large variations with heating power, isotopic mass, density peakedness, lithium conditioning, toroidal rotation, and perturbation experiments.

## References

[1] D. R. Ernst, Ph.D. thesis, Physics Dept., Mass. Inst. of Technology, 1997.
[2] D. R. Ernst *et al.*, Phys. Plasmas **5**, (1998).
[3] M. Kotschenreuther, W. Dorland, M. Beer, and G. W. Hammett, Phys. Plasmas **2**, 2381 (1995).
[4] R. E. Waltz, G. D. Kerbel, and J. Milovich, Phys. Plasmas **1**, 2229 (1994).

*Mass. Inst. of Technology, Cambridge, MA 02139

# NUMERICAL SIMULATION MAGNETIC RECONNECTION IN THE MRX EXPERIMENT

D. D. Schnack and A. Tarditi
Science Applications International Corp.
10260 Campus Pt. Dr.
San Diego, CA 92121.

The TRIM code[1] is used to perform numerical simulation of the MRX experiment[2]. MRX is a basic plasma physics experiment designed to study magnetic reconnection phenomena in a controlled setting. The Lundquist number $S = \tau_R/\tau_A$ can be varied in a range $10 < S < 3 \times 10^3$, which is directly accessible by numerical simulation. The relatively low temperatures also allow the insertion of probes to measure the dynamical properties of the reconnection layer. The geometry of the initial experimental setup is two-dimensional and axially symmetric. The effects of magnetic helicity can be studied, and the boundary conditions controlling the reconnection can be varied.

The TRIM code uses an unstructured, adaptive grid of triangular cells to represent the poloidal plane. This allows the exact geometry of the MRX experiment, including the non-simply connected flux cores, to be captured in the simulations. Poloidal and toroidal voltages are applied at the flux core boundaries to simulate "push" and "pull" modes of operation. Both null injection (zero toroidal field) and co-injection (uni-directional toroidal field) cases are studied. Both zero-beta and finite-beta models are used. Adaptive mesh refinement is used to enhance the resolution near the reconnection layer. In the axisymmetric model, secondary magnetic islands are formed during the pull reconnection phase with no toroidal field. Comparison with experimental results are given, and a scaling of reconnection rate with Lundquist number is presented.

1. D. D. Schnack, I. Lottati, Z. Mikić and P. Satyanarayana, to appear in J. Comp. Phys. (1998).
2. M. Yamada, H. Ji, T. A. Carter, S. C. Hsu, R. M. Kulsrud, N. L. Bretz, F. C. Jobes, Y. Ono, M. Katsurai, T.-H. Watanabe, T. Sato, and T. Hayashi, in*Proc. Sixteenth IAEA Fusion Energy Conference* (Vienna: IAEA), paper IAEA-CN-64/CP-19 (1996).

# Convergence properties of a 3D non-linear gyrokinetic $\delta f$ code in magnetic coordinates*

T. M. Tran, K. Appert, M. Fivaz, J. Vaclavik

*CRPP, Association Euratom-Confédération Suisse Ecole Polytechnique Fédérale de Lausanne, Switzerland*

A 3D nonlinear global gyrokinetic $\delta f$ [1] code has been developed, using a finite element representation [2] for the fields and the particle markers. Linear, quadratic and cubic splines in the magnetic coordinates $(s, \chi, \phi)$ are chosen and expected to reduce the numerical noise associated with the non-smoothness of the discretized electric fields. In the present version, the particles and the associated weigths are pushed in the $(R, Z, \phi)$ space in order to simplify the gyro-averaging procedure, while the quasi-neutrality equation is solved in the $(s, \chi, \phi)$ coordinates, using an iterative method. The other feature of the code is the integration of numerically calculated MHD equilibrium [3], in order to perform non-linear gyrokinetic simulations with realistic tokamak equilibria.

The first simulations using this code are aimed (1) at validating the numerical model, and (2) at assessing the feasibility of realistic global non-linear simulations using the present day super-computers such as the Cray T3E. The convergence of the numerical model is studied for a plasma with a minor radius $a \simeq 100\rho_i$ and an aspect ratio 3. We find that the quadratic splines bring significantly better conservation properties than the linear ones, while little is gained by using the cubic splines. We also find that the measured anomalous transport depends critically on the number of particles used. The numerical algorithm and the diagnostics implemented for the convergence studies will be described in detail.

## References

[1] G. Hu, J.A. Krommes, *Phys. Plasmas 1*, 863 (1994)
[2] M. Fivaz et al., to appear in *Comp. Phys. Comm.*
[3] H. Lutjens et al., *Comp. Phys. Comm. 69*, 287 (1992)

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# Effect of phase-shifts on feedback stabilization schemes for the control of the resistive shell mode in tokamaks*

Edmund P. Yu
*Institute for Fusion Studies, UT Austin*

Richard Fitzpatrick
*Institute for Fusion Studies, UT Austin*

A formalism has been developed for optimizing the design of feedback coils placed around a tokamak plasma in order to control the resistive shell mode. [1] Feedback schemes for controlling the resistive shell mode fail whenever the distortion of the mode structure by the currents flowing around the feedback coils becomes too strong, in which case the mode escapes through the gaps between the coils, or through the centres of the coils. The main aim of the optimization process is to reduce this distortion by minimizing the coupling of different Fourier harmonics by the feedback currents. The optimal configuration is to have many, large, overlapping coils in the poloidal direction. Configurations in which there are only a few coils in the poloidal direction only operate effectively when the resistive shell mode is weakly unstable.

The type of feedback scheme under investigation consists of an array of rectangular saddle coils placed immediately outside the shell. Each coil is accompanied by an equal area flux-loop which detects magnetic flux escaping through the coil. The feedback algorithm is simply that the feedback current circulating around the coil is proportional to *minus* the flux detected by the flux-loop.

We investigate the effect of *phase-shifts* between the feedback loops and the flux-loops. These could be produced, for example, by displacing the flux-loops toroidally with respect to the feedback loops. Phase-shifts are inevitable in any real-life feedback system. Thus, it is important that the feedback algorithm should be relatively robust to phase-shifts. Phase-shifts are generally found to have a beneficial effect: in some cases, greatly reducing the critical feedback gain required to stabilize the resistive shell mode. The main reason for this is that phase-shifts reduce the coupling of different Fourier harmonics by the feedback currents. Naively, one would expect that phase-shifts greater than 90° would send the system into positive feedback: *i.e.*, such that the growth-rate *increases* with increasing gain. At low feedback gain, this is indeed the case. However, at somewhat higher gain the feedback induced distortion of the mode sends the system back into negative feedback. Thus, it is actually possible to stabilize the mode with phase-shifts greater than 90°. The maximum phase-shift which can be applied at high gain is limited by a mode which is best described as an instability of the feedback system.

The fact that phase-shifts generally have a beneficial effect on feedback stabilization schemes for the resistive shell mode—even, in some circumstances, phase-shifts greater than 90°—gives us some measure of confidence that such systems can be realized in practice.

## References

[1] R. Fitzpatrick, *Optimal design of feedback coils for the control of external modes in tokamaks*, to appear in Physics of Plasmas.

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# COMPARISON OF FLUX TUBE AND GLOBAL GYROKINETIC SIMULATIONS

CHARLSON KIM and SCOTT PARKER
*DEPARTMENT OF PHYSICS, UNIVERSITY OF COLORADO , BOULDER*

The two most widely used computational domains of tokamak turbulence simulations are global and flux-tube. Full annulus simulations do not reduce the computational plasma volume significantly and have difficulty in implementation of radial boundary conditions. Global codes model the entire volume of the tokamak, neglecting edge physics, while flux-tube codes model a small subspace; a magnetic flux-tube following a field line. The advantages of flux-tube codes are higher spatial resolution or the capability of simulating a larger tokamak plasma for a given amount of computational resources. However, there have been past discrepancies and qualitative differences between global and flux-tube codes that have brought flux-tube models under some scrutiny. [1,2]

We report on the resolution of some of these discrepancies, in particular, the presence of global radial modes and lower flux levels in global gyrokinetic simulations. All results use the usual ITG paradigm, assuming adiabatic electrons, and zero $\beta$ magnetic equilibria. We will show results comparing three simulations: global with profile variation and radial modes, flux-tube with radially periodic boundary conditions with profile variation, and flux-tube bounded in the radial direction with profile variation. We will also compare flux-tube cases with and without profile variation. It is seen that the introduction of significant profile variation (relative to radial box size) results in the same behavior exhibited by global simulations. These include the global radial modes, similar time histories and heat flux levels. Comparison of the various flux-tube cases shows that profile variation is the dominant factor in the generation of the global radial modes and not the radial boundary conditions. In addition, large global simulations with 33.5 million particles, a minor radius of 160 $\rho_i$, and weak profile variation show a broken up, more turbulent radial mode spectra.

## References

[1] J. Cummings, PhD Thesis, 1995
[2] H. E. Mynick and S. E. Parker, Phys. Plasma **2**, 1217 (1995)

# Study of Resistive Wall Mode in Tokamak Plasma: Implications to Feedback Stabilization*

Dae-Young Lee
*Korea Advanced Institute of Science and Technology*

Stabilization of the kink mode is crucial in achieving high $\beta$ plasmas in tokamaks. The ideal kink is not completely stabilized by the external resistive walls such as passive plates or vacuum vessel unless other physical mechanisms [1] or external stabilization tools [2, 3] are added. It instead becomes the so-called resistive wall mode which grows on a slower time scale of the resistivity of the wall. This still needs to be stabilized for the long pulse or steady state operations in the future advanced machines.

In this presentation the resistive wall mode is first examined in the cylindrical plasma. Effect of plasma rotation [1] on the mode is discussed. Rotation may or may not stabilize the resistive wall mode depending on situations. There may be some possibility to suppress the resistive wall mode by external feedback coils [2]. Discussions on such a possibility are also given, in particular in the presence of plasma rotation. Suggestions for the design of feedback coils in the proposed tokamak of Korea Superconducting Tokamak Advanced Research are given as well.

## References

[1] A. Bonderson and D.J. Ward, Phys. Rev. Lett. **72**, 2709, (1994).
[2] R. Fitzpatrick and T.H. Jensen, Phys. Plasmas **3**, 2641 (1996).
[3] T.H. Jensen and R. Fizpatrick, Phys. Plasmas **4**, 2997 (1997).

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# Progress on Iterative Coupling of Uedge/Monte-Carlo Simulations*

L. L. LoDestro, M. E. Rensink, T. D. Rognlien
*Lawrence Livermore National Laboratory*

One approach to accurate modelling of edge-plasma interactions with neutral species in intermediate or varying mean-free-path regimes is to employ a Monte-Carlo description of the neutrals, coupled to a fluid description of the plasma. This approach has been carried out by several authors and reported previously.[1]

Successful calculations to date have been carried out with numerically explicit time-stepping coupling schemes, and are therefore constrained to operate on the shortest (generally the charge-exchange) time-scale, although the solution itself does not vary on this scale. The number of time-steps required for finding steady states in Cartesian slab geometry is typically $\sim 10^3$; DIII simulations require even more steps ($> 5$K), and exhibit prolonged slow-time-scale behavoir.

A variety of techniques for significantly reducing the computation time of fluid/Monte-Carlo coupled problems were proposed in Ref. [2]. One method in particular, based on straightforward relaxation-stabilized functional iteration in concert with UEDGE's fully implicit fluid-solver, was introduced in some detail. Initial applications (with the UEDGE neutral-fluid model used to represent a Monte-Carlo simulation in the interests of speed), indicated that although stability of the iteration cycle appears to be readily obtained, asymptotic convergence rates are poor. In this paper, we develop a scheme to treat the latter problem. Results of a range of coupled calculations using the UEDGE neutral-fluid model will be used to assess the overall performance of the method, and first results coupling to the Monte-Carlo neutrals code EIRENE will be presented.

## References

[1] R. Schneider et al., J. Nucl. Mat. **196-198** (1992) 810; D. P. Coster et al., Contr. Plasma Phys. **36** (1996) 150; M. E. Rensink et al., 6th Int. Workshop on P.E.T., Oxford, (1997), P.04; M. E. Rensink et al., Bull. Amer. Phys. Soc. **42**, No. 10 (1997), paper hTupP2.07.

[2] L. L. LoDestro et al., Bull. Amer. Phys. Soc. **42**, No. 10 (1997), paper oThaP1.10.

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# Stability of Tearing Modes for Finite Mercier Index

F. L. Waelbroeck
*Institute for Fusion Studies, University of Texas*

J. M. Greene
*General Atomics, San Diego*

Access to the regime of second stability is controlled by regions where the Mercier stability index, $D_I$, is negative and of magnitude comparable to unity. For $D_I \leq -1$, however, the conventional theory of tearing mode stability fails. This failure manifests itself by a sequence of singularities in the magnetostatic matching data $\Delta'$ describing the free energy available to drive the mode.[1] The singularities occur for $D_I = -j^2$, where $j$ is a whole number. At the same values of $D_I$, the resistive layer matching data $\Delta(\gamma)$ vanishes. Here $\gamma$ is the growth rate of the instability. $\Delta(\gamma)$ behaves similarly for ideal ballooning modes near marginal stability.

For ideal ballooning modes, we show that the singularity at $D_I = -1$ is resolved by extending the asymptotic analysis to higher order. The dispersion relation is

$$\left(\frac{\gamma}{4s\omega_A}\right)^2 \log\left(\frac{\gamma}{4s\omega_A}\right) = \frac{k_\perp^2}{\hat{\Delta}'}$$

where $s$ is the magnetic shear, $k_\perp$ is the perpendicular wavevector,

$$\hat{\Delta}' = \lim_{D_I \to -1}\left[\Delta'(D_I) - \frac{R_1}{D_I + 1}\right]$$

is a regularized $\Delta'$ and $R_1$ is the residue of the pole. This may be compared to the low beta dispersion relation that describes the internal kink mode for finite shear $s$,

$$\frac{\gamma}{s\omega_A} = -\frac{\pi}{2}\frac{k_\perp}{\Delta'} = -\frac{2\pi}{s^2}\delta\hat{W},$$

where $\delta\hat{W}$ is the normalized magnetohydrodynamic energy. Note that the above dispersion relations apply only to modes near marginal stability, or with sub-Alfvénic growth rates.

For ideal modes, the breakdown of the conventional asymptotic matching procedure occurs when inertial effects become important outside the layer. In the resistive case, similarly, the breakdown occurs when resistive effects become important in the matching region. This may be seen by considering the form of the dispersion relation valid for $DI > -1$,

$$\Delta' \propto \left(\frac{V_0}{X_0}\right)^{2\mu} sin(\mu\pi)\left(\frac{\gamma}{\gamma_R}\right)^{\mu}$$

where $\mu = (-D_I)^{1/2}$, and $X_0$, $\gamma_R$ are normalization factors that scale with the one third power of the resistivity. Note that the right-hand side, representing $\Delta(\gamma)$, vanishes for $D_I = -j^2$. For $D_I \to -1$, however, the growth rate scales with the first power of the resistivity, which also calls into question the basic assumptions of tearing mode theory. The singularity in the growth rate can again be resolved by extending the asymptotic analysis to higher order.

## References

[1] A. D. Miller and R. L. Dewar, J. Comp. Phys. **66**, 356 (1986).

# Theory of Enhanced Reversed Shear Mode+

K. C. Shaing, A. Y. Aydemir, W. A. Houlberg*, and M. C. Zarnstorff#
Institute for Fusion Studies
University of Texas-Austin

Recent experimental observation in TFTR [ R. E. Bell, Bull. Am. Phys. Soc. **42**, 1945(1997)] indicates that enhanced reversed shear (ERS) mode is triggered by a sudden increase in the magnitude of the radial electric field $E_r$ and followed by the turbulence suppression that leads to better confinement. This phenomenon implies that the bifurcation mechanism is in the momentum equation just like that in the H-mode theory. Here, we present a theory for ERS mode, based on the bifurcation of poloidal **ExB** rotation over the local maximum of the nonlinear viscosity and the subsequent turbulence suppression ( which is not the same as linear instability stabilization ) by the radial gradient of the **ExB** and the diamagnetic angular velocity. The theory basically is an extension of the H-mode theory to the core region. The mechanism that drives $U_{pm}$, defined as a combination of parallel flow speed and **ExB** speed, away from its standard neoclassical value is the viscosity associated with the additional ion loss beyond the conventional neoclassical flux. The theory shows that $U_{pm}$ bifurcates from a value smaller than unity to a value larger than unity. The bifurcated value of $U_{pm}$ is in good agreement with the experimental observation.

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*ORNL
#PPPL

# Simulation of Alpha-driven Toroidicity-Induced Alfven Eigenmodes in TFTR*

Yang Chen, Roscoe White, Guoyong Fu, Raffi Nazikian
*Princeton Plasma Physics Laboratory*

We will first summarize a numerical scheme for the simulation of the nonlinear evolution of Toroidicity-Induced Alfvén eigenmodes in a tokamak, driven unstable by energetic particles. In this scheme, the TAE modes are described by time-varying amplitudes and phases with fixed spatial structure, and the energetic particles are described by the drift-kinetic equation with various collisional effects included. The guiding center Hamiltonian code ORBIT[1] and a recently developed $\delta f$ method[2] are used to carry out the simulation. Emphasis will be on the simulation of the pure alpha-driven TAEs recently observed on Tokamak Fusion Test Reactor[3]. Input parameters to the simulation are based on direct measurement or transport analysis. Simulation results, such as the saturation amplitude, mode induced alpha loss, and possible nonlinear frequency modulation, will be compared with observations.

## References

[1] R. White, M. Chance, Phys. Fluids,27,2455(1984).
[2] Y. Chen, R. White, Phy. Plasmas,4(10), 3591(1997).
[3] R. Nazikian et. al., Phys. Rev. Lett. Vol.78, No. 15, 2976(1997).

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# $\delta f$ Simulations of Neoclassical Transport in Stellarator *

W. M. Tang, H. E. Mynick, Z. Lin, R. B. White
*Princeton Plasma Physics Laboratory*

A 3D gyrokinetic neoclassical simulation code based on the $\delta f$ scheme has provided realistic assessment of the neoclassical transport properties in magnetically confined plasmas [1]. Recently, the very important capability for treating general MHD equilibria has been implemented by utilizing magnetic coordinates [2] and Hamiltonian guiding center equations of motion [3]. These new features enable us to study neoclassical transport in both advanced axisymmetric devices as well as stellarators. An application of significant relevance involves the assessment of the neoclassical transport in quasi-axisymmetric (QA) stellarators currently under design. Initial investigations have focused on the bootstrap current which can affect the rotational transform and the width of magnetic islands. In addition, we will carry out self-consistent simulations of the ambipolar potential due to the difference between the particle diffusivities of electron and ion species in the absence of toroidal symmetry. Monte Carlo simulation results [4] indicate that the favorable thermal confinement in some QA devices relies heavily on such a radial electric field. Therefore, an accurate prediction of the ambipolar potential is crucial in both the machine design and operation aspects of advanced stellarators.

## References

[1] LIN, Z., TANG, W. M, LEE, W. W. (1997), *Phys. Rev. Lett.* **78**, 456.
[2] BOOZER, A. H., (1981), *Phys. Fluid* **24**, 1999.
[3] WHITE, R. B., (1990), *Phys. Fluid B* **2**, 845.
[4] MYNICK, H. E. (1997), *Plasmas Physics Reports* **23**, 547.

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# Excitation of Contained Modes by Energetic Particles*

G. Penn, B. Coppi
*Massachusetts Institute of Technology, Cambridge MA 02139*

C. Riconda
*JET Joint Undertaking, Abingdon, OXON, U.K.*

In experiments with fusing plasmas, enhanced radiation emission at harmonics of the ion cyclotron frequency of the fusion products has been observed[1, 2, 3]. In fact this radiation is strongly correlated with the neutron flux. A model for this emission has been developed[4] based upon the interaction of fusion products with a class of collective modes of the plasma having radially localized solutions that we refer to as "contained modes". These modes can have frequencies on the order of or greater than the ion cyclotron frequency, and their local properties have the characteristics of magnetosonic-whistler waves. The conditions under which energetic particles from fusion or an external source will excite these modes is evaluated for a toroidal configuration[5]. Emphasis is placed on the dependence of the growth rate on finite Larmor radius effects of the fusion products,[6] and the characteristics of the particle distribution function. In particular, a sufficient degree of velocity space anisotropy in the energetic particle distribution is required in order to have a positive growth rate for realistic parameters.

## References

[1] JET Team, *Phys. Fluids* **B5** (1993) 3.
[2] G. A. Cottrell, V. P. Bhatnagar, O. Da Costa et al. , *Nucl.Fusion* **33** (1993) 1365.
[3] S. Cauffman, R. Majeski, *Rev. Sci. Instrum.* **66** (1995) 817.
[4] B. Coppi, *Fusion Tech.* **25** (1994) 326.
[5] B. Coppi, G. Penn and C. Riconda, *Ann. Physics* **261**, 117 (1997).
[6] Y. P. Chen, S. T. Tsai, *Phys. Plasmas* **2** (1995) 3049.

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# Theory of Simulation Thermostats†

John A. Krommes
*Plasma Physics Laboratory, Princeton University*
*P. O. Box 451, Princeton, NJ 08543–0451*

The theoretical and practical issues underlying the use of thermostats for collisionless $\delta f$ particle simulations [1] are discussed. Those include

- derivation and interpretation of the generic entropy-balance equation relating flux and dissipation;
- the significance of, and contrast between (1) the Liouville theorem for conventional collisionless $\delta f$ and (2) the phase-space volume contraction in dissipative systems;
- the importance of true steady states in maintaining low sampling noise at long times;
- deep analogies between (1) spatially homogeneous methods for measuring thermal and other fluxes in nonequilibrium molecular dynamics (NEMD) simulations and (2) multiple-scale $\delta f$.

A well-known criticism of conventional collisionless $\delta f$ methods is that the mean-squared particle weight increases indefinitely at long times, calling into question the accuracy and even relevance of time-asymptotic measurements of fluxes $\Gamma$ (of, e.g., particles or heat). The proposed solution is the use of generalized thermostats to stabilize the weights. In NEMD, thermostats are used to hold fixed the kinetic energy (Gaussian thermostat) or the canonical temperature (Nosé–Hoover thermostat), which would otherwise increase as the system heats in response to the thermodynamic force driving the heat flow. In the $\delta f$ method, temperature is input as a parameter of the analytically specified background distribution and does not need to be thermostatted. However, if $\Gamma$ does not vanish, entropy (in the form of the mean-squared weight $W \doteq \langle w^2 \rangle$) increases without bound in the absence of explicit dissipation and is therefore a candidate for a generalized thermostat. The thermostatting algorithm modifies the usual equation for particle weight $w$ by adding a dynamical damping term that is constructed, at every time step, in such a way that $W$ is held fixed, either exactly or upon time averaging. The thermostatted $w$ equation is physically satisfying, having the form of a Langevin equation in which random excitation ($\delta f$ source term, proportional to profile gradient and random potential) is balanced by dynamical friction (the generalized thermostat). The procedure deliberately violates Liouville's theorem, just as would a faithful description of collisional processes. The inverse of the constrained value of $W$, a specified parameter, plays the role of a collision frequency $\nu$. Theoretically, $\Gamma$ should be independent of $\nu$ as $\nu \to 0$; this suggests an extrapolation procedure in which the steady-state $\Gamma$ can be inferred from several measurements of $\Gamma$ at finite values of $W$. The method may help to justify the common procedure of calculating $\Gamma$ from the first observed quasi-plateau; more rigorously, it provides a low-noise procedure for measuring $\Gamma$ at times that are indefinitely long.

## References

[1] J. A. Krommes, Thermostatted $\delta f$, *Bull. Am. Phys. Soc.*, 42:1982, 1997.

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# E × B shear suppression of turbulence by time-dependent $E_r$*

T. S. Hahm
*PPPL*

E × B shear suppression of turbulence is the most likely mechanism to be responsible for various forms of confinement enhancement[1, 2]. The E × B shearing rate in a shaped tokamak[3] has been derived under the assumption of slow time variation of $E_r$ (much slower than the eddy turn-over time), and has been widely used for comparisons to experimental data which indeed show such slow time variation of the macroscopic $E_r$. On the other hand, there is accumulating evidence from nonlinear simulations[4] that E × B shear flow can be generated by turbulence[5]. Recent toroidal gyrofluid simulations[6] show that such E × B shear flow contains significant components with radial scale and frequency comparable to those of the turbulence. The nonlinear theory in Ref. 3 is extended to include the fast time variation of the E×B shear flow and is therefore applicable to comparisons with the nonlinear simulation results. It is shown that the fast varying component is not effective in suppressing turbulence, since the flow shear pattern changes before the eddies get distorted. This also suggests the importance of the long term behavior of the fluctuation driven flow as emphasized in the recent work by Rosenbluth and Hinton[7].

## References

[1] K.H. Burrell, Phys. Plasmas **4**, 1499 (1997).
[2] E.J. Synakowski *et al.,* Phys. Plasmas **4**, 1736 (1997).
[3] T.S. Hahm and K.H. Burrell, Phys. Plasmas **2**, 1648 (1995).
[4] M. Beer *et al.,* Bull. Am. Phys. Soc. **37**, 1478 (1992),
W. Dorland *et al.,* Bull. Am. Phys. Soc. **37**, 1478 (1992),
R. Waltz *et al.,* Phys. Plasmas **1**, 2229 (1995),
A. Dimits *et al.,* Phys. Rev. Lett. **77**, 71 (1996).
[5] P.H. Diamond and Y.B. Kim, Phys. Fluids B **3**, 1626 (1991).
[6] M. Beer and G.W. Hammett, Private Communication (1997).
[7] M.N. Rosenbluth and F.L. Hinton, Phys. Rev. Lett. **80**, 724 (1998).

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# Compressible Alfven Turbulence in One Dimension

J. Fleischer
*University of California at San Diego, La Jolla, CA 92093*
P.H. Diamond
*University of California at San Diego, La Jolla, CA 92093*

Burgers' equation for 1-D compressible fluid dynamics is extended to include the effects of magnetic pressure. The resulting system is the simplest model which allows for Alfvenization, i.e. energy transfer between the fluid and the magnetic field. For the special case of equal fluid viscosity and magnetic diffusivity, the system is completely integrable, reducing to two decoupled Burgers' equations in the characteristic (Elsasser) variables $v \pm v_A$. For arbitrary diffusivities, renormalized perturbation theory is used to calculate the effective transport coefficients for forced Burgerlence. It is shown that energy equi-dissipation, not equipartition, is fundamental to the turbulent state. Both energy and dissipation are localized to shock-like structures, in which wave steepening is inhibited by small-scale forcing and by pressure back-reaction. The velocity structures lead to an asymmetric velocity pdf, as in Burgers' turbulence. The magnetic structures, however,! are symmetrically distributed. For Gaussian-correlated noise sources, asymptotic forms for the pdf's are derived from a Fokker-Planck equation. It is found that smooth regions of flow are distributed super-exponentially, while the shock-like structures have algebraically decaying pdf's. The implications for more complicated (i.e. higher-dimensional) MHD phenomena are also discussed.

# Nonlinear Electron Acceleration by RF and Random Fields*

J.A. Tataronis

*University of Wisconsin, 1500 Engineering DR, Madison, WI 53706*

V. Petržílka

*Institute of Plasma Physics, P.O. Box 17, 182 11 Praha 8, Czech Republic*

This study treats enhancement of nonlinear RF electron acceleration in fusion plasmas. Enhanced electron acceleration leads to stationary electric fields that can strongly alter plasma properties. Two modes of RF plasma waves are specifically treated, the lower hybrid (LH) mode and the lower frequency helicon mode.

In the LH range of frequencies, induced random electric fields are key to enhanced electron acceleration [1]. Strong random electric fields are generated in front of the exciting waveguide array principally through two mechanisms: (1) *nonlinear* parametric decay, and (2) scattering of waves from plasma density fluctuations. In the present study, it has been found that spontaneously excited random electric fields significantly enhance the electron acceleration near the LH antenna. Moreover, the width of the acceleration layer is increased by the random fields. Because of the enhanced acceleration, electrons are expelled from the grill region. This results in strong radial and toroidal stationary electric fields that induce a plasma vortex front of the LH grill [2]. The vortex, which results in poloidal plasma inhomogeneities in front of the grill, can significantly impact RF wave coupling and thermal loading of the walls. There is evidence of these induced vortices from the ASDEX [3] and TdeV [4] tokamak experiments.

An analogous acceleration process in the lower frequency helicon mode [5] is also explored. This mode is important because it can be effectively used for efficient plasma generation in fusion devices [6]. As will be demonstrated, this efficiency is considerably enhanced through *nonlinear* acceleration of electrons. Previous theoretical modeling of electron acceleration by the helicon mode in terms of *linear* Landau damping of a single wave, or even of a wave with a broad spectrum of phase velocities, does not completely explain experimental data [7]. Our proposal is that nonlinear processes play a very important role. In the present study real antennae that radiate wave fields with a distribution of RF phase velocities are treated. Numerical simulations of the resulting nonlinear electron acceleration point to the importance of *cascade, stepwise, nonlinear, electron trapping* by wave Fourier components with higher and higher phase velocities. The role of random fields in the acceleration process is also demonstrated. The random fields in helicon plasmas may arise from nonlinear processes such as high harmonic field generation and also from wave reflection from plasma boundaries. The resulting enhanced dissipation by nonlinear electron acceleration will enhance RF dissipation and thereby enhance the efficiency of plasma production.

## References

[1] J. A. Tataronis, V. Petržílka, V. Fuchs, and L. Krlín: Sherwood'97 Conf., paper 1C28.
[2] R.W. Motley et al., Phys. Rev. Letts. **43** (1979) 1799.
[3] V. Petržílka, F. Leuterer, F. Soeldner et al.: Nuclear Fusion **31** (1991) 1758.
[4] Y. Demers, private communication (1998).
[5] V. Petržílka and J. A. Tataronis: Bull. Am. Phys. Soc 42 (No. 10) 1930.
[6] B. D. Blackwell et al.: H-1 Project, Int. Stellarator Workshop, Madrid 1995, p. 26.
[7] B. Fischer, M. Krämer and Th. Enk: Plasma Phys. Controlled Fusion **36** (1994) 2003.

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# Nonlinear Simulation of Kinetic Instabilities in Tokamaks

J. Candy

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

A comprehensive numerical method to compute the nonlinear evolution of kinetic instabilities in general tokamak geometry has been developed [1, 2]. The scope of the method is wide enough to describe the nonlinear evolution of various Alfvén eigenmodes (AE) and fishbone modes. The fast ion current is computed using a $\delta f$ particle algorithm – for nonstandard particle orbits in general geometry – and the self-consistent effect of this current on the mode amplitude is then determined by an operator technique [2, 3]. The MHD wave-wave nonlinearity is neglected, but is known to be weak in the case of TAE and diamagnetic fishbone modes. The nonlinear code has been extensively benchmarked in the linear regime against the general-geometry CASTOR-K code [4], and a variety of different machines and instability scenarios have been successfully simulated:

1. *Diamagnetic (perturbative) as well as precessional drift (nonperturbative) fishbones in JET ICRH-heated plasmas, PDX beam-heated [5], and ITER-like burning plasmas.* Loss/redistribution calculations for these modes correlate with experiment – specifically, significant losses in PDX, and strong redistribution without loss in JET. Strong alpha redistribution due to fishbones is predicted for ITER-like devices. The large nonlinear downshift (chirp) in frequency which accompanies mode saturation has been reproduced self-consistently.

2. *Moderate-$n$ TAE modes in JET driven by both trapped ICRH ions and by passing DT-produced alphas.* Enhancement of the nonlinear saturation level due to resonance overlap has been predicted for these plasmas [4]. However, particle transport is found to be insignificant.

3. *Comprehensive simulations of the high-$n$, alpha-particle-driven core-localized TAE instability [2, 6] in ITER.* Even for scenarios in which the linear growth rates were ten times higher than expected values, no alphas were lost and redistribution was negligible.

This is the most modern tool available to simulate the self-consistent anomalous transport of fast ions in tokamak plasmas caused by unstable, discrete plasma modes. Software to distribute the computational workload in parallel to a pool of N client workstations has also been developed. Each client performs a fraction of the computation using an identical C++ code, with the overall simulation managed by a central Java-based server [for multithreading].

## References

[1] J. Candy, J. Comput. Phys. **129** 160 (1996).
[2] J. Candy, H.L. Berk, D.N. Borba, G. Huysmans and W. Kerner, Phys. Plasmas. **4** 2597 (1997).
[3] B.N. Breizman, J. Candy, F. Porcelli and H.L. Berk, Phys. Plasmas, to be published.
[4] D. Borba, J. Candy, W. Kerner and S. Sharapov, JET–P(96)35, Oct. 1996; D. Borba, J. Candy, A. Fasoli, W. Kerner and S. Sharapov, JET–P(96)30, July 1996.
[5] J. Candy, F. Porcelli, B.N. Breizman and H.L. Berk, Proc. 24th EPS Conf. Berchtesgaden, Vol 21A III 1189 (1997).
[6] J. Candy and M.N. Rosenbluth, Nucl. Fusion **35**, 1069 (1995).

# Gyrokinetic Simulations in General Geometry *

Z. Lin, W. W. Lee, W. M. Tang, R. B. White
*Princeton Plasma Physics Laboratory*

A fully three-dimensional gyrokinetic particle code using magnetic coordinates has been developed and rigorously benchmarked. In addition to general geometry capabilities and superior particle noise properties, this new global code can treat equilibrium profile variation effects. This exciting new capability has been applied to the investigation of ion-temperature-gradient turbulence in toroidal geometry. Using representative DIII-D $H$-mode plasmas parameters, simulation results indicate that the well-converged ion heat conductivity obtained is close to the experimental value. The coherent nonlinear mode history indicates a weak turbulence regime. Our results also support the important conclusion that sheared flows can significantly reduce the turbulent transport. In order to understand this key process, the dynamics of fluctuation-driven sheared $E \times B$ flows have been analyzed. Linear flow damping simulations were first carried out and found to exhibit a finite residual from an initial flow perturbation and the generation of poloidal flow from a perturbation that is non-symmetric in the poloidal angle. Associated nonlinear simulations reveal a radially global structure of the self-generated $E \times B$ flow. These simulations are carried out using both global and annular geometry with a variety of boundary conditions to address the issue of validity of local simulations in studying global energy confinement in tokamaks.

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# The Earth's Magnetosphere at High Reynolds Number

Joseph E. Borovsky
*Los Alamos National Laboratory*

An overview is given of the Earth's magnetosphere: where the plasmas come from, where they go, and what some of the outstanding questions are. Then two high-Reynolds number flows are examined: one in a high-beta plasma and one in a low-beta plasma. The high-beta case involves the plasma sheet in the magnetotail, where the flow appears to be an MHD turbulence with very large distortions of the ambient magnetic field. The low-beta case involves the plasmasphere in the dipole region, where the $E \times B$ drift of this cold, high-density plasma leads to a highly structured flow.

# Existence of ion temperature gradient driven shear Alfvén instabilities in tokamaks

F. Zonca
*Associazione Euratom-ENEA sulla Fusione*

L. Chen, J.Q. Dong
*Department of Physics and Astronomy, University of California, Irvine*

R.A. Santoro
*Naval Research Laboratory, Washington, D.C.*

In the present work we address the issue of whether shear Alfvén waves may be destabilized by the free energy of thermal particles for $\alpha(\beta) < \alpha_{crit}(\beta_{crit})$, where $\beta$ is the ratio between plasma and magnetic field pressures, $\alpha = -R_0 q^2 \beta'$, and the *critical* values $\alpha_{crit}$ and $\beta_{crit}$ refer to the marginal stability boundary of ideal ballooning modes.

In a tokamak plasma, shear Alfvén (s.A.) waves are generally characterized by a continuous spectrum with gaps, due to *lattice* symmetry breaking. For low-frequency, $|\omega| \ll |\omega_A| \equiv |v_A/qR_0|$, it has been shown that the s.A. continuum can become *unstable* due to finite $\nabla T_i$ [1]. However, introducing finite ion Larmor radius (FLR) and finite drift-orbit width (FOW) effects, the *unstable continuum* is *discretized* and, as a result, it may be shown that there exist unstable Alfvénic $\nabla T_i$ eigenmodes (AITG).

Using an $(s, \alpha)$ model equilibrium for tokamak plasmas with shifted circular magnetic flux surfaces, we derive a set of integral eigenmode equations which allow us to handle arbitrary $k_\perp \rho_i$ (FLR) and $k_\perp \rho_d$ (FOW). Numerical solutions of the coupled integral equations for the two fields $\left(\delta\phi, \delta A_{\|}\right)$ are discussed, showing that the AITG instability is actually stronger than the usual electrostatic ITG for $0.4 \div 0.5 < \alpha/\alpha_{crit} < 1$. Comparisons with the results of a reduced 4th-order differential system for $\left(\delta\phi, \delta A_{\|}\right)$, derived analytically, will also be presented.

## References

[1] F. Zonca, L. Chen and R.A. Santoro, PPCF **38**, 2011 (1996).

# Gyrokinetic Theory and Computational Methods for Electromagnetic Modes in Tokamaks*

H. Qin, W. M. Tang, G. Rewoldt
*Princeton Plasma Physics Laboratory, Princeton University*

Using a newly developed gyrokinetic formalism and computational methods for arbitrary wavelength electromagnetic modes, we have carried out kinetic studies of internal kink modes and TAE modes. The system of equations consists of the linear gyrokinetic equation, Poisson's equation, and the gyrokinetic moment equation which are derived using phase space Lagrangian Lie perturbation methods[1]. A computer algebra package for vector analysis in general coordinate systems is also utilized in the analytical derivation[2]. In tokamak geometries, the differential equations which need to be solved numerically can be cast into the configuration dimensions. This is accomplished by solving the linear gyrokinetic equation in terms of the perturbed fields, and substituting the solution for the distribution function back into Poisson's equation and the gyrokinetic moment equation. A two dimensional finite element code has been developed and tested[3, 4]. This fully kinetic approach enables selfconsistent investigations of kinetic effects, such as the influence of trapped particles, Landau damping, finite gyroradius, and hot particles, on the MHD modes. The results of including these kinetic effects for background plasma species on the internal kink mode and the TAE mode are presented. A generalized Ohm's law derived from our gyrokinetic formalism is also discussed.

## References

[1] H. Qin, W. M. Tang, and G. Rewoldt, to be published in Phys. Plasmas, April, 1998.
[2] H. Qin, W. M. Tang, and G. Rewoldt, Report PPPL-3267 (1997).
[3] R. Marchand, W. M. Tang, and G. Rewoldt, Phys. Fluids **23**, 1164 (1980).
[4] W. M. Tang and G. Rewoldt, Phys. Fluids B **5**, 2451 (1993).

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# Multidimensional theory of wave emission in a mode conversion region*

Yu. Krasniak, E.R. Tracy
*College of William & Mary, Williamsburg, VA 23187-8795*

A.N. Kaufman
*Lawrence Berkeley National Laboratory, Berkeley, CA 94720*

An important feature of non-uniform media is the possibility of linear mode conversion due to the near-degeneracy of the dispersion relations of two wave modes in localized region of the medium. The effects of mode conversion on wave emission have been a subject of discussion in several recent publications [1, 2]. In [2] a formal solution to this problem was presented which allows one to compute the far-field wave forms in arbitrary spatial dimensions and for arbitrary sources. Here we present further details of this solution, with particular emphasis given to the physical interpretation.

## References

[1] D. G. Swanson, *Rev. Mod. Phys.* **64** (1995) 837.
[2] Yu. Krasniak, E. R. Tracy and A. N. Kaufman, *Proceedings of the 12th Conference on RF power in plasmas*, AIP Conference Proceedings 403 (Savannah, GA, 1997).

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# Statistical model of the test particle transport in chaotic magnetic fields

Attila Montvai
*FOM Instituut voor Plasmafysica 'Rijnhuizen'*
*Associate EURATOM-FOM, Trilateral Euroregio Cluster,*
*P.O.Box 1207, 3430 BE Nieuwegein, The Netherlands*

Results of a detailed statistical analysis of local test particle drift velocity distributions and the resulting drift trajectories in a wide class of chaotic magnetic fields are reported. The investigations were carried out by defining chaotic magnetic fields of substantially varying statistical properties in a periodic cylinder (10 m length of one period, 0.5 m radius).

The implemented particle dynamics contained the local gradient- and curvature drift velocities, the local $[\vec{E} \times \vec{B}]$ drifts (using a prescribed, not self-consistent electrostatic field distribution) and a discretized model of the pitch-angle- and energy scattering processes.

Particle histories were evaluated by using randomly chosen initial conditions for the electron- and ion populations separately. The starting points of trajectories have been chosen in several cylindrical shells of 0.05 m thickness, centered around different values of the radius. Their density diminished quadratically with growing distance to the geometric axis. The individual particle energies followed Maxwellian distributions with mean energies derived from a quadratic temperature profile along the radius of the cylinder. (Peak values at the magnetic axis were: 1 keV electron- and 600 eV ion temperature.) Finally, equipartition of energy was assumed between the local parallel- and perpendicular (with respect the magnetic field) degrees of freedom.

In postprocessing the derived database methods of correlation- and factor analysis, structural equation modeling (also known in statistics as SEPATH method), nonparametric statistics, etc. were applied. Particular attention was paid to the interdependences of the local curvature-, gradient- and electric drift velocities, the local characteristics of the magnetic fields and the components of a tensorial quantity (analogous to that of the strain tensor in fluid dynamics) derived from the local components of the induction vector.

A consistent factor-structure has been found in the local characteristics of the drift processes. This structure remained stable against a wide range of variations in the statistical properties of the input magnetic field. Using the derived factors with eigenvalues larger than unity, a SEPATH model has been set up in order to arrive at a statistically efficient, predictive approximation of the transport coefficients. The resulting local heat conductivities showed variations as large as about one order of magnitude.

Observed values of the correlations between the strength of magnetic fluctuations and the local drift velocities were in the order of $r \sim 0.1$, whereas they were as high as $r \sim 0.7...0.8$ with respect to the components of the tensor, constructed by using the derivatives of the magnetic vector field. Collisionless heat conductivities showed a stronger than quadratic growth with growing amplitudes of the magnetic fluctuations. This result is incompatible with predictions of known models.

Finally, the evolution of the average distance of drifting electrons and the initial line of force (a key parameter in assessing the particle - field line decorrelation dynamics) indicated the presence of a strongly varying cross-field transport, which could be attributed to the presence of the chaotic structure.

# The Role of Flows in the Formation and Control of Internal Transport Barriers*

D. E. Newman, B. A. Carreras, D. Lopez-Bruna
*Oak Ridge National Laboratory*

P. H. Diamond
*University of California, San Diego*

Enhanced confinement regime in systems with reversed and weak central magnetic shear have been observed in a number of magnetic confinement devices [1, 2, 3]. A simple model [4, 5] incorporating the nonlinear coupling between the turbulent fluctuations and the sheared radial electric field is added to a more complete transport model. This enables us to investigate the dynamics of the transition to the enhanced confinement mode in these discharges. An intrinsically nonlinear radially coupled model is needed to explain the bifurcation to "enhanced confinement" from the regular reversed shear regime. In this simple model by incorporating both the instability growth rate profiles and particle/power deposition profiles a rich variety of transition dynamics are found. In the course of investigating the transitions, the models have illuminated potential methods for triggering and controlling these enhanced confinement regimes. Due to the importance of this enhanced confinement regime for fusion devices, a detailed investigation of the initiation dynamics with their concomitant thresholds are examined. In particular, recent work [R. Bell et al.] suggests that transient poloidal flows may play an important role in the natural triggering of some transitions. To investigate this within the context of the transition model, poloidal and toroidal flow evolution equations, driven both externally and via a self consistent Reynolds stress are added to the model. Some features similar to those seen experimentally are found in the model. This may suggest additional control mechanisms. Many of these potential control techniques exploit both the hysteresis intrinsic to these transitions and the transient nature of the transition itself. Some of these methods including current profile control, flow control, RF heating pellet injection will be discussed.

## References

[1] F. M. Levinton, M. C. Zarnstorff, S. H. Batha, M. Bell, R. E. Bell, R. V. Bundy, C. Bush, Z. Chang, E. Fredrickson, A. Janos, J. Manickam, A. Ramsey, S. A. Sabbagh, G. L. Schmidt, E. J. Synakowski, and G. Taylor, Phys. Rev. Lett. **75**, 4417 (1995).

[2] E. J. Strait, L. L. Lao, M. E. Mauel, B. W. Rice, T. S. Taylor, K. H. Burrell, M. S. Chu, E. A. Lazarus, T. H. Osborne, S. J. Thompson, and A. D. Turnbull, Phys. Rev. Lett. **75**, 4421 (1995).

[3] Y. Koide and JT-60U Team, Bull. Am. Phys. Soc. **41**, 1419 (1996).

[4] P. H. Diamond et al., Phys Rev. Lett. **78**, 8 (1997).

[5] D. E. Newman et al., Physics of Plasmas to appear (1998).

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# Fokker-Plank Modeling of Ion Temperature Gradient Instability

S. V. Novakovski, J. F. Drake, C. S. Liu, and R. Z. Sagdeev
*Institute for Plasma Research, University of Maryland at College Park, College Park, MD, 20742*

A Fokker-Plank modeling of the Ion Temperature Gradient (ITG) instability is presented. A modified version of the code "ELECTRIC", developed earlier[1] for modeling of the neoclassical relaxation, is used. New elements include 3D real (not twisted or ballooning) geometry, the parallel electric field and the electron dynamics (in the form of the Boltzman distribution). An initial value approach is used first to determine the thresholds and growth rates of the instability. Our particular interest is related to the stabilization of the lowest mode numbers due to acoustic effects, influence of collisions and magnetic drifts. Preliminary results of the $\mathbf{E}\times\mathbf{B}$ flow shear influence on the ITG stability as well as the quasilinear model for self-consistent $\mathbf{E}\times\mathbf{B}$ dynamics are also presented.

## References

[1] S.V. Novakovski, C.S.Liu, R.Z. Sagdeev, and M. N. Rosenbluth, Physics of Plasmas, **4**, p.4272, 1997

# Stabilization of the m=2/n=1 neoclassical tearing mode in ITER using a continuous localized current drive

A. Pletzer
*ITER-JCT*
*11025 N. Torrey Pines Rd.*
*La Jolla CA 92037*
*and*
*CRPP-EPFL*
*PPB-Ecublens*
*CH-1015 Lausanne, Switzerland*

F. Perkins
*ITER-JCT*
*11025 N. Torrey Pines Rd.*
*La Jolla CA 92037*

The saturation of the neoclassical tearing requires the mathing index $\Delta'$ to be large and negative. In ITER, the combination of neoclassical bootstrap current drive with $\Delta' < 0$, but small for low $m/n$ modes, is predicted to give rise to large neoclassical islands which may impact on the soft $\beta$ limit. To control the size of these islands, we propose to apply a continuous, localized current drive about the rational surface. However, contrary to Refs. [1] and [2], we find that the dominant stabilizing effect does not come from replacing the bootstrap current within the island, but rather from the large and negative $\Delta'$ values obtained by tailoring the the current profile [3]. The origin of the stabilizing effect lies in the favourable current gradient that is introduced on both sides of the rational surface.

Numerical calculations of $\Delta'$ for a realistic ITER equilibrium show that this stabilization is very effective; the reduction of $\Delta'$ is approximately proportional to the amplitude of the driven current density and inversely proportional to the current channel width. Such a dependence in current amplitude and channel width is also confirmed by a simple analytic model.

If the current drive is not properly centered about the rational surface, however, the stabilizing effect can be lost or become destabilizing. Thus, we have also studied the effect of applying a Gaussian current distribution somewhat shifted on either side of an ($m = 2, n = 1$) tearing mode. It appears that the local current drive stabilization is more robust when aiming just outside of the rational surface, as this compensates for the rational surface moving out as the safety factor profile flattens. The destabilizing effect of the local current drive on neighbouring tearing modes is also determined.

The saturated island width for each case is evaluated using a neoclassical tearing mode model with quasi-linear correction terms to account for the pressure and current flattening.

## References

[1] C. C Hegna and J. D. Callen, Phys. Plasmas **4**, 2940 (1997).
[2] H. Zohm, Phys. Plasmas **4**, 3433 (1997).
[3] E. Westerhof, Nucl. Fusion **27**, 1929 (1983).

# Hole-Clump Dynamics with Collisions

D Eremin, H L Berk, B N Breizman, J Candy
*Institute for Fusion Studies, The University of Texas at Austin, Austin TX 78712*

Previous work [1] has shown that kinetic instabilities can produce nonlinear phase space structures (holes and clumps) that give rise to large frequency shifts of the unstable mode. These structures arise in near-threshold regimes for which the instability drive from the kinetic component slightly exceeds the linear mode damping. A collisionless adiabatic theory shows that the emerging structure is a constant-amplitude BGK wave, with the background dissipation balanced by the power extracted from the kinetic component by a moving phase space bucket.

The theory is now being extended to describe collisional processes that eventually destroy the phase space structures. The description of the collisional phase is predicated by an analysis of the frequency shifts predicted by the adiabatic theory. An additional extension to the nonlinear theory is to replace a fixed background damping with a self-consistent kinetic damping. The extended model includes two kinetic species: one provides the instability drive while the other absorbs the mode energy. This model exhibits different nonlinear scenarios depending on the mass ratio of the two species. If the instability drive is from the lower-mass species, frequency sweeping can develop. If the instability drive is from the higher-mass species, the mode abruptly saturates, without sweeping, at a level that is independent of the background dissipation rate. If the masses of the two species are equal, the saturation level depends on the increment above marginal stability. This extended model can be applied to a variety of weak, kinetically-driven instabilities by translating matrix elements that appear in linear theory to an effective mass in our theory.

## References

[1] H.L. Berk, B.N. Breizman and N.V. Petviashvili, Phys. Lett. A **234** 213 (1997).

# Two-point Boundary Value and Cauchy Formulations in an Axisymmetrical MHD Equilibrium Problem

Calin Vlad Atanasiu*
*Dept. of Applied Physics, Columbia University, New York, NY 10027*

Alexey A. Subbotin
*Russian Research Center, I. V. Kurchatov Institute, 123182 Moscow, Russia*

Two equilibrium solvers for axisymmetrical toroidal configurations have been developed, both based on the expansion in poloidal angle method.

The first one has been conceived as a two-point boundary value solver. By writing Maxwell equations and the equilibrium equation in a system of coordinates $(a, \theta, \zeta)$ with straight field lines and using the coordinate transformation through Fourier series in $\omega$ (the poloidal angle in the general "unrectified" curvilinear coordinate system $(a, \omega, \zeta)$)

$$\rho^2(a,\omega) = a^2 + \mathrm{Re}\left[\sum \delta_m e^{im\omega}\right] \quad \delta_m(a) \; = \; \text{complex moments}, \;\; m \in [-\infty, +\infty], \;\; m \neq 0,$$

we have obtained the following system of complex differential equations

$$Y_m'' + \left(3 + 2\mu' a/\mu\right) Y_m'/a - (m^2-1)Y_m/a^2 = -2W_m/\mu a^2,$$

where $Y_m = \delta_m/a$, $\mu = 1/q$ is the rotational transform and $W_m = W_m(a, \mu(a), g_{ik}(a,\omega), p'(a), B_0, R, \delta_{l,l\neq m})$ is a nonlinear functional. By solving this system as a Cauchy problem for $m = 1$: $\delta_1(0) = \delta_1'(0) = 0$, and as a two-point boundary value problem for $m > 1$: $\delta_{m,m\neq 1}(0) = 0$ and given $\delta_{m,m\neq 1}(1)$, one obtains the $\delta_m(a)$ dependence over the full plasma region.

The second solver uses the Cauchy formulation of the problem in a general curvilinear coordinate system $(a, \omega, \zeta)$ with the following coordinate transformation

$$x = a^2/b \cos\omega + \sum x_m \cos m\omega; \;\; y = b \sin\omega; \;\; b = \lambda^{1/2} a; \;\; m \in [0, +\infty], \;\; m \neq 1,$$

with $x_0, \lambda, x_2, x_3, \ldots$ the shift, the ellipticity, the triangularity, the quadrangularity, etc. of the flux surfaces, respectively. One can prove that near the magnetic axis, for $m \geq 2$, $x_m \sim C_m a^m$, with $C_m$ some free parameters, and $x_0 \sim a^2$. The Grad-Shafranov equation has been put in the form of a system of differential equations

$$\mathbf{W}'' = \mathbf{A}^{-1}\mathbf{B} = \mathbf{F}(a, \mathbf{W}, \mathbf{W}') \text{ with } \mathbf{W}^T = [\Psi \;\; x_0 \;\; b \;\; x_m/a_{m-1} \;\; \ldots \;\; x_M/a_{M-1}],$$

where the $a_{ij}$ coefficients depend on $a$, $b$ and metric coefficients, while $b_j$ depends on $\Psi'$ too. Note that for this Cauchy formulation, the problem is well-conditioned; for each moment $w_m$, only the "large" solutions $\sim a^m$ play a role. The "weak" solutions $\sim a^{-m}$ which could appear due to numerical errors, vanish near the plasma boundary. The integration of this system of differential equations takes place in one "iteration" only.

For the second solver a fixed boundary equilibrium problem can also be formulated, i.e. with given values of the moments at the magnetic axis and at the plasma boundary. In this case, an iterative Newton-like method has been used.

To determine the external equilibrium currents, the virtual casing principle has been used.

To test our moment methods, a comparison of the moment solutions with analytical solutions obtained for a Solov'ev equilibrium has been performed.

*Permanent address: Institute of Atomic Physics, 76900 Bucharest-Măgurele, Romania

# A Newton Method For The 3D MHD Equilibrium Equations

Hilary Oliver, Allan Reiman, Don Monticello
*Princeton Plasma Physics Laboratory, Princeton University*

Newton's method is a well known technique for solving a set of nonlinear equations, $\mathrm{f}(\mathrm{x}) = 0$, given a sufficiently good initial estimate of the root, and provided the gradient $\nabla\mathrm{f}(\mathrm{x})$ is available. Successive approximations to the solution are given by,

$$\mathrm{x}_{i+1} = \mathrm{x}_i - \frac{\mathrm{f}(\mathrm{x}_i)}{\nabla\mathrm{f} > (\mathrm{x}_i)}$$

We have applied Newton's method to the MHD equilibrium equations through modification of an iterative algorithm that is currently used by the PIES 3D MHD equilibrium code. The PIES code is used internationally for a number of applications. It utilizes a two-step Picard iteration scheme that can be summarized as,

$$\left.\begin{array}{r}\mathbf{J}_i(\mathbf{B}_i) \times \mathbf{B}_i = \nabla P \\ \nabla \cdot \mathbf{J}_i(\mathbf{B}_i) = 0\end{array}\right\} \implies \mathbf{J}_i(\mathbf{B}_i)$$

$$\left.\begin{array}{r}\nabla \times \mathbf{B}_{i+1} = \mathbf{J}_i(\mathbf{B}_i) \\ \nabla \cdot \mathbf{B}_{i+1} = 0\end{array}\right\} \implies \mathbf{B}_{i+1}$$

To effect the Newton method the second step is modified. The right hand side of Ampere's Law is replaced with a linear approximation to $\mathbf{J}_{i+1}(\mathbf{B}_{i+1})$, so that we solve both sets of equilibrium equations simultaneously to first order in the iterative correction to the magnetic field. In practice the Newton method is best formulated in terms of a vector potential, **A**, for the magnetic field. We choose a gauge in which the radial covariant component of A vanishes. The modified Ampere's Law equation is,

$$\nabla \times \nabla \times \delta\mathbf{A}_{i+1} - \mathcal{L} \cdot \delta\mathbf{A}_{i+1} = \mathbf{J}_i(\nabla \times \mathbf{A}_i) - \nabla \times \nabla \times \mathbf{A}_i$$

The Newton correction, $\mathcal{L} \cdot \delta\mathbf{A}$, is analogous to the gradient term in the basic Newton method above. The new algorithm is computationally feasible only because the linear operator $\mathcal{L}$ is local to a magnetic flux surface and can be calculated analytically.

Preliminary results indicate that the Newton method performs very well for simple flat current-profile test cases. Details of the algorithm will be presented together with further results from the testing of the Newton method.

# Recent Results on Simulation of Turbulence in Boundary Plasmas *

X. Q. Xu, R. H. Cohen, G. D. Porter
*Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

J. R. Myra, D. A. D'Ippolito
*Lodestar Research Corp., Boulder, CO 80301*

R. Moyer
*University of California, San Diego 92093*

We simulate tokamak boundary plasmas using the 3D electromagnetic turbulence code BOUT. This code models the boundary plasma using fluid equations for plasma vorticity, density, parallel ion momentum (along the magnetic field), electron temperature, and parallel momentum. A realistic DIII-D X point magnetic geometry is used. The turbulent transport coefficients can be expressed in the form:

$$\chi_\perp = \chi_{GB} F(\hat{\beta}, \rho_s/R_0, L_\perp/\rho_s, L_{||}/\rho_s, \hat{s}, \hat{\nu}, \Lambda)$$

Here $\chi_{GB} = (cT_e/eB_0)(\rho_s/L_\perp)$ is the gyro-Bohm coefficient, $L_\perp$ is density, temperature, parallel velocity or ion pressure gradient scaling length $L_n$, $L_{Te}$, $L_v$, or $L_{Pi}$. $\hat{s}$ is the magnetic shear parameter. F is a dimensionless function of the dimensionless arguments to be determined from theoretical arguments and/or from simulations.

We present results for L mode and H mode runs, which show that as the electron temperature is increased and the gradient scale length is reduced, the velocity shear is increased and the turbulence fluctuation levels are reduced. This lends credence to the possibility of an SOL-based L-H transition mechanism such as that reported by Cohen and Xu[1] and related works.

We identify the quasi-coherent mode observed in DIII-D H-mode SOL's with linear analysis.

We report on progress surveying the dependence of the turbulence on the seven dimensionless plasma parameters. We will compare these results to mixing-length estimates obtained using growth rates from a shooting code, with the goal of parameterizing the ratio (which may be more slowly varying than $F$ itself) and thus obtaining a transport model useful in the 2-D edge fluid codes. Comparison is made with data from the DIII-D tokamak where probe measurements give turbulence fluctuation levels and fluxes in the boundary plasma.

Finally, we review the conditions under which the electron heat conduction term can be neglected in the underlying electromagnetic fluid equations.

## References

[1] R.H. Cohen and X. Xu, Physics of Plasmas Vol.**2** 3374-3383(1995).

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# Theory and Modeling of SOL and Edge Turbulence*

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

X. Q. Xu, R. H. Cohen, G. D. Porter
*Lawrence Livermore National Laboratory, Livermore CA 94550*

R. Moyer
*University of California, San Diego 92093*

Recent progress in identifying important physics for scrape-off-layer (SOL) and edge turbulence has enabled the formulation of relatively simple (i.e. 4, 5 or 6 field) models which describe the physics of resistive ballooning modes, drift waves, and instabilities driven in the SOL by divertor plate sheaths and parallel shear in the E×B flows. The fundamental equations include the evolution of vorticity, density, Ampere's law, Ohm's law, and optionally electron temperature and parallel ion momentum. Our models incorporate realistic geometry including the X-point region. Direct 3-D numerical simulation of the governing nonlinear equations is being exploited, using the BOUT code, to obtain the characteristics of the turbulence and induced diffusion. We have also developed a linear high-n ballooning model and numerical code BAL, discussed here, based on these equations. The BAL code can be used to obtain stability thresholds, growth rates and $\gamma/k^2$ estimates of the diffusivity in the boundary plasma. It is useful for parameter surveys, mode identification, and benchmarking of the nonlinear simulations. Progress in these areas will be discussed. The linear analysis is being employed to compare the relative importance of the various instability drives just inside and outside the separatrix. Most importantly, it is hoped that the BAL estimates of diffusivity, when fit to the results of the full nonlinear code, will be useful for rapid numerical assessment of SOL/edge properties, and ultimately for self-consistent profile evolution in a transport code.

Our work is presently being applied to understand experimental results from the DIII-D tokamak on general SOL/edge turbulence levels, and specifically the recent observations of a quasi-coherent mode in the DIII-D edge plasma. This mode arises during the L-H transition, and appears to be driven by, and in turn limits, the density and/or pressure gradient in the transport barrier. Results from our analysis of relevant DIII-D shots will be presented.

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# Coils for Prescribed 3D Finite-$\beta$ Equilibria

Peter Merkel
*Max-Planck-Institut für Plasmaphysik*
*Teilinstitut Greifswald*
*IPP-EURATOM Association*
*D-17489 Greifswald, Federal Republic of Germany*

The NESCOIL code [1], [2] has been extended to determine coils producing the appropriate vacuum field for 3D finite-$\beta$ MHD equilibria.

Originally, the NESCOIL code was developed to compute external currents for the Helias class of optimized stellarator configurations on which the W7-X device is based. For these equilibria the effect of finite $\beta$ on the magnetic field structure is small because of the strongly reduced parallel plasma current density. Therefore the coils were designed to produce a field approximating the vacuum solution of the optimized fixed boundary configuration.

However, to treat cases with large plasma currents as quasi axially-symmetric tokamak configurations the effect of the plasma current cannot be neglected any more.

A fixed boundary equilibrium magnetic field $\vec{B}_{eq}$ is the sum of a vacuum field $\vec{B}_{vac}$ and the field $\vec{B}_j$ produced by the plasma current with $(\vec{B}_{vac} + \vec{B}_j) \cdot \vec{n} = 0$ on the boundary ($\vec{n}$ = exterior normal).

Because $\vec{B}_{vac}$ is the field to be produced by the coils one needs to know $\vec{B}_{vac}$ for the extended NESCOIL procedure separately. It can be shown that $\vec{B}_{vac}$ in the plasma domain is the field produced by a surface current on the boundary, defined by $\vec{j}_s = \vec{B}_{eq} \times \vec{n}$ (virtual casing principle) [3]. Then, the coils are determined by a minimization procedure: $\int df\,[(\vec{B}_{coil} - \vec{B}_{vac}) \cdot \vec{n}]^2 = \min!$ on the plasma boundary.

## References

[1] P. Merkel, Nucl. Fusion **27** (1987) 867.
[2] P. Merkel, In: Theory of Fusion Plasmas, Varenna, Italy, EUR 11336 EN, 25.
[3] V. D. Shafranov, L. E. Zakharov, Nucl. Fusion **12** (1972) 599.

# Structure of Parallel-Velocity-Shear Driven Mode in Toroidal Plasmas

J.Q. Dong, W.B. Xu
*Southwestern Institute of Physics, P.O. Box 432, Chengdu People's Republic of China*

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

It is shown that the Fourier ballooning representation is appropriate for the study of short wavelength drift-like perturbations in toroidal plasmas with a parallel velocity shear (PVS). The radial structure of the mode driven by a PVS is investigated. The Reynolds stress created by PVS turbulence and proposed as one of the sources for a sheared poloidal plasma rotation is analyzed. It is demonstrated that a finite ion temperature is crucial for the creation of Reynolds stress, and that the higher the ratio $T_i/T_e$, the easier a poloidal shear flow be created. Here, $T_i$ and $T_e$ are ion and electron temperature, respectively. The correlation of this observation with the requirement that ion heating power be higher than a threshold value for the formation of an internal transport barrier is discussed.

# Theory of Low-n External Kinks in High-$\beta$ Toroidal Plasmas

Riccardo Betti
*Laboratory for Laser Energetics and Department of Mechanical Engineering, University of Rochester*

Evgeni Fedutenko
*Laboratory for Laser Energetics, University of Rochester*

According to the ideal MHD model, low-$n$ external kink modes limit the maximum achievable beta in tokamaks. The beta limits can be improved by the presence of a superconducting shell sufficiently close to the plasma. It is common wisdom that the external kinks can only be completely stabilized when the shell is in contact with the plasma, i.e. the shell radius $b$ is equal to the plasma radius $a$. However, it is easily shown that some special MHD equilibria are stable to the external kinks for arbitrary values of $\beta$ and the shell detached from the plasma. In order to study the stability of low-$n$ external kinks, we have developed a simple theory retaining the lowest order poloidal coupling. We use the standard high-$\beta$ tokamak ordering $\beta \sim \epsilon$, $q \sim 1$ and $\epsilon = a/R_0 << 1$ where $q$ is the safety factor and $\epsilon$ is the inverse aspect ratio. A complete analytic calculation can be carried out in the presence of a flat pressure profile with a sharp gradient at the plasma edge. Instead, the stability of diffuse pressure profiles is numerically investigated. It is found that the plasma is stable for arbitrary betas when the ratio $b/a$ (wall radius/plasma radius) is below a critical value $(b/a)_1 \sim 1.1 - 1.2$. In the $(b/a)$-$(\beta/\epsilon)$ plane, the area $1 < b/a < (b/a)_1$ is denoted as "absolute stability region". Furthermore, a wall induced "second stability region" is found for larger wall radii above $(b/a)_1$ and below a second critical value $(b/a)_2 \sim 1.3$. In the latter, the plasma is stable for beta below and above two thresholds $\beta < \beta_1$, $\beta > \beta_2$, and unstable in the intermediate range $\beta_1 < \beta < \beta_2$. The size of the "absolute stability" region depends on the edge safety factor $q_a$. As expected, the critical wall radius for absolute stability decreases as $q_a$ increases. For $b/a > (b/a)_2$, no second or absolute stability is found at high betas. Even though the ideal external kinks are stable, it is shown that the resistive wall mode continues to grow inside the "absolute" and "second" stability region. However, because of its slow growth rate, such instability could be controlled with a feedback system or plasma rotation.

# Generalized Force-Free Equilibria*

Parvez N. Guzdar
*IPR, University of Maryland*

Swadesh M. Mahajan
*IFS, University of Texas at Austin*

In a recent work by Mahajan and Yoshida[1], it was shown that in an ideal magnetofluid with flows, the equlibrium magnetic field for generalized force-free states, is described by a two-parameter double curl ($\bigtriangledown \times \bigtriangledown$) system of equations. In the absence of plasma flows the equation reduces to the pure magnetic force-free Woltjer[2] states. The novel feature of these generalized force-free states with flow is that, pressure confining, minimum $|B|$ configurations are allowed. In the present work we address the issue of relating the two parameters to physical constraints of the system, like total plasma current and toroidal momentum and obtain one-dimensional and two-dimensional equilibria as a function of realistic control parameters. The imposition of these constraints leads to a complex relationship between the two parameters and the plasma size. We map the equilibrium magnetic field,flow velocities and pressure profiles as a function of the two control parameters. Also we examine the accessibility of these special states using a two dimensional MHD code.

## References

[1] S. M. Mahajan and Z. Yoshida,submitted to PRL
[2] L. Woltjer, Proc. Natl. Acad. Sci. USA **44**, 489 (1958)

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# Transport of Angular Momentum in Hot Accretion Disks and in Laboratory Plasmas*

Paolo S. Coppi
*Department of Astronomy and Physics*
*Yale University, New Haven CT 06511*

Bruno Coppi
*Massachusetts Institute of Technology, Cambridge MA 02139*

The collective modes that have been considered for the transport of momentum or angular momentum in magnetically confined plasmas with a flow velocity along the field are driven by the combined effects of the finite electron temperature and of the plasma velocity gradient. Dissipative electrostatic modes[1] with this characteristic have in fact been observed recently in separate ad hoc experiments[2]. In magnetized accretion disks the electromagnetic modes that can be excited and can transport angular momentum (in the outward direction as needed for accretion to occur) are shown to require, in a similar way, the combination of the effects of the finite plasma temperature[3] and of the gradient of the rotation frequency $\Omega(R)$ in the realistic case where the magnetic field has a toroidal component. For this the important contribution of finite plasma compressibility $(\nabla \cdot \mathrm{v} \neq 0)$ is to be taken into account. Accordingly, the relevant instabilities would not grow out of a cold plasma disk and heating should precede the occurrence of momentum transport and accretion. The theory of a new kind of modes[4] with these features is presented. These modes are inherently non-local, corotate with the plasma at the radius where their amplitude is maximum, and owe their existence to the gradient of the relevant Doppler shifted frequency $\bar{\omega} = \omega - n^o\Omega$ ($n^o$=toroidal mode number). Considering the case where a toroidal and a vertical component of the magnetic field are present, for these modes the bending of the magnetic field lines is minimized. Two driving factors are identified, one involves the square of $d\bar{\omega}/dR$ and the other, whose importance for rotating magnetized plasmas was pointed out by Velikhov[5], involves the linear contribution of $d\Omega/dR$ to the perturbed toroidal field[6]. The same modes are shown[3] to persist as dissipative instabilities when the effects of finite longitudinal ion viscosity[1] are considered. The quasi-linear transport velocity of angular momentum associated with these modes is evaluated in terms of an appropriate quadratic form of the mode amplitude. The key role of the finitness of the plasma temperature makes this theory consistent with the derivation of the Shakura-Sunyaev[7] scaling, of the effective viscous coefficient for accreting disks, that is proportional to the sound velocity.

## References

[1] B. Basu and B. Coppi, *J. Geophysical R.* **34**, 5316 (1989).
[2] J. Willig, R. L. Merlino, and N. D'Angelo, *J. Geophysical R.* **102**, 27249 (1997).
[3] B. Coppi and P. S. Coppi, *Phys. Lett. A* **237**, 58 (1997).
[4] B. Coppi and P. S. Coppi, MIT Report PTP(RLE) 97/6 Cambridge, MA, to be published in *Phys. Lett. A* (1998).
[5] E. Velikhov, *Soviet Phys.* JETP **36**, 1938 (1959).
[6] S. A. Balbus and J. F. Hawley, *Ap. J.* **376**, 214 (1991).
[7] N. I. Shakura and R. A. Sunyaev, *Astron. Astrophys.* **24**, 337 (1973).

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# Edge Bootstrap Current and High $\ell_i$ Advanced Tokamak Operational Mode

Y.R. Lin-Liu, M.S. Chu, R.L. Miller,
A.D. Turnbull, and T.S. Taylor

*General Atomics*
*San Diego, California*

Both high normalized beta, $\beta_N = \beta(\%)\, B(\mathrm{T})\, a(\mathrm{m}) / I(\mathrm{MA})$, and high confinement enhancement, $H = \tau_E / \tau_{E-ITER89P}$, have been robustly observed in high internal inductance ($\ell_i$) discharges on the DIII–D and other tokamaks. These high performance, high $\ell_i$ discharges are obtained by transient inductive means. However, in steady state, high $\ell_i$ is undermined by the combinations of the large edge bootstrap current resulting from the finite edge pressure gradient in the H–mode and the finite value of the central safety factor $q(0)$ required by MHD stability. The goal of the present study is to determine whether a moderately high value of $\ell_i$ and high beta values are compatible and, in particular, without the requirement of wall stabilization. We have used the TOQ equilibrium code to construct self-consistent bootstrap equilibria of typical DIII–D H–mode pressure profiles and a peaked current profile. The high-$n$ ballooning stability of these simulated discharges was examined by the BALOO code, and the kink stability by the MARS and GATO codes. We have found stable steady-state equilibria with moderately high value of $\ell_i$ ($\ell_i \sim 1.0$) and $\beta_N$ of about 4.0, and a bootstrap current fraction of 65%–70% for the full-size DIII–D configuration. The $\beta$ -limit is consistent with the semi-empirical scaling law of $\beta_N < 4\ell_i$ A modest central current drive will be required to sustain such discharges in steady state. Strong plasma shaping will also be needed to achieve the high $\beta$ operational scenario without wall stabilization.

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# Weakly nonlinear dynamics of marginally stable plasmas*

Diego del-Castillo-Negrete
*University of California San Diego*

We derive a self-consistent, reduced equation that describes the weakly nonlinear evolution of electrostatic perturbations in marginally stable plasma equilibria [1]. The equation is universal in the sense that it is independent of the equilibrium, and it contains as special cases the beam-plasma, the bump-on-tail, and the two-stream instability problems, among others. In particular, the present work offers a systematic justification of the O'Neil-Winfrey-Malmberg single-wave beam-plasma model. But more importantly, the analysis shows that the single-wave model has a wider range of applicability: it can be applied to localized perturbation in any marginally stable equilibrium. We discuss the linear theory of the reduced equation, construct families of exact nonlinear solutions, and study numerically the nonlinear evolution and saturation of instabilities. Using an analogy between the Vlasov equation and the two-dimensional Euler equation [2] we show that the reduced equation also describes the dynamics of localized vorticity perturbations in the critical layer of a marginally stable shear flow.

## References

[1] D. del-Castillo-Negrete, *Nonlinear evolution of perturbations in marginally stable plasmas*, accepted for publication in Physics Letters A (1998).
[2] N. J. Balmforth, D. del-Castillo-Negrete, and W. R. Young, *Dynamics of vorticity defects in shear*, J. Fluid Mech. **333**, 197–230 (1997).

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# Theory and Interpretation of Internal Modes in Alcator C-Mod

Francesca Bombarda
*Associazione Euratom-ENEA sulla Fusione*

Bruno Coppi, Ambrogio Fasoli, Stefano Migliuolo, Joseph Snipes
*Massachusetts Institute of Technology**

Wolfgang Kerner, Guido Huysmans
*Jet Joint Undertaking*

The linear stability of internal ideal and resistive modes is considered for various regimes that are encountered in Alcator C-Mod plasmas. Detailed numerical calculations, employing the equilibrium and stability code PEST-1 [1], have been carried out and suggest that, for the most part, these plasmas are stable against ideal n=1 pressure driven modes (n = toroidal mode number). This has been obtained both in ohmic regimes as well as regimes where ion cyclotron heating has been employed. In some cases where the auxiliary heating has been particularly effective, our analysis provides circumstantial evidence that high energy ions may play a substantially beneficial role against these instabilities. A qualitative agreement has been found between the presence/absence of sawteeth in Alcator C-Mod discharges and the location of the marginal stability boundary for resistive internal n=1 modes. This latter calculation employs simple analytic formulae, based on two–fluid models developed for circular plasma cross sections. One parameter is especially important in order to obtain a quantitatively accurate answer on stability: $\lambda_H$ (which is proportional [2] to the negative of the change in potential energy due to the perturbation). Accurate knowledge of this parameter requires a detailed solution of the normal mode equations in the single fluid resistive approximation for appropriately shaped plasmas (C-Mod plasmas are often diverted, with a single null). For that purpose we are porting the CASTOR [3] code, which will be used to compute the growth rates of resistive internal modes in the appropriate geometry.

Another problem of considerable interest, theoretically as well as for the interpretation of observations in Alcator C-Mod, and of great potential concern for well confined plasmas, is the transition [4] from shear Alfvèn modes, excited by resonance with high energy particles, to ballooning modes driven by the plasma pressure gradient. The CASTOR code will also be used to study this transition for parameters relevant to these experiments.

## References

[1] R. C. Grimm, R. L. Dewar. amd J. Manickam, *J. Comp. Phys.* **4**, 94 (1983).
[2] B. Coppi, R. Galvão, R. Pellat, M. N. Rosenbluth, and P. H. Rutherford, *Sov. J. Plasma Phys.* **2**, 533 (1976).
[3] W. Kerner, J. P. Goedbloed, G. T. A. Huysmans, S. Poedts, and E. Schwartz, JET Joint Undertaking preprint JET-P(97)04 (1997).
[4] B. Coppi and F. Pegoraro, *Ann. Phys* (NY) **134**, 2 (1981).

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# NIMROD: An Overview of Code Status, Validation, and First Research Topics*

C. R. Sovinec
*Los Alamos National Laboratory, Los Alamos, NM 87545*

T. A. Gianakon
*University of Wisconsin-Madison, Madison, WI 53706*

S. J. Plimpton
*Sandia National Laboratory, Albuquerque, NM 87185*

A. G. Tarditi
*Science Applications International Corporation, San Diego, CA 92121*

and the NIMROD Team

Two years since the inception of the NIMROD code development project, all major components of the code system are functional, and research simulations of tokamaks and alternates are underway. Here we present the status of and plans for the physics kernel and a summary of validation simulations and new research simulations. More details on validation and research are presented in the accompanying papers by Gianakon, Glasser and Schnack.

NIMROD (Non-Ideal Magnetohydrodynamics with Rotation, an Open Discussion project) is a nonlinear 3D plasma simulation code based on fluid models. It solves initial value problems in either toroidal or periodic linear geometry. Spatial discretization is finite-element in the poloidal plane and Fourier series in the toroidal direction. For accuracy, the computation grid is aligned with equilibrium magnetic flux surfaces inside the separatrix. The grid is decomposed into blocks of quadrilateral cells and separate blocks of triangular cells for geometric flexibility; this is particularly useful for modeling regions bounded by complicated wall shapes. Block decomposition is also used for computing on massively-parallel machines, where different blocks are assigned to different processors. Temporal discretization is treated with a time-split, semi-implicit algorithm that allows large time steps relative to the propagation of natural modes across the grid without associated numerical stability constraints.

Recent additions to the code include equilibrium flow and a simplified neoclassical closure scheme.[1] This development is part of a collaborative effort with *General Atomics* to model the nonlinear evolution of internal modes seeding neoclassical islands in DIII-D. Work on including the geometric axis within the computational domain for simulations of compact torus geometries has been initiated. Initial linear test cases of a spheromak-like configuration, albeit with a thin conductor at the axis, will be presented.

Finally, we present a nonlinear simulation of the magnetohydrodynamic dynamo in a reversed-field pinch. The simulation shows sustained field reversal in toroidal geometry, and it is compared with a similar simulation in periodic linear geometry. A recent modification allowing parallel decomposition of different Fourier components is facilitating this study.

## References

[1] S. P. Hirschman and D. J Sigmar, Nucl. Fusion 9, 1079 (1981).

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# The Application of NIMROD to Tearing Modes*

A. H. Glasser
*Los Alamos National Laboratory, Los Alamos, NM 87545*

S. E. Kruger
*University of Wisconsin-Madison, Madison, WI 53706*

J.-N. Leboeuf
*Oak Ridge National Laboratory, Oak Ridge, TN 37831*

M. S. Chu
*General Atomics, San Diego, CA 92186*

and the NIMROD Team

The NIMROD code has been developed to study long-wave-length, long-time-scale, nonlinear, time-dependent phenomena in toroidal plasmas, *e.g.* tokamak disruptions. Unstable tearing modes with low toroidal mode number $n$, and their nonlinear consequences, constitute a major class of such phenomena. They present many numerical challenges: narrow singular layers where many small physical effects compete to determine the stability, separated by broad ideal regions of near force balance; long time scales which must be treated efficiently in the presence of much faster modes; geometric and nonlinear coupling of many Fourier components. Many features of NIMROD are designed to address these challenges; finite element discretization on a nonorthogonal equilibrium flux coordinate system to resolve singular behavior; an implicit time step for efficiency and accuracy; domain discretization on multiple grid blocks and explicit use of message passing for efficient operation on massively parallel computers. Great care has been taken to ensure accurate representation of low-frequency modes. Extensive use is made of advanced scientific visualization techniques to understand and verify the results.

The purpose of this paper is to present results of applying NIMROD to low-$n$ tearing modes. Test cases include both large-aspect-ratio, circular-cross-section, low-$\beta$ plasmas; and realistic models of D-IIID discharges with moderate $\beta$ and reversed shear. Extensive comparisons will be presented between NIMROD results, analytical theory, and numerical results obtained with the FAR and EPEIUS codes. Grid packing normal to equilibrium magnetic surfaces is used to enhance resolution of tearing layers while economizing on the size of the grid. Efficient scaling on the T3E is demonstrated. Nonlinear evolution is visualized by means of computer movies of Poincare surfaces of section.

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# Two Tokamak Applications of NIMROD: Ballooning Modes and Secondary Island Generation by Mode Coupling*

T.A. Gianakon
*University of Wisconsin—Madison, Madison, WI 53706*

C.R. Sovinec, A.H. Glasser
*Los Alamos National Laboratory, Los Alamos, NM 87545*

M. Chu
*General Atomics, San Diego, CA 92121*

and the NIMROD Team

NIMROD is a new three-dimensional initial-value fluid code designed for the analysis of advanced fusion experiments. As such, the NIMROD code has been designed with the flexibility to study a wide range of physical effects which include ideal and resistive MHD, two fluid effects through the Hall and electron inertia terms, and eventually a wide range of fluid closures (Braginski and neoclassical). The code also flexibly handles geometry, which can be either slab, periodic cylinder, toroidal with a conducting wall at the separatrix, or toroidal with real machine boundaries. As a demonstration of the capability of NIMROD to solve ideal and resistive MHD problems associated with $\beta$ limiting phenomena in tokamaks, simulation results for two cases will be presented: ballooning modes and seed islands for neoclassical tearing modes.

The first set of simulation results is a comparison of the threshold for infinite n ballooning modes with results from NIMROD based on linear resistive MHD for toroidal mode numbers of n=5 and n=10. Initial scalings for n=10 at a magnetic Reynolds number of $S = 4.5(10^4)$ indicate growth rates of $\gamma\tau_a \simeq 0.30$, which then fall towards zero below the ideal $\beta$ limit. As the resitivity is further decreased, the expectation is that this ideal $\beta$ limit should be more clearly reproduced.

The second set of simulation results are motivated by the observation that neoclassical tearing modes can be triggered by the magnetic perturbation associated with a sawtooth crash. The magnitude of such secondary islands is controlled both by the resistivity, which dictates the shape and magnitude of the eigenfunctions, and by the toroidal shear rotation, which tends to decouple resonant surfaces[1]. Preliminary scaling studies will be presented based on DIIID shot 86144.

## References

[1] "Mode Coupling Trigger of Neoclassical Magnetohydrodynamic Tearing Modes in Tok amaks," T.A. Gianakon, C.C. Hegna, J.D. Callen, UW-CPTC 97-6, May 1997.

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# The Los Alamos Intense Neutron Source and the Periodically Oscillating Plasma Sphere (POPS)

R. A. Nebel, D. C. Barnes
*Los Alamos National Laboratory*

The Intense Neutron Source (INS) is an Inertial Electrostatic Confinement (IEC) fusion device[1] presently under construction at Los Alamos National Laboratory. It is designed to produce 1e11 neutrons per second steady-state using and will be used for nuclear assay applications. This device is a three grid IEC ion focus device. In this paper we describe the physics principles of operation of this device, the engineering design parameters, and the empirical scaling used to determine the design parameters.

Further work is also presented on the Periodically Oscillating Plasma Sphere. This oscillating plasma scheme has the following properties:[2, 3]

1. It allows a plasma in local thermodynamic equilibrium (LTE) to be compressed to ultra-high density leading to high fusion yield.
2. These compressions do not distort the plasma away from LTE.
3. These compressions do not viscously heat the plasma independent of the collisionality.
4. The plasma is stable to multi-dimensional perturbations.
5. The stable spectrum is a continuum so Landau damping is likely.

These properties strongly suggest that these solutions are attractors. This speculation is being tested with PIC simulations. Results will be presented.

## References

[1] R. L. Hirsch, J. Appl. Physics 38, 4522 (1967).
[2] R. A. Nebel, D. C. Barnes, accepted for publication in Fusion Tech.
[3] D. C. Barnes, R. A. Nebel, submitted to Physics of Plasmas.

# Global Toroidal Gyrokinetic Particle Simulation of Turbulent Transport in a Diverted Tokamak Plasma

R. D. Sydora
*Department of Physics, Univ. of Alberta, Edmonton, Canada and Department of Physics and Astronmomy, UCLA*

O. Hurricane, V. K. Decyk, S. C. Cowley, J. M. Dawson
*Department of Physics and Astronomy, UCLA*

It has been established from linear theory that magnetic equilibrium effects, trapped electron dynamics and impurity species can significantly alter the linear growth rate of drift-type microinstabilities in toroidal plasmas. Here, we investigate the influence of these effects on the nonlinear evolution of the toroidal modes along with the inclusion of a divertor region. Since we are attempting to include the core and divertor region in a single simulation calculation, the presence of steep pressure gradients near the divertor region and the sensitivity of temperature gradient-driven fluctuations to wave-particle interactions requires an accurate kinetic simulation model. For this purpose we use a nonlinear global gyrokinetic $\delta f$-particle simulation model designed for massively parallel, distributed computing architectures such as the CRAY-T3E. This allows us to use realistic experimental parameters and equilibria as inputs to the model. A novel orthogonal polynomial fitting method is used to compute the particle drifts in a general equilibrium for toroidal cylindrical coordinates and we also are able to include a divertor region in the simulation domain. By taking appropriate flux surface averages we properly include the fluctuation-driven $E \times B$ flows. Initial studies using this model, with DIII-D type equilibria, reveals that during the linear phase of wave growth, radially separated zones of instability develop but in the nonlinear phase turbulent spreading of the fluctuations occurs and finite thermal fluxes develop in regions which are linearly stable. Strong radial variations of the diamagnetic drift, particularly near the divertor region, is shown to affect the localization and strength of the turbulent fluctuations. The self-organized flow patterns and the spatial distribution of turbulence in the core region as well as the diverted region will be presented.

# Improving The Multi-Mode Transport Model*

Arnold H. Kritz, Glenn Bateman, Aaron J. Redd
*Physics Department, 16 Memorial Drive East,*
*Lehigh University, Bethlehem, PA 18015*

Gregory Rewoldt
*Plasma Physics Laboratory, Princeton University,*
*Princeton, NJ 08543-0451*

Jan Weiland
*Chalmers University of Technology, Göteborg, Sweden*

Jon Kinsey
*Oak Ridge Associated Universities, Oak Ridge, TN.*
*Present address: General Atomics, P. O. Box 85608, San Diego, CA 92186-5608*

Bruce Scott
*Max-Planck-Institut für Plasmaphysik,*
*8046 Garching bei München, Germany*

The Multi-Mode model has now been held fixed for more than two years. Recent theoretical advances, particularly with regard to the effects elongation and finite $\beta$, have motivated us to consider changes in the model. The Weiland theory for transport driven by drift wave turbulence, which is a dominant component of the Multi-Mode model, has been modified using a variational form to account for the structure of perturbation eigenfunctions along magnetic field lines. Consequently, in this new model, the elongation of the plasma has a direct effect on the predicted transport. For transport near the edge of the plasma, a new model is being developed based on drift Alfvén turbulence simulations. These simulations predict heat fluxes that are comparable with experimental data. We are also developing an improved model for transport driven by interchange and ballooning modes, when they are unstable in the deep core of the plasma. The Multi-Mode model currently used in the BALDUR transport code has predicted temperature and density profiles that are in good agreement with experimental data. Our objective, with the new modifications, is to remove the empirical elongation factor and to improve the accuracy of the finite-$\beta$ effects.

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# Axisymmetric ideal magnetohydrodynamic equilibria with incompressible flows

H. Tasso and G. N. Throumoulopoulos[1]

*Max-Planck-Institut für Plasmaphysik, EURATOM Association*
*D-85748 Garching, Germany*

December 1997

## Abstract

It is shown that the ideal MHD equilibrium states of an axisymmetric plasma with incompressible flows are governed by an elliptic partial differential equation for the poloidal magnetic flux function $\psi$ containing five surface quantities along with a relation for the pressure. Exact equilibria are constructed including those with non vanishing poloidal and toroidal flows and differentially varying radial electric fields. Unlike the case in cylindrical incompressible equilibria with isothermal magnetic surfaces which should have necessarily circular cross sections [G. N. Throumoulopoulos and H. Tasso, Phys. Plasmas **4**, 1492 (1997)], no restriction appears on the shapes of the magnetic surfaces in the corresponding axisymmetric equilibria. The latter equilibria satisfy a set of six ordinary differential equations which for flows parallel to the magnetic field $\mathbf{B}$ can be solved semianalytically. In addition, it is proved the non existence of incompressible axisymmetric equilibria with (a) purely poloidal flows and (b) non-parallel flows with isothermal magnetic surfaces and $|\mathbf{B}| = |\mathbf{B}|(\psi)$ (omnigenous equilibria).

[1]Permanent address: Section of Theoretical Physics, Physics Department, University of Ioannina GR 451 10 Ioannina, Greece

# Gyrokinetic Stability and Plasma Flux Surface Shape

R.E. Waltz and R.L. Miller

*General Atomics*
*San Diego, California*

This paper gives a systematic study of the effect of plasma flux surface shape on general gyrokinetic stability in the high-$n$ ballooning mode representation. Previous studies of general geometry tokamaks and microstability have been organized about surface by surface analysis of global MHD equilibria making it difficult to isolate parametric dependences. The present study uses a generalization of the local $\hat{s}-\alpha$ equilibrium recently formulated by Miller *et al.* [1]. This formulation characterizes the local equilibrium for a shifted, elongated, and triangulated ellipse with minor horizontal radius $r$ in terms of nine local flux surface variables: aspect ratio $A = R_0 / r$, Shafranov shift $\partial_r R_0$, elongation $\kappa$, triangularity $\delta$, safety factor $q$, shear $\hat{s} = (r/q)\partial_r q$, and the MHD pressure gradient $(-\partial_r P)$ variable $\alpha$, as well as two nearly degenerate variables $s_\kappa = (r/\kappa)\partial_r \kappa \approx (\kappa - \kappa_0)/\kappa$, $s_\delta = [r/(1-\delta^2)^{1/2}]\partial_r \delta \approx \delta/(1-\delta^2)^{1/2}$. The general pure plasma gyrokinetic maximum growth rates normalized to $c_s / r$ depend on plasma $\beta$, and separate inverse temperature and density gradient length ratios $-r\partial_r \ln T_i$, $-r\partial_r \ln T_e$, $-r\partial_r \ln n_e$ in place of the pressure gradient variable. The temperature ratio $T_i / T_e$ and collisionality also influence growth rates. The careful delineation of the local variables allows systematic study of maximum growth rate against shape variables $A$, $\kappa$, and $\delta$ at fixed $r$. Kotschenreuther's gyrokinetic code [2] modified for $B_\parallel$ perturbations and general geometry is used and recovery of the ideal MHD critical point is verified. We quantify the general stabilizing effect of low aspect ratio, high elongation and triangularity at high beta [3].

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[1] R.L. Miller, M.S. Chu, J.M. Greene, Y.R. Lin-Liu, and R.E. Waltz, ''Noncircular, finite aspect ratio, local equilibrium model,'' General Atomics Report GA-A22625, to be published in Physics of Plasmas.

[2] M. Kotschenreuther, Bull. Amer. Phys. Soc. **37**, 1432 (1991).

[3] W. Dorland, M. Kotschenreuther, Q.P. Liu, R.L. Miller, and Y.R. Lin-Liu, Bull. Amer. Phys. Soc. **42**, 2003 (1997), paper oThaI1-3.

# The M3D Project for Plasma Simulation Studies *

W. Park, E.V. Belova, G.Y. Fu
*Princeton Plasma Physics Laboratory*

H.R. Strauss
*New York University*

L.E. Sugiyama
*Massachusetts Institute of Technology*

The M3D (Multi-level 3D) project[1] carries out simulation studies of plasmas of various regimes using multi-levels of physics, geometry, and grid models in one code package. More physics levels are also being added for a more complete object oriented code package, which can be used to simulate a wide range of plasma regimes, spanning various fusion devices, space plasmas, and astrophysical plasmas.

Such a general code package would have a profound impact on the search for better confinement schemes. The capability of the code package to apply to a full range of general plasma states will stimulate one's imagination, at the same time requiring it to be firmly based on reality. The interrelations between fusion, space, and astro plasmas borne out by using the same code package would also be of mutual benifit. The object oriented modular code design ensures that carrying the multi-level capability in one code package would incur only a minimal overhead.

The code is also used to study existing fusion devices. For this application, the benefits include: the most suitable physics, geometry, and grid models, can be chosen for the problem at hand; and running the same problem with physics models of differing complexity aids in physics understanding by isolating the most important physics, and also helps code validation.

The physics levels which are already available and have been used extensively include MHD[2], Two-fluids[3], the hybrid Gyrokinetic Hot Particle/MHD levels.[4, 5] Recently, a bulk Ion Gyrokinetic Particle/Two-fluid hybrid level has been added. A Full-kinetic Ion Particle/Fluid Electron hybrid level will be added shortly. For grid schemes, both structured and unstructured mesh[6] options are available. Recently, neoclassical parallel viscosity has also been incorporated in the two-fluid level.

Various recent results will be presented.

## References

[1] W. Park et al., *Plasma Physics and Controlled Nuclear Fusion Research* (IAEA, Vienna, 1997), Vol. 1, p.411.

[2] W. Park et al., Phys. Rev. Lett. **75** 1763 (1995).

[3] L.E. Sugiyama, Proceedings of the Workshop on Nonlinear MHD and Extended-MHD (U. Wisconsin Report, UW-CPTC 97-5, 1997).

[4] G. Y. Fu and W. Park, Phys. Rev. Lett. **74** 1594 (1995).

[5] G.Y. Fu et al., *Plasma Physics and Controlled Nuclear Fusion Research* (IAEA, Vienna, 1997), Vol. 1, p.453.

[6] H.R. Strauss and W. Park, (submitted to Phys. Plasmas, 1998)

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# Rotation in Toroidal Plasmas*

L. E. Sugiyama
*Massachusetts Institute of Technology, Cambridge MA 02139*

W. Park
*Princeton Plasma Physics Laboratory*
*Princeton University, Princeton NJ 08543*

The poloidal rotation of a magnetically confined, toroidal plasma is still not well understood. The possibility of self-sustained or self-generated poloidal rotation in a real, dissipative plasma has long been recognized ("Stringer spin-up"[1][2][3]), as has the existence of strong damping mechanisms (e.g., viscosity[4], magnetic pumping[5]). MHD and two-fluid (or kinetic) theory predict very different values for the possible steady state rotation. MHD stresses the poloidal sound speed, $v_E \sim (B_\theta/B_\phi)c_S$, where $v_E$ is the $\mathbf{E} \times \mathbf{B}$ velocity and $c_S$ is the usual sound speed, while two-fluid effects introduce the electron and ion diamagnetic velocities[2][6]. Neoclassical effects further introduce a diamagnetic velocity based on the temperature gradient, related to the heat flux. Steady state rotation, even at speeds near the diamagnetic velocities, can involve shocks. The poloidal rotation can also couple to strong changes in the toroidal rotation, despite global conservation of toroidal angular momentum in axisymmetry. Existing theory is based on aspect ratio expansion; rotation and related effects appear in higher order and certain effects are neglected or incompletely treated. We investigate the poloidal rotation in a fully toroidal numerical model MH3D-T, that includes two-fluid and neoclassical effects.

## References

[1] T. E. Stringer, *Phys. Rev. Lett.* **22** 770 (1969).
[2] E. Bowers and N. L. Winsor, *Phys. Fluids* **14** 2203 (1971).
[3] A. B. Hassam and J. F. Drake *Phys. Fluids B* **5** 4022 (1993).
[4] M. N. Rosenbluth and J. B. Taylor, *Phys. Rev. Lett.* **23** 367 (1969).
[5] T. H. Stix, *Phys. Fluids* **16** 1260 (1973).
[6] T. E. Stringer, *Phys. Fluids* **13** 1586 (1970).

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# MHD Simulations of Pellet Injection and Disruptions using the MH3D++ Code

H.R. Strauss
*NYU*

W. Park
*PPL*

The location at which pellets are injected into a plasma has a significant effect on what fraction of the pellet mass remains in the plasma for refueling purposes. MHD simulations confirm the results of pellet injection experiments [1]: toroidal curvature makes it favorable to inject pellets from the inboard side or from the top or bottom, rather than from the outboard side.

Sufficiently large pellets injected at the inboard edge can reach the plasma center, and in the process drive magnetic reconnection to produce negative central shear. Inboard pellet injection might solve refueling problems while improving confinement.

Injection at the top (or bottom) of the tokamak causes relatively little MHD displacement of the pellet. A scaling law is obtained for pellet displacement which agrees well with the simulations. The MHD simulations were carried out with the new MH3D++ [2] unstructured mesh finite element version of the MH3D full MHD code.

The simulations are initialized with a 2D, ITER - like MHD equilibrium, to which a pellet is added. The simulations assume that the pellet ionizes and ablates rapidly, compared to the Alfvén and sound wave time scales. The pellet is the source of a plasma cloud, which has a non uniform density and pressure distribution on magnetic surfaces. The 3D perturbed plasma then relaxes by parallel streaming of heat and density, and major radius displacement akin to the Shafranov shift.

If the background plasma beta is sufficiently high, the presence of a pellet can destabilize ballooning modes. Nonlinearly these modes can break up the pellet cloud.

Simulations are also being carried out of current driven disruptions, with the aim of calculating halo currents. The simulations employ a self consistent 3D resistivity calculated from the temperature.

The MH3D++ code combines a 2D finite element discretization in the poloidal plane with a Fourier expansion in the toroidal coordinate. The finite element unstructured mesh discretization has been incorporated into MH3D++ with an object oriented approach. Most of the original MH3D code is retained, except for the previous discretization with radial finite differencing and Fourier expansion in poloidal and toroidal angles. The two versions have been benchmarked against each other and are in agreement.

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## References

[1] P.T. Lang, K. Buechl, M. Kaufmann, R.S. Lang, V. Mertens, H.W. Mueller, J. Neuhauser, ASDEX Upgrade, and NI Teams; “High-Efficiency Plasma Refueling from the Magnetic High-Field Side into ASDEX Upgrade” Physical Review Letters 79, 1487-1490 (1997)

[2] H. Strauss, and W. Park, “Unstructured Mesh 3D MHD Simulations with MH3D++,” B.A.P.S. **42** 1854, (1997).

# 3D Hybrid Simulations with Gyrokinetic Particle Ions and Fluid Electrons*

E. V. Belova, W. Park, G. Y. Fu
*Princeton Plasma Physics Laboratory*

H. R. Strauss
*New York University*

L. E. Sugiyama
*Massachusetts Institute of Technology*

The previous hybrid MHD/particle model has represented energetic ions as gyrokinetic (or drift-kinetic) particles coupled to MHD equations using the pressure or current coupling scheme[1]-[3] (*MH3D-K* code). The small energetic to bulk ion density ratio was assumed allowing the neglect of the energetic ion perpendicular inertia, and the use of MHD Ohm's law. A generalization of this model in which all ions are treated as gyrokinetic/drift-kinetic particles and fluid description is used for the electron dynamics is considered. The ion perpendicular inertia is retained by calculating the ion fluid velocity from momentum equation, in which the ion density and pressure are calculated using particle simulations. The calculated ion fluid velocity is used in the Ohm's law, which includes Hall term and electron pressure gradient; quasineutrality is assumed.

The ion pressure is taken to be in CGL form and the gyroviscous part of the stress tensor is calculated in order to take into account the diamagnetic effects. The gyroviscous tensor (or the off-diagonal elements of the stress tensor) can be calculated from particles or taken into account in a fluid way [4]. The gyroviscous terms appear naturally in the gyrokinetic description, when the transformation from the gyro-center to particle coordinates is made in the pressure integral, however, this approach requires the ion Larmor radius to be resolved in the simulations. In order to include the diamagnetic effects in the drift-kinetic formulation, the small ion Larmor radius expansion can be made in a pressure tensor integral, which gives the expression for gyroviscous stress tensor in terms of the gyrofluid moments. It is shown that the previous fluid results of [4] can be recovered in a simple geometry. The higher order corrections, which in this case represent the difference between the gyrofluid moments (calculated in the code) and the particle-fluid moments can also be taken into account.

Dispersion analysis in the slab geometry shows that the model correctly describes ion kinetic effects. The effect of the thermal ion particles on the stability and structure of the internal kink mode will be investigated and compared with MHD results. Initial numerical results including diamagnetic effects will be presented and the particle and fluid approaches will be compared.

## References

[1] W. Park et al., Phys. Fluids B4,2033 (1992).
[2] G.Y. Fu and W. Park, Phys. Rev. Lett. **74**, 1594 (1995).
[3] E.V. Belova et al., J. Comput. Phys. **136**, 324 (1997).
[4] Z. Chang and J. D. Callen, Phys. Fluids B4, 1766, (1992).

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# On the Fluctuation Spectrum of a Vlasov Plasma*

P. J. Morrison
*Institure for Fusion Studies and Department of Phsysics, UT Austin.*

B. A. Shadwick
*Physics Department, UC Berkeley.*

Since the early work of T. D. Lee and L. Onsager, many attempts have been made to describe homogeneous fluid turbulence by means of arguments based on statistical mechanics. For example, the statistical dynamics of incompressible fluid flow governed by the two-dimensional Euler equations has been described by Fourier transforming the vorticity and then calculating averages of various quantities by functional integrals involving various kinds of constraints. The subject is rife with controversy: different authors have used different constraints, and every now and then the work of Lynden-Bell is rediscovered in different guises. Here we take a different approach. We treat the turbulent fluctuations of a Vlasov plasma by expanding in the eigenfunctions of the continuous spectrum — van Kampen modes. We are able to calculate the functional integrals exactly, and a surprising result is obtained.

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# Discontinuity Model for Transport Barrier Formation in Reversed Shear Tokamaks

Y. Kishimoto, Y. Koide
*Naka Fusion Research Establishment, JAERI, Naka, Ibaraki 310-0195 Japan*

W. Horton, T. Tajima
*Institute for Fusion Studies, The University of Texas at Austin*

J.-Y. Kim
*Korea Basic Science Institute, Taejon 305–33, Korea*

The structure of the drift waves in toroidal systems with reversed magnetic shear and/or $E_r$ shear is a complicated mathematical problem. Global particle simulations have been important tools for showing the relative importance of the competing mechanisms. New particle simulations in reversed magnetic shear configurations will be reported that show the formation of a radial discontinuity across the $q_{\rm min}$ surface. Away from $q_{\rm min}$ the simulations are interpreted with the two dimensional ballooning mode representation that include the formulas for the Block angle $\theta_0$ which jumps from a positive value in the core where $\widehat{s} < 0$ to a negative value in the outer region where $\widehat{s} > 0$. Low order coupled equations are written to cross the ballooning mode break down layer at $q_{\rm min}$. Nonlinear orbit calculations of test particles support the observation in the nonlinear stage of the simulation of a leaky transport barrier with both $T_i$ and $T_e$ showing the characteristics of the JT60-U experiments of sharp gradients with $L_T \sim \rho_p$ across the transport barrier.

# Effects of Non-Circular Plasma Geometry on Finite-$\beta$ Kinetic Ballooning and Trapped-Electron-$\eta_i$ Modes*

Aaron J. Redd, Arnold H. Kritz, Glenn Bateman
*Physics Department, Lehigh University,*
*16 Memorial Drive East, Bethlehem, PA 18015*

Gregory Rewoldt
*Princeton Plasma Physics Laboratory,*
*P. O. Box 451, Princeton, NJ 08543–0451*

We conduct comprehensive linear stability analyses using the FULL code[1]. This kinetic stability analysis is fully electromagnetic in nature, and includes effects from trapped and untrapped particles, finite banana-orbit width, Landau damping and finite Larmor radius. The FULL code can be used to analyze the stability of tokamak discharges with respect to both finite-$\beta$ kinetic ballooning modes (an analogue to the ideal MHD ballooning mode that includes all the kinetic effects) and trapped-electron-$\eta_i$ modes (also known as Ion Temperature Gradient and/or Trapped Electron Modes). The kinetic stability analysis in the FULL code requires a self-consistent numerical MHD equilibrium, which is calculated by solving the Grad-Shafranov equation in the JSOLVER code[2].

Using JSOLVER, we construct families of numerical equilibria with noncircular cross-sections in which we hold fixed, from one equilibrium to the next, the major radius $R$, minor radius $a$ and safety factor profile $q(r)$, varying only the elongation $\kappa$ and the triangularity $\delta$. Here, $r$ is defined as the plasma half-width in the midplane. In each case, the $< \vec{J} \cdot \vec{B} >$ current profile was altered to maintain the fixed $q(r)$ profile. For all of the resulting equilibria, we utilize the same density and temperature profiles. In this manner, we isolate the dependence of the instabilities on the cross-sectional geometry.

Thorough analysis with the FULL code provides linear growth rates, mode frequencies and the $k_\theta$-spectra for each instability at all radial locations in the plasmas we consider. Comparisons reveal the dependence of the kinetic ballooning and trapped-electron-$\eta_i$ growth rates, $k_\theta$-spectra and onset thresholds on the plasma elongation $\kappa$ and triangularity $\delta$. We present results of scans over both $\kappa$ and $\delta$, clearly showing the stabilizing effects of increased elongation and nonzero triangularity. Quasilinear estimates for the energy and particle fluxes are also calculated, and their dependencies on $\kappa$ and $\delta$ are explored.

## References

[1] G. Rewoldt, W. M. Tang, M. S. Chance, Phys. Fluids **25**, 480 (1982);
G. Rewoldt, W. M. Tang, R. J. Hastie, Phys. Fluids **30**, 807 (1987);
G. Rewoldt, L. L. Lao, W. M. Tang, Phys. Plasmas **3**, 4074 (1996).

[2] DeLucia, Jardin and Todd, J. Comput. Phys **37**, 183 (1980).

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# Invariants in Lie–Poisson Systems*

Jean-Luc Thiffeault†, Philip J. Morrison
*Institute for Fusion Studies and Department of Physics,*
*University of Texas at Austin*

Lie–Poisson brackets are a type of noncanonical bracket and are ubiquitous in the reduction of canonical Hamiltonian systems with symmetry. Finite-dimensional examples include the heavy top and the moment reduction of the Kida vortex, while for infinite dimension we have the 2-D ideal fluid, reduced MHD, and the 1-D Vlasov equation. We study Lie–Poisson brackets not necessarily as arising from a reduction but obtained directly from extensions of Lie groups. We derive a classification scheme for low-dimensional extensions using cohomology theory for Lie algebras. We then derive the Casimir invariants for the classes of Lie–Poisson brackets where the inner bracket is of canonical type. An interpretation of some of the Casimirs is offered.

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# Full Plasma Cross Section Landau Fluid Calculations of Ion Temperature Gradient Driven Turbulence in Tokamaks*

J.-N. Leboeuf, V. E. Lynch, B. A. Carreras
*Oak Ridge National Laboratory*

J. D. Alvarez, L. Garcia
*Universidad Carlos III, Madrid, Spain*

Landau fluid calculations of ion temperature gradient-driven turbulence (ITGDT) which cover the whole plasma cross section have been initiated in both cylindrical and toroidal geometries. To keep these full cross section calculations at a computationally manageable level, we only include time evolution equations for the perturbed ion density (vorticity) and perturbed ion parallel velocity, and a perturbed ion temperature equation with a simple parallel linear Landau closure. Moreover, the electrons are treated as adiabatic and the electrostatic approximation is used throughout. Flux coordinates with straight field lines have been chosen to describe the general toroidal magnetic geometry. Both analytic and realistic fixed boundary equilibria from a solution of the Grad-Shafranov equation are used as input. This allows us to study ITGDT for shaped, high plasma beta equilibria.

Large scale nonlinear calculations in cylindrical geometry have been performed in parallel on the CRAY T3E at NERSC. Calculations with and without Landau closure but with identical profiles and parameters demonstrate the reduction in linear growth rates and the spatial localization of the linear eigenfunctions expected with Landau damping. Nonlinear calculations close to marginal stability (with the ratio of density to temperature gradient scalelengths $\eta_i = 1.2$) further show that spatial localization persists nonlinearly and is not adversely affected by the generation of sheared poloidal flow through Reynolds stress. The radial scales of the turbulence are of the order of the Larmor radius $\rho_i$. The radial correlation length in the steady-state phase is about $3.0\rho_i$. No large-scale structures are observed, which tends to indicate that the induced transport is local.

Full cross section toroidal Landau fluid calculations of ITGDT are also being performed for eventual comparison with flux tube models. Linear and nonlinear results from these calculations will be given. In particular, the effect of elongation and triangularity on the stability to $\eta_i$ modes will be reported. Preliminary results from nonlinear toroidal calculations show that the flux surface averaged poloidal flow generated by ITGDT through Reynolds stress is dominated by large radial scale structures. The effect of parallel nonlinearities and compressibility on the structure of the flow is currently under study.

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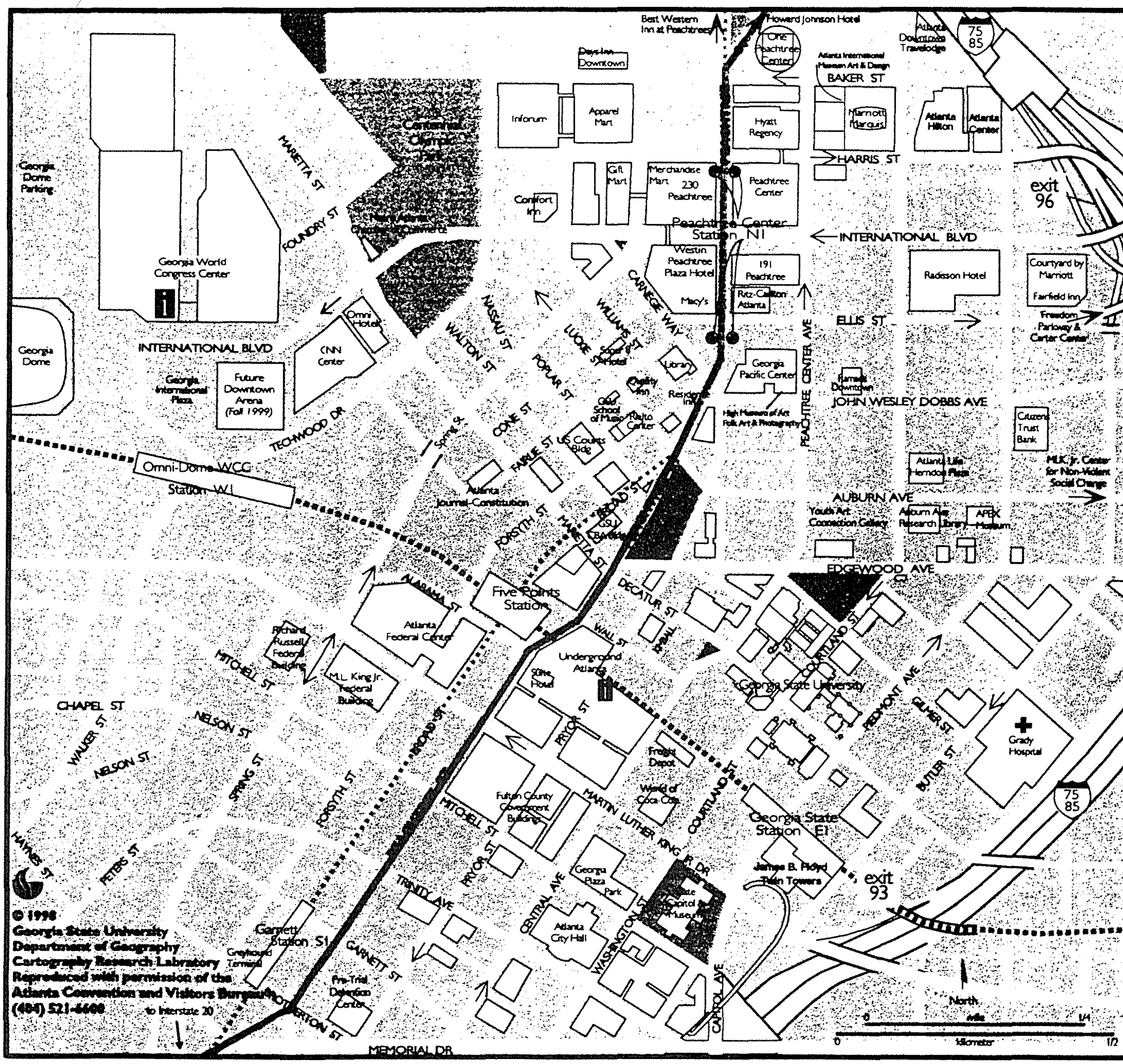
# DOWNTOWN ATLANTA



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