2001 International Sherwood Fusion Theory Conference April 2-4, 2001 Santa Fe, New Mexico

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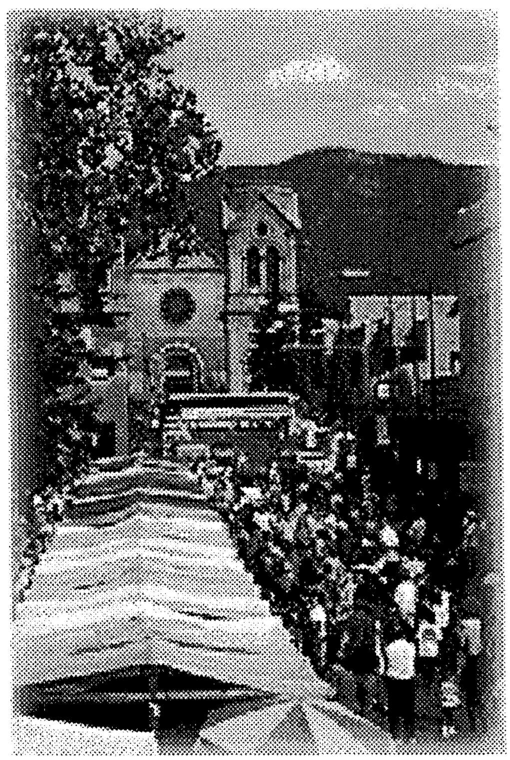

Hosted by

Members of the Plasma Theory Group,
Los Alamos National Laboratory

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Saralyn Stewart

2001
International
Sherwood Fusion Theory Conference

April 2-4, 2001
The Eldorado Hotel
Santa Fe, New Mexico

Hosted by

Members of the Plasma Theory Group,
Los Alamos National Laboratory

United States Department of Energy
Office of Fusion Energy Sciences

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David Newman, U Alaska
Barrett Rogers, U Maryland
Thomas Rognlien, LLNL
Carl Sovinec, LANL
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Jay Kesner, MIT
Sergei Krasheninnikov, UC San Diego
Barrett Rogers, U Maryland
Carl Sovinec, LANL
Roscoe White, PPPL

GENERAL INFORMATION

A total of 174 papers were contributed, and 13 were selected by the Program Committee for oral presentation out of 45 requests. There are three review papers and a special presentation from the National Energy Research Supercomputing Center (NERSC). Ancillary meetings are also scheduled during the conference.

MEETING PROGRAM

- The **review papers** (1A01, 2A01, 3A01) will be presented in the Anasazi Ballroom at 8:30 AM, Monday through Wednesday.
- The **oral papers** will be presented in the Anasazi Ballroom.
  - Session 1B will take place Monday, 10:00 AM-12:30 PM,
  - Session 1D will take place Monday, 4:00 PM-6:00 PM, and
  - Session 2B will take place Tuesday, 10:00 AM-12:00 PM.
- The **poster sessions** will be held in the Sunset Room and along the Concourse.
  - Session 1C will take place Monday, 2:00 PM-4:00 PM,
  - Session 2D will take place Tuesday, 7:30 PM-9:30 PM, and
  - Session 3B will take place Wednesday, 9:30 AM-11:30 AM.
- A **special session** entitled, "Roadmap for the Cray PVP Systems at NERSC," will take place Tuesday 12:00 PM-12:30 PM in the Anasazi Ballroom.

IMPORTANT INFORMATION

- The **conference registration desk** will be located in the Concourse near the Anasazi Ballroom, and it will be staffed
  - Sunday, 4:00 PM-7:00 PM,
  - Monday, 7:30 AM-11:00 AM and 1:30 PM-4:00 PM,
  - Tuesday, 8:00 AM-11:00 AM, and
  - Wednesday, 8:00 AM-10:00 AM.
- A complimentary **reception** with hors d'oeuvres and cash bar will be held Sunday evening from 5:30 PM-8:00 PM in the Anasazi Ballroom.
- A complimentary **companions' breakfast** will be served in the Eldorado Court, Monday 8:30 AM.
- **Coffee** will be served at 9:30 AM Monday-Tuesday in the Concourse outside the Anasazi Ballroom. On Wednesday, it will be served at 9:30 AM in the Sunset Room.
- **Beverages** will be served in the Sunset Room beginning at 2:30 PM on Monday and at 7:30 PM on Tuesday.

ANCILLARY MEETINGS

- Steve Jardin of PPPL will hold an **MHD group** discussion of burning plasma issues, Sunday evening, 7:00 PM-9:00 PM in Zia B-C.
- Jeff Freidberg of MIT will hold a **public comment meeting** regarding issues for burning plasmas on Tuesday, 3:00 PM-5:00 PM in the Anasazi Ballroom.
- The **2002 International Sherwood Fusion Theory Conference** will be hosted by the University of Rochester, April 8-10 in the Rochester, New York area.

The Eldorado Hotel, 309 W. San Francisco Street
Santa Fe, New Mexico
April 2-4, 2001

Registration Schedule

Sunday	4:00 PM-7:00 PM	Concourse near the Anasazi Ballroom
Monday	7:30 AM-11:00 AM and 1:30 PM-4:00 PM	Concourse near the Anasazi Ballroom
Tuesday	8:00 AM-11:00 AM	Concourse near the Anasazi Ballroom
Wednesday	8:00 AM-10:00 AM	Concourse near the Anasazi Ballroom

Presentation Schedule

Review and Oral Presentations: Anasazi Ballroom
Poster Presentations: Sunset Room and Concourse

Monday			
8:20 AM - 8:30 AM		Welcome	C. R. Sovinec
8:30 AM - 9:30 AM	1A	Review Paper	R. E. Ecke
10:00 AM - 12:30 PM	1B	Oral Session	(5 30-minute talks)
		Lunch Break	
2:00 PM - 4:00 PM	1C	Poster Session	
4:00 PM - 6:00 PM	1D	Oral Session	(4 30-minute talks)
Tuesday			
8:30 AM - 9:30 AM	2A	Review Paper	J. F. Drake
10:00 AM - 12:00 PM	2B	Oral Session	(4 30-minute talks)
12:00 PM - 12:30 PM	2C	Special Session	J. Carter
		Free Afternoon	
7:30 PM - 9:30 PM	2D	Poster Session	
Wednesday			
8:30 AM - 9:30 AM	3A	Review Paper	R. Laflamme
9:30 AM - 11:30 AM	3B	Poster Session	

Coffee will be served in the Concourse at 9:30 AM Monday and Tuesday. On Wednesday, it will be served at 9:30 AM in the Sunset Room.
Beverages will be served in the Sunset Room at 2:30 PM on Monday and at 7:30 PM on Tuesday.

Review and Oral Presentations

Monday Morning

Review Paper	1A	J. Finn presiding
8:30 AM		R. E. Ecke, *Pattern Formation in Systems far from Equilibrium*
Oral Session	1B	B. Breizman presiding
10:00 AM		J. B. Taylor, *Resistive Wall Modes and Non-uniform Wall Rotation*
10:30 AM		W. X. Wang, *Self-consistent Radial Electric Field and Neoclassical Transport*
11:00 AM		C. S. Chang, *X-Transport as an Irreducible Baseline Phenomenon for Er, H-Mode, and Edge Pedestal Formation*
11:30 AM		L. Chacon, *Fully Implicit, Nonlinear Resistive-Hall MHD Computations of Magnetic Reconnection*
12:00 PM		S. Benkadda, *Streamers and Zonal Flow Dynamics in Edge Tokamak Turbulence*

Monday Afternoon

Oral Session	1D	R. White presiding
4:00 PM		P. N. Guzdar, *Zonal Flow and Zonal Field Generation by Finite Beta Drive Waves-a Theory for L-H Transitions in Tokamaks*
4:30 PM		J.-N. Leboeuf, *Comparisons of Nonlinear Gyrokinetic Calculations with Experimental Results for DIII-D-Like Tokamak Discharges*
5:00 PM		F. Jenko, *Theory of Electron Temperature Profile Stiffness*
5:30 PM		F. Porcelli, *Phase Mixing in Collisionless Reconnection*

Tuesday Morning

Review Paper	2A	B. Rogers presiding
8:30 AM		J. F. Drake, *The Physics of Magnetic Reconnection*
Oral Session	2B	J. Kesner presiding
10:00 AM		Y. Todo, *Simulation of Intermittent Fast Particle Loss due to Alfven Eigenmode Bursts*
10:30 AM		X. Q. Xu, *Studies of Boundary Turbulence and Transport in NSTX*
11:00 AM		A. Simakov, *Kinetic Plasma Stability in a Dipolar Magnetic Field*
11:30 AM		R. Fitzpatrick, *Control of Tearing Modes via "Designer" Resonant Magnetic Perturbations*
Special Session	2C	T. Gianakon presiding
12:00 PM		J. Carter, *Roadmap for the Cray PVP Systems at NERSC*

Wednesday Morning

Review Paper	3A	C. Sovinec presiding
8:30 AM		R. Laflamme, *Quantum Computation*

Conference Presentations

Sherwood 2001

The Eldorado Hotel, 309 W. San Francisco Street
Santa Fe, New Mexico
April 2-4, 2001

Monday Morning

Welcome: 8:20 AM—C. R. Sovinec, *Local Arrangements Chair*

1A **Review Paper** Anasazi Ballroom, 8:30 AM - 9:30 AM, J. Finn presiding

1A01 *Pattern Formation in Systems far from Equilibrium*
R. E. Ecke

Coffee: 9:30 AM—Concourse

1B **Oral Session** Anasazi Ballroom, 10:00 AM - 12:00 PM, B. Breizman presiding

1B01 *Resistive Wall Modes and Non-uniform Wall Rotation*
J. B. Taylor, J. W. Connor, C. G. Gimblett, H. R. Wilson, R. J. Hastie

1B02 *Self-consistent Radial Electric Field and Neoclassical Transport*
W. X. Wang, F. L. Hinton, S. K. Wong

1B03 *X-Transport as an irreducible baseline phemonenon for Er, H-Mode, and Edge Pedestal formation*
C. S. Chang, H. Weitzner, T. Carlstrom, J. deGrassie, D. Darrows, R. White

1B04 *Fully implicit, nonlinear resistive-Hall MHD computations of magnetic reconnection*
Luis Chacon, John M. Finn, Dana A. Knoll

1B05 *Streamers and Zonal Flow Dynamics in Edge Tokamak Turbulence*
S. Benkadda, P. Beyer, N. Bian, O. Garcia, X. Garbet, P. H. Diamond

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Lunch Break: 12:30 PM - 2:00 PM

Monday Afternoon

Beverages: 2:30 PM—Sunset Room

1C **Poster Session** Sunset Room and Concourse, 2:00 PM - 4:00 PM

1C01 *Tearing Mode Marginal Stability in a RFP*
Antonio Bruno, Jeffrey P. Freidberg

1C02 *Invariant Symbolic Cycles Distribution in Chaotic and Turbulent Dynamics*
A. B. Rechester and M. Lehrman

1C03 *Calculation of gradient scale lengths in the edge pedestal*
Weston M. Stacey

1C04 *Hybrid Magnetohydrodynamic-gyrokinetic δf PIC simulation of energetic particle excitation of Alfven modes in a magnetic dipole configuration*
Sean Dettrick, Liu Chen, Lin-jin Zheng

1C05 *A Neoclassically-Consistent Model of Nonlinear RF-Driven Sheared Flows*
J. R. Myra, D. A. D'Ippolito

1C06 *Microinstability analysis of experimental NSTX plasmas*
C. Bourdelle, R. E. Bell, W. Dorland, D. R. Ernst, G. W. Hammett, S. Kaye, B.P. LeBlanc, F. Paoletti, G. Rewoldt, E. J. Synakowski

1C07 *Rogue waves in plasmas*
Eugene R. Tracy, A. R. Osborne

1C08 *Two Fluid Tearing Instability In Force Free RFP Configuration*
V. V. Mirnov, C. C. Hegna, S. C. Prager

1C09 *Kinetic Electron Closure for Electromagnetic Simulation of Drift and Shear Alfven Waves*
B. I. Cohen, A. M. Dimits, W. M. Nevins, Y. Chen, and S. E. Parker

1C10 *Magnetohydrodynamic Equilibria with Poloidal Flow*
Riccardo Betti, Maxim Umansky, Jeffrey Freidberg

1C11 *A Global Optimization Algorithm for Stellarator Design*
H.E. Mynick, N. Pomphrey

1C12 *Some Single-Particle Aspects of Approach to Self-organization of a Toroidally Confined Plasma*
D. Subbarao and R. Uma

1C13 *Fusion Reactor Control*
Dirk A. Plummer

1C14 *Convective Transport in Tokamak SOL Plasmas*
D.A. D'Ippolito, J.R. Myra, S.I. Krasheninnikov

Posters, Monday 2:00 PM - 4:00 PM

1C15 *Driftwave Growth Rate Comparisons Between the GLF23 Transport Model and Real Geometry Gyrokinetic Stability Calculations*

J. E. Kinsey, R. E. Waltz, G. M. Staebler

1C16 *Structural stability of the Grad-Shafranov equation: transport barriers and fragile equilibria*

Emilia R. Solano

1C17 *Kinetic Theory of Macroscopic Modes for Spherical Inertial Electrostatic Confinement*

George H. Miley and Hiromu Momota

1C18 *Virtual Cathode in a Stationary Spherical Inertial Electrostatic Confinement*

Hiromu Momota, George H. Miley

1C19 *Profile Consistency of a Field-Reversed Configuration*

D. C. Barnes

1C20 *Angular Momentum "Generation" and Transport in Axisymmetric Plasmas*

B. Coppi

1C21 *Anomalous Angular Momentum Transport and the Structure of Turbulence*

N. Attico, B. Coppi

1C22 *Angular Momentum Transport in Thin Accretion Disks and Intermittent Accretion*

P. S. Coppi, B. Coppi

1C23 *Extended MHD simulations of DIIID 86144*

T. A. Gianakon, D. D. Schnack

1C24 *Numerical Studies of High-Beta Disruptions in DIII-D Shot 87009 Using the NIMROD Code*

D. D. Schnack, S. E. Kruger, A. Tarditi, M. S. Chu, and The NIMROD Team

1C25 *Gyrokinetic δ-f particles in a finite element MHD simulation*

Charlson C. Kim, Scott E. Parker, and The NIMROD Team

1C26 *Nonlinear, Initial-Value Simulations with the NIMROD Code Including the Vacuum Region*

S. E. Kruger, D. D. Schnack, C. R. Sovinec, and The NIMROD Team

1C27 *Derivation and implementation of time-dependent, neoclassical electron heat flux closure in NIMROD*

E. D. Held, C. R. Sovinec

1C28 *Toroidal Geometry Effects in the Low Aspect Ratio RFP*

Carl Sovinec, Chris Hegna

1C29 *Field-line Stochasticity of the Stabilized Pinch, Theory and Measurements, and Flux Conversion in Astrophysical Dynamos*

Stirling Colgate, Carl Sovinec, Hui Li, and John Finn

Posters, Monday 2:00 PM - 4:00 PM

1C30 *Nonlinear Evolution of Driven Ideal MHD Instabilities*
S. Mahajan, J. D. Callen, C. C. Hegna

1C31 *Resistive Drift Modes in Tokamak and l=2-Stellarator Configurations*
Ralf Kleiber

1C32 *The Role of Beam-Alfven Wave Interaction in the Evolution of Ion Rings*
A. V. Gretchikha, J. B. Greenly, W. J. Podulka, Y. A. Omelchenko

1C33 *Non-Gaussian transport in strong plasma turbulence*
S. V. Annibaldi, G. Manfredi, R. O. Dendy, L. Drury

1C34 *Global Stability of the Field-Reversed Configuration*
E. V. Belova, S. C. Jardin, H. Ji, R. Kulsrud and M. Yamada

1C35 *Evidence for Transitions in the Transport Dynamics of a SOC System with Classical Diffusion*
D. E. Newman, Raul Sanchez, B. A. Carreras

1C36 *Quite times and other tests of a SOC System*
Raul Sanchez, D. E. Newman, B. A. Carreras

1C37 *SOC Dynamics with Varying Driving Force, Transport Size, and Classical Diffusion Coefficient*
Willis Ferenbaugh, D. E. Newman, Raul Sanchez, B. A. Carreras

1C38 *Radial and Poloidal Dynamics of Turbulent Transport in a Self Organized Criticality Model with Sheared Flow and Diffusive Spreading*
Ryan Woodard, D. E. Newman, B. A. Carreras, Raul Sanchez

1C39 *Ideal MHD Continuum Modes in General Toroidal Geometry*
J. A. Tataronis, R. Torasso, A. Salat, C. Phillips

1C40 *Exact Axisymmetric MHD Equilibria*
Marco A. Brambilla, Harold Weitzner

1C41 *Simulation of Edge Plasmas in Double-Null Configurations*
M. E. Rensink, G. D. Porter, T. D. Rognlien

1C42 *BOUT simulations of the Quasi-Coherent Mode in the EDA Regime of Alcator C-Mod*
W. M. Nevins, X. Q. Xu, A. Mazurenko, M. Porkolab

1C43 *Study Nuclear Physics for Nuclear Fusion*
Xing Z. Li; Ming Y. Mei; Jian Tien

1C44 *Nonlinear Gyrobounce-kinetic Vlasov-Poisson Equations*
Alain J. Brizard, Allan N. Kaufman

1C45 *Self-Adjoint Formulation for Diffusive Plasma Stability*
Eliezer Hameiri

1C46 *Particle Simulations of Plasma Confinement in a Levitated Dipole*
Chengkun Huang, John Tonge, Jean-Noel Leboeuf, and John M. Dawson

Posters, Monday 2:00 PM - 4:00 PM

1C47 *Non-white Noise and a Multiple-rate Markovian Closure Theory for Turbulence*
Gregory W. Hammett, John C. Bowman

1C48 *Error Field Amplification and Rotation Damping in Tokamaks*
Allen H. Boozer

1C49 *Resistive Ballooning Instability in Tokamak Edge Plasmas*
R. J. Hastie, J. J. Ramos and F. Porcelli

1C50 *Compressional Alfven Eigenmode Instability can Explain Sub- Ion Cyclotron Frequency Modes in NSTX*
N. N. Gorelenkov, C. Z. Cheng, D. S. Darrow, E. D. Fredrickson, S. M. Kaye

1C51 *Lorentz-covariant fluid description of relativistic magnetized plasma*
R. D. Hazeltine and S. M. Mahajan

1C52 *Finite β effects on internal transport barrier formations*
P. Zhu, G. Bateman, A. H. Kritz, W. Horton

1C53 *Edge transport modulation by radially coherent zonal flows*
K. Hallatschek

1C54 *Alfven cascades in JET discharges with non-monotonic q-profile*
H. L. Berk, D. Borba, B. N. Breizman, C. Challis, A. Fasoli, J. Mailloux, S. Pinches, S. E. Sharapov, D. Testa

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1D **Oral Session** Anasazi Ballroom, 4:00 PM - 6:00 PM, R. White presiding

1D01 *Zonal Flow and Zonal Field Generation by Finite Beta Drift Waves a Theory for L-H Transitions in Tokamaks*
P. N Guzdar, R. G. Kleva, A. Das, P. K. Kaw

1D02 *Comparisons of Nonlinear Gyrokinetic Calculations with Experimental Results for DIII-D-Like Tokamak Discharges*
J. N. Leboeuf, T. L. Rhodes, J. M. Dawson, V. K. Decyk, R. D. Sydora

1D03 *Theory of electron temperature profile stiffness*
Frank Jenko, William Dorland

1D04 *Phase Mixing in Collisionless Reconnection*
F. Porcelli, D. Grasso, F. Califano, F. Pegoraro

Tuesday Morning

2A **Review Paper** Anasazi Ballroom, 8:30 AM - 9:30 AM, B. Rogers presiding

2A01 *The Physics of Magnetic Reconnection*
J. F. Drake

Coffee: 9:30 AM—Concourse

2B **Oral Session** Anasazi Ballroom, 10:00 AM - 12:00 PM, J. Kesner presiding

2B01 *Simulation of Intermittent Fast Particle Loss due to Alfven Eigenmode Bursts*
Y. Todo, H. L. Berk, B. N. Breizman

2B02 *Studies of Boundary Turbulence and Transport in NSTX*
X. Q. Xu, W. M. Nevins, M. E. Rensink, J. R. Myra, S. Zweben, R. Maqueda

2B03 *Kinetic Plasma Stability in a Dipolar Magnetic Field*
Andrei N. Simakov, Peter J. Catto, and R. J. Hastie

2B04 *Control of tearing modes via "designer" resonant magnetic perturbations*
Richard Fitzpatrick, Enrico Rossi, Edmund Yu

2C **Special Session** Anasazi Ballroom, 12:00 PM - 12:30 PM, T. Gianakon presiding

2C01 *Roadmap for the Cray PVP Systems at NERSC*
Jonathan Carter

Free Afternoon

Tuesday Evening

Beverages: 7:30 PM—Sunset Room

2D **Poster Session** Sunset Room and Concourse, 7:30 PM - 9:30 PM

2D01 *Gyrokinetic Particle-in-Cell Simulation of Ion-Temperature-Gradient Modes in Plasma Confined in a Dipole Field*
Gang Zhao, Liu Chen

2D02 *A Proposal for the Startup of a Spherical Torus without using OH coils*
S. C. Jardin

Posters, Tuesday 7:30 PM - 9:30 PM

2D03 *Magnetic Relaxation in Spheromaks Using Spectral Expansions in Cylindrical Geometry*

E. C. Morse, D. D. Hua, T. K. Fowler

2D04 *Radial Propagation of GAMs and Zonal Flows*

F. L. Hinton, M. N. Rosenbluth, P. H. Diamond

2D05 *Flowing Equilibria of Compact Plasmas*

Loren Steinhauer

2D06 *A Basic Experiment on Isotope Scaling of Transport*

T. Bose and A.K. Sen

2D07 *Multiple Ion Species Formulation of the Radial Force Balance*

W. A. Houlberg, P. I. Strand, D. Heading

2D08 *Stability Boundaries for Ideal MHD Ballooning Modes in Three-Dimensional Equilibria*

C. C. Hegna, S. R. Hudson

2D09 *The effect of equilibrium flow on the stability of tearing modes in the reversed-field pinch*

R. Gatto, P. W. Terry, C. C. Hegna

2D10 *Is Muon Fusion Possible?*

Russell M. Kulsrud

2D11 *Local Gravitational Instability of Magnetized Shear Flows*

Gregory Howes, Steven Cowley

2D12 *Nonlinear Collisional Dynamics of Flow Shear in Gyrokinetic Global Evolution of Ion Temperature Gradient Instability*

S. V. Novakovski, C. S. Liu, and R. Z. Sagdeev

2D13 *Belt Pinch ignition devices and reactors*

M. Kotschenreuther, L. J. Zheng, J. Manickam, J. Menard, A. D. Turnbull, M. S. Chu, W. Dorland

2D14 *VORPAL: a multidimensional, parallel plasma simulation code*

Chet Nieter and John Cary

2D15 *Stellarator Optimization Using the Levenberg-Marquardt Method with Broyden Update*

Michael A. Kraemer, Andrew S. Ware, Steven P. Hirshman

2D16 *Plasma Confinement Levitated Dipole*

J. Kesner, A. Ram, D. Garnier, M. Mauel

2D17 *Variational Principle for V-states (Waterbag) Models*

Evstati Evstatiev, Philip Morrison

2D18 *Plasma Simulation Studies using M3D code*

W. Park, G. Y. Fu, S. Hudson, S. C. Jardin, S. Klasky, J. Menard, A. Pletzer, X. Z. Tang, H. R. Strauss, L. E. Sugiyama

Posters, Tuesday 7:30 PM - 9:30 PM

2D19 *Resistive MHD Simulation on Massively Parallel Computers*
Xianzhu Tang, G. Y. Fu, S. C. Jardin, W. Park, L. L. Lowe, H. R. Strauss

2D20 *Simulations of Energetic Particle-driven MHD Modes using M3D code*
G. Y. Fu, W. Park, X. Z. Tang, S. Hudson, S. C. Jardin, S. Klasky, A. Pletzer, H. R. Strauss, L.E. Sugiyama

2D21 *Nonlinear Magnetic Reconnection in Toroidal Systems*
L. E. Sugiyama, W. Park, H. R. Strauss

2D22 *MHD Simulations of Compact Stellarators and M3D Development*
H. R. Strauss, W. Park, X. Tang, S. Hudson, G. Y. Fu, L. E. Sugiyama

2D23 *E X B rotation shear stabilization of resistive pressure-gradient-driven turbulence and turbulent transport*
C. F. Figarella, I. Voitsekhovitch, P. Beyer, S. Benkadda, X. Garbet

2D24 *Error Indicators and Grid Adaptation for Application to Elliptic and Hyperbolic Problems*
Giovanni Lapenta, L. G. Margolin, M. J. Shashkov

2D25 *Stability investigation of the ideal MHD modes in elongated tokamak configurations*
L.-J. Zheng, M. Kotschenreuther, J. Manickam, J. Menard, A. Glasser, A. D. Turnbull, M. S. Chu

2D26 *Limiter and X-point Configurations in Ignition Experiments*
F. Bombarda, G. Cenacchi, C. Ferro, A. Airoldi, B. Coppi, C. S. Pitcher

2D27 *Efficient Density Profiles for Fusion Burning and the Ignitor Experiment*
A. Airoldi, B. Coppi, F. Bombarda, G. Cenacchi, P. Detragiache

2D28 *Interaction of Liquid Metal Walls with the Tokamak Equilibrium Fields*
A. Y. Aydemir

2D29 *Anomalous Transport along Filamented Invariant Surfaces*
George M. Zaslavsky, Mark Edelman

2D30 *Coulomb Scattering in a Magnetic Field*
B. Hu, W. Horton, T. Y. Petrosky

2D31 *Clebsch Potentials and Closures of the Vlasov-Poisson System*
C. S. Jones, P. J. Morrison

2D32 *Directional Fractional Kinetics*
Harold Weitzner, George M. Zaslavsky

2D33 *Resonant Plasma Heating by Electrostatic and Alfven Waves*
Liu Chen, Roscoe White, Zhihong Lin

2D34 *Dynamics of holes and clumps in Vlasov-Poisson plasmas*
Marie-Christine Firpo, Diego del-Castillo-Negrete

2D35 *Zonal flow excitation by nonlinear EPM dynamics*
Fulvio Zonca, Sergio Briguglio, Gregorio Vlad, Liu Chen

Posters, Tuesday 7:30 PM - 9:30 PM

2D36 *Kinetic theory of magnetic reconnection in the whistler frequency regime*
F. Califano, N. Attico, F. Pegoraro

2D37 *Ion Kinetics in a Helicon Plasma Source*
Alexey V. Arefiev and Boris N. Breizman

2D38 *A Fluid Code for Relativistic Laser-Plasma Interactions*
B. A. Shadwick, G. M. Tarkenton

2D39 *The Role of Dispersive Waves in Collisionless Magnetic Reconnection*
Barrett Rogers, James Drake, Micheal Shay, Richard Denton

2D40 *Effects Of Magnetic Islands In Axisymmetric Equilibria*
J. D. Callen, C. C. Hegna

2D41 *Helium removal by collisional ripple transport in a tokamak reactor*
Gunyoung Park, C. S. Chang

2D42 *Liquid Metal Wall Equilibria and Consequences of Fluid Surface Waves*
H. L. Rappaport, H. Ji, M. Kotschenreuther, R. Fitzpatrick

2D43 *Searching for Surfaces: A Hamiltonian Algorithm for Finding Stellarators with Near-Perfect Surfaces*
Ilon Joseph, Allen Boozer

2D44 *An Explicit, Nonperiodic, Nonlinear Eulerian Gyrokinetic Solver for Microturbulence Studies*
J. Candy, R.E. Waltz, M. N. Rosenbluth

2D45 *Calculation of Plasma Transport Using Monte Carlo Determination of Pressure Anisotropy*
Jeff Williams, Allen Boozer

2D46 *Calculation of the Neoclassical Radial Electric Field using the Global Toroidal Code*
Jerome L.V. Lewandowski, Allen Boozer, Jeff Williams, Zhihong Lin

2D47 *Squeezed Potato Orbits in a Magnetic Well*
K. C. Shaing

2D48 *Radial Patterns of Instability and Transport in JT-60U Internal Transport Barrier Discharges*
G. Rewoldt, K. W. Hill, R. Nazikian, W. M. Tang, H. Shirai, Y. Sakamoto, Y. Kishimoto, S. Ide, T. Fujita

2D49 *A multi-fluid kinetic model for a beam propagating in a plasma. The problem of trapped particles.*
Annalisa Ambroso

2D50 *Convective Intermittent Transport in Plasma Turbulence*
O. E. Garcia, N. Bian, S. Benkadda, P. Beyer, X. Garbet

2D51 *Collisionless Equilibrium and Stability of a Uniform, Spherical Electron System*
D. C. Barnes, L. Chacon, J. M. Finn

Posters, Tuesday 7:30 PM - 9:30 PM

2D52 *Electron Bernstein Waves in the Castor Tokamak*

J. Preinhaelter, M. Hron, F. Zacek, M. A. Irzak, E. Tregubova, L. Vahala, G. Vahala

2D53 *A ray-based algorithm for numerical computation of multi-dimensional linear mode conversion*

Allan N. Kaufman, Eugene R. Tracy

2D54 *A Collisionless Kinetic-Fluid Closure and its Properties for ∇T -driven Transport*

W. Horton, H. Sugama, T-H. Watanabe

Wenesday Morning

3A **Review Paper** Anasazi Ballroom, 8:30 AM - 9:30 AM, C. Sovinec presiding

3A01 *Quantum Computation*

R. Laflamme

Coffee: 9:30 AM—Sunset Room

3B **Poster Session** Sunset Room and Concourse, 9:30 AM - 11:30 AM

3B01 *Self-Similar Solutions with Good Flux Surfaces As Attractors for Reversed Field Pinches*

R. A. Nebel, D. D. Schnack

3B02 *Fast formation of magnetic islands in a plasma in the presence of counterstreaming electrons*

N. Attico, F. Califano, F. Pegoraro, G. Bertin, S. V. Bulanov

3B03 *Kinetic Interchange-Ballooning Stability of Geotail Flux Tubes*

C. Crabtree, W. Horton, H.V. Wong, J. Van Dam

3B04 *MHD Dynamic of Oscillating Field Current Drive*

F. Ebrahimi, S. C. Prager, J. C. Wright

3B05 *Steady-State, High-Bootstrap-Fraction Discharges: Prospects for DIII-D*

F. W. Perkins, T. A. Casper, P. A. Politzer

3B06 *Driven collisionless reconnection at a magnetic X-point*

J. J. Ramos, F. Porcelli and D. Strozzi

3B07 *Applications of the MARG2D formulation to internal and external MHD modes in a tokamak*

Shinji Tokuda

3B08 *Progress Toward Resistive DCON*

Alan H. Glasser

Posters, Wednesday 9:30 AM - 11:30 AM

3B09 *The Role of Plasma Rotation, Magnetic Shear and Radial Electric Field Shear for the Change of Internal Transport Barrier in JT-60U Plasmas*

H. Shirai, T. Takizuka, Y. Sakamoto, Y. Koide

3B10 *Split-Weight Perturbative Scheme for Gyrokinetic Particle Simulation of Shear-Alfven Waves*

W. W. Lee, J. L. V. Lewandowski

3B11 *Equilibrium, Stability and Transport in the LHD Stellarator*

Paul Garabedian, Mark A. Taylor

3B12 *MHD Shocks and Magnetic Helicity*

G. Craddock

3B13 *The role of magnetic perturbation during ICRF-heating in Tokamak plasmas*

M. Tribèche, R. Hamdi, H. Houili, and T. H. Zerguini

3B14 *Spontaneous Neoclassical Tearing Modes*

E. Fredrickson

3B15 *Reduction of islands in high-beta free-boundary stellarator equilibria*

S. R. Hudson, D. A. Monticello, A. Brooks, and A. H. Reiman

3B16 *Effect of neutral atoms on tokamak edge plasmas*

T. Fülöp, Peter J. Catto, P. Helander

3B17 *Field Reversed Configuration Formation Simulations with MACH2*

Michael H. Frese and George J. Marklin

3B18 *A Finite Volume Differencing Scheme that Exactly Preserves div(B)=0 on a Quadrilateral Mesh*

George J. Marklin and Michael H. Frese

3B19 *High Compression Inertial Confinement Fusion at Low Temperatures*

Heinrich Hora

3B20 *Non-Linear MHD Alfven Wave Current Drive in Axisymmetric Toroidal Plasmas*

R. Torasso, J. A. Tataronis, C. C. Hegna

3B21 *Development of a New Theory-Based Transport Model*

Glenn Bateman, Garold Borse, Arnold H. Kritz, Alexei Pankin, Aaron Redd, Bruce Scott, Jan Weiland

3B22 *Symmetry Breaking Localization of the Ballooning Instability in Compact Quasiaxially Symmetric Stellarators*

Martha H. Redi, John Canik, Robert L. Dewar

3B23 *Tokamak Equilibria with Sheared Flow*

Ch. Simintzis, G.N. Throumoulopoulos, G. Pantis, H. Tasso

3B24 *The Dynamo Effect of Externally Driven and Unstable MHD Waves*

J. C. Wright, S. C. Prager, C. Litwin

Posters, Wednesday 9:30 AM - 11:30 AM

3B25 *Spontaneous formation of stratified shear layers in a model of turbulence suppression by shear*

Diego del-Castillo-Negrete, Benjamin Carreras

3B26 *Nonlinear Gyroviscous Force in a Plasma with Nonuniform Temperature*

E. V. Belova

3B27 *Continuum Gyrokinetic Turbulence Simulations with Profile Shear Stabilization and Broken gyroBohm Scaling*

R. E. Waltz, J. Candy, M. N. Rosenbluth

3B28 *Use of Low Order Interpolation Schemes in Gyrokinetic Particle Simulation*

Scott E. Parker

3B29 *Mach 0.5 Jet Flow between Isothermal Walls using Lattice Boltzmann Methods*

Pavol Pavlo, George Vahala, Linda Vahala

3B30 *Ph.D.Radio-physics*

Olėh Borodyk

3B31 *Magnetic Dipole Configurations--Effects of Finite Larmor radius and non-uniform Equilibrium Electric Fields on MHD Stability*

J. V. Van Dam, H. Vernon Wong, W. Horton, M. Kotschenreuther

3B32 *A Backward Monte-Carlo Method for Parabolic Equations*

Johan Carlsson

3B33 *Temperature Pedestal Limits and ELMs: A Model Based on Full Spectrum Stability Analysis and Nonlinear Simulation*

P.B. Snyder, J. R. Ferron, L.L. Lao, M. S. Chu, A. D. Turnbull, H. R. Wilson, X.Q. Xu

3B34 *Gyrokinetic Turbulence Simulations with Trapped and Passing Kinetic Electron Physics*

Yang Chen and Scott E. Parker

3B35 *Nonlinear Prediction Filters for Loading-Unloading Dynamics as in Substorms and Sawtooth Events*

J. C. Sprott, C. Crabtree, W. Horton

3B36 *Feedback Stabilization of the Resistive Wall Mode in General Geometry*

M. S. Chu, M. S. Chance, M. Okabayashi

3B37 *Numerical Analysis of Singular Modes in Thin Accretion Disks*

I. Dimov, B. Coppi, J. Gagnon

3B38 *Kinetic Ballooning Mode in Low Aspect Ratio Plasma*

C. Z. Cheng, N. N. Gorelenkov

3B39 *Predictive Modelling of Axisymmetric Toroidal Configurations with CalTrans*

L. L. LoDestro, R. H. Bulmer, T. A. Casper, R. H. Cohen, T. B. Kaiser, L. D. Pearlstein, H. L. Berk

Posters, Wednesday 9:30 AM - 11:30 AM

3B40 *Dissipative Incompressible MHD using Octagonal Lattice Boltzmann Models*
Angus MacNab, George Vahala, Linda Vahala, Pavol Pavlo

3B41 *Predictive Transport Modeling with the Weiland Drift Wave Model*
Pär Strand, Johan Anderson, Hans Nordman, Jan Weiland

3B42 *Efficiently Finding Trends in Macroscopic MHD Stability Using Perturbed Equilibria: Review of Screw Pinch and Initial Application to Toroidal Geometry*
K. J. Comer, J. D. Callen, C. C. Hegna, S. C. Cowley, A. D. Turnbull

3B43 *Weakly Nonlinear Vlasov-Poisson Hamiltonian Dynamics*
T. W. Yudichak, P. J. Morrison

3B44 *Particle Hall-MHD Simulation of Collisionless Reconnection: Ion Gyro-Radius Correction*
L. Yin, D. Winske, J. Birn, and S. P. Gary

3B45 *Algorithmic Unification of Particle-In-Cell and Vlasov Methods*
Srinath Vadlamani, Scott E. Parker and Yang Chen

3B46 *Simulations of Field Reversed Configuration Plasmas with the NIMROD Code*
A. Tarditi

3B47 *Realizability in a Closure for MHD Turbulence*
Leaf Turner, Jane L. Pratt

3B48 *A Model for the Height of the H-mode Pedestal*
Thawatchai Onjun, Glenn Bateman, Arnold H. Kritz, Gregory Hammett

3B49 *Effect of Shear Damping and of the Ion Temperature Gradient on the Polarization Current near Magnetic Islands*
F. L. Waelbroeck, J. W. Connor, and H. R. Wilson

3B50 *Predictive simulations of energy and particle transport in LHCD discharges of Tore Supra using the Multi-Mode Model*
I. Voitsekhovitch, G. Bateman, A. Kritz, and A. Pankin

3B51 *Physics Properties of Compact, Low Field Period, Quasi-Poloidal Stellarators*
D. A. Spong, S. P. Hirshman, L. A. Berry, J. F. Lyon, R. H. Fowler, D. J. Strickler, A. S. Ware, D. Alban, R. Sanchez, G. Y. Fu, D. A. Monticello, W. H. Miner, Jr., P. M. Valanju

3B52 *Linear stability, mode structure and nonlinear behavior of drift tearing modes*
Maurizio Ottaviani, Daniela Grasso, Franco Porcelli

3B53 *Gyrokinetic simulations with kinetic electrons*
Z. Lin, L. Chen

Abstracts

Arranged in presentation order,
including Review, Oral, Poster and Special Sessions

1A01

Pattern Formation in Systems Far from Equilibrium

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Systems driven far from thermodynamic equilibrium and governed by nonlinear evolution equations display a wide variety of interesting behavior. One of the most generic is the formation of patterns that can occur near a bifurcation from a uniform state. Linear stability analysis is typically used to identify the simplest features of such patterns such as the characteristic length and time scales and the critical control parameter value. Building on that foundation one is led to weakly nonlinear analysis based on pertubation expansions in a small parameter such as the "distance" from the critical parameter value. Patterns that form can be ordered rolls, hexagons, squares or textured patterns with multiple defects or time dependent patterns of various types. I will use examples from a very well studied problem - Rayleigh-Benard convection - to illustrate the generality of this approach in the form of amplitude equations. In particular, the Ginzburg- Landau Equation describes stationary patterns where the system has the nonequilibrium analog of a free- energy minimization principle known as a Lyapunov functional. Traveling wave problems can be treated in a complex generalization known as the complex Ginzburg-Landau equation. I will use experimental examples to convey the success of this theoretical approach in a real physical system. I will then present two examples of harder problems that have interesting time dependence where the spatial textures of the patterns are complex and the dynamics are nonperiodic. Throughout my talk I will emphasize how experiment and theory have combined to give an impressive understanding of pattern formation far from equilibrium. Despite this progress there remain many outstanding problems when the nonlinearity can no longer be considered weak.

Resistive Wall Modes and Non-uniform Wall Rotation

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The resistive wall mode (RWM) poses a threat to many plasma confinement devices. Continuous rotation of the wall relative to the plasma can provide partial stabilization in that, because of the skin effect, the wall appears to the plasma as perfectly conducting. However, this is ineffective if the mode locks to the wall. The suggestion of a flowing lithium wall-blanket raises the question whether a non-uniformly rotating wall provides greater stabilization - since the mode presumably cannot lock to the wall at all points.

In this paper we analyze the effect of non-uniform wall rotation, in both the toroidal and poloidal directions, on resonant and non-resonant plasma perturbations. The basic equations involve only the flow velocity **V**, the wall resistivity, and a set of indices Δ'_m. These indices depend on the plasma profile but are independent of rotation; for our purposes they are considered given.

In the case of a poloidally varying *toroidal* wall rotation, we show analytically that for sufficiently large **V** both the resonant and non-resonant RWMs are stabilized, even though the non-resonant mode locks to the wall at its maximum velocity.

The case of *poloidal* wall rotation is different. In this situation RWMs are also stabilized by large wall velocity. However, they do not lock to the wall and can have a complicated behavior at intermediate velocities. In some cases modes that are purely growing at small V, acquire a complex frequency as the velocity increases before becoming stabilised at higher velocity.

For both toroidal and poloidal rotation we determine numerically the wall velocity required to stabilize RWMs in a typical tokamak.

This work is jointly funded by UK DTI and EURATOM and by US DoE.

Self-consistent Radial Electric Field and Neoclassical Transport

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The standard neoclassical transport theory is routinely compared with tokamak experimental results. In internal transport barrier region where plasma gradient is so steep that ion orbit width is comparable to the gradient scale length, ion thermal transport is observed to be significantly lower than the neoclassical level. Under these conditions, however, the standard neoclassical theory must be modified by the effects of finite orbits and the radial electric field. Without a self-consistent radial electric field, neoclassical particle transport is not ambipolar because of self-collision driven ion flux; ambipolarity requires the development of a radial electric field E_r. The electric field in turn affects the collisional transport rates through finite orbit effects, even though the neoclassical transport rates do not depend on the radial electric field in the limit of small orbit width. Here, neoclassical transport with finite ion orbits is studied, including for the first time, the self-consistent radial electric field, using a low noise delta-f particle simulation. We show how a self-consistent electric field guarantees neoclassical ambipolarity. We demonstrate the general feature of E_r dynamics: geodesic acoustic oscillations appear in the initial phase and then relax to a neoclassical quasi-steady-state through different damping mechanisms; the neoclassical E_r is subjected to further relaxation in transport time scale to equilibrium through angular momentum transport. The state-state E_r is found, regardless of the steepness of the density profile, to be consistent with the standard neoclassical expression for parallel flow(for uniform temperature and zero toroidal rotation, the expression reduces to the Boltzmann relation). A deep electric field well (with strong shear) is found in a region with steep density gradient. Ion thermal transport is reduced on the side of the well with negative E_r shear and increased on the outer side with positive shear, relative to the standard neoclassical level. This is consistent with the orbit squeezing effect of the E_r and is observed for the first time in numerical simulation. Also, the ion heat flux near the magnetic axis is largely reduced by the effects of finite orbits and the electric field. Preliminary results show that strongly sheared E_r and, possibly, sheared toroidal flow may modify the standard neoclassical poloidal flow through finite orbit effects.

This is a report of work supported by U.S. DOE Grant DE-FG03-95ER54309.

1B03

X-Transport as an irreducible baseline phemonenon for Er, H-Mode, and Edge Pedestal formation*

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General Atomics

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PPPL

A new classical transport mechanism has been identified which can be a robust baseline source of Er and edge pedestal formation immediately inside the separatrix surface in a diverted tokamak. A turbulence theory will need to use this new classical phenonemon as its irreducible basis, instead of the usual neoclassical phenomena. Due to the vanishing poloidal magnetic field near the X-point, plasma particles in the X-region cannot be subject to the usual tokamak confinement, but drift in to the divertor chamber if the Grad-B drift is in the proper direction. This X-transport is non-ambipolar and induces an ion-dominant loss, leading to a strong negative Er shear layer. The X- transport is fundamentally different from the usual orbit loss theories. It is a poloidally localized transport phenomenon to the X-region. It does not rely upon the wall-hitting of long-lived collisionless orbits. In fact the X-transport exists regardless of the ion collisionality or the presence of the first wall. The X-transport can explain many of the unresolved questions in the H-mode and edge pedestal observations, including the difference between single and double nulls, importance of Grad-B drift direction, insensitiveness to the ion collisionality, existence of a pedestal even in an L-mode, power threshold scaling, dependence on the X-position and flux shape, etc. The understanding may also lead to a simple scheme to suppress an H- mode transitioion in a tokamak reactor. Theoretical analyses and comparison with existing experiemental observations will be presented.

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Fully implicit, nonlinear resistive-Hall MHD computations of magnetic reconnection

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In Hall MHD, plasma transport effects and electron dynamics are included, resulting in disparate time scales and scale lengths (collisionless skin depths and resistive scale vs. system size). In addition, very stiff waves (whistler) are supported linearly, while nonlinear couplings introduce significant nonlinear stiffness. The stiff linear and nonlinear couplings involved have precluded the development of efficient, fully implicit numerical algorithms so far, and explicit and semi-implicit time stepping techniques have typically been employed. Explicit codes for Hall MHD are particularly inefficient because of the whistler wave CFL stability limit $\Delta t_{whistler} \propto (\Delta x)^2$. Semi-implicit algorithms succeed in enhancing the efficiency of Hall MHD calculations by eliminating wave CFL restrictions, but have time step restrictions for accuracy due to approximations introduced in the semi-implicit operator, operator splitting errors, and errors due to linearization.

A fully implicit treatment can potentially work around the issues of accuracy and efficiency, and present a viable path to 3D Hall MHD simulations. Here, we present proof-of-principle 2D compressible resistive [1] and 2D incompressible Hall MHD numerical codes with implicit, nonlinear time stepping. The solver combines Newton's method for nonlinear convergence, and Krylov-subspace methods for inverting the associated Jacobian systems. Newton-Krylov techniques are implemented Jacobian-free (avoiding computing and storing the Jacobian matrix), and require effective preconditioners for efficiency. Here, physics-based preconditioners are described. Implicit time steps with this algorithm are only limited by the dynamical time scale of interest. We routinely achieve $\Delta t > 250\Delta t_{Alfven}$ for resistive MHD, and $\Delta t > 500\Delta t_{whistler}$ for Hall MHD.

Numerical results on the efficiency and CPU time scalability with time step size and grid refinement will be presented. Hall MHD calculations for the linear and nonlinear regimes of the Hall MHD tearing problem (with the same configuration as in the GEM reconnection challenge) will be presented and compared against its resistive MHD counterpart. While in the resistive case there is a Sweet-Parker current sheet which can lead to plasmoid formation and coalescence, the Hall-MHD case results in a Petschek-like reconnection topology with violent oscillations on an Alfvénic time scale. The Hall-MHD case has a substantial enhancement of both the linear tearing growth rate ($\gamma \sim 1/\tau_{Alfven}$) and the maximum reconnection rate.

Novel resistive MHD calculations for the nonlinear regime of the parallel velocity shear/tearing instability [2] will also be shown. This resistive instability is driven by a parallel velocity shear flow interacting with a Harris current sheet in the poloidal plane via the magnetic field curvature. Linear theory predicts [2] that a tearing mode should grow even when the matching parameter $\Delta' < 0$. This is confirmed by direct numerical computations. Nonlinearly, when $\Delta' > 0$, a laminar saturated nonlinear state occurs in which a poloidal shear flow is generated spontaneously. When $\Delta' < 0$ and dissipation is small, the mode is electrostatic and the nonlinear state may be turbulent due to the existence of many unstable modes.

References

[1] L. Chacón, D. A. Knoll and J. M. Finn, "An implicit, nonlinear reduced resistive MHD solver," submitted to *J. Comput. Phys.* (2000)
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1B05

Streamers and Zonal Flow Dynamics in Edge Tokamak Turbulence

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Turbulent fluctuations at the edge of a tokamak plasma are characterized by the interplay of two different self-generated structures [1]: First, radially extended convection cells (streamers) build up intermittently and give rise to large scale transport events [2,3]. Second, the generation of poloidal zonal flows tends to self-regulate the turbulence. The impact of these features on turbulent transport is studied using two different three dimensional simulation codes related to resistive ballooning and ion temperature gradient turbulence [4]. The spatial structure of large scale transport events is found to adapt to magnetic shear [1]. The average turbulent flux is reduced by the generation of zonal flows that tend to increase the frequency of appearence of bursts and to reduce the amplitudes of single events. The turbulent flux is found to have inherent statistical properties so that its average value may be not sufficient for transport predictions. A generalized one dimensional transport model is derived [5,6] that includes the dynamics of streamers and zonal flows.

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1C01

Tearing Mode Marginal Stability in a RFP

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A Reversed Field Pinch (RFP) configuration for a magnetically confined plasma, is known to always be unstable vs. pressure driven resistive interchanges. It has been shown as well that the presence of resistive diffusive flow can have a stabilizing effect on Tearing Modes (TM) in a case with no pressure.

The goal of the present work is to analyze the influence of the diffusion velocity on plasma stability vs. TM, in a more general case of non-zero pressure. A third order system of ordinary differential equations is derived and studied both analytically and numerically, in order to derive a marginal stability criterion for RFP vs. TM.

This criterion will give a crucial condition for the next step, which will deal with the development of a transport model for RFP, based on the main assumption that the core of the plasma, within the field reversal surface, is in a highly turbulent state, dominated by small scale instabilities, resulting from tearing modes, which cause the profiles to relax to the marginal stability state.

Invariant Symbolic Cycles Distribution in Chaotic and Turbulent Dynamics*

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The method of computing symbolic cycles distribution function (SCD) is introduced. It is applied for the analysis of uncorrelated signals generated by chaotic and turbulent models. Results of our computations demonstrate that SCD is invariant with respect to fluctuating variables chosen for computations. This new distribution contains information about nonlinear stability of cycles and is much more informative than Fourier power spectra which does not possess invariance property. Method presented in this paper has been also applied for the analysis of turbulent hydrodynamic fluctuations measured in water flow in a pipe (Mason Laboratory at Yale University) and turbulent plasma fluctuations measured in the tokamak (MIT).

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Calculation of gradient scale lengths in the edge pedestal

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A 'pedestal model' for the calculation of characteristic scale lengths in the steep-gradient region in the edge of H-mode plasmas is proposed. The density gradient is calculated from the net particle current passing through the edge and the ionization rate, and the temperature gradient scale lengths are calculated from the net heat fluxes passing through the edge and atomic physics cooling effects. The allowable values of these gradient scale lengths are constrained by a pedestal beta limit critical pressure gradient constraint [1] of the form given by ideal first stability ballooning mode theory, but with an enhancement factor. The model has been incorporated in a coupled calculation of the core plasma and divertor plasma power and particle balances and a recycling neutral calculation [2]. Model problem calculations reproduce the magnitude and several trends of the characteristic scale lengths observed experimentally. The model should be of value as a framework for the correlation of experimental measurements of characteristic pedestal scale lengths and, ultimately, for the prediction of characteristic pedestal scale lengths in future devices.

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Hybrid Magnetohydrodynamic-gyrokinetic δf PIC simulation of energetic particle excitation of Alfven modes in a magnetic dipole configuration*

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A hybrid gyrokinetic-magnetohydrodynamic δf PIC simulation code is used to study high-m ($m \gg 1$ is the azimuthal wavenumber) Alfvén ballooning and drift-Alfvén-balooning modes excited by energetic particles in plasmas in a dipole magnetic field. An anisotropic (bi-Maxwellian) energetic particle distribution is assumed, and the self-consistent energetic particle effect on the equilibrium magnetic field is incorporated [Chan, Xia, Chen; JGR **99**, 17351 (1994)]. Full kinetic effects such as finite Larmor radii and particle magnetic bounce and precessional drift motions are retained nonperturbatively. While perturbative analytic studies [Chen and Hasegawa; JGR **93**, 8763 (1988)] show that the lowest odd mode is the most unstable, our nonperturbative initial value simulations demonstrate that the even mode can be equally important. In this paper we examine the stabilizing/destabilizing effects of plasma compression and the ballooning term on odd and even modes. Growth rates, real mode frequencies, and critical beta values for both odd and even modes are presented with reference to the anisotropy in the energetic particle distribution. Detailed comparisons with analytic theories will also be presented in order to elucidate the underlying wave excitation mechanisms.

*Supported by DoE and NSF grants
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A Neoclassically-Consistent Model of Nonlinear RF-Driven Sheared Flows*

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The modification of background plasma flows in a tokamak by applied rf is of interest as a possible means of controlling turbulence, and triggering the formation of internal transport barriers. Previous sheared-flow drive calculations [1][2][3] have neglected some toroidal features of the problem, including the coupling of poloidal and toroidal flows and related ambipolarity considerations. Here we begin with a neoclassical approach to the problem, along the lines of Ref. [4]. A formalism is developed to enable i) an evaluation of localized (in radius) poloidal and toroidal forces by the rf, ii) a rigorous calculation of the resulting poloidal and toroidal flow rates in the presence of neoclassical damping due to plasma viscosity and a phenomenological radial diffusion of momentum, and iii) implicit treatment of ambipolarity issues in the presence of rf.

We consider the case where the driving rf forces are due to the localized absorption of rf waves in a radially narrow resonance layer in which both the hot plasma Larmor radius effects and rf dissipation play important roles. When the net momentum imparted by the wave to the plasma is small, there is no bulk rotation driven, but there can be layers in which local bipolar flows survive and the resulting sheared flow is strong. Drawing on previous work, [3] which was developed for arbitrary hot plasma electromagnetic waves, the relevant rf force components are obtained for input to the neoclassical formalism.

The rf interactions with the plasma are treated to all orders in $k\rho$, allowing a description of the ion Bernstein wave (IBW), which is at present the leading flow-drive candidate that is emerging from rf simulation [2] and from experiment. As an example, we consider IBW interaction within a narrow resonant ion-cyclotron layer where the wave absorption and sheared flow drive occurs. The effect of wavenumber orientation both perpendicular and parallel to the magnetic field is addressed and the resulting flows are calculated relative to the power absorption.

References

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Microinstability analysis of experimental NSTX plasmas*

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High beta spherical tokamak plasmas present exciting prospects regarding unexplored microinstabilities properties. High beta operation in the National Spherical Torus Experiment (NSTX) and the recent commissioning of profiles diagnostics enable, for the first time, examination of the microinstability properties of these regimes. Initial studies of such plasmas are presented here. Unlike in standard tokamaks, the magnetic perturbations play a dominant role in these plasmas. Therefore an accurate microinstability analysis cannot neglect them compared to the electrostatic perturbations. Also, the geometric magnetic configuration of a low aspect ratio ma chine causes important changes. In fact, the trapped particle wells and the regions of maximum curvature and ∇B drifts can be localized at poloidal angles other than zero. Finally, the $\mathbf{E} \times \mathbf{B}$ shear is expected to be higher because of the strong spatial variation of $\mathbf{B}$. Before performing stability analysis using linear gyrokinetic codes, a benchmark between two of these codes has been done to verify the accuracy of the physics treatment of magnetic perturbations. The codes used are the eigenvalue code FULL [1, 2], and the initial value code GS2 [3]. The GS2_PREP code is used to automate GS2 calculations. Both FULL and GS2 take into account the perturbed electrostatic potential as well as both components of the perturbed magnetic potential $\delta A_{\|}$ and $\delta A_{\perp}$. Although they are using two very different computational methods, both codes find the same behavior of the kinetic ballooning modes above the same critical value of beta. The effect of $\delta A_{\perp}$ on the growth rates reaches up to 35% on the kinetic ballooning modes branch. The agreement on the absolute value of the frequencies of unstable modes between the two codes across a beta scan lies within 15%. Ion temperature, toroidal velocity, and electron temperature and density profiles are now being measured on NSTX. The magnetic equilibrium is reconstructed by EFIT. The growth rate evaluations for these plasmas will be presented here. This microinstability analysis is performed using the two benchmarked codes. This approach allows cross-checking between both tools while exploring new types of plasmas.

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Rogue waves in plasmas*

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A basic problem in the study of nonlinear waves is to develop an understanding of the full range of behavior that is possible in a given physical circumstance. As a specific example: consider nonlinear wave trains subject to modulational instabilities. What is the long-term behavior of such systems? How likely are they to develop high amplitude localized transient pulse (which we call 'rogue' waves)? Can these pulses be predicted in advance? Can they be controlled (e.g. can they be suppressed or shaped)? In this poster we report on recent developments in the analytical theory of unstable nonlinear waves. We focus attention on the nonlinear Schrodinger (NLS) equation ($iq_t + q_{xx} + 2|q|^2 q = 0$) which is solvable via the Inverse Scattering Transformation (IST). Using the IST, a new class of 'rogue wave' solutions of the NLS has been found (Osborne and Tracy, in preparation). Here we discuss the physical interpretation of these new solutions and the statistical distribution of rogue waves.

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Two Fluid Tearing Instability In Force Free RFP Configuration

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Tearing instabilities play an important role in reversed field pinch (RFP) physics. They are responsible for the relaxation to the Taylor state, dynamo effect, formation of islands, anomalous radial transport in stochastic magnetic field and so on. As RFP experiments obtain higher temperatures, the viability of standard resistive MHD models for the plasma dynamics becomes questionable. In this work, we include two-fluid effects in the theory of tearing instabilities to more closely model parameters of experimental relevance. In particular, the effect of a guiding magnetic field is included in the analysis which is present in the RFP, but absent in many theoretical treatments of Hall-MHD and collisionless reconnection.

The analytic theory is developed for a plasma in slab geometry with a force free equilibrium as a crude model for the RFP near a rational surface. Uniform density, temperature and pressure profiles are assumed for both electrons and ions. The equilibrium magnetic field consists of a small shearing magnetic field and large guiding magnetic field. The collisionless effect of electron inertia and finite resistivity are taken into account as a means to break the frozen flux theorem. Interaction of three plasma modes which are decoupled in uniform magnetic field (shear Alfven, acoustic and fast magneto-sonic) is considered on the basis of three second order differential equations. With a two fluid model, additional length and time scales enter the problem in the form of whistler and ion sound radius effects. They describe mutual fluid and electron motion (Hall effect) without an assumption of incompressibility. This approach allows us to calculate the rates of reconnection in a wide range of parameters. We investigate the transition from pure electron MHD which takes place in a weak guiding field and has a high growth rate to the case of strong guiding field which is similar to the usual resistive MHD and driven by the fluid motion.

Kinetic Electron Closure for Electromagnetic Simulation of Drift and Shear Alfven Waves*

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Nonadiabatic electron effects significantly modify the stability and concomitant turbulent transport of drift- waves in tokamaks. Incorporating electron kinetic and electromagnetic effects into gyrokinetic particle-in-cell drift-wave turbulence simulations is computationally challenging: electrons and electromagnetics introduce additional time and space scales that alter numerical stability, increase temporal and spatial resolution requirements and, hence, increase the computational burden. Here we extend the electromagnetic hybrid scheme of Chen and Parker (fluid electrons and gyrokinetic ions, see Y. Chen and S. Parker, Phys. Plasmas **8**, 441 (2001)) to include a kinetic electron closure valid for finite β, where $\beta=4\pi nT_e/B^2$. This new scheme incorporates partially linearized δf drift-kinetic electrons whose pressure and number density moments are used to close the fluid momentum equation for the electron fluid (Ohm's law) using the departure of the perturbed kinetic pressure from the isothermal perturbed pressure response. Comparisons are made between the results of the hybrid scheme with kinetic electron closure, the purely fluid electron hybrid scheme, and a conventional δf algorithm for drift-kinetic electrons and gyrokinetic ions in a two-dimensional slab model. The test cases used are small amplitude kinetic shear-Alfven waves with electron Landau damping, the ion- temperature- gradient instability, and the collisionless drift instability (universal mode) in an unsheared slab as a function of the plasma β. The hybrid scheme has the desirable properties that it does *not* require that the mesh size perpendicular to the applied magnetic field be smaller than the skin depth c/ω_{pe} and naturally accommodates zonal flow physics (radial modes) with non-adiabatic electron effects. The algorithm introduced here for the kinetic electron extension of the hybrid scheme of Chen and Parker gives very good results for $\beta m_i/m_e>1$ and poor results for $\beta m_i/m_e<1$.

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Magnetohydrodynamic Equilibria with Poloidal Flow

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A major issue for MHD equilibrium and stability of tokamak plasmas is one of plasma rotation. Recent theoretical results have indicated that equilibria with poloidal flow exhibit some interesting features which can significantly affect the macro and micro stability of tokamaks. The main effects of poloidal flow are: the stabilization of the resistive wall mode, the stabilization of the resistive kink mode [1], and the mitigation of turbulent transport [2]. The last two are induced by the shear in the flow velocity profile. MHD equilibria with poloidal flow are extremely interesting and attractive for a toroidal device as they allow a set of solutions with a velocity sheared layer in the region where the flow velocity equals the poloidal sound speed $C_{s\theta} = C_s B_\theta / B$ (transonic flow). It has been recently discovered [3] that the equilibria with poloidal flow have radial discontinuities not only in the velocity, but also in the density, temperature and pressure profiles at the flux surface where the flow is transonic. Note that the poloidal sound speed vanishes at the center (because B_θ=0) and at the edge of the plasma column (because $C_{s\theta} \sim \sqrt{T} \approx 0$) implying that even when the flow is subsonic over most of the plasma cross section, a transonic surface can exist near the plasma edge and/or near the plasma center. Other interesting equilibria are obtained when the poloidal flow velocity is of the order of the poloidal Alfven speed. In this case, the Grad-Shafranov equation yields a set of solutions with a magnetic axis shifted towards the inner side of the torus when the flow velocity exceeds a critical value. Such an equilibrium is maintained by the centrifugal force that is peaked on the inner side and balances the pressure forces pushing outward. We have also performed a set of two dimensional simulations of a poloidally rotating plasma that relaxes to a quasi-equilibrium configuration. Both numerical and analytic results are compared and presented at this conference.

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A Global Optimization Algorithm for Stellarator Design *

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The search for attractive stellarator designs has been greatly enhanced by the development of optimization codes which search configuration space **Z** using a specified cost function. The NCSX design team has relied heavily on such an optimizer (Stellopt) for its work, which uses a Levenberg-Marquardt (LM) algorithm. While efficient in suitable cases, the LM algorithm can become trapped in local minima of the cost function, in the large and sometimes highly corrugated Z-space. To surmount this difficulty, and perform more global searches in Z-space, we have implemented a variant (Stellopt-DE) of Stellopt, which uses a "differential evolution" (DE) algorithm[1], which is far less prone to become locally trapped, and thus permits a more robust, though more time consuming, exploration of Z-space. We apply the DE algorithm to studying the Quasi-Axisymmetric configurations being investigated for the NCSX project, covering a broader domain of Z-space than has been used for the LM-based studies.

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SOME SINGLE-PARTICLE ASPECTS OF APPROACH TO SELF-ORGANIZATION OF A TOROIDALLY CONFINED PLASMA*

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We construct a simple mean-free model based on the single-particle picture of plasma to throw some light on the now well known self-organization of a plasma confined in toroidally confining device like the tokamak that has the ultimate aim of confining thermonuclear plasmas. Instead of following either the MHD model or other well-known plasma models, a simple single particle approach is followed in the paper. MHD theory based approaches have been used in the past to model nonlinear dynamics through bifurcations to account for the high confinement regimes of the toroidal plasmas. We consider certain other bifurcation phenomena using the single-particle approach.

The aim is to see if simple mean-free models like the Bragg-Williams model or the x-y model can be constructed to describe the self-organizational tendencies in such plasmas. We start by considering the interaction of a couple of current elements near a particular axis-symmetric magnetic surface in a cross-section. Our interest includes gyro-phase self-organization in such a device. The calculation is then extended to include a large number of current elements. It is seen that for large enough currents, there is a certain kind of pinching of the currents that is also responsible for self-organization of the safety factor.

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1C13

Fusion Reactor Control

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The plasma kinetic temperature and density changes, each per an injected fuel density rate increment, control the energy supplied by a thermonuclear fusion reactor in a power production cycle. This could include simultaneously coupled control objectives for plasma current, horizontal and vertical position, shape and burn control. The minimum number of measurements required, use of indirect (not plasma parameters) system measurements, and distributed control procedures for burn control are to be verifiable in a time dependent systems code.

The International Thermonuclear Experimental Reactor (ITER) has the need to feedback control both the fusion output power and the driven plasma current, while avoiding damage to diverter plates. The system engineering of fusion reactors must be performed to assure their development expeditiously and effectively by considering reliability, availability, maintainability, environmental impact, health and safety, and cost.

Convective Transport in Tokamak SOL Plasmas*

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Recent measurements on C-MOD and other fusion devices shows that non-diffusive transport of particles can play a major role in the SOL. The mechanism for this transport is not yet understood. One possible mechanism for fast convective plasma transport in the SOL may be related to the plasma filaments observed in experiments with both fast cameras and probes. Previous work [1] suggested that high density plasma filaments or "blobs" (highly localized perpendicular to **B** but with extended structure along **B**) could detach from the bulk plasma, possibly as a result of turbulence, and would propagate to the outer wall due to the curvature-drift induced polarization and the associated $\mathbf{E} \times \mathbf{B}$ radial drift. In the present paper, we extend the physical arguments of Ref. 1 by calculations using a two-field (density, potential) fluid model. The properties of high density blobs are elucidated and extended to include the effects of vorticity. Conditions for blob existence and propagation are calculated. It is shown that ionization of background neutrals can be important in sustaining the blob against parallel flow losses as it transits across the SOL. Blobs with high vorticity and constant background density are also investigated and the relation between these and density filaments is explored.

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Driftwave Growth Rate Comparisons Between the GLF23 Transport Model and Real Geometry Gyrokinetic Stability Calculations

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The GLF23 transport model [1] was derived for circular geometry $s-\alpha$ model and normally applied in the electrostic limit. Transport from the model vanishes when the $E \times B$ shear rate ($\gamma_{\rm E}$) exceeds the maximum growth rate ($\gamma_{\rm max}$). The model has been successful in reproducing the observed profiles in a wide range of L–, H–mode, and Internal Transport Barrier discharges [2]. Over nearly a hundred shots from DIII–D, TFTR, and JET, the RMS error in the incremental confinement time (excluding the pedestal) is within 15%. Nevertheless, there is some indication that model overpredicts the thermal transport for L–mode discharges where the $E \times B$ shear effects are smaller and the net growth rates ($\gamma_{\rm max} - \gamma_{\rm E}$) is larger suggesting the model could be improved with more accurate growth rates and thresholds. Work is now underway to compare the linear growth rates from the model against a version of the GKS gyrokinetic stability code [3] extended to real geometry using a local equilibrium model by Miller *et al.* [4]. Systematic parameter scans are conducted to compare the GLF23 rates against the GKS rates in both $s-\alpha$ and real geometry in order to assess the effects of plasma shaping on the growth rates. Possible extensions of the GLF23 transport model are considered in order to capture at least some of the dependencies of non–circular geometry. In particular, an effective B–field increasing linearly with elongation [5] is considered. This alters the gyro-radius resulting in a lower diffusivity at higher elongation.

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Structural stability of the Grad-Shafranov equation: transport barriers and fragile equilibria

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An equation, such as G(u)=0, is said to be structurally unstable (or critical) if a small perturbation of the equation (the operator G) leads to an essential change in its solution. Essential changes are changes in existence and multiplicity of solutions. A solution u of a critical equation is called a critical solution

The theory of structural stability of polynomial equations is well known [1,2]. We derive its generalisation to quasilinear partial differential equations. A simple analytical criterium for structural instability is derived.

The structural stability of the tokamak plasma equilibrium equation is then considered in detail. We discuss how criticality relates to equilibrium fragility and multiplicity of equilibrium states near the critical equilibrium. In tokamaks, criticality is associated with non-monotonic toroidal current density profiles inside the plasma.

In particular, we present the equilibrium conjecture: criticality, leading to multiple solutions, is related to the sudden appearance of steep gradient regions in tokamak plasmas: "transport barriers". We show how a transport barrier could be associated with a steep gradient of the poloidal flux, Ψ, and with local diamagnetism in the plasma. This explains why all profiles, including the electric potential, typically exhibit steep gradients at roughly the same location.

Also, criticality may point to fragile solutions, thereby providing a very simple criterium for identification of potentially MHD unstable regions in the plasma.

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1C17

Kinetic Theory of Macroscopic Modes for Spherical Inertial Electrostatic Confinement

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Intensive theoretical and experimental research on Spherical Inertial Electrostatic Confinement (SIEC) has been carried out over several years at the U. of IL . In a SIEC, ions produced near the wall of a spherical vessel are accelerated by a negatively biased (~ -100kV) spherical mesh grid towards the center, forming a high-density ion core region where fusion reactions occur. Due to the non-Maxwellian and non-neutral character of this core plasma, the fluid description frequently employed to analyze equilibrium and macroscopic stability is inadequate. Thus a kinetic description is employed. A force balance equation is used to describe MHD equilibrium changes to stationary Vlasov and Poison's equations. Using a stationary solution to the kinetic equilibrium state, Vlasov's equation is linearized with respect to perturbed quantities. The perturbed potential is expressed in terms of a product of Legendre's spherical functions and spherical Bessel's functions. The perturbed distribution function is then obtained by integrating the linearized Vlasov's equation along zero-order particle trajectories. Upon substituting this distribution function into the linearized equations, a dispersion equation is obtained that determines stability and a computer -based code is used to calculate each perturbation mode. Resultant conditions for stability of an SIEC against a spherically symmetric perturbation will be presented.

1C18

Virtual Cathode in a Stationary Spherical Inertial Electrostatic Confinement

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"Double-well" potential structure (virtual cathode) is studied in a stationary sherical inertial electrostatic configuration (SIEC). We consider a case where ions and electrons are collision-free and whose velocities are roughly aligned towards the center, but with a slight divergence.

A solution to Vlasov's equation gives the ion density and the electron density that is needed to determine a self-consistent profile of electrostatic potential. A force balance equation (as is Grad-Shafranov's equation in MHD theory) is satisfied automatically. Instead, we have to obtain the solution to Poisson's equation to determine the self-consistent potential profile. The integral-differential equation can be simplified significantly by introducing an approximated expression for particles densities.

Analyses show that the angular momentum of ions and smaller one of electrons create a virtual cathode, i. e. a double well structure of the electrostsatic potential on a potential hill near the center. A density limit of an SIEC is discussed and condition relevant to yield deep potential well is presented.

1C19

Profile Consistency of a Field-Reversed Configuration*

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The new theory described here shows that, in contrast to a tokamak, the equilibrium profile of a FRC is nearly completely determined by a few global quantities.

Previous calculations of FRC equilibria have observed an extreme sensitivity of the solution to the pressure profile. The present analysis shows that the pressure is not a free function, but is nearly completely determined. In the limit of large elongation, the closed-field pressure profile of a FRC is completely determined in terms of the open-field profile. The open-field profile may be specified only within very strict limits, so that the closed-field profile is essentially invariant. Two surprising constraints are that: 1) there is always a jump of a factor of two in the pressure gradient p' across the separatrix; and 2) the open field plasma forms a $\beta = 1$ θ-pinch at the outflow (axially beyond the ends of the closed-field region). These conclusions from leading-order (in inverse elongation $\varepsilon = r_w / z_s$, wall radius divided by separatrix ½ length) equilibrium determine radial profiles and global quantities as a function of experimental observables. Thus, the excluded flux and separatrix β are found as functions of (normalized) separatrix radius and compared favorably with experimental observations. To leading order, any axial profile (separatrix shape) is allowed. It is shown that the axial profile is uniquely determined by the order ε^2 equilibrium, consistent with the observed sensitivity of elongated solutions. The pressure profile is determined through order ε^2 and 2D solutions are found by solving the Grad-Shafranov equation for a variety of separatrix shapes. The consequences of this profile consistency for FRC formation and transport are briefly discussed.

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Angular Momentum "Generation" and Transport in Axisymmetric Plasmas*

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The accretion theory [1] of spontaneous toroidal rotation [2] connects this phenomenon to the energy particle transport properties of the plasma column and to the relevant collective modes. The consequent prediction that an inversion of the velocity direction in the transition from the H to the L regime should occur has been verified by the experiments [3,4]. The theory is consistent also with the observation that the velocity is depressed when a peaked density profile appears as a result of a transport barrier [5]. The fact that the rotation velocity increases with the total energy content is explained by the fact that the inflow of angular momentum, whose source is at the edge of the plasma column, results from the excitation of modes driven by the plasma pressure gradient. A quasi- linear derivation of the angular momenutm transport produced by these modes, whose novel feature is the inflow, is given and a model of the relevant (transport) equation is solved. Fluctuations at the edge of the plasma column are considered responsible for the scattering, out of confinement, of particles that transfer, to the surrounding material wall, angular momentum in the same direction as that of the phase velocity of the prevalent modes. Thus the fact that the plasma rotates in the direction of the ion diamagnetic velocity of the H-regime, when the prevalent modes are expected to have phase velocity in the direction of the electron diamagnetic velocity, can be explained and the rate of rotation decrease, as the plasma current is increased, can be justified.

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Anomalous Angular Momentum Transport and the Structure of Turbulence

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We study the problem of spontaneous plasma rotation in toroidal devices. In the accretion theory the angular momentum is created at the outer wall and it is anomalously transported toward the center by the gradient driven instabilities, due to the inhomogeneities of the radial profiles.

With this work we gain insight in the theoretical understanding of the connection between the proprieties of the plasma fluctuations and the features of the stationary rotation state of the plasma column, observed in the experiments.

In particular, we propose a simplified model of turbulence, in order to study the flux of angular momentum obtained with the quasilinear theory, and we show, using this model, that a small unbalance of the turbulent spectrum toward values of $k_\phi k_\theta > 0$ must be assumed in order to understand experimental observations.

Angular Momentum Transport in Thin Accretion Disks and Intermittent Accretion*

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The modes, which can transport angular momentum outward in thin accretion disks, under the least restrictive conditions, are shown to be of the singular type when the ideal MHD approximation is adopted. Thus, a similarity with the theory of the better known modes, which produce magnetic reconnection in current carrying plasmas, is established. The combined effects of finite plasma temperature, of plasma compressibility, of the gradient of the rotation frequency and of small but not negligible transport coefficients (i. e. , violation of the ideal MHD approximation), are shown [1] to be needed for the onset of these non axisymmetric modes in realistic magnetic field configurations where both a vertical and a toroidal component of the field with the same magnitudes are present. By contrast, the ballooning mode form of the ideal MHD axisymmetric instability, which can fit in a thin disk, is derived [1] and demonstrated to be difficult to excite. Thus, accretion is envisioned as an intrinsically intermittent process, similar to that of the so-called sawtooth oscillations observed in magnetically confined laboratory plasmas. This process involves a preheating phase of accumulated matter in the outer regions of the disk followed by a phase of infall under the effect of gravity when the modes that allow for the needed transport of angular momentum are excited.

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Extended MHD simulations of DIIID 86144.*

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Modern fusion plasma experiments are rich in low-frequency, long-wavelength electromagnetic (i.e., MHD-like) activity. An example is discharge number 86144 from the D3D experiment at General Atomics Corp. in San Diego. This hot plasma has a Lundquist number S of about 10^8, and a magnetic Prandtl number Pr [the ratio of the (perpendicular) viscous diffusion time to the resistive diffusion time] of about 100. For the first 2250 milliseconds of the discharge, the plasma internal energy, increases in response to the energy injected by the neutral beam. This first phase of the plasma discharge is a self-sustaining system with good confinement, but also exhibits quasi-periodic oscillations in the n = 1 magnetic signal (sawtooth oscillations), and occasional bursts in the edge spectroscopic signal (ELM's, or edge localized modes. After 2250 milliseconds the nature of the discharge changes dramatically, when an m/n = 3/2 magnetic perturbation appears and grows to large amplitude, while the sawtooth (n = 1) oscillations continue unabated. In this second phase the internal plasma energy fails to increase in response to increases in the injected neutral beam power, and the ELMs occur much more frequently. After 3340 milliseconds, the nature of the discharge again changes dramatically when a large m/n=2/1 magnetic perturbation locks to the wall and the plasma disrupts. This typical discharge illustrates important nonlinear physics that can not be described solely with resistive MHD equations.

Extended-MHD is a successful attempt to overcome the limitations of the resistive MHD model by inclusion of additional physics in the resistive MHD model which includes: two-fluid terms (Hall and electron inertia), kinetic based forms of the viscous stress-tensor (gyro-viscosity and neoclassical), energetic hot particles, and also realistic boundary conditions (vacuum and resistive wall). Simulations from the NIMROD code based on extended MHD models which explore D3D shot 86144 will be presented that first demonstrate that resistive MHD is insufficient to describe the discharge. Specifically, the resistive MHD model will predict saturation of the perturbation associated with the sawtooth; an instability associated with medium n resistive ballooning modes, no tearing instability during the second phase, and no mode-locking/disruption at the end of the discharge. The extended-MHD simulations will demonstrate the importance of anisotropic thermal diffusion on the sawtooth oscillation during the first phase of the discharge; scaling of the magnetic perturbation and seed island generated by the 1/1 as a stimulus for the neoclassical tearing mode in the second phase; the nonlinear growth and saturation of the neoclassical tearing mode during the second phase, and the termination of the discharge with a resistive wall mode in the final phase.

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NUMERICAL STUDIES OF HIGH-BETA DISRUPTION IN DIII-D SHOT 87009 USING THE NIMROD CODE

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We are using the NIMROD code to study a high-beta disruption that occurred in DIII-D shot 87009, a discharge with reversed shear and large triangularity. Previous analysis [1] has suggested that the disruption occurred as the plasma was heated by neutral beams beyond a critical pressure limit. In the present work a conducting wall is placed at the last closed flux surface, so the value of beta-normal corresponding to the marginal stability point is larger than it is experimentally. Equilibria are obtained from TOQ [2] calculations using experimental profiles. Above the ideal marginal point the discharge is unstable to a rapidly growing global n=1 mode. Below the ideal marginal point, a slower growing resistive mode occurs that is localized at the outer q=2 surface. Converged linear results, and comparisons with GATO above the ideal marginal point, are presented. In the nonlinear regime, the the pressure is slowly increased from just below the marginal point, and the onset and evolution of the ideal mode is followed in time. Results showing the nonlinear evolution, and comparisons with theoretical predictions [1], will be presented as available.

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1C25

Gyrokinetic δ-f particles in a finite element MHD simulation

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Preliminary results from the implementation of gyrokinetic δ-f particles in NIMROD (Non- Ideal Magnetohydrodynamic with Rotation, Open Discussion) is presented. NIMROD is a 3-D, parallel MHD simulation that utilizes finite elements allowing the simulation of general geometries in fusion devices. With the inclusion of kinetic particle, we will be able to study the effects of alpha particle stabilization on internal kink modes (and other kinetic particle effects) in real geometry fusion devices. The implementation of particles in an unstructured finite element grid requires addressing the issues of efficient tracking of particles in the finite element grid, gathering field information to advance the particles, and scattering particle information (e. g. hot particle pressure or current contribution) onto the finite element grid. Implementing δ-f particles introduces additional complexities. In particular, proper particle loading to represent a given distribution function on a non-uniform grid is especially important. Details of the implementation will be presented as well as preliminary results of kinetic effects on the stabilization of MHD modes.

Nonlinear, Initial-Value Simulations with the NIMROD Code Including the Vacuum Region

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MHD stability limits in experiments depend on the presence of a vacuum region and on the location of a (geometrically- complicated) conducting wall. The NIMROD code currently models the vacuum region as a highly resistive region. To track the movement of the plasma- vacuum interface, a scalar variable is advected from which the resistivity is derived. This method, which is similar to techniques used in the field of two- fluid computational fluid dynamics [1], has the advantage of being computationally tractable, and allowing more complicated models of the vacuum region to be implemented. The implementation of this model into the NIMROD code is discussed along with recent results using the new higher-order element version of NIMROD.

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1C27

Derivation and implementation of time-dependent, neoclassical electron heat flux closure in NIMROD*

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Rapid electron heat flow along magnetic field lines represents a dominant process in nearly collisionless plasmas possibly leading to anamolous transport in reverse field pinches and tokomaks [1] and neoclassical tearing modes in tokamaks [2]. This work seeks to improve the understanding of and the ability to simulate electron heat flow by deriving a kinetic closure for the heat flux and implementing this closure in a plasma fluid code. A solution of an electron drift kinetic equation that includes time-dependent, free-streaming and particle-trapping effects is presented. This solution involves a flow- and heat-flow-conserving collision operator which is approximately valid for arbitrary collisionality, an average over the rapid bounce motion of electrons in magnetic wells which accounts for free- streaming and trapping effects and an integration along characteristics which incorporates time dependence into the expression for the heat flux closure. The explicit implementation of the heat flux in the nonlinear fluid code NIMROD [3] is described and results are presented regarding a calculation of an effective, radial thermal diffusivity, χ, for heat transport along a chaotic magnetic field [4]. Results show an order of magnitude reduction in the effective χ when particle trapping and time-dependent effects are included in the electron heat flux closure. Additional calculations of heat transport in the presence of helical magnetic islands will be discussed.

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Toroidal Geometry Effects in the Low Aspect Ratio RFP*

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Most numerical simulations and analytic calculations for the reversed-field pinch (RFP) have been performed in periodic linear geometry, which is usually a good approximation. Among perturbations that are resonant in the average magnetic field distribution, the strongest coupling is between those resonant in the core (m=1 perturbations) and those resonant at the q=0 "reversal" surface (m=0 perturbations). A strong nonlinear coupling between these m=1 and m=0 perturbations exists for standard multi-helicity states in linear geometry [1], regardless of toroidal effects. Therefore, additional coupling due to toroidal effects is not significant, particularly at large aspect ratio. In addition, pressure gradients cannot stabilize tearing modes, since q<1 [2].

In regard to the existence of single-helicity states, however, toroidal effects should be considered. These sustained states represent a laminar version of the RFP dynamo [3], where most nonlinear couplings are absent. Nonlinear resistive MHD simulations performed with the NIMROD code [4] show that conditions leading to single-helicity states in periodic linear geometry excite both m=0 and m=1 perturbations of the same toroidal index (n) in toroidal geometry. Whereas the linear geometry computations produce large helical island chains without stochastic field, toroidal geometry leads to stochastic field in the core. Our study examines the resulting field configuration as the aspect ratio (R/a) and pinch parameter are varied. The narrowing of the fluctuation spectrum with decreasing R/a demonstrated in linear geometry [5] is also present in toroidal geometry, but it does not culminate in single helicity at low R/a.

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Field-line Stochasticity of the Stabilized Pinch, Theory and Measurements, and Flux Conversion in Astrophysical Dynamos

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Non-linear time-dependent equations of resistive magnetohydrodynamics have been solved numerically for spheromak formation starting from the stabilized pinch configuration. Poloidal magnetic flux imbedded in the electrodes undergoes "flux amplification" as an unstable helical kink mode saturates [1]. Redistribution and conversion of flux changes the field line mapping between electrodes from an integrable mapping to a chaotic mapping [2]. The chaotic nature is evident from Poincare surfaces of section and from plots of field line length as a function of electrode intercept location. Previously, measurements of these magnetic field line trajectories have been made as a function of time during formation of a laboratory stabilized pinch, using a short pulse (10^{-8} s) high energy (0. 5 MeV) electron beam imaged on a phosphor screen electrode [3]. A comparison between these observations and the numerical simulation results will be presented.

The configuration of a stabilized pinch with applied electrostatic fields is topologically similar to an astrophysical accretion disk around a black hole where magnetic field lines intercept the differentially rotating disk. The physics of spheromak-like flux conversion and its associated dissipation can shed light on several long-standing astrophysics puzzles including the stability and large-scale structure of the jet, the origin for strong magnetic field collimation, and the dissipation of magnetic energy, which eventually leads to particle acceleration and synchrotron radiation.

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Nonlinear Evolution of Driven Ideal MHD Instabilities*

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Ideal MHD is quite successful in determining the equilibrium and linear stability regimes of plasmas confined in toroidal magnetic configurations. However, many present day tokamaks operate in high performance regimes (*i.e.,* high β) very close to the ideal MHD threshold. Thus, high β disruptions caused by ideal MHD modes is a key issue. For example, a particular disruption in the DIII-D plasma has been well modeled [1] by an ideal MHD interchange-like instabilities driven slowly (via heating) through its instability threshold - a "driven ideal MHD instability".

In order to understand these events, attempts have been made to study the nonlinear fate of ideal MHD modes. Beklemishev [2] studied possible helical equilibria for ideal interchange modes. On the other hand, Cowley *et.al.* [3] studied the nonlinear dynamics of high mode number ideal ballooning modes using a perturbative approach. The Beklemishev approach lead to a final state in the form of current sheets (similar to one obtained for m=1 kink mode[4]) while the Cowley *et.al.* approach lead to an explosively unstable final state.

Here, we will present a generalized set of equations for studying the nonlinear evolution of ideal, long wavelength, interchange–like MHD modes. We have used the reduced MHD equations derived by Kruger *et.al.*[5] as our starting equations and the Lagrangian coordinates to cast the quasi-neutrality condition (*i.e.,* $\vec{\nabla} \cdot \vec{J} = 0$) into a Possion bracket form for general magnetic configurations. Useful forms of these equations and progress towards their analytical solution will be presented.

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Resistive Drift Modes in Tokamak and ℓ=2-Stellarator Configurations

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In the context of anomalous transport in the boundary region of stellarator devices resistive drift ballooning modes may be important. This kind of modes was investigated with a code that allows the calculation of global (here this means inside a hollow torus) linear resistive drift modes in general geometry without any restriction on the mode structure. The drift-wave model uses a two-fluid description of the plasma and assumes electrostatic perturbations, vanishing temperature perturbation and cold ions (with their parallel dynamics neglected).

In order to validate the code a simple tokamak model equilibrium with different rotational transform profiles was used to calculate the eigenvalue and mode structure of resistive ballooning modes by the global approach and by solving a one-dimensional ballooning equation along a field line. The results of both approaches were in good agreement. Increasing ι and/or switching from negative to positive ι' led to a decrease in the growthrate. Also the global code was able to find more eigenmodes (with different structure) in configurations with positive ι' than the adopted ballooning approach.

The code was applied to a straight and a toroidal $\ell = 2$ stellarator equilibrium. In the straight equilibrium only interchange-like modes with weak helical coupling could be found. Depending on the size of the poloidal wave number the mode maxima coincide with the minima or maxima of the magnetic field. For the toroidal equilibrium the modes which were found show strong toroidal and only weak helical coupling. Thus the mode structure is dominated by strong poloidal ballooning with only small helical variations.

The Role of Beam-Alfven Wave Interaction in the Evolution of Ion Rings

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Results of particle-in-cell (PIC) modeling are presented, showing that interaction of an ion ring with Alfven waves in the background plasma provides the mechanism of efficient control of the formation of an ion ring, its stability and lifetime. In the formation stage, the ring axial motion should be well coupled to Alfven waves, to dissipate its axial energy. After the ring is formed, its azimuthal stability requires the minimization of such coupling for the remaining cyclotron motion. These two opposite requirements determine the optimal window of parameters for the background plasma in the ion ring experiment.

Non-Gaussian transport in strong plasma turbulence

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It is important to understand the basic features of particle transport in a strongly turbulent plasma. For magnetically confined plasmas, a simple two dimensional model for the strongly turbulent electrostatic field, in the plane perpendicular to the magnetic field, is provided by the Hasegawa Mima equation [1], which also has wider physical application [2]. We have investigated [3] the poloidal transport of ensembles of test particles moving in the Hasegawa Mima field, and its dependence on the relative weight of the nonlinear and linear terms in the equation (determined physically by the background density gradient). The density gradient induces anisotropy in the turbulent electrostatic field, which is characterised by zonal flows - potential structures elongated in the direction of propagation of drift waves, whose consequences for radial particle transport within the Hasegawa-Mima framework have been investigated previously [4].

For poloidal transport, the case where only the linear dispersive term is present is known to lead to Gaussian diffusion, while the nonlinear term on its own gives quasi-normal diffusion or subdiffusion. We have found[3] that the simultaneous presence of both linear and nonlinear terms qualitatively changes the poloidal transport: it can become superdiffusive or even ballistic, depending on the relative strength of the two terms. The particle probability distribution function, which is close to a Gaussian when the observed transport is normal, becomes considerably flatter in the supradiffusive regimes.

These results are among the first to show that non-Gaussian ('strange') kinetics can emerge naturally from a relatively simple model for test-particle transport in magnetised plasmas with strong electrostatic turbulence. This may have implications for the range of concepts needed to interpret the phenomenology seen in larger scale numerical simulations and in real plasma confinement systems.

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Global Stability of the Field-Reversed Configuration

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The global stability of the Field-Reversed Configurations (FRC) has been investigated using hybrid (fluid electrons and kinetic ions) simulations. The delta-f method is utilized to reduce numerical noise in the particle simulations. The role of kinetic effects on the $n=1$ tilt mode and other global modes in prolate FRCs have been studied. The linearized hybrid simulations show that there is a reduction in the tilt mode growth rate when $s/E<1$, but no absolute stabilization has been found for s/E values as small as 0. 1, where s is the approximate number of ion gyroradii between the field null and the separatrix, and E is the separatrix elongation. One of the possible explanations of the instability existing beyond the FLR theory stability threshold is the resonant interaction of the wave with ions for which the Doppler shifted wave frequency matches the betatron frequency. The evidence for the existence of betatron resonance- driven instabilities in the large Larmor radius (kinetic) regime is presented. The results of nonlinear hybrid simulations at low values of s indicate that the tilt instability may saturate nonlinearly through the lengthening of the initial equilibrium and modification of the ion distribution function. These saturated states have been calculated to exist for many Alfven times, maintaining field reversal.

Evidence for Transitions in the Transport Dynamics of a SOC System with Classical Diffusion*

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Self-Organized Criticality (SOC) has been for some time been advanced as a paradigm [1,2] for turbulent transport in magnetically confined plasmas. However, in a realistic confined plasma system the transport dynamics is more likely to be a combination of the coherent anomalous transport (the SOC part) and a more classical diffusive component. To investigate the interaction between these 2 components, a diffusive term is added to a simple SOC model. The dynamical regimes as a function of the drive and classical diffusivity are then explored. The inclusion of the diffusive term allows access to a regime in which the bursty behavior characteristic of the SOC dynamics is reduced and eventually eliminated. In the intermediate regime both the dynamical character and average dimension of the avalanches change. Evidence for 2 transitions, one with the characteristics of a roughening transition and one an edge dominated dynamical transition will be presented. The implications and possible tests for transport dynamics in various experimental regimes and devices are discussed.

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Quite times and other tests of a SOC System*

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The concept of Self-Organized Criticality (SOC) has been advanced as a paradigm [1,2] for turbulent transport in magnetically confined plasmas. Many complex physical systems seem to be well described when examined in the light of self-organized criticality (SOC). This concept brings together the ideas of self-organization of nonlinear dynamics with the often- observed near- critical behavior of many natural phenomena, when the system exhibits self- similarity over extended ranges of spatial and temporal scales. This self-organized state is a fixed point of the dynamics that can be reached without any tuning. In it, the system displays the same spatial and temporal self-similar spectra characteristic of critical points in phase transition theory as well as long spatial and temporal correlations. Both self- similar spectra and long correlations have been found in a wide variety of physical and biological systems for many years, from earthquakes to forest fires and from solar flares to plasma turbulent transport in magnetic confinement devices of interest for controlled fusion. These signatures are however not unique to self- organized criticality (even when necessary) which, together with the lack of a definitive experimental test for SOC behavior in real physical systems, has raised some criticism on the applicability of this concept in many cases. Recently, a different "necessary" SOC signature has been proposed, in the context of solar flare dynamics, which seems to have confirmed some of this criticism. It is based on a different type of statistics that deals with the waiting-times, i. e. , the time intervals between two successive bursts or avalanches. It was suggested that for a system to be SOC it must exhibit Poisson waiting times.

It is shown here that the lack of Poisson waiting-time statistics in any physical system does not necessarily preclude the existence of underlying SOC dynamics. The waiting-time probability distribution function of a SOC system is shown to be able to display power laws rather than exponentials whenever the experimental resolution lies within the self-similar scale range or if the system is slowly driven in a correlated way. It is also shown that the sampling methods used can strongly bias some of the characteristic signatures.

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SOC Dynamics with Varying Driving Force, Transport Size, and Classical Diffusion Coefficient*

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Much work has been done with cellular automaton models which exhibit self-organized criticality (SOC). Often referred to as sandpile models, these systems produce very rich dynamics from a very simple set of rules and a very large number of iterations. In light of these dynamics, the SOC concept has been advanced as a paradigm for many physical systems in which a gradient is relaxed in an irregular series of events. The parameters in the sandpile model are expected to be analogous to characteristics of the specific system under consideration. The simplest of the automata have just a few parameters, but more are introduced with additional sandpile rules. These new rules can simulate additional physical effects on the real system, producing more realistic results. Although detailed investigation of the entire parameter space can be daunting in these SOC models, it is certainly a more feasible proposition than the analogous experimental twiddling. Two specific aspects are explored here for a 1-D SOC model. The first involves parameter variation to investigate the scaling laws associated with driving rate and transport size. The second adds classical diffusion to the structure of the automaton. This diffusion is added in order to more accurately model a system that has both critical gradient driven (SOC) transport and continuous (diffusive) transport. Such a system can exhibit interesting new dynamical features. Of particular interest are regions within the parameter space which display markedly different dynamical regimes and transport characteristics. The results are discussed in terms of both the sandpile and its physical analogs.

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Radial and Poloidal Dynamics of Turbulent Transport in a Self Organized Criticality Model with Sheared Flow and Diffusive Spreading*

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Self organized criticality (SOC) models have been used both to describe the dynamics of plasma transport without relying on the underlying local fluctuation mechanisms and to explain the radial profile resilience and universal transport behavior observed in many confinement devices. Computations based on a cellular automaton model have found that SOC produces dominant transport scales on the order of the system size rather than on the order of the underlying local fluctuation scales.

However, by adjusting the rules of the cellular automaton model we have seen changes in the PDF of transport events. Two specific adjustments are: 1) shear flow is added to the dynamics to model sheared electric fields in real plasmas and 2) poloidal diffusive spreading is added to model the anomalous diffusion in real plasmas, which takes place both radially and poloidally, and to model other mechanisms such as parallel transport, which can cause poloidal spreading. By adding shear flow and/or diffusive spreading to the dynamics, system scale transport events are reduced. Fluctuation scale transport events are concomitantly increased to maintain the constant flux through the system.

Additionally, adjusting the parameters of the model can create a simpler change in the dynamics, which can have an impact on the PDF of the gradients and on the steady-state mass of the system. By making at least one of four parameters incommensurate with the other three, more of the gradient state space is explored by the dynamics and the final steady-state mass is changed.

This work looks at the PDFs of transport events and the radial and poloidal correlation lengths in models with and without shear and diffusive spreading. We also discuss the significance of the changes in the PDF of gradients and the changes in the steady-state mass for systems where one parameter is slightly changed.

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Ideal MHD Continuum Modes in General Toroidal Geometry

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It is well known that the spectrum of the linearized equations of ideal magnetohydrodynamics (MHD) have both discrete and continuous components. The continuous spectrum is characterized by spatially singular modes that can be a source of RF heating and current drive in plasmas. The mathematical nature of the spatial singularity is a key component of the continuum modes and their applications. A viewpoint that has evolved from early studies of the MHD continuum is that the singularities are distributed uniformly over a frequency dependent magnetic surface, $\psi_0(\mathrm{r}) = \mathrm{const}$, that the component of the plasma displacement along the magnetic surface normal has a logarithmic singularity, $\ln(\psi - \psi_0)$, about the magnetic surface $\psi = \psi_0(\mathrm{r})$, and that the displacement components within magnetic surfaces have singularities of the type $(\psi - \psi_0)^{-1}$. However, recent studies have revealed that the $[\ln(\psi - \psi_0), (\psi - \psi_0)^{-1}]$ singularities occur only in certain plasma configurations. [1, 2] More generally, a power law singularity with an imaginary exponent, $(\psi - \psi_0)^{i\nu}$, i.e. an essential singularity with an undulatory variation with respect to ψ, is characteristic of the continuum modes in many plasma configurations. For example, the logarithmic singularity predicted by Pao [3] for an axisymmetric toroidal plasma occurs only if the plasma cross section is up-down symmetric. Without up-down symmetry, the power law characterizes the continuum singularity. These general results hold for both compressible and incompressible plasmas. Surprisingly, however, a logarithmic singularity is found in nonaxisymmetric toroidal geometry if the plasma is pressureless. [2]

The mathematical foundation of the MHD continuum singularities, for both axisymmetric and nonaxisymmetric toroidal plasmas, is the subject of this presentation. An expansion scheme is proposed to solve the linearized MHD equations about magnetic surfaces. This leads to an eigenvalue problem in the form of an ordinary differential equation along the equilibrium magnetic field lines, $\mathcal{L} \cdot \mathbf{u} = 0$, that governs the existence of a continuous spectrum and the analytical nature of the continuum singularities. The number of independent solutions of $\mathcal{L} \cdot \mathbf{u} = 0$ for a given eigenvalue determines whether logarithmic or essential singularities exist.

For nonaxisymmetric toroidal geometry, the continua of a pressureless plasma are analyzed. As in axisymmetric configurations, modes may exhibit a singularity that uniformly covers magnetic surfaces. However, with nonaxisymmetry and zero pressure, a logarithmic singularity appears in general rather than an essential singularity. If the nonaxisymmetry is too strong, the surface-covering property of the singular modes may be lost, consistent with results that have previously been reported. [4] An important feature of the continuum equations analyzed here is that elements of the gap modes can be treated.

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Exact Axisymmetric MHD Equilibria

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Axisymmetric MHD equilibria are usually represented as solutions of the Grad-Schluter-Shafranov equation. An equivalent formulation is given by the inverse problem in which the cylindrical coordinates r, ϕ, and z are given as $r = r(\psi, \theta)$, $\phi = \phi$, and $z = z(\psi, \theta)$, where θ is the poloidal angle and ψ is the poloidal flux coordinate. We consider the inverse problem in the large aspect ratio limit, corresponding to a straight cylinder. In this limit we find a wide class of separate MHD equilibria, and we describe these in greater detail.

Simulation of Edge Plasmas in Double-Null Configurations*

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We investigate the behavior of divertor plasmas in double-null magnetic configurations via simulations with the UEDGE code[1, 2]. Particle and heat loads on the divertor plates are strongly affected by magnetic imbalance and cross-field drifts. The magnetic imbalance is characterized by "drsep" which is the radial distance between upper and lower x-point flux surfaces at the outboard midplane. We will report on progress in systematically varying the core power, anomalous radial transport, divertor pumping and magnetic imbalance.

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BOUT simulations of the Quasi-Coherent Mode in the EDA Regime of Alcator C-Mod*

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The Quasi-Coherent (QC) mode, is found to always be in the EDA H-mode [1], by phase contrast imaging (PCI) diagnostic in the Alcator C-Mod tokamak. The typical QC mode is characterized by high frequency (100kHz) "quasi-coherent" fluctuation mode and high poloidal wavenumber is $k_\theta \sim 4\ cm^{-1}$, localized in the edge steep density gradient region (pedestal). In order to understand the QC mode, simulations have been carried out using BOUT (a 3D nonlocal electromagnetic BOUndary plasma Turbulence code) simulations [2]. The measured dispersion and mode stability is in good agreement with the resistive ballooning X-point mode predicted by the BOUT code. While similar modes have been seen in past experiments, this is the first time that the mode has been identified and its physics interpreted in terms of a realistic theoretical model. BOUT calculated the profile of the radial electric field (E_r) and the fluctuating magnetic field ($\delta B_\perp$) at the outboard midplane. The peak amplitude of the fluctuating magnetic field seen in BOUT is about 17 Gauss, or about 0.04% of the total magnetic field near the separatrix at the outside midplane, and the magnetic perturbations fall off rapidly with distance from the separatrix in the plasma scrape-off layer. The peak amplitude of the negative E_r is about 300 kV/m inside the separatrix. Although it is predominant in both wavenumber and frequency spectrum, the QC mode is responsible for only about 1/2 of the 'power' in the density fluctuations (that is, 1/2 of the average of δn^2 over z and t). The rest of the power in the density fluctuations is associated with a broadband 'noise' in both wavenumber and frequency that is observed in BOUT. Dependence of the mode stability on shaping (elongation and triangularity) as well as q will be presented. Implication of this mode to the next generation tokamaks will be discussed.

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Study Nuclear Physics for Nuclear Fusion

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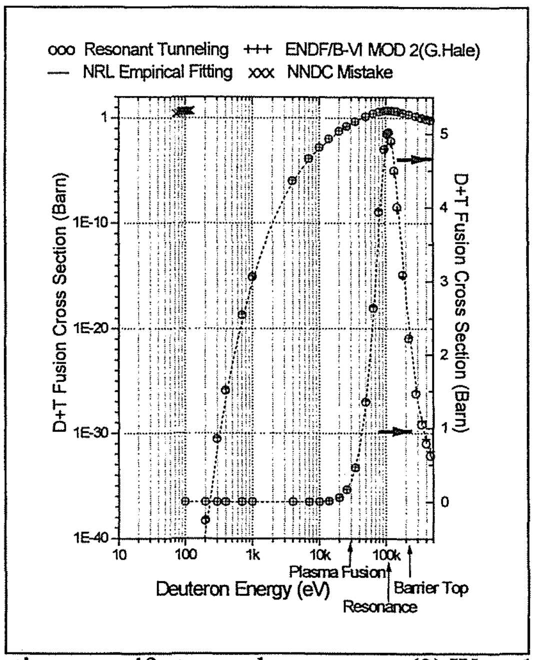
More than 50 year fusion study has been focused on high temperature plasma physics. In contrast, the fundamental research on nuclear physics has been somehow ignored. It has caused three misleading: (1)The Coulomb barrier is overcome by the kinetic energy of high temperature plasma; (2)The Gamow penetration factor will vanish the fusion cross-section at low energy in any case; (3)The neutron and gamma radiation are the necessary products when the deuteron penetrates the Coulomb barrier. These misleading were caused by unconsciously using the compound nucleus model, which is valid only for the intermediate or heavy nuclei with two independent steps for a nuclear reaction. A new single-step model is set up for d+t fusion using a square nuclear well in connection with a Coulomb barrier. A new formula for resonance cross-section has been derived as

$$\sigma = \frac{\pi}{k^2}\frac{-4W_i}{W_r^2 + (W_i - 1)^2}$$

Here k is the wave number of the relative motion; W_r and W_i may be calculated using a nuclear potential with an imaginary part. This expression of cross-section identically equals to the traditional one for s-wave in Nuclear Physics, but there is no Taylor expansion involved here. Hence, it may be valid at the energy far away from the resonance where W_r=0. Another advantage of this expression is that the width of the resonance may be calculated based on the resonance peak position and the peak value of the cross-section of that resonance. The comparison between d+T fusion data (ENDF/B-VI) [1] and our calculation justifies this single-step resonance model, which corrected the aforementioned misleading as follows: (1)Plasma kinetic energy is mainly for approaching the resonance energy near 100 keV. Indeed the fusion cross-section is much less when the kinetic energy of deuteron reaches the top of the Coulomb barrier (>200 keV); (2)Once resonant tunneling appears(W_r =0 and W_i = -1), there is no Gamow penetration factor in the expression of cross-section even if at very low energy; (3) W_i= -1 simply means that at low energy there will be no resonance for the channel which emits neutron or gamma radiation.{see references [2-4]). In other words, if there is any resonant tunneling at low energy, it must be a fusion reaction without neutron and Gamma radiation. The physical reason is as follows: the fusion reaction is the absorption of the penetrating wave function. It is equivalent to the damping in the case of resonance. When the driving force is very weak, a strong damping will kill the resonance before it grows up. The neutron emission channel is a strong damping channel; hence, there will be no chance for any resonant penetration to this channel at low energy.



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Nonlinear Gyrobounce-kinetic Vlasov-Poisson Equations

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The dynamics of magnetically-confined charged particles involves three distinct orbital time scales associated with fast gyromotion, intermediate bounce motion, and slow magnetic-drift motion. Since much of the anomalous particle and energy transport in magnetized fusion plasmas is due to low-frequency fluctuations with characteristic drift time scales, there are tremendous numerical and analytical advantages in deriving energy-conserving self-consistent reduced dynamical equations in which the gyromotion and bounce-motion time scales have been eliminated.

We present results on the derivation of nonlinear reduced Vlasov-Poisson equations in which both the gyromotion and bounce time scales have been eliminated. Nonlinear gyro-bounce Hamilton equations describing reduced particle dynamics in nonuniform magnetic geometry perturbed by low-frequency electromagnetic fluctuations were recently derived by Lie-transform methods [1]. To derive a self-consistent reduced Poisson equation, with the charge density expressed in terms of a moment of the reduced gyro-bounce Vlasov distribution, we use the *constrained* variational principle for the Vlasov-Maxwell equations [2]

$$\mathcal{A} \equiv - \int d^8 \mathcal{Z}\, \mathcal{F}(\mathcal{Z})\, \mathcal{H}(\mathcal{Z}) + \int d^4 x\, \frac{F_{\mu\nu} F^{\nu\mu}}{16\pi},$$

where the extended phase-space Vlasov distribution $\mathcal{F}$ depends on the extended canonical particle coordinates $\mathcal{Z} = (\mathbf{z}; t, w)$ (w denotes the energy coordinate), and the extended particle Hamiltonian is $\mathcal{H}(\mathcal{Z}) = H(\mathbf{z}, t) - w$. The derivation of the self-consistent reduced Poisson equation proceeds by first performing (in succession) the guiding-center and bounce-center phase-space transformations associated with the background electromagnetic field (Φ_0, A_0) and the low-frequency fluctuating scalar field ϕ. The derivation of the gyro-bounce reduced Poisson equation then proceeds with the variation of the action functional with respect to arbitrary variations in ϕ.

A magnetized plasma with general magnetic geometry is considered and a relativistic treatment for the single-particle dynamics is adopted to ensure greater applicability in future work.

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Self-Adjoint Formulation for Diffusive Plasma Stability*

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We consider a configuration where some magnetic field lines enter a resistive wall, as is the case with the scrape-off layer of a divertor tokamak or in many space plasmas. It was previously shown† that the ballooning stability question of an ideal plasma on such an open field line can be given a self-adjoint formulation, so that stability can be determined by minimizing an energy integral. Indeed, this energy integral was constructed as if the wall is an insulator with no currents allowed to flow into it.

Here we extend the result to the case where the plasma itself is resistive. It is again possible to give the stability question a self-adjoint formulation, so that not only ballooning modes but also global modes are covered. In particular, tearing mode stability is determined from the standard δW integral if magnetic field lines are allowed to break, yielding the well-known $\Delta' > 0$ criterion. Our technique is extenable to viscous plasmas and perhaps other types of diffusivities.

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Particle Simulations of Plasma Confinement in a Levitated Dipole*

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Stability for a low beta (β) plasma confined by closed magnetic field B lines is $PV^{\gamma} = A_0$ (A_0 is a constant), P = pressure, V = flux tube volume, γ is the ratio of specific heats. Kesner (J. Kesner, Innovative Confinement Concepts Workshop, Mar. 3-6, 1997) proposed a levitated current ring with the plasma stabilized satisfying this condition as an alternate fusion reactor. At radii large compared to the ring radius, V goes like r^4; the stability condition is $Pr^{20/3} = A_1$. If $nr^4 = A_2$, then an interchange keeps the density constant. The remaining variation in P with r can be accomplished by a variation in the temperature; the temperature can drop according to $Tr^{8/3} = A_3$. If the chamber is ten times the ring radius, the density can drop from 10^{14} cm^{-3} near the ring to 10^{10} cm^{-3} at the edge and the temperature can drop from 50 KeV near the ring to 100 eV at the edge.

Reacting plasma near the ring would raise its temperature, upsetting the stability relation and cause convection. This will carry burnt plasma to the edge, and it will cool adiabatically. The convection can bring in fresh fuel from the outside which will be compressed and heated to ignition. The process should be self regulating.

If the physics for the stability are correct or essentially correct, one might make an attractive reactor this way. The main areas where there might be problems are kinetic driven instabilities, drift instabilities, and finite β instabilities.

We have constructed a 3 dimensional fully electromagnetic particle code suitable for investigating the physics of plasma confinement in a levitated internal conductor device. We have been investigating plasma confinement by the B field surrounding a straight wire. Because the code is a full particle code we have limited ourselves to electron positron (ion mass equals electron mass) plasmas. So far we have confined our studies to electrostatic particle interactions. We have used systems which are 128x128x64 (we have made one or two runs on systems of 256x256x128). Up to 50×10^6 particles have been used. A current carrying wire runs down the center and a circular limiter is imposed at the outside. A range of temperature and density profiles have been run.

Density and temperature profiles that satisfy the theoretical marginal stability condition are stable over the lengths of our runs. By and large if the density and/or temperature profiles are such that we would predict instability, we see instability with growth rates about what we would estimate. In general we find that density gradients produce stronger instabilities than do temperature gradients. If the density is inversely proportional to the volume of a flux tube and the temperature gradient is such that there is an instability, then we see strong convective cells develop but the density profile is not changed.

The problem of floating a ring in a fusion plasma appears to be solvable (J. M. Dawson, FUSION, edited by Edward Teller, Vol. 1, Magnetic Confinement, Part B, Ch. 16, Academic Press, 1981).

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Non-white Noise and a Multiple-rate Markovian Closure Theory for Turbulence*

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Markovian models can be used directly in studying turbulence in a wide range of physical problems (including zonal flows, of recent interest in plasma physics), or they may be a useful starting point for deriving sub-grid turbulence models for computer simulations.

Markovian models of turbulence can be derived from the renormalized statistical closure equations of the direct-interaction approximation (DIA). Various simplifications are often introduced, including an assumption that the two-time correlation function is proportional to the renormalized infinitesimal propagator (the Green's function), i.e. that the decorrelation rate for fluctuations is equal to the decay rate for perturbations. While this is a rigorous result of the fluctuation–dissipation theorem for thermodynamic equilibrium, it does not necessarily apply to turbulence.

Building on previous work on realizable Markovian closures, here we explore a way to allow the decorrelation and decay rates to differ (which in some cases allows a more accurate treatment of effects such as non-white noise), while retaining the computational advantages of a Markovian approximation. This approach also provides additional motivation for the limiting operator $\mathcal{P}(\eta) = \mathrm{Re}\,\eta\, H(\mathrm{Re}\,\eta) + i\,\mathrm{Im}\,\eta$ previously introduced to preserve realizability.

Some Markovian approximations differ only in the initial transient phase, but the multiple-rate Markovian closure (MRMC) presented here could in principle modify the steady state spectra as well. We find that deep in the inertial range of a steady state the MRMC predicts that the decorrelation rate and decay rate are equivalent (thus reducing to previous DIA-based Markovian closures), though this may be an artifact of the dominance of the energy containing scales due to the loss of random Galilean invariance in the DIA.

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Error Field Amplification and Rotation Damping in Tokamaks*

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Toroidal rotation is weakly damped in a nominally axisymmetric tokamak. However, strong damping of toroidal rotation has been seen in DIII-D as the plasma approaches marginal stability for a kink instability [Garofalo et al, Phys. Rev. Lett. 82, 3811 (1999)]. We show that the damping of toroidal rotation by small departures of the external magnetic field from symmetry (error fields) can be enhanced by orders of magnitude as marginal stability for kink modes is approached. The derivation is based on the representation of the plasma perturbations as well as the chamber walls as a set of electrical circuit equations. The representation is exact as long as the plasma perturbations are in a linear regime. If the internal plasma response times are either very fast or very slow compared to the time scale of the experiment, then the plasma response is determined by two dimensionless constants plus the strength of the part of the error field that drives the least stable plasma perturbation. The first dimensionless constant is the ratio of the energy required to drive the least stable perturbation with and without the plasma. The second is the ratio of the toroidal torque exerted on the perturbation by the rotating plasma to the energy required to drive the perturbation if the plasma is not present. The theory gives a number of predictions that can be checked by experiments on DIII-D or on other tokamaks.

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Resistive Ballooning Instability in Tokamak Edge Plasmas*

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Recent observations of a localized instability (the quasi coherent mode) in the edge pedestal of some H-mode discharges in C-Mod appear to be consistent with linear stability predictions of the Carreras-Diamond[1] resistive ballooning mode. The linear theory of such modes has therefore been extended by employing an optimal ordering in which the growth rate γ is of the order of the sound frequency C_s/Rq. A two scale analysis of the coupled 4th order ballooning equations is then employed to derive a 2nd order resistive layer equation, which is solved analytically to obtain a new linear dispersion relation for resistive ballooning.

This dispersion relation contains the geodesic curvature drive, responsible for Carreras-Diamond instability, together with the effects of competing sound wave propagation along the field, favorable average curvature and matching to the solution in the Ideal region, characterized by Δ'_B. The extension to the drift-resistive ballooning dispersion relation (in the strongly collisional regime) has also been obtained.

Numerical solution of the dispersion relation for an s-α model equilibrium shows that, in the absence of favorable average curvature, the Carreras-Diamond mode connects smoothly onto the Δ'_B driven mode and remains weakly unstable for all values of α. Comparison is made with the numerical results of ref. [2]. The effect of favorable average curvature is also under investigation.

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Compressional Alfvén Eigenmode Instability can Explain Sub- Ion Cyclotron Frequency Modes in NSTX *

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Recent observations of magnetic field oscillations measured by edge Mirnov coils in the frequency range below the ion cyclotron frequency are explained as Compressional Alfvén Eigenmodes (CAE) driven by energetic beam ions. The model is based on the theory developed in [1]. CAEs are localized radially at the plasma edge and poloidally on the low magnetic field side of the torus. Energetic ions can be in transit and Doppler shifted cyclotron resonances with CAEs. CAEs in this frequency range can be damped by electrons only, possibly opening a way to enhance transfer of NBI ion energy to thermal particles. The CAE frequencies are determined by the Alfvén frequency at the mode location and the poloidal wavevector $\omega_{CAE} = v_A m/r$, where m is the poloidal mode number, and r is the minor radius. Properties of CAE instability driven by different NBI ion distributions are studied. The sensitivity of the instability to the pitch angle distribution is demonstrated, and the results agree with observations.

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1C51

Lorentz-covariant fluid description of relativistic magnetized plasma

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Many astrophysical plasmas (as well as some laboratory plasmas) are relativistic, in that either the thermal speed or the fluid flow speed approaches the speed of light. Conventional fluid theories of magnetized plasma are not consistent with special relativity. Indeed the usual definition of what constitutes a magnetized plasma must be reformulated in the relativistic case. Beginning with exact moments of the kinetic equation, this work derives a fluid description that is Lorentz covariant and therefore applicable to relativistic plasma. The system allows for anisotropy of the pressure tensor as well as heat flow along the magnetic field. When anisotropy and heat flow are suppressed the closed set of fluid equations becomes a manifestly covariant expression of relativistic MHD.

Finite β effects on internal transport barrier formations

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The finite β effects on toroidal drift modes in tokamak plasma with impurities are investigated, and the results are used to interpret the role of finite β in the formation of internal transport barriers observed in JET and DIII-D. The growth rates are calculated with both a kinetic model and Weiland's advanced fluid model. The maximum growth rate of the full system first occurs on the drift mode branch which decreases with β in low β region, then increases with β in higher β region above the critical value β^{crit} on an MHD-like branch. In inner regions of tokamak plasmas, where the internal transport barriers locate in a JET Optimizd Shear (OS) and a DIII-D Negative Central Shear (NCS) discharges, the experimental β are found in the stabilizing branch below the critical value β^{crit}. In the simulations carried out for the JET OS and the DIII-D NCS discharges with Multi-Mode model in the transport code BALDUR, gaps form in the radial profiles of thermal diffusivity. This produces steep gradients in the ion temperature profiles form, even in the absence of the $\mathbf{E} \times \mathbf{B}$ flow shear. The important role of the stabilizing effect of finite β in the formation of internal transport barriers is demonstrated by comparing simulations with the finite β effect included and omitted. Linear stability analyses also indicate the importance of the finite β effect as well as the effects of magnetic shear and/or strong $\mathbf{E} \times \mathbf{B}$ flow shear stabilizing mechanisms.

Edge transport modulation by radially coherent zonal flows

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Zonal flows in simulations of the tokamak core turbulence are radially incoherent and subject to random fluctuations. Different from the core and the very edge, in the transitional core/edge regime a rich variety of radially coherent flow structures has been discovered in simulations of 3D-drift-Braginskii turbulence. Domains covering up to a full flux surface have been used to model the poloidal coherence effects of the zonal flows correctly [1]. The investigated coherent flows propagate radially and range from solitary jets to sinusoidal structures with definite radial wavenumber.

Apart from reducing the average transport, the coherent flow structures modulate the transport *locally* in space and time. Different from conventional wisdom on shear stabilization, transport minima do not occur at the points of strongest shearing rate but at the flow maxima in the ion diamagnetic direction (positive radial electric field). The poloidal flow maxima in the electron diamagnetic direction correspond to the transport maxima. A transport minimum is only $\sim$10% of a maximum, i.e., the transport is completely quenched in the regions of positive electric field. By several numerical experiments and analytical studies, this phenomenon has been traced back to wavekinetic effects [2, 3], which up to now have not been studied in numerical simulations. Essentially, a shear flow acts like a force field on the turbulence eddies, biasing their collision-dominated radial diffusion and concentrating the turbulence in the regions of negative electric field.

Near the tokamak edge, the poloidal flows are essentially geodesic acoustic modes (GAM), i.e., (0,0) potential perturbations toroidally coupled to (1,0) pressure perturbations with a real frequency proportional to the ion sound velocity. Their generation and radial propagation is primarily not due to the Reynolds stress but due to the Stringer-Winsor term, facilitated by the long parallel sound transit time compared to the turbulence time scale due to high safety factor. In short, the simultaneous action of the $\mathbf{E} \times \mathbf{B}$ shear and the magnetic shear leads to an up-down asymmetric transport. The produced up-down pressure asymmetry results in unbalanced forces due to the magnetic field inhomogeneity, which exert a torque on the plasma column. Different from the conventional Stringer spin up, the parallel sound wave is not needed as mediator.

Numerical experiments at fixed turbulence parameters show a wide variation of the time averaged transport for a sole change of either the GAM frequency or the magnitude of the various curvature terms acting on the flows. The linear flow damping rate tends to be only of minor importance. Since the coherent flows strongly modulate the transport in the transitional core/edge region, in which the pedestal is formed, the details of their physics are of considerable importance. This and their clear signature in the numerical simulations make the radially coherent flows an interesting target of experimental investigation, e.g., by microwave reflectometry.

First results of nonlocal electromagnetic two fluid edge turbulence simulations in general geometry will be reported.

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Alfven cascades in JET discharges with non-monotonic q-profile

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Experiments on JET to generate Internal Transport Barriers (ITBs) have created plasmas with non-monotonic $q(r)$ - profiles where $q(r)$ has a minimum q_{min} at a finite radius. In this case the spectrum of ICRH-driven Alfven instabilities exhibits "cascades" of Alfven perturbations, generally of increasing frequency similar to JT-60U [1]. Each Alfven cascade consists of several modes with different toroidal mode numbers and frequencies. The toroidal mode numbers vary in the range from $n = +1$ to $n = +6$. The frequency starts from $f \approx 20 - 40$ kHz and increases up to the frequency of the TAE gap. The rate of the frequency increase is proportional to the mode number, $df/dt \propto n$, and modes of different n occur with different periodicity in time.

In the framework of the ideal MHD model, we have found a close correlation between the time evolution of Alfven cascades and evolution of Alfven continuum. Modelling with the CSCAS code [2] has shown that the frequencies of Alfven cascades are close to the extremum of the Alfven continuum frequency as a function of radius at $q = q_{min}$ and that the extremum is usually a maximum. The time evolution of the MHD cascade can be described by the formula

$$\omega(t) = \left| \frac{m}{q_{min}(t)} - n \right| \frac{V_A(t)}{R_0} + \Delta\omega,$$

where q_{max} and $V_A(t)$ vary in time in accordance with the experiment, m and n are poloidal and toroidal mode numbers of the perturbation, respectively, and $\Delta\omega$ is an off-set frequency due to a Doppler shift, coupling with ion-sound continuum and perhaps other non-ideal effects which include energetic particle kinetic effects.

Interpretation of the Alfven cascades is given. Importance of the "cascading" Alfvenic instability for future experiments with non-monotonic $q(r)$-profile and comparison to the well-known Alfven instability drives are discussed.

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1D01

ZONAL FLOW AND ZONAL FIELD GENERATION BY FINITE BETA DRIFT WAVES- A THEORY FOR L-H TRANSITIONS IN TOKAMAKS*

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We derive a system of equations for the generation of zonal flow and zonal field in a finite beta plasma. These equations are a finite-beta generalization of the equations derived earlier[1]. Recent 3D simulations[2] of edge fluctuations with finite magnetic perturbations have shown that finite-beta effects play a significant role in edge transport. They obtained a curve in a two dimensional parameter space, involving the ideal MHD ballooning parameter and a diamagnetic parameter, which separates the poorly confined state (L mode) from the good confined state (H mode). These results were found to be in good agreement with measurements on C- MOD and ASDEX. Our modulational instability analysis for the generation of zonal flow/field yields a threshold criterion for L- H transitions, which agrees with the simulations and the observational data. Furthermore we have derived a criterion for the electron temperature and the density gradient scale length in terms of the plasma parameters for the onset of the transition. The basic theoretical model and comparison with observations will be presented.

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1D02

Comparisons of Nonlinear Gyrokinetic Calculations with Experimental Results for DIII-D-Like Tokamak Discharges*

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We have been performing global nonlinear three-dimensional gyrokinetic particle-in-cell calculations in full toroidal geometry with parameters and profiles appropriate to several different types of DIII-D discharges.

Among these, plasmas specifically designed to excite ion temperature gradient driven turbulence (ITGDT) and plasmas exhibiting quiescent double barriers (QDB) have been of particular interest. Results from our global gyrokinetic calculations have compared favorably with experimental data obtained in these cases, even though they are performed in circular geometry, in the electrostatic limit, and with adiabatic electrons.

For ITGDT discharges, our calculations corroborate the experimental evidence of significant ITG activity for the appropriate set of profiles and parameters. For the QDB discharge studied, they appear to exhibit the same lack of trend in the radial correlation length as a function of minor radius which is observed experimentally.

We have also used our global gyrokinetic calculations to anticipate the behavior of DIII-D discharges as fundamental parameter changes are effected. In particular, we have performed scans in the poloidal magnetic field to assess whether the turbulence tracks the resulting changes in poloidal Larmor radius. Previous calculations had in fact suggested that the turbulence might follow such changes based on common radial correlation length diagnostics [J. N. Leboeuf et al. , Phys. Plasmas 7, 1795- 1801 (2000)]. The present calculations show a significant change in the radial correlation length of the fluctuations when the poloidal Larmor radius is increased by decreasing the poloidal magnetic field. The changes are less perceptible when the poloidal Larmor radius is decreased in the same way, probably because of lack of resolution.

Further characterizations and visualizations of the turbulence in all of these DIII-D-like discharges will also be presented as available.

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1D03

Theory of electron temperature profile stiffness

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Linear and nonlinear electromagnetic gyrokinetic simulations of tokamak plasmas are presented. Both the electron temperature gradient (ETG) mode and the trapped electron mode (TEM) are found to induce a large electron heat flux which can be sensitive with respect to the normalized electron temperature gradient. It is shown that these two microinstabilities together may explain the stiffness of electron temperature profiles that is observed in many experiments. We present detailed comparisons with a particular discharge from Tore Supra. Based on linear toroidal gyrokinetic simulations, we have also derived a new formula for the critical threshold for ETG modes which encompasses previous analytical results by Romanelli [1] and Hahm et al. [2] in certain limiting cases. For a wide range of parameters, it reproduces the toroidal gyrokinetic simulation results within an error bar of the order of 15%.

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1D04

Phase Mixing in Collisionless Reconnection

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Collisionless reconnection processes, of relevance to both astrophysical and laboratory plasmas, can be described on the basis of a generalized Ohm's law, where electron inertia, electron compressibility and the Hall term play an important role. This collisionless Ohm law, together with the plasma equation of motion, leads to a Hamiltonian two-fluid plasma model. It has been shown [1] that collisionless magnetic reconnection can occur at a fast rate, at variance with the standard Sweet-Parker paradigm for resistive reconnection. Fast reconnection is associated with the formation of complex structures for the reconnection region, which can be explained as the result of topological invariants that are preserved in the dissipationless limit.

In this presentation, after a brief review of the results mentioned above, we concentrate on recent work on the long-term evolution of collisionless reconnection [2]. We show that, in spite of energy conservation and the presence of topological invariants, large delta-prime reconnecting modes can lead to macroscopic, saturated magnetic island equilibria and fine-scale spatial structures. The latter arise from the phase mixing of the Lagrangian invariants associated with the conserved fields. These equilibria are shown to be the analog of the BGK equilibrium solution for electrostatic Langmuir waves.

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2A01

The Physics Of Magnetic Reconnection*

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Magnetic reconnection plays a critical role in the dynamics of the space, astrophysical and laboratory plasma by providing a mechanism for the fast release of stored magnetic energy. Often magnetic reconnection is a collisionless process, either because collisions are essentially absent (the Earth's magnetosphere) or because the intense electric fields which are generated during reconnection exceed the Dreicer runaway field, rendering collisions irrelevant (solar corona and tokamak sawteeth). The rate of magnetic reconnection is controlled by the geometry of the dissipation region, where the ideal MHD description breaks down and the frozen-in condition is violated. The Sweet-Parker model, which is based on resitive MHD theory fails to explain the fast rates of reconnection observed in nature and the laboratory. An important discovery of the past several years is that the coupling to dispersive whistler and kinetic Alfvén waves at the small spatial scales which characterize the dissipation region dramatically increases the rate of reconnection to levels consistent with observations. A surprise is that the coupling to these waves renders the rate of reconnection insensitive to the mechanism which breaks the frozen-in condition. The quadratic dispersion character of these "kinetic" waves is the essential ingredient required to produce the fast rates of reconnection. The physical basis for this result will be discussed. For some values of the plasma parameters (magnetic field strength and β) coupling to dispersive waves is not possible and the rate of reconnection, as expected, remains low. The important implication of these results is that the resistive MHD model, which does not describe whistler and kinetic Alfvén waves, is inadequate to describe magnetic reconnection in plasma systems. The minimalist model is a two-fluid system of equations which includes the Hall term in Ohm's law.

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*This work was carried out in collaboration with R.E. Denton, B.N. Rogers, M.A. Shay and M.Swisdak.

Simulation of Intermittent Fast Particle Loss due to Alfven Eigenmode Bursts

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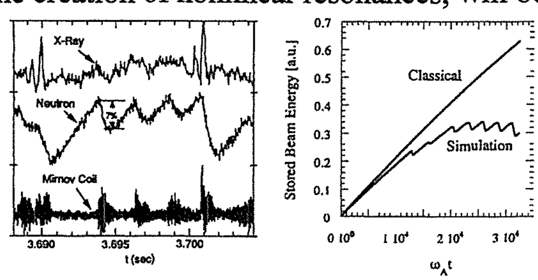
Recurrent bursts of toroidicity-induced Alfven eigenmodes (TAE) are studied using a reduced computer simulation model. We reproduce bursts of fast particle losses observed in the TFTR NBI experiment [1] using the experimental parameters. It is shown that the fast-ion loss time scale closely matches those in the experiment. The simulation uses a perturbative approach where the TAE spatial profile is assumed to be independent of mode amplitude, while the amplitude and phases and the nonlinear fast-ion dynamics are followed self-consistently. Particles are injected with a constant velocity (corresponding to 110keV which is roughly the Alfven velocity parallel to the magnetic field) and the NBI heating power is 10MW. The particles that are transported to the plasma edge are removed. Concentric circular magnetic surfaces are considered. Three eigenmodes with the toroidal mode numbers of n=1, 2, and 3 are taken into account. The linear damping rate of each mode is assumed to be constant at 2×10^3 s^{-1}. The magnetic field is 1.0 T on axis, the aspect ratio is 3.2, the q-profile varies quadratically with minor radius with the central value of 1.2, an edge value of 3.0, and the slowing-down time is 100 ms. It is found that synchronized TAE bursts take place with a fairly regular time interval of 1.8 ms, which is close to the experimental value of 2.2 ms. The stored beam energy saturates at 20% of that of the classical slowing-down distribution. The stored beam energy drop associated with each burst has a modulation depth of 9% which is also close to the inferred experimental value of 7%. The fast-ion distribution hovers around a marginal stability state. A discussion of the primary loss mechanism due to resonance overlap, possibly due to the creation of nonlinear resonances, will be given.



Results of the TFTR NBI experiment [1] (left) and the simulation results of time evolution of stored beam energy with that of the classical slowing-down distribution (right).

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Studies of Boundary Turbulence and Transport in NSTX*

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In order to understand the boundary turbulence of the National Spherical Torus Experiment (NSTX), simulations have been carried out using BOUT (a 3D nonlocal electromagnetic turbulence code) simulations [1]. BOUT models boundary-plasma turbulence in a realistic divertor geometry using Braginskii equations [2] for plasma vorticity, density (n_i), electron and ion temperature (T_i, T_e) and parallel momentum. It has been generally found that X-point damping coupled with the change in boundary plasma flow direction plays a crucial role in determination of the fluctuation levels. The main results that are specific to NSTX are as follows. (1). The X-point geometry affects poloidal mode structures. (2). Poloidal fluctuation phase velocity v_p from the boundary turbulence shows structure across separatrix similar to that observed in many fusion devices. (3). There is a strong poloidal asymmetry of the particle flux in the proximity of the separatrix. (4). A coherent mode is identified in NSTX with $f \simeq 11$kHz and $k_\theta \simeq 0.35/cm$. 5) Due to large Larmor radius, radial streamer structure has been observed across the separatrix. A qualitative comparison will be made with the turbulent structures observed in NSTX using the Gas Puff Imaging diagnostics. The detailed comparison with dedicated experiments will be discussed.

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*Work performed under the auspices of the U. S. Department of Energy (USDOE) by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48. We are pleased to acknowledge useful conversations with R. H. Cohen G. D. Porter, T. D. Rognlien, and D. D. Ryutov.

Kinetic Plasma Stability in a Dipolar Magnetic Field*

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High beta plasmas confined in dipolar magnetic fields with closed lines are common in the Universe and are of interest to magnetic fusion. Dipole confinement is to be investigated in the Levitated Dipole Experiment (LDX) [1], currently under construction at MIT.

Ideal MHD stable plasma equilibria can be obtained in dipole magnetic fields at arbitrary beta = (plasma pressure / magnetic pressure) because the unfavorable field line curvature of the dipole configuration is counteracted by the stabilizing effects of plasma compressibility due to closed field lines [2,3]. However, many important effects are not described by the ideal MHD equations. Moreover, in many cases of interest the standard MHD ordering is inadequate and a kinetic description of dipole stability must be employed.

We consider the kinetic stability of a plasma in a dipole field for an ordering relevant to LDX, namely $\omega_b >> \nu >> \omega \sim \omega_d \sim \omega_*$ with ω_b, ν, ω, ω_d, and ω_* the bounce, collision, mode, magnetic drift, and diamagnetic drift frequencies. We allow arbitrary variation of magnetic field along the field line.

We focus on electrostatic perturbations (zero beta limit) and calculate collisional dissipation effects, extending the results of Refs. [4,5]. Stability of the two possible classes of modes [4], namely the low frequency entropy mode [5] and the high frequency MHD-like mode, can be conveniently described in terms of the parameters η = (temperature gradient / density gradient) and $d = \omega_*(1+\eta)/\omega_d$. The stability boundaries are considerably modified by the ion gyro-relaxation [6] collisional effects $\sim O(\omega_{di}/\nu_{ii})$, describing the relaxation of the distribution function towards a Maxwellian. The gyro-relaxation effects must be obtained by solving the gyro-kinetic equation to higher order. In the fluid description, they come from the ion viscosity, and are not present in Braginskii's fluid equations. These effects had not been calculated before for an arbitrary poloidal field variation and may also be important for tokamak edge plasmas. We find that even in the presence of collisional modifications large stable regions exist in d, η space.

Electromagnetic perturbations will also be discussed.

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Control of tearing modes via "designer" resonant magnetic perturbations*

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Further progress in obtaining thermonuclear reactor grade plasmas in either tokamaks or reversed field pinches is dependent on the development of some reliable method for controlling tearing mode amplitudes. One of the most promising options for achieving this task is active feedback by means of externally applied, resonant magnetic perturbations (RMPs). According to conventional theory, a magnetic island chain naturally locks to an RMP in a helical phase such that the perturbation has a *destabilizing* effect on the chain. In fact, the stabilizing phase is unstable to a *phase instability* which typically develops in a few milli-seconds. Thus, an active feedback system must be capable of modifying the phase of the applied RMP on such a time-scale in order to maintain a stabilizing phase relation. This inevitably implies that the coils which generate the feedback signals must be located *inside* any of the conducting structures surrounding the plasma—otherwise, the signals would be shielded from the plasma by eddy currents. Unfortunately, placing feedback coils this close to a plasma is essentially *impossible* in a reactor environment.

Suppose that it were possible to design an RMP with the unconventional property that a magnetic island chain would lock to it in a *stabilizing* phase. We could control the amplitude of the island chain, using such a perturbation, without the need for fast phase modulation, because there would be no need to overcome the phase instability. This type of magnetic feedback would be feasible in a reactor environment, since the coils needed to generate the perturbation could be placed *outside* the conducting structures surrounding the plasma, where they could be properly shielded. The aim of this paper is to demonstrate that the novel scenario just outlined is a real possibility.

We take the rigorous perturbation analysis of Thyagaraja[1], which describes the nonlinear saturation of an m, n magnetic island chain, and extend it to deal with the nonlinear coupling of the island chain to lm, ln magnetic perturbations (for $l > 1$). We demonstrate that this coupling profoundly modifies the island dynamics in the presence of a special class of RMP. A perturbation of this class is made up predominantly of lm, ln (where $l > 1$) helical magnetic fields, with a much smaller m, n component. It is possible to adjust the relative amplitudes and phases of these components in such a manner that an m, n island chain of sufficiently large amplitude will lock to the perturbation in a stabilizing phase. We call such a perturbation a "designer" RMP.

We have developed a set of evolution equations which describe the dynamics of a magnetic island chain in the presence of a programmable RMP. The novel features of these equations include an extremely accurate formulation of the crucial viscous coupling between the island chain and the plasma, a correct treatment of ion polarization, and allowance for "designer" RMPs. Using these equations, we have investigated island dynamics in the presence of a "designer" RMP, and have demonstrated locking in a stabilizing phase.

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2C01

Roadmap for the Cray PVP Systems at NERSC*

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We expect to retire the NERSC Cray PVP systems around October 2002. There is a possibility that there will be no viable vector replacement. This talk will share the preliminary findings of, and collect input for, a project to determine possible paths for traditional vector computer users at NERSC.

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Gyrokinetic Particle-in-Cell Simulation of Ion-Temperature-Gradient Modes in Plasma Confined in a Dipole Field*

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Abstract

The ion temperature gradient (ITG) modes have been suggested to play important roles in the confinement of Tokamak plasma. In this work, we propose to analyze the behavior of ITG modes in a dipole magnetic field relevant to both the Earth's magnetosphear and the proposed dipole fusion scheme. Our study employs an electrostatic gyrokinetic particle-in-cell δf code. Ions are treated via linear gyrokinetic equations. Meanwhile, various electron models are employed. In the adiabatic electron limit, simulation results are compared with preivous analytical works†. Qualitative agreement is found for the modes that depend on parallel dynamics, and the condition for interchange mode, i.e., $\bar{\phi} = \phi$ is discussed. We have, furthermore, employed the bounce averaged drift-kinetic model. Numerical and analytical results will be presented and discussed.

*Work supported by NSF and DOE Grants.

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2D02

A Proposal for the Startup of a Spherical Torus without using OH coils.*

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Three methods are described for startup of a Spherical Torus (ST) without using any OH coils on the small major radius side of the plasma. The first method requires two coils internal to the vacuum vessel. The plasma is formed around the internal coils, like the S-1 plasma was formed around the flux core, and the separate plasmas are merged together and compressed. This is similar to the scheme used in MAST. The second method uses a "plasma OH coil". It involves first creating a plasma discharge from the inside bottom to the inside top of the vacuum vessel. The toroidal plasma current in this discharge plays the role of the current normally in the OH coil. When this discharge is made to terminate abruptly and the outer coils are swung appropriately, a ST plasma discharge is formed through induction. The third method uses a new PF coil on the outer midplane, just outside the vacuum vessel and an insulating break between the bottom and top of the vacuum vessel. The new coil initially has a current of several hundred dA. A large bias voltage is placed between the upper and lower halves of the vacuum vessel, causing a halo current to flow along the field lines. The toroidal part of this current is strong enough to make a "o-point" just inside the vessel. Subsequent ramping down and reversing the new outer midplane PF coil will induce a large toroidal current in the plasma with good closed field lines. A "normal" 1+MA ST plasma can be formed in this manner. Variants of this method could use two coils above and below the midplane rather than one coil on the midplane. TSC simulations will be presented.

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2D03

Magnetic Relaxation in Spheromaks Using Spectral Expansions in Cylindrical Geometry

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A code has been developed to solve incompressible resistive MHD equations in cylinder geometry using eigenstates of the curl operator to expand both magnetic and velocity fields, with applications to transport in spheromaks including applications of spheromaks to Magnetized Target Fusion (MTF). The code has been benchmarked against a theoretical calculation of tearing modes in the linear limit, and against the Rutherford equation for the non- linear evolution of a single island. As examples, non- linear calculations are presented for a decaying spheromak and for a driven system simulating the creation of a spheromak by gun injection. These example calculations have demonstrated the value of non-linear turbulence calculations made possible using the spectral method and offer some understanding of the implications of resistive MHD turbulence on transport in spheromak devices.

Radial Propagation of GAMs and Zonal Flows

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We derive the collisionless dispersion relation for Geodesic Acoustic Modes in tokamaks, in the limit where ion Landau damping is exponentially small. We show that electron Landau damping is also very small. Nonlinear scattering is thus expected to be the dominant attenuation mechanism for propagating GAMs. A lower limit on attenuation is set by ion-ion collisions. For tokamak reactor parameters, the GAM group velocity multiplied by the collision time is comparable to the minor radius. Thus, the GAMs may be a candidate for wave transport of energy in reactors.

The radial propagation of zonal flows is also considered. In the presence of global velocity shear, the zonal flow characteristics may allow for radial propagation, which may take the form of heat pulses [1]. We revisit the problem of poloidal rotation decay, with an equilibrium (long wavelength) velocity shear. The residual flows are found to have a real frequency determined by the equilibrium velocity shear.

This is a report of work supported by U.S. DOE Grant DE-FG03-95ER54309.

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2D05

Flowing Equilibria of Compact Plasmas*

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The properties of two- fluid flowing equilibria are explored. This is facilitated by limiting attention to compact toroids in a "stationary-energy" state and assuming uniform density. Flowing equilibria are found to fall into two classes, coupled and decoupled, referring to the linkage between the magnetic field and the flows. The coupled class is force-free and may have significant flows. Spheromaks fall into this class. The decoupled class is diamagnetic and has Alfvenic poloidal flows. FRCs fall into this class. Both classes admit arbitrarily large equilibria. Both classes have certain "allowed" and "forbidden" regions in "helicity space," a two- dimensional parameter map with the electron and ion helicities as coordinates. Allowed regions for the two classes overlap; over much of the overlap the decoupled class is energetically favorable. The helicity map sheds light on the FRC- spheromak bifurcation observed in experiments. Analytic equilibrium are also found within both classes. These can play a role similar to the familiar Hill's vortex and Bessel function models in static, magnetohydrodynamic equilibria.

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2D06

A Basic Experiment on Isotope Scaling of Transport

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There is considerable divergence between theoretical predictions and tokamak experimental results for the isotopic mass effects on transport. This motivated a basic physics experiment in the Columbia Linear Machine. Experiments were done using two different gases: Hydrogen and Deuterium. Measurements of particle transport due to an E x B rotationally driven mode were made via the cross-correlation of potential and density fluctuations. Unlike in tokamaks, the plasma parameter profiles and fluctuation spectra were maintained nearly invariant for both gases, thus enabling a meaningful comparison and estimation of scaling. The first series of data reveal smaller transport values for the deuterium plasma and a scaling that ranges as D~ - 0. 6 to - 0. 8 power of ion mass. This is in contradiction to most theoretical predictions but is similar to the tokamak experimental results and raises serious questions about turbulent transport theories.

Multiple Ion Species Formulation of the Radial Force Balance *

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The radial force balance equation relating toroidal and poloidal rotation, pressure gradients, and the electric potential gradient is formulated for plasmas with multiple ion species. The formulation allows for different toroidal and poloidal rotation velocities and pressure gradients for each species. An equation for the bulk toroidal rotation velocity is derived using a rigid body approximation (low toroidal Mach number) for each ion species. It includes mass-weighted particle transport and momentum diffusion terms expressed in terms of metrics of the full toroidal geometry, and toroidal momentum sources. The electric potential gradient (radial electric field) is expressed in terms of the bulk toroidal rotation velocity and mass-weighted poloidal rotation and pressure gradients. The neoclassical poloidal rotation velocity flux function and pressure gradient for each species, along with the electric potential gradient and the local magnetic field can be used to reconstruct the local toroidal and poloidal rotation velocities of any species. Examples of the mass-weighted and individual contributions to the radial potential gradient will be shown for standard and ITB plasmas.

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Stability Boundaries for Ideal MHD Ballooning Modes in Three-Dimensional Equilibria*

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In theoretical assessments of many stellarator configurations, ideal MHD ballooning stability criterion are the most restrictive. In this work, the role of three dimensional geometry on the stability boundaries of ideal ballooning modes is investigated. We employ a novel method for delineating the effects of plasma profiles and the three-dimensional shape of the magnetic surface by using a technique for constructing a class of solutions to the 3-D magnetostatic equations local to a magnetic surface [1]. By application of this method, one is able to calculate stability boundaries for modes localized to magnetic surfaces as functions of the independent 3-D shaping and profile parameters. An application of this analysis technique allows one to introduce a generalized version of s-α curves to denote stability boundaries for three-dimensional equilibria.

By using a simple analytic parametrization for the local 3-D equilibria, we address the geometric properties of a quasi-symmetric configuration. In particular, the relationship between the symmetry properties of the local shear and the magnetic curvature is investigated. For this case, the magnetic curvature is dominated by a single magnetic helicity while the local shear contains a helical harmonic content with incommensurate helicities in general. The presence of symmetry breaking terms in the local shear can produce localized unstable ballooning modes in regions of small average magnetic shear which lower first ballooning stability thresholds and can potentially eliminate the second stability regime. Since the small average shear region has considerable relevance for many stellarator experiments, we surmise that generically the helical content of the local shear has a direct impact on practical ballooning stability limits and the accessibility to second ballooning stability regimes.

*Research supported by U. S. DoE under grant no. DE-FFG02-99ER54546.

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The effect of equilibrium flow on the stability of tearing modes in the reversed-field pinch.*

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In the spontaneous enhanced confinement regime recently observed in the Madison symmetric torus (MST) reversed-field pinch (RFP)[1], both electrostatic and magnetic fluctuations are greatly reduced with respect to more standard discharges. The suppression of magnetic fluctuations, which in the RFP are generated mainly by core-resonant global tearing modes, has no counterpart in the improved confinement regimes observed in tokamaks, where fluctuations are predominantly electrostatic and of local character.

Presently there is no clear understanding of the physical mechanism which suppresses magnetic turbulence in the spontaneous enhanced confinement regime. Experimental observations indicate however that, like in the tokamak case, spontaneously generated flows always accompany the transition to enhanced confinement regimes.

In this work we investigate the possible role of a self-generated equilibrium flow in the suppression of magnetic turbulence in the spontaneous enhanced confinement regime. We consider the linearized ideal magnetohydrodynamic (MHD) equations in cylindrical geometry, and solve them numerically to calculate the tearing mode stability factor Δ' in the presence of an equilibrium flow. We investigate a variety of flow profiles to obtain qualitative insight on several characteristic examples. In particular, we examine flow profiles with localized regions of flow shear away from the rational surface which are typical in many spontaneous enhanced confinement regimes.

We have found that the inclusion of an equilibrium flow in the ideal MHD model can lead to both stabilization and destabilization, depending on the details of the flow profile and its location, as well as on the equilibrium magnetic field profiles. The parameters which play a key role on the stability of the tearing modes in the presence of an equilibrium flow are elucidated. Experimental data relative to the spontaneous enhanced confinement regime in the MST are re-examined in the light of our results to verify the likelihood that an equilibrium flow could be a contributing factor in the reduction of magnetic fluctuations observed in this regime.

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*Work supported by USDOE

Is Muon Fusion Possible?

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A major stumbling block for effective power from muon catylazed fusion is the sticking probability of the muon to the alpha particle emerging from the fusion reaction. It turns out that it is possible to get around this problem by the application of cyclotron resonance acceleration of the alpha particle to which the muon is attached, keeping it going until the muon is stripped [1]. This must be done at low temperature and leads to the second problem of replacing the low temperature DT sources that the catalysis acts on. For the proposed scheme to work the rate of muon molecular formation has to be quite large and up till now the results on this rate have been too low for net power to be made.

However, new results that appeared last summer that indicate that this rate is much higher than at first supposed [2]. These new rates appear to be large enough to reach break even for the fusion power to exceed the cost of the muons plus the costs of the sources. A value of the net power gain, Q, of about 4 now seems possible. The details of the scheme and the estimate for the parameters to achieve these Q's will be presented.
This work was supported by DOE Contract No. DE-AC02-76-CHO-3073.

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Local Gravitational Instability of Magnetized Shear Flows

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The effect of magnetic shear and shear flow on local gravitationally induced instabilities is investigated. A simple model is constructed allowing for an arbitrary entropy gradient and a shear plasma flow in the Boussinesq approximation. A transformation to shearing magnetic coordinates achieves a model with plasma flow along the magnetic field lines where the coordinate lines are coincident with the field lines. The solution for the normal modes of the system depends on two parameters: the Alfvén Mach number of the plasma flow and the entropy gradient. The behavior of the unstable normal modes of this system is summarized by a stability diagram. Important characteristics of this stability diagram are the following: magnetic shear is stabilizing and the entropy gradient must exceed a threshold value for unstable mode growth to occur; flow acts to suppress mode growth in a substantially unstable regime as expected, yet near marginal stability it can lessen the stabilizing effect of magnetic shear and enhance the growth rates of the instability; and, as the Alfvén Mach number approaches one, the instability is completely stabilized. Analytical work is presented supporting the characteristics of the stability diagram and illuminating the physical mechanisms controlling the behavior of the model. A derivation of the stability criterion for the case without shear flow, asymptotic solutions in the limit that the Alfvén Mach number approaches one and in the limit of zero growth rate, a complete WKB solution for large growth rates, an exactly soluble bounded straight field case, and energy conservation relations are all presented. The implications of this work for astrophysical and fusion applications and the potential for future research extending the results to include compressibility are discussed.

2D12

Nonlinear Collisional Dynamics of Flow Shear in Gyrokinetic Global Evolution of Ion Temperature Gradient Instability

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A self-consistent gyrokinetic global evolution of the ion temperature gradient (ITG) instability is studied, both analytically and numerically. A Fokker-Planck kinetic model with a full nonlinear collision operator, conserving the number of particles, momentum and energy is being used. It is found that typical mechanisms for the ITG instability saturation include a quasilinear evolution of the distribution function, both in the co-ordinate and velocity space, as well as a generation of the Zonal Flows (ZF) which provides stabilization through the flow shear. Several mechanisms for the Zonal Flow (ZF) generation, including Reynolds stress, FLR effects, curvature drifts, and finite beta, are considered, and their relative importance is analysed. Efects of the finite collisions and the magnetic shear are of primary interest. A modulational instability of the ZF is also considered, both for a coherent ITG wave, as well as for a system of random-phased multi-modes. Thresholds and growth rates for this instability are also presented.

2D13

Belt Pinch ignition devices and reactors*

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The advantages and feasibility of elongated tokamak configurations (elongation ~ 3- 5, or "belt pinches") are considered, for applications as a low cost ignition experiment or power reactor. It is practical to stabilize the vertical instability with a fininte resitivity metalic shell (b/a ~ 1. 1-1. 2), for feedback with conventional response times. However, multiple independent active feedback loops are required. Ideal MHD calculations find a large increase in the "no wall" kink mode current limit, for elongation ~ 4-5 together with strong indentation. The beta limit for high bootstrap fraction cases with wall stabilization is also increases by ~3. (See the related poster of L. J. Zheng. et. al.) Because of these advantages, (using rules similar to FIRE's), a copper burning plasma device with major radius of only . 7 meters is possible (i. e,similar to CMOD). The cost of a superconducting ignition experiment can also be strongly reduced. Neoclassical tearing modes can be stabilized by appropriate shaping (indentation). Velocity shear stabilization of microinstabilities is also much stronger.

In a breeding reactor, a close fitting conducting shell may have to be made of a liquid Li alloy. Issues associated with this will be examined.

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2D14

VORPAL: a multidimensional, parallel plasma simulation code

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We are developing a object oriented framework for a new plasma physics simulation code, named VORPAL, which will provide greater flexibility and extensibility than is available in current codes. The details for a fully general, 3D domain decomposition along with the message passing have been implemented using MPI. This gives us the capacity to incorporate load balancing into the code. Using recursion, VORPAL can run in any number of physical dimensions. This is set at run time rather than compile time, allowing the user to do a quick run in 2D to get qualitative results, then move to 3D with the same code and nearly the same input file. The VORPAL framework can support multiple models for both the fields and particles, although at present only fluid representations for the particles and the Yee finite differencing scheme for the electromagnetic fields are in place. VORPAL stores data in HDF5 files, thus allowing for parallel I/O, and for subsequent visualization by a number of packages, including RSI's IDL and IBM's OpenDX (formerly known as Data Explorer). VORPAL is designed to run on any flavor of UNIX and will be distributed freely over the internet.

STELLARATOR OPTIMIZATION USING THE LEVENBERG-MARQUARDT METHOD WITH BROYDEN UPDATE

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Optimization of quasi- omnigeneous stellarator (QOS) configurations has led to the discovery of a new class of compact configurations with high beta ballooning stability limits. The design of the stellarator leads to nonlinear least squares problems with typically n=40 parameters and several hundreds of target functions. A Levenberg- Marquardt iterative method has been used to solve these problems. In each iteration the Jacobi matrix is approximated by a difference scheme that requires n+1 function evaluations. Each function evaluation takes several minutes of supercomputer time to solve the MHD equations and to determine ballooning stability.

By the utilization of a Broyden update - a generalization of the secant method in one dimension - only one function evaluation is required to update the approximate Jacobi matrix in each Levenberg- Marquardt iteration. Although the number of iterations necessary to satisfy the convergence criteria may be increased, the total number of function evaluations is reduced. An example comparing numerical results of the two methods is presented.

2D16

Plasma Confinement Levitated Dipole*

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Plasma confinement in the field of a levitated ring offers a new approach for magnetic confinement. A dipole confined plasma is intrinsically steady state and can have $\beta>1$. Compared with a tokamak, a dipole plasma does not require current drive and is free of disruptions.

In the Levitated Dipole Experiment (LDX) now under construction, the dipole magnetic field will be created by an axisymmetric levitated superconducting current ring, and there will be no applied toroidal magnetic field. The plasma in LDX will be heated by multi-frequency ECRH to permit control of the pressure profile. Ray tracing in the LDX geometry using a finite temperature code [1] indicates that singles pass absorption can be obtained.

A critical issue for the dipole fusion concept is the nature of plasma equilibrium and stability at very high local plasma beta. In closed field line systems such as a levitated dipole gross plasma stability in bad curvature regions can derive from plasma compressibility. MHD studies indicate that when the plasma has a sufficiently gentle pressure gradient it will be stable to interchange modes at all β values. The limitation on the maximum pressure gradient determines that the peak beta will only be limited by the size of the device. Furthermore, MHD studies have shown that when interchange modes are stable, ballooning modes will also remain stable (at all β values) [2]. The dipole confinement concept differs from other fusion concepts since the diamagnetic frequency, ω_*, proportional to the plasma pressure gradient, is less than twice the magnetic drift frequency, ω_d, proportional to the magnetic field gradient. (i. e. $\omega_*/\omega_d<2$). Kinetic studies have been carried out for both collisional and collisionless plasmas and they indicate that for an appropriate value of $\eta=d(\ln T)/d(\ln n)$ a dipole will also be stable to drift frequency modes, such as temperature gradient driven modes [3]. Thus when $\eta\sim2/3$ a dipole plasma can be free of both MHD and drift wave generated instability.

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2D17

Variational Principle for V-states (Waterbag) Models*

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The Vlasov-Poisson system and the two-dimensional Euler equation possess reductions where the dynamics is reduced to that of boundaries of regions of constant phase space density and vorticity, respectively. The Vlasov-Poisson system has solutions that describe nonlinear plasma oscillations, while Euler's equation has special solutions of uniformly distributed vorticity called V-states. We write down the Hamiltonians for these systems and then insert trial functions depending on parameters that approximate the plasma oscillation and the V-state solutions. Properties of these solutions are studied. For the Vlasov-Poisson equation we derive, in the first (linear) approximation, the Bohm-Gross dispersion relation. For Euler's equation we establish the existence of limiting V-states, a result known before only numerically. Stability results for V-states will be discussed.

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Plasma Simulation Studies using M3D code[1]

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M3D code[2, 3, 4] simulates plasma discharges using various levels of physics models and using various grid options. To understand physics, results from different physics levels have to be compared. The efficiency of numerical grids and other methods depend on the problem at hand. For example, even for a simulation of a single discharge, a Fourier representation is efficient in the linear and early nonlinear phase, while configuration space representation is more efficient in later more singular phase, if sharp structures develop nonlinearly.

At present, M3D code has the following capabilities in one code, except some options are still being updated to the newest version.

- Physics levels: MHD, Two-fluids, particle/fluid hybrid models,
- Geometries: 2D boundary, 3D boundary such as a stellarator,
- Representations: unstructured mesh, unstructured poloidal mesh with toroidal Fourier, structured mesh with (θ, ϕ) Fourier space,
- Processing modes: serial, MPP.

The capability to run both in serial and in massively parallel machine architectures has been achieved by combining with the parallel processing structure of ParM3D[5]. ParM3D is a massively parallel implementation of the MHD physics of M3D, utilizing the PETSc[6] library.

Visualization is done using AVS/Express, and MDSplus data management software is planned to be used.

For easier coupling to experimental data, capabilities to read in equilibria from EFIT and JSOLVER have beem added, in addition to existing interfaces to ESC and Chease equilibrium codes and equilibria generated by M3D itself. Simulation results of plasma discharges such as NSTX will be presented.

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Resistive MHD Simulation on Massively Parallel Computers

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A parallel resistive magnetohydrodynamics code, ParM3D, has been developed for studying the global dynamics of magnetized plasmas in toroidal geometries[1]. Mixed field and flux(stream) function representations are adopted for both the magnetic field and the plasma flow field. The scalar equations that are evolved in time are of a current-vorticity formulation. Adequate boundary conditions are prescribed for the current-field formulation in a general toroidal geometry via Ohm's law. A three dimensional domain decomposition is implemented. The parallel data layout conforms with PETSc, which provides high quality parallel iterative sparse matrix solvers.

Validation and benchmarking of the code have been done for axisymmetric equilibrium check, stable TAE mode calculation, ideal and resistive kink calculation, and their comparison with NOVA and MARS results. Recent progress on slowly growing tearing modes and nonlinear evolution of resistive kink will be reported.

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Simulations of Energetic Particle-driven MHD Modes using M3D code*

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The energetic particle-driven MHD modes are studied using a multi-level extended MHD code M3D[1]. In the extended MHD model, the plasma is divided into the bulk part and the energetic particle component. The bulk plasma is treated as either a single fluid or two fluids[2]. The energetic particles are described by gyrokinetic particles following the self-consistent electromagnetic field. The model is self-consistent, including nonlinear effects of hot particles on the MHD dynamics and the nonlinear MHD mode coupling.

Previously we had shown the results of nonlinear saturation of TAE[3], energetic particle stabilization of internal kink modes and excitation of fishbone[1], and nonlinear saturation of fishbone in a circular tokamak[4]. In this work, we extend the simulations to general geometry using unstructured mesh[5]. We also use a gyrofluid model for fishbone in order to study the role of MHD nonlinearity in saturation near the marginal stability. Recent Progress will reported.

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Nonlinear Magnetic Reconnection in Toroidal Systems*

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The possibility of a self-consistent nonlinear drive for magnetic islands in a toroidally confined plasma, due to the "two-fluid" electron pressure gradient term $\nabla_{||}p_e$ in the Ohm's law, is confirmed. While the parallel gradient of the electron temperature $\nabla_{||}T_e$ can be assumed to be small, due to the rapid electron thermal equilibration along the field lines, the density variation, smoothed by slower ion sound wave propagation, can be substantial and it evolves in a manner that can self-consistently drive magnetic reconnection. Numerical simulations with the MH3D-T code, for resistive $m = 2$, $n = 1$ islands, show that this term can produce a substantial nonlinear reconnection rate even when its effect on the linear growth is small. The variations of temperature and density along the 3D magnetic field lines, in and around a magnetic island, are investigated. The effects are compared to those of other potential driving terms. To further study these phenomena, the two-fluid model is also being incorporated into the massively parallel version of the M3D code with unstructured mesh capability.

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MHD Simulations of Compact Stellarators and M3D Development

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M3D [1] simulations are being done of compact stellarator equilibrium and stability. Simulations are initialized with VMEC [2] equilibrium data. Results of simulations of NCSX equilibria will be presented. An issue with the NCSX design has been the integrity of the magnetic flux surfaces. Initialization with VMEC contains islands, even though VMEC assumes flux surfaces, because the VMEC output does not accurately account for singular currents necessary, in general, to suppress islands. In M3D simulations the islands often get smaller as the equilibrium evolves. Islands are being compared with results of the PIES [3] code.

As the simulation evolves in time, resistive and ideal ballooning modes begin to grow exponentially in time. The onset of fast ideal growth is consistent with the beta limits obtained with Terpsicore and other codes [4]. The velocity perturbations have the appearance typical of ballooning modes. Calculations of growth rate in a set of NCSX design equilibria with different β will be presented.

In other work, the M3D code has been given a massively parallel option by writing an interface to ParM3D [5]. ParM3D is a massively parallel implementation of the unstructured mesh and equations of M3D, using the Petsc [6] library. The interface uses the grid and solvers of ParM3D, while using the equations and time advancement routines of M3D. This allows comparative benchmarking of the serial and parallel versions of M3D.

Work is also in progress on the use of a field line following grid. The grid is aligned, on every flux surface containing grid points, with a rational approximation to the rotational transform. This allows the grid to be periodic. The shearing of the grid cells is alleviated by reconnecting the triangles of the mesh, while keeping the meshpoints fixed. The field line following mesh may be useful for stellarators, and for hybrid simulations in tokamaks.

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E X B rotation shear stabilization of resistive pressure-gradient-driven turbulence and turbulent transport

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Resistive pressure-gradient-driven (RPGD) turbulence is a possible candidate producing the cross-field particle and energy losses at the plasma edge in a tokamak. This turbulence is driven by a pressure gradient in the bad curvature region partially reduced by a resistive field line bending while the saturated fluctuation level is determined by the collisional dissipation. The properties of the RPGD turbulence have been actively studied analytically and numerically and the scaling of turbulent transport coefficients with plasma parameters has been predicted [1,2,3]. Previous simulations of the RPGD turbulence with a fixed pressure source were motivated by the E X B rotation shear stabilization of the turbulence during the L-H transition, showed an importance of self-consistent approach [4]. This approach applied for a study of the second-order phase transition illustrates an effect of self-generated flow shear. An analysis of the evolution of the cross phase between velocity and pressure fluctuations with a change of the poloidal flow performed under the assumption of weak flow shear showed the decrease of the cross phase with an increase of the mean flow value both for particle and heat flux.

In this paper we continue the study of the E X B rotation shear effect on the RPGD turbulence and analyze the behavior of this turbulence in the presence of imposed E X B rotation shear. Such study may be motivated by experiments with an edge biasing or other techniques where the E X B rotation shear is produced by the mechanisms different with the self-generation of poloidal flow by the Reynolds stress (enhancement of the fast particle losses due to ripples). In contrast to previous studies of the RPGD turbulence our simulations have been performed in the toroidal geometry using the 3D resistive ballooning mode (RBM) code [5]. In addition to the trivial results illustrating the E X B rotation shear stabilization of the RBM and the reduction of the associated transport accompanied with the formation of the barrier on the pressure profile, we present here the analysis of the E X B shear effect on the fluctuation amplitude and the cross correlation between the pressure and electrostatic potential fluctuations (cross-phase effects). The effect of toroidal magnetic field on the RBM and associated transport is shown by performing the simulations at different values of the toroidal magnetic field. Finally, the E X B rotation shear effect on turbulent diffusivity is quantified using the fit of numerical simulations and the E X B shear correction (edge turbulence scaling) to the RBM-driven diffusivity is proposed. The agreement of the simulations with experiments will be emphasized [6,7,8].

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Error Indicators and Grid Adaptation for Application to Elliptic and Hyperbolic Problems

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A new method for grid adaptation will be presented. The method uses a variational approach based on a least squares moving finite volume definition of the error measure.

Variational grid generation (often referred to as Brackbill-Saltzman or Winslow approach) is based on the solution of elliptic Euler-Lagrange equations that minimize suitably defined functionals. In its most common implementation, adaptation is achieved using an heuristic error measure that the variational method uses for guidance in determining where the grid should be finer and where it should be coarser. This method has the great advantage to provide always unfolded, smooth grids. But the definition of the error measure is left to the experience of the user and to the knowledge of the physical behaviour of the solution.

Least squares moving finite volume (LSMFV) methods (or more generally any moving finite element (MFE) method), instead, rely on a well defined a posteriori error definition. The method has a precise prescription on how the error should be computed. However, attempts to use the method for grid adaptation have to overcome the difficulty that a straight error minimization leads to folded and ill-defined grids. Although, ways to overcome this difficulty have been formulated within the MFE community, another approach is proposed here.

We propose to combine the powerful and reliable elliptic grid generation provided by the variational grid apaptation method, with the error measure provided by the LSMFV method. The theoretical tool that allows to make a rigorous link between the two approaches to grid generation is the Baines'equivalence theorem which will be described.

The talk will present briefly the properties of the variational grid adaptation method and of the LSMFV method. The presentation will then focus on the new method presented here and on the theoretical derivation of its features based on the variational approach, on the LSMFV error measure and on Baines' theorem.

Examples of the application will be presented. The method for grid adaptation will be applied to elliptic problems and hyperbolic problems in 1D and 2D. The elliptic problem considered is the classic Poisson's equation of electrostatic. A number of hyperbolic problems are considered: Gas Dynamics, Shallow Water and Burger's equation. The hyperbolic problems considered are treated within the ALE (Arbitrary Lagrangian Eulerian) method, where the grid adaptation tool presented here is used for the rezoning phase.

Stability investigation of the ideal MHD modes in elongated tokamak configurations*

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Highly elongated tokamak configurations (belt pinches) with elongation $\kappa \sim 3-5$ and aspect ratio $A \sim 4$ has several advantages over conventionally elongated tokamaks. For example, they can have higher beta and normalized current I/aB (see also M. Kotschenreuther's presentation at this conference). However, MHD mode stability in belt pinches is still an open subject. Numerical investigation has been performed for this purpose. For equilibrium calculations, both "TOQ" (and "BALMAP") and "JSOLVER" are employed. The codes "PEST2" and "DCON" (as well as "GATO") are used for stability investigations. These codes are compared, because of the numerical convergence in the belt pinch configuration is highly non-trivial. Both inductive and bootstrap-current-sustained steady-state equilibria are considered. As for the stability investigation, the low n modes (toroidal mode number n = 1 - 5), as well as the high n ballooning modes are investigated. It is found that there is a general tendency that beta and I/aB to increase with elongation. Saturation of these improvements for $\kappa \geq 2.5$, found previously, can be overcome by increased triangularity and/or indentation. The numerical results are presented and the underlining physics are discussed.

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Limiter and X-point Configurations in Ignition Experiments*

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The introduction of a proper divertor in meaningful fusion burn experiments is at times advocated with the argument that it addresses the "reactor relevant" issue of ash and impurity control and it allows access to the H-mode regime. On the other hand, a divertor decreases the volume available for the plasma and introduces structures that have to withstand high thermal wall loadings and the effects of disruptions in a high magnetic field environment. Other related questions are whether the density profiles that characterize the H-regime are optimal for ignition, whether the divertor has indeed led to cleaner core plasmas than those produced in limiter devices, and whether other means to remove the α-particles produced by fusion reactions, e.g. during their slowing down, are more appropriate even in principle. A new view of the divertor and of the roles played by particle recycling from the main chamber and cross field diffusion has been pointed out by the Alcator C-Mod group [1], challenging the standard picture of the divertor as the sole power and particle sink, in plasma regimes that are similar to those expected in Ignitor. In high density plasma experiments the level of impurity contamination has consistently been observed to be low, thanks to low plasma temperatures at the edge. For many reasons the limiter solution appears as the most suitable one for the plasma conditions expected in Ignitor at ignition. The first wall, covered with molybdenum tiles, acts as an extended toroidal limiter and the resulting thermal wall loads are rather modest. Nevertheless, given the highly flexible Poloidal Field Coil system in Ignitor, X-point configurations can be produced at somewhat reduced parameters and the relevant plasma-wall interaction issues are discussed. Modelling of the edge conditions for limiter geometry has been undertaken with the new EDI (EDge of Ignitor) code, taking into account impurity radiation, parallel temperature gradients in the boundary plasma and the effects of neutrals on the scrape-off ionization. The results indicate that limiter operation in Ignitor will have many desirable features, including low molybdenum sputtering and high power dispersal due to radiative processes.

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Efficient Density Profiles for Fusion Burning and the Ignitor Experiment*

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To attain ignition, where the energy deposited on the thermal reacting plasma by the high energy fusion products compensates for all the losses, a number of conditions have to be satisfied at the same time. The most critical ones are a sufficiently low value for the particle and energy transport coefficients, the macroscopic stability of the plasma column, and a high level of plasma purity. Compact toroidal experiments that can sustain average poloidal fields greater than 3 T and operate at peak electron densities of about 10^{21} m^{-3}, of the type represented by the Ignitor device [1], are at present the only viable concepts that can comply with the entire spectrum of ignition conditions. A series of 1-1/2 dimensional transport simulations have determined the optimal ignition conditions for Ignitor under a variety of assumptions regarding the plasma thermal transport properties. Low peak temperatures ($T_0 \sim 11$ keV) and relatively peaked density profiles are found to optimize the thermal energy content of the burning plasma column. In fact, at ignition the plasma is observed to assume a "consistent" pressure profile [2]. Peaked density profiles were suggested originally as a cure for the onset of ion temperature gradient driven modes and have been shown experimentally to exhibit superior confinement properties while maintaining, at high densities, the desired plasma purity. The earliest relevant experiments involved the Alcator A and C machines, and the latest the FTU [3] and Tore Supra [4] devices. We observe that not all the peaked density regimes that have been achieved experimentally are suitable for ignition, as some of them exhibit an excessive impurity accumulation and some are prone to plasma instabilities. The predicted performances of Ignitor in view of these results are illustrated, as well as the characteristics of the pellet injector that is a key part of the machine design.

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Interaction of Liquid Metal Walls with the Tokamak Equilibrium Fields*

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There are significant advantages to having a liquid metal first wall. For instance, it can effectively deal with high heat loads, and it can stabilize resistive wall modes, remnants of the external modes that survive with a conventional resistive wall. However, interaction of a moving conducting fluid with the ambient tokamak fields also poses potentially serious problems. Starting with the assumption, now supported by a number of studies[1, 2], that the complete stabilization of external modes requires the wall Reynolds number, S_W, to be of order unity ($S_W = \mu_0 \sigma u \delta$, where u is the flow velocity, and δ is the layer thickness), we have examined the effects of a liquid metal flow of this magnitude on the magnetohydrodynamic equilibrium, and to some degree, stability, of a number of configurations.

When the liquid metal flow does not conform to flux surfaces, we find that the interaction of the flow with the poloidal field modifies the equilibrium to such an extent that any stabilizing effect becomes irrelevant. A uniformly rotating flow rotates with it the plasma column itself. A nonuniform vertical flow that avoids the X-points of a double-null equilibrium also leads to large-amplitude and persistent (R,Z) excursions of the magnetic axis. With such large scale effects on the original equilibrium, both these options are probably not viable, although it is possible to minimize these effects to the extent that the flow can be made to conform to the flux surfaces.

Even if the flow were perfectly conforming, we would still need to consider the effects of the toroidal field. For various flow geometries, we show that the interaction of the moving conducting liquid with the large toroidal field induces large poloidal currents in the liquid metal wall. For velocities such that $S_W \sim 1$, the maximum current density in the liquid metal exceeds the plasma current density at the magnetic axis for typical tokamak equilibria with $q_0 \simeq 1$. Again, this is a surprising result that does not seem to have been anticipated or fully appreciated in recent studies[2, 3, 4, 5]. In addition to their large amplitude, the direction of these currents also poses a serious problem. In all cases we examined, the currents flow in opposite directions in two opposing halves of the chamber; thus, the resulting $\mathbf{J} \times \mathbf{B}$ forces push the liquid against the supporting wall in one half of the chamber and into the plasma in the other half, which would detach the flow from the wall. The current densities expected here are more than three orders of magnitude larger than those assumed by earlier studies[3].

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2D29

Anomalous Transport along Filamented Invariant Surfaces

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Filamented invariant magnetic surfaces can appear in toroidal equilibrium plasmas, in reconnection processes, in the solar corona, etc. Despite the invariant surfaces, field lines exhibit a specific chaotic dynamics with the zero Lyapunov exponent. Such dynamics are characterized by a so-called weak mixing property and allowed arbitrary large and long-lasting fluctuations which may be responsible for the plasma's disruption. We study transport along such surfaces, show that it is anomalous, and estimate characteristic exponents. We also describe different analogical phenomena related to billiard-type systems and granular materials.

Coulomb Scattering in a Magnetic Field

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The problem of Coulomb scattering between opposite signal charges is identical to the Keplerian problem of two masses. For the electron-ion scattering the orbits of electrons are like those of the planets and comets with Keplerian orbital frequency replaced by $\Omega_K = (Ze^2/mr^3)^{1/2}$ where r is the radius of the orbit. Adding the magnetic field brings in the added degree of freedom and the new frequency $\omega_c = eB/\mathrm{mc}$ of the cyclotron orbit. Thus, the combined system is a 2-degree of freedom Hamiltonian system with overlapping resonances for a range of orbital radii around that defined by $\Omega_K(r) = \omega_c$ which gives $r_c = (Z\mathrm{mc}^2/B^2)^{1/3}$. For $r \gg r_c$ the motion is almost adiabatic guiding center motion, since $\omega_c \gg \Omega_K$ and the result is to modify the Coulomb logarithm as given by Geller and Weisheit [1] and with exponential cut-off as in Glinsky *et al.* [2]. For electrons in the range of r_c from the ions there are chaotic scattering events when the outgoing electron velocity is exponentially sensitive to the incoming velocity vector as given by Schmidt *et al.* [3]. The 3/2-power law divergence of the orbital period makes the large Keplerian orbits exhibit a wider band of chaos than for the pendulum-type separatrix [4]. We present simulations of beam ensembles of Coulomb-scattered electron orbits with various ranges of impact parameters and compare the number of electrons scattered in solid angle $d\Omega$ with those obtained from the Rutherford cross-section $d\sigma = (Z^2e^4/2m^2u^4)\sin^{-4}(\theta/2)d\Omega$. We look for Cantor-like sets of the impact parameter associated with lower resonances $l\Omega_K = n\omega_c$ where the scattering angle is anomalous.

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Clebsch Potentials and Closures of the Vlasov-Poisson System*

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Closures of the Vlasov-Poisson and related systems are considered which preserve the dynamics of a class of initial distributions. Examples of such closures include the cold plasma approximation and the water bag model. In such cases, the closure may be understood as a reduced description of the dynamics within a symplectic leaf of a Poisson manifold. Clebsch potentials provide a means for introducing a reduced set of variables with which to describe the system. A comparison is presented between the dynamics of the Clebsch potentials and the dynamics of a closely related system of nonlinear conservation equations.

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2D32

Directional Fractional Kinetics

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Kinetic equations used to describe systems with dynamical chaos may contain fractional derivatives of an order α in space and β in time in order to represent processes of stickiness, intermittency, and so on. We demonstrate for a simple example that the kinetics is anisotropic not only in the angular dependence of the diffusion constant, but also in the angular dependence of the exponents α and β. A theory of such kinetic proceses has been developed on the basis of integral representation and asymptotic solutions for different cases have been obtained. The results show the existence of self-similar solutions as well as possible logarithmic deviations.

2D33

Resonant Plasma Heating by Electrostatic and Alfven Waves

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Resonant heating of particles in large amplitude electrostatic and Alfven waves is considered. Resonant heating of particles in a magnetic field has been examined by many authors and is of importance in the heating of magnetically confined laboratory as well as extraterrestrial plasmas[1-5]. To our knowledge however, a breaking of the invariance of the magnetic moment at frequencies a fraction of the cyclotron frequency has never been reported. We find that large amplitude electrostatic waves and large amplitude Alfven waves are capable of producing stochastic heating at a small fraction of the cyclotron frequency, the Alfven wave accelerating particles to a significant fraction of the Alfven velocity. The resonance phenomena producing these effects is described, and some effects calculated analytically. The relevance for ion heating in the solar corona is discussed.

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Dynamics of holes and clumps in Vlasov-Poisson plasmas

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We study the dynamics of holes and clumps in Vlasov-Poisson plasmas in the context of a single wave model. The model assumes a fixed marginally stable background electron distribution perturbed by an excess of electrons (clumps) and by depletions of the electron distribution (holes). We study the role of self-consistent chaos in the formation of dipole structures consisting of hole- clump pairs. Also, we present preliminary results on the statistical mechanics of ensembles of holes and clumps.

Zonal flow excitation by nonlinear EPM dynamics

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Using a hybrid MDH-Gyrokinetic simulation code [1], we investigate the nonlinear dynamic evolution of Energetic Particle Modes [2]. In particular, we show that the coherent nonlinear EPM eddies tend to be radially fragmented by the onset of a nonlinear axisymmetric perturbation of the mode structure. The underlying physical mechanism is demonstrated to be that of the interaction of the EPM mode with the low frequency axisymmetric nonlinear modification of the energetic particle distribution function, eventually yielding to EPM saturation [3]. It is possible to demonstrate that, in correspondence of the radial fragmentation of the coherent EPM eddies and of EPM nonlinear saturation, a *zonal flow* is also formed. However, the interaction of EPM with zonal flows has little effect on nonlinear EPM dynamics, which is essentially regulated by resonant interactions with fast ions. Numerical calculation of zonal flow intensity (mainly given by thermal plasma nonlinear response) and decorrelation rates will be presented. In the nonlinear regime, we show that the finer radial structures in which the EPM mode is *eventually broken*, also reflect onto the fast particle radial profile, yielding particle and energy diffusion [3]. The possibility that the zonal fields are modulationally unstable [4] is also analyzed.

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Kinetic theory of magnetic reconnection in the whistler frequency regime

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It is well known that a neutral sheet configuration allows a fast electron tearing mode to grow, due to a resonant wave-particle interaction near the null line [1]. In this work we study the transition between this electron resonant tearing mode and the well-known fluid cold tearing mode in the whistler frequency range [2], using a fully kinetic treatment. A set of two coupled differential equations for the perpendicular perturbed components of the magnetic field, valid over the whole range of spatial coordinates, is derived by performing a suitable approximation of the Parker orbits. This new set of equations includes all kinetic effects in the direction of, and perpendicular to, the equilibrium magnetic field. From this set the fluid and the resonant limits are recovered and the condition for the transition between them can be studied.

These results are important in the context of the magnetic field dynamics on the electron time scale in the laser-plasma interaction, where magnetic reconnection is expected to be an important process in the wake of a ultra intense laser pulse.

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2D37

Ion Kinetics in a Helicon Plasma Source*

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Steady- state operation of a helicon plasma source implies that the ionization of the background gas is balanced by the outgoing ion flow along the field lines of the equilibrium magnetic field. Ion motion is controlled by the ambipolar electric field and charge- exchange collisions with the background gas. We assume that the length of the system is large compared to the charge-exchange mean free-path. We find that in this case the ion distribution function is half- "Maxwellian" with characteristic ion energy proportional to the ambipolar electric field. For a given electron temperature, this distribution leads to a universal ion density profile along the magnetic field lines. Our analysis gives the amount of background gas needed to support a steady-state discharge.

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A Fluid Code for Relativistic Laser-Plasma Interactions

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Much of the physics relevant to understanding the interaction of intense laser pulses with underdense plasmas is contained in the Vlasov equation coupled to Maxwell's equations. In limited, specialized cases, analytical progress can be made towards solving the Vlasov equation, but in full generality, the Vlasov–Maxwell system is considered to be intractable to analytic solution. Fluid models (both warm and cold) represent a significant simplification over full kinetic treatments of plasma dynamics; of course, this simplification comes at the price of having discarded most of the kinetic behavior (such as particle trapping), but retains enough physics to be qualitatively and quantitatively useful.

We describe the various computational issues arising in a recently developed code [1] for modeling the interaction of a cold, relativistic plasma with an intense laser pulse in the 2-D fluid limit. This code is unique in that the laser time-scale is explicitly resolved, *i.e.,* no approximations are made beyond the hydrodynamic assumption. We discuss the subtleties involved in numerically solving a non-linear hyperbolic system of equations. In particular, we examine the steps necessary to ensure proper flux transport in the density equation, thereby avoiding unphysical negative densities. We compare the two standard approaches: flux-corrected-transport and flux-limiting.

We show that the usual "momentum" formulation of the fluid model leads to unphysical results in regions of vanishing density and that the correct results are obtained from the (conservative) momentum-density formulation which is a natural consequence of a covariant derivation of the model.

We discuss various possible far-field boundary conditions including periodic boundary conditions and perfectly absorbing boundaries.

Finally we present various examples demonstrating the physics potential of this code. We make comparisons to known analytical results and explore the validity of the time-scale separation underlying quasi-static models. We also present some examples relevant to the current self-modulated laser wakefields experiments carried out at CBP-LBNL.

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The Role of Dispersive Waves in Collisionless Magnetic Reconnection

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Theoretical studies of magnetic reconnection have debated for many years the viability of two fundamentally different models for the basic magnetic geometry. In one model (the Petschek model), an open X-point configuration allows the inflowing plasma to reach high velocities approaching the Alfven speed of the reconnecting magnetic field. In the other (the Sweet-Parker model), the reconnected plasma is forced to flow through a narrow, elongated layer (the width of which is determined by non-MHD effects such as resistivity or some collisionless analogue), resulting in much lower inflow velocities and much smaller rates of magnetic energy release. Numerical simulations carried out over the years based on conventional resistive MHD have supported the latter model, while the former seems more consistent with rapid rates of energy release often observed in reconnection phenomena in space an laboratory plasmas. Here we describe the results of numerical simulations of reconnection in a collisionless plasma that show that in fact either geometry is possible. The open X-point geometry that allows fast reconnection is produced by the dynamics of whistler and kinetic Alfven waves at small scales. These waves, which are introduced by the Hall term in the generalized Ohm's law, are present in nearly all collisionless systems of practical interest. However, for extreme parameters, the dynamics of these waves can be suppressed. In this case, simulations show an elongated Sweet-Parker layer of width c/ω_{pe} is formed, and the reconnection rate is much slower.

Effects Of Magnetic Islands In Axisymmetric Equilibria*

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The nonlinear growth and saturation of tearing mode instabilities produces magnetic islands in toroidal, magnetically-confined plasmas. Both classical and neoclassical tearing modes often occur in axisymmetric plasmas and induce islands that break the axisymmetric property of toroidal equilibria and introduce three-dimensional structure. If these islands are "small" (island width w small compared to the radius of the resonant surface r_s), they can be approximated by a single helical magnetic flux perturbation $\tilde{\psi}(r, m\theta - n\zeta)$ that is resonant on the mode-rational surface $q(r_s) = m/n$. (In these formulas, r and r_s are "radial" flux surface labels.) The question to be addressed here is: how can such "small" magnetic islands be taken into account, at least approximately, in the determination of the MHD equilibrium magnetic flux surfaces for experimental devices that are axisymmetric (e.g., tokamaks, STs, RFPs)?

The MHD equilibria for axisymmetric toroidal plasmas are usually determined from numerical codes (e.g., EFIT, VMOMS) that solve the axisymmetric MHD force balance equations, which result in the Grad-Shafranov equation. Rigorously speaking, the introduction of a magnetic island produces a fully three-dimensional (3-D) situation and one should solve for the fully 3-D equlibrium magnetic flux surfaces. However, for isolated, small magnetic islands one can obtain the approximate properties of the 3-D equilibrium magnetic flux surfaces by just adding to the axisymmetric magnetic flux sufaces $\psi_0(r)$ the helically-resonant magnetic island structure. Then, the pressure becomes constant along helical magnetic field lines and hence $P(\psi) \to P(\psi_*)$, where $\psi_* \equiv \psi_0(r) - \psi_0(r_s) + \tilde{\psi}$ is the helical magnetic flux function. (The additional "nonresonant" magnetic flux surface variations due to toroidal mode coupling produce "fluctuating" components whose average over the helically resonant angle are negligible.) The resultant equilibrium reflects the magnetic island structure in the vicinity of the magnetic island but reduces to the usual axisymmetric equilibrium far from it (i.e., for $|r - r_s| >> w$) where $P(\psi_*) \to P(\psi_0)$. Upon averaging the magnetic island structure over the helical angle $m\theta - n\zeta$, one obtains an "island shape function" $P_w[(r - r_s)/w]$ that should be used to modify the (axisymmetric) pressure profile function $P(\psi_0)$ in the vicinity of the magnetic island, when trying to obtain the best "axisymmetric" equilibrium fit for toroidal plasmas in experimental devices that are axisymmetric but have isolated, small magnetic islands in them. Detailed forms of the magnetic island structure and the island shape factor $P_w(\psi)$ will be presented and discussed in this poster.

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2D41

Helium removal by collisional ripple transport in a tokamak reactor

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Completely thermalized helium ash particles may follow the background ion transport processes, either neoclassical or turbulent, and their removal across a quiescent H-mode layer can be a serious problem in a burning tokamak plasma. However, the warm helium particles spend a long slowing-down time (of order particle confinement time) at energy much above the background thermal energy. Thus the warm helium transport may have a significant impact on the ash removal rate and their radial accumulation profile. In the absence of an MHD activity, the most significant radial flow of warm helium ions in a tokamak reactor may be from the collisional ripple transport. The magnetic ripple exists inevitably due to the discreteness of the toroidal field coils.

In the present work, we reevaluate the collisoinal ripple transport processes of banana tips below the collisionless stochasticity criterion in a more careful and complete way. Both numerical and analytic studies have been performed. We first report a significant new progress in the particle transport theory in a collisional web mapping, which occurs without toroidal precession [1]. We then add the toroidal precession, which introduces phase spanning KAM surfaces in between the web structures [2]. A realistic collisional ripple transport is then described as a combination of web and KAM effects. It is found that there are three different diffusion regimes determined by the relative strength of the collision frequency, ripple magnitude, and toroidal precession rate. A new analytic formula for the collisional ripple diffusion coefficient is derived. It is found that a moderate ripple (about 0. 1%) can lead to a large helium diffusion coefficient (about 1 m^2/s), which is much greater than what the previous ripple-plateau theories predicted. The new theoretical result compares reasonably well with the anomalously fast beam- ion transport rates observed in TFTR.

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Liquid Metal Wall Equilibria and Consequences of Fluid Surface Waves

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Liquid metal wall equilibria in axisymmetric toroidal geometry is considered. A combination of centrifugal acceleration and J $\times$ B forces are used to ensure adherence of the liquid metal wall to an underlying solid wall. We find that the needed wall fluid injection velocity depends , in part, on the machine minor radius, the magnitude of the toroidal magnetic field, and the magnitude of externally imposed poloidal currents.

The theory of liquid metal surface waves is reviewed. A comparison of theoretical predictions of liquid metal surface wave dispersion and damping with laboratory measurements is shown. We find that the wave motions may be unstable due to gravitational forces, in the toroidal equilibria described above. Thus, liquid metal walls must be designed with sufficiently high flow velocities so that gravitationally driven fluctuations do not grow too strongly during the time the fluid is within the machine.

While rapid flow speeds are desirable from the point of liquid wall equilibria and stability with respect to gravitational instabilities, Kelvin-Helmholtz instability growth rates increase with higher wall fluid flow speeds. Kelvin-Helmholtz instability theory, as applied to liquid metal walls is described. We find that K-H growth rates can be the same order as resistive wall mode growth rates for the APEX parameter set.

A couple of novel wall fluid schemes are described. The first of these is known as the "soaker-hose" scheme in which liquid metal flows primarily through pipes. The second scheme involves tilting a torus up on its side and driving liquid metal flows the long way around a torus. Advantages and disadvantages of the various schemes are discussed.

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2D43

Searching for Surfaces:
A Hamiltonian Algorithm for Finding Stellarators with Near-Perfect Surfaces

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Stellarators require nested toroidal magnetic surfaces for optimal performance. Even in vacuum, islands appear due to the instrinsic 3D shaping of a stellarator. An algorithm is presented to essentially eliminate the islands in an arbitrary vacuum field. The hamiltonian description of a magnetic field allows us to identify a smooth integrable field with surfaces as well as resonant fields which break up surfaces. As we add on the resonant fields, we use infinitessimal canonical transformation theory to change the boundary conditions in such a way as to render the perturbations nonresonant. In this way we can smoothly deform the field into one without islands. The procedure is illustrated with a code which "heals" islands in a periodic cylinder with 3D shaping.

An Explicit, Nonperiodic, Nonlinear Eulerian Gyrokinetic Solver for Microturbulence Studies

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The General Atomics gyrokinetic-Maxwell solver (GYRO) – which relied on an implicit parallel motion advance with operator splitting for nonlinear terms – has been largely rewritten. In the new code, eGYRO, an orbit-time grid replaces the more familiar fixed poloidal grid in the gyrokinetic equation, allowing full resolution of bounce-point cusps. More systematic, high-accuracy quadrature rules yield superior convergence with number of velocity-space points. Velocity integrals in the Maxwell equations are projected onto a set of poloidal "blending"-functions to obtain the theta-dependence of fields. The full nonlinear equations (including zonal flows) are advanced in time using an explicit 4th-order integrator. These changes were motivated to overcome the unacceptably poor time-step convergence of semi-implicit splitting methods, and to more elegantly treat nonperiodic radial boundary conditions.

eGYRO is parallelized using a more efficient domain decomposition algorithm than that in GYRO, making it suitable for MPP simulation with greater than 10^3 processors. Linear ballooning modes can be computed rapidly and with high accuracy using suprisingly small phase-space grids. CYCLONE ITG benchmark cases are reproduced with timesteps on the order of $(c_s/a)dt = 0.1$. Moving beyond periodic radial boundary conditions, we examine systematically the modification of transport properties when density and temperature profiles vary within the simulation domain. Presentation of this work is highlighted by exhaustive MPEG animation of linear and nonlinear simulations. The scope of the presentation will be broadened by an intuitive, nontechnical component, which we hope will make it equally appealing to experimentalists and theoretists.

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2D45

Calculation of Plasma Transport Using Monte Carlo Determination of Pressure Anisotropy

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A method is described to calculate the neoclassical transport, and thus the ambipolar electric field, using results from a δf Monte Carlo code combined with the single-fluid force balance equation. It is difficult to obtain direct measurements of the plasma transport due to large noise in the measurements. Using the fluid equations, however, it is possible to relate the transport to the pressure variation on a magnetic surface. This allows a more accurate determination of the plasma transport. The application of this method to the calculation of the rotation damping of the plasma will also be demonstrated.

Calculation of the Neoclassical Radial Electric Field using the Global Toroidal Code

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The calculation of the radial electric field in stellarator devices is an important issue in neoclassical transport. The radial electric field, which is also related to the formation of transport barriers, can affect the anomalous transport. In stellarator configurations which depart only weakly from axi-symmetry, a direct Monte Carlo calculations of the radial electric is difficult due to the large statistical fluctuations. We present a novel method based on the evaluation of the perpendicular $(p_\perp)$ and parallel $\left(p_{||}\right)$ pressures. The variation of $\widehat{p} \equiv \left(p_{||} + p_\perp\right)/2$ on the magnetic surface provides a low-noise calculation of the radial electric field. The low-noise method has been implemented in a three-dimensionsal gyro-kinetic particle code[1]. The calculation of the radial electric field for the National Compact Stellarator Experiment will be presented.

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2D47

Squeezed Potato Orbits in a Magnetic Well*

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In advanced tokamaks, such as PEGASUS, and NSTX, the plasma beta, which is the ratio of the plasma pressure to the magnetic field pressure, in the near axis region can be very high (> 50%). It is important to take into account finite beta effects in developing a transport theory. It has been demonstrated that banana orbits are squeezed in a magnetic well [Phys. Plasmas **3**, 2843(1996)] in high beta tokamaks. Here, we illustrate that potato orbits are also squeezed in a magnetic well in the near axis region. The squeezing factor is the same as that for the banana orbits and is proportional to the particle energy. For high energy particles, the size of the orbits is not sensitive to their energy and only depends on the geometric factor. This indicates that the confinement for high energy particles is improved in high beta tokamaks. It also implies that plasma confinement for advanced fuels can be better than the prediction based on the conventional theory.

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Radial Patterns of Instability and Transport in JT-60U Internal Transport Barrier Discharges*

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One class of internal transport barrier discharges ("box-type") in the JT-60U tokamak is characterized by two relatively flatter regions of the pressure separated by a region with very large pressure gradient. Linear growth rates for toroidal drift-type modes are calculated by the FULL code[1, 2] for discharges in this class, without and with sheared $\mathbf{E}\times\mathbf{B}$ rotation effects, calculated by a recently implemented rotation model[3, 4]. For cases with fully-developed barriers, the results with rotation are consistent with a picture in which the radial electric field generated in part by the steep pressure gradient causes local stabilization, and thus reduction of the local anomalous transport, which allows the steep pressure gradient to persist. If rotation is omitted from the calculation for these cases, or if rotation is included for cases without barriers or with partially developed barriers, the unstable region spreads into the steep pressure gradient region.

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A multi-fluid kinetic model for a beam propagating in a plasma. The problem of trapped particles.*

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We analyze the nonlinearity arising from the coupling of the movement of particles of opposite charges in a self-consistent electric field. In particular we introduce a new mathematical way to treat trapped particles.

The system we study is formed by a proton beam propagating in presence of a plasma. This situation occurs in the low energy part of an ion accelerator. The ion beam, extracted form the reaction chamber, reaches the first accelerating device through a drift tube where a residual neutral gas is present. A process of ionization takes place and secondary electrons and ions are created. The motion of these secondary particles is essentially *transverse* to the beam. The secondary electrons are trapped in the self-consistent electric potential of the beam and oscillate in the corresponding potential well while the secondary ions are accelerated towards the wall. As a consequence, the secondary electrons almost neutralize the space charge of the beam (see for example [1]), which is then transported through the drift tube with very low divergence. Indeed, since this neutralization process has a strong influence on the beam transport, it has to be studied and simulated carefully in order to estimate the beam losses that could occur along the accelerator.

Experiments show that the ionization of a residual gas by a continuous beam in the drift tube gives birth to a *stationary* plasma of secondary electrons and ions [2]. Stationary models of neutralization of the beam space charge have been derived by Dunn and Self [3] and Holmes [4]. They are all based on the thermalization of secondary electrons. However, in cases of interest, this assumption is not realistic and we have adopted here a kinetic description for both the secondary electrons and ions. A fairly natural kinetic model is provided by a stationary multi-fluid Vlasov-Poisson system with source terms.
By introducing the concept of *trapping set* we prove that this problem does not admit solutions [5]. To overcome this difficulty, we propose an heuristic model which consists in modifying the electron source term. In this new frame, we prove that the problem can be solved [6].

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2D50

Convective Intermittent Transport in Plasma Turbulence

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A two-dimensional model for convective transport is investigated numerically both as a gradient and flux driven system, allowing the profiles to evolve self-consistently. Such convection models are well suited for describing tokamak edge turbulence and is frequently used as a toy model for the low-dimensional description of the L-H transition.

Here we present simulations of the turbulent state and show that intermittent transport events in the form of fronts or avalanches occurs due to boundary layer instabilities as well as profile fluctuations in the source region in the flux driven case. These fronts are known as thermal plumes in Rayleigh-Benard convection. The transport is mediated by large, stable convection cells extending over the whole radial domain. Similar transport events and flow structures are also observed in three-dimensional simulations of ion-temperature-gradient and resistive balloning mode turbulence.

2D51

Collisionless Equilibrium and Stability of a Uniform, Spherical Electron System*

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Equilibrium and stability of a collisionless, spherical Vlasov system are considered. Previous uniform-density solutions are extended to arbitrary dependence on energy. In contrast to the previous special case, these general equilibrium distribution function and their first derivatives may be made non-singular. The linear stability of general spherical equilibria is considered. This problem is reduced to a one-dimensional calculation by the introduction of a spherical harmonic decomposition. All azimuthal mode numbers are degenerate. For low (zero) temporal frequency of these linear modes, a closed form is obtained for the response of number density to electrostatic potential. A numerical investigation of this stability problem is carried out with a linearized, initial value PIC approach. Equilibria are computed including the possibility of a background confining well (as in a spherically tuned Penning trap). These are characterized by two parameters: energy spread DEo compared to total electrostatic potential; and density n compared to density associated with the electrostatic potential hill. Stability results are obtained for total harmonic numbers l = 0, 1, and 2. In comparison to previous fluid treatments, exactly uniform density, stable solutions exist in the collisionless case.

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ELECTRON BERNSTEIN WAVES IN THE CASTOR TOKAMAK

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We examine the possibility of ECRH in an over-dense plasma that can be found in the CASTOR tokamak. This is a small tokamak in Prague, with low magnetic field so that the 1st electron cyclotron resonance is situated on the plasma column axus.

In over-dense plasmas, only O-X-EBW process can lead to significant heating of the central region of the plasma. A full wave finite element code has been used to investigate the propagation of electromagnetic waves in a warm tokamak plasma with boundary conditions appropriate to the ECE scenario.

Here we consider the inverse problem : that of RF emission arising from EBW conversion. In particular, there are two possible processes : EBW-X or EBW-X-O. We also present results on the effect of plasma turbulence on ECE, using experimentally measured instantaneous radial density profiles. The surface plasma turbulence has a profound effect on the EBW-X mode conversion, since this is very sensitive to the distance between the upper hybrid resonance (UHR) and the R-cutoff. On the otherhand, the EBW-X-O conversion is relatively insenstiive to the flucutating electron density.

This gives promise for successful ECHR at 18 GHz on CASTOR.

A ray-based algorithm for numerical computation of multi-dimensional linear mode conversion*

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A new algorithm is proposed for connecting the incoming and outgoing disturbances in numerical studies of mode conversion in multiple spatial dimensions. It is demonstrated that, in principle, one can compute all quantities needed for the S-matrix connection formulas directly from the rays computed using the full 3×3 determinant as the ray hamiltonian. The first task at hand for implementing a numerical ray tracing algorithm which includes mode conversion is to ask: What quantities can be monitored following the rays which detect that one has entered a conversion region? We conjecture that these signatures will be of two types: 1) One (or more) of the other eigenvalues will become 'small' in certain characteristic ways. And 2) the ray, or the surface swept out by a family of rays (the *lagrange manifold*), will have a certain distinctive 'shape' in the vicinity of the conversion. In order for a quantity to carry 'shape' information it should be invariant under the following transformations: a) Congruence transformations acting on the dispersion tensor **D** and the field **E**. b) Reparameterization of the ray. c) Linear canonical transformations of the phase space variables. The first two requirements are relatively straightforward to enforce. Requiring invariance under linear canonical transformations leads us to the subject of *affine symplectic geometry*. (We thank Alan Weinstein for pointing out this fact and for suggesting the references cited.) The restriction to *linear* canonical transformations is analogous to the restriction to translations and rotations in the usual Frenet theory. As we will discuss, it is possible to develop a Frenet-type theory of curve shapes, and to introduce 'curvatures' for surfaces which are symplectic invariants [1-3]. The application to multidimensional mode conversion will then be discussed.

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A Collisionless Kinetic-Fluid Closure and its Properties for ∇T-driven Transport*

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A new closure model is presented for the strongly magnetized fluid equations that preserves essential features of the collisionless system. In our new Nondissipative Closure Model, the parallel heat flux is related to the temperature and the parallel flow such that this relation is valid for the unstable normal mode as well as for its complex conjugate. By this relation, the time reversal symmetry of the original kinetic equation is kept in the unstable wavenumber region in the fluid model. The closure model applies to highly collisionless regimes of ITG and ETG plasmas and space plasmas. Examples comparing the shearless slab ITG dynamics with the new closure model with the dissipative closure models of Hammett-Perkins and Chang and Callen are given in detail with high resolution simulations. Comparison of the entropy balance equation between the different models shows the qualitative difference of a local dissipative balance of the H-P and C-C models versus a nonlinear transfer through mode coupling to ever short scales in the Nondissipative Closure Model. Also, these fluid simulation results are compared with results of collisionless kinetic simulations, for which a nondissipative and time-reversible integrator preserving a symplectic 2-from of a drift particle motion is applied to time-integration of the collisionless gyrokinetic fluid equations. Validity of the scheme is checked by the plasma echo simulation experiments, which is the demonstration that the Landau damping is a collisionless and time-reversible phenomenon. Low-order models (LOMS) such those of Lee and Krommes are examined and shown reversible nonlinear oscillations for $\nabla T > \nabla T_{\text{crit}}$. When more modes are included the deterministic chaotic orbits set in and the systems exhibits the features of turbulence.

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3A01

Quantum Computation

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Advances in computing are revolutionizing our world. Present day computers advance at a rapid pace toward the barrier defined by the laws of quantum physics. The quantum computation program short- circuits that constraint by exploiting the quantum laws to advantage rather than regarding them as obstacles. Quantum computer accepts any superposition of its inputs as an input, and processes the components simultaneously, performing a sophisticated interference experiment of classical inputs. This "quantum parallelism" allows one to explore exponentially many trial solutions with relatively modest means, and to select the correct one. This has a particularly dramatic effect on factoring of large integers, which is at the core of the present day encryption strategies (public key) used in diplomatic communication, and (increasingly) in business. As demonstrated approximately five years ago, quantum computers could yield the most commonly used encryption protocol obsolete. Since then, it was also realized that quantum computation can lead to breakthroughs elsewhere, including simulations of quantum systems, implementation of novel encryption strategies (quantum cryptography), as well as more mundane applications such as sorting. I will describe recent work done in quantum computation, in particular the discovery and implementation of method to make quantum information robust against corruption, both in theory and experiments.

Self-Similar Solutions with Good Flux Surfaces As Attractors for Reversed Field Pinches

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Steady-State Reversed Field Pinches require a sustainment mechanism that maintains the toroidal field profile. This mechanism is believed to result from nonlinear m=1 ideal and resistive modes. Unfortunately, these multi-helical instabilities cause a large stochastic field region that limits confinement in these devices. In this paper we will demonstrate that with properly imposed boundary conditions (i. e. field programming) self-similar zero beta time and space separable solutions exist which have good flux surfaces and are tearing mode stable. Furthermore, these solutions are attractors in that the plasma will asymptotically approach them from stochastic initial conditions.

A class of 1-D solutions to the zero beta transport equations[1] has been found that are attractors when the plasma is ramped down at a rate approximately 10 times faster than the resistive diffusion time. This is demonstrated with a 3-D nonlinear zero beta simulation code (periodic cylinder) which has an initial state that is quasi-steady due to the presence of several m=1 instabilities. With an initial state is stochastic, we then apply the field programming boundary conditions prescribed by the self- similar solutions. The simulations then indicate that all of the instabilities stabilize and rapidly decay (leaving good flux surfaces) while the plasma asymptotes into the self-similar state. Two necessary criteria have been identified for these solutions to be attractors: the self-similar solutions must be linearly stable to tearing modes and the Hartman number needs to be larger than about 250. Also, the stable self-similar 1-D solutions require a reversed toroidal electric field. This same feature was seen during the "quiescent phase" observed on the Zeta Reversed Field Pinch. [2] The solutions are very robust and are relatively insensitive to the radial velocity boundary condition in that similar behavior is observed for both zero velocity and ExB convective boundary conditions.

Unfortunately, 1-D solutions require decaying discharges due to Cowling's theorem. A second class of separable solutions has also been found for helically symmetric profiles. Helical ohmic states are a special case of these solutions that have zero ramp rate. [3,4,5,6] Work is proceeding to study these states and determine the size of their basin of attraction. Toroidally symmetric states can also be found which implies that the analysis is easily extendable to Spheromaks and Tokamaks.

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Fast formation of magnetic islands in a plasma in the presence of counterstreaming electrons

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In this work we study the interplay of the Weibel and of the reconnection instabilities in the case of a plasma with two counterstreaming electron populations and show that the full isotropization of the electron distribution is accompanied by the formation of a magnetic field that develops magnetic islands.

With the help of 2-1/2 dimensional Vlasov simulations we show that the magnetic field generated by the Weibel-type instability, driven by the anisotropy represented by the two counterstreaming electron populations, develops magnetic islands due to the onset of a fast reconnection process that occurs on the electron dynamical time scale.

The main driving mechanism for both the Weibel and the reconnection instabilities is the electron anisotropy. The plasma evolution observed in numerical simulations is also in agreement with the theory of electron-resonant reconnection in anisotropic neutral sheets.

This process is relevant to magnetic channel coalescence in relativistic laser plasma interactions.

Kinetic Interchange-Ballooning Stability of Geotail Flux Tubes

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Kinetic theory is used to investigate the stability of ballooning-interchange modes for high pressure geotail flux tubes. A variational form of the stability problem is used to compare new kinetic stability results with earlier MHD, FAST-MHD and Kruskal-Oberman stability results. Previous analytic analysis [1] for the fully kinetic variational form gave sufficient conditions for instability in two frequency regimes (i) the kinetic MHD frequencies $|\omega| >> \omega_{*pi}, \omega_{Di}$ and (ii) the drift frequencies $\omega \sim \omega_{*pi}, \omega_{Di}$ where ω_{*pi} is the ion diamagnetic drift frequency and ω_{Di} is the particle drift frequency. A new numerical procedure for minimizing the variational form ($\delta\mathcal{L}$) of the stability problem is developed, based on

$$\mathcal{L} = \int \frac{ds}{B}\left\{\frac{1}{\mu_0}\left(\frac{\partial \xi^\psi}{\partial s}\right)^2 + \frac{1}{\mu_0}Q_L^2 - 2\frac{\kappa}{B}\frac{\partial P}{\partial \psi}\xi^\psi\xi^\psi\right\} -$$
$$\sum_a \int \frac{ds}{B}\int d^3\mathrm{v}\frac{F_a^M}{T_a}\left[q_a^2\phi^2 - \frac{\omega-\omega_*}{\omega-\overline{\omega}_D}\overline{\left(q_a\phi + \mu Q_L + (2E-\mu B)\frac{\kappa}{B}\xi^\psi\right)}^2\right].$$

The variational solutions include non-local kinetic effects which among other things will allow equilibriums with finite parallel potential drops to be examined. Also, arbitrary forms of the fully electromagnetic perturbations may be considered. The numerical procedure is implemented with the help of the parallel libraries, ScaLAPACK, and PETSc on a cray T3E. Polarizations for δE_y, $\delta B_\perp$, and $\delta B_\parallel$ are predicted for the substorm growth phase where the FAST-MHD mode instability has yet to be reached. These new non-local stability results are compared with previous local analytic calculations. *

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3B04

MHD Dynamic of Oscillating Field Current Drive

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Oscillating Field Current Drive (OFCD) is a technique proposed[1] to drive steady-state current in a Reversed Field Pinch (RFP). Poloidal and toroidal surface voltages are oscillated, out of phase, to inject magnetic helicity into the plasma (a form of ac helicity injection). The oscillating fields directly drive edge current, and plasma relaxation (fluctuations) is expected to cause current penetration into the core. In the present work, 3-D nonlinear, resistive, cylindrical MHD computation (the DEBS code) is used to understand the dynamic response of the plasma to the oscillating fields - the evolution of both the mean current and the fluctuating fields. The present computation is at relatively high Lundquist number, $S=10^5$, and low aspect ratio, R/a=1. 5. Analytical and computation solution of the 1-D equations are used as a reference, to understand behavior in the absence of fluctuations. In this case the oscillating fields produce a time average $< V \times B >_{\|}$ effect and mean plasma current confined to the plasma outer region. The 3- D computation indicates that resistive MHD fluctuations cause the current to diffuse into the plasma (by the tearing mode dynamo effect). The mean parallel current can be sustained by OFCD while the mean toroidal voltage is zero. Dependence of steady state fluctuations on plasma parameters, a critical question for confinement, will be presented.

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Steady-State, High-Bootstrap-Fraction Discharges: Prospects for DIII–D

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Given knowledge of the plasma pressure gradient, it is a straightforward procedure to construct solutions of the Grad-Shafranov equation with almost 100% bootstrap current. This has been carried out by Miller [1] for the case of spherical tokamaks and yields near-perfect alignment between the bootstrap current density profile and the actual profile. We report similar solutions for discharges representative of high-bootstrap-fraction, fully noninductive DIII–D discharges [2] in magnetic steady-state. Two models for the steady-state pressure gradient, which drives the bootstrap current, are investigated: (1) The critical gradient model wherein $d(lnp)/dr = -(\text{const.})/R$ and (2) a gyroBohm conductvity model where the steady-state heat conduction equation $h = \chi\nabla P$ determines the pressure gradient. Here h denotes the heat flux through a magnetic surface and χ is a gyroBohm thermal diffusivity $\chi = \chi_o T^{1/2}|\nabla T|M^{1/2}c^2q^2/e^2B^2$. The q^2 factor is needed to replicate the plasma current scaling of confinement. For the gyroBohm model, one finds that $\nabla p \propto q^{-2}$, reversing the usual dependence of bootstrap current on poloidal field. For both models, the density is taken as constant to replicate H–mode confinement. The resulting equilibria are investigated for stability against magnetic and heat diffusion, including auxiliary power and thermonuclear sources for h. To diminish NBI current drive with respect to bootstrap current, DIII–D will be operated at high densities $\sim 5 \cdot 10^{19}$ m^{-3} and low temperature (at fixed β_θ). Moreover, this increases the rate of magnetic diffusion and equilibrium should be attained within the allowable 5–10 s discharge duration. Technical limitations on total injected energy constrain these discharges to $\beta_{\text{tor}} \approx 0.01$. Consequently, β-limit physics will not complicate the study of mutual heat and magnetic diffusion.

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3B06

Driven collisionless reconnection at a magnetic X-point*

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Two dimensional, two-fluid collisionless models are proposed to simulate the VTF driven reconnection experiment at M. I. T. In the VTF toroidal plasma device, the externally created magnetic field is a quadrupole poloidal cusp with an optional toroidal component. Plasma flows towards and away from the X-point are induced through ExB drifts associated with an externally imposed electric field. We use two-field reductions of the collisionless MHD system in the vicinity of the background cusp X-point, with ExB driven flows as boundary conditions at far distances. Two alternative simple closure conditions are considered: constant plasma density, and constant electron temperature with cold ions in the strong toroidal magnetic field limit. For these, the linearized MHD equations admit a spatial separation of variables. The resulting 1- D system is also equivalent to the non- linearized system obtained under the assumption of a one-dimensional sheared flow. A closed-form solution is given in terms of integral transforms. From this we can calculate the current and electric field at the X-point hence the "effective resistivity" and reconnection rate.

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Applications of the MARG2D formulation to internal and external MHD modes in a tokamak

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An eigenvalue method, which solves the two dimensional Newcomb equation in a tokamak and is used in the MARG2D code[1], is applied to derive the dispersion relation (an equation of the growth rate) of an unstable ideal MHD modes. We also apply the method to derive a functional which expresses the change in the energy due to the perturbation at the plasma surface[2] and analyze the stability of an external MHD modes. We will discuss the extention of the present method to the resistive wall mode stability analysis.

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Progress Toward Resistive DCON

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The DCON code is widely used for fast and accurate determination of the ideal MHD stability of axisymmetric toroidal plasmas. Interfaces with many widely-used equilibrium solvers allows uniform stability analysis for all of them. Unusual speed and accuracy are afforded by the use of cubic and bicubic spline interpolation of equilibrium quantities, adaptive integration of perturbed quantities with tight tolerance, and mathematically correct continuation past singular surfaces. These features make DCON especially useful for challenging equilibria, such as those with high β, large vertical elongation κ, large range of safety factor q, high toroidal mode number n, and proximity to a separatrix. For internal, or fixed-boundary, modes, DCON uses a generalization of Newcomb's method, in which a change of sign of a critical determinant indicates the existence of a test function which makes δW negative. For external, or free-boundary, modes, it computes the plasma, vacuum, and total energy eigenvalues and determines stability according to the sign of the lowest eigenvalue. Output of tabular and graphic surface eigenfunctions at the plasma-vacuum interface in, and associated energy eigenvalues, in physical units provides data on the plasma response for comparison to experimental measurements and for feedback control codes. Recent improvements allow DCON to work in any straight-fieldline coordinate system.

Further development is in progress to enable DCON to compute "resistive" instabilities. These should include any modes characterized by singularities in the ideal MHD eigenfunctions, resolved by a variety of inner region dynamics, such as kinetic and drift tearing modes and nonlinear neoclassical tearing modes. For such modes, DCON computes matching data at the singular surfaces and writes them to a file. Another code, MATCH, reads this file and uses it to compute matching quantities Δ' at each singular surface and to match the ideal region data to particular singular region models and obtain Nyquist plots, growth rates, and eigenfunctions.

The most difficult challenge in completing this task is accurate computation of the ideal matching data at the singular surfaces. The adaptive integration procedure used in DCON is completely different from that of codes using finite element representations and requires a correspondingly different method for computing and using the matching data. The key step is evaluation of asymptotic coefficients in the expansion of the numerical solutions as a linear combination of large and small resonant and nonresonant power series solutions near the singular surface. A new transformation of the equations has been developed to improve this convergence. In addition, the method for computing the power series has been improved.

Excellent agreement has been achieved with published values of Δ' for cylindrical equilibria. Results will be presented on toroidal equilibria.

The Role of Plasma Rotation, Magnetic Shear and Radial Electric Field Shear for the Change of Internal Transport Barrier in JT-60U Plasmas

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Since the reversed shear plasmas with internal transport barrier (ITB) has quite favorable energy confinement property, they have been investigated as a promising operational option in the future fusion reactors. There are "box-type" ITB and "parabolic-type" ITB in JT-60U [1] . The energy confinement of the box-type ITB is much better than that of the parabolic-type ITB. However, since the extremely steep pressure gradient of box-type ITB is the cause of MHD instability, the control of pressure gradient is necessary for the stable plasma operation. In JT-60U the momentum injection by using the tangential NBI can control the pressure gradient at ITB, and the type of ITB changes from box-type to parabolic-type and vice versa [2, 3] . In this experiment, the radial electric field shear plays an important role.

On the other hand, the tangential NBI also affects the profile of plasma rotation (toroidal rotation of carbon impurity) and the local magnetic shear (beam driven current and bootstrap current). The box-type ITB has a distinctive rotation profile of impurity with "notch". As the ITB type changes, this rotation profile deforms . In the conference, the relation between the momentum transport and the change of ITB type will be presented by analyzing the time evolution of momentum flux and the toroidal rotation profiles. Also the effects of the change of local magnetic shear caused by the beam driven current and the bootstrap current will be discussed in relation to the change of ITB type.

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Split-Weight Perturbative Scheme for Gyrokinetic Particle Simulation of Shear-Alfven Waves*

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A new split-weight δf scheme for gyrokinetic particle simulation of shear-Alfven waves has been developed. The scheme is an extension of the electrostatic split-weight scheme† based on the Darwin approximation of Ampere's law, in which the transverse induction current is neglected. It uses the parallel canonical momentum in the direction of the external magnetic field,

$$P_{\|} \equiv p_{\|} + (q/c)A_{\|},$$

as the phase space variable, instead of the mechanical momentum $p_{\|}$, where $A_{\|}$ is the vector potential in the parallel direction and c is the speed of light and q is the charge. The resulting potential,

$$\psi \equiv \phi - (v_{\|}/c)A_{\|},$$

is then used to split the electron particle distribution as

$$F_e = (1 + e\psi/T_e)F_{0e} + \delta h_e,$$

where δh is followed dynamically via the particle-in-cell method. The scheme is an improvement over the original finite-β split-weight scheme which uses

$$\psi \equiv \phi + (1/c)\int(\partial A_{\|}/\partial t)dx_{\|}$$

as the split-weight,‡ and is, therefore, more suitable for general geometry.§ This new scheme can be useful for studying finite-β effects on microinstabilities as well as magnetic reconnection problems. For example, to the lowest order in mass ratio, the basic governing equations reduce to the well-known two-field MHD equations,

$$\nabla_\perp^2 \frac{\partial \phi}{\partial t} + \frac{1}{\beta}\hat{\mathbf{b}}_0 \cdot \nabla\nabla_\perp^2 A_{\|} = 0,$$

and

$$\frac{\partial A_{\|}}{\partial t} + \hat{\mathbf{b}}_0 \cdot \nabla\phi = 0,$$

where $\hat{\mathbf{b}}_0$ is the unit vector in the direction of the external magnetic field. To introduce the electron inertia, these two equations are modified to include the kinetic effects from δh_e together with the modified Poisson's equation and Ampere's law by taking into account the respective split weights of ϕ and $A_{\|}$. The ions are pushed with the usual δf scheme.¶ Details will be reported.

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3B11

Equilibrium, Stability and Transport in the LHD Stellarator

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Equilibrium, stability and transport in stellarators can be studied theoretically by running the NSTAB and TRAN computer codes written at NYU. These codes have excellent resolution, and experimental data have been used to validate results from numerical calculations. We are now analyzing recent measurements from the large LHD experiment in Japan to see how they compare with the theory. Observations of confinement time at low collisionality like that in a reactor agree well with estimates using a quasineutrality algorithm to determine the electric potential. A nonlinear MHD analysis of stability for various pressure profiles gives predictions of the beta limit that are consistent with the observations. These preliminary calculations call for more detailed analysis. Correlation of the theory with the LHD measurements justifies using the codes as a tool to design quasiaxially symmetric configurations for a modular stellarator experiment promising better performance at reactor conditions.

3B12

MHD Shocks and Magnetic Helicity

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In this work the role of an MHD shock and magnetic helicity conservation is examined analytically. The original motivation behind this work was the explanation of numerical results from multi-component magnetic field penetration due to the Hall effect, although a portion of the results do not depend on the presence of the Hall effect. Careful attention is paid to the constraints that magnetic helicity might put on shock behavior. The role of magnetic helicity is examined in the partition of energy between thermal and magnetic with shock passage. A shock is also examined as a means of helicity injection. Because shocks can occur with field lines exiting the considered volume, the helicity injection process must be considered in light of a relative helicity definition. This consideration necessarily mixes the local nature of a shock and the non-local nature of magnetic helicity.

3B13

The role of magnetic perturbation during ICRF-heating in Tokamak plasmas

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The The Hamiltonian guiding center drift orbit formalism is used which permits the efficient calculation of ionic trajectories perturbed by a fast-wave in a stochastic magnetic field. The magnetic field is assumed to be a small perturbation from a zero- order ``equilibrium" field possessing magnetic surfaces, toroidal symmetry and modeled analytically. A numerical code based on the formalism is used to analyze the effects of magnetic field line stochasticity (MFLS) on the ion cyclotron range of frequencies (ICRF) heating in a collisional Tokamak plasma. Numerical calculations reveal large changes in magnetic moment and drift orbit of the RF-heated ion.

3B14

Spontaneous Neoclassical Tearing Modes*

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We find that data from the Tokamak Fusion Test Reactor (TFTR) which seemingly contradict the commonly held belief that most Neoclassical Tearing Modes (NTMs) require extrinsic MHD events to provide the trigger seed islands. The majority of NTMs in TFTR occur above the threshold for sawtooth stabilization and we find that many NTMs are triggered in the absence of observable extrinsic MHD activity or with very weak MHD activity. Conversely, large sawteeth or fishbone-like MHD activity occurring in plasmas above the NTM b threshold often do not trigger NTMs. The analysis is carried out using a numerical delta-prime code with the neoclassical term calculated using the local bootstrap current from the "nclass" package in TRANSP. This approach results in slightly different time evolution of the island width than with the standard approach of approximating the bootstrap current evolution as proportional to the local pressure gradient. These results highlight the uncertainty in the present theoretical understanding of neoclassical tearing modes and suggest that further work is necessary before confident predictions of the NTM's affect on reactor plasmas can be predicted.

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Reduction of islands in high-beta free-boundary stellarator equilibria.

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The control of magnetic islands is a crucial issue in designing stellarators. Islands are associated with resonant radial magnetic fields at rational rotational-transform surfaces, can lead to chaos and poor plasma confinement, and are a generic feature of three-dimensional equilibria. Earlier work at island reduction examined vacuum configurations; however in high-beta plasma states the plasma currents play an important role in the formation of magnetic islands. To address this issue, a fully general process has been developed for ensuring good flux surface quality in the design and operation of three-dimensional experiments.

By combining various computational algorithms, a procedure is developed by which full-pressure plasma configurations for the National Compact Stellarator Experiment may be designed to control islands. The procedure utilizes the VMEC and PIES codes to calculate equilibrium configurations, a sensitive computational island width diagnostic based on construction of quadratic-flux minimizing-surfaces, and a coupling matrix which describes the plasma response to changes in independent variables describing the configuration. Inversion of the coupling matrix allows a Newton procedure to iteratively reduce a set of resonant fields -- thus reducing island widths.

Fixed boundary calculations are performed in which the independent parameters to be varied are selected boundary harmonics. Low order island chains are significantly reduced. To illustrate the flexibility of the procedure, an island chain is recreated with opposite phase.

The `healed' fixed-boundary configuration is reconstructed using external coils in free boundary calculations. In the free boundary case, the coil geometry provides the independent parameters to be varied, and a coil design is achieved which reduces error fields responsible for island formation. Also in free boundary computations, the procedure is applied to determine the trim-coil currents to be used to produce good flux surfaces at a variety of plasma states.

Effect of neutral atoms on tokamak edge plasmas

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The effect of neutral atoms in tokamak edge plasmas might be important for the global confinement of the plasma, since the sharp radial and poloidal variation of the neutral density might introduce a strong shear into the poloidal ion flow and the electrostatic potential. Consequently, neutral atoms may influence the sheared flow stabilization observed in reduced transport regimes.

Earlier work [T. Fülöp, Peter J. Catto and P. Helander, Phys. Plasmas, **5**, 3969, (1998)], assuming *short mean-free path* neutrals and Pfirsch-Schlüter ions, has shown that the ion-neutral coupling through charge-exchange affects the transport significantly. However, the mean- free path of the neutrals is not always small in comparison with the radial scale length of densities and temperatures in the edge pedestal. It is therefore desirable to determine what happens when the neutral mean free path is comparable with the scale length.

In the present work we use a self-similar solution for the neutral distribution function allowing for strong temperature variation and include the effect of the background ion flow, following the analysis of [P. Helander and S. I. Krasheninnikov, Phys. Plasmas, **3**, 226, (1995)]. The self-similar solution is possible if the ratio of the mean free path to the temperature scale length is constant throughout the plasma. The resulting neutral distribution function is used to investigate the neutral effects on the ion flow.

Field Reversed Configuration Formation Simulations with MACH2*

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A Field Reversed Configuration (FRC) plasma is formed by applying a modest magnetic bias field to a gas, then ionizing the gas - perhaps with a high frequency electromagnetic field - and, finally, quickly applying a much larger field of opposite polarity. The theta- pinch that results can produce magnetically insulated plasma of hundreds of eV in temperature.

Simulations of this experiment can now be performed using the 2½- dimensional magnetohydrodynamic code MACH2. This poster will briefly describe how the code was modified. The poloidal components of the magnetic field are now defined from the flux function which replaces them as the primary state variable and a new finite volume differencing scheme is used which exactly preserves div(B)=0. [1]

A critical issue in simulations of this type is the anomalous resistivity model. Spitzer resistivity is never adequate because it invariably leads to hot, highly conducting vacuum regions, which prevent electric fields from diffusing into the plasma. Past FRC experiments at LANL have shown that the Chodura model with empirically determined parameters has led to good agreement with simulations [2] so this model, with their parameters, was used. Three runs were done using this model, with three different initial densities. Additional runs used the lower hybrid model with MACH2's default parameters, and the Spitzer model with Ohmic heating turned off in low-density regions.

Contour plots are shown of the flux, density and temperature as a function of time using the different resistivity models. The maximum density and temperature depend weakly on the resistivity model, and strongly on the initial density.

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A Finite Volume Differencing Scheme that Exactly Preserves div(B)=0 on a Quadrilateral Mesh*

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Many different techniques are used to preserve the div (B) =0 constraint in shock-capturing magnetohydrodynamic codes. [1] Most involve making periodic corrections to the magnetic field to project out the diverging component. Some preserve div (B) =0 exactly, but only on a simple rectangular mesh. This poster will present a new finite volume differencing scheme that is capable of exactly preserving div(B)=0 on a 2D mesh of arbitrarily shaped quadrilateral cells. It has been implemented in MACH2 and used to simulate the formation of field reversed configurations [2] and will be used to simulate their implosion by current driven liners.

In the standard finite volume method, numerical approximations for the differential operators div, curl and grad are constructed from surface integrals over the boundary of a control volume around each field point. The new method uses the same control volume, but only for the divergence. The curl is computed from a control surface and the gradient is computed from a control line. If the control surfaces are the boundaries of the control volume, and the control lines are the boundaries of the control surfaces, then the resulting numerical operators will exactly satisfy div(curl)=0 and curl(grad)=0. The magnetic field is computed from the curl of the electric field (Faraday's law), so it will have zero divergence, which is related to conservation of flux. The new operators also satisfy several adjoint relationships, which are related to other conserved quantities such as energy.

Numerical expressions for the new operators will be derived and explained and proofs will be given for all the exact relationships. Extension of this method to three dimensions is currently under investigation and some preliminary 3D results may be shown if time permits.

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High Compression Inertial Confinement Fusion at Low Temperatures

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Compression of plasmas with laser pulses in the 10kJ range reached densities up to 2000 times the solid state ns where however the temperatures were rather low within few hundred eV. This result inspired [1] the fast ignitor concept: adding a sub-picoseond laser pulse channeled into the center of the compressed DT should provide the necessary temperature to ignite a very high gain fusion. Based on the long years work on volume ignition [2,3], we derived conditions of low temperature ignition in the range of few hundred eV such that the necessary additional picosecond laser pulse with its well known very complex interaction properties is not necessary. Examples are to use a red laser pulse of 10MJ (twice that of NIF) and 10000ns compression to reach volume ignition at 560eV with a net gain of 130 per energy of the incident laser pulse based on 10% hydroefficiency at the compression by ablation. Though these gains are not as high as of the fast ignitor and only in the range of the usual spark ignition, the very natural and "robust" [3] compression as seen from the highest gains before [2], may provide at least a presently feasible DT fusion power station with possible improvements by the other schemes. The use of the higher energy red light pulse is possible by suppression of the stochastic pulsation by appropriate beam smoothing [4].

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Non-Linear MHD Alfvén Wave Current Drive in Axisymmetric Toroidal Plasmas

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A previous study conducted in planar geometry establishes that a steady state current density is generated in the Alfvén resonance region by a wave dynamo process through non-linear wave mixing of Alfvén waves.[1] Even though no net current is produced because of the antisymmetric nature of the current density in the resonance region, a steady state unidirectional magnetic field in the thin layer emerges. If an antenna with multiple spectral components is used, a series of magnetized layers can be generated, thereby allowing the synthesis and modification of existing magnetic fields. These results were obtained to leading order in a perturbation expansion which assumes resistivity as a small parameter.

In our study, we extend the analysis in Ref. 1 in two ways. First, we calculate second order corrections to the induced current density in planar geometry and we show that a net total current is generated only if the equilibrium magnetic field of the plasma is inhomogeneous. This is consistent with the results reported in Ref. 2. Second, we examine the production of a toroidal current in the Alfvén resonance region in axisymmetric toroidal geometry. Incompressible resistive MHD is assumed. To leading order in a perturbation expansion that assumes resistivity as a small parameter, the toroidal current density in the resonance region is derived as a non-linear function of the first order velocity and magnetic fields. The equations of resistive MHD that govern the first order fields are solved by assuming a toroidal configuration with a large aspect ratio. The expression for the toroidal current density is also determined in the large aspect ratio expansion and a net toroidal current appears to second order in the small inverse aspect ratio.

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Development of a New Theory-Based Transport Model*

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A new theory-based transport model is being developed for use in integrated predictive transport codes such as BALDUR or the NTCC Code. The process used to develop this transport model is described. The objective is to develop a model that agrees with turbulence simulations, which is complete and robust enough for use in predictive transport codes. The new model is constructed from a combination of components representing different modes of turbulent transport as well as neoclassical transport. Some of these components are being developed directly from turbulence simulations. For example, a model for transport driven by Drift Alfvén modes is being developed directly from the results of nonlinear turbulence simulations with realistic equilibrium geometry at the edge of the plasma [1]. Another component, the Weiland model for transport associated with drift modes in the plasma core, is developed from a quasi-linear analytic theory that is calibrated with gyro-kinetic turbulence simulations. The new version of the Weiland model involves a nonlinear iteration of the eigenvalues in order to obtain a more accurate approximation of finite beta and plasma geometry effects. Issues associated with the effects of metric elements and the localization of plasma profile gradients are addressed.

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Symmetry Breaking Localization of the Ballooning Instability in Compact Quasiaxially Symmetric Stellarators

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A new method[1] to study the ballooning instability of toroidal plasmas is used to examine a quasiaxially symmetric stellarator (QAS), which is expected to have ballooning limited performance. Symmetry breaking localization of the ballooning mode has been identified as analogous to Anderson localization[2] of electron eigenfunctions in condensed matter. Recent optimization has shown that magnetohydrodynamic stability as well as good particle confinement are likely to be achievable in a compact QAS for values of the plasma beta near 4%[3]. For the QAS we find new types of non-symmetric structures, including toroidal and poloidal localization of helical eigenvalue isosurfaces in the stable spectra. The method has previously been applied to the H1 and LHD stellarators[1], as well as to rippled tokamaks.

The ballooning eigenvalue isosurfaces are found to exhibit unusual and unique topologies for a plasma configuration near marginal stability at 4.3% beta as well as far above the ballooning stability boundary, at 6.8% beta. Here λ is the eigenvalue, ρ is the toroidal flux, $\alpha = \zeta - q\theta$ the distance along the field line and θ_k denotes the poloidal position of maximum displacement. Distinct structures are found in different ranges of λ in the stable spectrum at 4.3% beta: a) helices rotating about an axis nearly constant in ρ and α, with fingers stretching toward the plasma center; b) tubes constant in θ_k, localized in ρ and α, at more stable frequencies. At 6.8% beta similar structures are found, although more global in extent.

The unstable spectra are less complex, consisting primarily of bands or quasicontinuous (in θ_k and α) tubules near the outer edge of the plasma, where shear goes to zero and the instability is more easily driven.The configuration is Mercier stable at both 4.3% and 6.8% beta. Anderson localization of the ballooning eigenfunction is seen as the shear drops to zero near the plasma edge. The isosurfaces are topologically spherical, indicative of strong quantum chaos[4].

This is a new aspect of linear, ideal MHD stability with many as yet unanswered questions. Can this new way of looking at stellarator stability be utilized to improve stellarator performance? Is ballooning mode localization always linked with good stability for global modes? Does the complex magnetic spectrum which provides acceptable particle confinement also moderate MHD instability through localization due to symmetry breaking?

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Tokamak Equilibria with Sheared Flow

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Analytic solutions of the magnetohydrodynamic equilibrium equations [1, 2] for a symmetric magnetically confined plasma with sheared incompressible flow associated with electric fields similar to those observed in the transition from the low- to the high- confinement mode in tokamaks are constructed in cylindrical and toroidal geometries. In particular, an exact toroidal solution is obtained which for vanishing flow reduces to the Solovév equilibrium which has been extensively employed in tokamak confinement studies. Depending on the density and the electric field profiles and their variation (shear) perpendicular to the magnetic surfaces, several toroidal configurations having either one or two stagnation points are possible in addition to the usual ones with a single magnetic axis. For flow pertaining to tokamak operational regime the extremum of the electric field becomes larger as flow and its shear increase, the location of the extremum being, however, nearly independent of these variations. In addition, the flow affects the safety factor profile and the shape of the magnetic surfaces and results in an increase of the magnetic shear and a decrease of the toroidal beta. The impact of plasma elongation on the above mentioned confinement figures of merit is also evaluated.

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The Dynamo Effect of Externally Driven and Unstable MHD Waves

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We are investigating the propagation of MHD waves in a bounded plasma that are driven by an external source. Using a three dimensional nonlinear resistive, cylindrical MHD code, we compare the behavior of different modes at both small and large amplitude. The waves are driven by phased electric fields at the plasma boundary. We have focused on the possibility of using these waves to drive current via their flux averaged parallel dynamo, $\langle v \times b \rangle_{||}$, in order to control the current profile. We have found, that a single Alfvén wave, driven with a real frequency, produces a large oscillating dynamo effect that is well localized at the shear Alfvén resonance. It's radial profile is odd about that resonance; however, the dc component that remains after averaging over a wave period is small. This is in line with theoretical calculations which predict that a harmonically driven mode's dynamo scales with the resistivity after a time and surface average. We are investigating whether the generation of multiple Alfvén waves with neighboring resonances can reduce the oscillating portion of the dynamo relative to the dc component. We also discuss the effect of launching a packet of Alfvén waves into the plasma in the presence of fully developed MHD turbulence and on any enhancement of dissipation of the wave packet which may be expected to arise from the stochasticity of the magnetic field.

We have examined the evolution of naturally unstable, purely tearing modes to elucidate the dependence of the dynamo effect on the wave time dependence (e.g., growing vs oscillating vs steady state), and have seen that for single modes, there is a large surface averaged effect on the $(m = 0, n = 0)$ mode whose final non-linear amplitude is determined by local parallel current gradients. We also see that the radial extent of the dynamo is larger than the extent of the flattening of the parallel current density and larger than the resistive MHD layer evaluated by linear resistive MHD. The final state is consistent with an electrostatic electric field supporting a parallel current. The behavior of these internally resonant modes will be compared with those whose rational value is above or below the $q(r)$ profile, by driving these modes externally.

3B25

Spontaneous formation of stratified shear layers in a model of turbulence suppression by shear

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In magnetically confined plasmas there is evidence of localized regions of improved confinement. These regions are usually associated with the existence of shear flows with radial structure, and an important problem is to understand how such flows form. To address this problem we consider a reaction- diffusion model that incorporates the mechanism of turbulence suppression by shear, and parameterizes turbulent transport as a nonlinear diffusivity. Numerical simulations of the model show the spontaneous formation of stratified shear layers in which regions of intense shear spatially alternate with regions of suppressed turbulence. We discuss analogies of this model with models used in the study of turbulent mixing in stratified fluids and segregation in granular media.

3B26

Nonlinear Gyroviscous Force in a Plasma with Nonuniform Temperature

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The gyroviscous force is calculated through the second order by taking gyrocenter-fluid moments of the nonlinear gyrokinetic Vlasov equation. The low-frequency gyrokinetic ordering is assumed. The gyroviscous force and the ion momentum equations are obtained both in terms of the gyrocenter-fluid moments and the particle-fluid moments by making expansion in the ratio of the ion Larmor radius to perpendicular wavelengh. It is shown that the heat fluxes must be included in order to obtain a generalized gyroviscous cancellation when temperature variations are considered. The comparison with previous fluid calculations is made. The equations obtained can be used to include the diamagnetic effects in the drift-kinetic formulation.

Continuum Gyrokinetic Turbulence Simulations with Profile Shear Stabilization and Broken gyroBohm Scaling

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Our newly developed field line following full radius continuum gyrokinetic code (GYRO) recovers standard ITG simulations in a radial annulus with cyclic radial boundary conditions and vanishing radial width ($\Delta r \to 0$): the so called flux-tube limit for vanishing ρ_* (ρ_s/a). We compare these flux-tube results with simulations in a finite Δr radial annulus at finite ρ_* with noncyclic boundary conditions. We experiment with a variety of zero value and zero gradient boundary conditions, with and without buffer boundary layers, to show that without radial profile variation, the flux tube linear instability rates and box average turbulent diffusivities can be reproduced. We term these "benign" boundary conditions. Having isolated or marginalized the effect of non-cyclic boundary conditions, we then can study the effect of radial profile variation within the annulus. We first introduce only linear shear in the equilibrium $E \times B$ velocity comparing the shear rate to the maximum linear growth rate. We then consider a normal full radius profile of temperature and density and $1/r$ cylindrical effects focusing on a Δr annulus at a given $r = r_0$ having the local gradient of the flux tube simulations (*e.g.*, $r_0/a = 1/2$, $R/a = 3.0$, $a/_{L\mathrm{T}} = 3.0$, $a/L_\mathrm{n} = 1$, $q = 2$, $s = r/q\ dq/dr = 1$). Fixing ρ_*, we first expand the annulus, increasing Δr (and the number of gyroradii in the annulus), showing how the diffusion decreases as more of the profile is sampled (up to some maximum correlation distance): this is the profile stabilzation effect. Secondly, we fix the annulus size Δr, but vary the ρ_* thus breaking the gyroBohm scaling of the flux tube simulations when ρ_* is large enough. Our goal (when the nonadiabatic electrons, finite-beta, and real geometry features of GYRO are included) is to accurately simulate transport in finite radial annuli of an actual DIII–D plasmas.

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Use of Low Order Interpolation Schemes in Gyrokinetic Particle Simulation

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Nearest grid point (NGP) interpolation has been used for years in large- scale gyrokinetic particle simulation[Parker, Dimits] because it makes the simulation 2-4 times faster overall and it avoids changes in particle shape due to non-orthogonal grids in field-line-following coordinates[Dimits]. The use of NGP seems a bit unusual, because it was more-or-less established in the 1970's that linear interpolation was an optimal choice in terms of speed. There is a trade off between using smooth higher-order interpolation versus simply using more particles. Here, we make an attempt at quantifying why NGP is indeed a good choice for gyrokinetic simulation. The reason NGP works so well is that the gyro-averaging algorithm[Lee] which averages (usually four) points on the gyro-orbit can be viewed as a particular finite particle size or shape function. Hence, the "bare" particle shape function becomes less important. We compare NGP and linear interpolation in a simple 2D shearless slab ITG gyrokinetic simulation of the dynamics of zonal flow generation.

Mach 0.5 Jet Flow between Isothermal Walls using Lattice Boltzmann Methods

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Jets, heat front propagation ... play an important role in tokamak physics (e. g. , L-H transitions, heat loads on divertor plates ...). While lattice Boltzmann methods (LBM) have proved themselves as excellent simulation tools for incompressible flows because of their ideal parallelization on massive PE systems, the solution space (n, u, T) for thermal compressible flows has been found to be too restrictive for use in tokamak research.

LBM algorithms are explicit and in their simplest form run at a CFL = 1, i. e. , they do not introduce any numerical dissipation or diffusion. These algorithms consist of Lagrangian streaming (a shift operation), and linear BGK collisional relaxation (only local operations).

There is a marked increase in macroscopic solution space (n, u, T) when the LBM uses the higher octagonal symmetry lattice. If, moreover, one introduces temperature-dependent octagonal lattices then in a reduced 9-bit model, we have found numerical stability even for T -> 0. The idea of using temperature-dependent streaming came from applying Gauss-Hermite quadratures to the thermal problem. Since the Reynolds number is inversely proportional to the viscosity (which itself is a function of T), very high Re flows can be simulated without pushing the relaxation rates past their stability limit. Moreover, the truncated 9-bit model allows simulation of flows for Mach numbers of 0. 5.

However, to model the full nonlinear energy equation we must generalize our energy-dependent lattices to 17- bits. Because the streaming step of LBM is now spatially nonuniform, standard interpolation schemes cannot be used to couple the velocity lattice and spatial grid. We have resorted to a non-trivial allocation scheme that enforces the moment constraints. We present results for the 17-bit model for jet flow between constant temperature walls as well as heat front propagation as a precursor for divertor work.

3B30

Ph.D.Radio-physics

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A prospect of creating the heat generators of middle power uses the coherent beams of particles and nucleus fusion.

The using the coherent beam of particle lithium and deuterium allows get interference area in that is reached sufficient concentration and sufficient energy for the realization of nucleus fusion. Reaction occurs by injection to the volume, which bases in the axial symmetrical magnetic field positively charge particles that have a different specific charge. On these particles influence a variable electromagnetic field with the frequency which in combinations with the magnetic field ensures the conditions for making the coherent beams of particles lithium and deuterium. These beams are move on circular paths around axis of symmetry of magnetic field and on the certain radius of path is ensured necessary phase velocity of beams for the realization of nuclear fusion. This configuration allows avoid losses of particles in process of reactions nuclear fusion since occurs dynamic deduction and stabilization of beams and recuperation the particles occurs automatically.

Magnetic Dipole Configurations–Effects of Finite Larmor radius and non-uniform Equilibrium Electric Fields on MHD Stability *

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A sufficient condition for MHD stability of magnetic dipole equilibria is $5\overline{\omega}_d/2 > \omega_{*p}$, where $\overline{\omega}_d$ is the bounce averaged drift frequency and ω_{*p} is the diamagnetic frequency. The equilibrium scale lengths of the plasma pressure gradient are therefore required to be comparable to or greater than the scale lengths of the magnetic field line curvature. The stabilising role of finite Larmor effects (FLR) and non-uniform $E \times B$ equilibrium flows (shear flow) are investigated in order to explore the possibility of reducing the plasma pressure gradient scale lengths to allow for more compact dipole configurations. The appropriate MHD eigenmode equations for magnetic dipole equilibria are derived and the stability of a steep plasma pressure gradient layer analysed. This analysis differs from earlier investigations [1],[2] in accounting for the strong field line curvature characteristic of high beta magnetic dipole configurations : the plasma pressure gradient at the equatorial plane is "balanced" by the field line curvature rather than by the magnetic field gradient. The criteria for FLR and shear flow stabilisation are discussed.

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A Backward Monte-Carlo Method for Parabolic Equations*

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The Monte-Carlo method is a statistical numerical method that can be used to solve parabolic equations. It is typically a last resort when other numerical methods fail, e. g. due to high dimensionality and/or complicated (internal) boundaries. An example from plasma physics would be the quasilinear Fokker- Planck equation in tokamak or stellarator geometry. The Monte-Carlo method has several drawbacks: statistical noise, poor time convergence, and a conflict between resolution and statistics. By using powerful tools from modern mathematical statistics, most notably the Feynman-Kac formula, it is possible to construct a new Monte-Carlo method with decreased noise, faster time convergence, and that allows for increasing the resolution without an accompanying increase of the statistical noise.

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Temperature Pedestal Limits and ELMs: A Model Based on Full Spectrum Stability Analysis and Nonlinear Simulation

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Maximizing the pedestal temperature ($T_{\rm ped}$) while maintaining acceptable ELMs is a key issue for optimizing tokamak performance. Theoretical analysis of edge instabilities which may limit the pedestal height and drive ELMs is complex, in part because the sharp pressure gradients, and consequent large bootstrap currents, near the H–mode edge can destabilize kink, peeling, and ballooning modes over a wide range of toroidal mode numbers (n). The dominant modes are often coupled "peeling-ballooning" modes, driven by both parallel current and the pressure gradient. An important modification of classical ballooning theory [1] allows treatment of the coupled system of edge ballooning and peeling modes at higher $n \gtrsim 10$. A new 2-D edge MHD stability code, ELITE, has been developed to solve Connor *et al.*'s edge ballooning equations through $\mathcal{O}(1/n)$, in order to study these intermediate to high-n coupled peeling-ballooning modes. The ELITE code, together with an enhanced version of the low-n MHD stability code GATO, allows the study of the ideal MHD edge stability of real tokamak equilibria over essentially the full spectrum of toroidal modes, leading to insights on ELMs and the importance of parallel current and second stability access. Using model equilibria, we investigate the variation of the maximum temperature pedestal with shape and collisionality, and analyze the type and structure of instability limiting $T_{\rm ped}$ in various regimes. These results are used to further elaborate and quantify the working model of ELMs presented in Ferron *et al.* [2], making predictions about the relationships between ELM size and frequency, and geometrical and bootstrap current effects. We also present edge stability analyses of reconstructed experimental equilibria from multiple tokamaks, to test the validity of our model.

Ultimately, nonlinear simulation is needed to study the coupled interaction of p', $J_{\rm boot}$, $v_{E\times B}$, and fluxes in ELMy H–mode edge plasmas. To gauge the impact of X-point geometry, non-ideal effects, and nonlinear dynamics, simulations are carried out with the electromagnetic Braginskii code BOUT, enhanced to include parallel current terms. The dynamics of coupled peeling-ballooning modes are studied, and compared to linear codes and ELM formation in experiments.

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Gyrokinetic Turbulence Simulations with Trapped and Passing Kinetic Electron Physics

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We have developed a toroidal three-dimensional field-line-following flux-tube simulation with kinetic electrons. the electrons are simulated using the split-weight scheme[1]. Although electromagnetic effects are included, the plasma beta is limited to $\beta m_i/m_e \leq 1$ due to the requirement for resolving the magnetic skin depth. However, the effects of kinetic electrons on turbulence and transport can be addressed, including the trapped electrons and nonadiabatic passing electrons. Our primary focus is on both the ion-temperarture-gradient and trapped-electron drive. Linear benchmarks show good agreement with GS2[2] for representative tokamak parameters. The growth rate of the ion-temperature-gradient instability is significantly increased relative to the results from simulations with adiabatic electrons, typically by a factor of $1.5 \sim 2$. Preliminary nonlinear runs indicate that the nonlinear ion heat flux is increased from that of adiabatic electron model by a factor of ≥ 5, and that the zonal flow effect in suppresing the turbulence is not as dominant as in the adiabatic electron case. However, the saturated heat flux shows a slow time-scale evolution after the initial saturation, which is our focus of current study. In addition, the technique of domain cloning[3] has been implemented to allow for more processors than the grid number in the parallel direction, along which the primary domain decomposition[3] is applied.

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Nonlinear Prediction Filters for Loading-Unloading Dynamics as in Substorms and Sawtooth Events

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A generic type of driven-damped system has been arrived at independently by Sprott [1] from studies of simple classes of "jerk functions $J(\ddot{x}, \dot{x}, x)$" for which the classical third-order chaotic equations, including the Lorenz, Rossler, and others, are described by $\dddot{x} = J(\ddot{x}, \dot{x}, x)$ and by Horton *et al.* [2] studying reductions of the 6-ode WINDMI [3] model of substorms. For the substorm problem the reduced equation is

$$\frac{d^3x}{dt^3} + b\frac{d^2x}{dt^2} + \frac{dx}{dt} = a - e^x$$

which has bifurcation diagram for variable driving-damping $a - b$ parameters that closely parallels that of the full 6D WINDMI model. At low forcing $a < b$ there is a stable fixed point (quiet-time magnetosphere) Hopf bifurcation at $b = a$ to a limit cycle, then a period doubling sequence of bifurcations to chaotic solutions. There is a beautiful, complex pattern in the $a - b$ plane of the mixture of the chaotic regions with the regular regions (fixed points and limit cycles on a torus). In the WINDMI substorm model a, b are the solar wind driving strength and ionospheric damping. The model shows that there is an intrinsic limit to the prediction time for substorm dynamics even for accurately-defined initial space weather data and physical system parameters. We find that for typical strong solar wind conditions the intrinsic limit to the prediction time of order 3 to 5 hrs. A similar model is being developed for sawtooth oscillations. *

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Feedback Stabilization of the Resistive Wall Mode in General Geometry

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Many magnetic confinement configurations require the presence of an external perfect conducting wall for their stabilization against the external kink mode. When the resistivity of the external wall is taken into account, long term stability of the plasma then depends on its being stable with respect to the resistive wall mode (RWM). At the present moment, the most promising method for stabilization of the RWM is feedback stabilization with external sensor loops and feedback coils. In this work, we present a general formulation for modeling of feedback stabilization of the RWM for an ideal plasma. We show that the stability of the plasma satisfies a generalized inhomogeneous energy functional. It is a generalization of the usual ideal MHD functional with the inclusion of the resistivity of the external wall and the currents from the external coils; the currents in the external coils provide the inhomogeneous source term. The eigenmodes of the system without the inclusion of the source terms corresponds to the observed RWM without feedback. The sensing of these modes by the sensor loops and the subsequent excitation of them by the external coils form a complete equivalent circuit description of the system during feedback. This set of equations is, in general, non-self-adjoint. However, various quantities, such as the transfer function [1], can be easily derived. In a special case, when the sensor loops and feedback coils are closely coupled to the wall and to each other, the system remains self-adjoint, and can be solved with a flux conserving constraint [2]. The general formulation of the problem have been implemented numerically and applied to the DIII–D tokamak. We found that installing the sensor loops inside of the resistive wall is superior to installing them outside. Numerical examples, which show the effectiveness of the feedback on stabilizing the RWM, are also presented.

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Numerical Analysis of Singular Modes in Thin Accretion Disks*

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The modes that can transport angular momentum in a thin accretion disk under the least restrictive conditions are of the non axisymmetric type and are such that at marginal stability they exhibit four singularities [1]. One of the singularities is in fact similar to that characterizing resistive modes with $m = 1$ and $n = 1$ in cylindrical current carrying plasmas [2] and another is similar to that typical of tearing modes that have $m > 1$ and $n \geq 1$ [3,4]. A complete numerical derivation of the relevant eigenfunctions, whose real and imaginary part have different radial dependence and parity, has been obtained. A class of transport coefficients that can remove the two main singularities has been identified and analyzed.

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Kinetic Ballooning Mode in Low Aspect Ratio Plasma *

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In the regime where the ballooning mode parallel phase velocity is smaller than electron thermal velocity and larger than ion thermal velocity, the combined kinetic effect of trapped electron dynamics and finite thermal ion Larmor radii has a strong stabilizing effect on the ballooning modes. The stabilizing effect arises because the combined kinetic effect produces a parallel electric field which drives an enhanced parallel perturbed current over the MHD current. The enhanced parallel perturbed current then increases the stabilizing magnetic field tension and thus increases the critical β threshold for the kinetic ballooning instability (KBI). The β threshold of the KBI is increased from the MHD β threshold by a factor proportional to the ratio of the total electron density to the untrapped electron density, n_e/n_{eu}, for $k_\perp \rho_i \simeq 1$. For low aspect ratio tokamaks such as NSTX this ratio can be much higher than unity, and we conclude that ballooning modes in NSTX should be stable for β on the order of unity. However, in the presence of energetic ions it is still possible that kinetic ballooning modes can be resonantly destabilized by energetic ion. Radially local ballooning equation is solved with numerical equilibrium for NSTX plasmas. Properties of KBI are studied and compared with the properties of ideal ballooning modes. Typically KBI is stabilized for minor radius $r/a > 0.6$, while MHD ballooning mode remains unstable.

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Predictive Modelling of Axisymmetric Toroidal Configurations with CalTrans*

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The CalTrans project [1] is a new transport-code collaboration undertaken by GA and LLNL, incorporating the transport codes ONETWO and Corsica, to better predict and analyze the DIII-D tokamak experiment. See Ref. [2] for recent application of the code to DIII-D.

The Corsica [3] side of CalTrans was developed as a comprehensive toroidal plasma simulation and design tool, and currently has applications to reversed-field-pinch (RFP) and spheromak configurations as well as to tokamaks. Recent areas of development include the angular momentum transport equation, together with an implementation of the GLF23 transport model; and the addition of the TORCH ECH/ECCD package, which includes warm-plasma relativistic effects on the ray-tracing, to be assessed against the standard TORAY-GA module in CalTrans. A particular strength of Corsica is its ability to carefully calculate fixed- and free-boundary equilibria coupled to Ohm's law (and transport models). The Ohm's law includes a "hyper-resistive" (i.e., current-diffusion) term, which we apply both to the MST RFP and the SSPX spheromak. At present we are implementing a model for the hyper-resistivity coefficient [4] based on tangled magnetic field-lines resulting from multiple tearing modes, with resonant surfaces, stability (determined from cylindrical Δ'), and island widths (Rutherford) self-consistent with the evolving equilibria. We are also undertaking Ohm's-law simulations for the study of edge current profiles in ELM'ing discharges; and examining the viability of feed-back control of ECH for neoclassical-driven growth of islands. A selection of results from these areas will be presented in the paper.

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Dissipative Incompressible MHD using Octagonal Lattice Boltzmann Models

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The use of lattice Boltzmann mode (LBM) to solve the nonlinear macroscopic conservation laws is spurred on by the ever increasing number of available PE's - e. g. , as the number of PE's increase from 512 to 2048 on the NERSC IBM- SP3. LBM is an explicit kinetic algorithm utilizing two simple subroutines: Lagrangian streaming along the chosen velocity space lattice, and collisional relaxation at each spatial grid node. As these subroutines employ only a shift operation and local node information, they are ideal for parallelization. In fact, in our thermal LBE codes (that solve the conservation equations of continuity, momentum and energy), we have seen no saturation effects - even up to the full 512 PE's currently available. The other significant feature of LBM is that they avoid the solution of the nonlinear Riemann problem which arises in conventional CFD methods because of the nonlinear convective derivatives. To increase the usefulness of LBM, we have been looking at octagonal velocity lattices - lattices that are now no longer space filling. As a consequence, one must introduce a new subroutine: second order interpolation to correlate the octagonal streaming onto the chosen spatial grid. This higher order symmetry lattice yields much more stable numerical algorithms.

Here we present our results on extending the Martinez et. al. (1994) LBM for MHD. Instead of either square or hexagonal velocity lattice, we introduce the higher order symmetry of the octagonal lattice. The bi- directional streaming is now chosen perpendicular to the given octagonal direction, leading to a simplified relaxation distribution in the BGK collision term. Because of the higher discrete symmetry of our MHD- model, we can perform simulations with greater variations in v and B . By generalizing the BGK collision operator, we can decouple the resistivity from the viscosity. Simulations will be presented for the sheet-pinch.

We will consider the issue of div B = 0 - since in LBM it is not automatically enforced. On the hexagonal lattice, Martinez et. al. found that LBM dynamics possessed self-adjusting mechanisms that reduce the level of magnetic monopoles in the sheet- pinch simulation. We discuss the corresponding results for the octagonal lattice.

To symmetrize MHD computations further, we investigate LBM using Elsasser variables - as these result in a symmetric form for the variables v+B and v - B. In particular, we shall investigate this symmetrization on the enforcement of div B = 0 and div v = 0.

Predictive Transport Modeling with the Weiland Drift Wave Model*

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The Weiland drift wave model [1, 2, 3] combines the toroidal branch of the η_i-mode, impurity η_i-modes, the collisionless trapped electron mode and ideal MHD ballooning modes in a single description. Here, this transport model is tested using predictive simulations of experimental data from the International Profile Database [4]. A subset of the database containing discharges with measured electron and ion temperatures have been modeled.

Simulations of DIII-D and JET data are in good agreement with experimental data for both L- and H-mode discharges with relative errors in thermal energy close to 15%. However, both ion and electron temperatures are over-predicted for TFTR data.

A recent strong ballooning implementation of the elongation effects described in [5] has also been tested against the database. The effects on the transport model are found to be very weak in H-mode plasmas whereas increasing elongation has a destabilizing effect under L-mode conditions.

In addition, the conditions needed for inward (pinch) heat flows are discussed in the context of the transport model and the results are compared with experimental observations. We find that the differences between the off axis heated discharges at DIII-D, where non-diffusive transport was observed, and JET are consistent with the predictions of the transport model.

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Efficiently Finding Trends in Macroscopic MHD Stability Using Perturbed Equilibria: Review of Screw Pinch and Initial Application to Toroidal Geometry*

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The effects of equilibrium parameters on long wavelength ideal MHD instabilities in toroidal plasmas are traditionally studied using numerical parameter scans. We explore these dependencies with a new perturbative technique that may be more efficient and offer more insight. Rather than run a stability code for every combination of plasma parameters, we mathematically determine changes in a known stability due to perturbations in the plasma force-balance equilibrium.

This technique first finds the equilibrium and stability of axisymmetric configurations using traditional methods. Subsequent small changes in the original equilibrium profiles and shaping properties result in a new stability for the perturbed conditions. This new stability is found using variations in the energy principle rather than with a traditional stability code.

With this approach, the effects of parameter variations on stability can be efficiently examined without numerically generating MHD equilibria or complete stability results for every set of parameters (which can be time-intensive for accurate representations of several configurations). Compared to a routine parameter scan, this approach may also provide the researcher a more intuitive feel for the effects of various parameters.

Here, we first review the perturbed stability analysis for screw pinch equilibria. The effects of various parameters and profiles on screw pinch stability are then discussed. These results validate the approach, but also indicate caution is required with *m=1* modes and high magnetic shear at the edge. Finally, an initial application of the technique to toroidal geometry is presented.

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Weakly Nonlinear Vlasov-Poisson Hamiltonian Dynamics*

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Adapting techniques from finite-dimensional Canonical perturbation theory, we study weakly nonlinear dynamics of longitudinal disturbances near linearly stable, homogeneous Vlasov-Poisson equilibria. We derive the continuous analog of a resonance Hamiltonian that accounts for the lowest order interactions among the modes of the continuous spectrum. The equations generated by this Hamiltonian describe the nonlinear behavior of transient phenomena, often ignored in weakly nonlinear theories of longitudinal waves. We show that, even in the presence of negative energy modes, the weakly nonlinear system is stable. We also consider the effects of the nonlinear interactions on the frequencies of the linear modes.

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Particle Hall-MHD Simulation of Collisionless Reconnection: Ion Gyro-Radius Correction

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In recent years, many simulation studies of plasma dynamics in a simple one-dimensional Harris sheet have been carried in order to improve understanding of magnetic reconnection in a collisionless plasma. These studies are motivated to a large degree by the Geospace Environment Modeling (GEM) Reconnection Challenge in which results from various numerical models, i. e., full-particle, hybrid (kinetic ions, fluid electrons), and Hall-MHD, mostly in two-dimensional configurations, have been compared for the same initial conditions. Reconnection in this geometry is induced by an imposed localized resistivity, electron inertia effects, or non-gyrotropic effects in the electron pressure tensor, as well as the imposition of an initial perturbation. An important result of the GEM study and subsequent research is that the reconnection rate is essentially independent of the reconnection mechanism, and that it depends on the Hall current. In this work, further study of collisionless reconnection in a thin current sheet is conducted using hybrid and Hall-MHD simulations that include the full electron pressure tensor in Ohm's law while neglecting resistivity and electron inertia. Fluid- ion dynamics from a Hall- MHD calculation using scalar ion pressure and test ions that are advanced in Hall-MHD fields are compared to the particle- ion dynamics obtained from a hybrid simulation of two-dimensional reconnection. These comparisons demonstrate that off-diagonal elements of the ion pressure tensor are important to correctly model the ion out-of-plane momentum transport from the X point. It is shown that these effects can be modeled efficiently in Hall-MHD simulations in a predictor/corrector manner that uses particle ions to implement the ion gyro-radius corrections. By advancing test ions in the Hall-MHD fields at every time step, accumulating the ion pressure tensor onto the spatial grid, and adding its divergence to the ion mommentum equation, this particle Hall-MHD simulation models well the ion out- of- plane momentum transport from the X point and improves the reconnection rate compared with the hybrid result.

Algorithmic Unification of Particle-In-Cell and Vlasov Methods

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A new numerical algorithm that encompasses both the δf particle-in-cell (PIC) method and a Vlasov method similar to Cheng and Knorr[1] is presented. This work is of value for two reasons: 1) It makes a connection between the particle-based δf and continuum methods for solving kinetic equations thereby allowing detailed comparisons of the two methods. 2) The method will in principle solve the "growing weight problem" in δf particle simulation of plasma turbulence[2, 3].

The basic algorithm is essentially a variant of the δf method. Briefly, the algorithm is the following:

1. Load particles (or characteristics) on a uniform lattice in phase space. The loading need not be uniform, but it greatly simplifies the algorithm.
2. Advance the characteristics M timesteps, using the usual δf PIC algorithm which involves a grid interpolation, deposition, then field solve all on a spatial grid only.
3. Every M timesteps, deposit δf on a higher-dimensional phase space grid, then reset the particle phase space coordinates back to their initial value on the phase space lattice. Also, reset the particle value of δf to the phase space grid value.
4. Return to step 1.

For M$\to \infty$ one recovers the usual δf PIC algorithm with a somewhat peculiar uniform loading of particles. For M=1 the algorithm is similar to the Vlasov method of Cheng and Knorr. Any value of M=$1, 2, 3, \ldots$ is permissible. Larger values of M might provide favorable smoothing properties of Vlasov methods with the speed of PIC algorithms thereby alleviating the growing weight problem. Any loading (e.g. random or bit-reversed) is possible, but then requires a more sophisticated interpolation scheme for a nonuniform and unstructured phase space grid (possibly using a finite element method). High order interpolation is a critical component for an accurate Vlasov method[1]. Presently, we are investigating the use of a cubic spline interpolation scheme. One subtle difference between typical Vlasov methods and the method presented here for M=1, is that conventional Vlasov methods involve a classic spline fit problem, whereas our algorithm requires a weighting scheme or the inverse of a classic spline fit.

We have implemented the scheme above for a small $(k_\perp \rho_i)^2$ two-dimensional bounded slab model, where the phase space is $(x, y, v_{||})$. The ion-temperature-gradient instability is studied assuming adiabatic electrons and gyrokinetic ion. We will present our initial results using linear interpolation and our developments in using higher order interpolation schemes.

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Simulations of Field Reversed Configuration Plasmas with the NIMROD Code

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Investigations on the stability of Field Reversed Configuration (FRC) plasmas with the NIMROD code are presented. Previous calculations [1] have been here extended by including in the code the continuity equation (presently only in two-dimensions, as it is reproducing only the n=0 toroidal mode) and a model for open-end boundary conditions along the longitudinal axis of the FRC.

Runs with the latest version of NIMROD using high order finite elements have been performed to control numerical instabilities that appeared in regions with strong gradients and flows. Results are presented both for one and two-fluid simulations while addressing the stability against tilt modes.

This study is also meant to constitute the basis for developing a simulation of a FRC acting as a plasma source (and eventually also power source) for an advanced space propulsion system. Preliminary efforts on the simulation of a FRC connected to a magnetic nozzle field are being reported.

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Realizability in a Closure for MHD Turbulence*

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Often the eddy-damped quasinormal Markovian (EDQNM) closure is utilized when describing a Navier-Stokes turbulence. In such a case, realizability is readily demonstrated. However, when one attempts to demonstrate realizability for this closure in the case of magnetohydrodynamic turbulence, more most be demanded of the EDQNM closure: One must demonstrate that all times the turbulent fluid energy spectrum remains positive, that the turbulent magnetic energy remains positive, and that the cross-helicity spectrum satisfies a Schwarz inequality. To do so, one must show that the equations that govern the evolution of the three spectra, which are obtained from the closure, yield spectra that always satisfy these "realizability" conditions above. In the absence of mean fields, we have done so using the Elsasser field variables, $\mathrm{v} \pm \mathbf{B}$.

We wish to apply these techniques and concepts to resistive MHD turbulence, and in particular to resistive MHD turbulence relevant to the MHD dynamo as applied to field-reversed fusion configurations such as the RFP and spheromak. We have already considered statistical turbulence in the case of ideal MHD for the RFP.[1] Now we wish to face directly the problem of dissipative effects (resistivity, viscosity) on the *statistical* evolution of the turbulence.

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A Model for the Height of the H-mode Pedestal*

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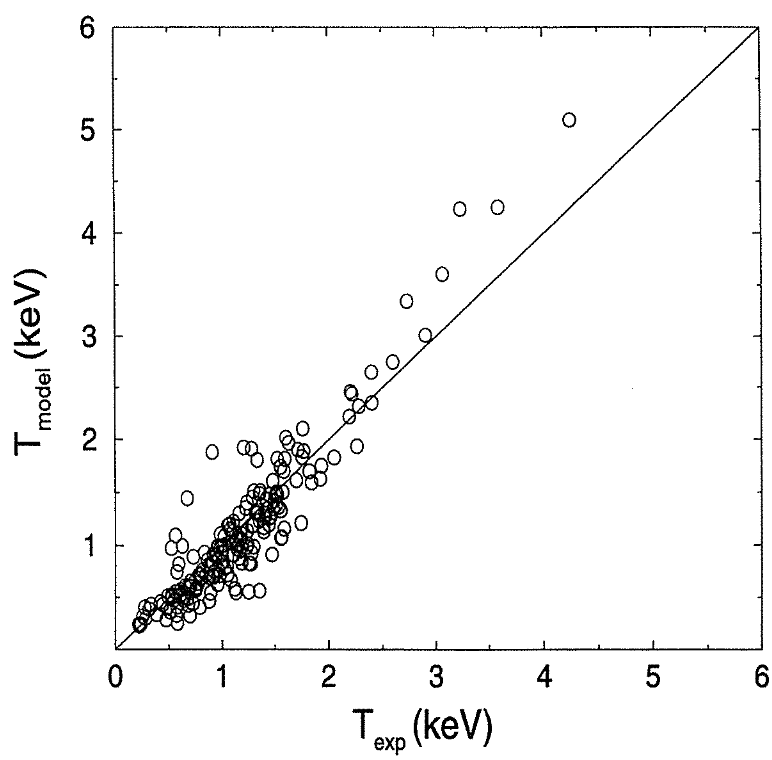
The height of the H-mode pedestal is a key boundary condition needed for integrated predictive modeling codes. This boundary condition is critically important for predicting the performance of both present day tokamaks and reactor designs. A model for the height of the H-mode pedestal has been developed based on the assumption that the width of the transport barrier is proportional to the square root of the poloidal Larmor radius. This model predicts a pedestal height in agreement with data from a limited number of discharges. However, we find an empirical modification based on dimensionless parameters such as collisionality, elongation, triangularity, and density relative to the Greenwald density, is required to produce agreement with a much larger set of data. Below is a comparison of the results of the empirical model and data for 190 discharges from the international edge database for DIII-D, JET, JT60-U and C-MOD.



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Effect of Shear Damping and of the Ion Temperature Gradient on the Polarization Current near Magnetic Islands*

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The polarization drift near a rotating magnetic island gives rise to a return current that plays an important role in the island's evolution. We have shown in previous work that this current is stabilizing for islands rotating in the ion diamagnetic direction at a frequency less than the ion diamagnetic frequency. We have also shown that islands rotating in the electron diamagnetic frequency excite drift waves. Using a kinetic model with a linear ion but nonlinear electron response, we consider here the effects of ``shear damping" and of the ion temperature gradient on the growth rate and rotation frequency of an island. We find that these effects have little influence on the emission of waves for islands rotating in the electron diamagnetic direction. For islands rotating in the ion diamagnetic direction, by contrast, ion temperature gradients pointing in the same direction as the density gradients ($\eta_i > 0$) give rise to wave emission for small to moderate rotation frequencies. In this case shear damping becomes important for the determination of the proper boundary conditions.

It is apparent from the above results that the complicated nature of the plasma response to a differentially rotating magnetic island provides a stringent test of fluid closures. We will review a selected set of closure with attention to their ability to reproduce the qualitative features of the kinetic theory, and discuss the implications for numerical modeling of neoclassical island evolution.

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Predictive simulations of energy and particle transport in LHCD discharges of Tore Supra using the Multi-Mode Model

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The Multi-Mode Model based on the quasilinear estimations of turbulent fluxes driven by different instabilities [1] has been used for the study of the physics of anomalous transport in Tore Supra discharges with monotonic and reversed q-profiles. The plasma current in these discharges is driven non-inductively by the lower hybrid waves [2]. The transport analysis has been performed with the BALDUR [3] and NTCC [4] transport codes. The results of our analysis show that the thermal electron transport in the gradient region is in a good agreement with the drift mode prediction (ITG turbulence and TEM) while the edge transport is well-described by the model based on the resistive ballooning modes. In addition, we found in the self-consistent energy and particle simulations with the BALDUR code that the anomalous pinch and particle diffusion included in the Multi-Mode Model provides a rather accurate description of the plasma density profile for these discharges. These results present the first test of the Multi- Mode Model for helium plasmas with dominant electron heating. The predictive electron temperature profiles for Tore Supra scenarios obtained with the Multi- Mode Model are compared with the simulations performed with the GLF23 model [5] and empirical mixed Bohm-gyroBohm model [6].

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Physics Properties of Compact, Low Field Period, Quasi-Poloidal Stellarators*

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A class of ultra compact (R/ = 2. 5 - 3) two and three field period stellarator configurations have been developed for which the magnetic field modulus, |B|, in magnetic coordinates is dominated by poloidally symmetric components. These configurations offer a new direction in stellarator optimization, unexplored by existing experiments. Such devices are expected to open up unique regimes of stellarator parameter space where the transport physics, equilibrium resilience, plasma flow dynamics, RF heating strategies and microturbulence are expected to be different than at higher aspect ratios. Two categories of configurations have been studied: (1) devices that achieve drift optimization and rotational transform at low beta and low bootstrap current by appropriate plasma shaping and (2) devices which have a greater reliance on plasma beta and bootstrap currents for supplying the transform, obtaining quasi–poloidal symmetry and generating a sufficient gradient in the B(0,0) component as to favorably influence energetic particle confinement. We have used a variety of recently developed physics tools to evaluate the transport and stability characteristics of these configurations. With respect to transport, good confinement is attained through minimizing the B x grad B drifts due to a closer alignment (on average) between the magnetic field lines and grad B than is possible with other forms of stellarator quasi- symmetry. With respect to stability, the configurations in group (2) can access second stability regimes at very high betas (~15%) while the lower bootstrap devices are limited by first stability beta limits in the 2 - 3% range which should be experimentally accessible with moderate amounts of heating power.

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Linear stability, mode structure and nonlinear behavior of drift tearing modes

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Ion viscosity and particle diffusivity effects on the linear stability and mode structure of drift-tearing modes are investigated in the collisional and semicollisional regime. The perturbed current density along the equilibrium magnetic field is localized radially near the reconnecting mode-rational surface. With ion viscosity, a fine structure of radial oscillations is found. This oscillating structure disappears at finite values of the particle diffusivity. The mode growth rate is reduced by ion viscosity, but it is left practically unchanged by particle diffusivity. The instability threshold is not modified. The analysis is based on the analytic and numerical solution of a reduced three-field fluid model.

The nonlinear dynamics of unstable drift-tearing modes is studied with a spectral code. The general goal is to explore how the diamagnetic effects change in the nonlinear regime. More specifically, we present the first studies aimed at determining the parametric dependence of the island width and of the rotation frequency on the control parameters of the three-field model.

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Gyrokinetic simulations with kinetic electrons*

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Nonlinear kinetic study of electromagnetic turbulence in plasmas has been hindered by the difficulty of treating the dynamics of electrons whose characteristic frequency is much faster than that of the low frequency modes of interest. In this work [1], a fluid-kinetic hybrid electron model for electromagnetic simulations of finite-beta plasmas is developed based on an expansion of the electron response using the electron-ion mass ratio as a small parameter. The model accurately recovers low frequency plasma dielectric responses and faithfully preserves nonlinear kinetic effects (e. g., phase space trapping). Maximum numerical efficiency is achieved by overcoming the electron Courant condition and suppressing high frequency modes. This method is most useful for nonlinear kinetic (particle-in-cell or Vlasov) simulations of electromagnetic microturbulence and Alfvenic instabilities in magnetized plasmas. The utility of such a model is demonstrated in full torus gyrokinetic particle simulations of ITG- TEM turbulence using the gyrokinetic toroidal code (GTC) [2].

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