2002 International Sherwood Fusion Theory Meeting April 22-24, 2002 Rochester, New York

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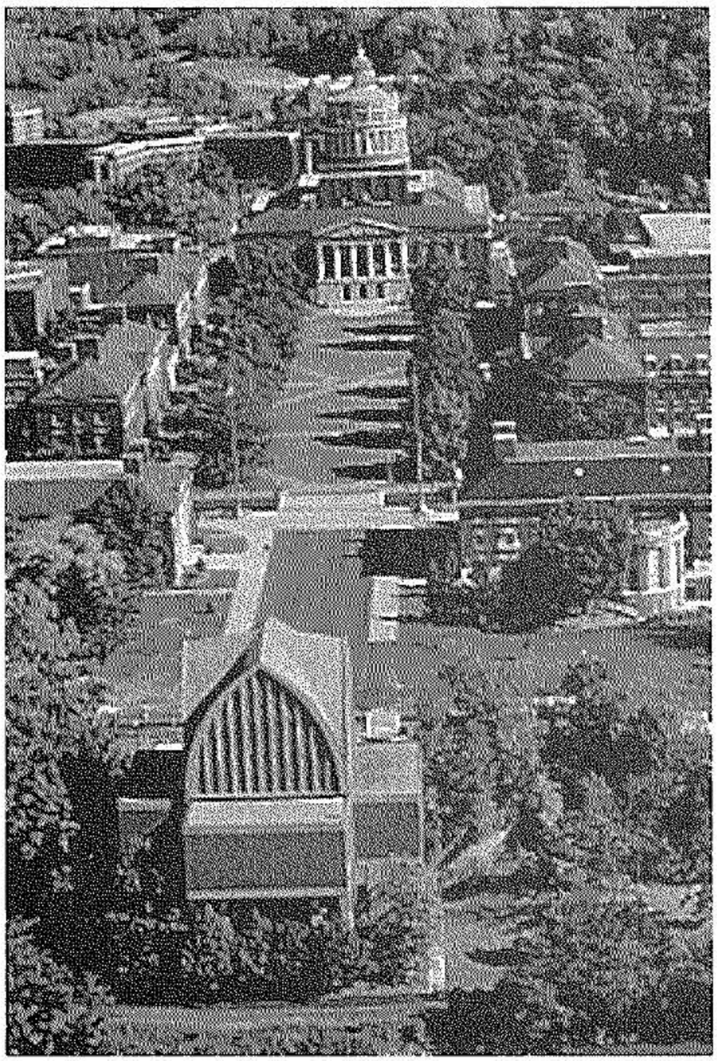
April 22–24
Rochester, New York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Hosted by Members of the
Department of Mechanical Engineering,
University of Rochester

Saralyn Stewart

2002

International
Sherwood Fusion Theory Conference

April 22-24
The Strathallan Hotel
Rochester, NY

Hosted by

The Department of Mechanical Engineering, University of Rochester

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GENERAL INFORMATION

A total of 157 papers were contributed, and 14 were selected by the Program Committee for oral presentation out of 41 requests. Ancillary meetings are also scheduled during the conference.

MEETING PROGRAM

- The **review papers** (1A, 2A, 3A) will be presented at the Memorial Art Gallery Auditorium, 8:30-9:30 AM, Monday through Wednesday.
- The **oral papers** will be presented in the Memorial Art Gallery Auditorium:
    - Session 1B will take place Monday, 9:50 AM-12:20 PM,
    - Session 2B will take place Tuesday, 9:30 AM-10:00 AM.
    - Session 2D will take place Tuesday, 8:00 PM-9:30 PM.
    - Session 3B will take place on Wednesday, 9:50AM-12:20 PM
- The **poster sessions** will be at the Strathallan Hotel in the Living/Canterbury Room
    - Session 1C will take place Monday, 2:00 PM-4:00 PM.
    - Session 1D will take place Monday, 4:00 PM-6:00 PM.
    - Session 2C will take place Tuesday, 10:30 AM-12:30 AM.

ANCILLARY MEETINGS

- **NIMROD Meeting** *(Contact: D. Schnack)*, April 20th, 8:00 AM-5:00 PM and April 21st 8:00 AM-12:00 PM at the Strathallan Hotel in the Berkeley Room.
- **Center for Extended MHD Modelling Meeting** *(Contact: S. Jardin)*, April 21st, 2:00 PM-6:00 PM at the Strathallan Hotel in the Berkeley Room.
- **Summit Framework Team Meeting** *(Contact: S. Parker)*, April 21st,
- 6:00PM-9:00 PM at the Strathallan Hotel in Suite 219.
- **MHD Workshop** *(Contact: J. Manickam)*, April 21st, 6:00 PM-8:00 PM at the Strathallan Hotel in the Berkeley Room.
- **ST Theory Meeting** *(Contact: J. Manickam)*, April 22nd, 7:00 PM-8:00 PM at the Strathallan Hotel in the Berkeley Room.
- **SNOWMASS Session** *(Contact: N. Sauthoff)*, April 23rd, 1:30 PM - 6:00 PM at the Memorial Art Gallery Auditorium.
- **Sherwood Executive Committee Meeting** *(Contact: S. Stewart)*, April 23rd, 12:00 PM-2:00 PM at the Strathallan Hotel in the Harvard Room.
- **Fusion Theory Meeting** *(Contact: V. Chan)* April 22nd, 8:00 PM-10:00 PM at the Strathallan Hotel in the Harvard Room.
- **Snowmass MHD Working Group Meeting** *(Contact: C. Hegna)* April 24th, 9:00 AM-6:00 PM at the Strathallan Hotel in the Berkeley Room and April 25th, 9:00 AM-6:00 PM at the Strathallan Hotel in the Berkeley Room.

Program Overview

Sunday
April 21

Registration
6:00 PM-10:00 PM
Strathallan Hotel

Welcome Reception
7:00 PM -9:00 PM
Strathallan Hotel

Monday
April 22

Registration
7:30 AM-9:15 AM *and* 9:30 AM-11:30 AM
Strathallan Hotel / Memorial Art Gallery

Oral Presentations
8:20 AM-12:20 PM
Memorial Art Gallery

Poster Sessions
2:00 PM-6:00 PM
Strathallan Hotel

Tuesday
April 23

Registration
7:30 AM-11:30 AM
Strathallan Hotel

Oral Presentations
8:30 AM-10:20 AM *and* 8:00 PM-9:30 PM
Memorial Art Gallery / Memorial Art Gallery

Poster Sessions
10:30AM-12:30 PM
Strathallan Hotel

Snowmass Session
1:30 PM-6:00 PM
Memorial Art Gallery

Wednesday
April 24

Oral Presentations
8:30 AM-12:30 PM
Memorial Art Gallery

Registration Schedule

Sunday:	6:00 PM-10:00 PM Strathallan Hotel Lobby ***Welcome Reception*** ***7:00 PM-9:00 PM*** ***Strathallan Hotel***	
Monday:	7:30 AM-9:15 AM Strathallan Hotel Lobby	9:30 AM-11:30 AM Memorial Art Gallery
Tuesday:	7:30 AM-11:30 AM Strathallan Hotel Lobby	

Presentation Schedule

MONDAY

Oral Presentations, 8:20 AM -12:20 PM at the Memorial Art Gallery

Welcome *8:20-8:30*	Riccardo Betti, Local Arrangement Committee
Review Paper 1A	Riccardo Betti Presiding
8:30-9:30	David D. Meyerhofer Direct-Drive Inertial Confinement Fusion Research: Theory and Experiments
9:30-9:50	*Coffee Break*
Oral Session 1B	Janardhan Manickam Presiding
9:50-10:20	Andrea Garofalo MHD Stability in a Tokamak Above the Free Boundary Pressure Limit
10:20-10:50	Wonchull Park Nonlinear Simulation of NSTX including Strong Sheared Flows
10:50-11:20	Jeff Candy GYRO Modeling of Anomalous Transport in Tokamaks
11:20-11:50	Swadesh M. Mahajan Variational Principles and Self-Organization in Two-Fluid Plasmas
11:50-12:20	Giovanni Lapenta A Simulation Study of 3D Kinetic Reconnection

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2:00-4:00 PM	**Poster Session 1C at the Strathallan Hotel**
4:00-6:00 PM	**Poster Session 1D at the Strathallan Hotel**

TUESDAY

Oral Presentations, 8:30-10:20 AM at the Memorial Art Gallery

Review Paper 2A	James Callen Presiding
8:30-9:30	Tamas I. Gombosi Adaptive Mesh Refinement MHD for Space Plasma Simulations
Oral Session 2B	James Callen Presiding
9:30-10:00	Stanley Kaye Results and Challenges from the NSTX Program
10:00-10:20	*Coffee Break*
10:30-12:30	**POSTER SESSION 2C at the Strathallan Hotel**

1:30-6:00 PM	**Snowmass Session at the Memorial Art Gallery**

Oral Presentations, 8:00-9:30 PM at the Memorial Art Gallery

Oral Session 2D	Jeffrey P. Freidberg Presiding
8:00-8:30	Antonio Bruno Transport Scaling in an RFP Dominated by Tearing Modes
8:30-9:00	Eun-jin Kim Statistics of Anomalous Transport Events
9:00-9:30	Bo Hu Chaotic Scattering and the Magneto-Coulomb Map

WEDNESDAY

Oral Presentations, 8:30 AM-12:30 PM. at the Memorial Art Gallery

Review Paper 3A	Wendell Horton Presiding
8:30-9:30	Jeremy Goodman A Review of Magnetorotational Instability in Astrophysics
9:30-9:50	*Coffee Break*
Oral Session 3B	Richard Fitzpatrick Presiding
9:50-10:20	Bruno Coppi Angular Momentum "Generation": Theory and Recent Experiments
10:20-10:50	Henry R. Strauss Nonlinear MHD and Energetic Particle Modes in Stellarators
10:50-11:20	Jon Kinsey Renormalization of the GLF23 Transport Model and Burning Plasma Projections on a Universal Curve of Q versus T_{ped}
11:20-11:50	Per Helander Ion Runaway Acceleration During Magnetic Reconnection in MAST
11:50-12:20	Vladimir V. Mirnov A Hall Dynamo Effect Driven by Two Fluid Tearing Instability

POSTER SESSIONS

POSTER SESSION 1C:
Monday April 22nd, 2:00-4:00 p.m. Strathallan Hotel

1C01. *Studies of Nonlinear Resistive and Extended MHD in Advanced Tokamaks Using the NIMROD Code*
D. D. Schnack, T. Gianakon, S.E. Kruger,A. Tarditi

1C02. *Magnetic Reconnection Studies Using the NIMROD Code*
S.E. Kruger, R. Lionello, Z. Mikic, D.D. Schnack

1C03. *Zero Electron Mass Limit of the Drift Kinetic Equation*
F. L. Hinton, M.N. Rosenbluth and R.E. Waltz

1C04. *A Study of Tearing Mode Evolution Near Ideal Stability Boundaries*
D. P. Brennan, M.S. Chu, S. Kruger, R.J. La Haye, L.L. Lao, T.C. Luce, D.D. Schnack, E.J. Strait and A.D. Turnbull

1C05. *Effectiveness of Feedback for Stabilization of the Resistive Wall Mode in Tokamaks.*
M. S. Chu, M.S. Chance and M. Okabayashi

1C06. *Modeling Kink Instabilities in NSTX*
J. Manickam, E. Fredrickson, M. Okabayashi and the NSTX team

1C07. *Scaling and Modeling Studies of Steady-State, High-Bootstrap-Fraction Tokamak Discharges*
F.W. Perkins, T.A. Casper and P.A. Poltizer

1C08. *ELMs and Constraints on the Pedestal: a Model Based on Peeling-Ballooning Modes*
P.B. Snyder, H.R. Wilson, X.Q. Xu, J.R. Ferron, L.L. Lao, A.W. Leonard, D. Mossessian, M. Murakami, T.H. Osborne, A.D. Turnbull

1C09. *Ergodization of Magnetic Flux Surfaces Due to Toroidally Asymmetric Error Magnetic Field*
K-I. You, L.L. Lao, M.S. Chu, T.E. Evans and R.J. La Haye

1C10. *Progress Towards Realistic Geometry and Global Implementations of the Summit Gyrokinetic Framework*
J.N. Leboeuf, V.K. Decyck, A. Dimits, D. Shumaker

1C11. *Temperature Change Effect on Minority Species rf Heating*
D. G. Swanson

1C12. *First Comprehensive DIII-D Transport Simulations with GYRO*
R. E. Waltz and J.M. Candy

1C13. *Calculations of Neutral Beam Ion Confinement for the National Spherical Torus Experiment*
M.H. Redi, D.S. Darrow, S.M. Kaye, R.B. White and J. Egedal

1C14. *Kinetic Stability of the Field-Reversed Configuration*
E.V. Belova, R.C. Davidson, H.Ji and M. Yamada

1C15. *Numerical Simulations of Compressional Alfven Modes in NSTX*
E.V. Belova, N.N. Gorelenkov, R.C. Davidson, C.Z. Cheng and E.D. Fredrickson

1C16. *SEL: A New 3D Adaptive-Grid Spectral Element Code for Macroscopic Modeling of Magnetic Fusion Plasmas*
A. H. Glasser and X.Z. Tang

1C17. *Streamer Formation in Thermal Rossby Wave Turbulence*
O. D. Gurcan, P.H. Diamond and S. Champeaux

1C18. *Numerical Simulation of Edge Pedestal Formation by X-Transport*
C.S. Chang, S.H. Ku, H. Wetzner and R. White

1C19. *Efficiently Finding Trends in Macroscopic MHD Stability Using Perturbed Equilibria: Application to Toroidal Geometry*
K. Comer, J. Callen, C. Hegna, A. Turnbull and S. Cowley

1C20. *Further Work with the Unified Particle-in-Cell and Continuum Method*
S. Vadlamani, S. Parker and Y. Chen

1C21. *Zonal Flows and Transport in ITG Turbulence*
S. Dastgeer, S. Mahajan and J. Weiland

1C22. *Bootstrap Current Simulation for W7as and W7x*
R. White, C.D. Beidler, S.V. Kasilov, W. Kernbichler, H. Maassberg, D.R. Mikkelsen, V.V. Nemov, M. Schmidt, V. Tribaldos, A. Wakasa, S. Murakami

1C23. *Stochastic Heating of Ions in NSTX*
D. Gates, N. Gorelenkov, R.B. White and E. Fredrickson

1C24. *Simulation of Neoclassical Tearing Modes Coupling in Tokamak Discharges Using 3D Nonlinear Code NFTC.*
A. M. Popov

1C25. *Convective Blob Transport and the Density Limit*
J. R. Myra, D.A. D'Ippolito, S.I. Krasheninnikov and S.A. Galkin

1C26. *Study of Ideal MHD Ballooning Modes and Stability Boundaries in Three-Dimensional Toroidal Geometry*
R. Torasso, C.C. Hegna and S.R. Hudson

1C27. *Noncanonical Drift Hamiltonian Dynamics in Perturbed Tokamak Plasmas*
A.J. Brizard and A.N. Kaufman

1C28. *Stability of Radial Streamers and Blobs in the SOL Plasma*
D. A. D'Ippolito, R.J. Myra, S.I. Krasheninnikov and S.A. Galkin

1C29. *Sources and Sinks in the Evolution of Zonal Flows in Toroidal Ion Temperature Gradient Turbulence*
A. M. Dimits, W.M. Nevins and D.E. Shumaker

1C30. *Nonlinear Magnetic Reconnection and the Pressure Balance Condition*
B.N. Rogers, J.F. Drake, M.A. Shay and M.Swisdak

1C31. *Alfven Eigenmodes in Shear Reversed Plasmas*
B.N. Breizman, H.L. Berk, D.N. Borba, M.S. Pekker, S.D. Pinches and S.E. Shaparov

1C32. *Interpretation of ECE measurement on MAST*
J. Preinhaelter, V. Schevchenko, M.Valovic, L. Vahala and G. Vahala

1C33. *Lattice Boltzmann Models for Resistive MHD*
A. Macnab, G. Vahala, L. Vahala, P. Pavlo and M. Soe

1C34. *A Simple Model of the Resistive Wall Mode in Tokamaks*
R. Fitzpatrick

1C35. *Progress on Electromagnetic Gyrokinetic Simulations of Microturbulence with Fully Kinetic Electrons*
Y. Chen and S.E. Parker

1C36. *Convective Density Transport in Tokamak SOL Plasmas by 2D and 3D Simulations*
S. A. Galkin, S.I. Krasheninnikov, D.A. D'Ippolito, J.R. Myra and X.Q. Xu

1C37. *Simulation of Tokamak Edge Plasma Transport Including Anomalous Cross-Field Plasma Convection*
A. Yu Pigarov, S.I. Krasheninnikov, J.A. Boedo, D.G. Whyte, W.P. West, J.G. Watkins and C.J. Lasnier

1C38. *Plasma Wall Interaction Physics in Ignitor*
F. Bombarda, G. Cenacchi, B. Coppi and C. Ferro

1C39. *Importance of Non-Linear Processes Near the Onset of Internal Modes*
M. C. Firpo, B. Coppi and L.E. Sugiyama

1C40. *Progress in Modelling Angular-Momentum Transport in DIII-D*
L. L. Lodestro, T.A. Casper, T.B. Kaiser, J.M. Moller and L.D. Pearlstein

1C41. *Hybrid Delta f-MHD Simulation of the Internal Kink Mode*
C. C. Kim, S.E. Parker and the NIMROD team

1C42. *Hurst-Like Approaches to System Dynamics Characterization*
W. Ferenbaugh, D.E. Newman and P.W. Terry

1C43. *Nonperturbative Study of Thermonuclear Alfven Instabilities in Next Step Burning Plasma Experiments*
N.N. Gorelenkov, H. Berk, R. Budny, C.Z. Cheng, G.Y. Fu, W.W. Heidbrink, C. Kessel, D. Meade and R. Nazikian

1C44. *The Interaction of Energetic Ions and Magnetic Islands in Toroidal Plasmas*
C.C. Hegna

1C45. *1D Formalism for External Ballooning Modes*
L. Zheng, M. Kotschenreuther, and J.W. Van Dam

1C46. *Comparing Helicon Models with Experiments*
M.D. Carter, F.W. Baity, R.H. Goulding, Y.N. Mori and K.F. White

1C47. *Comparison of Turbulence Simulation with Experiment — Issues and Discussion*
D. W. Ross

1C48. *Multi-Dimensional Wave Conversion: a Ray-Based Algorithm*
E. R. Tracy, A.N. Kaufman and A. Jaun

POSTER SESSION 1D
Monday April 22nd, 4:00-6:00 p.m. Strathallan Hotel

1D01. *Neutral Effects on Flows and the Radial Electric Field*
P. J. Catto, T. Fulop and P. Helander

1D02. *Self-Organized Compact Toroid States with Flow*
L. C. Steinhauer

1D03. *All-Orders Spectral RF Calculations Using Local or "Windowed" Fourier Transforms*
E. F. Jaeger, L.A. Berry, J.R. Myra, D.A. D'Ippolito and D.B. Batchelor

1D04. *Equilibrium, Stability, and Nonlinear Saturation of a Toroidal Plasma with Co-axial Helicity Injection*
X. Tang, A.H. Glasser, A.H. Boozer and R. Raman

1D05. *Numerical Modeling of Zero Core Current Density Clamping in Tokamaks*
J.A. Breslau, W. Park, B.C. Stratton, H.R. Strauss and S.C. Jardin

1D06. *NIMROD Simulations of Coaxial Gun Spheromak Formation*
B. I. Cohen, S. Woodruff and C. R. Sovinec

1D07. *Scaling Analysis of Resistive MHD Fluctuations in RFP's and Spheromaks*
R. H. Cohen and L.L. LoDestro

1D08. *Theory of Plasma Confinement in a Levitated Dipole*
J. Kesner, D.T. Garnier, A. Hansen and M.E. Mauel

1D09. *Overview of the Summit Framework: Open-Source Software for Large-Scale Gyrokinetic Turbulence Simulation*
S. E. Parker, Y. Chen, B.I. Cohen, A.M. Dimits, W.M. Nevins, D. Shumaker, J.N. Leboeuf, V.K. Decyck

1D10. *Effects of Fast Particles on Internal Kink Modes in Reversed Field Pinches*
V.A. Svidzinski and S.C. Prager

1D11. *Calculations of Non-linear and Geometric Effects on Aflven Wave Current Drive Efficiency*
J. C. Wright and S.C. Prager

1D12. *Kinetic Effects of Hot Electrons on the Stability of a Closed Field Line Plasma*
N. Krasheninnikova, P.J. Catto and A.N. Simakov

1D13. *Application of the NTCC Modular Approach to the TRANSP Code*
A. Pankin, G. Bateman, K. Indireshkumar, S.C. Jardin, A.H. Kritz, D. McCune and the NTCC Team

1D14. *Stability of Axisymmetric Plasmas in Closed Line Magnetic Fields*
A. N. Simakov, P.J. Catto, R.J. Hastie and J.J. Ramos

1D15. *The 3-D MHD Dynamics of ac Helicity Injection*
F. Ebrahimi, S.C. Prager, J.C. Wright and J.S. Sarff

1D16. *Distinction of a Measured Poloidal Rotation Velocity V_p in a Tokamak Plasma by Corpuscular and CXRS Methods from a Neo-Classical Collisionless V_p*
A. Romannikov

1D17. *Short Wavelength Temperature Gradient Driven Modes in Tokamak Plasmas*
A. Smolyakov, M. Yagi and Y. Kishimoto

1D18. *Betatau of the Strategy of the Magnetic Fusion Reactor*
L. E. Zakharov

1D19. *Simulations of Energetic Particle Mode in Tokamaks and Stellarators*
G.Y. Fu, W. Park and H.R. Strauss

1D20. *Rotation Frequency of Magnetic Islands*
F.L. Waelbroeck

1D21. *Anomalous Poloidal Momentum Transport in Toroidal Geometry*
G.M. Staebler

1D22. *Poloidal Flow in Toroidally Rotating Plasma*
W.X. Wang, F.L. Hinton, S.K. Wong and Z. Lin

1D23. *Magnetohydrodynamic Equilibria with Pedestals Induced by Poloidal Flow*
T. A. Gardiner and R. Betti

1D24. *Poloidal Rotations Induced in Tokamak Plasmas by Ion Bernstein Waves*
A. Cardinali, C. Castaldo and R. Cesario

1D25. *Fluid Closure Ansatz for Collisionless MHD*
J. J. Ramos

1D26. *Collisionless Reconnection Revisited with a New Computational Framework*
A. Y. Aydemir

1D27. *Exhausting the Separatrix Flux Through the TF Coils*
M. Kotschenreuther and L. Zheng

1D28. *Two-Fluid Effects on Instabilities in Realistic Confined Plasma Geometries*
L. E. Sugiyama, W. Park, H.R. Strauss and G.Y. Fu

1D29. *Influence of E x B Drifts on ELM Transport in the Scrape-Off Layer*
T. D. Rognlien and M. Shimada

1D30. *High Beta Stability of Magnetic Dipole Configurations*
H.V. Wong, W. Horton, J.W. Van Dam, H.L. Berk, M. Kotschenreuther and C. Crabtree

1D31. *Plasma and Momentum Transport Processes in the Vicinity of a Magnetic Island in a Tokamak*
J. D. Callen, K.C. Shaing and C.C. Hegna

1D32. *Magnetic Island Effects on Axisymmetric Equilibria*
X. Liu, J.D. Callen and C.C. Hegna

1D33. *Global Anisotropy Via Inverse Cascade in Turbulence with Symmetry Breaking*
P.W. Terry, R. Gatto and D.A. Baver

1D34. *Squeezed Superbanana and Improved Superbanana Transport in Stellarators*
K. C. Shaing

1D35. *Stability of Virtual Cathodes in INS-E*
R. A. Nebel

1D36. *Linear Undamped Waves in Near-Maxwellian Plasmas with Applications to Stimulated Raman Scattering in Laser-Produced Plasmas*
R. W. Short

1D37. *Symmetries in Dissipation-Free Linear Mode Conversions*
A. Bers and A.K. Ram

1D38. *A Warm Fluid Model of Intense Laser-Plasma Interactions*
B.A. Shadwick, G.M. Tarkenton and E.H. Esarey

1D39. *Studies of Laser-Plasma Interactions with VORPAL*
J. R. Cary and C. Nieter

1D40. *Reduced Hermite Interpolation in Many Dimensions*
B. J. Braams

1D41. *Symbolic Cycle Analysis of Turbulent Plasma Fluctuations*
A.B. Rechester and M. Lehrman

1D42. *Extracting Symbolic Cycles from Turbulent Fluctuation Data*
M. Lehrman and A.B. Rechester

1D43. *Drift Instabilities in Beta>>1, Collisional Plasmas*
D. D. Ryutov

1D44. *Angular Momentum Transport in Accretion Disks, Relevant Magnetic Reconnection Theory, and Experimental Observations*
B. Coppi

1D45. *Theory and Numerical Analysis of Singular Modes in Thin Accretion Disks*
I. Dimov, B. Coppi and R. Bhatt

1D46. *Vlasov-Maxwell Simulations of a Finite Amplitude, Longitudinal Ion Cyclotron Wave in a Magnetized Plasma*
C. Marchetto, F. Califano, M. Lontano

1D47. *Simulations of Ion Beam-Alfven Wave Dynamics in the Cornell Ion Ring Experiment*
A. V. Gretchikha, J.B. Greenly and W.J. Podulka

POSTER SESSION 2C:
Tuesday April 23rd, 10:30a.m-12:30 p.m. Strathallan Hotel

2CO1. *On Sand Piles with Bi-stable Automata Rules-Towards a Minimal Model of Pedestal Formation and Structure*
I. Gruzinov and P.H. Diamond

2CO2. *Recent Progress in Magnetic Dynamo Theory*
E. Blackman

2CO3. *Anomalous Electron Thermal Transport from Overlapping and NonOverlapping Drift Magnetic Islands*
R. D. Sydora

2CO4. *Numerical Simulation of Magnetic Reconnection using AMR*
R. Samtaney, S. Jardin, P. Colella and T. Ligocki

2CO5. *Numerical Studies of Laminar States and PPCD in RFPs*
C. Sovinec and J.M. Reynolds

2CO6. *Modeling of Plasma and Neutral Transport in the Stellarator Edge*
M.V. Umansky, T.D. Rognlien, M.E. Fenstermacher, M. Borchardt, J. Reimann, R. Schneider, L.W. Owen

2CO7. *Nonlocal Simulation of finite B-effects in L-mode Edge Plasmas*
K. Hallatschek, J.L. Terry, B. LaBombard, B.N. Rogers and S.J. Zweben

2CO8. *Generalized Basis Function Analysis for All-Orders, Full-Wave RF Computations*
L.A. Berry, E.F. D'Azevedo, E.F. Jaeger, D.B. Batchelor and M.D. Carter

2CO9. *Solvers for Stiff Transport Equations*
J. Carlsson and J.R. Cary

2C10. *Alfven Waves in Gyrokinetic Plasmas*
W. W. Lee, J.L. Lewandowski, H. Qin and I. Manuilskiy

2C11. *General Parallel Closures for Plasma Fluid Simulations*
E.D. Held

2C12. *Effects of Kinetic Electrons on Microturbulence*
Z. Lin

2C13. *Overview of the QPS Experiment*
J. F. Lyon et al

2C14. *Hamiltonian Description of Fluid and Plasma Systems with Continuous Spectra*
P.J. Morrison

2C15. *Models for the Pedestal Temperature at the Edge of H-mode Tokamak Plasmas*
A. H. Kritz, T. Onjun and G. Bateman

2C16. *Testing H-mode Pedestal and Core Transport Models Using Predictive Integrated Modeling Simulations*
G. Bateman, A.H. Kritz, T. Onjun, A. Pankin and C. Nguyen

2C17. *Study of Critical Pressure Gradient at the Edge of Type I ELMy H-mode Plasmas*
T. Onjun, A.H. Kritz, G. Bateman and V. Parail

2C18. *Numerical Studies of Transport Near Magnetic Islands*
M. K. Addae-Kagyah, J.W. James and E.D. Held

2C19. *Analysis of Multifield Phase and Frequency Effects in Ion Temperature Gradient Driven Turbulence*
D.A. Baver and P.W. Terry

2C20. *Outstanding Theoretical Problems for Analysis of Burning Plasma Experiments*
S. C. Jardin, C.E. Kessel and D. Meade

2C21. *Turbulent and Neoclassical Processes Determining Particle Transport in Alcator C-MOD Internal Transport Barriers*
D. Ernst, P.T. Bonoli, P.Catto, W.M. Dorland, M. Porkolab, M.Redi and the ALCATOR C-MOD Group

2C22. *QPS Transport and Energetic Particle Physics*
D.A. Spong, L.A. Berry, S.P. Hirshman, J.F. Lyon

2C23. *QPS Plasma and Coil Optimization*
D.J. Strickler, D.A. Spong, L.A. Berry, G.Y. Fu, S.P. Hirshman, J.F. Lyon, R. Sanchez and A.S. Ware

2C24. *Magnetic Secondary Instabilities in ETG Turbulence*
C. Holland and P.H. Diamond

2C25. *Fully Covered Solutions of Ion Bernstein Wave Mode Conversion in Toroidal Geometry*
P. T. Bonoli, E.D'Azevedo and M. Brambilla

2C26. *Hole-Clump Coherent Structures and Self-Consistent Chaos in the Wave-Particle Interaction*
D. del-Castillo-Negrete, M.C. Firpo

2C27. *Stratified Shear Layers and Fronts in a Model of Turbulence-Shear Flow Interaction*
B.A. Carreras, D. del-Castillo-Negrete and V. Lynch

2C28. *Reconnection and the Ideal Evolution of Magnetic Fields*
A. H. Boozer

2C29. *Nonlinear Dynamics of a Shear-Localized Ideal Interchange Instability*
S. Gupta, C.C. Hegna and J.D. Callen

2C30. *Stabilization of the Resistive Wall Mode by Differentially Rotating Walls in a High-Beta Tokamak*
L. Guazzotto and R. Betti

2C31. *Investigation of the Resistive Wall Modes in Toroidal Geometry*
L. Zheng, M. Kotschenreuther, P. Snyder and H.R. Wilson

2C32. *Diffusive Effects on Plasma Stability*
E. Hameiri

2C33. *Dynamical Transitions in SOC Systems with Additional Transport Mechanisms*
R. Sanchez, D.E. Newman and B.A. Carreras

2C34. *The Dynamics of the Co-evolution of Electron and Ion Channel Transport Barriers*
D.E. Newman, B.A. Carreras and D. Lopez-Bruna

2C35. *NIMROD Code Simulation of Field Reversed Configuration Plasmas for Application to Fusion Propulsion*
A. G. Tarditi

2C36. *Current Ramping to Achieve Reversed Shear Confinement for Ignitor and CMOD*
W. Horton, P. Zhu and B. Hu

2C37. *Renormalization and Destruction of Tori in the Standard Nontwist Map*
A. Apte, A. Wurm and P.J. Morrison

2C38. *Ignitor Equilibria with JSOLVER*
P. Detragiache

2C39. *Optimal Rate of Injected Heating for the Attainment of Ignition*
A. Airoldi, G. Cenacchi and B. Coppi

2C40. *A Hybrid Ion Temperature Gradient and Kelvin-Helmholtz Instability*
A. K. Sen, V. Reva and K. Avinash

2C41. *Importance of Non-linear Effects for the Excitation of "Singular" Modes in Thin Accretion Disks*
P. S. Coppi and B. Coppi

2C42. *High Current Densities Through the Sheath in a Grazing Magnetic Field*
D. D. Ryutov and R.H. Cohen

2C43. *Small Sample Effects in Symbolic Time Series Methods*
A. G. Davis, E.R. Tracy and D.M. Weaver

2C44. *Nonlinear Pulse Control Using Nonlinear Schrodinger Targets*
C.W. Kulp, E.R. Tracy and A.R. Osborne

2C45. *Potential Well Formation in Ion-Injected IEC*
G. H. Miley, H. Momota, Y. Shaban and L. Wu

2C46. *Self-consistent Modelling of Helicon Plasma Sources*
A. Arefiev and B.N. Breizman

2C47. *Spontaneous Pulse Formation in Bistable Systems*
G. A. Andrews, E.R. Tracy, W.E. Cooke and W. Yang

2C48. *Coherent and Stochastic Motion of Magnetized Ions by Oblique Electrostatic Waves*
D. J. Strozzi, A.K. Ram and A. Bers

Monday Morning

8:30 AM-9:30 AM

Memorial Art Gallery Auditorium

Review Paper 1A

Direct-Drive Inertial Confinement Fusion Research: Theory and Experiments

David D. Meyerhofer

Laboratory for Laser Energetics, University of Rochester,
250 East River Road, Rochester, NY 14623-1299

Inertial confinement fusion (ICF) ignition research is being carried out with both direct and indirect drive. Each approach has advantages. The direct-drive approach to ICF offers the possibility of higher gain than indirect-drive ICF and simpler engineering of an inertial fusion energy power plant. Many different physical processes occur during the implosion, including the physics of laser interaction with the target, the growth of nonuniformities due to the Rayleigh–Taylor instability during the acceleration and deceleration phases of the implosion, assembly of the compressed core, and nuclear burn. These processes can be studied in an integrated sense by performing spherical target implosions, and in a piece-wise sense, where individual processes are studied with little effect of others. This talk will describe experimental and theoretical research in direct-drive ICF, concentrating on the strong interplay between these efforts. It will concentrate on research carried out at the University of Rochester, where the primary experimental tool—the 60-beam, 30-kJ OMEGA laser system—is used for both integrated and individual physics process experiments. A brief comparison of direct and indirect drive and examples from other laboratories will be included. The intermediate-term goal of the ICF program is target ignition on the 1.5-MJ National Ignition Facility, currently under construction at LLNL. Direct-drive ignition designs will be reviewed, and the relationship of the current research to these designs will be described. These include the performance of cryogenic target experiments on the OMEGA laser system.

This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

Monday Morning

9:50 AM-12:20 PM

Memorial Art Gallery Auditorium

Oral Session 1B

MHD Stability in a Tokamak Above the Free Boundary Pressure Limit

A.M. Garofalo1,[1] M.S. Chu,[2] T.H. Jensen,[2] L.C. Johnson,[3] R.J. La Haye,[2]
G.A. Navratil,[1] M. Okabayashi,[3] J.T. Scoville,[2] E.J. Strait,[2] T.S. Taylor,[2] A.D. Turnbull[2]

[1] Columbia University, New York, New York, 10027
[2] General Atomics, P.O. Box 85608, San Diego, California 92186
[3] Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543

Abstract

Sustained, stable plasma operation at high pressure above the free boundary limit for the n=1 ideal MHD external kink mode has been achieved in DIII-D with a combination of high plasma rotation and a resistive wall close to the plasma surface. The no-wall limit theoretically predicted for a number of plasma configurations has been tested to unprecedented accuracy (±5%) using a technique that exploits the stability properties of the resistive wall mode (RWM). Magnetic braking of the plasma rotation leads to an RWM-induced beta collapse at beta just above the predicted no-wall limit, while it has virtually no effect on the plasma at beta just below the no-wall limit. At twice the free-boundary pressure limit, a disruption precursor is observed, which is consistent with having reached the "ideal wall" pressure limit predicted by stability calculations. At beta below the no-wall limit, the negative growth rate of the RWM has been measured using a low-frequency analog of the active MHD measurements carried out for Alfven Eigenmodes on JET [1]. A quasi-DC pulse of n=1 magnetic field is applied externally at different beta values. A forced, resonant, plasma response and strong rotation damping are observed at beta above the no wall limit, while a response about the noise level is observed at lower beta. Acting like an "adaptive magnetics" system, the resistive wall mode feedback system in DIII-D can exploit the strong plasma response to external n=1 fields as beta exceeds the no-wall limit, to serve as an indicator of the presence of small magnetic field asymmetries. In closed loop, the system is able to drive appropriate correction fields. These corrections are necessary to sustain the plasma rotation above the threshold for stabilization of the RWM.

[1] Fasoli, A., *et al.*, Phys. Rev. Lett. **75** (1995) 645

Presented at the Sherwood meeting, Rochester, April 22-24, 2002

Nonlinear Simulation of NSTX including Strong Sheared Flows

W. Park, J. Breslau, J. Chen, G.Y. Fu, S.C. Jardin, S. Klasky, J. Menard, A. Pletzer
Princeton University Plasma Physics Laboratory
H.R. Strauss, *New York University*
L.E. Sugiyama, *Massachusetts Institute of Technology*

A multilevel physics, parallel processing plasma simulation code, M3D [1] has been used to study NSTX including strong sheared flows. The physics levels of M3D utilized in the current study are MHD, two-fluids, and hybrid gyrokinetic-particle/MHD models. M3D uses unstructured meshes, and the parallel processing structure utilizes MPI and the PETSc framework.

Many NSTX discharges end with an internal reconnection event (IRE) with the measured central q value near unity. Numerical simulations of such IRE's often show crashes similar to sawtooth crashes. Experimental and theoretical soft X-ray data substantially agree during the crash phase. However, the experiment often shows a long saturated m=1 phase, which a usual MHD simulation cannot reproduce. The saturation may be explained by stabilizing effects of strong sheared rotation, the ω* effect, and energetic particle effects as described below.

Neutral beam driven totoidal sheared rotation can be a substantial fraction of the Alfven speed for ST's such as NSTX. Numerical 2D steady states show that for a case with aspect ratio A=1.3, peak beta β_0=30%, and peak rotation Alfven Mach number of M=0.2, the density peak shifts outward relative to the magnetic axis by 0.2*a due to centrifugal force where a is the minor radius. Two-fluid effects of thermal plasma do not change the equilibrium substantially. The hybrid gyrokinetic particle/MHD level results show that as long as the energetic particles have an isotropic distribution, they do not change the equilibrium profile substantially. When taking all the energetic particles as passing, a further equilibrium shift of about 0.05*a occurs. These results are generally consistent with experimental measurements.

For global internal modes, the linear growth rates are typically reduced by several-folds due to sheared rotation. 3D nonlinear evolution of an m=1 internal kink shows a complex behavior, one important factor being the rate of the toroidal momentum source (and sink to keep the peak rotation Alfven Mach number at M=0.2). For a slow source rate, complete reconnection eventually occurs with the toroidal flow profile evolving closely with the magnetic topology change. For a fast enough momentum source rate, a saturated state can occur in the MHD description. For an intermediate source rate, a slow first crash can be followed by a second reconnection process, which saturates partly due to the fact that the pressure inside the magnetic island becomes higher than the pressure inside the 'hot' spot.[2] This occurs spontaneously due to strong density peaking inside the island due to centrifugal force, and results in a curious profile where the temperature is higher at the hot spot while the density and pressure are higher in the island, as shown in Fig. 1. Although there is no momentum source except in the toroidal direction, poloidal flow develops in the 3D nonlinear phase, and forms profiles somewhat reminiscent to 2D states with poloidal flow shown in Ref. 3. Scaling studies are being performed to determine quantitative criterions such as the required momentum source rate. Thus, MHD physics with shear flow could explain some of m=1 saturation cases seen in NSTX. Aforementioned 2D studies using the two-fluid and hybrid particle/MHD levels are also being continued to the 3D nonlinear phase to study additional stabilizing effects of ω* and energetic particles.

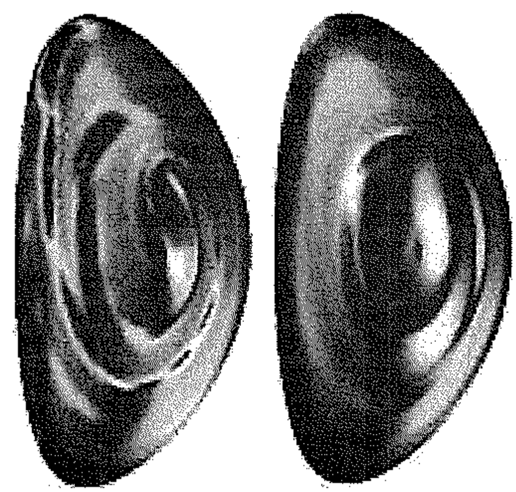

Figure 1. Density and temperature profiles during a 3D nonlinear phase, with the density (and pressure) peak inside the island and temperature peak inside the original hot spot.

1. W. Park et al., Phys. Plasmas **6** 1796 (1999).; H.R. Strauss and W. Park, Phys. Plasmas **5** 2676 (1998); L.E. Sugiyama and W. Park, Phys. Plasmas **7** 4644 (2000); G.Y. Fu and W. Park, Phys. Rev. Lett. **74** 1594 (1995); X.Z. Tang et al.,, Proc. of tenth SIAM conf. on parallel processing of scientific computation (2001).
2. W. Park, D.A. Monticello, and T.K. Chu, Phys.Fluids **30** 285 (1987).
3. R. Betti and J.P. Freidberg, Phys. Plasmas **7** 2439 (2000).

GYRO modeling of anomalous transport in tokamaks*

J. Candy and R.E. Waltz

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

Abstract

The General Atomics gyrokinetic-Maxwell solver, GYRO[1], has matured into a comprehensive and relatively efficient tool for the study of tokamak microturbulence. Numerous algorithmic innovations in combination with a zero-noise Eulerian grid allow the global study of electromagnetic turbulence in shaped plasmas with fully kinetic trapped and passing electron dynamics (no fluid approximation). In the simple case where electrons are taken to be adiabatic, high-resolution nonlinear simulations with realistic geometry and profiles – including equilibrium rotation – can be made in a few hours on 32 IBM-SP POWER3 processors (this is ten to twenty times faster than cases with full electron dynamics). Using GYRO, we have been able to systematically explain the mechanisms which lead to the breaking of gyroBohm transport scaling in toroidal plasmas, as well as the dynamics of transport reduction by equilibrium $\mathbf{E} \times \mathbf{B}$ flow[2].

In this presentation, we explore state-of-the-art physics results obtained from GYRO. An important milestone in the work which we will discuss is simultaneous inclusion of finite-β and finite-ρ_* effects. Here, $\rho_* \equiv \rho_i/a$, where ρ_i is the ion gyroradius, and a is the plasma minor radius. Numerically-determined thermal and particle diffusivities are shown to be very sensitive to the levels of equilibrium $\mathbf{E} \times \mathbf{B}$ flow. The diagnosis of numerical results is facilitated by our established IDL-based graphical analysis tool, vuGYRO, along with a new suite of tools based on the open-source Visualization ToolKit (VTK). The latter C++ class library provides an interface for surface and volume rendering in general toroidal geometry, and allows isosurface rendering of (i) electrostatic/electromagnetic potentials; (ii) local density and temperature fluctuations; (iii) $\mathbf{E} \times \mathbf{B}$ motion; and (iv) transport flows. We are also interested in elucidating the role, if any, of so-called "avalanche" effects in the generation of radial transport. The presentation, which summarizes the core of our new physics results, will consist primarily of MPEG movies of the time-evolution of the isosurface functions described above. For this reason, we hope it will be of interest to experts and nonexperts alike.

[1]J. Candy and R.E. Waltz, submitted to J. Comput. Phys.
[2]R.E. Waltz, J. Candy and M.N. Rosenbluth, Phys. Plasmas, to be published May 2002.
*This is a report of work supported by the U.S. Department of Energy under Grant Nos. DE-FG03-95ER54309.

Variational Principles and Self-Organization in Two-Fluid Plasmas

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Tokyo, Japan

We investigate the phenomenon of the self-organization of plasmas into "relaxed states" of varying complexity.

Although many of the relaxed states in recent literature follow from apparently standard variational principles, self-organization is not a general tendency of plasmas. We have found that self-organization towards an ordered structure occurs only under rather restrictive conditions. Not all variational principles are well posed; even when they are, not all solutions to variational principles lead to stable equilibria—an essential minimum qualification for relaxed states.

We have derived a new theoretical framework [1] for a well-posed variational principle, which invokes a target functional whose form is mathematically "coercive" (i.e., involving higher-order derivatives than in the associated constraint functions). The coercive target functional is the measure of turbulence (and, simultaneously, of the dissipation), and its minimization is exactly the characterization of self-organization. During the approach towards equilibrium, the constraints (viz., constants of motion of the ideal model) are adjusted, through a weakly dissipative process, so that the relaxed state is a stable equilibrium independent of the direct effects of dissipation.

Using the generalized ion enstrophy as such a target functional, we have derived a criterion for the self-organizing relaxation of a two-fluid plasma into so-called magneto-fluid states. These states of stable equilibria, also known as double Beltrami states [2], are formed by a strong interaction between the plasma flow and the magnetic field. The sheared velocity field is essential to determine the existence, as well as the properties, of these equilibria. The generalized ion enstrophy can, in fact, be viewed as the Hamiltonian associated with the magneto-fluid field, which unifies the flow and the magnetic fields.

In addition, this new formalism provides a fresh interpretation for Taylor relaxation, to which it reduces in the limit of zero flow. An important difference with the Woltjer-Taylor force-free relaxed states, however, is that these new magnetofluid states are able to confine a plasma by means of the generalized Bernoulli mechanism.

These new states, which do not require spatial symmetry (i.e., flux surfaces) for equilibria, may be important for understanding plasma structures found in astrophysics (e.g., coronal mass ejections and solar smoke rings) and laboratory plasmas with strong flow (e.g., field-reversed configuration and possibly the H-mode). Preliminary results from a small experiment to realize these magnetofluid states [3] will also be presented.

[1] Z. Yoshida and S. M. Mahajan, to appear in Phys. Rev. Lett. (March, 2002); available as IFS Report No. 938 at w3fusion.ph.utexas.edu/ifs/reports2002.html.
[2] S. M. Mahajan and Z. Yoshida, Phys. Rev. Lett. **81**, 4863 (1998).
[3] H. J. Quevado, R. Bengtson, S. M. Mahajan, and P. M. Valanju, Bull. Am. Phys. Soc. **46** (8), 275 (2001) QP1-93.

A simulation study of 3D kinetic reconnection

G. Lapenta [1,2] , J.U. Brackbill [1] and P. Ricci [2,3]

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Abstract

Reconnection is a key aspect of the evolution of many problems in laboratory, space and astrophysics plasmas. In most cases reconnection is observed to occur at a fast rate and to require non-ideal processes to explain its presence. In the present work we describe a simulation effort to understand reconnection within the most accurate model for collisionless plasmas: the Vlasov-Maxwell model. Our study assumes as reference configurations modified Harris equilibria that can include normal magnetic field to describe the Earth's magnetotail, coronal helmet streamers and astrophysical jets. We consider a 3D Cartesian geometry, to include the presence of field aligned modes and current aligned modes [1]. We use the CELESTE3D implicit plasma simulation code. The moment implicit method is used to handle efficiently multi time and multiple length scale process. The implicit moment method allows to resolve accurately the relevant time and length scale while effectively averaging over faster time scales (e.g. electron plasma frequency) and shorter length scales (e.g. Debye length). The primary practical consequence of this feature of CELESTE3D is the ability to handle realistic mass ratios and to simulate macroscopic systems while retaining a kinetic description of both ions and electrons.

In 3D kinetic reconnection three classes of instabilities are possible: 1) in the field aligned direction, the tearing instability; 2) in the current aligned direction, the lower hybrid drift instability (LHDI) at short wavelengths and odd parity modes such as the Kelvin-Helmholtz (KHI) [3] and drift-kink instability (DKI) [1] at long wavelengths; 3) at oblique angles oblique modes can cause reconnection with properties different from the tearing mode [2]. The complete picture of 3D riconnection requires the inclusion of all the instabilities listed above. The traditional paradigm of magnetotail reconnection in 2D based on the tearing mode and leading to the formation of magnetic islands (plasmoids) needs to be revised entirely. We will show that in the current aligned direction the LHDI evolves causing velocity shears that lead to the KHI and alters the initial equilibrium in the direction of current flow. Consequently, reconnection loses its 2D symmetry with two important consequences. First, systems otherwise stable to the pure collisionless tearing instability become unstable. Second, the 3D structure created in the cross tail direction by the KHI results in a more complex magnetic field topology after reconnection.

[1] G. Lapenta, J.U. Brackbill, J. Geophys. Res. , 102, 27099 (1997)
[2] G. Lapenta, J.U. Brackbill, Nonlinear Processes Geophys., 7, 151 (2000)
[3] G. Lapenta, J.U. Brackbill , Phys. Plasmas (in press).

Monday Afternoon

2:00 PM-4:00 PM

Strathallan Hotel
Living/Canterbury Room

Poster Session 1C

STUDIES OF NONLINEAR RESISTIVE AND EXTENDED MHD IN ADVANCED TOKAMAKS USINGTHE NIMROD CODE

D. D. Schnack*, T. Gianakon**, S. E. Kruger*, A. Tarditi*
and
The NIMROD Team

*Science Applications International Corp.
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**Los Alamos National Laboratory
Los Alamos, NM USA

The long wavelength evolution of modern tokamaks is largely dominated by slowly evolving, nonlinear dynamics that require either very small but non-vanishing dissipation qnd/or extensions to the usual resistive MHD model for their physical description. Geometric details are also important for analysis of relevant experimental data. Deriving and testing the proper extensions to the usual fluid models, and the spatial and temporal stiffness of the resulting equations, present extreme challenges to both analytic theory and computational physics. The NIMROD code is being developed to address these issues. Here we present applications of the NIMROD code to the detailed analysis of experimental discharges: DIII-D shots #87009 and #86144. Shot #87009 is a highly shaped discharge that undergoes a high-beta disruption during slow neutral beam heating. Results relevant to slow heating of the discharge through an ideal stability boundary and the growth and nonlinear saturation of the resulting mode will be presented, and comparisons with analytic theory[1] will be made. It is found that small but finite resistivity in the nonlinear regime can lead to a configuration that is suggestive of degraded confinement. Shot #86144 is a shaped discharge that exhibits growth of a neo-classical tearing mode (NTM) after a sawtooth crash. This has been simulated with NIMROD using analytic closures to capture the destabilization of the NTM. The mode is generated self-consistently as a secondary island driven by a sawtooth crash at high-S. Threshold behavior and nonlinear growth of the NTM have been studied. Together, these calculations explore the frontiers of computational fluid modeling as applied to modern tokamaks.

1. J. Callen, C. Hegna, B. Rice, T. Strait, and A. Turnbull, Phys. Plasmas **6**, 2963 (1999)

Magnetic Reconnection Studies Using the NIMROD Code

S.E. Kruger, R. Lionello, Z. Mikic, D.D. Schnack

Science Applications International Corporation, San Diego

It has been suggested [1] that localized resistivity leads to fast reconnection by giving a Petschek configuration. In this work, this effect as well as the role of initial conditions and boundary conditions on reconnection rates is studied with the NIMROD code. Although the NIMROD code was designed primarily for fusion applications in toroidal systems, it has a number of features useful for studying this problem including good scaling on massively parallel architectures, flexibility in geometry (slab, cylinder, torus), flexibility in gridding, and flexibility in boundary condtions (non-periodic, periodic, doubly-periodic). Preliminary results will be presented.

[1] D. Biskamp and E. Schwartz, Phys. Plasmas **8**, 4279 (2001)

Zero electron mass limit of the drift kinetic equation*

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In simulations of electromagnetic turbulence which use explicit finite difference schemes, the electron transit time scale sets a very short limit on the time step for stability, making these simulations computationally challenging. Also in particle simulations, following disparate time scales is difficult because of noise buildup. We have derived a set of reduced equations from the electron drift kinetic and Maxwell equations, corresponding to the limit of zero electron mass, in which the short electron transit time scale is removed, thus eliminating these problems. Unlike some previous work, the electrons are not treated as a fluid; trapped and passing electrons are treated differently.

The passing electron equations are shown to reduce to an Ohm's law,

$$E_{\|} = -\vec{b} \cdot \nabla \delta\psi$$

where $\vec{b}$ is a unit vector along the perturbed magnetic field lines, and

$$\delta\psi = \left(T_e/e\right)\left[\delta n_p/n_p + \delta\vec{x} \cdot \nabla n_e/n_e\right]$$

in which δn_p and n_p are the perturbed and equilibrium densities of passing electrons and $\delta\vec{x}$ is the displacement of the perturbed magnetic field lines. Time advance equations are obtained for the parallel vector potential and displacement:

$$\frac{\partial A_{\|}}{\partial t} = -\vec{v}_{E0} \cdot \nabla A_{\|} - \vec{b} \cdot \nabla(\delta\phi - \delta\psi)$$

where $\vec{v}_{E0}$ is the equilibrium E×B drift and $\delta\phi$ is the perturbed scalar potential, and

$$\frac{\partial \delta\vec{x}}{\partial t} + \vec{V}_F \cdot \nabla\delta\vec{x} = \vec{V}_F$$

where the field line velocity is

$$\vec{V}_F = \vec{b} \times \nabla\left(\Phi_0 + \delta\phi - \delta\psi\right)/B$$

in which Φ_0 is the equilibrium potential. Magnetic flux is conserved in a frame moving with this field line velocity.The equilibrium potential has the effect of introducing a Doppler shift in the equations for $A_{\|}$ and $\delta\vec{x}$. For the case of a simple slab model, the condition for numerical stability of an explicit finite difference scheme is shown to be the Courant condition using the Alfvén speed, which is considerably smaller than the electron thermal speed for relevant values of β_e, the ratio of electron pressure to magnetic pressure. The trapped electron equation is a bounce-averaged drift kinetic equation, in which the electron mass also does not appear.

The complete set of equations includes the exact electron continuity equation, Ampere's law, quasineutrality, and the gyrokinetic equation for the ion distribution function, written in a form such that the time derivative acting on the gyroaveraged perturbed potential is eliminated. The equations have the time-advance form

$$\frac{\partial Y}{\partial t} = F(Y)$$

where Y is the vector of dependent variables, and F represents operators which do not contain time derivatives.

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*Work supported by U.S. Department of Energy under Grant DE-FG03-95ER54309.

A study of tearing mode evolution near ideal stability boundaries*

D.P. Brennan,[1] M.S. Chu,[2] S. Kruger,[3] R.J. La Haye,[2] L.L. Lao,[2] T.C. Luce,[2]
D. Schnack,[3] E.J. Strait,[2] and A.D. Turnbull[2]

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[2]General Atomics, P.O. Box 85608, San Diego, California 92186-5608 USA
[3]Science Applications International Corporation

Tearing stability calculations on time series of kinetic equilibrium reconstructions in DIII–D discharges indicate that the tearing modes in these discharges are classically unstable at the time of onset, with a rapid increase in the linear tearing stability index Δ' just before onset, as shown in Fig. 1. A theoretical mechanism for the onset of tearing modes due to the approach of ideal stability boundaries and the increase in Δ' is studied as a mechanism for the onset of NTMs in these discharges. On the approach to an ideal limit in β_N in a tokamak, tearing modes become linearly unstable with Δ' becoming large and positive as it approaches a pole discontinuity at the ideal limit. This increase in Δ' causes large and rapid growth of magnetic islands before the ideal limit is reached. Several ideal modes seed NTMs through forced reconnection. However, tearing modes often appear suddenly and grow quickly without an obvious ideal mode causing a seed island through forced reconnection, which could be explained by this mechanism. A directly measurable theoretical prediction is that the time integration of the Rutherford equation with an increasing Δ' indicates that the point in β_N space at which these islands reach a certain small size should increase monotonically with the rate of approach to the pole $d\beta_N/dt$. This dependence is unique to a classical mechanism of destabilization, with positive Δ'. This approach is applicable to any tearing stability model that shows Δ' going through a pole discontinuity at the ideal limit, and the relative timescales of the change in Δ' versus the effects of finite island width will determine the evolution of the island, and the eventual nonlinear state. These theoretical and numerical predictions will be compared with results from a new DIII–D experiment designed specifically to test this hypothesis.

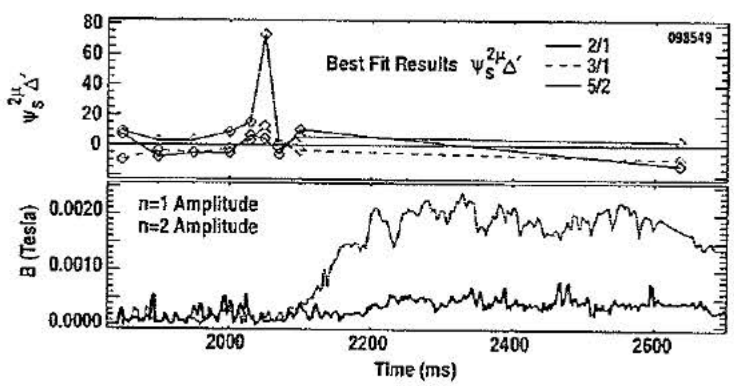

Fig. 1. The Δ' results from PEST-III for various modes at various times during a DIII-D discharge. The Δ' values for the 2/1 surface become large and positive just before onset of the 2/1 NTM, indicating that this mode is classically unstable at the point of onset.

*Work supported by US Departement of Energy under Contracts DE-AC03-99ER54463, DE-AC05-76OR00033 and Grant No. DE-FG03-95ER54309.

Effectiveness of feedback for stabilization of the resistive wall mode in tokamaks*

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The effectiveness of feedback on the stabilization of the resistive wall mode (RWM) in DIII–D geometry is studied systematically by using the normal mode approach [1,2]. In this approach, the normal modes during the open loop operation of the dynamical system of tokamak and resistive wall are used as basis. This system has only one unstable mode, the RWM, and the rest of the modes are stable. Incorporation of the external coils, the sensor loops, and the feedback logic extends the dynamical system and couples the stable modes with the unstable RWM. Stabilization results when the feedback geometry and logic are properly implemented. We report here the dependence of the effectiveness on the coil and sensor geometry and different feedback logic. The optimal dimension and sensitivity of the poloidal extent of the coils is obtained. We also found that poloidal sensor is much more effective than radial sensors. For a single array of feedback coils, these results are related in terms of the strength of the residues in the open loop transfer functions of the feedback system [3]. The residue for the RWM with poloidal sensor is much stronger than that with radial sensor. The contribution from higher order poles also alternate in sign, giving effective cancellation of their contributions. For multiple arrays of feedback coils, the results are not as easily understood, but are easily obtained from the solution of the characteristic equations.

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Modeling Kink Instabilities in NSTX

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The ideal external kink instability is expected to play an important role in determining MHD limits in a tokamak. We have investigated kinks dominantly driven by the current density near the edge. We have designed an experiment that focuses on this instability in NSTX. The aim was to make a plasma with large current densities near the plasma edge and then to vary q_{edge} to study the instability's dependence on the current density and q_{edge}. The current near the plasma edge was varied by varying the I_p ramp-rate. The tool for varying q_{edge} was a controlled ramp-down of the toroidal field. This had the effect of scanning q_{edge} while holding the shape of the current profile approximately fixed. The principal difficulty was in avoiding the coupling to the internal m=1 mode in spite of the early beam heating to hold q_{axis} above unity. A handful of discharges were obtained with clear evidence of external kink activity. Modeling of these discharges confirms the identification of ideal external kinks. In addition there is evidence of locked modes, possibly resistive wall modes, and of coupled internal-external modes. Some observations indicate the presence of helical current filaments, presumably in the non-linear stage of the instabilities development. Details will be presented.
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Scaling and modeling studies of steady-state, high-bootstrap-fraction tokamak discharges*

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A steady-state tokamak reactor must rely on bootstrap current for nearly all of its plasma current. This contrasts with completely non-inductive discharges reported in the contemporary literature, where the bootstrap current fraction is ≈50%, with the remaining current being generated by auxiliary radiofrequency and/or NBI power. At the reactor scale, the required auxiliary power is excessive. This work reports theoretical examination of coupled heat and poloidal field transport physics for non-inductive discharges driven by a power source that only heats and does not directly drive plasma current as is the case for thermonuclear, ECH, and fast wave sources. A simplified uniform-density circular-tokamak model utilizes bootstrap current as a source for the poloidal field and an anomalous thermal diffusivity χ which is constructed to have properties observed in confinement experiments and first-principles simulations: 1) gyroBohm scaling, 2) dependence only on the poloidal magnetic field so that confinement time depends on plasma current and not torioidal field, and 3) a characteristic scale length of $L_T = T/(dT/dr)$.

$$\chi = C_\chi \frac{T^{1/2} r^2 M^{1/2}}{e^2 B_\theta^2 R^2}\left(\frac{\partial T}{\partial r}\right)$$

One adjustable constant $C_\chi \approx 0.05$ is normalized to agree with observations. This reduces the problem to the solution of a nonlinear, second-order ordinary differential equation. The associated eigenvalues determine the plasma temperature and current in terms of plasma size, density, and applied power:

$$T_{keV}(0)^{3/2} = 0.60 \cdot P_{MW}\left(\frac{R}{a}\right)^{1/2} C_{bs}$$

$$I_{p,MA} = (0.15)(C_{bs})^{5/6}(n_{19})^{1/2}(P_{MW})^{1/3} a_m \left(\frac{R}{a}\right)^{1/12}$$

Here, $C_{bs} = 0.8 + 4.0\eta$ determines the bootstrap current level where $\eta = (T/n)(dn/dT)$ is a measure of non-uniform density. Interestingly, the plasma temperature depends only on the applied power and not at all on density, plasma current, toriodal field, or plasma size. The solution also returns current density, q/q(a), and pressure profiles for use in MHD stability analyses. As applied power increases, q* will decrease and $\beta \propto (q^*)^{-2}$ will increase until MHD activity sets in.

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ELMs and constraints on the pedestal: a model based on peeling-ballooning modes*

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Edge localized modes (ELMs) can limit tokamak performance both directly, via large transient heat loads to divertor plates, and indirectly, through constraints placed on the edge pedestal height which strongly impact global confinement. Maximizing the pedestal height (T_{ped}) while maintaining acceptable ELM behavior is a key issue for optimizing tokamak performance. We present a model for ELMs and pedestal constraints based upon theoretical analysis of instabilities which can limit the pedestal height and drive ELMs. The sharp pressure gradients, and consequent large bootstrap currents in the pedestal region can destabilize peeling, ballooning, and kink modes over a wide range of toroidal mode numbers (*n*). The bootstrap current plays a complex dual role in the stability physics, on one hand driving peeling modes, while on the other lowering edge shear and opening second stability access to high-*n* ballooning modes. Consequently, the dominant modes are often intermediate-*n* coupled ``peeling-ballooning" modes, driven by both parallel current (J_{ped}) and the pressure gradient (p'_{ped}) [1,2].

A new MHD stability code, ELITE [2,3], employs a novel finite-*n* extension of ballooning theory [3] which allows accurate and efficient study of $5 \sim< n < \sim 100$ peeling-ballooning modes in shaped toroidal geometry. ELITE, together with low-*n* MHD codes, allows quantitative study of the full relevant spectrum of *n*. ELITE results and analytic insights are used to develop a model of various types of ELMs and stability constraints on the pedestal.

Because of the strong collisionality dependence of the bootstrap current, there is a monotonic relationship between the pedestal temperature and J_{ped} in the regime of interest. Hence, stability boundaries can be transformed from p'_{ped}, J_{ped} space into p'_{ped},T_{ped} space, yielding direct stability limits on the pedestal height at a given pedestal width. The pedestal stability boundary is also a strong function of discharge shape. Improving shaping, for example by increasing triangularity, decouples peeling and ballooning modes, opening up second stability access for high-*n* modes, and leading to a stability boundary at higher p'_{ped}, J_{ped} (and hence higher T_{ped}). Models for various ELM cycles can be envisioned in this p'_{ped}, J_{ped} parameter space. The ELM model takes the lost ELM energy to be proportional to the radial width of the calculated most unstable mode, and this, along with the location in parameter space at which the instability occurs, provides an explanation for large observed variations in ELM behavior.

Model predictions are compared to data from several tokamaks, with encouraging agreement in predicted ELM onset times, ELM depth, and variation in pedestal characteristics with discharge shape. Projections of pedestal stability constraints on T_{ped} for Next Step fusion designs, and nonlinear simulations of peeling-ballooning modes in the edge using the BOUT boundary turbulence code [4] are also presented.

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Ergodization of magnetic flux surfaces due to toroidally asymmetric error magnetic field*

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The enhanced edge confinement of H–mode discharges often leads to large edge density and temperature pedestals with very narrow widths. In these discharges, accurate determination of the edge separatrix location becomes extremely crucial for proper interpretation and understanding of the governing physical processes. The separatrix location is typically determined by extrapolating the external magnetic measurements inward to find the last closed magnetic surface, assuming the discharge is in a 2-D toroidally symmetric equilibrium state. Results from a previous study indicate that the last closed magnetic surface can be significantly modified by an 1–2 cm radial shift of the external coil location [1]. An edge magnetic stochastic region with observable change of the plasma shape is formed. In DIII–D, a six-loop coil set (C-coil) is routinely used to correct the error field due to the toroidal asymmetry of the external shaping coils or to produce an error field for physics study. In this work, we investigate the combined effects of the toroidally asymmetric magnetic field from the main shaping coil as well as the C-coil on the reconstructed magnetic surface. The plasma is assumed to stay nearly axisymmetric. A perturbative method is used to analyze the effects of the externally imposed asymmetric error magnetic field on the magnetic surfaces. The 3-D corrections to the flux surfaces are then computed by super-imposing the asymmetric external magnetic field onto the background toroidally symmetric magnetic field due to the plasma using the Green's function approach. To improve the spatial resolution, a high spatial grid 257×257 version of the EFIT equilibrium reconstruction code has been developed to accurately compute the background axisymmetric 2-D equilibrium. Details will be presented.

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Progress Towards Realistic Geometry and Global Implementations of the Summit Gyrokinetic Framework*

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Abstract

The Summit Framework is a gyrokinetic particle-in-cell turbulence simulation environment that incorporates several algorithmic advances including the delta-f solution of the toroidal gyrokinetic Vlasov equation for the ion dynamics, field-aligned "quasi-ballooning" numerical representation and a flux tube simulation domain[1,2]. The ions have equilibrium temperature and density gradients. Self-generated and external flows are included. The Summit Framework, written in Fortran 90, provides a unified object-based environment for sharing common components in a massively parallel setting. Work is underway though the Summit Framework to include kinetic electron models and electromagnetic effects[3,4], realistic magnetic geometry using quasi-ballooning coordinates[2] and global effects under one software environment. This will allow the scientist to choose the physics components (and associated numerical advantages and disadvantages) most appropriate for the given problem at hand. This presentation will report on progress towards realistic geometry and global implementations of the Summit Framework building from the PG3EQ code[1]. Work on general geometry starts with the base code that is electrostatic and the electron response is taken to be adiabatic, with a zero response to the flux surface averaged potential. Serial and parallel versions of the set-up routines based on an interface to EFIT data necessary for realistic equilibria are being retrofitted into the Summit Framework. In addition, ways of covering more of the plasma minor radius within the context of the quasi-ballooning representation are being investigated. Procedures and tests will be reported as available.

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Temperature change effect on minority species rf heating

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Abstract

Although the idea of using the two-ion hybrid resonance for rf heating of the minority species has been around for a long time and been in use in many experiments, the effects of the changing temperature of the minority species on the mode conversion process has not been carefully examined. In this paper it is shown that the behavior of the mode converted ion Bernstein wave not only changes quantitatively as the minority temperature changes, but changes qualitatively, so that the ion Bernstein wave switches sides and changes from a backward wave to a forward wave (or vice versa). For the case with minority ^{3}He in Deuterium, it is shown that as the minority/majority temperature ratio increases, the mode-converted Bernstein wave which begins on the high magnetic field side of the hybrid resonance switches to the low magnetic field side as the ratio exceeds 4. After this change, the Bernstein wave propagates towards the minority fundamental resonance, and is absorbed quickly. If the objective were to use this case for rf current drive, the location of the driven current would depend strongly on the temperature ratio, and one would need to limit the minority heating to avoid the crossover. For minority Deuterium in ^{3}He, however, the transition is unlikely, occurring with the minority temperature *below* the majority temperature, with the mode converted Bernstein wave virtually always propagating toward the minority fundamental, and thus effectively useless for current drive. The mode conversion analysis which includes only first order terms in λ, the finite Larmor orbit parameter, gives an explicit value for the critical temperature ratio. For high temperature plasmas, the first order analysis is not highly accurate, but the transition still occurs near the critical temperature ratio. Defining $\alpha \equiv \omega_{p2}^2/\omega_{p1}$ and $\mu \equiv \omega_{c2}/\omega_{c1}$ where species 1 is majority species, the critical temperature ratio where the crossover occurs is found to be given by $(T_2/T_1)_c = m_2(4-\epsilon)/m_1(4/\mu^2-1)$ where $\epsilon = (1+\alpha/\mu^2)/(1+\alpha)$.

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First comprehensive DIII–D transport simulations with GYRO*

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Over the course of the last three years, a nonlinear continuum gyrokinetic code GYRO [1] has been developed at General Atomics to comprehensively simulate turbulent transport in tokamaks and allow direct quantitative comparisons to the experimental transport flows using actual experimental profiles and parameters. To arrive at this goal, GYRO not only treats the now standard ion temperature gradient (ITG) mode turbulence, but also treats trapped and passing electrons with collisions and finite beta, and all in real tokamak geometry. Most importantly the code operates on a radial grid at finite relative gyroradius $\rho^* = \rho_s/a$ so as to treat the profile shear stabilization effects which break gyroBohm scaling: $\chi \propto \chi_{gB} = \chi_{Bohm} \cdot \rho^*$. ($\rho_s$ is the ion gyroradius and a is the outer minor radius.) GYRO is designed specifically to treat the dependence of tokamak turbulent transport on ρ^* - a crucial parameter in scaling to reactors. While similar to the continuum gyrokinetic code GS2 [2], which effectively operates at vanishing ρ^* within a cyclic flux tube of infinitesimal small cross section and produces only gyroBohm scaled diffusion, GYRO can operate in a cyclic as well as radially noncyclic tube of finite size. The latter operation allows the addition of profile variation across a radial annulus and introduces a shearing in the mode phase velocities. It is now well established that shear in the equilibrium E×B velocities have a strong stabilizing effect on the plasma turbulence when the velocity shear rate is comparable to the maximum linear mode growth rate [3]. Apart from the E×B rotation driven by toroidal flows, the mode phase velocity shear rates from profile variation are proportional to ρ^* and the linear mode growth rates are independent of ρ^*. The competition between these rates results in the basic paradigm for broken gyroBohm scaling first explored by Garbet and Waltz [4] using a gyrofluid treatment. The paradigm has a mixed power law scaling in ρ^*: $\chi \propto \chi_{gB}(1 - \rho^*/\rho^*_{crit})$. The ρ^*_{crit} for complete stabilization (as in an H–mode edge layer or internal transport barrier) is larger when far above threshold, where growth rates are larger. Thus Bohm scaling is apparent only when χ/χ_{gB} approximates a $1/\rho^*$ dependence over some limited range of ρ^*. The code was recently used to demonstrate this paradigm with circular ITG-adiabatic electron profile simulations [5]. The focus of this poster is on the first use of the full capabilities of GYRO with finite-beta electrons to simulate actual DIII-D ρ^*-scaled L-mode profiles [6] in real geometry [7]. The stabilizing effects of profile variation and a careful treatment of experimental error bars on driving temperature gradients and E×B shear profiles are crucial to any match of simulated transport flows to experimental flows.

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Calculations of Neutral Beam Ion Confinement for the National Spherical Torus Experiment

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The spherical torus (ST) concept underlies several contemporary plasma physics experiments, in which relatively low magnetic fields, high plasma edge q, and low aspect ratio combine for potentially compact, high beta and high performance fusion reactors. One concern for the ST is the confinement of high energy ions in the spherical torus, for the National Spherical Torus Experiment (NSTX)[1], NSTX is a medium-sized, low aspect ratio toroidal device (R=0.85 m, a=0.67m, R/a = 1.26, Ip = 1.4 MA, Bt = 0.6 T) with a 5 MW neutral beam injector (NBI) and a RF antenna capable of delivering 6 MW. 80 keV neutral beam ions at tangency radii of 0.5, 0.6 and 0.7m are routinely used to achieve plasma betas of up to 25%. We examine collisionless losses for the NSTX neutral beam ions.

Several methods are being used to calculate the neoclassical transport and confinement of neutral beam ions, to assess the heating of plasma electrons and ions, needed for transport analysis and perfomance studies. Results will be compared for the collisionless losses calculated with the EIGOL[3], GYROXY[4], and CONBEAM[5] codes for a group of NSTX plasmas, which range from 0.6 to 1.0 MA and for toroidal fields of 0.3 to 0.45 T. All these codes include realistic antenna and plasma gap to wall geometries to avoid overestimates of loss. The EIGOL code has predicted prompt losses of 15% or less of beam ions. The CONBEAM code follows ion guiding centers to which is added the edge Larmor radius width, determining loss. CONBEAM predicts losses of from 20% to 50%. Not surprisingly, best confinement occurs at high current and field and for small Larmor radius. GYROXY and EIGOL are being benchmarked for a test 80 KeV, 0.5m tangency radius beam, with an equilibrium taken from an NSTX 23% beta case. The codes are in good agreement: 21% (EIGOL) and 25+/-3% loss (GYROXY) for times of ~ 7.5e-5seconds. For a similar case 26% loss is found by CONBEAM. The roles of nonadiabaticity, first orbit and delayed losses, as well as collisional effects will be examined.

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Kinetic Stability of the Field-Reversed Configuration [1]

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Abstract

New computational results are presented which advance the understanding of the stability properties of the Field-Reversed Configuration (FRC). We present results of hybrid and two-fluid (Hall-MHD) simulations of prolate FRCs in the strongly kinetic and small-gyroradius, MHD-like regimes. The n=1 tilt instability mechanism and stabilizing factors are investigated including effects of the particle loss along the open field lines and Hall stabilization. Previous calculations demonstrated a significant reduction in the linear growth rates in prolate FRCs with $E \gtrsim 4$ due to kinetic effects [1,2], and a nonlinear saturation of instabilities for $\bar{s} \lesssim 2$ [3], where E is the separatrix elongation, and $\bar{s}$ is a kinetic parameter which measures the number of thermal ion gyro-radii in the configuration. Analysis of the simulation results for small $\bar{s}$ shows that a relatively small fraction of resonant particles contributes significantly to the energy balance, and is important for maintaining the tilt instability in the large gyroradius regime. The nonlinear saturation occurs due to wave-particle trapping, and the nonlinear deviation of the ion distribution function from a local Maxwellian. Such saturation explains the observation in the low $\bar{s}$ experiments of initial $n = 1$ tilt motion that does not result in total loss of confinement. However, the reported FRC stability for larger values of $\bar{s}$ ($\bar{s} \gtrsim 4$) has not been explained so far. Our hybrid simulations with larger values of $\bar{s}$ (small gyroradius regime) and loss boundary conditions show that the particle loss has a destabilizing effect on the $n =$ 1 tilt mode. For $\bar{s} \gtrsim 6$, the linear growth rate is very close to the MHD one, however, the nonlinear evolution is shown to be considerably slower than that in the MHD simulations. Thus, despite the loss of about half of the particles, the closed field lines and a field reversal of $B_z \approx -0.5B_{ext}$ are still present by $t = 32t_A$. Significant ion spin up in toroidal (diamagnetic) direction is also observed at $t > 20t_A$ with $V_i \approx 0.3v_A$. Since end mirror coils are likely to improve particle confinement and further slow down the nonlinear evolution, our large-$\bar{s}$ nonlinear results potentially can provide an explanation of the observed FRC behavior for $\bar{s} > 4$ cases. In order to assess the importance of different stabilizing factors, in particular Hall stabilization [4], we have also performed Hall-MHD simulations of the $n = 1$ tilt mode. Calculations with E=6 and elliptical separatrix shape show a reduction of the linear growth rate and a significant change in the mode structure. However, for $S^*/E \gtrsim 3$ this reduction is small ($\lesssim 10\%$) and not sufficient to explain the stability. Thus, finite Larmor radius and other kinetic effects are essential, and a combination of kinetic and nonlinear effects is likely to provide an explanation of the experimentally observed FRC stability properties.

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Numerical Simulations of Compressional Alfven Modes in NSTX[1]

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Abstract

Hybrid MHD/particle ion simulations are performed to study the excitation of Compressional Alfven Eigenmodes (CAE) by resonant interaction with energetic ions in NSTX. Recent experimental observations and analytic calculations [1] suggest that CAE are excited by energetic neutral beam ions during neutral beam injection in NSTX. The modes are predicted to be localized near the plasma edge on the low magnetic field side, and driven unstable through cyclotron resonance with the beam ions. The strong anisotropy in the fast-ion pitch-angle distribution provides the energy source for the CAE instability. In the numerical model, energetic ions are treated using delta-f particle simulations, while the one-fluid resistive MHD description is used to represent the background plasma. The two plasma components are self-consistently coupled using a current coupling scheme. Self-consistent equilibria with anisotropic fast ion pressure has been calculated. It is shown that contribution of the fast ions with energy $E = 80keV$ and density about 3% can be comparable to that of the background plasma, and the equilibrium profiles are significantly modified in the presence of the beam ions. Initial simulation results for CAE will be presented.

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[1] Research supported by U.S. Department of Energy

SEL: A New 3D Adaptive-Grid Spectral Element Code for Macroscopic Modeling of Magnetic Fusion Plasmas

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We describe a new 3D adaptive grid code, eventually intended for incorporation into the NIMROD simulation code for macroscopic modeling of magnetic fusion plasmas. The code uses the parallelized Newton-Krylov methods of the PETSc library to implement a fully-implicit time step on massively parallel computers. It should enable faster and more accurate treatments of the most challenging and important low-frequency, long-wavelength phenomena in tokamaks, and will also provide new abilities to treat non-axisymmetric systems such as the NCSX stellarator experiment now planned for PPPL.

Spatial discretization uses arbitrarily high-order spectral elements on a structured, adaptive, non-orthogonal flux coordinate grid. Spectral elements are characterized by exponential convergence in the degree of the polynomial. While any basis of the space of polynomials, such as Lagrange interpolatory polynomials with uniformly-spaced nodes, exhibits such exponential convergence, the Jacobi polynomials used in the method have two important advantages: avoidance of near-degeneracy in basis functions; and a natural measure of the local spatial truncation error in the magnitude of the highest polynomial. The latter is used for dynamic adaptation of the grid in the direction normal to flux surfaces, allowing accurate treatment of nearly-singular high-S resistive and neoclassical tearing modes.

The dependent variables are expressed in each grid cell as a linear combination of basis functions,

$$u(x,t) = \sum_{i=0}^{n} u_i(t)\alpha_i(x)$$

The norm of the function in each cell is defined as

$$||u||_n^2 \equiv \sum_{i,j=0}^{n} u_i u_j (\alpha_i, \alpha_j),$$

allowing for non-orthogonal basis functions. The local truncation error,

$$\epsilon_n^2 \equiv \frac{||u||_n^2 - ||u||_{n-1}^2}{||u||_n^2},$$

can vary by many orders of magnitude over the domain. On each step of regridding, the grid cell with the largest error is bisected, and a node is removed from the pair of grid cells with the smallest error, thereby adapting to regions of sharp gradients while conserving the total number of grid cells. In the nonlinear phase of the evolution of tokamak instabilities, the magnetic field does not remain axisymmetric, but evolves into a helical distortion.

Existing fusion plasma simulation codes use static flux-surface-aligned grids based on the initial magnetic field, and cannot adapt to this helical distortion and must eventually lose accuracy. The code uses a variational principle, minimizing the functional

$$\mathcal{L} \equiv \int_\Omega d\mathbf{x} |\mathbf{B} \cdot \nabla\psi|^2$$

to occasionally realign the approximate flux coordinate ψ with the evolving magnetic field $\mathbf{B}$ as well as possible, even in the presence of the magnetic islands and stochasticity characteristic of a fully 3D magnetic field. This alignment, together with the 1D adaptation described above, allows for the most efficient possible adaptation to nonlinear tearing modes. The fully-implicit Newton-Krylov time step of the code allows more accurate treatment of the most difficult problems, including 2-fluid effects, using much larger time steps than semi-implicit method without loss of accuracy. The parallel Newton-Krylov capabilities of the PETSc library, together with new methods of physics-based preconditioning, allow for unprecedented speed and accuracy.

Streamer formation in thermal Rossby wave turbulence

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Abstract

Modulational stability analysis of thermal Rossby wave turbulence is performed for both inviscid, and viscous limits. This analysis provide a simplified model for study of nonlinear structure formation in toroidal drift-ITG at the lowest order with magnetic, curvature and ion diamagnetic drifts. The similarity arising from the common form of nonlinearity, namely advection of vorticity, and analogous mechanisms of instability. Performing a reductive perturbation expansion, an amplitude equation, similar to Nonlinear Schrödinger Equation (NLS) is derived in the inviscid limit. This equation has a different type of nonlinearity than the usual NLS. Phase plane analysis, is performed, and analytical travellling wave solutions of the envelope modulations, together with a localized "spike" solution is found. Using the virial theorem, it is also shown that for a certain range of parameters and sufficient local initial flow, collapsing wave solutions are possible, akin to collapse in Langmuir turbulence. In the viscous limit, for a marginally unstable mode, another envelope equation similar to the Ginzburg-Landau equation, but with a different nonlinearity, is derived. Using the dynamical systems method, fixed points corresponding to nonlinear saturation of the linear growth and the condition for secondary instability is identified.

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Numerical Simulation of Edge Pedestal Formation by X-Transport

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A Monte Carlo guiding center code has recently been developed to simulate the X-transport phenomenon since the introduction of the concept during the last Sherwood Conference [1]. It is found that the main X-transport process occurs by Coulomb scatterings of main ions into and out of the loss cone in the X-region. Possibility for the usual orbit loss has been eliminated by removing the limiters from the simulation domain. Particles are considered to be lost from the system when they enter the divertor chamber. Losses from the collisional X-transport is found to be dominant over losses from the usual neoclassical transport. Density and temperature pedestal formation have been observed under various plasma conditions and device geometries (DIII-D, JET, C-Mod, NSTX, etc). An initial uniform distribution of ions is allowed to relax for 50 toroidal transit periods. In general, a rapid pedestal formation process occurs until about 20 toroidal transit periods, and afterwards a steadier collisional X-transport process begins to set in. A density pedestal gradient is sharper near the separatrix, but becomes milder deeper inside. The kinetic energy distribution is off-Maxwellian in the edge layer. A pedestal in the average kinetic energy penetrates deeper into the plasma than the density pedestal does, and the kinetic energy pedestal is anisotropic between parallel and perpendicular directions: the X-transport yields a broader perpendicular kinetic energy gradient. We find that the energy loss through the X-transport channel may constitute a significant fraction of the H-mode threshold power. Interesting torque generation profiles by the X-transport are also observed, indicating that there is a source of co-momentum in the edge region. A higher power requirement for edge Er generation in a spherical tokamak is also discussed.

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Efficiently Finding Trends in Macroscopic MHD Stability Using Perturbed Equilibria: Application to Toroidal Geometry[1]

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The effects of equilibrium shaping and profile variations on long wavelength ideal MHD instabilities in toroidal plasmas are traditionally studied using numerical parameter scans. Previously, we introduced a new perturbative technique to more efficiently explore these dependencies. Assuming small equilibrium variations, new stability properties are found using a perturbation of the energy principle rather than with a traditional eigenvalue-solver stability code. 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 new stability properties for the perturbed conditions. The stability of the perturbed equilibria is found by mathematically expanding the energy principle and observing the change in δ-W, rather than by re-solving the eigenvalue equation.

With this approach, the effects of parameter variations on stability can be efficiently examined without numerically generating complete MHD 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 how variations in equilibrium parameters impact the ideal MHD stability properties.

Here, we first review the derivation of the perturbed stability analysis and a few applications to screw pinch equilibria. Next, we extend the approach to toroidal geometry using the TOQ and GATO codes. Finally, we apply the perturbative technique to selected D-IIID shots.

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Further work with the Unified Particle-In-Cell and Continuum Method

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Abstract

A new numerical algorithm that encompasses both the δf particle-in-cell (PIC) method and a continuum similar to Denavit's "hybrid" method [1,2] has been further analyzed using a new interpolation schemes [4]. 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.

For M$\rightarrow \infty$ 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=$1, 2, 3, ...$ is permissible. A quadratic weighting interpolation scheme is now implemented [4] 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 ions. We will present results with both linear and quadratic interpolation. We will calculate the effective phase space diffusion by such a repeated interpolation and compare with simulation results [1].

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Zonal Flows and Transport in ITG Turbulence

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Abstract

Nonlinear fluid simulations of self interactive ion temperature gradient (ITG) modes in magnetically confined fusion plasmas, using a reactive fluid closure, exhibit generation of zonal flows. These have been found to inhibit ion heat transport significantly upto certain critical level approximately equal to the nonlinear Dimit's upshift [2]. These flows also cause the damping of long wavelength eddies present in the turbulence. Our simulation results have been in fairly good agreement with the earlier analysis of advanced reactive fluid model, based upon reductive perturbation method, that demonstrates resonant excitation of the zonal flows close to linear marginal stability of the ITG mode [1]. The magnitude of ion heat diffusivity in our numerical simulation as well as analytical work agree reasonably well with the results presented in the cyclone simulation work [2].

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Bootstrap Current Simulation for W7as and W7x[1]

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Abstract

Bootstap current in the stellarators W7as and W7x has been simulated with δf techniques[2] using the Monte-Carlo guiding center code ORBIT[3] which computes the particle trajectories in numerical equilibria. The results are compared to DKES bootrap current coefficients, obtained by solving the linearized drift kinetic equation in the 3D phase space of theta, phi and pitch.

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Stochastic Heating of Ions in NSTX[1]

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Abstract

Ion heating due to Compressional Alfven modes excited by high energy beam particles in NSTX[2] has been investigated with Monte-Carlo techniques using a Lorenz code which computes the particle trajectories in numerical equilibria. Energy transfer rates from the beam particles to the modes and heating rates of the cold background ions through stochastic heating below the cyclotron frequency[3] are examined.

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SIMULATION OF NEOCLASSICAL TEARING MODES COUPLING IN TOKAMAK DISCHARGES USING 3D NONLINEAR CODE NFTC.

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Abstract

The problem of neoclassical tearing modes (NTM) coupling is important in sawteething discharges in tokamak and for active control of instability [1]. Nonlinear self-consistent MHD stability simulations of NTM in tokamak discharges are investigated using the nonlinear three-dimensional MHD code NFTC. Toroidal shaped equilibria with parameters of DIII-D tokamak and ITER parameters is considered.Neoclassical terms are included in the basic dynamic equations of NFTC code for the magnetic field and pressure. An effective fully implicit numerical scheme allows the transport profile to evolve self-consistently with the nonlinear MHD instabilities and an externally applied source such as ECCD. Simulations are directed to the understanding of the mechanism of 3/2,2/1 and 1/1 mode coupling during sawteeth precursors and sawtooth crash periods. A rotational-transform-dependent coupling mechanism between the driver m=1 current helix and the m=2 perturbation of the bulk current surrounding it is investigated.Influence to the critical β and the values of a seed island for NTM excitation due to mode coupling is discussed. Effect of the resistivity and heat conductivity profiles on 2/1 mode destabilization is determined. The effect of differential toroidal plasma rotation on NTM stabilization and mode decoupling is determined. Effectiveness of NTM suppression by the radially localized electron cyclotron current drive (ECCD) is estimated. Required parameters of ECCD such as ECCD magnitude, the CD location with respect to the rational surface, and the width of the spatial distribution are determined for NTM suppression.

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Convective blob transport and the density limit*

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Starting with the physics of ideal MHD in the scrape-off-layer (SOL), and standard sheath boundary conditions, we derive a reduced 2D model (perpendicular to B) for the convection of density blobs.[1,2] In the resulting dimensionless equations (using $\Omega_i t$ and $k_\perp \rho_s$), the density is naturally normalized to a parameter n_G, which has the same B/qR dependence as the Greenwald-Hugill density limit. In the model, n/n_G controls the onset of the electromagnetic (EM) terms, and the small n/n_G limit recovers the previous electrostatic theory.[1,2] The only additional parameters in the model are $q = L_\parallel/R$ and the parallel loss parameter $\alpha = \rho_s/L_\parallel$. The properties of these equations are being studied in the full 2D model[3] and in a further reduced 1D model which is described here.

Following a procedure given in Ref. 4, our 2D equations are reduced to 1D (in the radial coordinate x) by projecting onto two Fourier modes $k_y = 0$ and k. Even this simple model retains the physics of convecting blobs with or without a background density profile and diffusion. As one raises the separatrix density, the nature of the equilibrium profile changes, and an MHD stability limit is eventually reached. Below this limit, we have investigated the response of the system to transient pulses and harmonic oscillations of the separatrix density. At sufficiently high density, a spiky response is obtained due to steepening of the leading edge of the wave-fronts and convection is transiently increased. An analytical shock solution, neglecting polarization drifts, shows that the shock velocity goes to infinity at a critical density.

The model produces qualitative effects which are reminiscent of the experimentally observed phenomena (increased convection, intermittency and finally a hard density limit). However, the interesting behaviors in the model occur at large $n/n_G \sim 4 - 30$. Progress in understanding this discrepancy with experiment will be reported.

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Study of Ideal MHD Ballooning Modes and Stability Boundaries in Three-Dimensional Toroidal Geometry

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A novel method of generating a set of three dimensional MHD equilibria has been developed by varying plasma profiles in the vicinity of a magnetic surface associated with an existing equilibrium [1]. Two free profile functions, in particular the variation of pressure and rotational transform gradients, appear in parametrizing the new class of equilibria. In this work, we examine the effect of the profile variations on ideal MHD ballooning stability properties of three dimensional toroidal equilibria. Marginal stability boundaries are denoted by constructing generalized $s - \alpha$ curves, where s and α are dimensionless measures of the rotational transform gradient and pressure gradient, respectfully. We explore the stability boundaries for configurations of the magnetic field that are relevant to the HSX Stellarator and we study the field line dependence of the eigenvalues of the ballooning equation.

In the case of a three-dimensional model of a quasi-helically symmetric equilibrium localized to one magnetic surface, it is shown [2] that the presence of a symmetry breaking contribution to the local shear can eliminate the second stability region for ballooning modes. Due to the representation chosen for the equilibrium surface, the effects of the flux averaged normal curvature were neglected. We assess the impact a magnetic hill or well has on the ballooning stability boundaries of a quasi-helically symmetric equilibrium. In particular, we explore the possibility of restoring a second region of stability by allowing for a non-vanishing favorable curvature.

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Noncanonical Drift Hamiltonian Dynamics in Perturbed Tokamak Plasmas

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The noncanonical formulation of Hamiltonian mechanics has revolutionized the guiding-center theory of charged-particle motion in magnetized plasmas [1]. The main advantages of the noncanonical formulation include the freedom of choice in adopting physically meaningful coordinates, the existence of a noncanonical variational principle, and the many useful numerical properties (such as a built-in energy-conserving property). The latter property is especially important when guiding-center Hamilton equations are integrated over long drift time scales (i.e., over many bounce and transit periods for trapped and circulating particles, respectively). Despite the usefulness of the noncanonical approach, we note that several attempts [2-3] have been made to find canonical guiding-center coordinates for the sake of analytical simplicity. A noncanonical Hamiltonian formulation for trapped and circulating particle dynamics in perturbed tokamak plasmas is presented. The unperturbed tokamak plasma is assumed to be axisymmetric and low-frequency electromagnetic field perturbations (with characteristic time scales on the order of drift time scales) are considered. Self-consistent effects are included through the variational derivation of reduced Maxwell equations [4]. The asymptotic elimination of the fast gyration and bounce/transit time scales introduces ponderomotive effects (2^{nd}-order in perturbation amplitude) into the Drift Hamiltonian while quasilinear diffusion results from drift resonances.

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Stability of Radial Streamers and Blobs in the SOL Plasma*

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Recent experimental data shows that non-diffusive transport of particles can play a major role in the SOL. This transport may be associated with the propagation of high density plasma filaments or "blobs" that have been observed in experiments with both fast cameras and probes. Previous theoretical work [1, 2] showed that these structures would propagate to the outer wall due to the curvature-drift induced polarization and the associated **E**×**B** radial drift. A remarkable feature of the theory is that experimentally observed properties, such as transport coefficients increasing toward the wall, emerge naturally in the theory as a result of the fundamental relation between the radial convective velocity and poloidal blob size, $v_x \propto 1/y_b^2$.

Here, we are motivated by two questions that arose in the previous work: What is the origin of the blobs? Is there a natural scale for the blobs? Both questions may be related to the question of whether blobs and radial streamers (observed in simulations) are stable on the time scale of their transport. The physical picture is that coherent structures of various sizes arise from turbulence by nonlinear interactions and then decay by secondary instability. The latter instability, which may set the characteristic size of the blobs, is the subject of the present work. Results will be reported on the linear stability analysis of two 1D equilibria: radial streamers and highly elongated blobs. In each case, the instability is driven by curvature and stabilized by FLR, but the details are different from the usual SOL stability problem for two reasons. First, the blob scale lengths are much shorter than the average radial scale length of the SOL density profile. Second, the instabilities of interest have the same scale length as the blob and thus require a global analysis. Progress on the 2D problem (e.g. cylindrical blob stability) will also be reported.

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Sources and Sinks in the Evolution of Zonal Flows in Toroidal Ion Temperature Gradient Turbulence

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Abstract

The relative contributions of various terms to the driving and damping of the zonal flows in toroidal ion temperature gradient turbulence are investigated. A computational diagnostic has been developed that distinguishes linear from nonlinear contributions to the rates of change of zonal-flow modes in gyrokinetic simulations. This is being applied to simulations using several widely studied sets of parameter values and the results are being compared with expectations from the Rosenbluth-Hinton-Waltz theory. The diagnostic is being refined to separate the nonlinear contributions further into the "standard" Reynolds stress, the diamagnetic contribution, and contributions of moments of the distribution function higher than the pressure. Experimental application of an analogous diagnostic in a tokamak is problematic because it involves the calculation of various flux-surface-averaged field quantities from the delta-f particle information. We therefore investigate whether data from smaller regions (e.g., subregions of a poloidal cut or a flux-surface), which would be more amenable to diagnostic techniques available in experiments, can yield similar information about the relative contributions of the various terms.

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Nonlinear Magnetic Reconnection and the Pressure Balance Condition

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Abstract

Recent simulations of magnetic reconnection in simple collisionless systems (eg, those involving the merging of two regions of uniform magnetic field) typically lead to an open X-point magnetic geometry with outflow speeds approaching the Alfven speed of the reconnecting field, V_A. Simple continuity arguments then lead to the estimate of the inflow velocity $V_{in} \sim \tan(\theta)V_A$, where θ is the half-angle subtended by the separatrices in the outflow region. Typically, this angle is small ($\theta \sim 0.1$ or less), and as a result, $V_{in} \ll V_A$. In agreement with the simulations, such small inflow speeds can be consistent with force balance in the inflow direction only if the total pressure $p_T = p + B^2/2$ remains approximately constant across the reconnection zone, even in the fully nonlinear phase. Since the reconnecting component of $\vec{B}$ vanishes along the centerline of the reconnection region, its contribution to the total pressure there must be replaced by variations in either the plasma pressure, the guide field component of $\vec{B}$, or both. We explore here the physics that determines these individual profiles, and how the pressure balance condition is actually satisfied. We show that, in the deep nonlinear phase, the profiles across the reconnection zone become independent of the initial conditions of the simulation. In the simplest case in which the values of p and B^2 are initially the same on either side of the layer, we find that the plasma β determines the type of profiles that are generated: at low β, the magnetic field profile becomes nearly force free. In this case, the out-of-plane (guide) component of the field balances the drop in the magnetic pressure due to the vanishing of the reconnecting component and the plasma pressure develops an antisymmetric perturbation across the layer that plays a negligible role in the force balance condition across the layer. At high β, on the other hand, the reverse is true: the plasma pressure balances the reconnecting field and the guide-field component develops a small antisymmetric perturbation that plays a minor role in terms of transverse force balance. The physics behind the antisymmetric components in each case can be traced to the the dynamics of whistler and kinetic Alfven waves in a simple model.

Alfvén Eigenmodes in Shear Reversed Plasmas

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Abstract

Plasma configurations with shear reversal are known to be propitious for creating internal transport barriers in tokamaks. Experiments on JT-60 [1] and JET [2] have shown that these configurations are also prone to excitation of unusual Alfvén eigenmodes by energetic particles. Surprisingly, these modes emerge significantly below the TAE frequency gap, where one would expect them to be strongly damped. The modes often appear in bunches and they exhibit a quasi-periodic pattern of predominantly upward frequency sweeping (Alfvén Cascades) as the safety factor q changes in time. This work presents a theory that explains the key features of the observed unusual modes including their connection to TAE's as well as the modifications of TAE's themselves near the shear reversal point. We interpret Alfvén Cascades in terms of new Energetic Particle Modes [3] localized at the point where $q(r)$ has a minimum. It is essential that energetic particles are not in resonance with the mode but their response is significantly different from that of the background plasma due to the large drift velocity. The mode structure and the mode deviation in frequency from the Alfvén continuum are determined by the local fast particle density gradient at the zero shear point $q(r)= q_{min}$. The mode existence requires this gradient to exceed a certain critical value. Formally, a supercritical gradient gives rise to an infinite set of radial mode numbers. However, only a few lowest radial modes may be observable in experiments since modes with shorter wavelengths are subject to stronger damping. The mode growth rate, associated with resonant energetic particles, can be calculated with the use of perturbation theory. The damping rates due to background plasma can be accounted for in a similar way. Also, the mode saturation level in a weakly nonlinear regime can be calculated straightforwardly. The cascade modes are basically "cylindrical", except near the TAE gap where they involve toroidal coupling of the primarily two neighboring poloidal harmonics (m and m -1). Transition to TAE occurs around $q_{min} =(m-1/2)/n$. The presence of the shear reversal point requires a modification of the standard TAE analysis. Unlike the conventional TAE's, the modified TAE's have neither ballooning nor anti-ballooning symmetry. The relationship between the two poloidal components of their eigenfunction changes with radius. Our analytic theory has been incorporated into a reduced numerical model and verified with full geometry codes. Work is currently underway on extending the numerical model to evaluate the mode growth rates for realistic energetic particle distributions. When combined with the experimental data, this will provide important local information about the safety factor and the energetic particle distribution.

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Interpretation of ECE measurement on MAST

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Extensive data corresponding to ECE measurements are available for MAST in the frequency range 16 to 100GHz. The low magnetic field and high plasma density in spherical tokamaks do not permit the typical radiation of O and X modes from the first 5 electron cyclotron harmonics - only electron Bernstein modes (modes not subject to a density limit), which are converted into electromagnetic waves in the upper hybrid resonance region, can be responsible for the measured radiation.
The good time resolution of ECE measurement (better than 1ms) coupled with the sensitivity of the mode conversion efficiency to the local density gradient - either in the upper hybrid resonance region (for EBW-X process at normal incidence) or in the plasma resonance region (for EBW-X-O process at oblique incidence) - raises the possibility of measuring the time development of the transport barrier density gradient in the H mode regime. Two recalibrations of the measured frequency dependent radiated power must be performed to obtain these very interesting results.
Using the EFIT code to construct the magnetic surfaces, we first determine the spatial localization on the separatrix from which the radiation emanates. Here we "attach" an auxiliary plane stratified slab of plasma where the full wave solution of wave propagation is used for the determination of the corresponding conversion efficiency. From high space resolution Thompson scattering measurements we interpolate the plasma density and temperature in the whole tokamak, and using ray tracing we determine the location of the EBW source on the corresponding harmonics. The information on the localized temperature and the determined conversion efficiency enable us to recalibrate the measured ECE emission coincident with the Thompson scattering density profile measurement. For subsequent times, the profile can be determined from the least square fitting of the power transmission coefficient of the O-mode through the plasma resonance region T:

$$T = \exp\left(-\int_{x_1}^{x_2} k_x \, dx\right)$$

to the recalibrated ECE data, assuming a fixed position for the EBW source. Here k_x is a wave vector of the O-mode which is dependent on the density profile (e.g. cubic with variable coefficients) and $x_{1,2}$ are the corresponding cut-offs.

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Lattice Boltzmann Models for Resistive MHD

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Lattice Boltzmann methods (LBM) provide a mesoscopic solution to nonlinear macroscopic conservation equations. The LBM approach avoids the computationally expensive nonlinear convective derivatives $\mathbf{v}.\nabla\mathbf{v}$ present in the direct CFD solutions. This is particularly important in MHD simulations because of the extra nonlinear terms $\mathbf{v}.\nabla\mathbf{B}$, $\mathbf{B}.\nabla\mathbf{B}$, $\mathbf{B}.\nabla\mathbf{v}$. LBM's which use the linear BGK collision operator produce simple algorithms which lend themselves to ideal parallelization on multiple PE platforms. The LBM models we have constructed for thermal fluid problems scale ideally to the 2048 processors on the NERSC IBM-SP3.

In our application of LBM to MHD we generalize the model of Martinez et.al. (1994) and Dellar (to appear). Instead, we work with the octagonal streaming lattice - a lattice we initially had introduced for thermal problems because of their superior numerical stability properties. By generalizing the BGK collision operator, the resistivity decouples from the viscosity. Moreover, in an incompressible framework, one can enforce the invariance of the scalar density field and eliminate the continuity equation. The remaining momentum and magnetic flux equations are modeled by two vector distribution functions whose zeroth moments define $\rho\mathbf{v}$ and $\mathbf{B}$, respectively. This vector approach reduces the dependence of the transport order convective terms on the streaming vectors thus allowing increased manipulation of the transport coefficients. While this vector-vector method is 33% more computationally expensive than the corresponding scalar-vector model, it is justified by its ability to reach more physically realistic Reynolds and Magnetic Reynolds numbers - a problem which has limited the applicability of LBM to MHD in the past.

We will present simulations for the Orszag-Tang vortex, a set of simple 2D initial conditions characterized by two alternating X and O points of vorticity and four varying current layers. These initial conditions give rise to most of the notable features of MHD turbulence such as selective decay, magnetic reconnection, and the formulation of jets.

A simple model of the resistive wall mode in tokamaks

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A simple set of evolution equations has been derived for the resistive wall mode (RWM) in a large aspect-ratio, rotating, viscous, tokamak plasma. The equations take into account the non-linear deceleration of the plasma rotation generated by mode interaction with both the resistive wall and a static error-£eld. Furthermore, the equations are largely able to explain resistive wall mode data recently obtained from the DIII-D tokamak. In particular, the role of the error-£eld in triggering plasma deceleration is elucidated.

The evolution equations are based on the previously published Fitzpatrick-Aydemir dispersion relation for the RWM [1]. At low plasma dissipation, there are two stable regions in the parameter space of plasma rotation versus plasma stability. The £rst stable region is restricted to relatively low plasma rotation rates, and lies well below the perfect-wall stability boundary. The second stable region only exists above a critical plasma rotation rate, which depends on the dissipation, and extends almost to the perfect-wall boundary. These two regions are separated by a band of instability. The thickness and extent of this band both decrease as the plasma dissipation increases. At high plasma dissipation, the band of instability disappears altogether, and the £rst and second stable regions merge.

It is found that the error-£eld resonance, at which the error-£eld deceleration torque attains its maximum amplitude [2], *does not* generally correspond to a RWM marginal stability curve in parameter space. The reason for this is that the RWM usually possesses a non-zero real frequency at marginal stability. Of course, the error-£eld resonance is associated with the response of the plasma to a *zero frequency* perturbation.

A number of simulations have been performed, using the above mentioned RWM evolution equations, in order to study access to the wall stabilized region in DIII-D. We generally expect a DIII-D plasma to start off well below the no-wall stability boundary, and to access the wall stabilized region via an NBI induced ramp in the plasma β and rotation. Unfortunately, the plasma must cross an error-£eld resonance and (possibly) an unstable region of parameter space in order to achieve this goal. The simulations indicate that this is possible provided that the error-£eld amplitude is not too large. If the error-£eld is too large then the RWM grows to a suf£ciently high amplitude to trigger plasma deceleration, which effectively blocks entry into the wall stabilized region.

The estimated critical plasma rotation frequency in DIII-D needed to stabilize the RWM is about 6 kHz. The estimated RWM amplitude required to trigger plasma deceleration is about 30 G. Finally, the estimated error-£eld amplitude needed to prevent access to the wall stabilized region is about 2 G. These estimate are in broad agreement with experimental observations.

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Progress on electromagnetic gyrokinetic simulations of microturbulence with fully kinetic electrons

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The effects of fully kinetic electrons, including both trapped and passing electrons, on Ion-Temperature-Gradient (ITG) driven turbulence transport are studied using a 3-dimensional gyrokinetic particle code that uses field-line-following coordinates in a flux-tube and the split-weight scheme for the electrons [1, 2]. Simulation shows that the evolution of the zonal mode is not changed by kinetic electrons. The Dimits' shift [3] on the R/L_T scan of turbulence transport is seen, despite significant changes to the linear physics due to trapped electrons. Algorithms for including ion-ion collisions and electron-ion collisions will be described. It was found that electron-ion collisions are important for achieving a saturated steady state of turbulence, suggesting a subtlety previously discussed concerning the role of dissipation in gyrokinetic simulations[4].

The problem of high plasma beta in kinetic simulation of electrons [2] is revisited. A problem arises from the large term, $\beta m_i/m_e A_{\|}$ in the Ampere's law (in dimensionles form) using canonical momentum formulation, $[-\nabla_\perp^2 + \beta \frac{m_i}{m_e}]A_{\|} = \beta \delta j_{\|}$. When $\beta m_i/m_e$ well exceeds $k_\perp^2$, finite β effects cannot be accurately simulated using previous algorithm[2]. Recently, we have applied a number of numerical techniques to improve the accuracy of the simulation, including evaluating the $\beta m_i/m_e$ term using the same discrete representation of marker distribution and the same scattering operation as that used for δf, and consistent representations of field quantities. Finite β effects for the three branches of wave – Alfvén wave, drift wave and ITG – are all accurately observed for $\beta m_i/m_e \geq 20$ in a 3-D shearless geometry. The implementation of the numerical technique in a toroidal geometry will be discussed.

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Convective Density Transport in Tokamak SOL Plasmas by 2D and 3D Simulations*

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Abstract

Reduced ideal MHD system of electromagnetic equations, applied to describe physics of the tokamak SOL and the divertor region[1,2], is further simplified[3] with an ansatz $\Phi(x,y,z,t)=\Phi_0(x,y,t)+\Phi_1(x,y,t)z^2$. That eliminates dependence on the dimension along magnetic field lines and leads to the 2D 3-field time-dependent model, which is solved numerically. Behavior of the seed blob propagation is investigated. Dependence of the radial convective velocity on blob and domain sizes as well as on initial profiles is studied and compared with the analytical estimation and the experimental data[1,2]. Impact of both the vorticity and the plasma density on the convective transport is considered. Behavior of the system near the density limit is analyzed.

We compare the 2D results with 3D blob propagation simulations based on 5-field fluid Braginskii model, realized in the BOUT code[4]. For the purpose, a simplified geometry, such as shifted circular cross sections of the plasma edge and the outer wall with a belt limiter, is used. The results of the comparison will be reported.

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Simulation of tokamak edge plasma transport including anomalous cross-field plasma convection.

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Abstract

Non-diffusive, intermittent, cross-field plasma transport in the scrape-off layer (SOL) has been studied theoretically [1,2] as well as experimentally on many tokamaks, e.g. DIII-D [3], Alcator C-Mod [4], and NSTX. Edge plasma transport simulations have been performed with the two-dimensional multi-fluid code UEDGE for C-Mod [5] and DIII-D [6] divertor tokamaks. As shown, non-diffusive transport must be included in order to explain the radial plasma profiles measured in the SOL. The non-diffusive transport strongly increases the plasma particle and power fluxes to the chamber walls and enhances the recycling of neutral particles in the main chamber.

Based on our results of UEDGE simulations for a series of DIII-D discharges, we describe the effect of anomalous non-diffusive transport on plasma parameters in the divertor and SOL regions. The non-diffusive transport is modelled by UEDGE in terms of time-independent anomalous cross-field convective velocity directed outward [6]. The 2D profile of anomalous convective velocity is adjusted until the simulated radial plasma profiles agree with profile measurements in the SOL and in the divertor as well as with measurements related to the impurities and the recycling of neutral particles (e.g. deuterium line emissivity and gas pressure measurements). Our analysis shows that non-diffusive cross-field transport plays important role in the edge plasma behavior, both in L- and H-mode discharges. This transport has an effect on core plasma fuelling, peak power load on divertor plates, impurity production, and divertor detachment.

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Plasma Wall Interaction Physics in Ignitor*

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Abstract

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 easier 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, for which a divertor is introduced, 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.

In the Ignitor operating scenario of reference, ignition can be reached by ohmic heating only. The edge conditions are characterized by relatively low temperatures and high densities. In high density regimes, an extensive series of experiments has observed a low level of impurity in the plasma core, thanks to both reduced sputtering from the wall and improved screening properties of the adjacent plasma. Radiation losses gain importance in dissipating the power leaving the main plasma and the whole scrape off layer contributes in dispersing the energy of the particles impinging on the material walls, even without the introduction of additional impurities. Therefore, the "extended limiter" solution, with the plasma wetting a large fraction of the first wall surface, has been preferred over that of a traditional divertor configuration. The resulting thermal wall loads are below 2 MW/m^2. Furthermore, the results by the Alcator C-Mod group [1] challenge the standard picture of the divertor as the dominant power and particle sink in plasma regimes like those of Ignitor, a new view of the divertor operation has been presented, and the role played by particle recycling from the main chamber and cross-field diffusion in the scrape-off layer has been pointed out.

Other operating scenarios are possible in Ignitor. The Poloidal Field System can produce X-point configurations in addition to the extended limiter ones, but at lower parameters, e.g., reduced current and smaller cross section. With the available additional RF heating power H-modes regimes should be accessible. The compatibility of fusion burning using this mode of operation with acceptable thermal loads on the first wall tiles has been considered and preliminary analyses [2] indicate sustainable values, as long as the expected radiating edge conditions can be maintained.

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Importance of Non-linear Processes Near the Onset of Internal Modes*

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Meaningful fusion burning experiments require large plasma currents that correspond to relatively low values of the magnetic safety factor, $q(\psi)$, and significant the plasma volumes enclosed by q=1 surface. In fusion ignition experiments designed along presently known lines, the ideal modes m=1, n=1 is at best either weakly unstable or close to marginal stability, due to the high values of the plasma pressure that need to be achieved. On the basis of the characteristic form of the equations that describe the transition of the radial profile of this mode at the q=1 surface, non-linear effects near marginal stability are shown to be important even for quite low values of the mode amplitude. Thus the effective instability threshold is re-evaluated by using the 3D MHD initial value code M3D [1]. A discussion is given for the plasma regimes relevant to the Ignitor experiment [2].

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Progress in Modelling Angular-Momentum Transport in DIII-D*

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Abstract

Rotation in DIII-D has an important impact on confinement through both the effects of velocity-shear on turbulence-driven transport and its effect on the resistive-wall mode. The modelling of angular-momentum transport has thus been a recent focus of the CalTrans project [1]. Initial results in analysis mode (extracting the angular-momentum diffusivity from DIII-D data) and predictive simulations using the GLF23 transport model were reported in [2,3]. The predictive simulations are run with fully implicit time-stepping and light spatial smoothing of the GLF23 transport coefficients; despite the extreme stiffness of the model, the method appears to be adequately robust. We are extending our analysis-mode capability by incorporating experimental data from several time points, making it possible to extract the angular-momentum pinch velocity independently from and in addition to the diffusivity. In this paper we present our recent results modelling L_z transport in DIII-D shot 106919, including progress in analysis, comparisons of GLF23 predictive runs with the data, and neutral-beam modelling.

* Work performed for the USDOE by U.C. LLNL under contract W-7405-ENG-48.

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Hybrid δf-MHD Simulation of the Internal Kink Mode

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It has long been known that kinetic effects play a vital role in the stabilization of MHD modes[1]. However, most treatment of kinetic particle effects have been limited to simple cases. Important effects such as geometry, nonlinearities, dynamics, and FLR effects are often neglected. The state-of-the-art in MHD simulation is now capable of modelling realistic fusion relevant plasmas and comparing with experimental data. NIMROD is a 3-D, massively parallel MHD simulation that utilizes finite elements and has been successful in modelling nonideal MHD phenomena in axisymmetric plasma devices[2]. The inclusion of δf particles in NIMROD will enable us to study the role of kinetic particles in the stabilization of disruptive MHD modes in devices such as DIII-D. Although finite elements allow for a great deal of flexibility, a conventional PIC scheme is not applicable. We follow the work of Allievi[3] in our application of δf PIC method to finite elements. This poster presents the particular details of the implementation of δf particles in NIMROD, including 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) onto the finite element grid. Parallelization and performance results will also be presented. The initial physics problem that we address is the stabilization of the internal kink mode due to hot particles. Preliminary linear results of the kinetic effects on the growth rate of internal kink mode will be presented.

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Hurst-Like Approaches to System Dynamics Characterization

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Abstract

Complex systems produce complex results, and it is often difficult to compare these results (even qualitatively) in their entirety. Quantitative measures which distill one specific quality and express it numerically are sought to aid these comparisons. The standard statistical measures - mean, variance, skewness - are very useful for characterizing the distribution of data, but they say nothing about the dynamics. A hierarchy of measures including the basic statistics as well as frequency spectra, bi-spectra, and correlations can be used to better describe the system, but this is not always possible. In order to add more measures to this list, Hurst exponent analysis has recently been applied to plasma systems. This is very useful and appealing as it is a statistical measure of some dynamical properties, namely the auto- (and potentially cross-) correlation functions. We investigate the possibility of expanding the R/S technique to generate a hierarchy of Hurst-like parameters which will more fully characterize the dynamics of complex systems including plasma systems.

Nonperturbative Study of Thermonuclear Alfvén Instabilities in Next Step Burning Plasma Experiments.

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Abstract

The stability of low frequency shear Alfvén eigenmodes for three major concepts of next step burning plasma experiments (ITER, FIRE and IGNITOR) is investigated by employing the High-n STability code, HINST, where n is the toroidal mode number. As a comparison, JET DT plasma is also included in the study. The HINST code [1] analyzes the stability of low frequency modes such as ballooning and Alfvén modes by computing nonperturbative solutions of high-n eigenmode equations which include effects such as finite ion Larmor radius, orbit width, trapped electrons etc. The TAEs are shown to be unstable locally due to alphas in all the devices under consideration. The TAEs in those devices may be stabilized by neutral beam ions. For larger tokamaks such as International Thermonuclear Experimental Reactor (ITER) the spectrum of unstable TAE modes is shifted to medium-/high-n.

Fusion α-particles will have close to isotropic distribution function, which distinguish Burning Plasma (BP) from present day (PD) experiments. This affects the drive of known instabilities in the plasma, such as Alfvén eigenmodes, fish-bones, and MHD macro-modes. Other important issue relavant to BP is the interaction of alphas with multiple Alfvén instabilities, which are difficult to achieve in PDs. Even with continued progress in PD experiments extrapolation to BP conditions may remain uncertain without BP experiment.

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The Interaction of Energetic Ions and Magnetic Islands in Toroidal Plasmas*

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Abstract

A population of energetic ions can influence the nonlinear dynamics of isolated magnetic islands and affect the torque balance in a toroidal plasma. The self-consistent interaction between an $m \geq 2$ island and an energetic ion population is calculated for a large aspect ratio tokamak plasma. The characteristic island width under study is taken to be large compared to thermal ion orbit sizes but comparable to the energetic ion banana width. For such islands, the energetic ion pressional drift and Landau resonances are important in describing the island/ion interaction. To leading order, the energetic ions equilibrate over the ion drift surfaces. Due to finite magnetic drifts, the ion drift surfaces are shifted relative to the helical magnetic surfaces which describe the magnetic island structure [1]. Drifting of the surfaces through the island region yields current perturbations which influence island dynamics. Additionally, energetic ion wave-particle resonances produce current perturbations that influence the plasma rotation properties [2].

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1D formalism for external ballooning modes

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Abstract

The H-mode confinement of tokamak operation has been widely accepted as a basic scenario of next step devices. The edge transport barrier, responsible for the H-mode confinement, supports a steep pressure gradient near the plasma edge. As observed experimentally, this pressure gradient is limited by the onset of so-called edge localized modes (ELMs). Theoretically, high-n external ballooning modes are widely believed to be responsible for the excitation of ELMs [1]. To investigate the external ballooning modes, considerable efforts have been made previously to generalize the internal ballooning representation to handle the external modes, in order to reduce the 2D eigenvalue problem to an 1D one. The next-order correction for the external ballooning modes was worked out [1], such that its lowest order 1D framework remains basically the same one as the conventional one used for investigating internal ballooning modes. It was realized that this approximation for lowest order treatment might only be good when a very small fraction of the poloidal Fourier modelets extends to the plasma edge. Reference [2] has proposed using complex θ_k, which includes the envelope change to lowest order. Complex θ_k opens a new window to find out the unstable roots in the internal ballooning stable domain with real θ_k. All these 1D theories, however, require the individual Fourier harmonics of the perturbation to vanish at both ends far away from their respective resonance surfaces, including the side toward the plasma-vacuum interface. This boundary condition imposed on the vacuum side is not supported by physics and therefore limits the type of free boundary modes that can be considered. To release this restriction, a new formalism is presented. In our new 1D formalism, the free boundary condition on the side toward the plasma-vacuum interface is made acceptable. The new feature of the current formalism attributes an alternative application of the so-called ballooning invariance [3] to the eigenmode system. Instead of considering the entire radial domain, the consideration is focused only to a single radial interval between two nearby singular surfaces, while the ballooning invariance assumption is applied to connect individual Fourier harmonics at both ends in this interval. Recall that a full 2D problem actually treats the whole radial domain. The current scheme represents, therefore, a narrowing of radial domain consideration to achieve the reduction from 2D to a 1D system. As a comparison, it is pointed out that the conventional ballooning formalism represents a reduction of the multiple poloidal components in the whole radial domain to a single component — i.e., a simplification in the poloidal direction. The advantage of the current approach is that it can be applied to investigate the external ballooning modes, as well as the internal modes, without losing generality with regard to the proper boundary condition at the plasma-vaccum interface. The formalism can be used to investigate various effects on high-n external modes. Preliminary application has been made to investigate the ideal MHD free-boundary ballooning modes. The numerical scheme will be described and results discussed.

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Comparing Helicon Models with Experiments

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Helicon plasma sources are capable of producing high density plasma using steady state solenoid or mirror-like magnetic fields with a wide variety of gases. Power to produce the plasma is supplied by various antenna configurations driven at frequencies typically ranging from 1 to 50 MHz. The ability to obtain high plasma densities with high fractional ionization using readily available, low-cost components makes the helicon a candidate plasma source for many applications including plasma rocket propulsion, fusion component testing, and materials processing. However, their operation can be a sensitive function of the magnetic field strength and geometry as well as the driving frequency, especially when using light feedstock gases such as hydrogen or helium. This sensitivity can make it difficult to design a helicon source with the characteristics required for a specific application without better modeling capability. In this paper, we compare results from a coupled radio frequency and transport model with experiments in the axially inhomogenous Mini-RFTF device. Experimental observations of the radial shape of the density profile can be quantitatively reproduced by iteratively converging an accurate radio frequency (RF) calculation including the RF parallel electric field with a transport equation using reasonable choices for the transport parameters. The experimentally observed transition into the high density helicon mode is also observed in the model, appearing as a nonlinear synergy between radial diffusion, the RF coupling to parallel electric fields near the plasma edge, and centrally deposited helicon waves.

Comparison of turbulence simulation with experiment—issues and discussion

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Abstract

The status of turbulence simulation for realistic experimental cases is discussed. The author's opinions are presented and illustrated with examples. Discussion, argument, and even refutation are welcomed.

There have been great advances in understanding the basic mechanisms of turbulent transport, mediated by plasma flow shear. Transport models that incorporate this understanding are routinely and successfully used to interpret the evolution of experimental discharges. Advances in turbulence simulation have contributed strongly to this understanding and these models. Nevertheless, the correspondence of the simulated local transport fluxes and fluctuation levels to those observed in the experiments has not been quantitatively demonstrated.

In the author's experience with the nonlinear gyro-kinetic continuum code GS2,[1,2] transport fluxes and density fluctuations in DIII-D and Alcator C-MOD are overestimated in the simulation by factors that are hard to reconcile with the observations, even with generous allowances for the error bars. This is true even in regions with small flow shear and lacking a transport barrier. The GS2 code takes account of the detailed plasma shaping and includes the relevant kinetic physics and the zonal flows. In particular, the effects of trapped and passing electrons, with collisions, are strongly destabilizing to the ion temperature gradient (ITG) modes. While most of our simulations are electrostatic, we have done some fully electromagnetic runs[3] that do not mitigate these results.

Thus, we must investigate what is missing from the physics in the simulations that could provide additional stabilization.

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Multi-dimensional wave conversion: a ray-based algorithm

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Abstract

A numerical algorithm is proposed for connecting the incoming and outgoing wave fields in studies of linear conversion. This is the first such ray-based algorithm for wave conversion in multiple spatial dimensions [1]. It is demonstrated that one can directly evaluate all quantities needed for the connection coefficients from the ray geometry. The field structure in the immediate vicinity of the conversion will also be discussed. The ray dynamics is generated using the determinant of the dispersion matrix as the Hamiltonian. Using information available while following an incoming ray, the algorithm automatically detects that the ray has entered a conversion region, evaluates the transmission and conversion coefficients, and launches the transmitted ray. The algorithm does not require any prior knowledge of the geometry of the conversion region. The algorithm is illustrated using a two-dimensional toroidal model with resonant conversion from a magnetosonic to an ion-hybrid wave.

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Monday Afternoon

4:00 PM-6:00 PM

Strathallan Hotel
Living/Canterbury Room

Poster Session 1D

Neutral Effects on Flows and the Radial Electric Field

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Abstract

The presence of neutral atoms at the edge of tokamaks may affect confinement by altering the radial electric field and plasma flow velocity through charge exchange and ionization interactions. Neutral effects dominate over neoclassical processes if the fraction of atoms in the plasma exceeds about 10^{-4}, as is typical in the plasma edge just inside the separatrix. To allow the neutral mean-free path to be comparable with the radial scale length we employ the neutral distribution function obtained from a solution of the neutral kinetic equation obtained by assuming the ratio of the neutral mean-free path to the temperature and density scale length is constant[1]. The resulting neutral distribution function is used to investigate neutral effects on the ion flow and electrostatic potential as this ratio varies from much less than one to order unity. In addition to recovering recent short mean free path results we find that neutral effects on the flow and radial electric field depend sensitively on the poloidal location of the neutrals, especially in a spherical tokamak. It is found that the radial electric field and toroidal flow velocity in a collisional edge plasma tend to be larger if the atoms are concentrated on the inboard side than on the outboard side. This may offer an explanation for recent observations on MAST and COMPASS indicating easier H-mode access when gas is puffed from the inboard side of the tokamak.

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Self-organized compact toroid states with flow

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Self-organization is well known in spheromaks and RFPs. Here the Taylor theory explains many observations, including the structure of the plasma core. Self-organization in other configurations, if it occurs at all, is much less obvious. The possibility of self-organized states with finite beta has attracted attention for more than two decades. An interesting focus for this kind of research is provided by field-reversed configurations (FRC). These curious objects have genuinely high beta and are grossly stable even though they have no standard means of stabilization. Even considering nonstandard effects, an explanation for the stability of FRCs has proved elusive. An interesting conjecture has emerged in recent years that FRCs are self-organized states in which the primary stabilization is provided by flow.[1] Although flow has lurked in the background for many years, *sheared* flow has lately emerged as a key player in such phenomena as the H-mode, reversed-shear, and internal transport barriers.

A revised theory of relaxation is needed. A *two fluid* offers a more general platform for this than single-fluid (MHD). A two-fluid has *two* ideal helicity invariants, one for each species. Minimizing the ordered energy (sum of flow and field energies) leads to two Euler-Lagrange equations that link the flow of each species to the field. These are identical to the double-Beltrami equations of Mahajan and Yoshida.[2] Simple 1D solutions for these "natural" states have been found,[1,2] and more recently 2D solutions for the uniform density case.[3]

Two-fluid stationary-energy states are investigated rigorously by expanding the Euler-Lagrange equations in eigenvectors of the curl operator. These eigenvectors (also called Beltrami functions) form a complete basis set for divergence-free vectors. This analysis is made possible by adopting the familiar artifice of uniform density. Further simplification follows by limiting attention to compact toroid (singly-connected) plasmas. This approach reduces the complicated system of coupled partial differential equations to ordinary algebra. Moreover, the solution spectrum collapses to a set of *double-mode condensates* as had been anticipated.[2] The solutions states appear in multiple families, one subset of which are single-mode condensates. A limiting case of these are the flow-free Taylor states.

Thus there is an infinite set of double- (and single-) mode states that are stationary-energy states of a two-fluid. That only a few, or maybe only one of these is stable suggests that a selection is needed to determine which is the preferred end-state of a self-organization process. For this more than one principle has been suggested. The simplest approach chooses the state with the lowest ordered energy. This follows thermodynamic intuition because the maximal entropy state subject to the constraints has the same Euler-Lagrange equations as the minimum ordered-energy state. However, the state selected by this principle has an extremely fine structure superimposed upon a smooth structure: this is unlikely to be the end-state in real, visco-resistive plasma. An alternative principle is to make a *selection* between the stationary-energy states by choosing the one with a minimum of dissipation driving terms. This approach borrows from both the familiar *selective decay* criterion and the recent *coercive functional* approach of Yoshida and Mahajan.[4] Depending on the values of the two helicities, this predicts generally selects a state with two *smooth* eigenfunctions. A notable result is that the ion helicity proves to be more rugged than the ordered energy, and that such states do *not* generally evolve toward a single-mode, flow-free Taylor state.

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All-Orders Spectral RF Calculations Using Local or "Windowed" Fourier Transforms*

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Abstract

Full-wave spectral models have been developed for rf heating applications in one, two, and three spatial dimensions (1-D, 2-D, and 3-D).[1] These models are based on global Fourier expansions and are valid to all orders in the ratio of the ion Larmor radius to the perpendicular rf wavelength. However, because of the global nature of the Fourier basis set, the calculation of local power deposition ($\partial W/\partial t$) and poloidal force (flow drive) can take much longer than the wave solution itself. In 1-D, it has been shown that an eikonal-based formulation[2] can be used to calculate $\partial W/\partial t$ much more efficiently for certain cases with well-defined modes. However, the extension to 2-D is numerically difficult. Here we investigate an alternate approach that uses local or "windowed" Fourier transforms. The rf fields are expanded in local sets of Fourier basis functions. These local basis sets must be connected by a sufficient number of boundary conditions to ensure continuity of all relevant fields and fluxes. This can be accomplished by combining a series of spatial intervals that overlap by several Larmor radii. Using only the interior (non-overlapping) regions, $\partial W/\partial t$ can be accurately calculated over the entire plasma volume. Results show that with this approach, the time required for the energy absorption and flow drive calculations is reduced by a factor of ~200 in 1-D and ~2,000 in 2-D. In addition, windowed Fourier transforms can be used as a basis set for the numerical wave field solution itself. The advantage is that these transforms yield banded rather than dense solution matrices, and can in principle be used to increase resolution in localized areas. This work is one element of a larger SciDAC project on numerical computation of wave-plasma interactions in multidimensional plasmas.

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Equilibrium, Stability, and Nonlinear Saturation of a Toroidal Plasma with Co-axial Helicity Injection

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The defining feature of the Spherical Torus (ST) concept is a very tight aspect ratio, which places severe limits on the center stack volume. Its full potential as a fusion reactor is difficult to fulfill without non-inductive current drive for startup and sustainment. Co-axial Helicity Injection (CHI) is an attractive concept for non-inductive startup. Understanding the physics of CHI helps predictive modeling, interpretation of experiments, and design optimization.

We report on theoretical analysis and numerical modeling of the equilibrium, stability, and nonlinear saturation of CHI plasmas. Advanced numerical techniques such as the Newton-Krylov method for nonlinear implicit partial differential equation solver; multi-grid preconditioning for fast convergence; and 3D domain decomposition for massively parallel computing, have been incorporated into CHIP (CHI-Petsc) code to understand toroidal plasma dynamics.

The simplest description of a steady-state 2D CHI plasma is a force-free plasma with open magnetic field lines. If one writes the magnetic field in mixed covariant-contravariant form,

$$\mathbf{B} = G(\psi)\nabla\varphi + \nabla\varphi \times \nabla\psi,$$

the force-free equilibrium of a CHI plasma is described by the Grad-Shafranov equation,

$$\Delta^* \psi = -G dG/d\psi.$$

This equation is closed by the integral form of the parallel Ohm's law along an open field line intercepting the electrodes, which relates the net current to the electro-static drive.

The generic state of a force-free open field line equilibrium has current density profile which is peaked at the edge of the injector flux and hollow inside except very close to the divertor plates. The peaking factor is proportional to the magnitude of the current drive, *e.g.* the voltage difference $V(\psi)$. Such a current profile is susceptible to the kink instability.

A more accurate steady-state calculation using initial-value 2D resistive MHD reveals the subtle effect of the plasma flow. Although the $\mathbf{v}_\perp$ associated with resistive decay is small (proportional to η) and a Grad-Shafranov equilibrium is a good description as in a resistive steady state Tokamak, the plasma flow around the absorber can be substantial, as $\eta\mathbf{j}$ is deliberately designed to be small to avoid absorber arching and the strong electro-static drive induces large $\mathbf{v}_\perp$. When this flow extends to the injector flux, it severely violates the force-free assumption and demands the inclusion of the inertia $\mathbf{v}\cdot\nabla\mathbf{v}$ and viscous terms. The consequence is that quantities like $\mathbf{j}\cdot\mathbf{B}/B^2$ are no longer flux functions. Nevertheless, the most crucial feature established in force-free equilibrium calculations, a peaked edge current profile under strong electrostatic drive, remains unchanged with plasma flows.

3D MHD simulations demonstrate that substantial flux closure in the toroidally averaged state can be achieved upon saturation of linear kink instabilities. Flux closure is found to be correlated with an internally localized self-generated negative plasma current that exists in a thin layer, in contrast with the positive plasma current backgroud in the closed flux region. The amount of closed poloidal flux is proportional to the magnitude of the electrostatic drive. A CHI plasma tends to be in a dynamic state, indicating that the time scale of the observed experimental diagnostic signal is representative of the internal MHD dynamics.

Numerical modeling of zero core current density clamping in tokamaks

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Abstract

In recent tokamak discharges with LHCD or bootstrap overdrive during the current ramp-up, core regions of zero current density have been observed [1,2]. There is evidence that such "current holes" have occurred in similar discharges in older experiments as well. These configurations are remarkably stable, having been shown experimentally to persist for several seconds. We have modeled them using M3D, a multilevel physics, parallel processing plasma simulation code [3]. We show that the clamping of the core current at zero is the result of reconnection events following the induction of small negative core currents by the off-axis current drive. As the central current is driven negative, a $q = \infty$ (or $\iota = 0$) surface enters the plasma. This surface is resonant to an axisymmetric $m = 1$ MHD mode (an "axisymmetric sawtooth"). There are two distinct driving terms for this mode. One is the term usually associated with the $n = 1$ kink-tearing mode in a cylinder; the other is purely toroidal and takes the form of a "Shafranov shift" whose magnitude tends to ∞ as $\iota \rightarrow 0$. The amplitude and period of the mode are sensitive to the distance of the $q = \infty$ surface from the magnetic axis. The characteristic scaling behavior of these modes and their relation to sawtooth collapses is examined systematically. Implications for a possible new physics regime of interest for a fusion reactor are considered.

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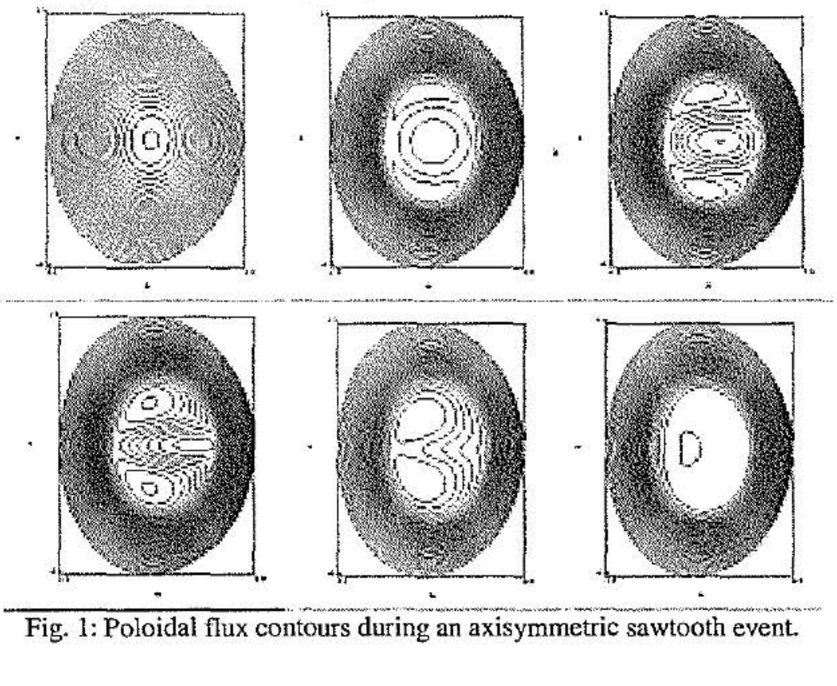

Fig. 1: Poloidal flux contours during an axisymmetric sawtooth event.

NIMROD Simulations of Coaxial Gun Spheromak Formation

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Abstract

We continue to use the NIMROD nonlinear, resistive, magnetohydrodynamic simulation code to study spheromak formation driven by an axisymmetric electrostatic field [1]. When the drive is strong, an n=1 current-driven instability breaks the symmetry and mediates the transition from a pinch to a spheromak-like configuration. Simulations show that the n=1 mode does not require finite pressure in which to occur. If the toroidal modes are suppressed, axisymmetric simulations in a gun geometry show that a spheromak can form as a time-dependent entity. With toroidal modes included and a constant voltage source (instead of a constant current source as in SSPX), a quasi-steady state can be obtained (electrostatic drive balancing resistive losses) with a finite n=1 component and its harmonics. Magnetic field line trajectory calculations (diagnosed with surface of section plots) show that the presence of the n=1 perturbation leads to tangled open field lines. If the voltage is turned off, the decaying plasma can become more axisymmetric and closed flux surfaces can form depending on the details of the configuration. These simulations attempt to model SSPX plasmas where the resistive decay time can be much longer than the pulse duration, which makes the inductive electric field effects important. Many of the macroscopic observables in the NIMROD simulations match typical features in SSPX discharges. We have pulsed the driving voltage to obtain a relatively smaller amplitude of n=1 mode (time averaged). We are also including finite pressure and thermal conduction effects to understand the relation between the field line configuration and the plasma temperature. Our simulations of spheromak formation with relatively realistic resistivity and thermal conductivities, convection and compression can be competitive with Joule heating and thermal conduction in conditions above 20eV for open field-line plasmas in the formation stage. We are using increasingly realistic parameters to simulate SSPX and improved capabilities in NIMROD, viz., higher order basis functions to improve resolution and the inclusion of the continuity equation.

This work was performed at the University of California Lawrence Livermore National Laboratory and was supported by the U.S. Department of Energy under contract W-7405-ENG-48 and at the University of Wisconsin under contract DE-FC02-02-02ER54668.

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Scaling Analysis of Resistive MHD Fluctuations in RFP's and Spheromaks*

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Abstract

We have revisted the Connor-Taylor scaling analysis of resistive MHD fluctuations in a reversed-field pinch. Connor and Taylor found that, through further simplification (dropping of terms) from the equations for radially local fluctuations in large-aspect ratio, they were able to obtain a unique scaling; in particular the confinement time scales as $1/S$ where S is the Lundquist number. We find several additional simplifications which yield unique scaling; in particular, for fluctuations in which the angle variable can be allowed to scale, less simplification is required for unique scalings. All scalings found share the $1/S$ scaling of confinement time, but differ in the scaling of other statistical quantities. We are repeating this analysis for spheromaks, for which the large-aspect-ratio approximation is inapplicable. Instead we perform a local expansion of the resistive MHD equations about a force-free spheromak equilibrium.

*This work was performed under the auspices of the U.S. Department of Energy by the Univ. of CA Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

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Theory of Plasma Confinement in a Levitated Dipole

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Plasma confinement in the field of a levitated ring offers a new approach for magnetic confinement. As observed in space plasmas a dipole confined plasma is intrinsically steady state and can have $\beta > 1$. In a laboratory plasma, losses to supports can be eliminated by levitating a superconducting coil within a vacuum chamber. Compared with a tokamak, a dipole plasma does not require current drive and is free of disruptions. Theoretical studies indicate the following:

- In the "inner" good-curvature region between the internal ring and the pressure peak the plasma is MHD stable. However, drift waves can be present in this region.
- In the "outer" region between the pressure peak and the limiter (or separatrix) the plasma will be stable to both MHD interchange and ballooning when $\delta(pU^\gamma) \geq 0$; $U = \oint d\ell/B$, $\gamma = 5/3$.
- In the outer region drift wave instability can exist for $\eta < 2/3$ ($\eta = d\ln T/d\ln n$). Drift wave stability boundaries are relatively independent of plasma collisionality regime.
- In the outer region convective cells can exist. They can give rise to non-local thermal transport. When $pU^\gamma \approx constant$ the flow is adiabatic and only transports particles (not energy).

These results indicate that a dipole confined plasma can have near-classical confinement, exhibit particle self-fueling without energy degradation and support high β. The pressure gradient limitation requires that a dipole confinement device consists of a superconducting magnet that floats freely within a relatively large vacuum chamber. We will discuss the theoretical under-pinings of the dipole concept as well as the state of completion of the joint MIT/Columbia LDX facility that is presently under construction at the PSFC.

Overview of the Summit Framework: Open-Source Software for Large-Scale Gyrokinetic Turbulence Simulation

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Summit is an open-source framework for both local and global massively parallel gyrokinetic turbulence simulations with kinetic electrons and electromagnetic perturbations [1]. The framework provides a unified object-based environment for sharing common components. Work is underway through Summit to include kinetic electron models with electromagnetic fluctuations [2-6], realistic magnetic geometry using quasi-ballooning coordinates and global effects [7-8]. All these features will be housed within one common software environment. This will allow the scientist to choose the physics models and algorithms that are most appropriate for the given problem at hand. Due to the dimensionality, nonlinearity and use of the latest particle-in-cell delta-f algorithms, Summit is designed primarily for experts in gyrokinetic particle simulation. This means the user base will be small and users will be developers and visa-versa. The primary goal of the project is for gyrokinetic simulators to share and re-use common features, allowing an individual researcher to really focus on solving a key physics/numerical problem of interest. The usual routine of adding one physics detail after another simply to maintain a competitive code is eliminated. The diverse interests and makeup of the software development team provide adequate coverage of the code development tasks. The net result is higher creativity, highly motivated code developers, less overall redundancy and more efficiency. Here, an overview of the project is given, outlining what code development projects are underway and what features will be added in the future. We will also present recent progress in simulating electromagnetic turbulence using a kinetic electron model based on closing zero-inertia drift-fluid equations [4-5]. This model is now running in three-dimensional toroidal flux-tube geometry and benchmarking with low-beta kinetic electron results is underway. This algorithm addresses the physics regime of higher plasma beta, but not so high that compressional Alfven physics needs to be included. Crosschecks of the results from this algorithm against other calculations will be presented. Of particular interest are the competing effects of trapped electrons that increase instability and finite beta that is stabilizing.

*This work is part of the Summit Framework, Computational Center for the Study of Plasma Microturbulence, an Office of Fusion Energy Sciences, United States Department of Energy Scientific Discovery through Advanced Computing (SciDAC) Project.

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Effects of fast particles on internal kink modes in reversed field pinches

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Abstract

Fast ion population in tokamaks is found to have a significant influence on the dynamics of global plasma modes. High energy particles appear to play an essential role in the suppression of sawtooth relaxation oscillations in tokamaks. These particles can also lead to the occurence of fishbone-like instabilities [1]. In a normal mode analysis of plasma oscillations the fast particles are described by drift kinetic equation in which the perturbed electric and magnetic fields are evaluated at the position of the particle's guiding center. In this treatment the effects due to spatial variation of perturbed fields within the gyroradius are not considered. In reversed field pinches (RFP) the magnetic field is an order of magnitude smaller than in tokamaks. The Larmor radius of neutral beam injected particles in the 10 KeV energy range in RFPs is a substantial portion of the minor radius. The perpendicular wave length of global plasma modes is comparable to the Larmor radius of fast particles; thus the finite Larmor radius effects mentioned above can be important. In this study we concentrate on these effects only. We apply a simple constitutive relation without drift contributions for the fast particle dielectric response obtained from the linearized Vlasov equation. We consider cylindrical RFP equilibrium and use the ideal MHD model for the description of the plasma bulk. The changes to the growth rates of the internal kink modes due to the fast particles with large gyroradius are calculated. Preliminary results of this analysis will be presented.

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Calculations of Non-linear and Geometric Effects on Alfvén Wave Current Drive Efficiency

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ABSTRACT

Alfvén Waves (AWs) driven from the edge of an RFP produce a localized current that may be used to control the current profile. This localization of the current drive (CD) effect is determined by the shear AW resonance. We calculate the current produced by the interaction of the AW dynamo generated electric field, $E_f \equiv -V \times B$, with the bulk plasma. We have simulated AWCD self-consistently in both cylindrical and toroidal geometries with the three dimensional initial value resistive-MHD codes, Debs[1] and Nimrod[2]. We present results of an analysis of the efficiency of AWCD as defined by $\eta_{\mathrm{AW}} \equiv < J_{||} > / < P_d >$, where <> denotes a time and flux surface average, $J_{||}$ is the parallel axisymmetric current driven by the wave and P_d is the power deposited by the wave. We will comment of the relative strengths of the dissipation due to the Ohmic and dynamo generate electric fields. Calculations done in cylindrical geometry show that non-linear effects become significant and decrease the efficiency before appreciable net current is generated. Preliminary toroidal calculations will be used to estimate the toroidal enhancement to the AWCD efficiency as predicted by Torasso and Tataronis (2002).

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Kinetic Effects of Hot Electrons on the Stability of a Closed Field Line Plasma*

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Abstract

Motivated by the planned electron cyclotron heating of the Levitated Dipole Experiment, kinetic effects of a hot species on the stability of a Z-pinch plasma have been investigated. A plasma of background electrons and ions with a small fraction of hot electrons is considered for frequencies intermediate between the background and hot species diamagnetic and magnetic drift frequencies. An analysis of the electrostatic dispersion relation shows that when only the modification of quasi-neutrality (charge uncovering) due to the presence hot electrons is retained, then it plays a stabilizing role in portions of MHD unstable region for the frequency range considered. However, destabilization by magnetic drift resonant particles, as well the entropy mode instability[1,2], effectively re-establish the MHD stability boundary. MHD and entropy mode stable operating regions of parameter space are then determined by details of the density and temperature profiles of both hot and background species.

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Application of the NTCC Modular Approach to the TRANSP Code

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The National Transport Code Collaboration (NTCC) project established module library standards in order to promote sharing and community ownership of modules required for predictive integrated modeling. The NTCC standards reflect general tendencies in modern computational physics that are focused on portability issues, as well as some elements of object-oriented programming (OOP), such as inheritance, modularity, and overloading. This report discusses two examples of the application of NTCC standards to the TRANSP code.

The TRANSP code is a Princeton Plasma Physics Laboratory (PPPL) interpretive transport code that has continued to develop and advance since the early 1970s. TRANSP is the primary code used in the fusion community for time dependent analysis of tokamak data. An essential element in the TRANSP code is the inclusion of the neutral beam injection (NBI) physics. The NBI treatment includes the physics of beam deposition, fast ion two dimensional orbiting, beam driven current and momentum transfer, and accounts for particle collisions and charge exchange transport of beam particles. The TRANSP NBI coding uses a Monte Carlo technique and has been tested using experimental data from numerous tokamaks. The treatment of neutral beam injection in the TRANSP code is widely acknowledged to be very accurate. However, the NBI coding was developed as an integral part of the TRANSP code and could not be used in other modeling codes. In order to make the TRANSP NBI package available to the fusion community, the NTCC module library standards have been employed in extracting the NBI coding from the TRANSP code, and the new NBI module has been submitted to the NTCC module library. All external dependencies that existed in the TRANSP code have been replaced using additional NTCC modules. The applied NTCC standards and structure of the NBI NTCC module will be described.

Another example of the application of the NTCC module library is the implementation of two transport models, Multi-Mode and GLF23, in the TRANSP and TSC codes, and the implementation of the GLF23 model in the BALDUR code. The TSC code is a free-boundary transport code that is widely used in the design of tokamaks. The BALDUR code is a integrated predictive modeling code that has been extensively used to predict plasma profiles, which are compared with the experimental data, in order to test the validity of theory motivated transport models. Implementation of the Multi-Mode and GLF23 models adds to the predictive capability of the TRANSP code. Comparative benchmarking between integrated predictive simulations with the BALDUR, TSC, and TRANSP codes will be presented.

Stability of Axisymmetric Plasmas in Closed Line Magnetic Fields*

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Abstract

The stability of axisymmetric plasmas confined by closed poloidal magnetic field lines is considered. The results are relevant to both natural systems, such as plasmas confined by dipolar fields of stars and planets, and laboratory experiments, such as the Levitated Dipole Experiment (LDX) [1], multipoles, Z pinches and field reversed configurations. The ideal MHD energy principle is employed to study the stability of pressure driven Alfvén modes. A point dipole [2] is considered in detail to demonstrate that equilibria exist, which are MHD stable for arbitrary beta [3]. Effects of sound waves and plasma resistivity are investigated for hard core Z pinch and point dipole equilibria by means of resistive MHD theory. Analytic treatment of the hard core Z pinch case demonstrates that there is no resistive instability with a growth rate proportional to a fractional power of resistivity. The point dipole case is being investigated numerically. Gyrokinetic theory is used to study drift frequency modes and their interaction with MHD modes near the ideal stability boundary for 'semi-collisional' plasmas (transit frequency > collision frequency > drift frequency) [4]. Effects of collisional dissipation on drift mode stability are explicitly evaluated and applied to a point dipole and hard core Z pinch.

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The 3-D MHD Dynamics of ac Helicity Injection

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Abstract

Oscillating Field Current Drive (OFCD), a form of ac magnetic helivity injection, is a proposed [1] technique to drive steady-state current in a reversed field pinch (RFP). It was suggested that by oscillating surface poloidal and toroidal voltages out of phase, helicity balance and plasma current can be maintained in a mean steady-state. Because of its low frequency and steady-state features, this technique may be a suitable candidate for current drive in future RFP reactors. Perturbative OFCD has been tested experimentally at ZT-40M RFP experiment. [2] Helicity injection as a means to drive current in magnetic configurations close to Taylor states was investigated by Jensen and Chu. [3] We investigate the full 3-D MHD dynamics of OFCD through nonlinear, resistive MHD computation in a cylinder (the DEBS code) at Lundquist numbers up to 5×10^5. We examine the penetration of driving oscillating fields, the response of the both oscillating mean profiles and the helical tearing instabilities during a cycle as well as the cycle average response. We also study the 1-D response of the plasma in the absence of tearing fluctuations to compare with the full 3-D response and understand the role of resistive MHD instabilities. In the absence of tearing fluctuations a steady-state axisymmetric edge current is driven by the dynamo effect ($< V \times B >_{\|}$) of the axisymmetric oscillating fields. With the full 3-D response, tearing fluctuations relax the driven edge current towards the center (by the tearing mode dynamo), resulting in a steady-state current over the entire plasma cross-section. It is shown that at higher Lundquist number S, the oscillating amplitudes decrease and positive current can be sustained by oscillating fields. Although the computations show a significant amount of current drive by oscillating fields, because of the excitation of edge modes by OFCD, the magnetic fluctuations are enhanced during part of the cycle. However, optimization of the time dependency of the oscillating fields might improve the confinement.

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Distinction of a measured poloidal rotation velocity V_p in a tokamak plasma by corpuscular and CXRS methods from a neo-classical collisionless V_p.

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Abstract.

Tokamak experiments have shown that the V_p measured by the CXRS [1] and CX [2] methods significantly differs from predictions of the neo-classical theory. An explanation of the discrepancy based on the evaluation of the role of the real measurement point location on "banana" trajectories is proposed. The point position depends on experimental set-up and toroidal rotation velocity V_{tor} as well. The example of the ideal CX method [2] for measurement of an ion function distribution shift (and, consequently, V_p) is used. Estimation of the measured velocity $V_{p,meas}$ is done using a model of circular magnetic surfaces and an assumption that the ion distribution is measured at the spatial point (R_0,±z), where R_0 is major tokamak radius, and ±z is a vertical co-ordinate. According to the estimation the $V_{p,meas}$ is:

$$V_{p,meas} \approx V_{p,neo} + \frac{c}{eZB_t} \cdot \frac{T_i}{n_i} \cdot \frac{dn_i}{dr} \cdot \left(1 + \frac{Bt}{Bp} \cdot \frac{V_{tor}}{V_T}\right),$$

where $V_{p,neo} = 1.17 \cdot \frac{c}{eZB_t} \cdot \frac{dT_i}{dr}$ is neo-classical poloidal rotation, V_T is the thermal velocity and the Maxwell ion function distribution for magnetic surfaces shifted in poloidal and toroidal directions ($V_{p,neo}$ and V_{tor}) was used. This simplified formula is obtained from more a general relation by averaging with the Maxwell ion distribution function. The sign of $\frac{B_t}{B_p} \cdot \frac{V_{tor}}{V_T}$ depends on the direction of B_p. So, there are experimental conditions when the term with $\frac{dn_i}{dr}$ determines the measured $V_{p,meas}$. This model can be modified to be applied to the CXRS method. Application of the measured $V_{p,meas}$ for calculating a radial electric field in tokamak plasma is discussed.

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Short wavelength temperature gradient driven modes in tokamak plasmas

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The ion and electron temperature gradient driven turbulence are believed to be responsible for the particle and energy transport in a tokamak. In this work we report on a new type of the temperature gradient driven modes [1] existing in the short wavelength regime. The most important element is a newly found regime of plasma response for large values of the Larmor radius parameter, $k_\perp^2\rho_\alpha^2 \gg 1$, $\alpha = (e, i)$. In this regime plasma density in essential way deviates from usually assumed Boltzmann distribution for $k_\perp^2\rho_\alpha^2 \gg 1$. A standard notion is that for large values of the Larmor radius parameter, $k_y\rho_\alpha > 1$, the density response of the respective plasma component is Boltzmann due to decaying asymptotics of $\Gamma_{0,1}(b_\alpha) \sim 1/\sqrt{b_\alpha}$ for large b_α. This, in fact, implicitly assumes that the ratio of $\omega_{n\alpha}/\omega$ is finite for large $k_y\rho_\alpha$. In turn, this requires that the mode eigen-frequency increases with $k_y\rho_\alpha$ (linearly or faster). The latter is true for drift wave type modes, where $\omega \sim \omega_{*\alpha}$. However, temperature gradient driven modes, are basically sound waves whose frequency is of the order of the transient (or sound) frequency, $k_\parallel v_{th\alpha}$. If the parameter $k_\parallel v_{th\alpha}$ remains constant (so ω is approximately constant), the ratio $\omega_{n\alpha}/\omega$ will increase with $k_y\rho_\alpha$ that compensates for the decaying $1/\sqrt{b_\alpha}$ factor from $\Gamma_{0,1}(b_\alpha)$. Then, for large $k_y\rho_\alpha \gg 1$ in the leading order, one has $\omega_{n\alpha}/\omega\Gamma_0(b_\alpha) = -e_\alpha v_{the}/(2\sqrt{\pi}e\omega L_n)$. In the local approximation one can get for the ion unstable mode is described by $\omega^3 = v_i^3 k_\parallel^2 \left(1 + \frac{\eta_i}{2}\right)/8\sqrt{\pi}L_n$.

New unstable branches exist in the regions $k_y\rho_i \geq 1$ and $k_y\rho_e \geq 1$. While the standard ITG mode has a peak growth rate around $k_y\rho_i \simeq 1$, and the standard ETG mode has a growth rate peaked at $k_y\rho_i \simeq 40$ (corresponding to $k_y\rho_e \simeq 1$), a new ion mode has a maximum growth rate around $k_y\rho_i \simeq 5$, and a new electron mode saturates to a constant growth rate quickly for large $k_y\rho_i > 200$ ($k_y\rho_e > 5$). One of the most interesting features of the short wavelength ion mode is its ability to produce a finite level of the electron transport because the mode growth rate remains finite well into the region $k_\perp^2\rho_i^2 > 1$. It is interesting to note that for moderate plasma pressures $\beta = 1 \div 2\%$ the ion short wavelength mode easily extends into the region $k_\perp \simeq c/\omega_{pe}$.

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Betatau of the strategy of the magnetic fusion reactor

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At present, magnetic fusion is experiencing a period of uncertainty when so much has been already accomplished in science and still the prospects of the fusion reactor are not crystallized. In this regard, it is necessary to realize, that TFTR, JET and JT-60 have culminated the plasma physics stage in fusion. The next step is different not only in terms of size, power and the cost on the facilities, but also in underlying logic of the research. This step will be the first one into fusion reactor physics and, thus, will have different priorities than those we had at the plasma physics stage.

So far, magnetic fusion have shown its unreadiness for the reactor physics phase. Attempts of ITER founders in late 80s to incorporate the reactor orientation to the project (including requirement of electricity production) were not successful. Instead, the final project essentially mimics the plasma physics research devices and ignores the reactor physics logic.

In presentation, the basics of the reactor strategy are outlined, including necessity of high-β plasma, distributed power extraction from the plasma, low-Z and liquid based materials for the first wall structures, high neutron wall loads, low activation, efficient power extraction from the neutron zone, and a reliable reactor stability control.

In these aspects the conventional approach was not lifted to the level of reactor physics. In contrast, as a reaction on deficiencies of ITER, the LiWalls concept was developed in a way consistent with the basic physics of the fusion reactor. Its own critical issues are specified in presentation as a challenge for both theory and experiment. Otherwise, the research path of this concept toward the practical fusion reactor is rather clear. In the plasma physics part it relies on tokamaks experiments with the side wall controlled plasma (e.g., the copper shell walls containing plasma facing lithium layer). In the reactor part it requires (independent) development of the flowing lithium technology together with the FLiBe blanket and a dynamically balanced first wall structure.

Simulations of Energetic Particle Mode In Tokamaks and Stellarators*

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The energetic particle-driven MHD modes are studied using hybrid model of the M3D code[1]. In the hybrid model, the plasma is divided into the bulk part and the energetic particle component. The bulk plasma is treated as a single fluid and the energetic particles are described by gyrokinetic particles. Previously we had shown the results of nonlinear saturation of TAE[2], energetic particle stabilization of internal kink modes and excitation of fishbone[1], and nonlinear saturation of fishbone in a circular tokamak[3]. The previous version of the M3D code was limited to axisymmetric tokamak geometry. In this work, the hybrid code has been extended to full 3D stellarator geometry using unstructured mesh[4] in poloidal planes and finite difference in toroidal direction. This new capability has been applied to study fast ion-driven TAE modes in a two field period compact stellarator. Initial results show an unstable global TAE mode with $n = 1$ as the dominant toroidal mode number. The mode peaks near the $\iota = 0.4$ ($q = 2.5$) surface with real mode frequency close to the the expected TAE frequency $\omega = V_A/(5R)$. The new code has also been applied to study fast ion-driven TAE in high-beta spherical tokamaks. The effects of fluid compression on a fast ion-driven n=1 mode is studied by varying the ratio of the specific heat coefficient Γ. At $\Gamma = 0$ (i.e., zero sound speed), an n=1 TAE mode is found. However, At $\Gamma = 5/3$, the mode frequency of the $n = 1$ unstable mode is reduced to about 1/3 of the TAE frequency. This new mode is located below the beta-induced continuum gap near the center of the plasma and can thus be called Beta-included Alfven eigenmode (BAE). Details of the results will be presented.

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Rotation frequency of magnetic islands

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The effect of the polarization current on magnetic islands has recently been shown to depend on the rotation frequency of the island, ω.[1, 2] Determining this rotation frequency is thus necessary to resolve the question of the stability threshold for neoclassical islands. Recent attempts to calculate ω confronted the obstacle that the torque balance equation used to determine ω in the quasilinear regime is identically satisfied in the nonlinear regime.[3] Here we show that this obstacle can be overcome by solving numerically the momentum and particle transport equations for a locked island as a function of applied torque. The rotation frequency is then determined by the limit where the locking torque vanishes. In the absence of temperature gradient we recover the analytic result that the island may rotate either at the electric drift frequency, or at the electron drift frequency (the sum of the electric and diamagnetic drift frequencies for the electron). Analytic solutions for small ion-sound gyroradius ρ_s suggest that other solutions may exist between these two frequencies. Results for finite electron temperature gradients will be presented.

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Anomalous poloidal momentum transport in toroidal geometry*

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The theory of momentum transport due to turbulence in toroidal geometry including both poloidal and toroidal flows is presented. In previous work the poloidal rotation has usually been assumed to be determined by neoclassical viscous damping. There are circumstances where the poloidal rotation can deviate strongly form its neoclassical value. For example, the transition region between open and closed magnetic surfaces cannot be bridged by neoclassical damping alone [1] but requires a term with the second derivative (normal to magnetic flux surfaces) of the poloidal velocity. The observed poloidal spin-up precursor [2] to some internal transport barriers is another case where strong deviations form neoclassical poloidal flow have been observed. For both of these situations, the contribution to the parallel viscous stress from turbulence must be included in the parallel momentum balance equation departing from the neoclassical ordering assumption. Here, a sytematic derivation of the theory of poloidal momentum transport by turbulent fluctuations is developed. It is shown how both poloidal and toroidal flows can be included in a distribution function which is an exact solution to the Vlasov equation in axisymmetric toroidal magnetic geometry. This equilibrium distribution function is in Maxwellian form with a Hamiltonian that is related to the usual single particle Hamiltonian by a canonical transformation. No restriction on the magnitude of the flow velocities is made. Expanding the distribution function to first order in the gyroradius/gradient length and assuming subsonic flows gives the same velocity moment flows as are found from a perturbation analysis of the Vlasov equation. Including coulomb collisions and the ensemble averaged fluctuation driven contribution to the time evolution of the distribution function, the turbulence induced cross field fluxes can be determined using the neoclassical ordering expansion to second order. In particular, the fluctuation driven poloidal and toroidal viscous stresses are determined. The parallel and toroidal momentum transport equations are derived including the turbulent viscous stresses. The toroidal geometry form for the E×B and parallel flow shear terms including poloidal flow are determined. These are the flow shear terms which influence the linear drive for drift-wave instabilities. The impact of relaxing the constraint of vanishing parallel viscous stress and the inclusion of the viscous stress due to turbulence on neoclassical theory is examined. It is shown that the neoclassical cross field particle flux is not changed. The energy flux and higher moments can be influenced. Since the neoclassical transport is subdominant to the fluctuation driven transport when the turbulence is active and since the standard neoclassical theory is reestablished when the turbulence is inactive, it is not practically required to compute the change in the neoclassical heat flux due to the turbulence in order to model the plasma transport.

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Poloidal Flow in Toroidally Rotating Plasma

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Abstract

In the standard neoclassical theory ion poloidal flow is proportional only to the ion temperature gradient, independent of toroidal rotation, electric field and density gradient. This result is modified by finite orbit effect in a toroidally rotating plasma. It is found, both numerically and theoretically, that toroidal rotation shear and density gradient can drive an additional poloidal flow by modifying the parallel flow. Numerically, neoclassical fluxes and ambipolar electric field of the rotating plasma are calculated self-consistently by δf simulation. Theoretically, a quasi-equilibrium solution of the distribution function for rotating plasma is constructed by making it as close to a shifted Maxwellian as possible, and exactly a function of constant of particle motion. The solution shows a nonzero poloidal flow in a sheared rotating plasma when the temperature is uniform. The simulation and theory are in good agreement. For nonuniform temperature plasma the simulation shows that the poloidal flow is significantly modified from the standard neoclassical result.

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Magnetohydrodynamic Equilibria with Pedestals Induced by Poloidal Flow

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An equilibrium code has been developed to solve the Grad-Shafranov-Bernouilli equations for magnetohydrodynamic equilibria with finite poloidal and toroidal flows. The code uses a multi-grid over-relaxation scheme for the G-S equation combined with a Newton-Rapson solver for the Bernouilli equation. The code is used to study equilibria with a poloidal flow profile ranging from subsonic to supersonic with respect to the poloidal sound speed $C_{s\theta} \approx C_s B_\theta / B$. As the poloidal sound speed is small at the plasma edge where the temperature is low, it is likely that even a slow poloidal flow becomes supersonic. We have studied a class of equilibria with a supersonic flow near the plasma edge and found that such equilibria develop a pedestal in the pressure, density and temperature as well as a shear layer in the velocity profile. The pedestal height is modulated in the poloidal angle; it is maximum on the outboard side ($\theta = 0$) and minimum on the inboard ($\theta = \pm\pi$). The pedestal structure is induced by the "discontinuous" solutions of the Bernouilli equation yielding a subsonic branch that can smoothly merge with the supersonic one only at the inner midplane ($\theta = \pm\pi$). As shown in Ref. [1], a subsonic-supersonic transition at any other poloidal angle $\theta \neq \pm\pi$ occurs discontinuously with a relative jump of the order $\sqrt{\epsilon}\cos(\theta/2)$. The absence of continuous transonic profiles is also an indication that transonic equilibria are bifurcated states. Poloidal rotation also induces a finite toroidal flow with a shear layer in correspondence of the pressure and density pedestals. The large velocity shear (both poloidal and toroidal) occurring in the pedestal region is likely to suppress turbulent eddies and reduce anomalous transport.

The close resemblance of these equilibria with the pedestal structure observed in H-mode operation may suggest that transonic poloidal flow at the plasma edge could be related to the L-H transition process.

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Poloidal Rotations Induced in Tokamak Plasmas by Ion Bernstein Waves

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A poloidal ion sheared flow can be produced by ion Bernstein waves (IBW) propagating in a tokamak plasma near an ioncyclotron resonant layer to stabilise turbulence and consequently improve plasma confinement[1]. A theoretical model of the IBW induced poloidal rotation has been developed in the framework of a kinetic approach based on the second order solution of the Vlasov equation. Consequenltly, the divergence of the second order pressure tensor[2,3] is exactly calculated. In this work, we attempt to explain the IBW induced poloidal rotation in terms of single particle dynamics of resonant (or near-resonant) ions. A numerical code which solves the phase-averaged ions dynamics equations in a space-varying electromagnetic field has been implemented and compared to an analytical solution based on the perturbation theory. Moreover, this code has been coupled to a ray tracing calculation which allows a realistic evolution of the IBW electric field inside the plasma. As a result, the power threshold to suppress turbulence is given as a function of the level of the injected IBW power. Applications to the ongoing IBW experiments on FTU for both hydrogen and deuterium plasma are performed.

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Fluid closure ansatz for collisionless MHD*

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In a recent piece of work, R. Hazeltine and S. Mahajan have derived an attractive fluid model for relativistic magnetized plasmas, based on the constraint of Lorentz covariance and the small gyroradius MHD ordering. The consequences of that formalism are investigated here, only at the level of particle and energy-momentum conservation, by casting the relevant collisionless equations in a form that is nearly isomorfic to the conventional non-relativistic fluid equations under the same small gyroradius MHD ordering. Comparison of the two systems suggests a new ad hoc truncation scheme to close the non-relativistic set. The result would be closed set of non-relativistic collisionless fluid equations in conservation form for the particle energy and momentum densities and the energy flux, allowing for pressure anisotropy and parallel heat flux. The physical implications of the resulting model are explored.

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Collisionless reconnection revisited with a new Computational Framework

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Collisionless reconnection, in addition to being a highly interesting problem of current interest, is also challenging computationally because of the demands it places on resources. We are reexamining this classical problem of high-temperature plasmas using a general, versatile, and efficient framework based on modern computational techniques. The current emphasis of the project is not on new physics but on new computational tools that will help us reproduce some of the well-known results from the field much more accurately and efficiently, both from the point of view of the human user and in terms of computer resources.

Exhausting the Separatrix Flux through the TF coils

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It is shown that the magnetic separatrix field lines can be tailored to exit the tokamak in between the outboard TF coils, so that there is no contact with material surfaces in vessel, and there is negligible non-axisymmetric field error at the plasma. New regimes of profoundly lower recycling may enable order of magnitude increases in tokamak energy confinement, by effectively replacing the usual energy confinement time with the particle confinement time, which can be much longer. Furthermore, ideal MHD stable beta (with a wall) might be increased by a factor of two or more because of changes in the bootstrap current profile and the possibility of slight edge current drive. To achieve this, axi-symmetric poloidal field coils outside the TF coils can bend both legs of the separatrix to exit outboard. Non-axisymmetric coils near the TF coils redirect the field lines to miss the TF coils and pass in between them. Designs have been found where additional axisymmetry from this process can be made much smaller than usual non-axisymmtry of the TF coils, and where there is sufficient clearance for realistic TF coils. Thus, the tokamak can become an open field line system, where the region of closed field lines is essentially axisymmetric, and with open field lines outside which become non-axisymmetric only near the TF coils. Outside the TF coils, there is room for much larger flux expansion and thus reduced heat loading, and the bulk plasma is isolated from neutral transport, easing divertor operation, and enabling much lower recycling.

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Two-Fluid Effects on Instabilities in Realistic Confined Plasma Geometries

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Abstract

A two-fluid plasma model (independently evolving electron and ion fluids connected through the assumption of quasineutrality) for nonlinear numerical simulation of confined plasmas has been implemented in the massively parallel code M3D [1]. The physics in the model extends beyond the standard two-fluid plasma theory, as a necessary step on the way to developing a physically and numerically consistent, nonlinear numerical model for separate electron and ion species [2J. Two-fluid theory typically includes at a minimum the diamagnetic drifts, the ion gyroviscous stress tensor, the Hall **J x B** term and the electron pressure gradient in the Ohm's law, the plasma density evolution, separate electron and ion temperature evolution, and resistivity, collisional viscosity, and perpendicular thermal conduction. Important additional processes are desirable for a consistent dynamical model. These include effects along the magnetic field lines, such as accelerated parallel thermal equilibration (related to Landau damping and also active in MHD), and the neoclassical parallel viscous forces. The massively parallel M3D code has the capability to simulate many different confined plasma configurations, including tight aspect ratio, shaped, and helical torii. The plasma configuration is expected to play a larger role. in two-fluid than MHD dynamics, because of the greater importance of the plasma density evolution and associated compressional parallel dynamics. Results are shown that compare these differences for typical instabilities, such as magnetic islands, in strongly shaped plasmas.

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Influence of $E \times B$ drifts on ELM transport in the scrape-off layer*

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Abstract

Edge Localized Modes (ELMs) in tokamaks result in intermittent injection of substantial amounts of core-edge plasma into the scrape-off layer region. The determination of the peak heat load from this plasma on material surfaces is a key issue for burning-plasma tokamak experiments. According to the observations in existing tokamaks, the ELM heat flux on the divertor can have a profile width about twice that of the steady-state heat flux [1]. When the ELM occurs, the plasma with parameters close to those at the top of the pedestal is assumed injected or connected to the open field-line scrape-off layer (SOL). Here the effects of the ExB drifts and parallel flow dynamics are considered for the injected plasma once it is transported to the open field lines, thus extending previous ELM/disruption modeling [2,3] that neglected $\mathbf{E}\times\mathbf{B}$ drift effects. One such mechanism is as follows: The time for the bulk of the plasma to reach the divertor plate is $\sim L/C_s$, where L is the connection length along B and C_s the sound speed. A poloidal (projected parallel) ambipolar electric field develops given by $E_p \sim T/d$, where T is electron temperature, and d is poloidal distance. The field E_p generates an $\mathbf{E}\times\mathbf{B}$ drift given by $v_d = E_p/B \sim T/(dB)$. Therefore, by this mechanism, the flowing plasma experiences a radial shift given by $s \sim v_d \times L/C_s \sim T/(dB) \times L/C_s = T/(hBC_s)$, where h is the pitch of the field line ($h = d/L = B_p/B_t$ in the divertor). Specific parameters yield the following estimates: For $T \sim 0.5$ keV, $h \sim 0.1$, $B \sim 3$ T, $s \sim 0.008$ m (for a present-day tokamak), whereas, $T \sim 3$ keV, $h \sim 0.1$, $B \sim 5$ T, $s \sim 0.01$ m (for a burning-plasma tokamak). A full assessment of these cross-field drift and parallel current effects is obtained from time-dependent simulations with the 2D UEDGE transport code.

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High beta stability of magnetic dipole configurations

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For ideal MHD flute stability of magnetic dipole equilibria, the equilibrium scale length (L_p) of the plasma pressure gradient is typically required to be comparable to or greater than the radius of curvature ($R_c = 1/\kappa$) of the magnetic field line, $\kappa L_p \geq 1$, resulting in large plasma volumes for laboratory dipole confinement devices. However, sharp pressure gradients ($\kappa L_p < 1$) at the outer flux surfaces may be possible since ideal MHD growth rates can be reduced by finite Larmor radius r_L effects and equilibrium shear flows. These non-ideal effects, which become significant when $r_L^2/\kappa L_p^3 > 1$, have been investigated for arbitrary particle Larmor radius. The analysis was simplified by considering the stability of a cylindrically symmetric Z-pinch, which models the large aspect ratio limit of a laboratory dipole plasma. In the limit $\kappa L_p < 1$, drift reversed particles will be present when the plasma beta is of order unity. The modifications of ideal MHD modes and the criterion for the onset of compressional instabilities are explored in this regime.

Plasma and Momentum Transport Processes in the Vicinity of a Magnetic Island in a Tokamak

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In the vicinity of a magnetic island the toroidal symmetry of the equilibrium magnetic field strength B is broken in tokamaks due to the finite width of the island. The magnetic field strength on a helical flux surface has the form

$$B/B_0 = 1 - [\frac{r_S}{R} \pm \frac{r_W}{R}(\bar{\Psi} + \cos m\alpha)^{1/2}]\cos\theta,$$

where B_0 is B on the magnetic axis, R is the major radius, r_S is the minor radius at the mode rational surface, $r_W = (\delta B/B)^{1/2}(2\, q_S^2 R/m\, q_S')^{1/2}$ is the island width, $\bar{\Psi}$ is the normalized helical flux function, m is the poloidal mode number of the island, $\alpha = \theta - \zeta / q_S$ is the helical angle of the island, $q_S' = \mathrm{d}\, q_S/\mathrm{dr}$, θ is the poloidal angle, and ζ is the toroidal angle. The magnitude of this broken symmetry is order $(\delta B/B)^{1/2}$ where δB the perturbed magnetic field strength that produces the magnetic island. For typical island widths, the broken symmetry is similar to a rippled tokamak with ripple strength of the order of a few percent. This leads to enhanced plasma transport in the vicinity of the island.

The symmetry breaking induced transport fluxes in the collisionless banana regime in tokamaks with an island has been calculated [1]. The ratio of the symmetric breaking induced heat flux to that of the banana regime axis symmetric neoclassical flux is of the order of $(m\delta_w/\varepsilon\nu_*)^2$, where ε is the inverse aspect ratio and ν_* is the ion collisionality parameter which characterizes the onset of the banana regime when $\nu_* < 1$. Electron and ion transport fluxes in the even lower collision frequency regime are also calculated. The magnitude of the island induced transport fluxes can be comparable to that of the anomalous transport fluxes.

It is also shown that these symmetry breaking induced fluxes are driven by the toroidal pressure tensor, *i.e.* $\langle NV\bullet\nabla\Psi\rangle=(c/e)\langle\nabla\Psi\times\nabla\theta\bullet\nabla\bullet(p\mathbf{I}+\pi)/B\bullet\nabla\theta\rangle$ where N is the density, V is the flow velocity, c is the speed of light, e is the charge, Ψ is the helical flux function, p is the isotropic pressure, $\mathbf{I}$ is the identity tensor, and π is the viscous stress tensor. The toroidal momentum can, thus, be affected by the presence of the island. The evolution equation without including the island-wall interaction, island-error-field interaction, and anomalous toroidal viscosity is

$$\partial\langle NMV\bullet\nabla\Psi\times\nabla\theta/B\bullet\nabla\theta\rangle\, \partial t = -\sum_j e_j\langle N_j V_j\bullet\nabla\Psi\rangle/c,$$

where the subscript j indicates the species. Island-induced fluxes can change the toroidal rotation to a new ion temperature-gradient-dependent value.

We also calculate the radial electric field (or the toroidal flow speed) in the vicinity of the island from the momentum balance. We find the momentum equation is a nonlinear function of the radial electric field. It can have bifurcated solutions. Thus, in the vicinity of a magnetic island, plasma confinement can have high-mode (H-mode) like phenomenon. This may play a role for the improved confinement in the vicinity of the lower order rational surfaces observed in several tokamaks [2].

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Magnetic Island Effects On Axisymmetric Equilibria[1]

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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 ρ_s), they can be approximated by a single helical magnetic flux perturbation $\tilde{\psi}(\rho, \theta - \zeta/q_s)$ that is resonant on the mode-rational surface $q_s \equiv q(\rho_s) = m/n$. (In these formulas, ρ and ρ_s are "radial" magnetic 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, introducing 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 surfaces $\psi_0(\rho)$ the helically-resonant magnetic island structure. Then, the pressure becomes constant along helical magnetic field lines and hence $P(\psi_0) \to P(\psi_h)$, where $\psi_h \equiv \int d\psi_0(q/q_s - 1) + \tilde{\psi}$ is the total 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 $|\rho - \rho_s| >> w$) where $P(\psi_h) \to P(\psi_0)$. Upon averaging the magnetic island structure over the helical angle $\theta - \zeta/q_s$, one obtains an "island shape function" $P_w[(\rho - \rho_s)/w]$ 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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Global anisotropy via inverse cascade in turbulence with symmetry breaking

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Abstract

A striking feature of turbulent systems with symmetry breaking is the formation of quasi stationary, global-scale fluctuation structure that imparts anisotropy to the turbulent spectrum. Examples include the creation of zonal flows in drift wave turbulence,[1] the development of long fluctuation scales along the mean magnetic field in MHD turbulence,[2] and the formation of large-scale cyclonic vortical columns in 3D rotating, stratified, non ionized turbulence.[3] In each of these systems the quasi stationary structure corresponds to the wavevector for which the mode frequency becomes zero relative to the frequency of the symmetry breaking process. (In the three cases mentioned above the latter is either the gyro frequency or the rotation frequency.) In situations where the turbulence is initially isotropic and forced at shorter scales, the emergence of these structures requires an energy cascade to large scale, a sense opposite the normal cascade direction.

We describe a spectral transfer theory that potentially unifies systems with the above properties under a single mechanism. This theory calculates nonlinear eigenmode structure as the projection onto a basis set composed of all linear eigenmodes, with amplitude-dependent coefficients determined from statistical closure theory.[4] The excitation of the quasi stationary structure is calculated from the spectral transfer rate of energy into the zero-frequency modes of each eigenmode in the basis set. In absence of dissipation the transfer rate into any mode is inversely proportional to the frequency of that mode. For zero frequency modes the rate is singular. In high Reynolds number turbulence the energy transfer rate to the quasi stationary, zero frequency structure is not singular, but much stonger than that of other (nonzero-frequency) modes, allowing the structure to grow despite a cascade in the opposite direction.

The details of this process are calculated for poloidally uniform zonal flow structure excited in 2D collisionless trapped electron turbulence. Under the electron nonlinearity, energy cascades to small scales, yet zonal modes, which have no linear drive, reach finite amplitude in simulations of saturated turbulence. Using strong turbulence statistical closure theory we solve the two coupled nonlinear evolution equations for both eigenmode branches to determine the eigenmode energies and eigenmode cross correlation for zonal and non zonal spectrum components. The results are: 1) The energy transfer rate to zonal modes exceeds that of non zonal modes by the ratio of diamagnetic frequency to the electron trapping rate. 2) Even though their excitation is entirely nonlinear, the zonal flow modes saturate at the same level as the non zonal, linearly unstable trapped electron modes. 3) The zonal flows are nonlinearly damped. Their level is governed by a balance of the nonlinear transfer rate and a finite-amplitude-induced dissipation rate.

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Squeezed Superbanana and Improved Superbanana Transport in Stellarators

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It is well known that one of the largest particle and heat loss mechanisms in stellarators is due to superbanana diffusive or direct loss. The size of the superbananas usually scales with the minor radius r. Thus, in some stellarator configurations superbananas may not be confined. To improve stellarator confinement, we develop a theory to include the effects of the magnetic well and the radial gradient of the radial electric field which can squeeze the superbananas. We find that the size of the superbananas is reduced by a factor of $S^{1/2}$, where S is the superbanana squeezing factor that depends on the magnetic well depth and the radial gradient of the radial electric field. The corresponding fraction of superbanana is increased by a factor of $S^{1/2}$. The diffusive loss is thus reduced by a factor of $S^{-3/2}$. The effects of the squeezed superbananas on plasma transport are similar to those for squeezed bananas in tokamaks. The definition of the squeezing factor S is, of course, different.

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Stability of Virtual Cathodes on INS-E

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Abstrtact

Recent theoretical work [R. A. Nebel, D. C. Barnes, *Fusion Technology* **38**, 28 (1998)] [D. C. Barnes, R. A. Nebel, *Physics of Plasmas* **5**, 2498 (1998)] has suggested that a tiny oscillating ion cloud (referred to as the Periodically Oscillating Plasma Sphere or POPS) may undergo a self-similar collapse that can result in the periodic and simultaneous attainment of ultra-high densities and temperatures. However, a major uncertainty in this plasma system is the behavior of the electrons. We demonstrate that the required electron cloud (which forms a harmonic oscillator potential) is susceptible to an instability that is analogous to the Rayleigh-Taylor mode present in fluid mechanics. Although no absolutely stable profiles exist, stable profiles that are close enough to the required harmonic oscillator potential are found. A simple two-stream analysis indicates that kinetic effects may add additional stabilization and lead to a critical limit in λ_{Debye}/a above which the virtual cathodes are stable. This result is consistent with previous experimental observations [R. L. Hirsch, *Physics of Fluids* **11**, 2486 (1968)] [D. A. Swanson, B. E. Cherrington, J. T. Verdeyen, *Physics of Fluids* **16**, 1939 (1973)].

The INS-E experiment is presently studying these stability limits. Electrostatic fluctuations are being measured to search for these instabilities, which should have frequencies near the electron plasma frequency [R. A. Nebel, J. M. Finn, Physics of Plasmas 8, 1505 (2001)]. Results will be presented.

Linear Undamped Waves in Near-Maxwellian Plasmas with Applications to Stimulated Raman Scattering in Laser-Produced Plasmas

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Abstract

Experimental observations of stimulated Raman scattering (SRS) in laser-produced plasmas consistently show short-wavelength scattering arising in plasma regions with high temperatures and low densities. According to linear theory the plasma waves involved in SRS should be strongly suppressed by Landau damping in these regions. This has recently led to proposals that small amplitude undamped BGK-type waves are actually involved in the scattering.[1,2] However, it is unclear that the nonlinear relations connecting the amplitudes, waveforms, and distribution functions of BGK waves would be satisfied throughout the initiation and amplification of the SRS process, and furthermore the stability of these waves is doubtful. These considerations make it desirable to investigate the possibility of accounting for the anomalous SRS using linear theory.

Here it is shown (contrary to assertions in the literature[3]) that smooth (analytic) distribution functions arbitrarily close to a Maxwellian can support linear undamped plasma waves. As in the case of BGK waves, the near-Maxwellian distributions are locally flattened near the phase velocity of the wave; however, it is unnecessary to make the additional assumptions required for a BGK equilibrium. The local flattening is the expected result of Landau damping of plasma waves associated with near-threshold SRS. The dielectric function for the locally flattened distribution function can be combined with the electromagnetic wave equation to obtain the dispersion relation for SRS. Since this dispersion relation is analytic, its roots are readily obtained numerically. For typical experimental parameters it is found that locally flattened distribution functions can significantly increase the SRS growth rate and may thus account for observations of anomalous SRS. Constraints on the SRS process obtained from linear theory are compared with those arising in the nonlinear theory.

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Symmetries in Dissipation-Free Linear Mode Conversions*

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Abstract

From general principles of wave energy flow conservation and Onsager-like time reversibility on energy flow, we derive symmetry properties that must be satisfied by the coupling of waves in mode conversion regions of an inhomogeneous plasma confined by a magnetic field [1]. The results are valid for any kinetic (Vlasov-Maxwell) full-wave description of a plasma in a magnetic field with an equilibrium distribution function symmetric in parallel (to the magnetic field) momentum. Thus, without solving the full-wave equations, we obtain the symmetries in transmission, reflection, and mode conversion excitation and emission, for scenarios of interest to plasma heating and current drive, and emission from plasmas. The important physical and practical consequences of the various symmetries will be illustrated for fast Alfvén wave coupling to ion Bernstein waves in the vicinity of an ion-ion hybrid resonance with adjoining cutoffs, and for O and/or X modes coupling to electron Bernstein waves in the vicinity of the upper-hybrid resonance with adjoining cutoffs.

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A Warm Fluid Model of Intense Laser-Plasma Interactions

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Abstract

For the laser-plasma configurations of interest to us (namely, those associated with advanced accelerator concepts), the bulk motion of the plasma is relativistic and the fractional spread in momentum is typically very small. Following up on our previous work on modeling intense laser-plasma interactions with cold fluids[1], we are exploring warm fluid models. These models represent the next level in a hierarchy of complexity beyond the cold fluid approximation. With only a modest increase in computation effort, warm fluids incorporate effects that are relevant to a variety of technologically interesting cases. We present a derivation of the relativistic warm fluid from a kinetic (i.e. Vlasov) perspective by means of non-canonical Poisson brackets. Among the notable features of this model is that the momentum and velocity are no longer parallel and the appearance of a "thermal inertia." The regime covered by this model is a substantial departure from the typical relativistic thermodynamics setting[2] where the velocity spread is assumed to be relativistic and the dynamics are collision dominated. We will provide examples in both one and two dimensions and discuss experimental parameters where these effects are believed to be important.

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Studies of Laser-Plasma Interactions with VORPAL

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Abstract

The dimension-free, parallel, plasma simulation code VORPAL, has been applied to the interactions of laser pulses and plasmas. VORPAL is a hybrid code that allows multiple particle models including a cold relativistic fluid model. The fluid model implements Zalesak's algorithm[1] for flux corrected transport in the density update but solves the momentum advection directly to allow for simulations of zero density. Test particles have been implemented and a fully self-consistent PIC model is nearing completion. Using the fluid model for the plasma, the generation of laser wake fields in two and three dimensions by a high intensity laser pulse is observed. VORPAL simulations are also used to predict the rate of loss of energy by pulse propagation through a plasma due to Raman scattering.

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Reduced Hermite interpolation in many dimensions*

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The MELKES package of codes addresses the problem of efficient numerical interpolation in many dimensions. The numerical methods and codes are described together with some possible applications in fusion science and molecular dynamics. The codes are available through the National Transport Code Collaboration library [1].

The MELKES codes perform "reduced Hermite" polynomial interpolation on rectangular cells in arbitrary many dimensions, following the approach laid out for two dimensions in ref. [2]. Hermite interpolation means interpolation using function values and gradient values, and possibly higher derivatives. If one thinks of using function values and gradients then in one dimension the appropriate local model is the cubic polynomial, which is defined by four coefficients that can be computed from the function values and first derivatives at the two endpoints of an interval. In higher dimensions a "tensor product" form of cubic Hermite (or also cubic spline) interpolation requires, locally, 4^d coefficients where d is the number of dimensions. Reduced Hermite interpolation means, in this context, the use of a multi-dimensional polynomial interpolant that contains fewer terms than the full tensor product form, without reduction in the order of accuracy. In rectangular geometry, reduced Hermite interpolation requires in the cubic case $(d + 1)2^d$ local coefficients, this number being equal to the number of data items for representing the gradient and function value on the vertices of a box in d dimensions. Reduced Hermite interpolation is a completely local method (the interpolant on any box is defined completely by data given on the vertices of that box) and is for that reason ideally suited for use with adaptive mesh refinement.

The MELKES codes grew out of a simpler set of codes written many years ago for reduced Hermite interpolation in three dimensions. The application at that time was the efficient representation of a tokamak magnetic field with error field components, for Monte Carlo simulations of charged particle losses. This kind of application remains of interest, but the present codes have other potential applications to problems involving more than three independent variables. In particular there is the potential for representing a discrete map obtained by orbit integration of drift kinetic or gyrokinetic equations of motion. Depending on how this is done this requires anywhere between 4 and 6 independent variables. The use of reduced Hermite interpolation on such data may greatly speed up Monte Carlo simulations of single particle stochastic transport. Other settings where interpolation in more than three dimensions is of interest include representation of the inter-molecular force field in molecular dynamics calculations.

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Symbolic Cycle Analysis of Turbulent Plasma Fluctuations [1]

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The method for computing symbolic cycles distribution function (SCD)[2] has been applied for the analysis: 1) Langmuir probes fluctuation data (Texas), 2) Mirnov probes magnetic fluctuation data (MIT), 3) Microwave reflectometry fluctuation data (Princeton). Our results demonstrate that approximately the same complex structure of cycles can be computed using time records of different variables. SCD contains information about nonlinear stability of cycles and is much more informative than Fourier spectra.

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Extracting Symbolic Cycles from Turbulent Fluctuation Data[1]

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The method for extracting symbolic cycles from the fluctuation data is presented.[2] For the example of the Lorenz model we demonstrate that approximately the same complex structure of cycles can be computed using time records of different variables. Our method has been applied for the analysis of turbulent fluctuations measured in water flow in a pipe. Even though the fluctuations in the bulk of the water and near the wall of the pipe appears to be very different, the majority of the most stable cycles extracted from the data are identical.

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Drift instabilities in beta>>1, collisional plasmas

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Some versions of Magnetized Target Fusion (MTF) devices will be using a very high beta plasma, with local betas in the range of 10-20 and more. Drift instabilities in such a plasma are electromagnetic and are quite different from the analogous instabilities in a low beta plasma. In a collisionless limit they have been analyzed by El Nadi and Rosenbluth [1] who have shown that the cross-field transport coefficients in such a plasma are of the order of the Bohm diffusion coefficient. On the other hand, high-density plasma in MTF systems is usually strongly collisional in the sense that the drift frequency for the most dangerous large-scale perturbations is smaller than the ion-ion collision frequency, and the mean free path is shorter than the parallel wavelength. This regime is studied in the present paper. We identify the following dimensionless parameters as most important in characterizing the plasma stability with respect to collisional drift modes: $\varepsilon \equiv \rho\lambda/2a^2$, $\mu \equiv \lambda/2aE$, and β, where a is the plasma radius, E *is* the ratio of the plasma length to its radius, ρ is the ion gyroradius, and λ is he ion mean free path. Based on the equations of a 2-fluid dynamics (with the drift-theory ordering, [2]) we derive expressions for the growth rate in the parameter domain characteristic of MTF. In the domain of betas exceeding 4-5, the instability is present in the absence of dissipation, whereas at modest beta the main drive comes from dissipative processes. For the typical parameters of MTF plasmas, the dominant dissipative processes are the ion gyropumping and the parallel electron heat conduction. We show that the plasma is generally more stable than in a collisionless case, and transport coefficients (evaluated in the simple mixing-lenth model, the same as in [1]) fall well below the Bohm level. This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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Angular Momentum Transport in Accretion Disks, Relevant Magnetic Reconnection Theory, and Experimental Observations

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The problem of identifying the collective modes that transport angular momentum in accretion disks, in the outward direction, at a meaningful rate leads to consider plasma disks in which a non-negligible magnetic field is present. In the realistic case where the disk is thin, corresponding to small values of the thermal particle velocity relative to the orbiting velocity, and where the magnetic energy is significant relative to thermal energy [1,2], the only kind of mode that can be excited, as in the case of magnetically (well) confined laboratory plasmas, is of the singular type when described by the linearized ideal MHD approximation. The vertical and toroidal components of the B-field are taken to be comparable. These modes are driven by $d\Omega / dR$, the gradient of the rotation frequency, are non-axisymmetric (disk-bending), involve finite compressibility $(\nabla \cdot \hat{\mathrm{v}} \neq 0)$, and are localized around the radius at which they corotate with the disk. There are two characteristic singularities [1,2] corresponding to the radii where the Doppler shifted frequency equals the slow magnetosonic and the shear-Alfvén frequency. At each singularity, the real and imaginary part of the mode eigenfunction each have a different kind of transition. By contrast, the singular modes found, for instance, in toroidal plasmas, that involve magnetic reconnection have only one singularity and both the real and imaginary part of the eigenfunction have the same transition. The same singular perturbation techniques are used to find the radial profile of the accretion disk modes, adopting appropriate equations, which represent relaxation models for the perturbed plasma pressure or include nonlinear effects, to describe the transition regions. Given the extreme ratio of the macroscopic scale distances to the microscopic ones that characterize astrophysical plasmas, nonlinear effects are shown to be more important than classical dissipative effects even for small values of the mode amplitude. The rate of angular momentum transport, in the same direction as that of its gradient (outward), is evaluated from quasi-linear theory, thus providing an explicit expression for the relevant transport coefficient which is compared to the empirical diffusion coefficients that are commonly used. The mode driving factor involves the finiteness of the plasma temperature in combination with $d\Omega / dR$, a similar feature to that of electrostatic velocity-gradient-driven modes found in laboratory plasmas. Therefore, this theory suggests that accretion is an intrinsically intermittent process, like that of the sawtooth oscillations in magnetically confined plasmas, involving a phase of plasma preheating followed by a precipitation phase where the instability producing the angular momentum transport develops and the plasma drifts toward the accreting object.

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Theory and Numerical Analysis of Singular Modes in Thin Accretion Disks*

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Abstract

A numerical analysis has been carried out for the modes that can transport angular momentum in the presence of significant magnetic energy density relative to the thermal energy density [1,2]. These modes have characteristic multiple singularities in the ideal MHD approximation. Different analytical models that can describe the transition across the singularities have been adopted and investigated. The fact that the spatial profile and spectrum of the modes near marginal stability conditions are independent of the considered modes is verified numerically. Non linear transition equations [3] have been given particular consideration.

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Vlasov-Maxwell simulations of a finite amplitude, longitudinal ion cyclotron wave in a magnetized plasma

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The possibility of generating sheared transverse ion flows in tokamak plasmas seems to be an efficient method to improve their transport properties. The aim af the work is to study the generation of an ion flow due to the injection of a purely electrostatic wave of finite amplitude propagating at right angle with the ambient uniform magnetic field.

The present investigation makes use of a kinetic code which solves the Vlasov equations for electrons and ions, coupled with the Maxwell equations, in 1 spatial and 2 velocity dimensions. A uniformly magnetized slab plasma is considered. The Vlasov equations contain a time and space dependent driving electric field which represents the external pump, acting all along the time integration, which models a monochromatic mode propagating transversely to the external magnetic field. The wave frequency is assumed in the range of the fourth ion cyclotron frequency, and the wavevector is chosen in order to model the excitation of an ion Bernstein wave in a magnetized plasma.

The kinetic approach allows one to investigate the problem from three points of view: the hydrodynamical aspect, the density and field fluctuation spectra, and the kinetic aspect of the interaction in strict sense.

The computation of the first order moment of the ion distribution function shows that indeed a transverse average ion drift velocity is produced which tends to a quasistationary value during the time evolution of the system. The frequency spectra and wavevector spectra give pieces of information on the modes which are excited nonlinearly in the plasma and on their mutual coupling. The time evolution of the ion distribution function shows a kind of "resonant" interaction, even if the parallel component of the wavevector is exactly zero. On the other hand the electron distribution function remains Gaussian-like, while increasing its energy content.

Simulations of Ion Beam-Alfven Wave Dynamics in the Cornell Ion Ring Experiment

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Sensitivity of Alfven wave dynamics to the ion ring and background plasma parameters in the Cornell FIREX experiment are being studied in simulations with 2D particle code FIRE in both (r,z) and (r,theta) geometry. Comparisons are made between the experimental B_dot probe data and the magnetic field in the simulations. Experimental diagnostics of ring proton orbits are also compared with simulations. Factors affecting ring axial formation and azimuthal stability are being discussed.

Tuesday Morning

8:30 AM-9:30 AM

Memorial Art Gallery Auditorium

Review Paper 2A

Adaptive Mesh Refinement MHD for Space Plasma Simulations

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Abstract

Modern approaches to numerical solutions of the MHD equations are extensively based on fundamental mathematical properties of the governing equations. While the different formulations of the MHD equations describe the same physics at the differential equation level, there are important practical differences when one solves discretized forms of the various formulations. According to the Lax-Wendroff theorem [1] only conservative schemes can be expected to get the correct jump conditions and propagation speed for a discontinuous solution. This fact represents an important constraint on global space plasma simulation codes that need to deal with the interaction of hypersonic plasma flows with solar system objects. Another important physics consideration is the presence of regions where the Alfvén speed can approach (or even exceed) the speed of light, while both the bulk and thermal speeds remain non-relativistic. These plasmas need to be described by semi-relativistic MHD, which limits all speeds in the system to the speed of light [2]. A third problem arises from the fact that in the vicinities of the Sun, Earth, Jupiter and Saturn strong intrinsic magnetic fields not only dominate the conserved total energy, but they also have very large gradients near the body representing a major challenge for conservative schemes. Finally, all MHD codes must face the religiously debated issue of how to control the divergence of the magnetic field. We will address these physics issues and their solution in global MHD codes.

In the last decade several developments have led to a new paradigm for numerical simulations of physical systems governed by partial differential equations. They are: (i) the advent of massively parallel computers; (ii) the evolution of solution-adaptive techniques from research topic to practical tool; (iii) advances in basic numerical methods, particularly for hyperbolic conservation laws. Methods that have been developed by the aerodynamics, applied mathematics and DoE communities have recently begun to be implemented in space-physics codes, which solve the governing equations for a compressible magnetized plasma. These techniques include high-resolution upwind schemes, block-based solution-adaptive grids and domain decomposition for parallelization [3]. While some of these techniques carry over relatively straightforwardly to space physics, space physics simulations pose some new challenges. We give a brief review of the state-of-the-art in modern space-physics codes, including validation studies of several of the techniques in common use.

Our group at the University of Michigan has developed a high-performance global MHD code called BATSRUS. We will briefly discuss the main features of the code and present some recent simulation results. These results focus on simulating space weather phenomena, including the generation, propagation and magnetospheric interaction of geoeffective solar storms.

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[2] T.I. Gombosi et al., J. Comp. Phys., submitted (2002)

[3] K.G. Powell et al., J. Comp. Phys., 154, 284 (1999)

Presented at the Sherwood Meeting, Rochester, NY, April 22-24, 2002

Tuesday Morning

9:30 AM-10:00 AM

Memorial Art Gallery Auditorium

Oral Session 2B

Results and Challenges from the NSTX Program

S.M. Kaye for the NSTX Research Team

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The National Spherical Torus Experiment (NSTX) has achieved a high degree of success in establishing the scientific basis for the ST concept. The results have also identified numerous challenges for theoretical work. Aided by up to 5 MW of neutral beam injection and 6 MW of High Harmonic Fast Wave (HHFW) heating, NSTX has achieved toroidal beta values of 25% and global confinement times up to twice those given by L-mode scalings and 1.4 times those given by ELMy H-mode scalings. H-modes have been obtained in the Lower Single Null configuration, but with threshold powers an order of magnitude greater than that predicted by the ITER threshold scaling.

Early implementation of kinetic profile diagnostics has enabled detailed local power balance calculations to be performed. The results of these calculations indicate extremely low ion thermal transport in most NSTX discharges, with the electron conduction being the primary energy loss channel. This result is consistent with inferences of transport barriers from impurity injection experiments and results from gyro-fluid calculations which indicate a suppression of ITG modes but unstable ETG modes. The experimental results may also, in fact, bring into question the use of the classical collisional heating and energy transfer as a basis for the power balance calculations; additional thermal ion heating due to stochastic processes associated with high frequency collective Alfven instabilities and/or ETG modes my have to be considered. In addition, it is expected that the high energy particles used to heat the plasma can exhibit significant non-adiabatic behavior due to their large gyroorbits ($\rho/a \sim 1/3$) in this low field device.

In order for the ST concept to realize its full potential, non-inductive current startup and sustainment must be developed in these overdense plasmas ($\varepsilon >> 1$) plasmas. Co-axial helicity injection (CHI) is being tested as a means of initiating a target plasma non-inductively to currents of order 0.5 MA. To date, 390 kA of toroidal current has been generated by this technique; however, the means to determine whether the current is on closed flux surfaces has been as elusive as understanding the fundamental physics processes that may lead to flux surface closure with CHI. It is also not clear if closed flux surfaces are even necessary for subsequent coupling to inductive or other non-inductive current drive mechanisms. 3D resistive MHD simulations are being used to study the reconnection process that might give rise to the closed flux surfaces.

The challenge to develop non-inductive current sustainment scenarios with HHFW is amplified by both the large field gradients and non-circular shaping in the ST geometry as well as the details of the thermal and fast ion populations. HHFW driven current efficiencies may be reduced by wave absorption on energetic ions present in the plasma due to neutral beam injection, and preliminary data indicates that the interaction between HHFW and NBI can be very strong. Current drive efficiency may also be reduced if the HHFW fields which propagate into the plasma develop a significant negative $k_{\parallel}$ component due to poloidal broadening of the launched wave spectrum.

Other theoretical challenges that relate directly to the interpretation of low aspect experimental results include the role of near Mach unity rotation in equilibrium and stability calculations, the role of the Glasser term in stabilizing neoclassical tearing modes, the effect of strong poloidal mode coupling in characterizing ideal instabilities and the possibility for their stabilization, and the nature of MHD beta and current limits.

This talk will describe the main experimental results with respect to the theory challenges that they have identified.

The work at PPPL was supported by the U.S. Department of Energy Contract No. DE-AC02-76CH03073.

Tuesday Morning

10:30 AM - 12:30 PM

Strathallan Hotel
Living/Canterbury Room

Poster Session 2C

On Sand Piles with Bi-stable Automata Rules - Towards a Minimal Model of Pedestal Formation and Structure

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Very simple bi-stable sand pile model, which incorporates second stability, is proposed. It differs from the standard sand pile models in several aspects: it has two stable and two unstable range of slopes to imitate a mechanism of flux suppression; it has a finite mixing time to allow an interplay between flux deposited and flux transported; and, finally, a variable size of flip for the second instability, which enable any deposited flux to be transported to the edge.

Varying only one parameter, namely, the deposition rate, which mimics the driving power, we observe the transition from critical states that resemble L-mode to critical states that resemble H-mode. This transition is neither gradual nor spontaneous, but bifurcative in nature: pedestal appears only when the deposition exceeds the threshold, once built, pedestal can persist for depositions below the threshold. Thus, edge deposition, mixing length variation, neoclassical diffusion or other complications are not intrinsic for pedestal appearance! The average gradient in pedestal is independent on driving power and, hence, on total flux transported, and stays in the stable range. The transport through the edge resembles ELMs, though the destruction of the pedestal by consecutive ELMS is a rare event.

The L $\rightarrow$ H transition manifests itself in the statistics of fluctuations: the power spectrum changes its frequency scaling from $\omega^{-2.7}$ in L-mode to $\omega^{-1.4}$ in H-mode, even though in both cases the fluctuations are dominated by first instability.

Transport function inherent to our model is well-behaving in L-mode and is strongly non-linear in H-mode, where it branches depending on total flux transported.

A small diffusion makes a pedestal more prominent, but introduces a substantial hysteresis in the transport function.

Sand pile has a complex dynamics: a mixture of random perturbations in the form of random rain of sand and avalanches triggered when slope exceed a critical value. To characterize the dynamics, we calculated correlation dimensions of critical states of diffusive and in non-diffusive sand piles with different number of cells. The general notion is that if the correlation dimension is independent on the phase space dimension, one can say that dynamics is governed by a deterministic chaos, rather than by a random noise, because in the later case the correlation dimension will increase indefinitely.

We found that the diffusion effectively eliminate the randomness. The correlation dimension of critical state of diffusive sand pile is 19 independent on the number of cells, while in the non-diffusive case we see the effect of randomness on a low-dimensional sand pile: the slope is higher at small scales where noise prevails. As the phase dimension increases, the random component goes away and the correlation dimension tends to saturate to a value of 50.

Recent Progress in Magnetic Dynamo Theory

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Abstract

Mean field dynamo (MFD) theory is a leading candidate to explain the amplification of large scale fields in astrophysical rotators (and magnetic field redistribution in Tokomaks) but it has been controversial. The "textbook" MFD theory is kinematic, ignoring the "backreaction" of the growing magnetic field on the velocities driving the field growth. Recently, progress has been made in understanding the backreaction. I will show that interpreting dynamos as non-linear "magnetic helicity transporters" is a successful approach and that semi-analytic modeling of the backreaction based on magnetic helicity conservation can explain the time-dependent, dynamical saturation seen in numerical simulations of box dynamos. I will discuss how this can apply to real systems with open boundaries, and the limitations of previous work.

Anomalous Electron Thermal Transport from Overlapping and Non-Overlapping Drift Magnetic Islands

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Abstract

The origin of the fine-scale turbulence causing anomalous electron thermal transport in tokamaks is not yet fully understood. Observations indicate that tokamak plasmas with internal transport barrier (ITB) can have ion thermal transport reduced to neoclassical levels but the electron thermal transport changes very little. Recent studies of density fluctuations, using reflectometer measurements in the Joint European Torus (JET), indicate that after formation of the ITB, long wavelength modes are suppressed while high frequency short wavelength modes are unaffected[1]. One possible origin of these short wavelength modes is the electron temperature gradient-driven (ETG) instability, which originates as a linearly unstable fluctuation above a certain critical electron temperature gradient. Another possibility is a nonlinear fluctuation known as a drift magnetic island (DMI)[2-6]. Both the ETG and DMI have perpendicular scale lengths on the order of the electron collisionless skin depth. A unique aspect of the DMI is that it is a magnetic island excited even when the tearing mode free energy parameter, $\Delta' < 0$. The parallel current which sustains the island arises from the finite ion gyroradius effect which produces a difference in the perpendicular drift between ions and electrons. A finite thermal gradient produces a real frequency and consequently a Landau resonance layer within the island for weak collisionality[5]. A two-fluid[4] and gyrokinetic[5] steady-state theory for the isolated DMI has recently been compared to results from gyrokinetic particle simulation of the DMI[6]. The gyrokinetic simulation results have characterized the initial growth and saturation phase of the nonlinearly evolving DMI[6]. The interaction between shorter wavelength ETG modes and the DMI has also been addressed in this work, within the sheared slab geometry configuration, and the generation of zonal poloidal flows and fields demonstrated. In this work we extend our previous gyrokinetic simulation study to include the effects of finite electron-ion collisions. Collisions are shown to reduce the plateau formation in the electron distribution function in the vicinity of the Landau resonance layer. For certain poloidal wavelengths this affects the saturated magnetic island width, mainly reducing it. We also examine the three dimensional, multiple helicity interaction case where adjacent magnetic island chains break up the isolated DMI mode structure and leading to large anomalous electron thermal transport. Since the DMI contains both vortical flows and even parity magnetic perturbations, a mixed ExB and magnetic flutter-induced electron thermal transport theoretical model is constructed to explain the simulation results.

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Numerical Simulation of Magnetic Reconnection using AMR

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Abstract

We have applied the Adaptive Mesh Refinement technique (AMR) to provide an accurate and efficient method for calculating magnetic reconnection, including the outer and inner regions. The 2D resistive MHD equations are solved in a rectangular domain. Two plasma columns are allowed to merge and the reconnection rate is calculated [1]. The finite difference equations are obtained using a second order in time and space generalized upwind method within the Chombo[2] framework. We employ the 8-wave formulation [3] suitably complemented with advancing at each time step an extra equation for the poloidal flux. The magnetic field is used for the eigenmode decomposition and the poloidal flux is used to adjust the magnetic field each time step to preserve the divergence-free property. We compare two methods which conserve the total energy and the entropy, respectively. The adaptive mesh is refined in zones where the toroidal current density exceeds certain critical values (See Fig. 1 for an example simulation). The AMR technique is very efficient in resolving both the inner reconnection region and the outer global region with appropriate precision. We demonstrate the expected Sweet-Parker scalings over a wide range of S values. Progress in extending this model to Hall MHD is discussed.

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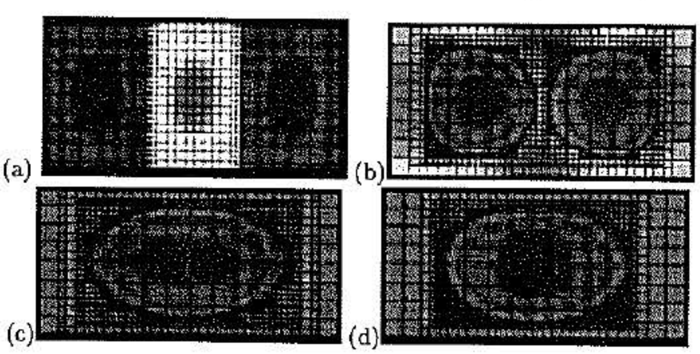

Figure 1: Time sequence of the toroidal magnetic field at various times. (a) depicts the initial condition.

Numerical Studies of Laminar States and PPCD in RFPs

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Abstract

One of the major hurdles for the reversed-field pinch (RFP) configuration is to improve upon energy confinement that is normally dominated by heat flowing along stochastic magnetic field lines. Laboratory observation of quasi-single-helicity states[1] and experimentation with Pulsed Parallel Current Drive (PPCD)[2] show promising evidence of RFPs with improved confinement properties. The current-driven MHD activity has a relatively benign saturation in the former case, while applied inductive effects alter the mean parallel current profile to improve the stability of core-resonant modes in the latter.

Nonlinear nonideal magnetohydrodynamic simulations with the NIMROD code[3] explore the evolution leading to the improved confinement states and the consequences of increasing plasma-β. We find that Hartmann numbers ($H \equiv S/\sqrt{Pm}$) below ~2000 produce laminar behavior in either toroidal or periodic cylinder geometry, consistent with the results of Cappello and Escande. While laminar conditions lead to single-helicity states in the cylinder,[4] geometric coupling in a torus precludes single helicity. This coupling is particularly significant between core-resonant m=1 helicities and the m=0 helicity, leading to stochastic magnetic field when m=0 is resonant in the plasma (reversed states). When the field is not reversed, laminar conditions in toroidal geometry lead to closed helical flux surfaces. The configuration is qualitatively similar to the cylindrical result, but a Shafranov shift is evident. Unlike symmetric RFP equilibria, these helical flux surfaces may have regions of good magnetic curvature. We use our simulation results to explore this feature and its relevance for pressure-driven activity.

RFP simulations with PPCD at β=0 conditions show a global evolution of the parallel current profile with the edge parallel current initially increasing then decreasing in time. The core-resonant modes are suppressed with energies decreasing nearly two orders of magnitude, while edge resonant modes are excited transiently. These effects are also evident in simulation results at nonzero β-values, but the temperature gradient increases simultaneously. With temperature-dependent resistivity included in the simulations, the current profile is then affected by the confinement change. The role of the pressure-gradient drive is isolated numerically for both the core-resonant and edge-resonant modes.

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Modeling of plasma and neutral transport in the stellarator edge*

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Abstract

We are developing tools for modeling of plasma and neutral particle transport in 3D geometry of the stellarator edge region, and for modeling of non-axisymmetric processes in the tokamak edge.

Our 3D neutral fluid model has been developed as a part of the 3D edge fluid code BoRiS [1] which solves the equations for plasma density, momentum and energy. The neutral model includes equations for neutral density and parallel momentum, and the relevant atomic processes of ionization, recombination, charge-exchange and radiation. The addition of neutrals is an important step towards making BoRiS an integrated plasma-neutral model suitable for variety of edge plasma applications. We benchmark the 3D model with the 2D edge code UEDGE and existing 2D neutral Monte-Carlo calculations.

The main focus of the present study is neutral transport in 3D edge plasma. In a stellarator, where the plasma cross-section varies significantly with toroidal position, neutral gas penetration can be enhanced at the elongated cross-sections. Neutral transport can have important consequences for plasma fueling and charge-exchange losses. We use a simplified model of the NCSX stellarator based on available magnetic field data, and the proposed design of NCSX plasma-facing components [2] to assess the effects of recycling neutral particles on the plasma in NCSX.

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Nonlocal simulation of finite β-effects in L-mode edge plasmas

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Edge turbulence in quiescent L-mode discharges of Alcator C-mod has been simulated in a local and nonlocal manner [1] and compared with gas puff imaging data [2] of the turbulent density fluctuations which were available about 1cm outside the separatrix.

The nonlocal simulations exhibit surprisingly large scale eddies generated in a (relatively) steep gradient near the separatrix. The eddies are caused by finite β effects altering drastically the nonlinear saturation amplitude of the resistive ballooning modes [3] although the gradients are everywhere far below the ideal ballooning limit. Since the eddy diameter is of the order of the density gradient length, the turbulent structures reach out into the flat gradient regions far outside the separatrix, where the experimental imaging is carried out. Compared to our preliminary local simulations of this area, this leads to much larger fluctuation amplitudes approaching 100% of the background amplitudes with all implied nonidealities (e.g. a non-gaussian fluctuation statistics, "convective" transport), and an increased scale length of the fluctuations.

The very strong dependence of the turbulence on the gradients (in particular of the density) in this regime requires a rethinking of the way, in which the simulations are set up. It is, e.g., not possible to just use the experimental density and temperature profiles as start-up parameters, since the experimental uncertainties in these (in particular of the gradients) are too large, resulting in either unreasonably large transport or very small transport. It is rather necessary to model the refueling of the particles by neutral ionization and let the profiles adjust consistently, to obtain a reasonable representation of the turbulence.

Such strikingly large fluctuations in the far edge of tokamaks are a widespread though perviously puzzling experimental phenomenon [4].

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Generalized Basis Function Analysis for All-Orders, Full-Wave RF Computations

L. A. Berry, E. F. D'Azevedo, E. F. Jaeger, D. B. Batchelor, and M. D. Carter
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Full-wave radio frequency calculations that model the finite Larmour radius interaction to all orders in $k_{\perp}\rho_i$ to describe, for example, high-harmonic IBWs and fast waves, have become possible in 1-D and 2-D as a result of advances in large-scale parallel computing [1-2]. However, our ability to carry out high-resolution calculations in 2-D, and even moderate-resolution calculations in 3-D, is limited by computing power. The inversion of large, dense matrices is the limiting numerical step. Matrix size and density are driven by the use of Fourier basis functions for the solution. The need for this basis set results from the ability to analytically calculate the plasma response to plane waves. While Sauter and colleagues have developed an approach to calculating the plasma response in configuration space, their technique is computationally intense and cannot be readily extended to higher dimensions [3]. We have developed an alternative technique that models the plasma response in "Fourier" space and then transforms it to configuration space where basis functions such as splines and wavelets can be easily utilized. This has been tested in 1-D for a second-harmonic mode conversion problem and we find that the solution can be represented by fewer than 100 configuration basis functions where 256 Fourier modes are required. A variety of basis functions have been evaluated, and, at least for this problem, second-order B-splines appear to be optimum. Extensions to other RF problems and to 2-D will be pursued. A critical issue will be the a priori (or at least iterative) ability to choose where high resolution is needed in order to obtain a converged solution. This effort is part of a larger SciDAC project on the numerical computation of wave-plasma interactions in multidimensional plasmas.

*Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the U.S. Dept. of Energy under contract DE-AC05-00OR22725.

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Solvers for stiff transport equations

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When a small change in local parameters can cause the diffusion coefficients to vary by orders of magnitude, the transport equation becomes very stiff. This is the case for recent transport models such as IFS/PPPL [1] and GLF23 [2J, which have diffusion coefficients that depend sensitively on the temperature and density profiles. The stiffness makes integration of the transport equation challenging because the size of the timestep is severely restricted by the rapid rate of change of the local parameters.

We will present results from an investigation and benchmarking of a novel iterative implicit finite-difference method. In particular, a comparison will be made with the solver implemented in the NTC physics server.

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Alfven Waves in Gyrokinetic Plasmas*

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It has been found that the noise properties of shear-Alfven waves in gyrokinetic plasmas require the use of split-weight δf scheme[1] in order to suppress the unwanted numerical noise,[2] which can prevent of the proper formations of eigenmodes. Here, we will present two numerical schemes for the simulation of finite-β effects in general toroidal geometry. The first one uses $v_{\|}$ as the phase space variable and, in turn, it requires the integration of certain field quantities along the unperturbed orbit as well as the use the third-order velocity space moments. The second scheme utilizes the canonical momentum, $p_{\|}$, as the phase space variable[3] and uses only second-order velocity moments without the complication of numerical integration. However, the latter faces the potential numerical difficulty of calculating the adiabatic response for the fast particles. Since we are working toward the implementation of these schemes in the global GTC code at PPPL[4] for studying global electromagneic microinstabilities including trapped particles and tearing physics, efficient numerical methods for solving the elliptic-type equations on parallel computers, such as multi-grid methods, are imperative. Details will be given. In addition, we have also explored the role played by the compressional Alfven waves in gyrokinetic plasmas[5] and the possible interplay between gyrokinetic particle codes for neoclassical simulations[6] and the equilibrium MHD codes.[7]

* Work supported by US DoE.

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General Parallel Closures for Plasma Fluid Simulations

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The rapid thermal motion of electrons along magnetic field lines represents a dominant process in astrophysical and terrestrial plasmas. The purpose of this talk is to describe the incorporation of this dominant physics in plasma fluid models.

In the first part of this talk, we discuss a closure scheme that incorporates the kinetic effects of free-streaming, time-dependence, pitch-angle scattering and trapped electrons in the parallel components of the heat flow and viscous stress tensor [1]. In the nearly collisionless limit, these closures map onto previous collisionless expressions for the parallel heat flow and viscous stress [2]. It is emphasized that the physics of both the fluid and adiabatic limits is incorporated in a unified formalism involving integrals along characteristics of the perturbed, non-Maxwellian part of the distribution function.

In the second part of this talk, we discuss the implementation of the closure scheme in the plasma fluid code NIMROD [3]. Over the course of a one-second simulation of a toroidal fusion experiment, electrons traveling at 1/7 the speed of light travel millions of meters along the magnetic field. Capturing the essential physics of this motion entails integrating kilometers along magnetic field lines at a sufficient number of locations in the computational domain to resolve the parallel closure dynamics. Modest estimates of the number of integrations needed at each time step exceed 10,000. Results show that a massively parallel computational approach that has hundreds of processors independently calculating the integral closure relations can be completed in a time comparable to that needed for the advance of the fluid equations. A further numerical complication involves the stiffness that results when the parallel closures are inserted into the fluid equations. In particular, a semi-implicit time advance for the electron temperature equation is discussed. The semi-implicit operator incorporates the anisotropic heat diffusion operator in the left side of the time-discretized equation to provide numerical stability.

In the final part of this talk, the application of the closure scheme to studies of transport in the vicinity of helical magnetic islands in tori of arbitrary aspect ratio and shaping is discussed. Calculations show the importance of trapped particle effects which reduce parallel heat transport by an order of magnitude in moderate-aspect-ratio ($A \sim 3$) tori. This reduction in parallel heat flow can significantly alter electron temperature flattening across magnetic islands and hence the development of neoclassical tearing modes, especially in low-aspect-ratio devices. The application of the closure scheme to studies of heat transport along chaotic magnetic fields in reversed field pinches (RFPs) is also discussed. Results show that the reduction due to particle trapping is essential to accurate estimates of electron heat confinement times in RFPs.

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Effects of Kinetic Electrons on Microturbulence

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Kinetic electron effects on plasma microturbulences are studied using full torus gyrokinetic particle simulations of toroidal ion temperature gradient and trapped electron mode instabilities. Electron dynamics is treated using a fluid-kinetic hybrid electron model 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. Nonadiabatic response by trapped particles and resonant electrons can affect the generation of the zonal flows which control the level of turbulence and transport. Electron transport driven by ion scale fluctuations will also be discussed.

OVERVIEW OF THE QPS EXPERIMENT

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A quasi-poloidal stellarator with very low plasma aspect ratio ($\langle R\rangle/\langle a\rangle \sim 2.7$, 1/2-1/4 that of existing stellarators) is a new magnetic confinement approach that could ultimately lead to a high-beta ($\langle\beta\rangle = 7\text{-}15\%$) disruption-free compact stellarator reactor. In this approach the dominant components in the magnetic field spectrum are poloidally symmetric in flux coordinates. The degree of quasi-poloidal symmetry decreases with radius but increases with β. In the plasma core the magnetic energy in non-poloidally symmetric field components is less than 10% of that in the poloidally symmetric field components and rises to 30% at the plasma edge. The quasi-poloidal symmetry leads locally to small B x grad B drifts out of a flux surface over most of the plasma cross section and reduced neoclassical transport at low collisionality. The high degree of quasi-poloidal symmetry and the reduced effective field ripple may also reduce poloidal viscosity, enhancing the naturally occurring E x B poloidal drifts and allowing larger poloidal flows for possible shear damping reduction of anomalous transport. For exact poloidal (θ) symmetry, the canonical angular momentum p_θ would be conserved and: (1) the orbit excursions from a flux surface limited to the gyroradius in the *toroidal* magnetic field ρ_T rather than in the *poloidal* magnetic field ρ_p (the banana width) where $\rho_T << \rho_p$; (2) no flow damping in the poloidal direction; and (3) the bootstrap current reduced by ι/N where ι is the rotational transform ($= 1/q$) and N is the number of field periods. The magnetic configuration is relatively insensitive to increasing beta and is similar to that in the W7-X approach, but at 1/4 the plasma aspect ratio. In contrast to W7-X, a self-consistent bootstrap current is included in the configuration optimization and a different physics mechanism is responsible for the reduced neoclassical transport.

The Quasi-Poloidal Stellarator (QPS) experiment [1] is being developed to test key features of this approach. QPS has $\langle R\rangle = 0.9$ m, $\langle a\rangle = 0.35$ m, $\langle B_0\rangle = 1$ T for a 0.5-s pulse, and $P_{heating} =$ 1-3 MW. The experiment is designed to study regimes in which either anomalous transport or neoclassical transport is dominant and to test stability limits at $\langle\beta\rangle \sim 2.5\%$, the configuration dependence of the bootstrap current, and equilibrium robustness at finite beta. Kink and vertical modes are stable at $\langle\beta\rangle \sim 5\%$ without feedback or close conducting walls. The poster will address the physics basis for the QPS approach, the relationship with other stellarator concepts, the key features of the proposed QPS experiment, and the connection to higher-beta quasi-poloidal-stellarator configurations.

Work supported by U.S. Department of Energy under Contract DE-AC05-00OR22725 with UT-Battelle, LLC.

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Hamiltonian Description of Fluid and Plasma Systems with Continuous Spectra

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Abstract

Most interesting plasma and fluid systems possess a continuous spectrum. A general integral transform is constructed that transforms a large class of such systems into a normal form. This amounts to a solution of the initial value problem for this class of systems. The integral transform is a generalization of the Hilbert transform. It will also be shown how this procedure amounts to the tranformation to action-angle varriables for a class of infinite degree-of-freedom Hamiltonian systems.

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

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22–24 April 2002

A procedure to determine the temperature at the top of the pedestal at the edge of type I ELMy H-mode plasmas in tokamaks has been developed. The pedestal temperature is a boundary condition needed for integrated predictive modeling codes in order to predict the performance of present day tokamaks, new experiments, as well as fusion reactor designs. In particular, the temperature in the plasma core depends on the pedestal temperature. The procedure for obtaining the pedestal temperature requires a model for the pressure gradient within the pedestal as well as a model for the width of the pedestal. The pressure gradient within the pedestal is assumed to be limited by the ballooning mode instability. Six theory-motivated models for the width of the pedestal are considered. These pedestal width models are based on 1) flow and magnetic shear stabilization, 2) flow shear stabilization, 3) diamagnetic stabilization, 4) neutral penetration, 5) ion orbit loss and 6) normalized poloidal pressure[1]. These models for the pedestal width, when combined with the model for the pressure gradient, are used to develop six models for the pedestal temperature. In all of these pedestal temperature models, the magnetic shear and q are computed at a distance of one pedestal width from the separatrix[2]. In a separate report at this meeting, presented by T. Onjun *et al.*, alternate methods for computing the magnetic shear in the pedestal region are examined. The effect of the bootstrap current is also included in the development of a predictive model for the pedestal temperature. An increase in the bootstrap current in the steep pressure gradient region at the edge of the plasma reduces the magnetic shear, thereby reducing the critical pressure gradient and thus the temperature at the top of the pedestal. The pedestal temperatures predicted by these models are compared with measured temperatures in the International Tokamak Physics Activity Pedestal Database, which is available at http://pc-sql-server.ipp.mpg.de/Peddb. The latest public version of the database, version 3.1, contains 384 type I ELMy H-mode data points, that is, 105 from ASDEX-U discharges, 5 from DIII-D discharges, 56 from JET discharges, and 218 from JT-60U discharges. The agreement between the pedestal temperatures predicted by these models and the experimental values will be presented. The pedestal temperature models, obtained using the procedures discussed here, are applied in the context of predictive integrated modeling simulations in a report presented by G. Bateman *et al.* at this meeting.

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Testing H-mode Pedestal and Core Transport Models Using Predictive Integrated Modeling Simulations

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In previous simulations of tokamaks with the BALDUR integrated modeling code, the boundary conditions for the temperatures and densities at the edge of H-mode plasmas were taken from experimental measurements. In simulations of H-mode plasmas, in particular, the boundary conditions were taken at the top of the pedestal that forms at the edge of H-mode plasmas (the edge transport barrier). The predictive capability of these simulations would be more complete if models were available to predict the boundary conditions. Predictive models have now been developed for the height of the temperature and density pedestal at the edge of H-mode plasmas[1]. The primary objective of the work reported here is to demonstrate tests of these new models for the H-mode pedestal, together with models for the core plasma, in the context of time-dependent predictive integrated modeling simulations. These simulations are carried out using each of three models for anomalous transport in the plasma core — Multi-Mode, mixed-Bohm/gyro-Bohm (JETTO), and the GLF23 model. Each anomalous transport model is used together with neoclassical transport. During the H-mode phase of each discharge, the boundary conditions for the simulations are provided by theory-motivated predictive models for pedestal temperature at the edge of type I ELMy H-mode plasmas[1], together with an empirical model for the pedestal density. A variety of models have been developed for the pedestal temperature using different scalings for the width of the pedestal and different approximations for the effect of the magnetic shear within the steep gradient region of the pedestal. These models include the effect of the bootstrap current on the magnetic shear in the steep gradient region of the pedestal. Each model for the pedestal has been calibrated against 384 data points from the International Pedestal Database. The calibration uses data for type I ELMy H-mode discharges in JT-60U, ASDEX-U, JET, and DIII-D. The derivation and calibration of these pedestal models are described in posters by T. Onjun and A. H. Kritz. The temperature and density profiles that result from the BALDUR integrated modeling simulations using these models for the pedestal and core transport are compared with experimental data for type I ELMy H-mode discharges in several tokamaks. Systematic scans over normalized gyro-radius, beta, and collisionality are used to elucidate the physics of the combined pedestal and core models. The combination of pedestal and core models is then used in BALDUR simulations of the burning plasma tokamak designs ITER-FEAT, FIRE, and IGNITOR.

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Study of Critical Pressure Gradient at the Edge of Type I ELMy H-mode Plasmas

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The critical pressure gradient for ballooning mode instability is one part of the model needed to predict the temperature at the top of the pedestal at the edge of type I ELMy H-mode plasmas in tokamaks. Studies of the critical pressure gradient, $(\partial p/\partial r)_c$, are usually carried out in terms of the normalized critical pressure gradient, $\alpha_c \equiv (2\mu_0 R q^2/B^2)(\partial p/\partial r)_c$. Two important contributions to the normalized critical pressure gradient model are the magnetic shear and the geometry in the pedestal region. Various models used to calculate the magnetic shear for the normalized critical pressure gradient are presented. For example, in one model, the magnetic shear is computed on the flux surface located at a distance of one pedestal width from the separatrix. In addition, the effect of the bootstrap current, which reduces the magnetic shear in the steep pressure gradient region at the edge of the plasma, is also considered. In another model, the magnetic shear is taken to be a constant times the effect of the bootstrap current. The consequences of the various shear models on the predicted pedestal temperature are examined. Two empirical models are developed for calculating the geometrical factor in the normalized critical pressure gradient. One model, which depends on elongation and triangularity, is based on the results suggested by experimental data[3]. Another model is developed using numerical results from the JETTO and IDBALL codes. In order to develop a model for the pedestal temperature, the models for the critical pressure gradient are combined together with the pedestal width proposed by M. Sugihara[2]. The scaling of this pedestal width is based on the magnetic shear and flow shear stabilization. Other models for the pedestal width are presented in the poster at this meeting by A. Kritz *et al.* The pedestal temperatures predicted by these models are compared with measured temperatures for 384 type I ELMy H-mode data points obtained from the International Pedestal Database. These 384 data points are from four tokamaks — JT-60U (218), ASDEX-U (105), JET (56) and DIII-D (5). Statistical techniques are used to compare the predictions from these models.

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Numerical Studies of Transport Near Magnetic Islands*

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Research has shown that the development of successful thermonuclear fusion systems depends on the clear understanding of plasma particle and heat transport. In this work, a fourth-order finite-difference code to study particle and heat transport in the vicinity of a growing magnetic island in slab geometry has been developed.

To study particle transport, we evolve the plasma continuity equation in conjunction with the parallel component of the plasma momentum equation using an adiabatic equation of state and a parallel damping term to close for the pressure and viscous stress tensor, respectively. To study heat flow in the presence of a magnetic island, we evolve a temperature equation using both a Braginskii and a Chapman-Enskog like closure for parallel heat flow-the latter involves solving a kinetic equation[1]. In each case, we evolve the temperature or density from an initial state to equilibrium and then allow the magnetic island to grow in time. In essence, we are calculating the flattening of each profile across the magnetic island. We see flattening of the electron temperature profile due to the large parallel heat flux from electron free-streaming along magnetic field lines. In contrast, we see flattening of the plasma density profile due to parallel sound wave propagation. Because the electron thermal velocity is much greater than the sound speed, the flattening of the electron temperature profile is more pronounced than the flattening of the plasma density profile.

One motivation of this work stems from a need to understand the difficulties inherent in time-discretization schemes. In the case of an explicit time advance, we encounter problems due to the numerical stiffness introduced by parallel sound wave propagation and parallel electron heat flow. For an implicit scheme, the dominance of the parallel transport along perturbed field lines is problematic because it results in a dense matrix which must be inverted. In regards to the evolution of the electron temperature equation, this code implements a semi-implicit method which utilizes the anisotropic heat diffusion operator to stabilize the time advance[2]. In addition to the insights gained into the physics of heat and particle transport in the vicinity of growing magnetic islands, the code provides a simple basis for comparison with the fluid code NIMROD[3]. The simple geometry also allows comparison of numerical solutions with analytic models.

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Analysis of Multifield Phase and Frequency Effects in Ion Temperature Gradient Driven Turbulence

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Abstract

We present results from a simple three-field fluid model of ion temperature gradient (ITG) turbulence. ITG turbulence is currently believed to be the dominant source of energy transport in large Tokamak experiments, and this model is intended to gain insight into aspects of this mode at saturation which standard analytic treantments ignore. Results so far show nonlinear excitation of the damped manifolds of the dispersion relation and supercritical nonlinear instability associated with three-wave coupling. Such behavior cannot be understood by methods which rely on linear growth rates and mode structures, and violates a number of common turbulence approximations such as mixing length estimates and quasilinear flux; simulations in fact show transient bursts of negative flux, which cannot be explained by the quasilinear flux approximation. This behavior is very similar to behavior observed in previous simulations of a two-field collisionless trapped electron mode (CTEM) model[1]. Since the nonlinear instability mechanism proposed to explain this behavior in CTEM turbulence is closely linked with the relative phase and frequency of different eigenmodes, we expect this will also be the case with the ITG model. By investigating the phase and frequency relations in the ITG model, we hope to verify that the mechanisms are analogous and come closer to a quantitative analysis of this type of instability. We will also present evidence for other prerequisites for this mechanism, such as eigenmode nonorthogonality and scale proximity of growth and damping rates.

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Outstanding Theoretical Problems for Analysis of Burning Plasma Experiments

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The fusion community is preparing for the summer Snowmass meeting where three specific designs for Next Step Burning Plasma experiments are to be assessed. As preparation for this meeting, intensive modeling efforts have begun in order to understand the capabilities of these devices. In the detailed performance modeling, many assumptions are made that are based more on empirical scaling and trends than on sound theoretical models and analysis. We illustrate this with a complete 1 1/2 D TSC model of a standard FIRE discharge, showing the sensitivity of the ignition parameter Q to some of these empirical parameters. In particular, we consider: the core ion and electron particle and thermal diffusivities determining the core temperature and density profiles, the height and width of the edge transport barrier for the density and the temperature, the mass deposition profile for a high-field side injected pellet, the period and mixing radius of the sawtooth, the onset conditions and saturation level for neoclassical tearing modes, the type and effects of the edge localized modes (ELMs). Other empirical scalings that are shown to enter in an important way are the H-mode power threshold and the Greenwald density limit. In addition to these baseline performance evaluation issues, we call attention to other unresolved issues involving plasma disruptions and Advanced Tokamak operation. For example, can we identify all the possible sequences of non-linear events that can lead to disruptions, the strength of the localized halo currents that can result from the disruption, and the magnitude of runaway electron generation during the disruption

Turbulent and Neoclassical Processes Determining Particle Transport in Alcator C-MOD Internal Transport Barriers

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Abstract

Recent experiments[1] on Alcator C-Mod, using off-axis ICRH, have produced strong internal particle transport barriers following the transition to EDA H-Mode. Central electron densities reach $6\times10^{20}\,\mathrm{m}^{-3}$ with edge pedestal densities of $2.5\times10^{20}\,\mathrm{m}^{-3}$, without core fueling. The barrier width extends over one-third of the plasma cross-section while the foot lies just outside the half-radius. Further, adding sufficiently strong central ICRH returns the density profile to flatness typical of EDA H-Mode. In this work, we use the GS2[2,3] nonlinear flux-tube gyrokinetic initial value code to carry out both linear stability analysis of C-MOD ITBs and to simulate turbulent transport in the barrier. The GS2 simulations are automated using tools[4] developed to prepare sets of inputs to GS2 from TRANSP and provide for convenient plotting of linear and nonlinear results. We have recently extended our arbitrary collisionality, multispecies, neoclassical code[5] to compute particle fluxes for arbitrary flux surface shape, using numerical magnetic equilibria. We have benchmarked both the GS2 linear stability analysis and our neoclassical rotation velocities against several other codes.

Our gyrokinetic stability analysis reveals a strong trapped electron mode (TEM) centered in the barrier. This mode has a phase velocity in the electron direction and wavenumber $k_\theta\rho_i \sim 0.5$, disappears with adiabatic electrons, and has a growth rate essentially independent of the temperature gradient. However, it is very sensitive to density and temperature through collisions. Turning off collisions triples the growth rate. This provides a favorable path to higher density, and further, the particle transport from this mode may explain the degradation with central heating through the collisionality dependence on temperature. With central heating, the mode growth rate increases and it is unstable over a larger fraction of the cross-section. Outside the foot of the barrier, we find toroidal ITG modes with growth rates increasing with radius and unaffected by trapped electrons. Our preliminary neoclassical calculations find an electron influx in the barrier due to the Ware pinch with little contribution from gradients, but an even stronger deuterium influx driven by the density gradient as well. Impurities are weakly screened as required by ambipolarity. Our GS2 turbulence simulations find an outward electron flux in the barrier nearly equal to the inward Ware pinch. The density gradient steepens in time until the TEM mode goes unstable, then an equilibrium is established. Preliminary results suggest that this equilibrium is characterized by the condition that the neoclassical and turbulent fluxes balance.

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QPS TRANSPORT AND ENERGETIC PARTICLE PHYSICS

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Quasi-poloidal symmetry is a new approach to stellarator confinement optimization that we have used to design very low plasma aspect ratio configurations ($\langle R \rangle / \langle a \rangle \sim 2.6$, 1/2–1/4 that of existing stellarators). An experiment, the Quasi-Poloidal Stellarator (QPS), is being developed to test the main features of this approach. QPS has $\langle R \rangle = 0.9$ m, $\langle a \rangle = 0.35$ m, $\langle B_0 \rangle = 1$ T for a 0.5-s pulse, and $P_{heating} = 1\text{-}3$ MW. An important criterion for our optimization has been to achieve sufficiently low levels of neoclassical transport so that the dominant losses are from anomalous transport. A number of recently developed/improved transport tools have been used to evaluate confinement in this configuration. These include: the DKES transport coefficient code, the DELTA5D Monte Carlo model, and several 0-D and 1-D models. We will apply these models to the QPS configuration and discuss the neoclassical properties of the various transport regimes it can access. In addition to perpendicular transport, the parallel transport properties (bootstrap current, neoclassical resistivity enhancement) are also important since this device relies on plasma current to supply a fraction of its rotational transform. Bootstrap current has been calculated using both the DKES and an asymptotic low collisionality calculation. These models will be applied to the QPS device and compared. Energetic particle confinement in QPS devices has also been evaluated using Monte Carlo techniques. Alpha, beam, and ICRF tail populations have been simulated. Improvements in confinement can be made through finite beta effects (which induce radial gradients in $B_{0,0}$ and improve the level of quasi-poloidal symmetry); also inward shifts of the magnetic axis have been found to improve confinement. In order to address energetic particle induced instabilities, a code (STELLGAP) has been developed to study Alfvén gap modes in 3D systems. Results of these studies will be presented.

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QPS PLASMA AND COIL OPTIMIZATION

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Compact stellarators offer the potential of both attractive fusion reactors as well as lower cost near term experiments at a fixed plasma minor radius. We have developed stellarator hybrid configurations with quasi-poloidal symmetry at very low aspect ratios ($<R>/<a> \sim 2.6$) that achieve low levels of neoclassical transport and good stability properties, including access to high β second stability states. The optimization of compact stellarators is a challenging physics and computational problem whose solution has required the development of a variety of new tools. These include: rapidly evaluated transport and 3D ballooning targets, a new version of the VMEC equilibrium code with improved convergence properties, and an overall MPI language parallelization method that tolerates a queue of computational tasks of varying length. Although our optimization initially targets quasi-poloidal symmetry, some remaining residual degree of non-symmetry is generally present. By adjusting the form of this residual, further gains in confinement and stability properties can be made. Following this physics optimization of the outer flux surface, a set of coils is developed (COILOPT code) by directly adjusting the coil currents and geometry so as to minimize the normal component of magnetic field on the outer flux surface. Recently we have combined the separate physics and coil optimizations into a single integrated optimization procedure. These new physics and coil optimization methods will be described and the properties of the resulting configurations discussed.

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Magnetic Secondary Instabilities in ETG Turbulence

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Abstract

Research in the last decade has established the importance of the ion temperature gradient (ITG) instability in determining ion particle and energy transport. However, understanding of electron transport has not kept pace. The electron temperature gradient (ETG) mode has been proposed as a primary mechanism for electron transport. The possibilities of magnetic secondary instabilities (zonal "fields" and magnetic streamers) are investigated as novel potential mechanisms for electron transport regulation and enhancement, respectively. In particular, we study in detail the properties and dynamics of the magnetic streamers (mesoscale radial magnetic fields) as mechanisms for efficient electron thermal transport. Streamer growth and saturation mechanisms are presented, as well as scaling and stability issues. Implications for electron thermal transport are discussed.

Fully Converged Solutions of Ion Bernstein Wave Mode Conversion in Toroidal Geometry*

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Abstract

The fast wave to ion Bernstein wave (IBW) mode conversion process can be difficult to study numerically in toroidal geometry owing to the short perpendicular (to **B**) wavelengths of the mode converted wave. If a spectral Ansatz is used to represent the electric field as a sum of poloidal Fourier modes in this process then **E**(x) can be written as:

$$\mathbf{E}(\mathbf{x}) = \Sigma\, \mathbf{E}_m(r) \exp(im\theta + in\phi),$$

where m is the poloidal mode number, n is the toroidal mode number, and θ (ϕ) are the poloidal (toroidal) angles. The maximum m-number required to resolve the mode converted IBW can then be estimated from the condition $k_\perp \rho_i \approx 1$. If $k_\perp \approx m / r$, where r is the radius of the mode conversion layer then $|m| \approx r / \rho_i$ and at least $2|m| + 1 \equiv N_m$ modes are required for convergence of the expansion. For parameters typical of $D(^3He)$ and $H(^3He)$ mode conversion scenarios in the Alcator C-Mod device [1] the required values of N_m fall into the range of 250 – 500. A full-wave ICRF field solver TORIC [2] has been modified to allow efficient computation of fully converged mode converted IBW using an out of core method for matrix inversion and storage (Thomas algorithm). The new algorithm requires less memory (factor of 25) and less cpu (factor of 3-4) than the original in-core method, which stored the entire matrix decomposition in memory. Full-wave simulations can now be done in routine fashion with up to 256 poloidal modes. Results will be presented which demonstrate rapid convergence of the mode expansion as N_m is increased from 161 up to 256. Mode converted IBW wavefields are observed to first converge on flux surfaces at smaller radius with the larger radius flux surface solutions converging as N_m is increased further. Results will be presented that demonstrate up tp 500 modes are actually required to converge IBW wavefields at radii well beyond the mode conversion surface. We will also discuss plans for implementation of TORIC on a massively parallel platform (MPP) which will ultimately allow the efficient computation of wavefields using up to 1000 poloidal modes.

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Hole-clump coherent structures and self-consistent chaos in the wave-particle interaction

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A study of phase space coherent structures and self-consistent chaos is presented in the context of a Hamiltonian mean field model of the wave-particle interaction in Vlasov-Poison plasmas [1]. The model describes the dynamics of electron "holes" and electron "clumps" (which are depletions and excesses of phase-space electron density) in marginally stable systems. Numerical simulations with finite-N and in the infinite-N kinetic limit (where N is the number of particles) show the existence of coherent, rotating dipole states. We approximate the dipole as two "macroparticles" (one hole and one clump) and consider the N=2 limit of the model. We show that this limit has a family of symmetric, rotating integrable solutions described by a one-degree-of-freedom nontwist Hamiltonian. A perturbative solution of the nontwist Hamiltonian provides an accurate description of the mean field and rotation period of the dipole. The coherence of the dipole is explained in terms of a parametric resonance between the rotation frequency of the dipole and the oscillation frequency of the self-consistent mean field. This resonance creates islands of integrability that shield the dipole from regions of chaotic transport. For a class of initial conditions, the mean field exhibits an elliptic--hyperbolic bifurcation that leads to the filamentation, chaotic mixing and eventual destruction of the dipole.

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Stratified shear layers and fronts in a model of turbulence-shear flow interaction

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In magnetically confined plasmas there is evidence of localized regions of improved confinement. These regions are usually associated with shear flows with radial structure, and an important problem is to understand how such flows emerge. To address this problem we consider a reaction-diffusion type model of turbulence-shear flow interaction [1]. The fixed points of the model correspond to the L (low confinement) and H (high confinement) modes of the system, and it is shown that for a range of parameter values the H-mode fixed point has a finite k instability. Numerical results show that this instability leads, in the nonlinear regime, to the formation of stratified shear layers in which bands of intense shear alternate with bands of suppressed turbulence. We present analytical solutions corresponding to H modes with radial structure. We also study traveling front solutions joining the L and H fixed points. Depending on the stability of these fixed points, the fronts are uniform or have spatial structure. In the latter case, the wake of the front exhibits a segregated, layered structure. A Ginzburg-Landau amplitude equation is used to describe the front dynamics near marginal stability.

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Reconnection and the ideal evolution of magnetic fields

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Abstract

The evolution of a magnetic field is called ideal if the evolution is consistent with the field being embedded in a perfectly conducting fluid. Remarkably, Faraday's law implies that the evolution of a generic magnetic field is always locally ideal. A magnetic field is consistent with an ideal evolution if the parallel component of the electric field can be balanced by the parallel gradient of a scalar potential. (A generic magnetic field can be zero only at discrete points. A field with zeros along a curve is turned into field with discrete nulls by an arbitrarily small perturbation.) For a generic magnetic field, a solution for the scalar potential always exists locally. Reconnection can occur only if a solution for the potential does not exist globally, which means a failure of the solvability condition. In systems with two periodic directions, such as toroidal plasmas, the failure of the solvability condition focuses reconnection into narrow regions around the surfaces on which the magnetic field lines close on themselves, the rational surfaces. In space and astrophysical plasmas field lines rarely close on themselves. Reconnection simulations using codes that have periodic boundary conditions in two directions are dominated by the rational surface effect, which does not arise in space and astrophysical reconnection. Several effects that break the solvability constraint can arise under astrophysical conditions and give reconnection.

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Nonlinear dynamics of a shear–localized ideal interchange instability

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The stability limit due to the ideal pressure driven interchange instability is given by Suydam's criterion i.e., $D_I \leq 1/4$, where $D_I \equiv (\beta/r_p\, r_s)\,(q/q')^2$ is the driving term for the instability. However, many present day tokamaks operating in the high confinement regimes (i.e., high β) operates very close to the ideal MHD threshold, Thus, a high β disruption caused by these ideal MHD modes is a key issue in this context. Linear stability analysis of a shear–localized ideal interchange instability indicates that the mode grows at an exponentially small growth rate well above the marginal stability condition $D_I = 1/4$ and the mode width is very narrow [1-3].

For studying the nonlinear fate of the ideal interchange instability, the small growth rate is used as an ordering parameter (δ) to expand the various perturbed quantities in the nonlinear vorticity equation, Ohm's law and pressure evolution equation. Thus, ordering in the inertial layer (i.e., a region with width ~ δ) is $\gamma\, L_s/C_A \sim k_y\, \Delta x \sim k_\parallel\, L_s \sim \delta < 1$ with $k_y\, a \sim \varepsilon^{-1} > 1$ and in a region far away from it, the ordering is $\gamma\, L_s/C_A \sim \delta < 1$, $k_y\, a \sim \varepsilon^{-1} > 1$ and $k_y\, \Delta x \sim k_\parallel\, L_s \sim 1$. Thus, in the region far away from the inertial region, the nonlinear dynamics of ideal interchange mode is governed to the lowest order by the ideal MHD physics $(\mathbf{B}\bullet\nabla)(J_\parallel/B) = -\nabla\bullet J_* = D_I\, \partial p/\partial y$ while in the inertial layer, the polarization nonlinearity competes with the $(\mathbf{B}\bullet\nabla)(J_\parallel/B)$ nonlinearity. The results of these nonlinear calculations will be presented.

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Stabilization of the Resistive Wall Mode by Differentially Rotating Walls in a High-β Tokamak

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Abstract

The resistive wall external kink mode is known to be one of the limiting factors for the performance of high beta tokamaks. The analysis of design characteristics, which could help in stabilizing such modes, has therefore been of major interest in recent years. Among the ideas under consideration, a promising one includes the use of rotating walls as a mean for stabilization. In particular, a liquid metal inner wall[1] supported by an outer fixed wall behaves as two differentially rotating walls leading to the RWM suppression for sufficiently large rotation velocities. Very recently, the stability analysis of the RWM in a cylindrical pinch with uniformly rotating differential walls[2] with frequency $\Omega \sim \tau_w^{-1}$ has shown that the wall mode remains unstable and acquires a rotation frequency equal to $m\Omega/2$ where m is the unstable mode number and τ_w is an average wall time. In the presence of uniformly rotating differential walls, the RWM stabilization occurs at large rotation frequencies of the order $\tau_w^{-1}\sqrt{b/d}$ when the skin effect becomes important (here b and d are the wall radius and thickness respectively). Instead, a two stream configuration with an upper and a lower stream flowing in opposite directions has shown better stability properties. The cylindrical analysis of Ref. 3 indicates that the critical rotation frequency for a two stream configuration scales as $\Omega \sim \tau_w^{-1}$.

We have extended the stability analysis of the RWM to a large aspect ratio, high beta tokamak with uniform and two-stream differentially rotating walls. The toroidal calculation is carried out using a sharp boundary model of the pressure profile and a beta ordering $\beta \sim \epsilon$ where $\epsilon = a/R_0$ is the inverse aspect ratio. Differently from the cylindrical case, an improvement of the beta limits is found even for uniform rotation and for the case of a single wall rotating with respect to the plasma. Similarly to the cylindrical case with uniformly rotating walls, the RWM acquires a frequency equal to $m\Omega/2$ where $m \geq 2$ is the lowest harmonic with a rational surface outside the plasma. Furthermore, the two-stream analysis has also been extended to the toroidal case and the critical velocity required for stabilization has been derived.

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Investigation of the resistive wall modes in toroidal geometry

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Abstract

Resistive wall modes are of particular concern in that they can nullify the ideal wall stabilization effect on the external kink modes, which poses a severe stability limitation on tokamak performance. Nevertheless, the resistive wall instability assumes usually a relatively small growth rate and is sensitive to various effects such as plasma rotation, flowing liquid metal (or rotating solid) wall effects. Considerable theoretical efforts have been made to investigate this mode. However, most of them are performed in cylindrical or slab models. The current work is trying to study the toroidal effect. Studies are made both for high-n and low-n modes. In the high-n limit, an existing 2D high-n MHD code [1,2] is connected to the vacuum-wall code to investigate the wall effects. The numerical results show that the resistive wall modes can be stabilized by a flowing liquid metal wall. It is found that in toroidal geometry the stabilization effect depends on the injection direction. Inner-side injection is proved to be more efficient than vertical injection. It is also shown that the liquid metal wall position should be considerably closer to the plasma than the ideal wall marginal stability position, in order to have efficient stabilization. A low-n code is also under construction, based on an analytical model equilibrium. Preliminary numerical results from this low-n code will be presented and discussed.

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Diffusive effects on plasma stability

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Abstract

We have shown recently that the stability question of a resistive or viscous plasma can be put in a self-adjoint form so that stability is determined by an energy principle. 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.

Here we extend the analysis to the case of finite heat conductivity κ. As a first step we investigate the easier equations of ballooning modes. Indeed, by taking $\kappa = O(\varepsilon^2)$, where ε is the width of the mode, the diffusive term reduces to an algebraic one which is more easily analyzed. We have obtained some precise stability criteria that do not involve the particular value of the heat conductivity. This suggests that our earlier results for other types of diffusivity will be generalizable.

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Dynamical Transitions in SOC Systems with Additional Transport Mechanisms

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Self-Organized Criticality (SOC) has for some time been advanced as a paradigm [1,2] for turbulent transport in magnetically confined plasmas as well as many other physical systems. However, in a realistic confined plasma system (and many of the other systems) the transport dynamics is more likely to be a combination of the coherent anomalous transport (the SOC part) and other transport channels such as a more classical diffusive component or even smaller scale background anomalous mechanisms[3]. To investigate the interaction between these various 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 a sharp change in the dynamics, with the characteristics of a roughening driven transition to an edge dominated dynamical regime will be presented. The implications and possible tests for such transport dynamics in various experimental regimes and devices are discussed. The important ramifications for SOC models in general will also be examined.

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The Dynamics of the Co-evolution of Electron and Ion Channel Transport Barriers

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A wide variety of magnetic confinement devices have found transitions to an enhanced confinement regime. A simple model incorporating the nonlinear interactions between the low-k turbulent fluctuations and the sheared radial electric field coupled to a transport model has been able to capture much of the observed dynamics[1,2,3] of ion transport barriers. However, an open question which remains is the nature and dynamics of the electron thermal transport channel sometimes observed in the presence of a standard ("ion channel") barrier. Adding to this simple model an evolution equation for electron fluctuations, such as a simplified version of the ETG model, one can investigate the interaction between the formation of the standard ion channel barrier and the somewhat less common electron channel barrier. While the ion channel barrier is sensitive to the alignment of the various gradients making up the sheared radial electric field, we find that the barrier formation in the electron channel is even more. The electron channel heat transport is found to significantly increase after the formation of the ion channel barrier but before the electron channel barrier is formed. This increased transport is important in the barrier development. The interaction between the channels and gradients will be discussed in the context of both initiation thresholds and the single or dual barrier evolutions.
The complex interrelated dynamics between the two channels allows for a number of potential control schemes such as utilizing the electron channel as a profile control valve.

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NIMROD Code Simulation of Field Reversed Configuration Plasmas for Application to Fusion Propulsion

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Previous NIMROD simulations [1] of Field Reversed Configuration (FRC) have been extended in 3D. Results obtained with the latest NIMROD version that includes the continuity and temperature equations are reported.

A modified version of the code has been used to implement open-end boundary conditions along the longitudinal axis of the FRC.

Theoretical analysis of the tilt instability in FRCs [2] indicates that the growth rate of the tilt mode in a two-fluid model is reduced with respect to the standard MHD model. A preliminary confirmation of this result was found with 2D NIMROD runs and a further simulation effort to confirm those findings is presented.

The possibility of applying an FRC configuration in a fusion-propulsion system is investigated in relation to the future developments of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR, [3]) experiment.

In this case, an FRC is feeding a plasma propulsion device through a flow along the FRC axis. The FRC field lines merge naturally in a magnetic nozzle and the "escaped" plasma, can be further heated via RF, as in the VASIMR concept, before the entering the nozzle region. Proper axial asymmetry for the FRC can be introduced to constrain the plasma loss only in the direction of the nozzle.

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Current Ramping to Achieve Reversed Shear Confinement for Ignitor and CMOD

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Abstract

Current ramping to create reversed shear confinement enhancement and peaked density profiles are crucial in achieving ignition conditions in Ignitor [1]. Several high performance tokamak operating regimes have been achieved in experiments through the peaking of density profiles. The peaked core density profiles bring down the value of $\eta_i (= d\ln T_i/d\ln n_i)$ below the critical threshold for the ion temperature gradient mode and help to produce internal transport barriers by generating a large sheared radial electric field, which is required for turbulence suppression, through the steep density gradient. In addition to enhancing the confinement, a peaked density profile is also necessary for maximizing the fusion reaction rate and the alpha heating power of a tokamak plasma with centrally peaked temperature profile to reach ignition.

In our simulations with the transport model JETTO, peaked density profiles result from the formation of an internal transport barrier due to reversed magnetic shear, which is produced by controlled plasma current and volume-averaged density ramping. This type of programmed Ohmic heating leads to density profile peaking and is demonstrated to be an effective approach to ignition of a burning D-T plasma. For example, we have used a current ramping rate of 8 MA/s, achieved ignition at $t = 4.24$ s for Ignitor before sawtooth happened and obtained fusion gain $Q = 8.2$, alpha power $P_\alpha = 14$ MW and energy confinement time $\tau_E = 0.67$ s.

As the discharge evolves, the reversed shear q-profile becomes an optimized shear type, which is nearly flat over the internal region, and creating a transport barrier where Bohm type diffusion is suppressed [2]. This reversed shear or optimized shear confinement enhancement is also planned in most advanced tokamaks, such as KSTAR and Tore Supra, even though their scenarios for obtaining reversed shear are different. The fast current ramps used to reach ignition in our simulation are similar to those used for the successful creation of an internal transport barrier in Tore Supra [3].

Simulations for this type of programmed wave forms for the current, density and auxiliary ion RF heating will be presented for CMOD parameters where up to 3 MA/s is thought to be feasible. The ion heating could be programmed to match what the alpha heating would produce in the scaled up high field D-T ignition experiment.

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Renormalization and destruction of tori in the standard nontwist map

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Abstract

It is by now well-known that area preserving and symplectic maps have applications in the study of magnetic field lines and particle orbits in toroidal plasma devices, as well as in other areas of physics. We consider the class of area preserving nontwist maps, i.e. maps that locally violate the twist condition, as is the case for maps that model magnetic field lines in reverse shear profiles. A representative example is the *standard nontwist map* that violates the twist condition along a curve called the shearless curve. In particular, we continue an investigation that was started in [1-2]. Using Greene's residue criterion[3] and the renormalization group framework, we study the destruction of shearless curves with irrational rotation numbers, different from the inverse golden mean, and we compute fixed points of the renormalization group operator.

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Ignitor equilibria with JSOLVER†

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Abstract

Ignitor[1] is a proposed ignition experiment characterized by a high magnetic field ($B_T = 13$ T), a high plasma current ($I_p = 11$ MA), compact dimensions ($R_0 = 1.32$ m, $a = 0.47$ m) and considerable cross section elongation and triangularity ($\kappa = 1.83$, $\delta = 0.4$). In Ignitor, important quantities for tokamak operational limits such as n_G (density limit) and $I_p/(a\,B_T)$ (beta limit) have values significantly higher than those in present-day experiments or in other proposed burning plasma ones ($n_G \simeq 1.6 \times 10^{21}$ m^{-3}, $I_p/(a\,B_T) \simeq 1.80$). Transport simulations with the JETTO code[1,2] have shown that ignition conditions may be achieved in Ignitor when only Ohmic heating is present with $n_e(0) \simeq 1.0 \times 10^{21}$ m^{-3}, $T_e(0) \simeq 11$ keV and an energy confinement time $\tau_E \approx 0.6$ s. In the present work, Ignitor equilibria with these plasma parameters, corresponding peaked pressure profile ($p(0)/\langle p \rangle \simeq 4$), and different forms of the current density profile are studied with the fixed-boundary toroidal MHD equilibrium code JSOLVER[3]. This code, which has recently been made available as source code[4] in the context of the NTCC (National Transport Code Collaboration) project[5], simultaneously solves for plasma equilibrium and the magnetic flux coordinates (ψ, θ), with ψ the poloidal flux/(2π) and θ the equal-arc poloidal angle, and returns the inverse functions $R(\psi, \theta)$, $Z(\psi, \theta)$ as well as many other quantities of interest. The results obtained confirm the characteristics of these Ignitor equilibria, with $q_{\rm edge} \simeq 3.6$, low values of toroidal beta $\beta_T \simeq 1.20\%$, normalized beta $\beta_N \lesssim 0.7$, poloidal beta $\beta_p^* \simeq 0.20$, and normalized density $\overline{n}_e/n_G \simeq 0.44$. Equilibria obtained with JSOLVER are a good starting point for further analysis of Ignitor plasmas, in particular with stability codes.

† I am grateful to the persons responsible for the NTCC project and, in particular, to Dr. A. Pletzer for providing the source codes used for this work.

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Optimal Rate of Injected Heating for the Attainment of Ignition

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Abstract

The plasmas to be produced by Ignitor have been extensively studied and the attainment of ignition has been shown to be possible with ohmic heating alone under realistic conditions for the high density regimes that characterize this experiment. The rate of increase of the plasma density needs to be optimized while both the toroidal field and the plasma current are ramped up [1,2]. A departure from the optimal conditions such as the presence of an impurity content producing a $\langle Z_{eff} \rangle$ value greater than 1.5, or a fuel composition poorer than the stechiometric 50/50 deuterium-tritium percentage leads to requiring an externally injected form of heating. A Radio Frequency (RF) system providing Ion Cyclotron Resonance Heating (ICRH) is included in the Ignitor design [3,4]. Here we present studies performed by considering a simple model for the ICRH power deposition for different timing of the RF heating pulse. The injected power is introduced in the equilibrium-transport code by assigning the region where the heating pulse is deposited and the total power absorbed during a selected time interval. Even by this simplefied model it is possible to identify different heating scenarios. A more centrally localized deposition profile assures the major boost to accelerate the attainment of ignition, in the case when the heating power is injected during the current ramp. Moreover applying auxiliary heating the end of the current ramp, and producing a wider deposition profile can modify the current density profile and offer the possibility to affect of the nature of the sawtooth oscillations that may be excited.

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A Hybrid Ion Temperature Gradient And Kelvin-Helmholtz Instability

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It is shown that Kelvin-Helmholtz drive due to shear in parallel flow can modestly enhance the ion temperature gradient (ITG) driven modes in the Columbia Linear Machine. A theory of ITG slab mode in the presence of parallel flow shear and anisotropic etai (present in CLM) confirm the experimental results. However, this modest enhancement does not substantially alter the large discrepancy between our experimental results and the theoretical estimates of stabilizing levels of transverse flow shear, necessary for stabilization of ITG modes.

Importance of Non-linear Effects for the Excitation of "Singular" Modes in Thin Accretion Disks

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The only known modes which can transport angular momentum in thin accretion disks, where the magnetic energy is significant relative to the thermal energy, are characterized by two sets of spatial singularities, one of them involving a divergence of the plasma pressure and compressibility[1, 2]. The simplest equations, allowing for the transition across this set, involve a relaxation term related to the local perturbed plasma pressure. Nonlinear effects are shown to be important in these transition regions, even for relatively small mode amplitudes [3]. The marginally stable modes are identified independently of the specific processes characterizing the transitions at the singularities. The angular momentum transport rate, resulting from the excitation of these modes, is derived from quasi-linear theory.

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High current densities through the sheath in a grazing magnetic field

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In the on-going experiments on the SSPX spheromak at LLNL [1], the parallel (to the magnetic field lines) current density is often higher than the ion saturation current density -- in contradiction with "standard" sheath theory. One might try to resolve this contradiction by noting that the cathode, where the current originates, forms a small angle with the magnetic field lines, and then relating the observed high current density to purely geometrical effects. However, we show that, even accounting for the strong tilt, one can not derive the required high current. We suggest several alternative explanations: 1) Significant electron emission from the cathode, caused by UV radiation and/or by ion bombardment; 2) Formation of a cold, dense plasma near the electrodes; 3) Development of an instability leading to formation of small-scale arcs with a high current density. For the parameters of the SSPX experiments, all three mechanisms can, in principle, lead to the observed effect. We discuss their experimental signatures and possibilities for their experimental discrimination.

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Small sample effects in symbolic time series methods

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Abstract

Symbolic time-series methods have received some significant attention recently due to their robustness to noise, numerical efficiency, and ability to use low-resolution sensor data [1]. Given a symbolic time-series, one often proceeds to estimate information-theoretic quantities as measures of information content (Shannon entropy), correlation between two symbolic processes (mutual information), and information transfer (transfer entropy [2]). If the dynamical system under study is weakly non-stationary, or if the real-time monitoring of the system would require rapid decision-making (*e.g.* early detection of a plasma instability for control purposes), then the amount of symbolic data in the observation window will be severely restricted. In this poster, we examine the problem of estimating these information-theoretic quantities using limited samples of data.

Supported by the US Dept. of Energy.

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Presented at the Sherwood Fusion Theory Conference, Rochester, NY, April 22nd–24th, 2002.

Nonlinear Pulse Control Using Nonlinear Schrödinger Targets

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Abstract

It has been previously demonstrated [1] how to excite high amplitude nonlinear phase locked states of the Nonlinear Schrödinger Equation (NLS) using autoresonance (i.e. a spatially non-uniform drive with a frequency chirp). In the present work, we explore the use of a special class of exact solutions [2] of the NLS as "targets" for autoresonant pulse excitation. These solutions have narrow pulse shapes and envelopes which are periodic in time. It is shown that these targets, developed using the integrable theory, work also for non-integrable theories that lie 'nearby' in some structural sense (*e.g.* Ginzburg-Landau and Dysthe's equation) provided one uses a strong enough coupling. Bifurcations associated with the control of these systems will also be discussed.

Supported by the US Dept. of Energy.

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Potential Well Formation in Ion-Injected IEC

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Abstract

Present Inertial Electrostatic Confinement (IEC) experiments have been dominated by charge-exchange effects, but still a small potential well that traps energetic ions has been observed experimentally in agreement with theory for this highly non-Maxwellian, non-neutral plasma [1]. However, future high power-density IEC operation, it is essential that the background neutral density be decreased several orders of magnitude to minimize charge exchange effects. This goal has been partially realized in recent experiments at the U of I where ions were injected into the IEC [2]. Here we present a theoretical model which describes the change in IEC plasma discharge characteristics as a function of the injected-ion current density and ion beam directional orientation. The model agrees well with measurements of the reduction of the Paschen breakdown voltage curve. Likewise under these conditions the central plasma core potential well is increased in both depth (negative voltage) and diameter. Predictions of the change in these parameters as a function of injected ion current are presented, based on a modified Vlasov-Poisson solver. These results are analogous to prior bounce-averaged Fokker-Planck calculations that treated the reverse case of an electron-injected Penning trap [3]. Stability limitations for the ion-injected case are also briefly discussed within the framework of this model.

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Self-consistent modelling of helicon plasma sources

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Abstract

This work presents a first-principle theoretical model and a simulation code aimed to describe operation of helicon plasma sources in light gases. Particle balance, power balance, and the structure of the rf-fields are treated self-consistently. A distinctive feature of the model is that the particle confinement time in the plasma is much longer than the energy confinement time. The underlying physics reason is that the plasma flow from the source is controlled by the ion kinetics whereas the power balance involves much faster electron kinetics. Ion distribution function is essentially non-Maxwellian, dominated by collisions with the background neutral gas. Charge-exchange collisions and the ambipolar electric field determine the density profile in the plasma flow [1]. Electron distribution is Maxwellian provided that electron-electron collisions dominate over the electron-atom collisions. Electron temperature is determined by a local energy balance condition, since electron heating by rf-field is balanced mainly by energy losses on atom excitation. The absorption of rf-power is due to the excitation of radially localized helicon modes [2] by external antenna. This model specifies the range of background gas densities and power inputs for which steady-state regime is possible. The model also deals with discharge stability issues and suggests a mechanism for transitions from peaked to hollow density profiles in the helicon sources.

[1] Breizman, B.N. and Arefiev, A.V., *Ion kinetics in a magnetized plasma source,* to be published in Phys. Plasmas, 9, March 2002.
[2] Breizman, B.N. and Arefiev, A.V., *Radially Localized Helicon Modes in Nonuniform Plasma,* Phys. Rev. Lett., 84, 3863 (2000).

Research supported in part by Johnson Space Center, NASA

Spontaneous pulse formation in bistable systems

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Abstract

We consider the spontaneous formation of localized pulses in nonlinear, dissipative systems that are far from equilibrium and which exhibit bistability. We show that such pulses can form in systems that are dominated by the combined effects of: 1) a saturable amplifying or gain region, 2) a saturable absorbing or loss region, and 3) cavity effects. Analysis is based upon novel models for both an inertialess material in which the absorber responds instantaneously and non-inertialess material in which there is temporal delay in the response. We demonstrate that, under very general assumptions regarding the slow saturable response, pulses tend to form. Additionally, we include the situation where the material does not fully relax between pulses, *i.e.* memory effects. This leads to new phenomenon not found in the memory-less situation, specifically period-two 'hopping' and a slow oscillatory behavior reminiscent of 'breathing'.

Supported by the US Dept. of Energy.

Presented at the Sherwood Fusion Theory Conference, Rochester, NY, April 22nd–24th, 2002.

Coherent and Stochastic Motion of Magnetized Ions by Oblique Electrostatic Waves*

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Abstract

The interaction of ions in a uniform magnetic field with two obliquely propagating electrostatic waves is studied. This extends the earlier work which considered waves propagating directly across the magnetic field [1,2]. When the wave frequencies differ by an integer multiple of the cyclotron frequency, a nonlinear resonance occurs which produces large, coherent variation in Larmor radius r. A second-order Hamiltonian for the coherent motion is derived, using Lie transformation methods, which accurately determines the bounds in r of the ion motion. The coherent motion in z can be expressed as a function of r. A second-order Hamiltonian for the coherent motion is derived, using Lie transformation methods, which accurately determines the bounds in Larmor radius of the ion motion. The coherent motion in z can be expressed as a function of Larmor radius. Although the full problem has 2.5 degrees of freedom, the coherent motion possesses only 1 degree of freedom and is, therefore, integrable. We find that significant energization is possible for finite parallel wavevector k_z provided the difference $k_{1z} - k_{2z}$ of the two waves is small. We also study the stochastic motion both parallel and perpendicular to B_0, and the prospects for ion energization by two oblique waves.

* Work supported in part by NDSEG Graduate Fellowship, by joint National Science Foundation/U.S. Department of Energy Grant DE-FG02-99ER-54555, and by U.S. Department of Energy Grant DE-FG02-91ER-54109.

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Presented at the International Sherwood Fusion Theory Meeting, Rochester, New York, April 22–24, 2002.

Tuesday Afternoon

1:30 PM-6:00 PM

Memorial Art Gallery Auditorium

Snowmass Session

Snowmass Session

Ned Sauthoff presiding

1:30-1:45	Ned Sauthoff **Introduction to the Snowmass Fusion Summer Study**
1:45-2:00	Stewart Prager **Overview of Physics Working Group Activities**
2:00-2:20	Francis Perkins **ITER-FEAT: An Integrated Reactor-Scale Research Facility**
2:20-2:40	Bruno Coppi **Highlights of the Ignitor Experiment**
2:40-3:00	Dale Meade **FIRE, Exploring the Frontiers of Burning Plasma Science**
3:00-3:20	-------------------------*Break*---------------------------------------
3:20-3:40	Don Batchelor **Wave-Particle Interactions Physics Subgroup Activities**
3:40-4:00	Raffi Nazikian **Alpha Physics Working Group Activities and Progress**
4:00-4:20	Chris Hegna **Objectives of the 2002 Fusion Summer Study** **MHD Working Group**
4:20-4:40	Ronald Waltz **Snowmass Transport Working Group**
4:40-5:00	Thomas Rognlien **Tokamak Boundary Physics Simulation** **Comparison for Snowmass 2002**
5:00-5:20	**Discussion on Physics Issues**
5:20-6:00	**General Discussion**

Tuesday Evening

8:00 PM-9:30 PM

Memorial Art Gallery Auditorium

Oral Session 2D

Transport Scaling in an RFP Dominated by Tearing Modes

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A self-consistent model of transport scaling in an RFP dominated by tearing modes is presented. Specifically the dependence of τ_E and β_p on *I, n, a,* and the pinch parameter θ is derived. The theory is based on two underlying assumptions: (1) The self consistent equilibrium magnetic fields B_θ and B_z are basically given by Taylor's relaxation model, with appropriate modifications to take into account the presence of a cold wall. Taylor's theory captures the essential structure of the magnetic field but predicts a zero pressure gradient as it is a "relaxation theory" that does not attempt to take into account heating sources which drive a non-zero steady-state pressure. (2) The self-consistent pressure profile is determined by assuming that the ohmic heating source raises the plasma pressure until the profile is locally marginally stable to tearing modes. A critical point here is the long held belief that an RFP, because of its bad curvature, would always be unstable to tearing or resistive interchange modes; that is, there no marginally stable state exists. This belief turns out to be untrue. The basis for this statement is some recent work by *Lutjens et al*[1] who considered the effect of thermal conductivity on tearing and resistive interchange modes in a tokamak. When these results are applied to an RFP the conclusion is that tearing and interchange modes can indeed be stabilized when $\Delta' < -f(\chi_\perp)\beta_p$. This expression determines the marginally stable pressure profile. From a physics point of view a careful ordering of the resistive layer dynamics shows that thermal conductivity dominates over convection and compressibility. Thus, the use of the adiabatic equation of state in earlier work is not accurate for an RFP.

The actual numerical determination of the marginally stable profiles is somewhat challenging. One must find profiles that are locally marginally stable to tearing modes, but whose stability boundary depends on the global parameter Δ'. Also, the critical pressure gradient depends on $\chi_\perp$. Thus, the energy equation actually becomes a nonlinear ordinary differential equation with the self-consistent $\chi_\perp$ being the dependent variable. The situation is further complicated by the fact that near the origin Suydam's criterion provides an even more stringent marginal stability boundary than tearing modes. These difficulties have been overcome and the result is a determination of the dependence of τ_E and β_p on *I, n, a,* and θ. It is worth emphasizing that there are no free parameters in the model. Point checks indicate reasonable agreement with typical experimental data. Parametric numerical studies are currently underway to span the operational space of RFP experiments. The tearing mode transport scaling relations for τ_E and β_p will be presented at the meeting as well as a comparison with other transport models.

[1] H. Lutjens, J. F. Luciani, X. Garbet, Phys. Plasmas **8**, 4267 (2001)

Statistics of Anomalous Transport Events

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Abstract

Prediction of particle and heat transport is essential to obtaining a controlled magnetic fusion. In particular, large transport events of substantial amplitude, even if rare, can be dangerous for confinement, on account of their strength. There is mounting evidence, from simulations and experiments, that transport is intermittent and consists of an ensemble of events, with a non-Gaussian probability distribution function (PDF). These events are associated with coherent structures such as streamers or blobs and are often bursty in time, thus leading to non-Gaussian statistics in the PDF tails. Here, we present a novel statistical approach to the prediction of these rare, large transport events.

Based on the observation that intermittent transport is often associated with coherent structure, we relate PDF tails to a probability of creation of various coherent structures (or, the transition amplitude between the state with no fluid motion and that with coherent structures) in a long time limit. An instanton, with spatial form given by a coherent structure, captures this very process of the creation of a coherent structure, and thus can be associated with bursty and intermittent events which are thought to be responsible for PDF tails. With this ansatz, PDF tails can be computed by finding an instanton which is a saddle-point solution of an effective action expression for the PDF, which can, in general, be given by a path integral.

This idea is exploited for the prediction of the PDF tails of flux transport in a magnetically confined plasmas. We consider the momentum flux (R) in a forced Hasegawa-Mima turbulence, which is responsible for the generation/destruction of a large-scale shear flow. Under the assumption that the nonlinear structure is a modon in space (an exact solution of a nonlinear Hasegawa-Mima equation), we find PDF tail for R with the specific form $\exp[-cR^{3/2}]$, which is a stretched, non-Gaussian exponential. A similar result is also found for the PDF tail of heat transport in a simple toroidal ITG, when the nonlinear structure leading to the tail is a modon. Possible extensions of this approach to the prediction of the PDFs for transport events will be explored. In particular, PDFs of (large-scale) structure formation, such as streamers or zonal flows, will be discussed.

Chaotic Scattering and the Magneto-Coulomb Map

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Abstract

A non-relativistic classical electron scattering by a fixed ion in a uniform magnetic field is discussed. The system is non-integrable, and there is chaotic scattering for certain class of initial conditions. Indeed, this has been noticed by Delos *et al.* [1] and analyzed later by Schmidt *et al.* [2] (also see [3,4,5,6] for the trapped motion of the electron and for the classical case as well as the quantum case). So far, all analyses were based on the continuous flow generated by the equation of motion. However, as we shall show below, that there are many cyclotron periods in a single scattering during the electron-ion interaction time interval. As a result, the numerical integration of the equation of motion for the continuous flow is very time-consuming and the predictions for long time behavior become unstable, which is the typical case of the chaotic scattering. For this reason, we derive a two-dimensional discrete map of the chaotic scattering from the equation of motion. Our map exhibits four different types of motion by changing the parameters which characterize the initial condition. The fractal structure for certain observables is obtained. The width of the chaotic scattering region in the impact parameter is estimated numerically. We suggest a certain class of plasma enviroments where the chaotic scattering may have an important role.

[1] J. B. Delos, S. K. Kundson and D. W. Noid, Phys. Rev. A **30**, 1208 (1984).
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Wednesday Morning

8:30 AM-9:30 AM

Memorial Art Gallery Auditorium

Review Paper 3A

A Review of Magnetorotational Instability in Astrophysics

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Abstract

Plasma parameters and other important physical characteristics of astrophysical disks are summarized. The observed luminosity of such disks is proportional to their radial mass flux (accretion rate) onto the central star or black hole around which the disk orbits. Anomalous outward transport of angular momentum is required to balance its inward advection by accretion. We explain why magnetorotational instability (MRI) is the most likely cause of this transport and sketch the essential physics of the linear MRI modes, together with the history of their discovery by Velikhov, Chandrasekhar, and Balbus and Hawley. Plasma inertia is essential to MRI, which appears to be an intrinsically high-β phenomenon. During the past decade, several groups have studied MRI-driven turbulence by numerical simulations. Dynamo action is observed, and indeed required for sustained MRI-driven turbulence (TMRI) absent an externally applied magnetic field. A consensus has emerged from this work, but important questions remain. Cool and weakly-ionized disks are probably too resistive for TMRI, but the threshold for TMRI is uncertain; Hall conductivity may be critical in this regime. In the opposing high-temperature limit, it is unclear whether the orbital energy dissipated by TMRI goes mostly into ions or electrons; observations of the Galactic Center and other low-luminosity systems appear to favor a two-temperature plasma. Even for fully-ionized disks of moderate temperature with $T_e = T_i$, simulations may underestimate the anomalous angular-momentum transport because of their limited range of resolved spatial scales. Also, the response of the turbulence to time-dependent perturbations of the disk, such as pressure waves excited by embedded planets, has scarcely been investigated but is likely to be nontrivial since the frequency of such perturbations is often comparable to, or shorter than, the MRI growth rate. If time permits, we will sketch prospects for laboratory studies of MRI in differentially rotating liquid metals.

Wednesday Morning

9:50 AM-12:20 PM

Memorial Art Gallery Auditorium

Oral Session 3B

Angular Momentum "Generation": Theory and Recent Experiments*

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Two of the key elements of the accretion theory [1] of the angular momentum "generation" phenomenon in axisymmetric toroidal plasmas are the transfer of angular momentum to the surrounding material wall by plasma modes excited at the edge of the plasma column and the transport of "negative" angular momentum toward the center of the plasma column by "remnant" ion temperature gradient driven modes. The phase velocity of the edge scattering modes is expected to reverse direction in the transition from poor confinement regime, for the ion thermal energy, to good confinement (e.g. H-regime). Consequently the oppositely directed toroidal velocity within the plasma column also reverses. The relationship of this theory to recent experiments that have provided support for it is pointed out.

The toroidal analysis of the main elements of the theory, that involve the quasi-linear angular momentum "pinch", the characteristics of the modified ITG modes involved, the excited spectrum and the related transport coefficient for the plasma thermal energy, is presented. The inadequacy of the neoclassical transport theory to explain the experimental observations is also pointed out on the basis of a complete analysis carried out for the regimes of interest.

In particular, the phase velocity of the modes at the edge of the plasma column in the JET machine have been observed to be in the direction of the electron diamagnetic velocity in the H-regime and to reverse in the L-regime [2]. The central toroidal velocity has been related to the peak ion pressure in the Tore-Supra [3] experiments. The formation of a steep density gradient within the plasma column in the Alcator C-Mod [4] has been observed to suppress the plasma rotation in the H-mode regime.

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* Sponsored by the U.S. Department of Energy

Nonlinear MHD and Energetic Particle Modes in Stellarators

H.R. Strauss[1]
G.Y Fu[2] , W. Park[2], J. Breslau[2]
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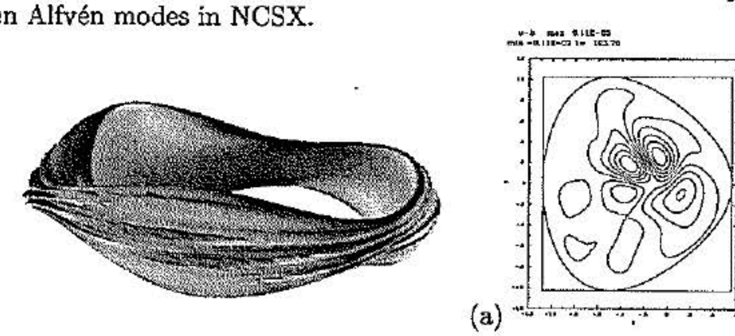
The M3D (Multi-level 3D) project [1] carries out simulation studies of plasmas using multiple levels of physics, geometry, and grid models. M3D combines a two dimensional unstructured mesh with finite element discretization in poloidal planes and fourth order finite differencing in the toroidal direction. The code is parallelized and runs on both shared and distributed memory computers.

The M3D code has been applied to ideal, resistive, two fluid, and hybrid simulations of compact quasi axisymmetric stellarators. Equilibria are initialized with the VMEC code [2]. M3D equilibria agree well with VMEC, except that M3D magnetic fields can contain islands. In ideal MHD simulations, when β exceeds a threshold, low poloidal mode number ($m \sim 6-12$) modes grow exponentially, clearly distinguishable from the equilibrium evolution. The β limit found for NCSX is significantly higher than the infinite mode number ballooning limits. In the presence of resistivity, these modes occur well below the ideal limit. Their growth rate scaling with resistivity is similar to tearing modes. With sufficient viscosity, the growth rate becomes slow enough to allow calculations of magnetic island evolution. Islands found by M3D are consistent with PIES [3] results.

Hybrid gyrokinetic simulations with energetic particles indicate that global shear Alfvén TAE - like modes can be destabilized in stellarators, as in tokamaks. Computations in a two - period compact stellarator obtained a predominantly $n = 1$ toroidal mode with about the expected TAE frequency $V_A/(2qR)$ at the q=2.5 surface. Work is in progress to study fast ion-driven Alfvén modes in NCSX.



(a) (b)

(a) Pressure isosurface in a ballooning unstable NCSX stellarator design (b) electrostatic potential in a TAE - like mode in a period two stellarator

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Supported by U.S. DOE grant DE-FG02-86ER53223 and contract DE-AC02-76-CHO-3073

Renormalization of the GLF23 transport model and burning plasma projections on a universal curve of Q versus T_{ped}*

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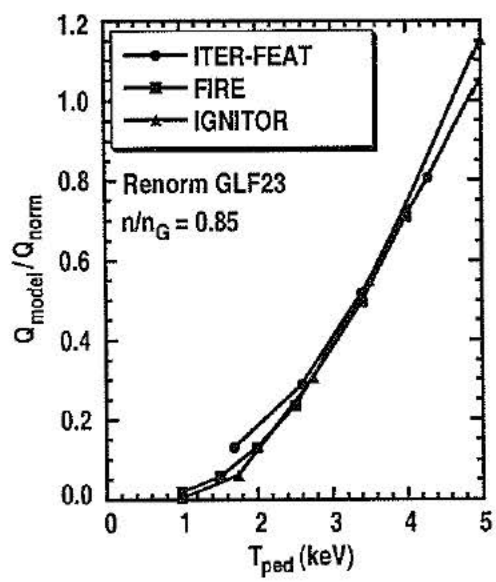
Abstract

Recent gyro-kinetic simulations[1] with adiabatic electrons indicate that the turbulent heat fluxes due to ion temperature gradient (ITG) modes are nearly a factor of four lower than gyro-fluid results used to normalize the original 1996 GLF23 drift-wave transport model.[2] Other simulations of electron temperature gradient (ETG) mode turbulence have shown that electron heat fluxes due to these modes is significantly larger than expected from simple isomorphic estimates found by root of the mass ratio scaling from ITG simulations. A renormalized version of GLF23 model has been found using experimental data from nearly fifty H-mode discharges from the DIII-D, C-Mod, and JET tokamaks consistent with the gyrokinetic simulations. The two normalizing coefficients of the ITG/TEM and ETG modes were adjusted separately to minimize the standard deviation of the core stored energy at zero offset over the database. The renormali-zation reduces the coefficient on the ITG/TEM modes by a factor of 3.7 while increasing the coefficient on the ETG modes by a factor of 4.8 with respect to the original model. The renormed ITG is less stiff and the ETG has a marked degree of non-isomorphism ($3.7\times4.8 = 17.8$) as suggested by the recent simulations.[1,3] The renormalization improved the statistical deviation on the core stored energy from 10% to 8.7%. Using the renormed model, the fusion performance for ITER-FEAT, FIRE, and IGNITOR was reassessed. As a result of the renormalization, we find the predicted performance is somewhat improved with a lower pedestal temperature required to reach a desired level of fusion power. The renormed model is still stiff and tracks the stiff model fusion gain scaling $Q = Q_{norm} \times$ Function (T_{ped}) where $Q_{norm} = \kappa R (I/a)^2 (n/n_G)^2/P_{aux}$ very well. Furthermore, since all three devices have nearly the same q, a/R, and κ, they all lie on the same universal curve of Q/Q_{norm} versus T_{ped}.



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*Work supported by U.S. DOE under Grants DE-FG03-95ER54309 and DE-FG03-92ER54141.

Ion runaway acceleration during magnetic reconnection in MAST

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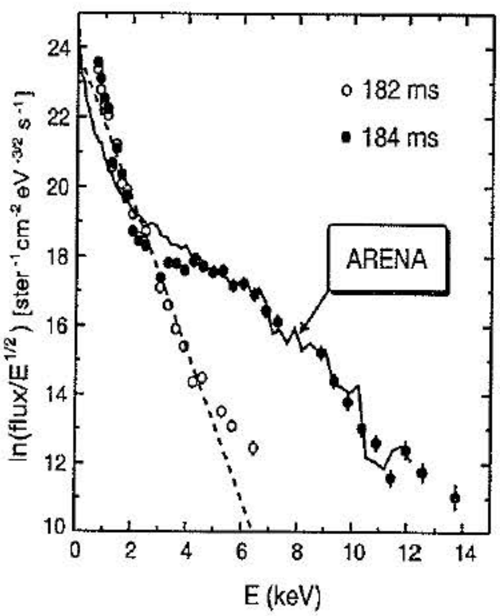
In MAST, suprathermal ions are routinely observed by the neutral-particle analyser in Ohmic discharges with internal reconnection events. In each such event, a high-energy tail is formed in the ion distribution function, which then relaxes back towards a Maxwellian on the collision time scale. In this paper a kinetic theory is developed to explain these observations in terms of runaway ion acceleration in the parallel electric field induced by the reconnection – a phenomenon predicted theoretically by Furth and Rutherford in 1972 but not commonly noted in tokamaks [1]. The observed ion acceleration in MAST is reminiscent of observations of ion heating and tail formation in reversed field pinches, and could shed light on this long-standing puzzle.

The electric field is calculated from a simple model of reconnection events based on magnetic helicity conservation, which successfully predicts their main characteristics: an increase in total plasma current, a broadening of the current profile, and a negative voltage spike at the plasma edge. The effective electric field acting on the plasma ions is then calculated using tools from neoclassical theory to account for the effects of impurity ions and toroidicity, these being crucial for achieving ion acceleration. Finally, the ion distribution function is calculated, both analytically and numerically. The analytical theory is a generalisation of a classic runaway calculation of Kruskal and Bernstein so as to account for the fact that only a finite time is available for ion acceleration. The numerical solution is obtained from the ARENA Monte Carlo code that solves the orbit-averaged kinetic equation in toroidal geometry [2]. These simulation results, which are obtained using no "free" parameters, are in excellent agreement with the experimental energy spectra of fast ions.



Ion distribution function before and after a reconnection event, as measured by the NPA and simulated with the ARENA code.

This work was funded jointly by EURATOM and the UK Department of Trade and Industry.

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A Hall Dynamo Effect Driven By Two Fluid Tearing Instability

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Abstract

The spontaneous generation of magnetic field (the dynamo effect) in laboratory and astrophysical plasmas has been extensively studied using single-fluid magnetohydrodynamics (MHD). In the MHD dynamo, large scale magnetic fields are driven by correlation between fluctuations in the plasma velocity and magnetic field. In laboratory plasmas, tearing instabilities that induce magnetic reconnection generate the fluctuations. The tearing mode dynamo effect driven by the **v** x **B** term in Ohm's law has been investigated through quasilinear theory [1], nonlinear computation [2] and experiment [3]. Two-fluid effects, considered here, affect dynamos in two ways: by altering the MHD **v** x **B** dynamo and by introducing the Hall dynamo mechanism generated by the **j** x **B** /en term in the generalized Ohm's law. **The quasilinear theory predicts that the two-fluid dynamo arising from the Hall term is much larger than the standard MHD prediction using a single fluid treatment.**

We calculate quasilinearly two-fluid dynamo effects from tearing instability in a force-free (constant pressure) slab equilibrium relevant to the RFP, as well as other laboratory and astrophysical situations. Two-fluid tearing mode eigenfunctions are evaluated using the generalized Ohm's law in a compressible plasma. Instability dynamics relate to the kinetic (shear) Alfven wave, decoupled from the fast compressional Alfven and slow magneto-acoustic modes. The growth rate is enhanced over the MHD growth rate, scaling as $\delta^{1/3}\rho_s^{2/3}$ where δ is a combination of collisionless and collisional electron skin depth and ρ_s is the ion-sound gyroradius. We evaluate the Hall dynamo (<**j** x **B**>/ne, where **j** and **B** are current density and magnetic fuctuations, and < > denotes a flux surface average) and the standard dynamo also captured in MHD (<**v** x **B**>). We examine the dynamo terms for two cases: the experimental case for which $\rho_s \gg \delta$ and, for comparison, the single-fluid MHD case for which $\rho_s \ll \delta$. For the experimental situation (in which two-fluid effects are important) the Hall dynamo effect is larger than the single-fluid MHD dynamo by a factor $\propto (\rho_s/\delta)^2$. This enhancement factor is typically more than an order of magnitude in RFP plasmas. The Hall dynamo is localized to within a distance δ of the resonant surface. In two-fluid theory, the <**v** x **B**> term is also enhanced by a smaller factor $\propto (\rho_s/\delta)^{2/3}$ and is broadened to a spatial scale of order ρ_s. These enhancements result from decoupling of electrons from ions in the vicinity of the resonant surface, and motivate experimental investigation of two-fluid effects in the RFP.

[1]see, for example, A.Bhattacharjee, and E.Hameiri, Phys. Rev. Lett., **56**, 206, (1986)
[2]see, for example, S.Ortolani, D.Schnack, *Magnetohydrodynamics of plasma relaxation*, 1993
[3]see, for example, P.W.Fontana, D.J.Den Hartog, G.Fiksel, and S.C.Prager, Phys.Rev.Lett., **85**, 566, 1999

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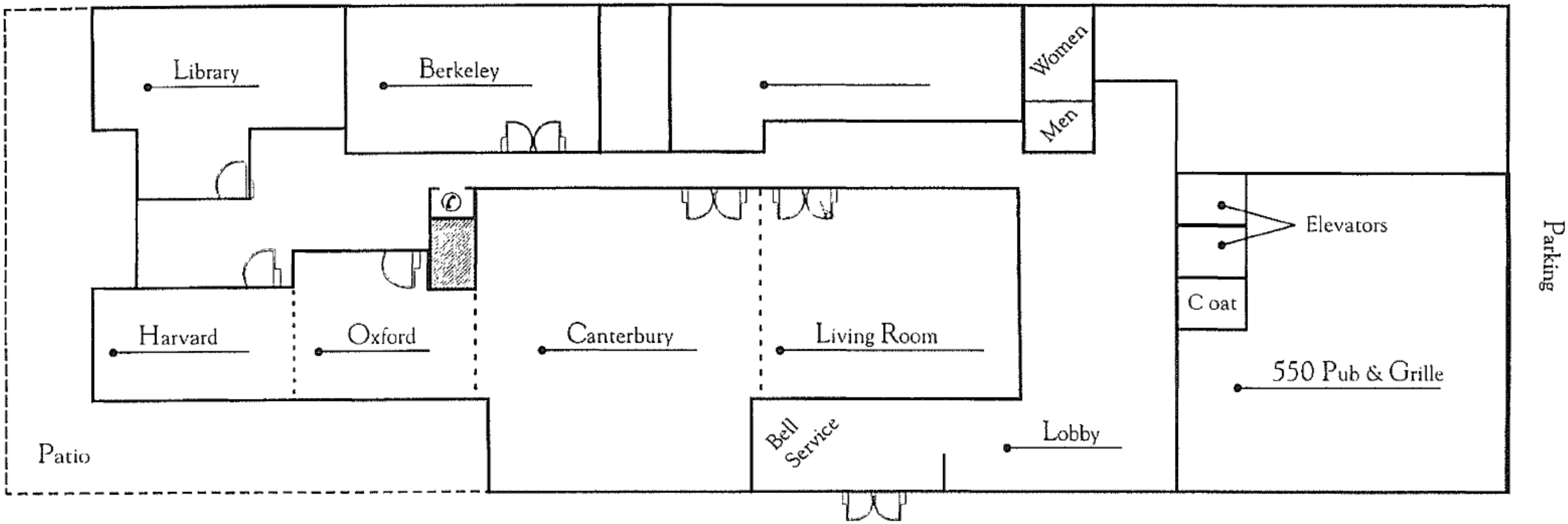

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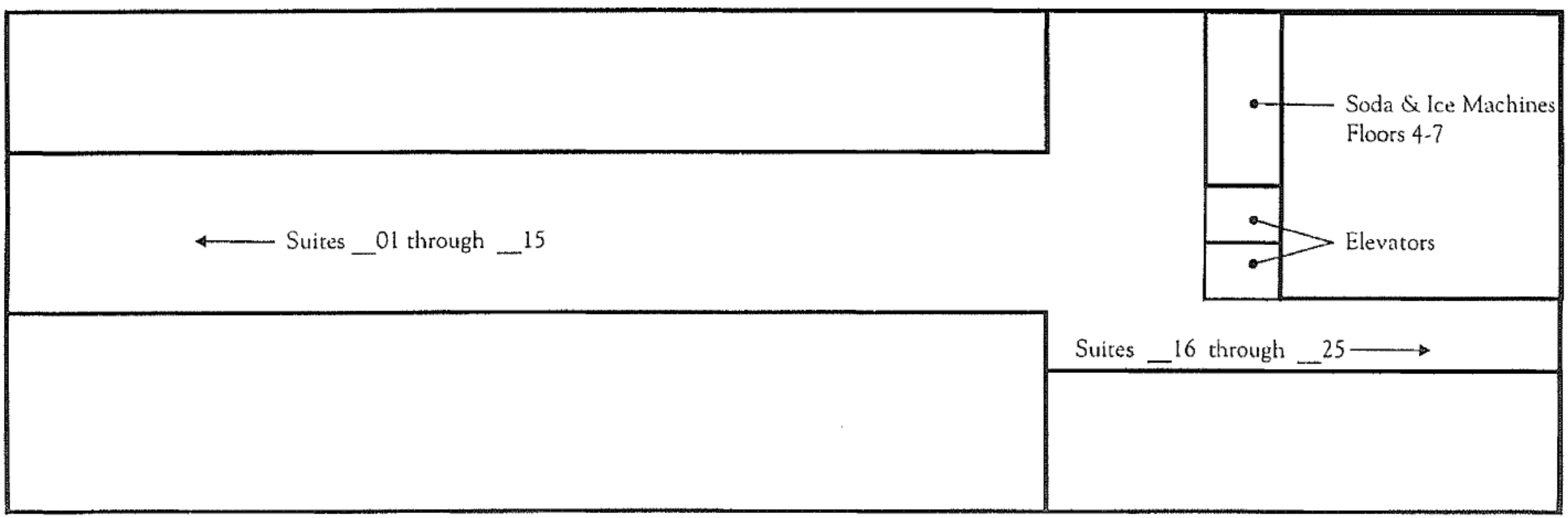

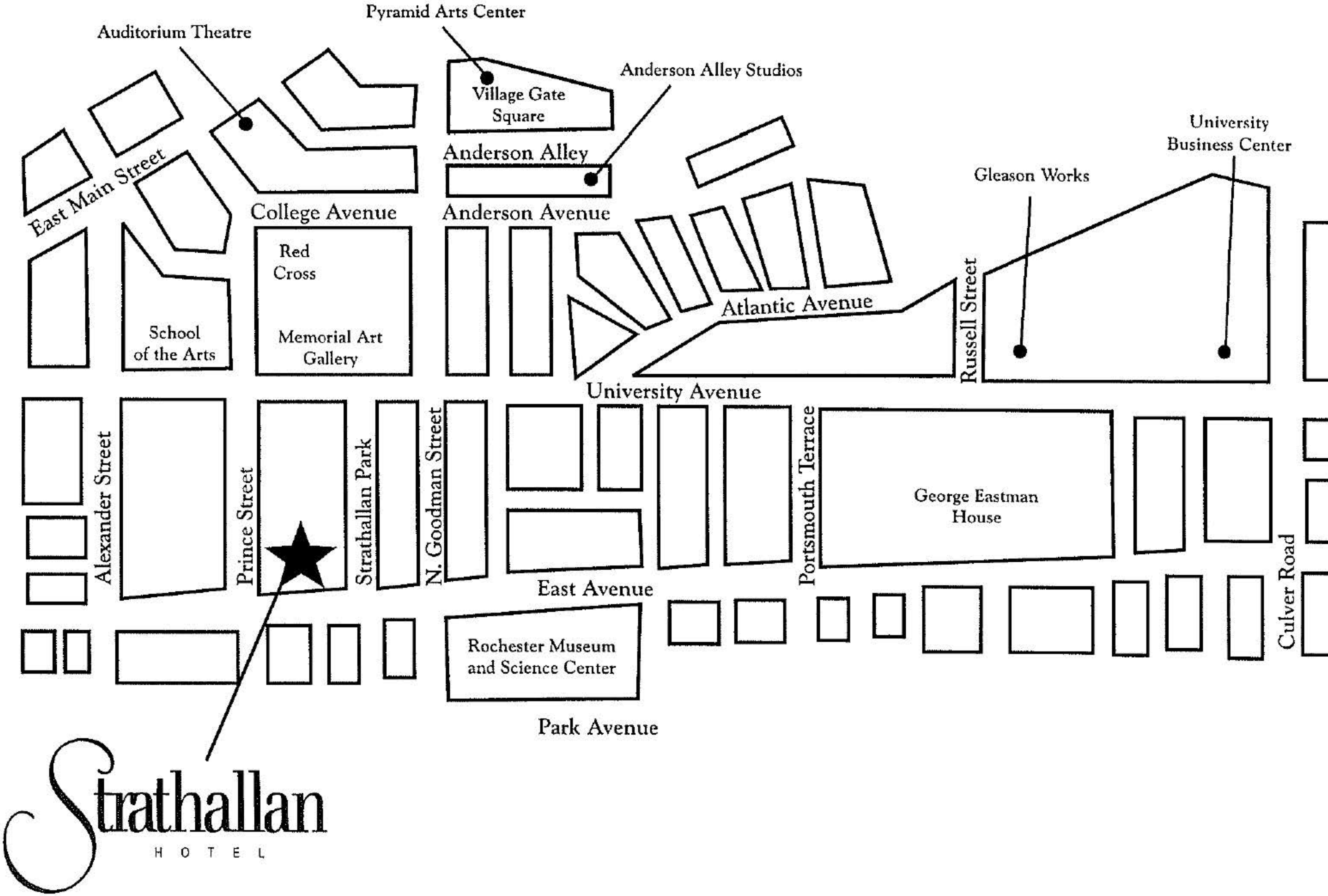
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