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1997 International Sherwood Fusion Theory Conference

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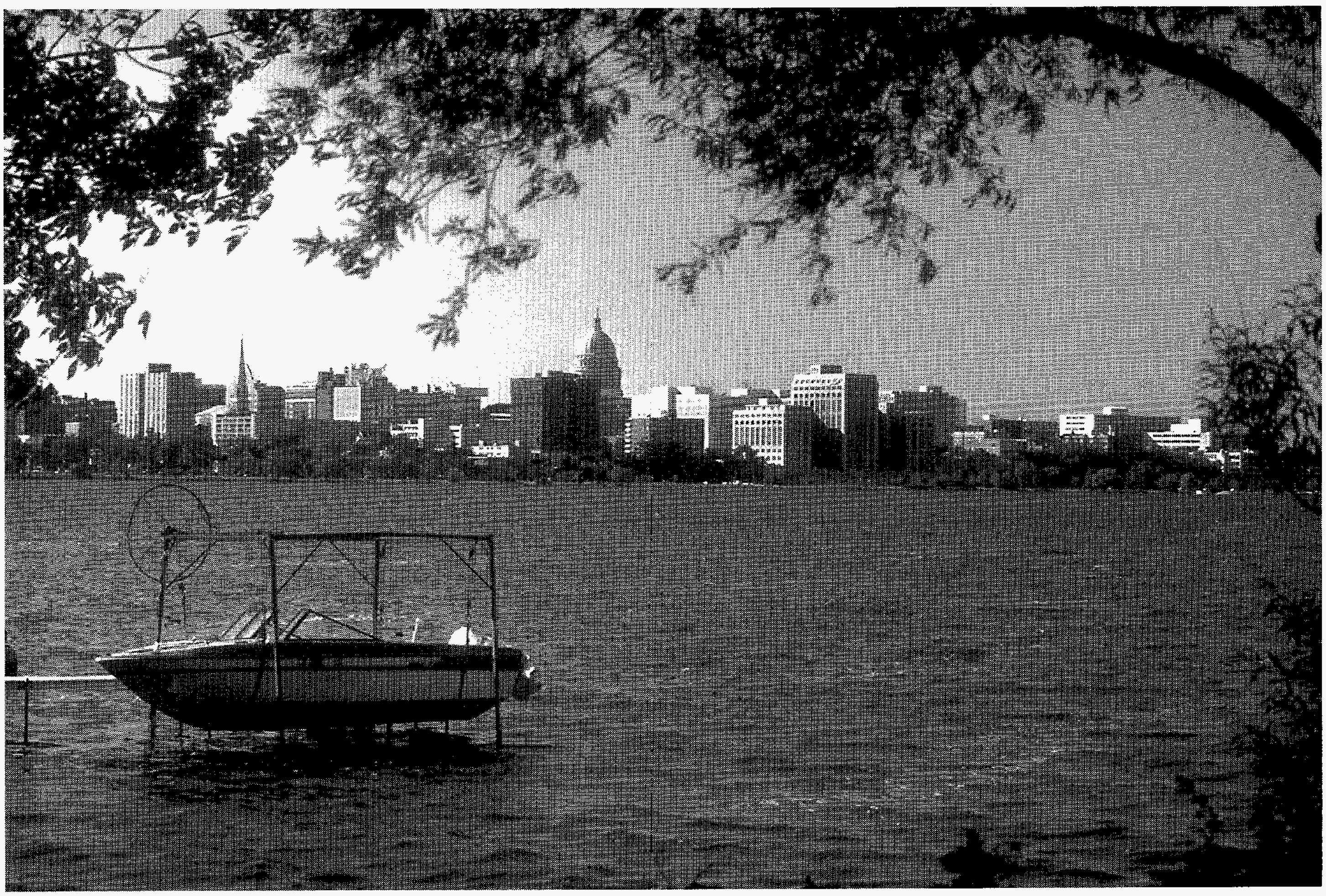
April 28–30, 1997
Madison, Wisconsin



Hosted By
University of Wisconsin–Madison

1997
International
Sherwood Fusion Theory Conference

April 28–30, 1997
The Wisconsin Center, 702 Langdon Street
Madison, Wisconsin

Hosted by

University of Wisconsin–Madison

United States Department of Energy
Office of Fusion Energy Sciences

Executive Committee

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Program Committee

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GENERAL INFORMATION

In all, 201 papers were submitted, 120 of these electronically. Of these, 13 were selected for oral presentation out of 41 requests. In addition, there are 3 review papers. Several ancillary meetings are scheduled as well.

MEETING PROGRAM

- The **review papers** (1A01, 2A01, 3A01) will be presented in the Lakeshore Room at 8:30 a.m. Monday through Wednesday.
- The **oral papers** will be presented in the Lakeshore Room as follows: On Monday from 9:30 a.m. to 12:00 noon (1B), on Tuesday from 9:30 a.m. to 10:30 a.m. (2B) and 7:30 p.m. to 9:30 p.m. (2D), and on Wednesday from 9:30 a.m. to 10:30 a.m. (3B).
- All **poster sessions** will be presented in two-hour sessions in the Alumni Lounge and Lee Lounge. They will be on Monday starting at 2:00 p.m. (1C) and 4:00 p.m. (1D), on Tuesday starting at 10:30 a.m. (2C), and on Wednesday starting at 10:30 a.m. (3C).
- **Poster boards** will be available for the review and oral speakers in a designated area of the poster session in the Alumni Lounge that follows their presentations.

MEETING MODALITIES

- **Registration** will be held in the main lobby on Sunday evening from 6:00 p.m. to 9:00 p.m. and on Monday morning from 7:30 a.m. to 12:30 p.m. It will then move to the Conference Office, Room 109 on the main hallway, and be open Monday afternoon from 1:15 p.m. to 6:00 p.m., Tuesday from 8:00 a.m. to 12:30 p.m. and 7:30 p.m. to 9:30 p.m., as well as Wednesday from 8:00 a.m. to 12:30 p.m.
- A complimentary **Reception** of light appetizers with a cash bar will be held on Sunday evening from 6:00 p.m. to 9:00 p.m. in the Alumni Lounge.
- A complimentary **Companions' Breakfast** will take place Monday morning at 9:00 a.m. in the Main Lounge.
- **Coffee** will be served 9:15 a.m. – 11:00 a.m. Monday in the Alumni Lounge, Tuesday and Wednesday in both the Alumni Lounge and the Lee Lounge.
- **Beverages** will be served in the Alumni Lounge and Lee Lounge beginning at 3:00 p.m. on Monday and 8:00 p.m. on Tuesday.
- A **Buffet Dinner** will be served on Tuesday evening in the Main and Lee Lounges beginning at 6:15 p.m., preceded by a cash bar at 6:00 p.m., in the Main Lobby.

ANCILLARY MEETINGS

- The **MHD Working Group** will meet Sunday afternoon, April 27, 2:00 p.m. to 6:00 p.m.
- A special session on **The New NERSC at LBNL** will be held in the Lakeshore Room, 1:15 p.m. to 2:00 p.m. on Monday, April 28.
- The **Numerical Tokamak Turbulence Workshop** will begin on Wednesday afternoon, April 30, and run through Thursday, May 1.
- The **Nonlinear MHD and Extended-MHD Workshop** will meet Wednesday afternoon, April 30, through Friday morning, May 2.
- **Future Sherwood** meetings: *Sherwood 98*, hosted by Auburn University, will meet in Atlanta, Georgia, March 23–25, 1998. *Sherwood 99*, will be held March 22–24, 1999, in Atlanta as an imbedded topical conference in the APS centennial meeting held there then. *Sherwood 00*, hosted by UCLA, will meet in Los Angeles.

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The Wisconsin Center, 702 Langdon Street
Madison, Wisconsin
April 28-30, 1997

Registration Schedule

Sunday	6:00 p.m. – 9:00 p.m.	Main Lobby
Monday	7:30 a.m. – 12:30 p.m.	Main Lobby
	1:15 p.m. – 6:00 p.m.	Room 109
Tuesday	8:00 a.m. – 12:30 p.m.	Room 109
	7:30 p.m. – 9:30 p.m.	Room 109
Wednesday	8:00 a.m. – 12:30 p.m.	Room 109

Presentations Schedule

Review and Oral Presentations: Lakeshore Room
Poster Presentations: Alumni Lounge and Lee Lounge

Monday

8:20 a.m. – 8:30 a.m.	Welcome	J.D. Callen, *Chairman*	
8:30 a.m. – 9:30 a.m.	1A	Review Paper	**J. Nührenberg**
9:30 a.m. – 12:00 noon	1B	Oral Session	(5 30–minute talks)
......		***Lunch break***	......
1:15 p.m. – 2:00 p.m.		Special Session: NERSC	Lakeshore Room
2:00 p.m. – 4:00 p.m.	1C	Poster Session	Alumni Lounge and Lee Lounge
4:00 p.m. – 6:00 p.m.	1D	Poster Session	Alumni Lounge and Lee Lounge

Tuesday

8:30 a.m. – 9:30 a.m.	2A	Review Paper	**R. Granetz**
9:30 a.m. – 10:30 a.m.	2B	Oral Session	(2 30–minute talks)
10:30 a.m. – 12:30 p.m.	2C	Poster Session	Alumni Lounge and Lee Lounge
......		***Free afternoon***	......
7:30 p.m. – 9:30 p.m.	2D	Oral Session	(4 30–minute talks)

Wednesday

8:30 a.m. – 9:30 a.m.	3A	Review Paper	**P.H. Roberts**
9:30 a.m. – 10:30 a.m.	3B	Oral Session	(2 30–minute talks)
10:30 a.m. – 12:30 p.m.	3C	Poster Session	Alumni Lounge and Lee Lounge

Coffee: 9:15 a.m. – 11:00 a.m. Monday in the Alumni Lounge, Tuesday and Wednesday in both the Alumni Lounge and the Lee Lounge
Beverages: 3:00 p.m. – 5:00 p.m. Monday and 8:00 p.m. – 9:00 p.m. Tuesday in both the Alumni and the Lee Lounge

Oral Presentations

Monday Morning

Welcome		
8:20 a.m.		J. D. Callen, *Local Arrangements Chairman*
Review Paper	1A	J.D. Callen Presiding
8:30 a.m.		**J. Nührenberg**, *Quasi-symmetries in toroidal confinement*
Oral Session	1B	J. Drake Presiding
9:30 a.m.		**S.G. Shasharina**, *Omnigenous non-quasihelical system*
10:00 a.m.		**J. Kesner**, *Stability of a levitated dipole*
10:30 a.m.		**R.A. Nebel**, *The periodically oscillating plasma sphere (POPS)*
11:00 a.m.		**B.N. Rogers**, *Electromagnetic enhancement of turbulence and spontaneous transport barrier formation in tokamaks*
11:30 a.m.		**B.H. Fong**, *Explosive ballooning modes and high-β disruptions*
Special Session:		
1:15 p.m.		**Horst D. Simon**, *The New NERSC (National Energy Research Scientific Computing Center) at LBNL*

Tuesday Morning

Review Paper	2A	V. Chan Presiding
8:30 a.m.		**R. Granetz**, *Disruptions in tokamaks*
Oral Session	2B	W. Dorland Presiding
9:30 a.m.		**A.M. Popov**, *Nonlinear 3D simulations of disruptions in NCS discharges in DIII-D*
10:00 a.m.		**S.C. Chiu**, *Fokker-Planck simulations of knock-on runaway electron generation in tokamaks*

Tuesday Evening

Oral Session	2D	R. Cohen Presiding
7:30 p.m.		**W. Kerner**, *Alfvén eigenmode stability and alpha particle transport in JET tritium discharges*
8:00 p.m.		**N.N. Gorelenkov**, *2-D high-n analysis of toroidicity induced Alfvén eigenmodes*
8:30 p.m.		**N.V. Petviashvili**, *Spontaneous hole-clump pair creation in a weakly unstable plasma*
9:00 p.m.		**T.D. Rognlien**, *Detached divertor plasmas with time variation*

Wednesday Morning

Review Paper	3A	J.M. Finn Presiding
8:30 a.m.		**P.H. Roberts**, *The Dynamo within the Earth*
Oral Session	3B	A. Reiman Presiding
9:30 a.m.		**F. Pegoraro**, *Finite temperature effects on collisionless magnetic reconnection*
10:00 a.m.		**E. Fernandez**, *Decorrelation dynamics, spectra, and transport in drift-Alfvén turbulence*

Conference Presentations

Sherwood '97

The Wisconsin Center, 702 Langdon Street,
Madison, Wisconsin
April 28–30, 1997

Monday Morning

Welcome: 8:20 a.m. — J. D. Callen, *Local Arrangements Chairman*

1A **Review Paper** Lakeshore Room, 8:30 a.m. – 9:30 a.m., J.D. Callen Presiding

1A01. J. Nührenberg, *Quasi-symmetries in Toroidal Confinement*

Coffee: 9:15 a.m.–11:00 a.m. — Alumni Lounge

1B **Oral Presentations** Lakeshore Room, 9:30 a.m. – 12:30 a.m., J. Drake Presiding

1B01. *Omnigenous non-quasihelical system*
S.G. Shasharina and John R. Cary

1B02. *Stability of a levitated dipole*
J. Kesner

1B03. *The periodically oscillating plasma sphere (POPS)*
Richard A. Nebel and Daniel C. Barnes

1B04. *Electromagnetic enhancement of turbulence and spontaneous transport barrier formation in tokamaks*
B.N. Rogers and J.F. Drake

1B05. *Explosive ballooning modes and high-β disruptions*
Bryan H. Fong and Steven C. Cowley

Lunch Break: 12:00 p.m. – 2:00 p.m.

Monday Afternoon

Special Session Lakeshore Room, 1:15 p.m. – 2:00 p.m., M. Crisp Presiding
The New NERSC (National Energy Research Scientific Computing Center) at LBNL
Horst D. Simon

Beverages: 3:00 p.m. – 5:00 p.m. — Alumni Lounge and Lee Lounge

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1C **Poster Presentations** Alumni Lounge, 2:00 p.m. – 4:00 p.m.

1C01. *Feasibility study of finite difference approach to kinetic neutral modeling in edge plasmas*
M.L. Adams, S.I. Krasheninnikov, O.V. Batishchev, D.J. Sigmar

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

1C02. *Long mean free path electron heat conduction modifications*
Peter J. Catto

1C03. *Theory of ion and impurity transport in edge plasmas*
P. Helander, F. Wising, Peter J. Catto and R.D. Hazeltine

1C04. *Radiation front jumps in a tokamak divertor*
S.I. Krasheninnikov, A.A. Batishcheva and D.J. Sigmar

1C05. *Simulation of neutral gas transport in a detached divertor using non-linear Monte-Carlo code*
A. Yu. Pigarov and S. I. Krasheninnikov

1C06. *Theoretical interpretation of experimental results from linear machine NAGDIS II*
D.J. Sigmar, A. Yu. Pigarov, S.I. Krasheninnikov, S. Takamura, N. Ohno and N. Ezumi

1C07. *Divertor scaling law simulations*
D.A. Knoll, Peter J. Catto and S.I. Krasheninnikov

1C08. *Study of Balmer spectrum and near photo-recombination edge in Alcator C-Mod divertor plasmas*
J.L. Terry, A. Yu. Pigarov and B. Lipschultz

1C09. *Reversed shear transport barriers*
W. Horton

1C10. *3D effects in turbulent compressible shear flows over toroidal cavities in the neutral gas blanket divertor region*
George Vahala, Linda Vahala and Joseph Morrison

1C11. *Effect of neutrals on SOL & divertor stability*
D.A. D'Ippolito and J.R. Myra

1C12. *Kinetic analysis of instabilities in tokamak plasmas*
Aaron J. Redd, Arnold H. Kritz, Glenn Bateman, Gregory Rewoldt and Jon Kinsey

1C13. *Fokker-Planck simulation of lower hybrid current drive in the reversed field pinch*
E. Uchimoto, R.W. Harvey, A.P. Smirnov, S.C. Prager, J.S. Sarff and M.R. Stoneking

1C14. *Fokker-Planck simulation of parallel electron transport in TdeV tokamak*
M. Shoucri, I. Shkarofsky, B. Stansfield, C. Boucher, G. Pacher, O.V. Batishchev, A. A. Batishcheva, S.I. Krasheninnikov and D.J. Sigmar

1C15. *Noncanonical Hamiltonian theory with applications to linear and nonlinear waves, conservation laws and variational structure*
Jonas Larsson

1C16. *A filament model for resistive wall mode feedback stabilization*
M. Okabayashi, N. Pomphrey, R. Hatcher and R. Woolley

1C17. *α-dynamo effect of Alfvén waves and current drive in reversed field pinches*
C. Litwin and S.C. Prager

1C18. *Improved theory of neoclassical electrical conductivity in a tokamak plasma*
C.S. Chang

1C19. *Effects of intense pulsed LH waves in tokamaks: nonlinear wave coupling, electric fields, plasma rotation and backward current*
V. Petrzílka, J.A. Tataronis, R. Kílma and L. Krlín

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

1C20. *Improved δf-discretization scheme for nonlinear gyrokinetic particle simulations*
R. Zorat and M. Tessarotto

1C21. *Diamagnetic effects on flow-shear MHD equilibria*
J.L. Johnson, M. Tessarotto, R.B. White and R. Zorat

1C22. *Data compression and information retrieval via symbolization*
X.Z. Tang and E.R. Tracy

1C23. *Gyrokinetic particle simulation of small-scale magnetic islands in high temperature tokamak plasmas*
R.D. Sydora

1C24. *Confinement of alpha particles in monotonic and reversed magnetic shear plasmas on TFTR*
M.H. Redi, R.B. White, S.H. Batha, F.M. Levinton, S.S. Medley, M.P. Petrov and M.C. Zarnstorff

Poster Presentations Lee Lounge, 2:00 p.m. – 4:00 p.m.

1C25. *Status and plans for the NIMROD code development project*
C.R. Sovinec, A.H. Glasser, R.A. Nebel, T.A. Gianakon, A.E. Koniges, M.W. Phillips, S.J. Plimpton and D.D. Schnack

1C26. *Numerical analysis of the NIMROD formulation*
A.H. Glasser and C.R. Sovinec

1C27. *Parallel structure and performance of the NIMROD code*
Steve Plimpton, Carl Sovinec, Dan Barnes and Alice Koniges

1C28. *Fast electrons generated by lower hybrid waves at the tokamak plasma edge*
J.A. Tataronis, V. Petrzílka, V. Fuchs and L. Krlín

1C29. *A mixed, shear dependent Bohm-Gyro-Bohm transport model*
G. Vlad, M. Marinucci, F. Romanelli, A. Cherubini, M. Erba, V. Parail and A. Taroni

1C30. *RF effects on neoclassical theory and the bootstrap current in tokamaks*
S.D. Schultz, A. Bers and A.K. Ram

1C31. *Comparative transport model testing using the ITER and DIII-D profile databases*
J.E. Kinsey, R.E. Waltz and D.P. Schissel

1C32. *MHD burgerlence: a model of compressible MHD turbulence*
J. Fleischer and P.H. Diamond

1C33. *Wave emission from mode conversion regions*
Yu. Krasniak, E.R. Tracy and A.N. Kaufman

1C34. *Nonlinear stability of tearing modes*
C. Ren, T.H. Jensen and J.D. Callen

1C35. *Evidence for non power-law scalings of confinement parameters and inward transport of thermal energy*
B. Coppi and W. Daughton

1C36. *Confinement at low aspect ratio*
M. Kotschenreuther, W. Dorland and Q.P. Liu

1C37. *δf simulation of the nonlinear evolution of toroidicity-induced Alfven eigenmodes with various collisional effects*
Yang Chen and Roscoe White

1C38. *New approach to non-Hamiltonian particle gyrokinetic theory*
M. Tessarotto, M. Pozzo, R.B. White and R. Zorat

1C39. *Modulation instability of electron waves in magnetized plasma*
V.I. Lapshin and V.I. Maslov

1C40. *UEDGE plasma simulations with Monte Carlo neutrals*
M.E. Rensink, L. Lodestro, G.D. Porter, T.D. Rognlien and D.P. Coster

1C41. *Interchange instabilities in a partially ionized plasma*
W. Daughton, P. Catto, B. Coppi and S. Krasheninnikov

1C42. *High mode number ballooning stability in stellarator configurations*
C.C. Hegna and N. Nakajima

1C43. *Alfven waves and wave-induced transport near an X-point*
J.R. Myra and D.A. D'Ippolito

1C44. *Finite orbit width and Larmor radius effects of fast particle drive on low-n TAE stability*
C.Z. Cheng, N.N. Gorelenkov and G.Y. Fu

1C45. *Investigations of the magnetic field structure of EPEIUS: a proposed low-aspect ratio torsatron-tokamak hybrid*
J.C. Wiley, A.J. Wootton, D.W. Ross, W.H. Miner, Jr., P.M. Valanju and S.B. Zheng

1C46. *Stability of low-shear Alfvén eigenmodes*
J.W. Van Dam, B.N. Breizman, J. Candy, H.A. Holties, G.T.A. Huysmans and S. Sharapov

1C47. *Effects of plasma inertia on stability of magnetic islands*
A.I. Smolyakov

1C48. *Electron cyclotron current drive for stabilization of neoclassical tearing modes in ITER*
R.W. Harvey, F. Perkins and M.N. Rosenbluth

1D **Poster Presentations** Alumni Lounge, 4:00 p.m. – 6:00 p.m.

1D01. *ICRF heating and current drive in high and low beta tokamaks*
J.E. Scharer, M.H. Bettenhausen and R.S. Sund

1D02. *Stimulated Brillouin scattering of an electromagnetic wave in a strongly magnetized plasma*
N.K. Jaiman and V.K. Tripathi

1D03. *E x B shearing rate in a stellarator with quasi-helical symmetry*
T.S. Hahm

1D04. *The effect of impurity charge state evolution on the stability of radiative modes*
Daniel R. McCarthy, A.E. Booth, J.E.J. Hutchinson and Sergei Krasheninnikov

1D05. *L and H modes in the guiding center plasma*
G. Knorr and B. Krane

1D06. *Progress to a theory for rotational shear stabilization*
R.E. Waltz, R.L. Dewar and X. Garbet

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

1D07. *Kinetic simulation of the radial electric field evolution in tokamak plasmas*
S.V. Novakowski, C.S. Liu and R.Z. Sagdeev

1D08. *Sheared E x B flow stabilization of global MHD modes*
B.A. Carreras, J.N. Leboeuf and D.A. Spong

1D09. *Electromagnetic Landau fluid models of collisionless plasmas*
P.B. Snyder, G.W. Hammett, M.A. Beer and W. Dorland

1D10. *An electron cyclotron heating and current drive approach for low temperature startup plasmas utilizing O-X-EBW mode conversion*
D.B. Batchelor and T.S. Bigelow

1D11. *Forced magnetic field line reconnection in electron-magnetohydrodynamics*
K. Avinash, S.V. Bulanov, T. Esirkepov, P. Kaw, F. Pegoraro, P.V. Sasorov and A. Sen

1D12. *Drift wave simulations of JET L- and H-mode discharges*
P. Strand, H. Nordman and J. Weiland and J.P. Christiansen

1D13. *Simulations on the feedback stabilization of neoclassical MHD tearing modes*
T.A. Gianakon, X. Garbet, G. Giruzzi, M. Zabiego, J.D. Callen and C.C. Hegna

1D14. *Optimization of formation of flux core and gun spheromaks*
R.A. Gerwin, J.M. Finn, A.H. Glasser and C.R. Sovinec

1D15. *Issues in nonlinear gyrokinetic simulations of tokamak turbulence and transport*
A.M. Dimits and B.I. Cohen

1D16. *Toroidicity effects and induced convection in the tokamak SOL*
R.H. Cohen and D.D. Ryutov

1D17. *Kinetic study of parallel transport in SOL plasma*
O.V. Batishchev, P.J. Catto, S.I. Krasheninnikov and D.J. Sigmar

1D18. *Analysis of localized electron heating and current drive via mode converted ion Bernstein waves in Alcator C-Mod*
P.T. Bonoli, P.J. O'Shea, A. Hubbard, M. Porkolab, Y. Takase, S. Wukitch and M. Brambilla

1D19. *Edge plasma in a spheromak*
E.B. Hooper, R.H. Cohen and D.D. Ryutov

1D20. *Reversed field pinch transport due to Suydam instabilities*
A. Bruno and J.P. Freidberg

1D21. *A class of high βp equilibria in strongly shaped finite-aspect-ratio tokamak plasmas*
Y.R. Lin-Liu, R.L. Miller, V.S. Chan, P.A. Politzer and A.D. Turnbull

1D22. *Classification and Casimir invariants of Lie-Poisson brackets*
J.-L. Thiffeault and P.J. Morrison

1D23. *Nonaxisymmetric studies of vertical displacement events*
A.Y. Aydemir

1D24. *Toroidal effects on adiabatic R-compression in tokamaks*
M.V. Gorelenkova, E.A. Azizov, N.N. Gorelenkov and A.N. Romannikov

Poster Presentations Lee Lounge, 4:00 p.m. – 6:00 p.m.

1D25. *Stellarator optimization methods for Small Aspect Ratio Toroidal Hybrid (SMARTH) devices*
S.P. Hirshman, D.A. Spong, J.C. Whitson, D.B. Batchelor, B.A. Carreras, V.E. Lynch, J.F. Lyon and J.A. Rome

1D26. *Numerical study of the nonlinear saturation of double tearing modes*
E.K. Maschke, M. Berroukeche and B. Saramito

1D27. *SOL instabilities and anomalous transport localized in divertor legs*
D.D. Ryutov and R.H. Cohen

1D28. *The shear Alfvén wave spectrum in a resistive MHD plasma without magnetic shear*
R. Torasso, J.A. Tataronis and S. Rauf

1D29. *Global nonlinear calculations of ion temperature gradient driven turbulence*
V.E. Lynch, J.N. Leboeuf, B.A. Carreras and L. Garcia

1D30. *Global nonlinear gyrokinetic simulations with self-consistent E_r shear and pressure profile variation*
Scott E. Parker, T.S. Hahm and W.W. Lee

1D31. *Experiment-Theory Comparison of Neoclassical Tearing Modes and Extrapolation to ITER*
Z. Chang, E. Fredrickson, R. Budny, K. McGuire, G. Taylor and M. Zarnstorff

1D32. *CORSICA: A Comprehensive Tokamak Simulation Code*
J.A. Crotinger, R.H. Cohen, S.W. Haney, T.B. Kaiser, L.L. LoDestro, N. Mattor, L.D. Pearlstein, T.D. Rognlien, A.I. Shestakov, G.R. Smith, A.G. Tarditi and X.Q. Xu

1D33. *Fluid equations for the self-consistent description of fluctuations and transport in tokamak plasmas*
J.J. Martinell, P.N. Guzdar and A.B. Hassam

1D34. *Theoretical features of relativistic particle gyrokinetic dynamics*
M. Pozzo and M. Tessarotto

1D35. *Toroidal transport via radiative collisionality*
Satish Puri

1D36. *Thermal lattice Boltzmann (TLBE) simulations of variable Prandtl number turbulent flows*
Min Soe, George Vahala, Pavol Pavlo, Hudong Chen and Linda Vahala

1D37. *Feedback stabilization of the resistive shell mode in tokamaks*
Richard Fitzpatrick

1D38. *Nonlinear coherent energization of magnetized ions in two or more electrostatic waves*
A.K. Ram, D. Benisti and A. Bers

1D39. *Neoclassical electron and ion transport in toroidally rotating plasmas*
H. Sugama and W. Horton

1D40. *Linear growth rates and nonlinear saturation amplitudes of TAE modes destabilised by ICRF heating*
H. Vernon Wong and H.L. Berk

1D41. *Interaction of self-generated phase-space holes and clumps*
H.L. Berk, J. Candy and B.N. Breizman

1D42. *Nonlinear dynamics of the fishbone*
J. Candy, F. Porcelli, H.L. Berk and B.N. Breizman

1D43. *Radial mode coupling saturation of a flute mode*
A. Ponomarev and A.K. Sen

1D44. *The 'moving-contact' plasma-wall instability and the appearance of halo currents*
A. Caloutsis and C.G. Gimblett

1D45. *Momentum transport and radial electric field in high temperature plasmas*
D.R. Ernst

1D46. *Nonlinear Landau damping in plasma and fluid*
M.B. Isichenko

1D47. *Hybrid MHD-gyrokinetic simulations of drift Alfven-ballooning modes*
E.V. Belova, M.K. Hudson and R.E. Denton

1D48. *Equilibrium flux surfaces in MHH2*
A. Reiman, L-P Ku and D. Monticello

Tuesday Morning

2A **Review Paper** Lakeshore Room, 8:30 a.m. – 9:30 a.m., V. Chan Presiding

2A01. R. Granetz, *Disruptions in Tokamaks*

Coffee: 9:15 a.m.–11:00 a.m. — Alumni Lounge and Lee Lounge

2B **Oral Presentations** Lakeshore Room, 9:30 a.m.–10:30 a.m., W. Dorland Presiding

2B01. *Nonlinear 3D simulations of disruptions in NCS discharges in DIII-D*
A.M. Popov, M.S. Chu, Y.Q. Liu, B.W. Rice and A.D. Turnbull

2B02. *Fokker-Planck simulations of knock-on runaway electron generation in tokamaks*
S.C. Chiu, V.S. Chan, R.W. Harvey and M.N. Rosenbluth

2C **Poster Presentations** Alumni Lounge, 10:30 a.m. – 12:30 p.m.

2C01. *Nonlinear interaction of the low-frequency electromagnetic excitations in the plasma edge and anomalous diffusion*
Maxim O. Vakulenko

2C02. *Three-dimensional computation of drift Alfvén turbulence*
B. Scott

2C03. *Toroidal resistive MHD steady states contain vortices*
Jason W. Bates and David Montgomery

2C04. *An integral equation approach to modelling of the observed phenomena of fast nonlocal heat transport in a tokamak*
A.B. Kukushkin

2C05. *Optimization of the magnetic field structure of EPEIUS: a proposed low-aspect ratio torsatron-tokamak hybrid*
W.H. Miner, Jr., D.W. Ross, P.M. Valanju, J.C. Wiley, A.J. Wootton, S.P. Hirshman, D.A. Spong and J.C. Whitson

2C06. *Necessary and sufficient instability condition for inviscid shear flow*
P.J. Morrison and N. Balmforth

2C07. *Fractal and multifractal properties of exit times and Poincaré recurrences*
V. Afraimovich and G.M. Zaslavsky

2C08. *Inductance operator and feedback stabilization of wall modes*
Allen H. Boozer

2C09. *The M3D (Multi-Level 3D) project for plasma simulation*
W. Park, G.Y. Fu, H.R. Strauss and L.E. Sugiyama

2C10. *3D MHD simulations on an unstructured mesh*
H.R. Strauss and W. Park

2C11. *Two-fluid toroidal effects on tokamak plasmas*
L.E. Sugiyama and W. Park

2C12. *Three dimensional particle/magnetohydrodynamic simulation of energetic particle driven MHD modes in tokamak plasma*
G.Y. Fu and W. Park

2C13. *Transport modeling for EPEIUS: a small aspect-ratio torsatron-tokamak hybrid*
D.W. Ross, W.H. Miner, Jr., P.M. Valanju, J.C. Wiley, A.J. Wootton, D.A. Spong, S.P. Hirshman and J.C. Whitson

2C14. *Nonlinear terms of fluctuation-averaged fluid equations as source of plasma rotation*
C.R. Gutierrez-Tapia and J.J. Martinell

2C15. *Unstructured adaptive grid technique to solve 2D and 3D elliptic boundary problems*
S. Galkin

2C16. *Rotation damping and ITG modes*
F.L. Hinton, M.N. Rosenbluth and R.E. Waltz

2C17. *Study of confinement and stability in KSTAR*
B.J. Lee, J.Y. Kim, KSTAR team, D.Y. Lee, C.S. Chang, H.K. Park, C.K. Kessel and J. Manickam

2C18. *Studies of kinetic effects in highly radiating divertor plasmas with the Monte Carlo Impurity (MCI) transport model*
T.E. Evans and D.F. Finkenthal

2C19. *Nonlinear MHD calculations of coherent modes in weak negative shear discharges*
E.D. Held, J.N. Leboeuf and B.A. Carreras

2C20. *Nonlinear simulations of tearing modes with a resistive wall and plasma rotation*
J.M. Finn and C.R. Sovinec

2C21. *Ripple induced stochasticity around the divertor scrape-off layer*
J.J.E. Herrera, D.Kh. Morozov, E. Chávez

2C22. *Neoclassical transport in advanced tokamaks configurations*
Z. Lin, W.M. Tang and W.W. Lee

2C23. *Routes to anomalous transport in the standard map*
S. Benkadda, S. Kassibrakis, R.B. White and G.M. Zaslavsky

2C24. *Equilibrium quantities on an arbitrary flux surface - a generalized $s - \alpha$ model*
R.L. Miller, Y.R. Lin-Liu, M.S. Chu, J.M. Greene and R.E. Waltz

Poster Presentations Lee Lounge, 10:30 a.m. – 12:30 p.m.

2C25. *The Quasi-Optical Grill (QOG): lower hybrid current drive in tokamaks in the 3-8 GHz range - IGNITOR and TdeV*
Josef Preinhaelter, Alain Cote, Linda Vahala and George Vahala

2C26. *Simple estimate of bootstrap suppression of field-error-induced islands in a quasi-toroidal stellarator*
Rob Goldston

2C27. *Interaction of converted ion-hybrid waves with neonatal alphas: a modular approach*
A.N. Kaufman, J.J. Morehead and E.R. Tracy

2C28. *Stability of Pegasus — ideal MHD and neoclassical MHD*
S.E. Kruger, C.C. Hegna and J.D. Callen

2C29. *Modular coil representation for optimized stellarator devices*
J.C. Whitson, S.P. Hirshman and D.A. Spong

2C30. *Synthetic experimental diagnostics: a simulation example*
B.I. Cohen, L.L. LoDestro, J.A. Crotinger, T.A. Casper and E.B. Hooper

2C31. *MHD stability with kinetic effects*
W. Dorland, M. Kotschenreuther and Q.P. Liu

2C32. *Beta limits in toroidal-resistive-rotating plasmas surrounded by a resistive shell*
R. Betti and E. Fedutenko

2C33. *Single particle motion in axisymmetric symmetric systems with large safety factor*
K. Imre and H. Weitzner

2C34. *Stability of small-wavelength tearing modes in a high-beta toroidal plasma*
F.L. Waelbroeck, R.L. Miller and M. Chu

2C35. *Particle simulation for super ion-acoustic double layer*
Hisanori Takamaru, Tetsuya Sato, Ritoku Horiuchi and Kunihiko Watanabe

2C36. *Control of large events in a SOC system*
H. Chen, D.E. Newman and B.A. Carreras

2C37. *Centrifugally confined plasmas for fusion*
A.B. Hassam

2C38. *Burgers turbulence, intermittency and non-universality*
S.A. Boldyrev

2C39. *Orbit squeezing and confinement improvement in tokamaks*
K.C. Shaing, R.D. Hazeltine and M.C. Zarnstorff

2C40. *MHD waves and plasma transport at the dayside magnetopause*
Jay R. Johnson and C.Z. Cheng

2C41. *Alpha particle redistributions due to sawtooth oscillations*
Y. Zhao and R.B. White

2C42. *Spectrum of contained interacting modes and their excitation by high energy fusion products*
G. Penn and B. Coppi

2C43. *Particle simulation study of collisionless driven reconnection*
Ritoku Horiuchi

2C44. *Solution and application of the multiple species parallel force balance equations for tokamak plasmas*
W.A. Houlberg

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

2C45. *Eigenmode solution of ballooning equation with sheared rotation*
L. Zakharov

2C46. *Near threshold transport in the standard map*
R.B. White, S. Benkadda, S. Kassibrakis and G.M. Zaslavsky

2C47. *Wake fields in plasma channels with arbitrary transverse density profiles*
B.A. Shadwick, J.S. Wurtele and G. Shvets

2C48. *Magnetic shear reduction and ballooning instabilities during the sawtooth crash*
Y. Nishimura, C.C. Hegna and J.D. Callen

Lunch Break: 12:30 p.m. – 2:00 p.m.

Tuesday Afternoon

Free afternoon: no formal conference agenda

3:00 – 5:00 p.m.
Open House at the UW-Madison Plasma/Fusion Experiments:
MST (Reversed Field Pinch), HSX (Stellarator), and Pegasus/Medusa (Low Aspect Ratio Tokamak)

Tuesday Evening

Evening Buffet Dinner
Featuring Wisconsin Specialties
Main Lounge and Lee Lounge
6:15 p.m. – 7:30 p.m.
Cash Bar from 6:00 p.m. in the Main Lobby

Beverages: 8:00 p.m.–9:00 p.m. — Alumni Lounge and Lee Lounge

2D **Oral Presentations** Lakeshore Room, 7:30 p.m. – 9:30 p.m., R. Cohen Presiding

2D01. *Alfvén eigenmode stability and alpha particle transport in JET tritium discharges*
W. Kerner, D. Borba, J. Candy, S. Pinches and S. Sharapov

2D02. *2-D high-n analysis of toroidicity induced Alfvén eigenmodes*
N.N. Gorelenkov, C.Z. Cheng, G.Y. Fu, G. Rewoldt and W.M. Tang

2D03. *Spontaneous hole-clump pair creation in a weakly unstable plasma*
N.V. Petviashvili, H.L. Berk and B.N. Breizman

2D04. *Detached divertor plasmas with time variation*
T.D. Rognlien, G.D. Porter, M.E. Rensink and F. Wising

Wednesday Morning

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

3A01. P.H. Roberts, *The Dynamo within the Earth*

Coffee: 9:15 a.m.–11:00 a.m. — Alumni Lounge and Lee Lounge

3B **Oral Presentations** Lakeshore Room, 9:30 a.m. – 10:30 a.m., A. Reiman Presiding

3B01. *Finite temperature effects on collisionless magnetic reconnection*
F. Pegoraro, E.Cafaro, D.Grasso, F. Porcelli and A. Saluzzi

3B02. *Decorrelation dynamics, spectra, and transport in drift-Alfvén turbulence*
E. Fernandez and P.W. Terry

3C **Poster Presentations** Alumni Lounge, 10:30 a.m. – 12:30 p.m.

3C01. *Landau-fluid equations, the stochastic oscillator and masses with springs: model closure problems*
S.A. Smith and G.W. Hammett

3C02. *Induced eddy current patterns on tokamak conducting shell and their implications on active feedback stabilization of external MHD modes*
D.-Y. Lee, M.S. Chance, J. Manickam, N. Pomphrey and M. Okabayashi

3C03. *Changes in the dynamics of turbulent transport in the presence of a sheared flow*
U.S. Bhatt, D.E. Newman, J.N. Leboeuf and B.A. Carreras

3C04. *Symbolic analysis of chaotic signals and turbulent fluctuations*
M. Lehrman, A.B. Rechester and R.B. White

3C05. *Experiences migrating a large Fortran plasma simulation code to a parallel computing environment using C++ and object oriented design methods*
Dave Nystrom and Geoff Furnish

3C06. *Control of internal transport barriers in reverse shear and weak shear discharges*
D.E. Newman, B.A. Carreras, D. Lopez-Bruna and P.H. Diamond

3C07. *Magnetohydrodynamic stability of tokamak discharges with negative central shear*
J.N. Leboeuf, V. E. Lynch and B.A. Carreras

3C08. *Optimization and confinement properties of Small Aspect Ratio Tokamak/stellarator Hybrid (SMARTH) devices*
D.A. Spong, S.P. Hirshman and J.S. Whitson

3C09. *Neoclassical transport in MHH2*
Harry E. Mynick

3C10. *Theory of semi-collisional nonlinear kink-tearing modes and sawtooth collapse in tokamaks*
A. Bhattacharjee and Xiaogang Wang

3C11. *Low collisionality stellarator steady states*
H. Weitzner

3C12. *W7-X equilibria with magnetic islands using the PIES code*
S. Arndt, D.A. Monticello and A.H. Reiman

<u>*Posters: Wednesday, 10:30 a.m. – 12:30 p.m.*</u>

3C13. *Localized interchange stability criterion for a toroidally rotating tokamak*
M.S. Chu and R.L. Miller

3C14. *Internal modes in well confined plasmas*
F. Bombarda, B. Coppi and S. Migliuolo

3C15. *Macroscopic stability of n = 1 internal modes in ITER plasmas*
P. Detragiache

3C16. *Sawtooth stability of plasmas in Alcator C-Mod*
S. Migliuolo, B. Coppi and F. Bombarda

3C17. *Assessment of the theory-based multi-mode transport model*
Glenn Bateman, Arnold H. Kritz, Aaron J. Redd, Jon Kinsey and Jan Weiland

3C18. *Modeling of MHD stability for Tore Supra discharges with LHCD*
M. Zabiego, E. Joffrin, A. Soubert, X. Garbet and T.A. Gianakon

3C19. *Forced reconnection and mode-locking due to time-dependent error fields in rotating plasmas*
Xiaogang Wang and A. Bhattacharjee

3C20. *Numerical simulation of the MRX experiment*
D.D. Schnack and M. Yamada

3C21. *Exact Landau fluid equations*
Nathan Mattor and Scott Parker

3C22. *Full MHD simulations of moderate-n ballooning modes with the XTOR code*
H. Lütjens and J.F. Luciani

Poster Presentations Lee Lounge, 10:30 a.m. – 12:30 p.m.

3C23. *On finite-η_i shear Alfvén instabilities in toroidal plasmas*
Liu Chen, R.A. Santoro and F. Zonca

3C24. *Kinetic modeling of detached plasmas in the PISCES-A linear machine*
L. Schmitz and O.V. Batishchev

3C25. *Relaxation theory of a two-fluid plasma*
Loren Steinhauer

3C26. *Outward momentum transport and inward coupled particle flow in accretion disks and laboratory plasmas*
P.S. Coppi and B. Coppi

3C27. *PIES analysis of DIII-D ITER-like discharges*
D.A. Monticello, S. Deshpande, A.H. Reiman, S. Jardin, J. Manickam, L. Lao, T.S. Taylor, E.J. Strait, R. La Haye and A. Turnbull

3C28. *The dynamics of transitions in models of internal transport barriers*
D. Lopez-Bruna, D.E. Newman, B.A. Carreras and P.H. Diamond

3C29. *Enhanced flexibility of EPEIUS: a small aspect-ratio torsatron-tokamak hybrid with extra TF and VF coils*
P.M. Valanju, D.W. Ross, W.H. Miner, Jr., C. Wiley and A.J. Wootton

3C30. *Self-organized critical gradient transport theory - comparison with the stellar transport*
T. Tajima, W. Horton, G. Hu and Y. Kishimoto

3C31. *On the way to a stellarator-spheromak*
Paul E. Moroz

3C32. *Bounce-averaged fast wave current drive calculations in general toroidal geometries*
J.C. Wright, C.K. Phillips and P.T. Bonoli

3C33. *Comparison of C++ and Fortran 90 for object-oriented scientific programming*
John R. Cary, S.G. Shasharina, Julian C. Cummings, John V.W. Reynders and Paul J. Hinker

3C34. *MHD stability analysis of shear optimised discharges in JET*
G.T.A. Huysmans, B. Alper, G. Cottrell, D. Kadau, D. OBrien and W. Zwingmann

3C35. *Hamiltonian formulation of magnetic field-lines with symmetry and relabeling symmetry in fluid systems*
Nikhil Padhye and P.J. Morrison

3C36. *Singular Hamiltonian equations and explosive non-periodic phenomena*
D. Laveder and B. Coppi

3C37. *Suppression and control of ideal and resistive MHD instabilities*
J. Manickam

3C38. *Boundary effects on the Alfven wave resonance*
Eliezer Hameiri

3C39. *Using adaptive grids to simultaneously simulate stiff confinement models and MHD evolution in the ONETWO transport code*
H.E. St. John, J.E. Kinsey and R.E. Waltz

3C40. *Low n kink stability of low aspect ratio torodial confinement systems*
A.D. Turnbull, R.L. Miller, Y.R. Lin-Liu, J.R. Ferron, L.L. Lao, V.S. Chan, M.S. Chu, D. Pearlstein and O. Sauter

3C41. *Global modeling of non-axisymmetric disruptions and halo currents in tokamaks*
J. McCarrick and J.P. Freidberg

3C42. *Development of implicit 3D fluid turbulence code in SOL plasmas with X-point geometry*
X.Q. Xu, R.H. Cohen and T.D. Rognlien

3C43. *Arnold diffusion in the standard map*
Halima Ali, Richard Truesdale, Alkesh Punjabi and Allen Boozer

3C44. *The low MN map for a single-null divertor tokamak*
Arun Verma, Terry Smith, Alkesh Punjabi and Allen Boozer

3C45. *The shear Alfvén wave in asymmetric MHD equilibria*
A. Salat and J.A. Tataronis

Abstracts

Arranged in presentation order,
including review, oral and poster talks

Quasi-Symmetries in Toroidal Confinement

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The concept of quasi-symmetries has alleviated two major deficiencies stellarators often show: large neoclassical transport in the long-mean-free-path regime and poor α-particle confinement. Quasi-helical symmetry is closest to the original stellarator idea; the approximate helical symmetry of the magnetic field strength in magnetic coordinates is most easily realized at medium to large aspect ratio and number of periods; the transition from W7-X type geometry to nearly helically symmetric geometry occurs at a relatively large number of periods. Quasi-axisymmetry is an extension of the stellarator concept to the tokamak regime and naturally occurs at relatively small number of periods and aspect ratio; for these configurations the bootstrap current will be a strong configurational characteristic, so that they can better be characterized as quasi-axisymmetric tokamaks. The third quasi-symmetry – poloidal quasi-symmetry or isodynamicity – does not exist. However, this notion can be generalized to quasi-isodynamicity denoting poloidal closure of the contours of the second adiabatic invariant. Vacuum-field configurations of this type have recently also been found and are of W7-X type geometry and structure of the magnetic field topography.

1B01

Omnigenous Non-Quasihelical Systems

S. G. Shasharina and John R. Cary*

Abstract
for 1997 International Sherwood Fusion Theory Conference

The criterion of approximate omnigenity, having bounce averaged drift lying within the magnetic surfaces, is much easier to satisfy than quasihelicity, the condition that B is a function of only a single linear combination of the poloidal and toroidal angles. Simple criteria for omnigenity are presented and used to construct exactly omnigenous forms for B that are far from quasihelical. Though this construction gives a nonanalytic function B, close to the constructed systems there exist other systems with analytic B. These results indicate that finding helical plasma confinement systems with minimal neoclassical transport is much easier than previously expected.

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Stability of a Levitated Dipole *

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

Hasegawa et al. has shown that a dipole plasma is stable to both MHD and drift frequency modes [1] when it collisionless and the lowest order distribution function is $F_0(\epsilon, \mu, \psi) \rightarrow F_0(\mu, J)$. We examine the stability of low beta electrostatic modes for confinement on a collisional time scale, i.e. when the distribution function is to lowest order Maxwellian, i.e. $F_0(\epsilon, \psi)$ [2]. It is shown that for sufficiently gentle density and temperature gradients the configuration would be expected to be stable to MHD interchange, as well as to dissipative trapped ion and collisionless trapped particle modes.

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

References

[1] A. Hasegawa, L. Chen and M. Mauel, Nuclear Fus. **30**, (1990) 2405.

[2] J. Kesner, Phys Plasmas 4 (1997) 419.

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1B03

The Periodically Oscillating Plasma Sphere (POPS)

Richard A. Nebel and Daniel C. Barnes

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A new confinement scheme which is suitable for operation in Inertial Electrostatic Confinement (IEC) devices is presented. In this scheme, large amplitude spherical oscillations are set up in the plasma by a small, resonant modulation of the background electrons. A set of self-similar solutions have been found which indicate that these spherical oscillations can compress the plasma to high densities and temperatures. These solutions reduce the oscillation problem to an ordinary differential equation for the plasma radius which is very similar to a Mathieu equation for most operating regimes of interest.

This operating scheme can be utilized in either Penning traps [1] or gridded systems [2]. Results indicate that this scheme will allow Penning Traps to operate at densities higher than the Brillouin limit. The oscillating ion plasma has a Maxwellian distribution which eliminates microstability and phase space scattering issues that have appeared to limit previous IEC schemes to low energy gain [3] [4].

An IEC neutron source is presently under construction at Los Alamos. This device is being built for the nuclear safeguards group for assay applications. The goal of this source is to produce 10^{11} neutrons per second steady-state. Phase I operation of this source will be as a standard ion focus device. Phase II operation will be as a POPS device. Calculations indicate that 10^{13} neutrons per second steady state may be achievable with peak temperatures of 75 Kev and peak densities of 10^{19} cm^{-3}. Although it is unlikely (but not inconceivable) that this device will reach breakeven, it should be capable of testing the physics of the POPS. Reactor scalings and plasma stability calculations will also be presented.

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[2] R. Hirsch, J. Appl. Phys. **38**, 4522 (1967).

[3] W. M. Nevins, Phys. Plasmas **2**, 3804 (1995).

[4] T. H. Rider, Phys. Plasmas **2**, 1853 (1995).

1B04

Electromagnetic Enhancement of Turbulence and Spontaneous Transport Barrier Formation in Tokamaks*

B. N. Rogers and J. F. Drake

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We model anomalous transport in the edge region of tokamaks with three-dimensional, electromagnetic simulations of plasma turbulence in a torus. The simulations are based on the Braginskii equations in a shifted-circle magnetic geometry, and are carried out in a poloidally and radially localized, flux tube-like domain that winds around the torus. The behavior of the electromagnetic system can be classified according to the strength of diamagnetic effects (*i.e.* temperature). When diamagnetic effects are weak (low temperature), we find the self-consistent magnetic fluctuations in the model lead to a drastic enhancement of the observed transport levels relative to electrostatic simulations well below the ideal ballooning instability limit – *i.e.* $\beta/\beta_{crit} \sim 0.1 - 0.2$. As diamagnetic effects become stronger (high temperature), the β-threshold for such enhancement can be substantially increased to the regime $\beta/\beta_{crit} \sim 1$. Finally, at still higher temperatures and $\beta/\beta_{crit} \sim 1$, the system makes a transition to a new laminar state, never before observed in electrostatic simulations, in which the radial transport vanishes. This state is characterized by spontaneously formed sheared poloidal $\vec{E} \times \vec{B}$ and $\vec{B} \times \nabla p_i$ flows, which exactly balance so that the net ion flow is zero. Magnetic perturbations play a critical role in the formation of these local transport barriers. The physical basis of this behavior, and the implications for transport barrier formation in the tokamak edge region, will be discussed.

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Explosive Ballooning Modes and High-β Disruptions*

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The importance of high-n ballooning modes for β-limited discharges in tokamaks has been evidenced by both observations on TFTR[1] and three-dimensional MHD computer simulations[2]. These experiments and simulations observe toroidally localized high-n ballooning modes destabilized by global $n = 1$ activity. Recently, Hurricane *et al.*[4] have developed a theoretical formalism for the nonlinear evolution of ballooning-type modes in arbitrary three-dimensional ideal MHD equilibria. The formalism generalizes the nonlinear behavior of gravitationally driven ballooning-type modes in the ideal MHD line-tied Rayleigh-Taylor-Parker instability. For the Rayleigh-Taylor-Parker instability, Cowley *et al.*[3] derived a nonlinear partial differential equation describing the evolution of the plasma displacement; in marginally unstable plasmas, the displacement could grow explosively towards a finite-time singularity. Similarly, the general nonlinear partial differential equation for the plasma displacement also exhibits explosive behavior for marginally unstable plasmas. Specialization of the general partial differential equation to axisymmetric tokamak equilibria results in an equation with structure identical to the original Rayleigh-Taylor-Parker instability equation. Thus, ideally marginally unstable tokamak ballooning modes can exhibit the same explosive behavior as gravity-driven Rayleigh-Taylor-Parker modes.

For tokamak plasmas, however, ideal MHD dynamics neglect important effects, such as the finite larmor radius. Inclusion of finite larmor radius effects (through the ion diamagnetic frequency) into the nonlinear partial differential equation allows for the possibility of nonlinearly saturated states, as well as the explosive behavior mentioned above. From the FLR-modified nonlinear partial differential equation we have derived a nonlinear ordinary differential equation for the amplitude of the plasma displacement. The equation predicts that plasmas with fixed linear growth rates just above linear marginal stability generally can be either nonlinearly stable (nonlinear oscillatory states) or nonlinearly unstable. However, for plasmas having both $n = j$ and $n = 2j$ ballooning modes linearly unstable, the equation predicts nonlinear explosive growth. In particular, if the plasma crosses the ideal stability boundary in some equilibrium evolution time-scale, both the j and $2j$ modes eventually destabilize. For TFTR ballooning modes with global equilibrium evolution on the 100 ms time-scale, we have determined the time-scale from marginally instability to the finite-time singularity to be $\sim 50\mu s$ with toroidal mode numbers $n \sim 10 - 20$ as the plasma crosses the nonlinear stability threshold.

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Special Session

The New NERSC (National Energy Research Scientific Computing Center) at LBNL

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In 1996 the NERSC program was established at Lawrence Berkeley National Laboratory with the purpose of accelerating progress in Energy Research with a world class computing and networking environment. Berkeley Lab was tasked to construct the program so as to align NERSC more closely with Energy Research efforts at Berkeley Lab and throughout the ER community and to couple it to research at the University of California. In this presentation the new NERSC will be introduced to the fusion community, where NE RSC had its historical roots. It will shown how the challenges of multiple transitions were met, and how NERSC will address the future requirements for large scale sceintific computing.

Building the new program required a new staff and deployment of equipment not only in order to provide the same or merely to improve the level of service NERSC had given in its previous form during the past years, but to participate in substantially more research and development activities. The new NERSC is not only capable of developing new application codes and algorithms in collaboration with its users in direct support of their work using the Center's resources, but is also able to expand and improve NERSC's capabilities and services by collaborating with the computer science community in universities and elsewhere to adapt and refine new tools and software for the increasingly diverse NERSC computing resources.

NERSC's purpose is to make possible "computational science of scale." Just as the Energy Research national laboratories provide a venue to do experimental science using large facilities and within large scale projects, they also enable computational scie nce on a scale not possible to accomplish with single principal investigators using only local facilities. To that end we must recognize that while high performance computers have become more powerful with new generations, they also have become more comp licated to use. The new NERSC is structured to help its users overcome barriers to usage, and this effort is at the heart of the Center's activities.

Just as important is the fact that NERSC must function as the working interface between computer science and the physical sciences. It is on this interface that the best advances in scientific computing have occurred. We are taking for granted interoperable systems from the desktop to the supercomputer using similar operating systems. We are expecting graphical user interfaces, sophisticated visualization tools, code management tools, powerful debuggers, libraries of parallel mathematical routines, a variety of parallel programming models, etc. All these form the new and evolving baseline fo r scientific computing. Today's computing was not conceivable a mere 15 years ago when we submitted decks of cards for overnight turn around. NERSC must adapt and select the newest concepts from the academic computer science community and introduce them i n a reliable manner to its client community.

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Feasibility Study of Finite Difference Approach to Kinetic Neutral Modeling in Edge Plasmas*

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Pragmatic approaches to neutral transport modeling in edge plasmas currently include: 1) linear Monte-Carlo (MC) — no neutral-neutral collisions; and 2) various fluid models — ranging up to sophisticated Navier-Stokes (NS) neutral models which allow for neutral-neutral collisions and charge exchange coupling of the neutrals and plasma. Unfortunately, for regimes of most interest to divertor operation, plasma and neutral gas parameters in the scrape-off layer (SOL) vary enough to prohibit either method from providing an entirely satisfactory description of neutral transport. This quagmire has resulted in neutral hybrid (Nhybrid) models which utilize salient features of each approach. Nhybrid models carry their own intrinsic difficulties, for example NS convergence may be effected when the MC method is noisy, and further investigation of alternative neutral transport models is important.

As an alternative approach to neutral transport modeling we investigate the feasibility of a finite difference approach to the exact neutral kinetic equation solution. We may write the single species Boltzmann equation with BGK collision operator as follows:

$$\vec{c} \cdot \nabla f(\vec{r}, \vec{c}) = \nu(f_M(\vec{r}, \vec{c}) - f(\vec{r}, \vec{c})), \tag{1}$$

where the Maxwellian velocity-distribution function $f_M(\vec{r}, \vec{c})$ is determined by self-consistent neutral gas density $n(\vec{r}) = \int f(\vec{r}, \vec{c}) d^3\vec{c}$, mean macroscopic velocity $\vec{c_o}(\vec{r}) = \int f(\vec{r}, \vec{c})\vec{c} d^3\vec{c}/n(\vec{r})$, and temperature $T(\vec{r}) = \int f(\vec{r}, \vec{c}) M(\vec{c} - \vec{c_o}(\vec{r}))^2 d^3\vec{c}/3n(\vec{r})$. An exact kinetic equation solution would then take the form:

$$f(\vec{b}, \vec{c}) = f(\vec{a}, \vec{c}) \exp(-\nu t_{ab}) + \int_0^{t_{ab}} f_M(\vec{a} + \vec{c}t', \vec{c}) \exp(-\nu t') dt', \tag{2}$$

where $\vec{b} = \vec{c}t_{ab} + \vec{a}$. This form of the kinetic equation has the advantage of allowing a set of discretised equations to be applied on a grid with mesh spacing much greater than the neutral-neutral free path. We examine this feature of Eq. 2 by using an inverse method of characteristics for discretisation and iteratively solve 2D2V couette flow around an obstacle for Knudsen (Kn) numbers 100-0.01.

As both the fluid limit ($Kn \to 0$) and rare gas limit ($Kn \to \infty$) exist for the set of discretised equations we use a benefit-cost analysis approach to measure computational efficiency. What we find is that computational cost increases with decreasing Kn and high mean molecular gradients. The latter factor is much more important that the former, allowing accurate cost efficient solutions in dense plasmas regions provided the mean molecular values do not vary much between nodes.

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Long Mean Free Path Electron Heat Conduction Modifications

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The Braginskii [1] plasma transport coefficients begin to fail even at small values of the ratio γ defined as the mean free path of a thermal particle $\lambda(cm) \approx 10^{12}T^2(eV)/N(cm^{-3})$ (with T and N the plasma temperature and density) over the parallel temperature scale length [2]. The Spitzer-Härm [3] electron heat transport coefficient, in particular, fails for $\gamma > 1/100$. The breakdown of fluid treatments occurs at these large values of collisionality because the collision frequency falls off as $1/v^3$. The rapid fall causes the heat conduction to be dominated by particles with energies on the order of seven times the thermal energy and energy weighted mean free paths roughly 50 times larger than that of the thermal particles. The values of γ in the divertor region of current tokamaks such as C-Mod and DIII-D, as well as the expected values for ITER, can be as large as 1/10. As a result, weakly collisional energetic particles are expected to have a strong influence on parallel plasma transport. To investigate long mean free path modifications of the electron heat conductivity the approach of Krasheninnikov [4] is adopted by seeking self-similar solutions of the high speed expansion of the full electron collision operator. However, to simplify the collision operator further the perpendicular distribution is assumed Maxwellian and an integration over perpendicular speeds is employed to obtain a collision operator depending only on the parallel velocity [5]. A self-similar solution of the electron kinetic equation for this model collision operator retains modifications of the parallel electron distribution due to electrons having energies E such that $\gamma E^2/T^2 \sim 1$. Non-expandable, exponentially small modifications to the heat conduction, proportional to $\exp(-1/\gamma^{1/2})$, that cannot be retained in conventional short mean free path treatments ($\gamma \ll 1$) are evaluated to demonstrate that they are responsible for the departure of the parallel transport from its Spitzer value. Because self-similar variables are employed these modifications are local, however, they are not of the form normally employed to limit the heat flux.

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Theory of Ion and Impurity Transport in Edge Plasmas

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The properties of edge plasmas are often determined by the balance between rapid ion streaming parallel to a magnetic field and diffusion across the field. However, conventional orderings of kinetic equations, e.g., the ones used to study transport in the tokamak core, do not allow such a balance and are therefore inappropriate in edge plasmas. We derive and solve novel kinetic equations, allowing for such a balance [1], and construct distinctive transport laws for collisional edge plasmas where the perpendicular transport is

(i) governed by anomalous diffusion driven by electrostatic turbulence, or

(ii) due to neutral atoms interacting with the plasma by charge exchange.

The resulting parallel transport laws assume an unconventional form, in which the relative flow between different ion species is driven by a combination of the conventional parallel gradients, and new (i) anomalous or (ii) collisional terms involving products of perpendicular derivatives of the temperature and density with the shear of the parallel velocity. Thus, in the presence of anomalous radial diffusion or neutral atoms, parallel ion transport is not entirely classical, as often assumed in edge modelling. Practically, these modifications could be important for impurity retention in a detached divertor plasma, preventing their migration into the plasma core. UEDGE simulations of C-Mod are used to illustrate the effects.

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Radiation Front Jumps in a Tokamak Divertor†

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Abstract

The plasma energy loss due to impurity radiation from a tokamak plays a very important role in the physics of detached divertor regimes. Experimental observations show that in highly radiative regimes a significant amount of impurity radiation is coming from a relatively small volume of rather cold (~ 10 eV) plasma which is usually localized in the vicinity of either the strike or X-points. Simple 1D theoretical models based on balancing the impurity radiation by the energy transport due to plasma parallel heat conduction contradicts these observations. In [1] it was shown that strong impurity radiation from a low temperature region can be explained by taking into account the effects of cross field plasma and neutral transport which result in a V-shaped radiation front extending in the poloidal direction.

We investigate the structure of the radiation region and conditions for which the V-shaped impurity radiation front can be formed. We analytically and numerically solve a 2D nonlinear heat conduction equation with an energy sink, $R(T,x)$, modeling impurity radiation:

$$\partial_x\left(\hat{\kappa}_\perp T^{\alpha_\perp}\left|\partial_x T\right|^\beta \partial_x T\right)+\partial_y\left(\hat{\kappa}_\parallel T^{\alpha_\parallel}\partial_y T\right)=R(T,x),$$

where x and y are the "radial" and "poloidal" coordinates; $\hat{\kappa}_\perp$ and $\hat{\kappa}_\parallel$ are the normalization constants and $\alpha_\perp$, $\alpha_\parallel$, and $\beta>-1$ are the constants determining the scalings of the perpendicular and parallel heat conduction coefficients. We show that the formation of the V-shaped radiation front can be sensitive to the energy flux and impurity radiation loss away from the separatrix in the SOL plasma ("wings"). When the energy flux (energy dissipation) in the "wings" is relatively high (low) the impurity radiation is localized close to the target. With decreasing (increasing) energy flux (energy dissipation) in the "wings" the localization of impurity radiation front can jump abruptly to the X-point. Simultaneously the magnitude of impurity radiation loss can strongly increase due to the formation of V-shaped radiation front.

These findings may explain following experimental observations: a) the jump of the impurity radiation region from the target to the X-point after transition to a detached regime, and b) easier access to a detached divertor regime for vertical target (which forces the formation of a V-shaped radiation front) in comparison with a horizontal one [2]. In addition they suggest that a "gas box" divertor geometry providing increased energy dissipation in the "wings", can be very beneficial for the formation and control of a V-shaped radiation front.

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Simulation of neutral gas transport in a detached divertor using non-linear Monte-Carlo code†

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Abstract

The detached divertor concept is characterized by a high neutral gas density in the divertor where neutral-neutral scattering collisions play an important role by affecting the spatial distribution of the neutral gas parameters and the local composition of the neutral gas. The non-linear multispecies Monte-Carlo code, TNG, is used to simulate transport of hydrogen neutral particles in a detached divertor. A direct Monte-Carlo simulation (DMCS) method is used to describe the scattering, absorption (by plasma) and conversion of neutrals due to collisions between the plasma and neutral particles and collisions of the neutrals with material surfaces.

The general features of the DMCS technique are the same as in an ordinary linear MC code [1]. However, neutral-neutral (N-N) collisions make the transport problem nonlinear with respect to the velocity distribution function (VDF) of the neutrals. To solve this problem the TNG code uses a reduced collision operator (RCO) model [2] which was used earlier in rarefied gas dynamics along with a BGK model [3]. The RCO model allows us to include the N-N collisions in a linearized form and to use DMCS as a method of solution. At the same time the RCO model requires an iterative treatment to determine the VDF moments.

Effective rates of some atomic processes (e.g. chemical reactions with molecules) strongly depend not only on plasma but also on gas parameters resulting in an additional non-linearity of neutral transport. Atomic physics data are calculated with the CRAMD package [4] which is directly coupled to TNG.

The modeling of neutral transport has been performed for a box geometry with a fixed spatial distribution of plasma parameters that are typical for detached operation. The spatial distributions of the gas parameters calculated with and without N-N collisions will be presented. The impact of N-N collisions on plasma particle, momentum and energy dissipation will be analyzed. Physical results and computational requirements (CPU time, number of iterations, accuracy) will also be discussed from the viewpoint of further development of a hybrid Monte-Carlo/Navier-Stokes neutral transport code and consequent coupling of these codes to a plasma transport code.

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Theoretical Interpretation of Experimental Results from Linear Machine NAGDIS II†

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Abstract

Plasma recombination and various atomic processes involving plasma and neutral gas interactions play an important role in the physics of tokamak divertor plasma, negative ion sources, and plasma etching, and in the development of UV lasers employing recombining plasmas. Recent experiments with helium-hydrogen plasmas on the linear machine NAGDIS II show that when the neutral gas pressure in the working chamber exceeds some critical level the plasma starts to detach from the target. In these regimes the experimental data indicate enhanced intensities of the He and H Balmer series of lines. For a pure He plasma Balmer spectrum is similar to that for a recombining (radiative and 3-body) plasma and the electron temperature estimated from the recombination continuum is about 0.2 eV. For helium-hydrogen mixtures both the He and H Balmer spectrums are more complex and the recombination continuum is not seen. We model the He and H Balmer spectrums with the CRAMD code [1] for the wide range of the plasma and neutral gas parameters which one expects in NAGDIS II. Different mechanisms of populating the excited states of He and H were investigated including: i) plasma radiative and 3-body electron-ion recombination (EIR), ii) excitation from the ground state of atoms, and iii) procasses associated with molecular activated recombination (MAR). Results of the modeling show that neither EIR nor excitation from the ground state can explain the observed He and H Balmer spectrum in helium/hydrogen mixture plasmas. Effects associated with MAR, resulting in a selective population of states with relatively low principle quantum numbers, become already important at low molecular hydrogen concentration (about a few %). We also analyze plasma flow for conditions similar to that of NAGDIS II. We show that in He plasma the electron temperature sharply drops to a level of about 0.15 eV due to electron-ion energy exchange and a strong ion cooling due to ion-neutral interactions. At that temperature electron-ion recombination becomes very strong and results in almost complete plasma recombination. In the downstream region the electron temperature stays almost flat due to the reduction of electron-ion energy exchange rate. In a helium-hydrogen mixture the plasma recombines at much higher temperature due to MAR and the effect of EIR is negligible. The estimate shows that the effect of MAR can be significant for a hydrogen content exceeding about a few %. These theoretical results are in agreement with the experimental observations.

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Divertor Scaling Law Simulations *

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Core plasma scaling laws are normally written in terms of dimensionless geometrical quantities and parameters corresponding to the Coulomb collisionality, gyro-motion, and plasma beta. However, the edge, scrape off layer, and divertor regions have an important influence on the core and are sensitive to atomic processes. To obtain the same atomic physics in these regions for similar discharges Lackner [1] observed that the temperature profiles must be the same as well. By removing the beta constraint he was able to obtain a power (P) over major radius (R) scaling that indicated none of the present tokamaks could be scaled to ITER. However, his argument implicitly assumed that only two-body interactions were significant. Subsequent work [2, 3] has demonstrated that non two-body (multi-step radiation, excitation, and ionization processes as well as three body recombination) cannot be ignored for plasma densities above $1.0 \times 10^{19} m^{-3}$: the regime in which the ITER divertor must operate. Under such operating conditions the simple constant P/R constraint for machine similarity is violated. Scaling laws must be obtained experimentally and by numerical investigations using complex simulations. From two-dimensional modeling of the coupled plasma and neutral fluid we are developing scaling laws for divertors which include non two-body effects. We present the results of our numerical investigations into the P/R and collisionality scaling of the target heat flux and saturation current for complete recycling boundary conditions at the walls. Moreover, we find that the location of the detached ionization front depends on the incoming heat flux which is sensitive to re-absorption of hydrogen Lyman alpha radiation.

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Study of Balmer spectrum near photo-recombination edge in Alcator C-Mod divertor plasmas†

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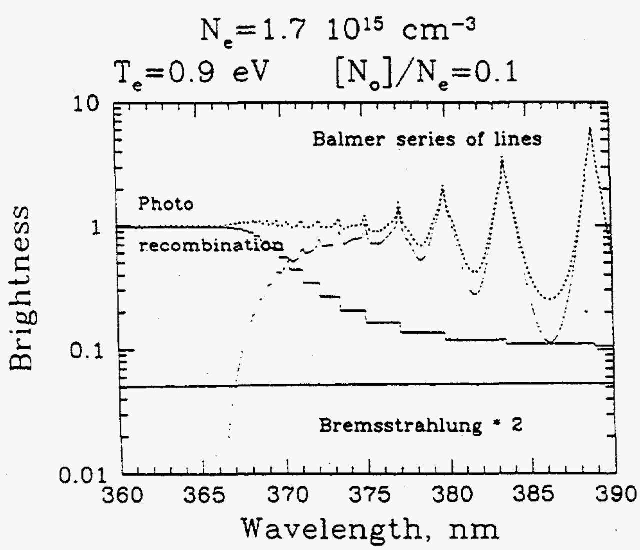
Abstract

Plasma recombination is considered as an important process leading to divertor plasma detachment in the C-Mod tokamak [1]. The measured emission spectrum from the divertor showed merging of Balmer lines and a strong photo-recombination continuum, typical for a high density (above 10^{21} m^{-3}) and low temperature (about 1 eV) plasma. Modelling was performed to reproduce the measured spectrum. The dependence of population of excited states, total intensities of spectral lines and continuum components on plasma parameters for the deuterium atom were calculated with the collisional-radiative code, CRAMD [2]. To treat properly the recombination edge, the code took into account the decay of atomic states (and correspondent change in the collisional rates) due to fluctuating plasma microfields. The calculations, performed for typical detached divertor conditions, showed that recombination (radiative and 3-body) is a dominant population mechanism of highly excited states. As a result of microfield ionization, the population densities of highly excited atomic states started to decrease (with the increase of their principle quantum number) weakening the intensities of the highest lines in a Balmer series. Simultaneously, the destruction of atomic states caused the increase in the intensity of free-bound transitions extending the photo-recombination continuum above the ideal limit towards longer wavelengths.



The resulting spectrum is shown in the figure. It was calculated as the sum of profiles of Balmer lines (Stark, Doppler, electrodynamic and instrumental brodening mechanisms were taken into account) and the extended continuum spectrum. The analysis of spectrum sensitivity to plasma parameters variation will be discussed. The estimate of divertor plasma density and temperature as the best fit to the experimental data will be given.

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Reversed Shear Transport Barriers

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Changing the q profile from monotonic to a profile with a minimum ($q_{\min}$ at $r_{\min}$) breaks the translational symmetry of the ballooning mode transformation and introduces a new local reflection symmetry ($x \rightarrow -x$) about $q_{\min}$. For drift waves and ITG modes the eigenmode structure depends on ρ_s/L_q where the scale length $L_q = r_{\min}\, q_{\min}/q''_{\min}$ appears instead of shear length L_s as the important parameter. Eigenmode calculations are given for the drift modes and the ITG mode where a new hybrid frequency $\omega_{*T_i}^{3/5}\,\omega_s^{2/5}$ with $\omega_s = c_s/qR$ appears. The mode width $W = \rho_s^{1-\alpha} L_q^{\alpha}$ with ($\alpha = \frac{1}{3}$) breaks the gyro-Bohm scaling and is associated with the gap that opens in the density of the mode rational surfaces in the transport barrier layer at $q_{\min}$. The relative importance of the gap appears to increase with increasing machine size (a/ρ_s) correlating with the importance of RS regimes in large machines.

Before the microscopic transport barrier gives way the experiments suggest that an $n = 1$ pressure gradient-kink mode terminates the rising current. Since the mechanism described depends on the geometry and the $\mathbf{E} \times \mathbf{B}$ nonlinearity it is thought to be valid for a wide class of transport models.

The odd mode is faster growing in accord with the global particle simulations. In the nonlinear regime the odd mode saturates in a chain dipolar vortices with a KAM transport barrier for $\mathbf{E} \times \mathbf{B}$ convection formed at $q_{\min}$. The presence of a (leaky) KAM barrier appears consistent with "particle integration" description of Zarnstorff and the lithium/helium particle confinement experiments of Efthimion-Synakowski *et al.* [1]. To investigate the breaking of the final barrier, a quasi-2D simulation is performed on a $(256\rho_s)^2$ grid.

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3D EFFECTS IN TURBULENT COMPRESSIBLE SHEAR FLOWS OVER TOROIDAL CAVITIES IN THE NEUTRAL GAS BLANKET DIVERTOR REGION*

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There are 3 basic simulation techniques to fluid turbulence: direct numerical simulations (DNS), large eddy simulations (LES) and Reynolds-Averaged Navier-Stokes (RANS) - and each method has its strengths and limitations because turbulence is 3D and intrinsically involves disturbances on all length scales. DNS resolves all turbulent scales: from the large scale eddies to the dissipation range eddies without any approximations and so is limited to low Reynolds number turbulence and simple geometry due to the limitations of computer memory and speed. While the Reynolds number for our divertor problem is quite low, the geometry is quite complex and cannot be readily handled by DNS. In LES, the large eddy structures are resolved and one must model the effects of the smaller scale structures on the large eddies. LES is found to be only factors of 5-8 faster than DNS. The other problem facing both DNS and LES is the need to obtain a sufficiently large sampling of the flow statistics - especially for inhomogeneous flows.

Here, we apply RANS, in which all the turbulence effects on the mean flow are modeled, to compressible turbulence. For complex flows, this is the tool of choice/necessity. On averaging the momentum equation, some closure approximation must be invoked to handle the off-diagonal turbulent Reynolds stress tensor. The trace of the Reynolds stress tensor is just the turbulent kinetic energy K. If the off-diagonal Reynolds stress components are approximated by linear gradients in the mean flow, one recovers the so-called K-ε model (where ε is the turbulent dissipation rate). A more sophisticated model, the so called Algebraic Stress Model (ASM) incorporates nonlinear gradients and is derived from integrity base analysis.

We have examined both 2D (toroidal + radial) and 3D mean shear flows over toroidal cavities in the neutral turbulent regime and determined the heat flux to the walls for both the K-e and the ASM models at Reynolds number of 750. We find that in 2D flows, the toroidal K-ε and ASM heat fluxes to the walls are within a factor of 2 of each other. However, in 3D mean flows - where the poloidal flow to the divertor plate is taken into account - it is shown that the more accurate ASM predicts heat fluxes that are factors of 20 -100 greater than K-ε. Laminar heat fluxes are significantly less than those for K-ε. These results could have significant bearing on thickness of the cold blanket regimes

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Effect of Neutrals on SOL & Divertor Stability

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Recently, the stability of the scrape-off-layer (SOL) to high-n (toroidal mode number) MHD modes was examined in X-point geometry retaining perpendicular and parallel variations of temperature, density and electrostatic potential to model a typical divertor equilibrium.[1] This work neglected the effect of electron and ion collisions with neutrals, which should be an important physical process in typical divertor plasmas. There are a number of ways in which neutral physics can alter the ballooning-interchange stability picture. Ion-neutral friction contributes both a stabilizing term and a drive term for the "ion-neutral drag" instability.[2-4] Also, the reduction in plasma density near the divertor plates associated with recombination modifies the sheath boundary condition in a way which is destabilizing for the curvature-driven interchange mode. The latter effect may become particularly important for lower values of the mode number n in detached divertor plasmas, since these modes would normally be partially line-tied under attached divertor conditions.[1] In this paper we examine the scaling of the neutral stability terms in a fluid model and evaluate quantitatively the importance of the various neutral effects on ballooning-interchange instability for an X-point model equilibrium relevant to diverted tokamaks.

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Kinetic Analysis of Instabilities in Tokamak Plasmas*

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In our time-dependent simulations of tokamak temperature and density profiles[1], we find that current models of transport driven by ion temperature gradients (ITG) and trapped electron modes (TEM), by themselves, do not adequately describe the transport near the magnetic axis. Presently, in our Multi-mode model, the transport in this region is given by a combination of neoclassical theory, Weiland ITG/TEM theory and a kinetic ballooning (KB) model. The KB model is more primitive than the models for the other modes. In order to put this model on a more secure theoretical foundation, we are conducting a comprehensive linear stability analysis using the FULL code[2]. This kinetic stability analysis takes account of all ion species present and is fully electromagnetic in nature. Quasilinear estimates for the driven energy and particle fluxes are calculated in regions where an instability is present. Kinetic effects from trapped and untrapped particles, finite Larmor radius, and Landau damping are included in the FULL code. This stability code has been used in the past to analyze the stability of experimental tokamak plasmas with respect to KB modes and ITG and TEM modes [3]. We are using this stability code to explore plasma parameter space by varying densities and temperatures of all species and their gradients as well as dimensionless parameters, such as the safety factor, magnetic shear, and β. We examine the threshold for the onset of the instability of the various modes, the transition from the dominance of one mode over another, and the parametric dependencies of the fluxes that are driven by the instabilities. We also compare the predictions of this kinetic code with the predictions of Weiland ITG/TEM transport theory[4].

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Fokker-Planck Simulation of Lower Hybrid Current Drive in the Reversed Field Pinch*

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Our earlier theoretical studies have shown that lower hybrid current drive (LHCD) is an effective method of modifying the current profile in the outer region of the reversed field pinch (RFP), and providing a means to suppress large amplitude resistive tearing modes.[1] Experimentally, pulsed poloidal current drive (PPCD) has been found to dramatically improve the energy confinement time (by up to a factor of five) of the MST RFP by suppressing the resistive modes and reducing plasma transport.[2] These results motivate us to experimentally implement the LHCD scheme, which is non-transient and potentially more controllable than PPCD.

To refine our earlier theoretical calculations and to optimize the design of LHCD for the MST, we have developed a new computer code package to simulate LHCD in the RFP. The code package consists of three codes: MSTEQ, GENRAY[3] and CQL3D.[4] MSTEQ solves the Grad-Shafranov equation to find axisymmetric toroidal MHD equilibria in the RFP. GENRAY is a generalized toroidal ray tracing code and determines the ray trajectories of the LH slow wave (and other modes) in the RFP magnetic topology. CQL3D is a 3-D, relativistic, bounce-averaged, quasi-linear, Fokker-Planck code and can self-consistently calculate the kinetic response of the plasma to incoming RF power. This code has been used extensively for the tokamak but modifications have been made to handle the RFP topology.

Our recent code results are consistent with and more promising than our earlier results, and this strongly supports the LHCD scheme on the MST. In a typical MST discharge ($T_{eo} \sim 375$ eV, $n_{eo} \sim 1.5 \times 10^{19}$ m^{-3}, $I_{tor} \sim 390$ kA), the slow wave of frequency 250 MHz and $n_{||} = 10$ (single ray as well as multiple rays centered at this value) launched from the outboard side of the plasma will make a little over three poloidal turns and about one quarter of one toroidal turn before being almost completely Landau damped by electrons. The driven parallel current density is found to peak at around $r \sim 0.6\,a$, and the current drive efficiency can exceed 0.6 A/W. The newly obtained features include a slight inward shift of the current peak and, more important, a higher current drive efficiency compared to our earlier results. These can be attributed to improvements in the ray tracing and quasi-linear models.

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Fokker-Planck Simulation of Parallel Electron Transport in TdeV Tokamak *

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TdeV tokamak operates with relatively rare and hot plasmas. Typical Knudsen number for plasma Coulomb collisions is about 0.1 at the separatrix. This indicates that fluid modeling can fail. We've chosen the Fokker-Planck approach [1] to study non-local kinetic effects. We model the parallel electron transport in the scrape-off-layer of TdeV using 1D2V adaptive code ALLA [2]. Our model uses detached and attached experimental data [3] given by Langmuir probes, and lithium and helium ablation. We use improved heat conduction model to reconstruct the plasma temperature and density. We obtain the electron distribution function on a precise 60x257x65 non-uniform grid in parallel dimension, velocity and pitch angle coordinates. Strong deviations of hydrogen and carbon excitation rates and heat conduction coefficient from their Maxwellian values is shown. We compare calculated variation of effective temperature at the reciprocating probe position with experimental measurements by multi-pin probes. We also explain by non-local effects why different experimental techniques show differences in the electron temperature, and why increased impurity radiation from cold divertor region is observed.

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Noncanonical Hamiltonian theory with applications to linear and nonlinear waves, conservation laws and variational structure.

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Hamilton's canonical equations have a well-known noncanonical generalisation. For many important non-dissipative continuum models, it has been explicitly expressed in terms of noncanonical Poisson brackets. We like to present a result for the class of Hamiltonian equation which turns out to be useful for perturbation calculations.

Linearised Hamiltonian equations have in case of unreduced dynamical variables (i.e. no Casimirs) and (less important) with finite degrees of freedom have a natural Hermitian structure with respect to an indefinite complex inner product.[1] The example of the linearised Maxwell-Vlasov system shows that this result may have some generalisations to reduced variables.[2] The generalisation involved a change of field variables from by the distribution function to its "canonical conjugate", the generator S of particle motion. The theory is useful for developing variational theory for linearised gyrokinetics[3] and for finding exact conservation laws of linearised dynamics.[1,4]

This linear theory is now generalised to the whole class of Hamiltonian systems. Also, much of the theory generalize to the nonlinear systems. A general Hamiltonian result underlying the Manley-Rowe relations in nonlinear wave interactions have been derived. Symmetries of the background state are shown to give exact conservation laws for the perturbation. A generalisation of the modified Hamilton's principle is also found.

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A Filament Model for Resistive Wall Mode Feedback Stabilization

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Demonstrating the ability to control the $n = 0$ vertical instability of shaped plasmas is crucial for modern tokamak operation. All major tokamaks presently in operation or being planned for the future, such as ITER, assume a non-circular plasma cross-section. The active control of the $n = 0$ instability relies on the use of passive conducting structures to slow the growth time of the mode from the alfven time scale to a time scale set by the resistive wall time constant, slow enough to be completely controlled by an active feedback system. Resistive wall mode stabilization is an $n = 1$ version of the $n = 0$ vertical position stabilization problem. For the vertical positional instability, the resistive radial flux loss through some $n = 0$ conducting path is the cause of the vertical plasma drift. For the $n = 1$ resistive wall mode, the helical flux leakage through the non-ideal shell is the main cause of the growth, once the ideal kinks are modified into resistive wall modes by the existence of the conducting shell. For both the $n = 0$ and $n = 1$ modes, the shell decay time constant plays the major role for stabilization. There is a possibility to achieve new operational regimes, once the resistive helical flux loss is successfully compensated by additional coil circuits.

Algorithms for the active feedback of resistive wall modes have been developed for RFP's [1] and, more recently for tokamaks by R. Fitzpatrick and T. Jensen [2].

Here, we have examined an approach for feedback stabilization of resistive wall modes using a filament model. For the $n = 0$ mode, various models using a filament element as a plasma column (i.e., plasma rigid displacement model) have been useful for the practical circuit design purposes. Here we discuss a filament element version of the resistive wall mode stabilization in comparison with a cylindrical MHD treatment.

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α-Dynamo Effect of Alfvén Waves and Current Drive in Reversed Field Pinches

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Some time ago Ohkawa [1] suggested that the helicity of Alfvén waves can be exploited to drive current in tokamaks. The specific mechanism has been identified [2, 3] as the α-effect of helical perturbations [4]. In a uniform magnetic field the resulting electromotive force is small and does not give rise to significant currents for realistic parameters (e.g., in tokamaks). However, in reversed field pinches in which the magnetic field in the plasma core is stochastic, a significant enhancement of the α-effect can occur, due to the filamentation of Alfvén wavepackets [5]. We analyze this effect, including the effect of finite ion Larmor radii that reduces the current drive efficiency by spreading the wave packet. For parameters of the Madison Symmetric Torus (MST) reversed field pinch we find that the current drive efficiency is comparable to that of the Ohmic drive. We further discuss the α-effect of Alfvén surface modes in the presence of equilibrium current.

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Improved Theory of Neoclassical Electrical Conductivity in a Tokamak Plasma[1]

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An accurate evaluation of toroidal electrical current profile, thus, neoclassical electrical conductivity, is an important issue in the study of tokamak plasmas since the plasma equilibrium and performance is sensitive to the radial current profile.

Neoclassical electrical conductivity in a tokamak plasma is significantly reduced from the so-called Spitzer conductivity due to banana trapping of electrons in toroidal magnetic well. In the present work, the effect of banana trapping on the neoclassical electrical conductivity has been analyzed more accurately by including distortion of electron orbits from the external toroidal electric field. The present study finds that the difference between the neoclassical electrical conductivity and the Spitzer conductivity is smaller by about 30% than the previous difference. The most significant correction comes from the barely passing electrons, which experience the strongest orbital distortion.

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Effects of Intense Pulsed LH Waves in Tokamaks: Nonlinear Wave Coupling, Electric Fields, Plasma Rotation and Backward Current

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Application of lower-hybrid (LH) power in short, intense, pulses in the $5-10$ GW range should overcome the limiting effects of Landau damping, and thereby permit the penetration of the LH power into the interior of large scale plasmas [1]. At these large power levels, toroidal ponderomotive forces in front of the antenna structure may expel plasma from the space near grill mouth and thus reduce the plasma density, with consequent nonlinear changes in the wave coupling. In the present paper, estimates of these nonlinear changes of the plasma density changes and the associated reflection coefficient for various values of the wave frequency, parallel index of refraction $N_{||}$, and plasma temperatures are presented. It is shown that wave coupling may deteriorate at large power densities. This reduction in wave coupling could be weakened if local plasma heating occurs in front of the antenna grill. Another consequence of intense pulses of LH waves is resonant electron acceleration [2] produced by the large wave electric field. Estimates of the acceleration levels are presented. A strong pulsed wave can also exert a strong poloidal ponderomotive force. This ponderomotive force may induce large stationary radial electric fields, up to about 10 kV/cm, which is approximately two orders of magnitude higher than the electric field required for induction of enhanced confinement H modes by plasma biasing. Poloidal ponderomotive forces in front of LH grills would likely arise from wave propagation in the poloidal direction with respect to the toroidal magnetic field. Poloidal wave propagation is a possibility if the mutual phasing of the horizontal waveguide rows of the grill were of a suitable value. The appearance of strong radial electric fields produces poloidal and toroidal plasma rotation because of the ponderomotive force exerted by the LH wave. As a consequence of LH wave absorption by fast electrons, a strong pulsed current appears in the plasma interior. Simultaneously, a backward electric field and an associated current that is carried by bulk and runaway electrons arise as a consequence of the plasma ring inductance. This induced backward current could have considerable impact on current drive efficiency.

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Improved δf-discretization scheme for nonlinear gyrokinetic particle simulations*

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Basic aspects of particle simulation methods concern both the construction of suitable physical models capable of describing with prescribed accuracy the concerned phenomenology, as well as the search of advanced weighting schemes yielding algorithms with reduced algorithmic complexity. Of special relevance, in this regard, are the δf-weighting schemes adopted for nonlinear gyrokinetic particle simulations in the physics of hot magnetoplasmas [1, 2, 3, 4].

In this work various issues regarding the definition of improved theoretical models, appropriate to describe the dynamics of confined magnetoplasmas, in principle in arbitrary geometry, are addressed. These concern, in particular, the specification of the single-particle gyrokinetic dynamics, capable of describing accurately the long-time behavior of thermal as well as of energetic particles in the presence of both equilibrium [5, 6] and perturbation-driven species-dependent flows [7], the definition of the initial and equilibrium distribution functions [8], and the treatment of binary, *i.e.*, Coulomb [9], collective electromagnetic interactions [10] as well as non-Hamiltonian particle dynamics [11]. In this investigation basic consequences and applications of the present theory are pointed out.

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Diamagnetic effects on flow-shear MHD equilibria*

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An outstanding issue in magnetic confinement is the establishment of MHD equilibria with enhanced flow shear profiles for which turbulence (and transport) may be locally effectively suppressed or at least substantially reduced with respect to standard weak turbulence models. Relevant examples concern flows in tokamak [1, 2, 3, 4] as well as stellarator plasmas [5, 6]. Strong flows develop in the presence of equilibrium $\mathbf{E} \times \mathbf{B}$−drifts produced by a strong radial electric field, as well as due to diamagnetic contributions produced by steep equilibrium radial profiles of number density, temperature and the flow velocity itself. In the framework of a kinetic description, this generally requires the construction of guiding-center variables correct to second order in the relevant expansion parameter. For this purpose, the Lagrangian approach developed recently by Tessarotto et al. [7, 8] is adopted. This allows the determination of the relevant guiding-center invariants which are required for the construcion of kinetically-described MHD equilibria, and in particular of those adiabatic invariants which exhibit the slowest possible time dependence (*maximal adiabatic invariants*). In this work [9] the conditions of existence of such equilibria are analyzed and their basic physical properties are investigated in detail.

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Data compression and information retrieval via symbolization

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Symbolization is a way of coarse-graining that utilizes the underlying dynamics itself. By transforming continuous data into discrete symbol streams, substantial data compression is achieved. This is done without the loss of much dynamical information. As we have shown [1, 2], the symbolic data are entirely adequate for extracting physical parameters for low dimensional chaotic systems, as well as spatio-temporal systems, if the class of the model is known. Lehrman, Rechester and White [3] have employed conditional symbol statistics to identify correlations between different components of a chaotic process. In this report, we will show that a symbolic (time delay) transformation is a robust means for estimating the correlation times for complex signals, which might be noisy, chaotic, turbulent or and admixture of these. Although substantial noise introduces a global bias in the symbol statistics, it turns out to have little effect on ones ability to estimate of the decorrelation rate. Because the algorithm involves only binary operations, it is ideal for real-time applications and is far more efficient than other standard nonlinear data analysis techniques, such as the mutual information. The CPU time scales as N with N the number of data points used. Another important application of our algorithm is its ability to detect a faint periodic signal masked by a noisy chaotic/turbulent background. The computational efficiency and small data storage/buffering requirements makes it especially attractive in situations where the intrinsic time scales are extremely short.

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Gyrokinetic Particle Simulation of Small-Scale Magnetic Islands in High Temperature Tokamak Plasmas

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Small-scale drift magnetic islands have been advanced as a possible candidate for anomalous electron thermal diffusivity in a current-carrying magnetically-confined plasma[1,2]. The regime where the islands radially interact[3] or remain isolated[4,5] from each other has been investigated but a rigorous analytical analysis for the nonlinear evolution, including the self-consistent spectrum of fluctuations, is a difficult problem particularly in the high temperature regime where Landau damping and finite gyroradius effects are important. Recent simulation work using fluid equations has shown it is possible to obtain self-sustaining magnetic islands under certain conditions[6]. In this presentation, the first results on this problem using a nonlinear gyrokinetic particle-in-cell simulation model in 2 and 3-dimensions are given. The basic model is collisionless and is based on the gyrokinetic Vlasov-Poisson-Ampere system of equations[7] with the addition of electron-ion collisions via the Lorentz operator, in order to understand the collisionality dependence of the results. As a first step, the low collisionality regime with single mode rational surface is considered and a saturated magnetic island with tearing mode parameter $\Delta' < 0$ is shown to exist in the presence of electron temperature and density gradients. The basic features of the saturated island characteristics such as the rotation frequency and island width agree well with a nonlinear dispersion analysis in the weakly collisional regime[5]. When a wider spectrum of modes is included in a single simulation calculation, such as modes with $\Delta' > 0$ then there are deviations from the single island, single poloidal mode theory predictions. A parameter space map outlining the regimes where islands can be self-sustained will be presented. Also, the comparison of the saturated electric and magnetic fluctuation spectrum and transport coefficients resulting from the three dimensional, interacting island scenario will be compared with the isolated island results in the weakly collisional regime.

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Confinement of Alpha Particles in Monotonic and Reversed Magnetic Shear Plasmas on TFTR*

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The confinement and loss of fusion alpha particles are examined for reversed magnetic shear plasmas in TFTR and compared to monotonic shear cases. Reversed shear plasmas, with high central q and non-monotonic q profiles can exhibit remarkably reduced energy and particle transport of the thermal ions. However, these same conditions are theoretically predicted to produce high levels of stochastic ripple loss of suprathermal particles, which may reduce the efficiency of plasma heating by the alpha particles and other heating schemes involving fast ions. Calculations of the alpha particle orbit loss with a guiding center code are compared to measurements made in DT reversed and monotonic shear plasmas of the confined alpha particle distribution.

A new, fast, Hamiltonian coordinate guiding center code[1] has been used for the simulations. The results, for plasmas with large major radius where toroidal field ripple is most significant, are compared to those previously published[2] for similar experiments on TFTR but with a monotonic shear profile, at both high and low current and neutral beam heating power. In the reversed shear plasma, the entire plasma is above threshold for stochastic loss of trapped alpha particles at their birth energy. All trapped alphas are lost rapidly either through unconfined orbit losses or stochastic ripple loss, as $q(r) > 2$ throughout the plasma. Pitch angle scattering of passing particles refills the trapped distribution and leads to continued alpha loss throughout the slowing down process. The predicted losses ($\sim 40\%$) are about twice the total alpha losses from a comparable plasma with a montonic shear profile and suggest severe constraints for allowed toroidal field ripple in reversed shear fusion reactor designs.

Measurements of confined alpha particles within a narrow range of pitch and poloidal angle have been made on TFTR with the pellet charge exchange (PCX) diagnostic[3]. To compare the predictive simulations with these measurements requires a final subset of simulated alphas in a very small region of phase space. This becomes computationally expensive, even with several methods to speed up calculations, including the use of conservation of angular momentum, energy and magnetic moment at τ_s and $2\tau_s$ to project the orbits of all surviving ions to $\theta = 0$. Simulations of more than 500,000 particles in the reversed shear case lead to about 100 confined alphas in the restricted window after one slowing down time. Predictions will be compared to measurements to see whether neoclassical transport can account for unusual alpha profiles in reversed magnetic shear without invoking kinetic ballooning, TAE modes or other wave-particle interactions.

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Status and Plans for the NIMROD Code Development Project*

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The NIMROD code development project is making rapid progress on a flexible and accurate numerical tool for studying the time-dependent behavior of low-frequency activity in magnetically confined fusion devices. The code presently solves a system of warm, two-fluid equations in toroidal or periodic linear geometry with an arbitrary cross section. The spatial representation is pseudo-spectral in the periodic direction and a combination of quadrilateral and triangular finite elements in the poloidal plane. The domain is decomposed into blocks for flexibility and to facilitate the use of message-passing parallel architectures. [Test results on Cray Research T3D and T3E computers are reported by Plimpton, et al. in a separate poster at this meeting.] The next major area for development of the physics kernel is the closures used for the fluid equations. This will include nonzero resistivity and neoclassical stress tensors in the species momentum and energy equations. Closure schemes based on the evolution of the distribution function along simulated particle trajectories is a topic for future plasma simulation research. The linear solver used to invert matrices is also an important aspect of NIMROD. The present version uses domain-decomposition preconditioning of the conjugate gradient technique in a manner suitable for parallel processing. Future development in this area will focus on multi-grid preconditioning.

A benchmarking plan will be presented along with the most recent results from the code. This includes linear tests in simple and realistic geometries, which exercise MHD and electron dynamics. Demonstration of nonlinear behavior will include the saturation of linearly unstable modes. We also plan to compare NIMROD results with other nonlinear codes and experiment. This testing program will build confidence prior to the production stage, when the code will be applied to contemporary research topics in tokamak and alternative concept physics.

The GUI, preprocessor, and graphical postprocessing are being developed in tandem with the physics kernel. The GUI includes a central executive program and lower-level interfaces to the suite of codes that constitute NIMROD. Future development will focus on expanding the real-time manipulation capabilities of the executive program. We are also examining the possiblity of using remotely driven visualization and I/O to drive a simulation. The preprocessor initializes the finite element grid and fundamental physical fields. The present version can generate a flux-surface aligned grid based on EFIT equilibrium calculations. We will expand its capabilities to generate the initial magnetic field based on equilibrium calculations and to use output from other codes. Postprocessing is being developed on a two-tier scheme. Extensive, routine graphics will use the XDRAW code, which is being enhanced to produce contour plots on arbitrary, decomposed domains. Presentation-quality graphics and movies are being produced with IBM's Data Explorer software. The GUI, preprocessor and graphical postprocessing will be demonstrated.

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Numerical Analysis of the NIMROD Formulation

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NIMROD studies the nonlinear evolution of long-wavelength tokamak instabilities, with long time scales, requiring an implicit time step; and strong anisotropy and near-singular mode structure, requiring high spatial resolution. Toroidal discretization is pseudospectral. *Multiple* grid blocks are used in the poloidal plane, allowing for efficient parallelization, and for specialized methods each designed for a specific subdomain. The plasma region uses logically rectangular grid blocks based on non-orthogonal flux coordinates, infrequently updated to track the axisymmetric component of the magnetic field. This region is broken into annular zones to minimize coupling among blocks. Metric quantities are fit to bicubic splines for greater smoothness. A scrape-off layer uses a grid-block of adaptive, unstructured triangles. The vacuum region uses cylindrical coordinates. Small grid patches in the neighborhood of the o-point and the x-point can be used to avoid numerical difficulties caused by the coordinate system singularities.

In order to obtain an accurate description of the low-frequency instabilities of greatest interest, it is essential to avoid certain numerical pathologies:

1. **LARGE TRUNCATION ERROR:** Anisotropy can amplify error, as in the problem of spectral pollution found in eigenvalue codes.
2. **THE RED-BLACK PROBLEM:** Decoupling of adjacent grid nodes can introduce jitter.
3. **INDEFINITE MATRICES:** Causes Conjugate Gradient Method to be unreliable.
4. **MANY VARIABLES PER NODE:** Causes excessive run time.
5. **SPURIOUS NUMERICAL MODES:** Introduces noise and uncertainty.

The presence or absence of these numerical difficulties is found to be sensitive to detailed choices about discretization. For example, truncation error varies considerably depending on whether the fundamental dependent variable is chosen to be the electric field $\mathbf{E}$, the magnetic field $\mathbf{B}$, or the vector and scalar potentials $\mathbf{A}$ and φ.

A necessary, though not sufficient, condition for avoiding these problems is that they be absent for linear modes in a uniform plasma. For this case, the discretized equations can be understood in terms of analytically derived dispersion relations. Techniques have been developed to automate the derivation of such equations with Mathematica. Using these techniques, many possibilities have been explored. Details will be presented and used to motivate the optimal choice of discretization strategy.

Parallel Structure and Performance of the NIMROD Code

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NIMROD is a new fusion modeling code that has been developed over the past year by a team of researchers at several institutions. It is designed to enable simulation of non-ideal, linear and non-linear, time-dependent 3-D MHD effects in realistic tokamak geometries. The computationally intensive physics kernel is written so as to run without modification on single processors or any platform that supports a message-passing style of programming. This includes workstations, traditional vector supercomputers, and essentially all current-generation massively parallel machines. Other presentations at this conference discuss the current status of the code * and its formulation of the two-fluid/Maxwell's equations † In this poster, we describe how the NIMROD kernel is structured to enable efficient parallelization and highlight its performance on several parallel machines including the new Cray T3E at NERSC.

NIMROD represents the poloidal simulation plane as a collection of adjoining grid blocks; the toroidal discretization is pseudo-spectral. Within a single poloidal block the grid is topologically regular to enable the usual 2-D stencil operations to be performed efficiently. Blocks join each other in such a way that individual grid lines are continuous across block boundaries. Within these constraints, quite general geometries can be gridded, and parallelization is achieved by assigning one or more blocks (with their associated toroidal modes) to each processor. In parallel, the only interprocessor communication that is then required is to exchange values for block-edge or block-corner grid points shared by other processors. For general block connectivity, this operation requires irregular, unstructured interprocessor communication. We describe our method of pre-computing the communication pattern and then exchanging values asynchronously, which enables this block-connection operation to execute efficiently and scalably on any number of processors.

NIMROD uses implicit timestepping to model long-timescale events and thus requires a robust iterative solver. To date, two iterative solvers have been implemented for NIMROD using conjugate gradient techniques. Both perform their computations on a block-wise basis and thus work in parallel using the block-connection formalism described above. The first method uses simple diagonal (Jacobi) scaling as a matrix preconditioner; the second method directly inverts the portion of the matrix residing on each block as a preconditioning step. We will present timings that illustrate the performance and convergence of both techniques as a function of (1) the number of blocks used to grid the poloidal plane and (2) the number of processors used.

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*C. Sovinec, et. al., poster at 1997 Sherwood Fusion Theory Conf.
†A. Glasser, et. al., poster at 1997 Sherwood Fusion Theory Conf.

Fast Electrons Generated by Lower Hybrid Waves at the Tokamak Plasma Edge

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It is well known that electrons may be accelerated in front of a lower hybrid (LH) waveguide array by a strong electric field of the slow LH wave at the mouth of the antenna grill [1]. In addition, such intense waves may generate through the nonlinear process of parametric decay strong sideband waves at the plasma edge [2, 3]. The frequencies of the sidebands are typically lower than the LH pump wave frequency by about ten percent. The present paper treats the effects of the axial LH field gradient at the sides of the grill, where the accelerated electrons pass when moving parallel to the magnetic field lines near the front of the grill mouth. In addition, effects on electron acceleration of random fields of LH sidebands generated by parametric instabilities are considered. It is assumed, in contrast to the assumptions in Ref. [1], that the influence of the near electric field of individual waveguides in the antenna array is not a dominant factor of the electron motion. In other words, the model is applicable to electrons moving along the magnetic field lines, which pass the grill at a distance greater than several millimeters.

The LH wave fields are approximated by the excited fields of a simplified antenna configuration that is an appropriate model of the grill mounted in TdeV [1]. The LH sidebands are modeled by wave trains with randomly varying phases. It is found that without the effects of the random LH sideband fields, especially for high spatial gradients with characteristic lengths L of the order of 1 mm at the grill side near the last waveguide in the direction of the magnetic field, the electrons may be pushed from the grill with a velocity corresponding to their maximum energy to which they were accelerated. For TdeV parameters, this corresponds to an energy of about 2 keV [1]. For characteristic lengths L of about 1 cm, however, the energy of electrons leaving the grill is much lower. The presence of the LH sideband fields significantly alters this picture by a significant enhancement of the energy of electrons which leave the grill. This effect is important mainly for smaller gradients, i.e. for larger values of L. Estimates of the electron acceleration for various LH wave frequencies and grill dimensions will be presented.

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A Mixed, Shear Dependent Bohm–Gyro-Bohm Transport Model

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An empirical, local, magnetic shear dependence was found to modify the model for the ion and electron thermal conductivity of the mixed Bohm and gyro-Bohm type of [1]. The proposed magnetic shear dependence takes its basis from a proper estimate of the radial correlation length of ion-temperature-gradient-driven modes [2] in toroidal configurations. A clear indication has emerged from experimental data that the most reliable empirical model is given by a combination of a Bohm type model and a gyro-Bohm type. The Bohm part of the model has a functional dependence on the magnetic shear for positive values of the shear and it is cut off for zero or negative shear. The shear dependence plays a fundamental role in giving to the model a large versatility and it is suggested both by experimental evidence of improved confinement in the central region of the plasma in the presence of flat or inverted shear, and by theoretical estimates of the dependence of micro-turbulence correlation length on the value of shear.

The above model has been used in the transport code JETTO to simulate a large number of pulses. The model was tested both on standard L-mode discharges taken from ITER Data Base and on various kind of central high temperature L-mode discharges of JET with flat or reversed magnetic shear, giving very good results in both cases. In particular the PEP-mode and Hot-Ion-L-mode discharges were also well simulated: in this type of discharges the model proposed is able to reproduce the strong thermal barrier observed on the temperature profiles at about half radius (in particular on the ions temperature profile), whereas models without the shear dependence fail.

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RF Effects on Neoclassical Theory and the Bootstrap Current in Tokamaks

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We consider the possibility of synergistic effects in combining bootstrap and RF current drive in tokamaks.[1] In neoclassical theory, the bootstrap current is derived from an electron velocity-space distribution satisfying the drift kinetic equation (DKE), with radial drifts due to magnetic field gradient and curvature. Numerical solutions to the DKE are found with KT3D-NC, a Fokker-Planck code with quasilinear diffusion[2] which calculates perturbations to the electron distribution due to the drift term of the DKE. The resulting bootstrap current is then found by taking the usual velocity-space moment of the RF-modified electron distribution. A quasilinear diffusion operator is chosen to represent several RF wave scenarios (lower hybrid, fast Alfvén waves, electron cyclotron). The numerical results are compared to analytic solutions obtained using several approximate techniques.

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Comparative Transport Model Testing Using the ITER and DIII–D Profile Databases

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A fast steady-state transport code using experimental sources is used to compare theory-based transport models including the IFS/PPPL [1], GLF23 [2], Multi-mode [3], and Itoh-Itoh-Fukuyama (IIF) [4] models. The IFS/PPPL and GLF23 models are based upon gyrofluid simulations of the toroidal ion temperature gradient (ITG) mode in a 3D nonlinear ballooning mode representation with extrapolated trapped electron (TEM) physics. The Multi-mode model combines the Weiland-Nordman "local" (2D) dispersion equations for ITG and TEM modes with contributions from resistive g-modes and kinetic ballooning modes. The IIF model differs from the other models in that it is not a drift wave based transport model. It can be characterized as a current-diffusive model based upon one fluid electrostatic "inertial" MHD equations. The gyrofluid models are very "stiff" tending to marginality to the ITG threshold and the Multi-mode less stiff. The IIF model has no threshold.

The predictions from these models are compared against an experimental profile database comprised of more than 50 L– and H–mode discharges from DIII–D, TFTR, and JET. These discharges, which include parameter scans in gyroradius, collisionality, beta, plasma current, density, and power, have been obtained from the ITER profile database [5] and the DIII–D profile database. Here, the experimentally analyzed sources and density profiles are assumed and only the electron and ion temperature profiles are predicted assuming a fixed boundary location of $\rho / a = 0.9$.

Also reported are results of a sensitivity analysis of the predicted profiles to variations in the boundary conditions and other quantities including $E \times B$ shear, magnetic shear, impurity content, and particle and heat sources. Ultimately, the sensitivity of each model impacts their respective ITER projections, therefore we compare the results of each model using various ITER target discharges and assess the sensitivity of the predicted performance to the prescribed boundary conditions.

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MHD Burgerlence: A Model of Compressible MHD Turbulence

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A simple, one-dimensional model of compressible MHD turbulence is presented. The fluid behavior is described by Burgers' equation, with the addition of magnetic pressure, while the magnetic field follows a convection-diffusion equation derived from Maxwell's equations. An exact solution, describing shock structures in compressible Alfven waves, is given for the case of unity magnetic Prandtl number. For arbitrary Prandtl number, the addition of random forcing is shown to inhibit shock formation but keep ballistic propagation. Renormalization group methods are used to calculate the turbulent transport rates. It is found that the effective viscosity and magnetic diffusivity are equal in the inertial range. Energy equipartition, however, depends on the equality of the forcing functions. Implications for spectral turbulence theory and self-organization phenomena in MHD are discussed.

Wave emission from mode conversion regions

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An important feature of nonuniform media is the possibility of linear mode conversion due to the near-degeneracy of the dispersion relations of two wave modes in localized regions of the plasma. The wave emission in the mode conversion regions has been a subject of a discussion in several recent publications [1]. Here we present a new approach to this problem which is based on the ray tracing technique of [2], extended to mode conversion regions, as discussed in [3]. This extension allows one to connect the local wave field emitted by a source to rays outgoing from the conversion region. The analysis is performed for both positive- and negative- energy waves.

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Nonlinear Stability of Tearing Modes*

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A code for the determination of nonlinear stability of tearing modes is being developed. The work is aimed at determining if the nonlinear "neoclassical tearing mode"[1] instability also exists in a single fluid MHD approximation, as well as the possibility of a tearing instability driven by a current density gradient at the singular surface[2]. The initial equilibria considered are 1D slab equlibria. They are perturbed by externally driven currents to produce equilibria with islands while the plasma is assumed to obey "almost ideal MHD"[3]. The stability is inferred from the sign of the energy exchange between the plasma and the external circuit. The first step for this project is to compare the code results for equilibria without pressure or current gradient at the singular surface to previously obtained results.

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Evidence for Non Power-Law Scalings of Confinement Parameters and Inward Transport of Thermal Energy*

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A new general scaling for confinement parameters and the associated transport coefficient that can simulate a wide range of discharges have been derived from a series of experiments including in particular those carried out by the Alcator C-Mod machine spanning a broad interval of relevant parameters. The relevant analysis shows that the forms of the scaling for the thermal energy content or the total energy confinement time which can fit the data do not have a unique representation [1]. The usually considered power law scalings are among the possible ones. However, it is shown that the scaling to be preferred is that directly related to the representation of relevant dimensionless quantities such as β_p in terms of other dimensionless quantities characterizing the experiments. Notable among these is the ratio $P_H/I_p\mathcal{V}_o$ where P_H is the heating power, I_p is the plasma current and $\mathcal{V}_o$ is a "universal" voltage scale (≈ 1 V! olt) with $\mathcal{V}_o \propto T_e C_o/e$ and $C_o \propto 1/T_e$ is an appropriate dimensionless quantity weakly dependent on density. For ohmic regimes $P_H/I_p\mathcal{V}_o \approx 1$. Thus the scaling of the confinement time for the so called L-regime is

$$\tau_E \approx \alpha_1 R q_E^{2/3} I_p \left(1+\alpha_2 \frac{I_p\mathcal{V}_o}{P_H}\right)\left(\frac{d_i}{a}\right)^{1/2}\left(\frac{\omega_{pe}}{\Omega_{ce}}\right)^{1/3} \overline{A}_i^{1/4}$$

where R is the major radius in meters, I_p is in MA, P_H is in MW, $\overline{A}_i$ is the effective mass number, $\alpha_2 \approx 0.22R/(ad_i)^{1/2}\overline{A}_i^{1/4}$, $d_i = c/\omega_{pi}$, $\omega_{pi} \equiv \overline{n}_e e^2/\epsilon_o m_i$ is evaluated with the electron line average density, $q_E = 2\pi a^2 \kappa B_T/(\mu_o R I_p)$, κ is the ellipticity, a is the horizontal minor radius, τ_E is in seconds, and $\alpha_1 \approx 3.1 \times 10^{-2}$.

The composite transport coefficient D_e^{th} for the electron thermal energy, introduced in Ref. [1] in order to justify a scaling of the type just mentioned, involves the difference of two terms. One represents the outflow of thermal energy and the other one an inflow that degrades as the heating power increases above the characteristic ohmic level. There are infact theoretical arguments [3] in support of a composite transport coefficient based on the symmetry properties of a transport matrix with an inflow term related to the features of the current density profile relative to those of the electron temperature. Of the two contributions to τ_E, the term with the coefficient α_2, corresponds to the inflow term in D_e^{th}. The coefficient D_e^{th} [1] includes the constraint of profile consistency and is inspired by the properties of the so-called "ubiquitous" modes [4] (reinvented later under the name of toroida! l ion and electron temperature gra dient modes) that have a significant dependence on the ion and electron pressure gradient.

The experimental database assembled for the ITER project [2] is used to compare D3D, JET, JT60, PDX, TFTR, FTU and Alcator C-Mod with this analysis. We have considered plasma regimes where T_e and T_i are not drastically different. In addition, we have selected relatively clean plasmas $Z_{eff} \leq 2.5$ close to equilibrium. The comparison is quite favorable.

For H-mode discharges, an addition inflow term at the plasma edge is introduced in D_e^{th} in order to represent the effects of a transport barrier. Thus D_e^{th} retains the same basic form but is modified from the L-mode version of it to contain a third term. Based on experimental observations of the Alcator C-Mod machine, a form for this inflow is proposed.

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Confinement at Low Aspect Ratio*

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Simulation methods based on the gyrokinetic and gyrofluid equations have advanced to the point where predictions of core tokamak confinement are roughly 20% accurate for standard tokamak discharges. Since no empirical information is used in these transport simulations, the approach is generalizable to experimentally unexplored geometries. Experimental verification of the physics predictions of the method in standard tokamks confirms the basic physics understandings, thereby enabling the use standard tokamak data to benchmark the performance projections of novel geometries. Previous results on standard tokamaks will be reviewed to show that marginal stability to drift type instabilities (with corrections for velocity shear) is the primary factor determining experimental temperature profiles, and to examine the relationship of advanced confinement modes (NCS and ERS modes) to velocity shear. The computational tools have been generalized to arbitrary axisymmetric geometry. Low aspect ratio ($R/a \sim 1.2$-1.8) configurations are examined here. Marginal stability criteria in low aspect ratio configurations without velocity shear are not appreciably better than standard tokamaks when full electromagnetic effects are included (unlike in electrostatic calculations). However, marginal stability improves much more strongly with velocity shear at low aspect ratio. A parameter is described which roughly measures the ratio of increased fusion power for the amount of power needed to drive velocity shear. This parameter is roughly two orders of magnitude higher in low aspect ratio tokamaks than in conventional ($R/a \sim 3$) "advanced" tokamaks. In conventional advanced tokamaks, it is difficult to reconcile velocity shear requirements with reactor relevent constraints, but low aspect ratio tokamaks seem to be a practical way to use such advanced confinement scenarios.

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δf simulation of the nonlinear evolution of Toroidicity-Induced Alfven eigenmodes with various collisional effects* *

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It has been shown [1] that, in the nonlinear evolution of Toroidicity-Induced Alfven Eigenmodes (TAE) driven by energetic particles, collisional effects, such as particle birth, charge exchange loss, slowing down and pitch angle scattering, are capable of competing with the wave-particle resonant interaction, and should be retained in numerical simulations. A generalized δf method has been developed, where in addition to the Hamiltonian guiding center motion[2] and slowing down, particles are randomly scattered using Monte Carlo techniques[3, 4]. Particles are also added into or removed from the simulation, in a convenient manner which might differ from the way physical particles are born or lost. Particle weights are introduced as a new dimension of phase space for the simulation particles, which allows a rigorous derivation of the weight evolution equation. Assuming the mode structure and frequency are fixed, the TAE is described by its slo! wly-varying amplitude and phase

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New approach to non-Hamiltonian particle gyrokinetic theory*

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A fundamental aspect of kinetic theory and particle simulation approaches for magnetoplasmas is the formulation of gyrokinetic theory, particularly non-linear gyrokinetics, when single-particle orbit dynamics is described by a non-hamiltonian system. The most notable example is given by the equations of the characteristics for the kinetic equation when the Landau-Fokker-Planck, or Lenard-Balescu, collision operator is retained to describe binary Coulomb interactions in collisional or weakly collisional magnetoplasmas. In this case, in fact, both Lie-transform [1, 2, 3, 4, 5, 6] and Lagrangian [7, 8] approaches are not directly applicable to describe the non-hamiltonian particle orbit dynamics, while previous iterative schemes [9, 10] appear inconvenient and unsystematic, especially for the purpose of developing higher-order perturbative formulations.

The purpose of the investigation [11] is to propose a new direct perturbative theory to nonlinear particle gyrokinetics applying to non-hamiltonian systems. Its formulation will be analyzed in detail and its basic features compared with those of previous perturbative approaches.

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MODULATION INSTABILITY OF ELECTRON WAVES IN MAGNETIZED PLASMA

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An important property of electron waves of plasma is their modulation instability which causes the collapse and the formation of Langmuir solitons. The ponderomotive force leads to a local evacuation of the plasma density which results to the wave trap and to enhancement of its amplitude. This process taking place on the ion-time scale leads to the nonlinear coupling between the short wavelength Langmuir waves and the longwavelength ion-acoustic waves, described by the so-called Zakharov equations [1]. In this paper the instability of electron waves in magnetized plasma has been considered. The dispersion relation of electron waves in such plasma differs from the dispersion relation of Langmuir waves in nonmagnetized plasma. This leads to different behaviour of Langmuir waves and electron waves of magnetized plasma during their propagation with group velocity along a nonhomogeneity of plasma density. Namely, one can show from the conservation law of energy flow that the amplitudes of Langmuir waves are larger in space interval where the plasma density is larger. But the amplitudes of electron waves with some frequencies in magnetized plasma are larger in space interval where the plasma density is smaller. This effect can lead to modulation instability of electron waves with these frequencies on ion time scale. The evolution equations for modulation instability development of electron waves of magnetized plasma have been derived. We consider the case of the large group velocities of electron waves $V_{gr} \gg V_s$ as well as the small group velocities $V_{gr} \sim V_s$. Here V_s is the ion-acoustic velocity. We consider the propagation of electron waves with small angle relative to the external magnetic field. An important property of electron waves of magnetized plasma is the existence the transversal as well as longitudinal components of electric field relative to the wavenumber. For the smaller plasma density the transversal component of electric field smaller. Hence the transversal component is transformed into the longitudinal one. This effect results that the longitudinal component of electric field is larger in the space interval where the plasma density is smaller.

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UEDGE Plasma Simulations with Monte Carlo Neutrals*

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We report on results from coupled UEDGE plasma and EIRENE Monte Carlo neutral models. A kinetic neutral particle model is attractive because it is straightforward to implement for complicated geometries and accurately models low-to-moderate collisional regimes that occur in most edge plasmas. A neutral fluid (Navier-Stokes) model is computationally faster and more naturally includes non-linear (neutral-neutral) interactions that are important in high-collisionality regimes. We previously reported favorable comparisons[1] of results from the EIRENE Monte Carlo model and the fluid neutral model in UEDGE, based on a simple rectangular slab geometry with a thermally attached plasma. Here we treat more realistic configurations, e.g., the DIII-D divertor[2], that include gaps between the plasma and sidewalls. We plan to test the validity of the fluid model for thermally detached plasmas with strongly radiating impurities, which may occur in the ITER divertor.

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Interchange Instabilities in a Partially Ionized Plasma*

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Low temperature plasmas are often coupled to a neutral population through charge exchange or elastic collisions. The edge and divertor region of a tokamak and the ionosphere are a few well know examples. The presence of neutrals within a plasma can give rise to new instabilities in several ways. It is well known that positive dissipation can cause negative energy waves to become unstable. Thus, the dissipation introduced by ion-neutral collisions can allow certain instabilities to proceed that would not otherwise occur. For example, the dissipative velocity shear instability proposed by Basu and Coppi [1] is driven by a gradient in the field-aligned ion flow velocity but requires ion-neutral collisions to proceed.

Another way in which a neutral population can give rise to a plasma instability is by providing an additional source of excitation energy to drive the instability. An instability of this type is identified in which the source of excitation energy is a neutral flow velocity. When perturbations in the neutral population are weak, the instability is directly analogous to a gravitational collisional interchange mode with the effective gravity $g_{eff} = \nu_{in} V_n$ arising from the collisional force the neutral flow exerts upon the plasma. The instability will occur when a flow of neutrals is directed opposite the plasma density gradient. Instabilities of this type are ubiquitous in nature. Linson and Workman [2] appear to be the first to suggest that a neutral flow can drive a plasma instability in connection with barium ion clouds in the E layer of the ionosphere. An interchange instability of this type was later proposed by researchers studying the equatorial spread F in the ionosphere [3]. More recently it has been proposed that similar instabilities might occur in the heliopause near the stagnation point at the "nose" of the heliosphere [4] and in the sunward ionopause of comets [5].

When deriving the dispersion relation, all of these researchers treat the neutral population as a uniform background insensitive to the perturbations in the plasma. While this approximation is justified for ionospheric plasmas where the the plasma density is much less than the neutral density it is not justified in the case of many laboratory plasmas where the neutral and plasma density are of the same order. In this work, the flute mode stability of a coupled plasma-neutral system in a magnetic field where the densities are assumed to be comparable is examined in plane geometry. The neutral population is treated first as a collisional fluid and then more generally using the Boltzmann equation with a charge exchange collision operator to determine the neutral response for both short and long neutral mean free path regimes. It is shown that the instability exists for both these limits and that under certain conditions neutral perturbations are quite strong.

The possible relevance of this instability to divertor plasmas is considered. Typically in the divertor region at some distance from divertor target, traversing across the field toward the wall the plasma density decreases while the neutral pressure increases. This results in a flow of neutrals in the direction of the plasma density gradient and thus a stable equilibrium. However, this neutral flow can be reversed in the so-called detached divertor regime characterized by a low plasma temperature ($T \leq 1$ eV) and strong plasma recombination in the divertor [6]. In this regime, the neutral pressure profile can be reversed and the resulting outward flow of neutrals can drive an instability of this type which may significantly alter plasma parameters and affect plasma recombination. This is important since recombination is a crucial element of detached divertor regimes [7].

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High Mode Number Ballooning Stability in Stellarator Configurations

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The characterisitics of high-n ballooning modes in stellarator configurations are examined by generalizing the method of Greene and Chance [1] to three dimensional systems. In this study, a set of equilibria are generated by imposing localized perturbations of the pressure and rotational transform on an arbitrary initial equilibrium. Equilibria that are consistent with the profile changes are calculated using Boozer coordinates assuming the perturbations are small, but their cross field gradients are order unity. In this way, changes in the magnetic flux coordinates can be derived analytically as functions of the perturbed pressure and rotational transform gradients. If an additional currentless constraint is imposed, the rotational transform and pressure perturbations are related, and only one free function classifies the deviations from the initial equilibrium. The advantage of using this approach for generating equilibria is that close scrutiny can be paid to the relevant ballooning mechanims, namely the role of local magnetic shear, curvature and net equilibrium current. In particular, we generalize previous results [2,3] by deriving analytic equations for the change in the flux surface averaged and local magnetic shear due to Pfirsch-Schlüter and equilibrium currents. In the limit of a configuration with a continuous symmetry, the accessibility of a second stability regime is quantified. The effect of a three dimensional perturbation on a nearly symmetric system tends to be destabilizing.

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Alfven Waves and Wave-Induced Transport near an X-point*

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Scrape-off layer (SOL) instabilities on the Alfven branch, driven by curvature and divertor plate sheaths, can contribute to anomalous transport in the edge plasma. Wave-induced transport in the vicinity of an X-point is of particular interest because it can control the SOL width at the divertor plates, and because the X-point region of the interior flux surfaces might tend to be "leaky" from the point of view of core confinement. The extent to which the X-point region dominates these processes is the central question we set out to address. Alfven-type waves are employed to examine the variation of the wave-induced transport coefficients along a field line including the X-point region. It is shown that several competing effects exist. Wave-induced transport tends to be large near an X-point because of two effects: the particle orbits dwell there for a long time, and the displacement $\xi \propto \mathbf{k} \times \mathbf{B}$ becomes relatively large in the X-point region, and between the X-point and the plates because magnetic shear increases $\mathbf{k}$. Conversely, the magnetic geometry makes gradients $\nabla \propto RB_p \partial/\partial\psi$ small near the X-point, and a tendency for the mode amplitude to avoid the X-point region has been noted in a previous study.[1] To quantify these competing effects, we present quasilinear and mixing length transport models which take the magnetic geometry of the X-point into account. To address the issue of mode amplitude and the validity of the eikonal approximation near the X-point, an exact analytical solution of the PDE describing Alfven-waves in the X-point region is obtained. Preliminary results suggest that the contribution of the X-point region to wave-induced transport can be significant.

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1C44

Finite Orbit Width and Larmor Radius Effects of Fast Particle drive on Low-n TAE Stability. *

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The effects of finite drift orbit radial width (FOW) and Larmor radius (FLR) of fast particles on the stability of low-n TAE are studied. The formulation is based on the solution of the low frequency ($\omega \ll \omega_c$, where ω_c is the cyclotron frequency) gyro-kinetic equation. A quadratic form has been derived in terms of invariant variables: energy $\mathcal{E}$, magnetic momentum μ, and toroidal momentum P_φ. The growth rate is computed perturbatively by averaging over the fast particle drift orbit. The TAE structure is calculated using the NOVA-K code [C. Z. Cheng, Phys. Reports **211** (1992) 1]. The results are benchmarked with previous calculations [G. Y. Fu and C. Z. Cheng, Phys. Fluids, **4** (1992) 3722] based on small radial orbit width approximation. It is shown that both FOW and FLR effects are typically stabilizing. However at certain conditions FOW effects may increase TAE growth rates. The FOW and FLR effects may reduce the growth rate by as much as a factor of 2 for TFTR supershots.

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Investigations of the Magnetic Field Structure of EPEIUS[1]: a proposed low-aspect ratio torsatron-tokamak hybrid*

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The magnetic field structure of a proposed small aspect ratio torsatron-tokamak hybrid machine which is the outgrowth of studies conducted at ORNL[2,3] has been investigated. The current point design consists of eight tilted-twisted modular coils in addition to the normal vertical field system. The coils' tilt and twist provides a vacuum ι profile that is tokamak like, i.e. decreasing away from the magnetic axis. The flux surface robustness to both changes in design parameters and to manufacturing and assembly errors have been examined using two numerical techniques. The first uses a standard field line following code such as AVAC, or HOMER[4]. These codes directly integrate the field line equations of motion where the magnetic field is computed at each point from the Biot-Savart law for a line segment (nonplaner coils approximated by line segments). The second technique uses the field line integrator to generate a numerical map which carries a point(R, Z) on a poloidal plane to its image on the same plane after one complete toroidal transit. Similar maps have been compared with both experiment and sem-analytic techniques[5,6,7]. By generating a full transit map, errors caused by nonperiodic misalignments can be investigated. The numerical generation of the map typically takes significantly longer than the integration of enough field lines to roughly map the field structure. Once generated, however, the map can be rapidly iterated so that many field lines (> 10) can be followed for a large number ($> 10^3$) of transits. Map iteration is sufficiently fast that interactive programs using byte interpreted languages (Java) provide adequate performance.

Studies to date show that for sufficiently large misplacement of a single coil in the assembly, (misplacements larger than typical engineering tolerances), large islands at the $q = 5$ surface can be generated. Details of the coil leads affect the flux surface shape while not generating large islands. Generally, the flux surfaces appear to be robust when assembly errors are within reasonable manufacturing tolerance of 1-2 mm, and 1-2 mrad for the classes of manufacturing errors than have been explored.

Results also indicate stochastic regions. The requirement that the diffusion from stochastic regions be significantly less than that expected from diffusion by other processes puts an upper limit on the acceptable width of stochastic regions of $\sim$ 1cm. This requirement appears to be readily achievable.

Details of the mapping technique and results are presented.

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Stability of Low-Shear Alfvén Eigenmodes*

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Recent theories have predicted the existence of multiple toroidicity-driven Alfvén eigenmodes (TAEs) corresponding to a single Alfvén gap when the shear is very low. Here, we report further information concerning such modes. Numerical simulations confirm the existence of numerous TAEs, for parameters that agree with the theoretical predictions. Analytical calculations show that the instability threshold for these low-shear TAEs is rather modest. The sensitivity of the mode spectrum to finite-beta effects is examined. Similar multiple modes may also exist in the low-shear regime for the case of ellipticity-driven Alfvén eigenmodes (EAEs). Comparison will be made with TFTR observations of alpha-excited Alfvén modes in low- and reversed-shear configurations.

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Effects of Plasma Inertia on Stability of Magnetic Islands*

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Dynamics of magnetic islands in the Rutherford regime is significantly affected by ion inertial (polarization) drifts in the perturbed electric field. In this paper, we show that the net effect of plasma inertia on an island stability is mainly determined by the velocity profile around the magnetic island. In the limit of zero viscosity, the perturbation of the plasma flow is localized around the magnetic island [it is maximal in the separatrix region] and decays at a large distance. We develop the two-fluid model describing the plasma motion in the nonlinear region. It is shown that the velocity profile can be regularized by the effective ion Larmor radius, $\rho_s^2 = T_e/m_e\omega_{ci}^2$. It is concluded that the plasma inertia is stabilizing in this case as was shown before [1, 2, 3]. In a plasma with a finite viscosity the plasma velocity profile is constrained to be flattened around the magnetic separatrix. The plasma is thus at rest in the vicinity of the island (in the rest frame of the magnetic island). Viscous coupling causes propagation of the velocity perturbation away from the moving island resulting in the velocity that grows linearly with the distance from the island. In this case inertial forces do not provide a stabilization mechanism against the island instability, but rather lead to the further island growth as it has been recently demonstrated [4].

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Electron Cyclotron Current Drive for Stabilization of Neoclassical Tearing Modes in ITER

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Bootstrap current is reduced within tearing mode magnetic islands in tokamaks, in proportion to the small radial pressure gradient there. This ''hole'' current contributes an important destabilizing effect to the ''neoclassical'' tearing mode [1,2]. As a result the islands can grow to large radial size, consistent with causing disruptions in DIII–D, and may be a limiting factor for ITER long pulse discharges [3]. Electron cyclotron (EC) current drive (CD) is particularly well suited to provide compensating stabilizing current due to its localizability, steerability, and possible pulsed application within the islands [4]. Localizability is important since smaller islands require proportionately less current. Thus the figure of merit for neoclassical tearing mode CD stabilization can be written $\gamma_{\text{neo}} \equiv \gamma/\Delta\rho$, where gamma is CD efficiency { ≤ 0.3 for EC, in units 10^{20} A/(W m^2) [5]} and $\Delta\rho$ is radial island width normalized to plasma radius. For complete compensation of the bootstrap current in tearing islands by 50 MW in ITER, typically $\gamma_{\text{neo}} > 1.0$ is required. The quantity γ_{neo} resulting from ECCD has been calculated for a broad range of toroidal and poloidal EC wave launch angles from midplane and off-midplane locations, into standard and advanced equilibrium ITER discharges. Values of $\gamma_{\text{neo}} > 1.0$ are obtained for ρ values from the plasma center out to 0.85 which is beyond the most limiting $q = 2$ resonance surface for a standard ITER discharge. The theory of island stabilization will be generalized to situations where the current drive deposition is greater than the island width, as well as being modulated in time. Results and optimization considerations will be discussed.

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ICRF Heating and Current Drive in High and Low Beta Tokamaks*

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We consider the effects of alpha particles in TFTR on heating and mode conversion current drive. The effects of nonlocal wave fields in absorption by the alphas are considered by the use of the SEMAL code. We have found substantial tritium ion tail formation at low tritium concentrations, in agreement with experimental observations. We also consider the coupling of ICRF power to alpha particles as the D-T mix and alpha concentration are varied. We present analysis of IBW coupling for TFTR and compare to experimental results. We also consider the nonlocal effects for wave heating and startup as well as non-inductive current profile control for high beta tokamak concepts such as NSTX, Pegasus and LCT-2. The scenarios examined include minority ion heating and mode conversion and higher harmonic current drive. The effects of high beta equilibria which modify the magnetic field profiles and affect wave absorption and localization are considered for these machines. We discuss our progress on developing improved computer codes for modeling ICRF heating and current drive in high beta tokamaks.

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Stimulated Brillouin Scattering of an Electromagnetic Wave in a Strongly Magnetized Plasma

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Abstract

In a strongly magnetized non-isothermal plasma, a large amplitude electromagnetic wave propagating at an angle θ_0 to a strong magnetic field undergoes Stimulated Brillouins Scattering (SBS) off the ion mode. In an isothermal plasma the process goes over to Stimulated Compton Scattering (SCS) with considerably lower growth rate. In both the cases the growth rate is sensitive to the angle $\theta = (\theta_1 - \theta_0)$, where θ_0 is the angle of the pump wave vector $\vec{k}_0$ with the d.c. magnetic field $B_s\hat{Z}$ and θ_1 is the angle of the sideband wave vector $\vec{k}_n$ with $B_s\hat{Z}$.

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$\mathbf{E} \times \mathbf{B}$ Shearing Rate in a Stellarator with Quasi-helical Symmetry *

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$\mathbf{E} \times \mathbf{B}$ shear suppression of turbulence is responsible for various forms of confinement enhancement in tokamaks[1]. In a shaped tokamak plasma, the radial variation of E_r/RB_θ (the effective toroidal flow driven by E_r) is a key quantity in determining the suppression of turbulence[2]. Keeping the correct geometric dependence is essential for meaningful comparison to experimental data[1, 3]. Indeed, there is experimental evidence that B_θ variation is as important as E_r variation[4, 5]. In this work, the $\mathbf{E} \times \mathbf{B}$ shear induced decorrelation dynamics is studied for a stellarator configuration with quasi-helical symmetry[6, 7]. The resulting $\mathbf{E} \times \mathbf{B}$ shearing rate recovers the previous results in an axisymmetric torus[2] and a cylinder[8] in these limiting cases. This formula provides quantitative guidance in achieving turbulence suppression via a proper combination of magnetic configuration optimization and E_r profile control in stellarators.

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1D04

The effect of impurity charge state evolution on the stability of radiative modes*

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A common assumption that is made in the study of radiative modes is that the impurities are in a state of coronal equilibrium i.e. the ionization state of the impurity evolves at a faster rate than the temperature. Interestingly, for the tokamak edge, the reverse limit, in which the impurities evolve slower than the temperature, is appropriate. The nonlinear evolution of radiative modes with the effects of finite recombination time of the impurities have been studied in a uniformly magnetized quasi two-dimensional plasma. In the one-dimensional limit, it was found that a plasma in non-coronal equilibrium (impurities evolve at a slower rate than the plasma), radiative modes were modestly more stable and evolved at a slower rate. A new unstable state was found in which the plasma initially cooled only to grow unstable to the radiative condensation mode. This nonlinearly unstable regime has a stability boundary an order of magnitude higher than predicted by linear theory. An analytical ananlysis is provided that supports the numerical findings. For a parameter regime appropriate to the tokamak edge, the nonlinear condensation mode proved to be more unstable in non-coronal equilibrium than in coronal equilibrium. When two-dimensional effects were added, little difference was found in the behavior of the mode in coronal equilibrium, but in non-coronal equilibrium, a new state evolved in which the condensation instability initially grew, but then flattened as the plasma continued to heat at a constant rate. The results provide insight as to why condensations (or MARFEs) are observed in tokamaks when they are seemingly stable to condensation modes.

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1D05

L and H modes in the guiding center plasma

by

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Abstract

We solve by numerical simulation the plasma guiding center model in annular geometry so that a bias voltage can be applied to the two circular boundaries. Without bias, the solutions show the usual behavior, e.g. two close vortices of equal sign tend to merge into a larger vortex. With sufficiently strong bias voltage, the vortices of one sign are either diminished in strength or destroyed and distributed in narrow filaments over the volume. The vortices of the opposite sign are essentially unchanged and keep their individuality. The salient qualitative features agree with a simple theory and it is shown that vortices of one sign are unstable under shear flow, whereas the vortices of the opposite sign are stable. Certain features of the plasma model are also observed in plasma devices of linear and toroidal geometry, where similar states have been observed and are called L-and-M modes.

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Progress to a Theory for Rotational Shear Stabilization

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The simple rule that the critical $E \times B$ rotational shear rate should exceed the maximum ballooning mode linear growth rate ($\gamma_E > \gamma_{max}$) to stabilize turbulence in tokamaks appears to have had some success in describing bifurcations to core and possibly L/H edge transport barriers. The simple rule is based on case studies [1] of toroidal ITG nonlinear gyrofluid ballooning mode simulations in a thin annulus with $\rho^* \to 0$ ($E \times B$ rotation much larger than diamagnetic rotation) and with no "profile curvature." We revisit these simulations considering the ballooning mode space "convection rule" [1] and also the slab limit. To understand rotational shear stabilization more generally, we explore the heuristic linear dispersion relation: $\gamma = \gamma_0 + \gamma_0' x + \gamma_0'' x^2/2 - (\gamma_0/\Delta k_x^2) k_x^2/2$ where γ is the complex growth rate [Re(γ) $- i\omega$] for a "global mode," and γ_0 is the complex growth rate (including $E \times B$ velocity in the phase velocity) for the most unstable "local" or ballooning mode at radius r_0 $(x = r - r_0)$. $\gamma_0' = d\gamma_0/dx$ is the generalized "profile shear," and $\gamma_0'' = d^2\gamma_0/dx^2$ the generalized profile curvature. $k_x = -id/dx$ is the transform space variable related to the ballooning mode angle θ_0 $(k_x = k_y \hat{s} \theta_0)$. The complex number Δk_x characterizes the width of unstable local modes with respect to k_x. Dewar [2] has recently treated a similar "ballooning Schrödinger equation" with WKB methods restricted to rotational shear $\gamma_0' = -i\omega_0'$ and real rather than complex γ''. Forcing the k_x model to the harmonic oscillator form (k_x^2) allows us to treat the general problem. Subject to the existence constraint $\mathrm{Re}[(-\gamma_0''\Delta k_x^2/\gamma_0)^{1/2}] > 0$, global mode stability relation is $\gamma = \gamma_0 - (1/2)(-\gamma_0''/\Delta k_x^2 \gamma_0)^{1/2} - (1/2)(i\gamma_0')^2/(-\gamma_0'')$. The second term corresponds to the usual $1/n$ "radial correction" and the third to generalized rotational shear stabilization. Note that the latter is inextricably bound with profile curvature. For vanishing profile curvature the smallest rotational (profile) shear forces global mode stability. Thus global mode stability has no relation to the nonlinear $\gamma_E > \gamma_{max}$ rule.

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Kinetic Simulation of the Radial Electric Field Evolution in Tokamak Plasmas

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The results of the first direct modelling of the poloidal rotation and the radial electric field evolution in tokamak plasmas are presented. All the neoclassical regimes, namely, the Pfirsch-Schluter, plateau, and banana regimes are considered. For that purpose a numerical code "ELECTRIC" has specifically been developed. This initial value code solves the ion drift kinetic equation with a full collisional operator in the Hirshman-Sigmar-Clarke[1] form, and a supplementary Maxwell equation. It is shown, that typically the relaxation consists of the slow evolution due to the "magnetic pumping" effect[2-5]. This can also be accompanied by the Geodesic Acoustic Oscillations (GAM)[6-8]. Different scenarios of relaxation are presented, in particular corresponding to a "soft" and "sharp" switch-on of the initial temperature gradient. The former case allows for an effective separation of the magnetic pumping from the GAM oscillations. Then it becomes possible to determine the scaling of the relaxation rates versus basic plasma parameters. Also we present different regimes of the relaxation in the presence of the Landau resonance interaction.

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Sheared E × B Flow Stabilization of Global MHD Modes*

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Sheared $E \times B$ flow stabilization is evaluated as a mechanism for feedback control of the MHD instabilities which terminate advanced confinement regimes. Since the basic turbulent suppression mechanism was proposed [1], there have been many studies of linear and nonlinear stabilization effects of flow shear on short-scale instabilities. Here we report on studies of the effect of sheared $E \times B$ flows on global MHD modes, such as low n resistive ballooning modes, and TAE modes.

The studies have been carried out with reduced MHD variants of the FAR [2] suite of codes, including a Landau fluid extension [3] appropriate for TAE modes. Linear calculations for DIII-D like geometry and parameters show that unstable $n = 2$ resistive ballooning modes can be stabilized by $E \times B$ flow with constant shear and that there is considerable distortion of the eigenfunction when the flow shear is large. Linear stability calculations of $n = 5$ TAE modes for parameters close to TFTR show that there is an asymmetry with the sign of the flow shear, positive gradients being more effective for stabilization.

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Electromagnetic Landau Fluid Models of Collisionless Plasmas*

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The dynamics of collisionless plasmas is of great interest both in astrophysics and in laboratory fusion research. Such plasmas have often been studied using models which implicitly assume high collisionality and which ignore important kinetic effects such as parallel Landau damping. Most models which include kinetic effects consider only electrostatic fluctuations. Here we present two fluid models which include both electromagnetic fluctuations and linear Landau damping effects. The models are relatively simple and should prove useful for numerical simulations.

The first model, referred to as 'Landau-MHD', is similar to Chew-Goldberger-Low (CGL) theory† with Landau closures used to model kinetic effects. This Landau-MHD model is fully electromagnetic and describes both the compressional and shear Alfvén waves, as well as ion acoustic waves. The model allows for separate equilibrium parallel and perpendicular pressures $p_\parallel$ and $p_\perp$, and, unlike previous models such as CGL, correctly predicts the instability threshold for the mirror instability. We develop both a simple four moment model and a more accurate six moment model which should be useful for nonlinear numerical simulations. Modified versions of the four moment model can be used to add Landau damping effects to MHD codes.

A second model is developed for studying long time scale turbulent processes in highly magnetized plasmas, where the fast compressional Alfvén time scale can be eliminated from the equations. This 'electromagnetic gyrofluid' model employs the gyrokinetic ordering and models electromagnetic fluctuations using only a parallel magnetic potential. This model can be used to describe shear Alfvén waves, as well as drift waves and ion acoustic waves. To make numerical simulations practical, the electron thermal time scale is analytically removed, resulting in a set of equations valid for $\beta \gg m_e/m_i$. These equations will be used in nonlinear gyrofluid simulations to investigate drift-Alfvén turbulence, and to calculate finite beta effects on tokamak transport.

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An Electron Cyclotron Heating and Current Drive Approach for Low Temperature Startup Plasmas Utilizing O-X-EBW Mode Conversion*

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To eliminate, or minimize, the inductive current drive system would be very attractive for advanced tokamaks. Particularly in spherical torus (ST), for which it is highly desirable to eliminate the Ohmic solenoid from the center stack, non-Ohmic techniques for plasma initiation, buildup and current ramp are needed. However, the modest density and low electron temperature obtained in non-inductive plasma initiation provide small optical depth for most wave heating and CD techniques. Recently Wu, *et al.* [1] have proposed an ECRF approach in which X-mode power is launched from the low field side, tunnels through the right hand cutoff, is mode converted to an electron Bernstein wave (EBW) at the upper hybrid layer which is subsequently damped at the fundamental cyclotron layer. An alternative approach to heating overdense plasmas was proposed by Preinhaelter and Kopecky [2] in which an O-mode wave is totally converted to X-mode at the $\omega = \omega_{pe}$ layer. The analysis was generalized to arbitrary angle of incidence by Weitzner and Batchelor [3]. The converted X-mode wave is reflected from a linear ray turning point and non-zero $k_\perp$ and returns to the upper hybrid resonance where it is converted to EBW [4]. This process may have advantages over the one proposed by Wu, *et al.* in that the incident O-mode propagates to higher density and at the critical angle for complete conversion to X-mode there is no cutoff region. This process has been experimentally demonstrated on W7-AS [5]. Both techniques should work for the low temperature, start-up plasmas. An analysis will be presented for the NSTX spherical torus experiments.

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FORCED MAGNETIC FIELD LINE RECONNECTION IN ELECTRON-MAGNETOHYDRODYNAMICS

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Electron Magnetohydrodynamic (EMHD) equations provide a convenient model for studying collisionless magnetic reconnection. An important similarity between ordinary magnetohydrodynamics, MHD, and EMHD arises from the fact that in both theories the magnetic flux is conserved when "non-ideal" effects, such as resistive dissipation and/or electron inertia, are neglected. In the case of MHD the magnetic field is frozen in the plasma flow, whereas in EMHD it is frozen in the flow of the electron component. In 2-D configurations, the EMHD equations, including the effect of electron inertia, take the well known form

$$\partial_t\vartheta - \{b,\vartheta\} = 0, \qquad \partial_t\beta - \{b,\beta\} = -\{\psi,\vartheta\}. \tag{1}$$

Here $\vartheta = \psi - \Delta\psi$, $\psi(x,y,t)$ is the z-component of the vector potential, $\beta = b - \Delta b$, b is the z-component of the magnetic field $(\mathbf{B} = \mathbf{b}_\perp + b\mathbf{e}_z = \partial_y\psi\,\mathbf{e}_x - \partial_x\psi\,\mathbf{e}_y + b\mathbf{e}_z)$ and $\{f,g\} = \partial_x f\,\partial_y g - \partial_y f\,\partial_x g$ are the Poisson brackets. Time is measured in $(\omega_{Be})^{-1} = m_e c/eB_0$ and coordinates in units of the electron inertial skin depth $d_e = c/\omega_{pe}$. The generalized flux $\vartheta(x,y,t)$ is conserved locally (Lagrangian invariant).

In this paper we present explicit equilibrium solutions of the 2-D EMHD equations that incorporate cross field motions and include scale-lengths as small as the electron skin depth. The field cross motions are described by introducing an external irrotational and divergence free electric field and analyze configurations with $\psi = -Et + \tilde{\psi}(x,y)$, i.e., with $\vartheta = -Et + \tilde{\vartheta}(x,y)$, where the electric field E is directed along the z-axis and is supposed to be uniform.

Then we investigate the long time evolution[1] of perturbations imposed from the boundary of a high conductivity plasma slab in the framework of the 2-D EMHD equations. The initial magnetic field has a null surface. The perturbations cause a change in the topology of the magnetic field. On the null surface a singular electric current layer is formed which is responsible for the decoupling of $\vartheta(x,y,t)$, that does not reconnect, and of ψ that does reconnect. As in [1], the plasma and the magnetic field evolve with the time scale of the linear [2] tearing mode . However, the Hamiltonian nature of the EMHD equations, where magnetic field reconnection is caused by electron inertia, changes the long time evolution of the current layer from algebraic, as in the case of the resistive tearing mode, to exponential. The connection between this behavior and the occurrence of phase-mixing in the case of oscillatory solutions is described. Phase mixing is shown to persist in the presence of electron inertia but to be saturated, e.g., by electron viscosity.

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1D12

Drift Wave Simulations of JET L- and H-mode Discharges

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Abstract

The predictions of a reactive drift wave model for anomalous transport in tokamaks are compared with JET profile data. The transport model is intended for the good confinement region and is a first principles gyro-Bohm model. It combines the toroidal branch of the Ion Temperature Gradient driven mode (ITG) and the Trapped Electron mode in the collisionless limit (CTE) in one description. The model includes first-order finite-Larmor-radius effects, polarization drift effects, compressibility due to field curvature, together with contributions from trapped electrons, impurities, parallel ion dynamics and finite β-effects.

Density and temperature profiles (n_e, n_q, $T_i = T_q$, and T_e) are self-consistently calculated using a predictive simulation code. In this code the temporal evolution of the profiles is followed under the assumption of quasi-neutrality.

Both L-mode and H-mode $\rho_\star$ similarity scans have been simulated. The experimental profiles are well reproduced by the simulations. In particular, apperent Bohm- and Goldston-like scalings of the local diffusivities are obtained in the L-mode scan, whereas gyro-Bohm scalings are obtained in the H-mode similarity experiment. The L-mode results are due to small systematic variations in the dimensionless parameters that are assumed to be held constant between the low field and the high field discharges as the gyro-radius is varied.

The general performance of the transport model has been investigated over a range of L-mode and ELM-free H-mode discharges, the agreement between predicted and experimental profiles are generally within $\lesssim$ 20% for the simulated profiles. The stabilizing influence of finite β is shown to be important for the ELM-free H-mode simulations whereas the electrostatic limit is appropriate for the L-mode cases.

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Simulations on the Feedback Stabilization of Neoclassical MHD Tearing Modes

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Numerical studies of the feedback stabilization of the nonlinear evolution of magnetohydrodynamic—type tearing modes in three-dimensional toroidal geometry with neoclassical effects are presented. The inclusion of neoclassical physics introduces an additional free-energy source (when $dp/dq < 0$) for the nonlinear formation of magnetic islands through the effects of a bootstrap current in the Ohm's law[1]. The instability mechanism is due to the helical deformation of the plasma pressure profile due to fast equilibration processes along field lines. In particular, this leads to the absence of bootstrap current inside the island separatrix associated with a flatspot in the pressure profile. Finite parallel transport also introduces a nonlinear threshold for the mode[2]. Such modes are a concern because they represent a soft beta limiting phenomena in current experiments[3] and are potentially problematic for ITER[4]. One proposed method for eliminating such modes, once they are detected, is to replace the lost bootstrap current with a current drive source. Such methods of stabilization of tearing modes have been previously investigated analytically [5, 6, 7] and in the absence of neoclassical effects numerically[8]. The intention here is to compare these analytical results with numerical simulation.

The model consists of a set of incompressible, reduced-MHD equations for the poloidal flux ψ, the velocity stream function ϕ, and the plasma pressure p, which have been implemented in the *neofar* code[9, 10]. *Neofar* is based on the fully three dimensional, toroidal, initial value *FAR*[11] code and includes a parallel Ohm's law that retains neoclassical viscous-stress effects ($\nabla \cdot \overline{\overline{\pi}}$) through analytical kinetic closures[12], a vorticity evolution equation, and a pressure evolution equation with an anisotropic pressure diffusivity. The effect of feedback stabilization currents are modeled by the inclusion of an additional current source term in the parallel Ohm's law. Presently, this source term is based on the equilibrium flux surfaces, but improvements in the model are expected to insure that the current source conforms to the island flux surfaces. The latter is believed to be important because the analytic model predicts that when the auxiliary current drive is a flux function (which, except at very early times, is likely the case experimentally) the island width can only be reduced to the deposition width of the auxiliary current drive[7].

Preliminary results based on a phased-resonant current perturbation localized to the vicinity of the island O-point, but not a flux function, indicate that current drive can be used to stabilize a preexisting neoclassical tearing mode and at sufficient levels eliminate the neoclassical mode, i.e., drive it below it's threshold. Once the mode is driven below it's nonlinear threshold, the feedback current is no longer necessary. The magnitude of this current, the effects of localization, the time scale for the current generation, and also the degree to which this current is a flux function will be presented.

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Optimization of Formation of Flux Core and Gun Spheromaks

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Axisymmetric simulations of spheromak formation with several configurations having differing electrode geometry and bias field distribution are presented. The focus is on formation schemes with negative bias field (*i.e.* flux core spheromaks) for the purpose of stabilizing the $n = 1$ tilt and shift modes. For all cases the formation schemes include poloidal current driven by electrodes (helicity injection) plus an inductive electric field caused by time variation of the bias field. Results on Mercier stability by means of DCON will be presented. The aim is to produce a spheromak which can be sustained on longer time scales by helicity injection or by RF, and which has optimal MHD properties, determined by the profile of q, p, and $\lambda = \mathbf{j} \cdot \mathbf{B}/B^2$.

ISSUES IN NONLINEAR GYROKINETIC SIMULATIONS OF TOKAMAK TURBULENCE AND TRANSPORT[1]

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We extend our earlier three-dimensional nonlinear gyrokinetic simulations of ITG turbulence in TFTR[2] and DIII-D[3] in directions that have impact on predictions for experiments and comparisons with gyrofluid simulations. (A) Convergence tests of the gyrokinetic simulation results with respect to particle number, spatial resolution, and system size have been undertaken. These tests use much larger simulation runs than were possible in our earlier studies and are made possible by a massively parallel version of our gyrokinetic code. Initial results[3] indicated that the spatial smoothing of the mesh gyrocenter density (which sets the spatial resolution) has a significantly smaller effect on gyrokinetic simulation results than has been reported when such smoothing is applied to gyrofluid simulations.[4] The implication is that spatial smoothing does not explain why gyrofluid simulations give higher transport rates than do gyrofluid simulations. These and additional results will be reported in detail. (B) New simulation runs have been made that extend the number of discharges (both TFTR and DIII-D), times per discharge, and radial points per profile that our simulations address directly. In particular, the sensitivity to temperature gradient of the ion-thermal transport rate for a range of base points and its implications for the range of predicted temperature profiles given the ion heat flow are examined. (C) A commonly used model of the effect of toroidal velocity shear on ion thermal transport involves a relative reduction proportional to the ratio of the $\boldsymbol{E} \times \boldsymbol{B}$ shearing rate to the maximum linear growth rate. However, our simulations have shown[2] that the parallel component of the velocity shear can negate the $\boldsymbol{E} \times \boldsymbol{B}$ stabilization, and that whether or not toroidal velocity shear is stabilizing depends significantly on the ratio of the poloidal and toroidal components of the magnetic field. We report further simulation results that quantify this threshold and examine selected TFTR and DIII-D discharges for evidence of this effect.

We also report issues that arise in and progress on the implementation of a new bounce-averaged drift-kinetic nonlinear-δf electron model. This model differs from earlier work in that it uses one simulation particle per bounce center and the transformations between bounce-center space and the "real" configuration space are handled through field operations.

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1D16

Toroidicity effects and induced convection in the tokamak SOL

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We study a plasma equilibrium in the open field line region of a tokamak scrape-off-layer (SOL). For a toroidally-symmetric configuration, we base our analysis on a representation of the plasma current as a superposition of two non-orthogonal vectors, a toroidal current and a parallel (to the magnetic field) current. We consider effects of parallel plasma flow and the pressure anisotropy on plasma equilibria. We find a broad class of equilibria where the parallel current between the divertor plates is absent.

We then introduce an external force acting on the plasma, representing friction from neutral particles. We assume that it is parallel to the magnetic field. We find that, for the toroidally symmetric situation, the presence of this force still allows static equilibria with no parallel current. If the neutral density is large enough, the plasma resistivity in the vicinity of the divertor plates is so high that the absence of a parallel current at the divertor plates becomes a natural requirement. We call such regimes "electrically detached regimes".

In the rest of the paper, we consider phenomena that appear if the friction force is varying in the toroidal direction. We find that, in the "electrically detached regimes", strong enough toroidal variations lead to impossibility of static equilibria with radially decreasing plasma pressure, unless very artificial assumptions regarding the distribution of heat and particle sources over the SOL are made. Static equilibria are then replaced by convective equilibria, with rapid heat and particle mixing across the magnetic surface. This conclusion may give rise to a practically realizable technique of reducing power loads at the divertor plates.

We discuss the optimum way of creating necessary non-uniformities by toroidally-asymmetric gas puffing. We show that the strongest toroidal variations of the friction force can be created if the gas streams are collimated by the limiters aligned with the field lines.

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Kinetic Study of Parallel Transport in SOL Plasma *

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We present results of modeling parallel electron transport in a scrape-off layer (SOL) plasma using the one dimensional in space and two dimensional in velocity Fokker-Planck code ALLA [1]. The code is adaptive in space, with a variable grid in both modulus of velocity and pitch angle fine grid, and has about a million nodes, to provide the accuracy required to evaluate higher moments of distribution function.

First we briefly discuss the benchmarking of the code against the short mean-free path limit results from [2], and exact self-similar solutions of the non-linear kinetic equation similar to one introduced in [3].

Next we introduce the kinetic model simulation of the SOL, which takes into account non-linear Coulomb collisions of electrons with electrons, while keeping only pitch-angle scattering for electron collisions with stationary background ions. The parallel electric field is obtained self-consistently, from the quasineutrality condition. We are extending the model presented in [4] by balancing the electron sink at the plate by a volumetric ionization source. To describe parallel heat flux we introduce an energy source with an amplitude that can vary in time.

To model transient effects, we run the code in a time-dependent mode until a stationary solution obtained. The stationary electron distribution function is then used to calculate the parallel heat flux in the simulation domain. We compare our results with Braginskii's formulas [2], and with analytical expressions from [5] and [6]. Finally, we evaluate the impact of non-local transport on electron the thermal force, flux-limit factor, and sheath potential at the divertor plate.

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Analysis of Localized Electron Heating and Current Drive via Mode Converted Ion Bernstein Waves in Alcator C-Mod*

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Highly localized (FWHM $\lesssim 0.2$ a) on-axis and off-axis electron heating via mode converted ion Bernstein waves (IBW) has been observed in the Alcator C-Mod tokamak.[1] The on-axis mode conversion electron heating (MCEH) experiments were done in H(^{3}He) discharges at $B_0 \simeq (6.2 - 6.5)$ T and the off-axis electron heating experiments were done in D(^{3}He) at $B_0 \simeq 7.9$ T. The relative concentration of ^{3}He was high in these discharges with $n_{^3\mathrm{He}}/n_e \gtrsim 0.2$. The experimental profiles of IBW electron heating were deduced using a break in slope analysis of the electron temperature versus time. Detailed numerical modelling of these experiments has been carried out using an improved toroidal full-wave ICRF code (TORIC)[2]. This numerical model solves self-consistently for the perpendicular and parallel components of $\vec{E}$. A numerical broadening of the ion-ion hybrid layer ($n_\parallel^2 \simeq S$) has been implemented which ensures a well-behaved solution for the electric field near mode conversion.

The experimentally measured rf power deposition profiles to electrons and the absorbed rf power fraction to electrons have been found to be in quantitative agreement with toroidal full-wave predictions. Toroidal full-wave modelling of on-axis MCEH experiments in H(^{3}He) discharges indicates the importance of volumetric and wave focussing effects in reproducing the measured rf power densities. We have used the TORIC code in conjunction with a parameterization of the current drive efficiency due to Ehst and Karney[3] to investigate the possibility of localized off-axis and on-axis current drive via mode converted IBW in C-Mod. Results will be presented for off-axis current drive in D(^{3}He) plasmas at $B_0 \simeq 4.0$ T, $f_0 = 40$ MHz and for on-axis mode conversion current drive at $B_0 \simeq 4.7$ T, $f_0 = 40$ MHz.

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Edge plasma in a spheromak

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The results of a preliminary analysis of the properties of the edge plasma in the Livermore Spheromak are reported. The main emphasis in this study was made on the plasma behavior on the open field lines, during the quasi-steady phase of the discharge (after the spheromak had been ejected from the gun to the flux-conserver). It has been shown that the main source of plasma heating is the Joule dissipation of the current flowing from one electrode to another. The main channel of heat losses is electron thermal conductivity to the walls. The balance of these two processes sets the plasma temperature on the open field lines. For the design parameters of the Livermore Spheromak one can expect the temperature and density in the range 20-30 eV, and 10^{14} cm^{-3}, respectively (in the middle of the field line ending on the opposite electrodes). Cross-field transport plays a subdominant role in the bulk of the open-field-line region. Therefore, field lines that begin and end at electrode surfaces of the same polarity (such field lines may appear because of the field errors, because of the skin effect, and, in some cases, by intention) are devoid of warm plasma. Impurity radiation does not play a significant role in the thermal balance on the open field lines (although the absolute value of the radiated power may be high, in the range of a few MW).

The role of the skin effect in the walls of the flux conserver has been analysed. The skin effect may lead to formation of a central plasma column that leans on the upper and lower plates of the flux conserver (the axis of the device will be vertical). The line-tying effect may provide additional stabilization to the global tilt and shift modes.

The expected current density is well above the ion saturation current for field lines which contact surfaces outside the gun barrel. This means that the current is carried predominantly by the electrons. For the open field lines this means also that the cathode should emit enough electrons, and/or that there should be a high density of cold plasma near where the field lines intersect material surfaces. The processes on the plasma-cathode interface are briefly discussed. The conclusion is drawn that one can expect sufficient electron emission in the Livermore Spheromak.

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Reversed Field Pinch Transport Due To Suydam Instabilities

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A simple calculation of transport in a Reversed Field Pinch (RFP) is presented. The basic assumption is that the core of the plasma, out to the field reversal surface, is dominated by small scale instabilities which cause the profiles to relax to the marginal stability state. A reasonable assumption is to assume that the stability criterion of interest corresponds to tearing modes. For the present calculation, however, we assume that marginal stability is defined by the Suydam criterion. This is primarily for calculational simplicity, and future work will use the actual tearing mode criterion. The calculation is carried out by constraining two of the three equilibrium profiles, B_p, and p, to simultaneously satisfy Suydam's criterion and the equilibrium pressure balance relation. The third profile, B_Z in our case, is modeled by an analytic function with several free parameters. It is a straightforward numerical problem to calculate the remaining profiles. Under the assumption that the main input power is due to ohmic heating, one can then easily calculate the energy confinement time as a function of the free parameters in B_Z. Tau is then optimized with respect to these parameters yielding the desires energy confinement scaling relation. The results of these calculations will be presented at the conference.

1D21
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A Class of High β_p Equilibria in Strongly Shaped Finite-Aspect-Ratio Tokamak Plasmas

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Auxiliary heating such as neutral beam injection (NBI) and radiofrequency heating (rf) in the early phase of plasma formation can save valuable volt-seconds in the ohmic transformer by lowering plasma resistivity and increasing bootstrap current. For low aspect ratio tokamaks, these early phase heating techniques will be particularly useful in the start-up and current ramp-up operations. However, the amount of heating which can be applied during the start-up phase is constrained by the β_p-equilibrium limit.[1,2] Previous theoretical studies have shown that $\varepsilon\beta_p < 1$ for circular cross-section plasmas in the limit of small inverse aspect ratio ε, and analytic model calculations have indicated that the upper bound could be increased with elongation. On the other hand, for strongly shaped plasmas at finite aspect ratio that upper bound has not been determined. In this work, we use the equilibrium code TOQ to construct a class of high β_p equilibria and examine the β_p limit. These equilibria are specified by a typical experimental L–mode pressure profile and a current density which is essentially constant when expressed in terms of the normalized poloidal flux. In the high β_p regime, these numerical equilibria possess many features similar to those of Cowley *et al.* high β equilibria.[3] In the full-size DIII–D configuration (aspect ratio of $A \approx 2.8$ and elongation of $\kappa \approx 2$), we have found that equilibria with $\varepsilon\beta_p \approx 3$ exist, which is about 50% higher than the record value of β_p observed in DIII–D.[4] The β_p limit of this class of equilibria as a function of shape parameters and aspect ratio will be presented. The interchange, high-n ballooning, and low-n kink stability of these equilibria will be investigated.

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1D22

Classification and Casimir Invariants of Lie–Poisson Brackets

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Several types of two-dimensional fluid and plasma systems admit a Hamiltonian formulation using Lie-Poisson brackets, including Euler's equation for fluids, reduced MHD for plasmas, and others.[1–5] Lie–Poisson brackets, which are examples of noncanonical Poisson brackets, consist of an inner product, $\langle\cdot,\cdot\rangle$, and the bracket, $[\cdot,\cdot]$, of a Lie algebra which we call the inner bracket:

$$\{F, G\} = \langle\Psi, [F_\Psi, G_\Psi]\rangle.$$

Here Ψ is a vector of field variables, and subscripts denote functional differentiation. The algebras corresponding to the inner brackets are algebras by extension: they are defined for multiple field variables from the bracket for a single variable. We derive a classification scheme for all such brackets using cohomology theory for Lie algebras.[6] We then derive the Casimir invariants for the classes of Lie–Poisson brackets where the inner bracket is of canonical type.

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1D23

Nonaxisymmetric Studies of Vertical Displacement Events*

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Loss of vertical stability in elongated tokamaks like ITER is of great concern beacuse of its potential to generate large electro-mechanical stresses on the vacuum vessel and related components. The vertical displacement of the plasma and the subsequent appearance of driven currents in the conducting structures around it, especially when they exhibit large toroidal asymmetries, can pose a serious threat to the mechanical integrity of the device. We will report on the results of a fully three dimensional study of this problem.

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Toroidal Effects on Adiabatic R-compression in Tokamaks

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Compression in a major radius (R-compression) proposed by Artsimovitch [1] is used in tokamak experiments as a method for auxiliary plasma heating [2], plasma diagnostic applications, etc. In this report we obtain the equations for the evolution of particle velocity and pitch angle during the compression. Basing on these equations and solving the bounce averaged drift kinetic equation we analyze plasma macro parameters, density and temperature, in different regimes with the respect to the collisionality.

Under the conditions necessary for the adiabatic compression, the drift approximation for the particle motion remains valid since the magnetic fields change slowly compared to τ_b, which is "bounce" time for trapped and transit time for passing particles. Therefore, two adiabatic invariants are conserved: magnetic moment μ and the toroidal momentum P_φ. To describe the particle motion during the compression we need the equation for the particle velocity. We introduce the perpendicular electric field from Ohm's low at zero resistivity $\mathbf{E} = -c^{-1}\mathbf{v}_E \times \mathbf{B}$, which leads to the equation for the particle energy $d\mathcal{E}/dt = e\mathbf{E} \cdot \mathbf{v}_{dr}$, where $\mathbf{v}_E$ is the plasma hydrodynamic velocity vector during the compression and $\mathbf{v}_{dr}$ is the particle toroidal drift velocity. Expressions for particle energy and pitch angle change of passing and trapped particles are obtained for plasmas with high aspect ratio and circular magnetic surfaces. Such an approach differs from one used earlier [3], where only toroidal component of the electric field was used. We also study the transitions between the trapped and passing particles during the compression near the loss cone which may be used for the diagnostic purposes.

Solving the kinetic equation we obtain that when the collisional frequency of given species exceeds inverse compression time τ_c^{-1}, the temperature and the density of plasma species change like $T \sim R^{-4/3}$ and $n \sim R^{-2}$, which may be obtained also from the MHD. In the opposite case $\nu \ll \tau_b^{-1}$ and high aspect ratio the heating of the plasma can be more efficient and the longitudinal component of the temperature changes like $T_\parallel \sim R^{-2}$, while the perpendicular one at time t is $T_\perp(t) = 2T_\perp(0)R_0^2(0)/(R_0^2(t) + R_0^2(0))$.

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Stellarator Optimization Methods for Small Aspect Ratio Toroidal Hybrid (SMARTH) Devices*

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A salient feature of the stellarator configuration is that many of its important physical properties are completely determined by the shape of its last closed magnetic surface. It is, therefore, possible to separate the physics design of a stellarator from the actual determination of external coils. This separation has made it possible to develop a robust optimization algorithm for designing low aspect ratio stellarators with specific and desirable confinement and transport properties. We describe the development of this optimization procedure, which is based on using the VMEC 3D MHD equilibrium code as the inner physics evaluation loop of a Levenberg-Marquardt solver. Because a stellarator is a three-dimensional configuration, there is a large space of possible boundary shapes which can be efficiently explored and evaluated by this optimization scheme.

The SMARTH research program at ORNL is described. Together with collaborators at UT Austin (EPEIUS) and Wisconsin (Spherical Stellarator, SS), this activity is directed toward exploring the design and physics properties of low aspect ratio ($A < 4$) stellarators. The SMARTH design attempts to reduce the steady-state toroidal current (compared with a tokamak) to control disruptions, thereby easing volt-seconds requirements, while allowing configuration flexibility (through the interaction of the VF field with the plasma current) to explore disruption and tearing mode control scenarios relevant to tokamak operation. Self-consistent, finite-pressure equilibria with net plasma currents are demonstrated to exhibit flexible rotational transforms with both standard and reversed-shear profiles. A new transport-optimized configuration achieves nearly complete confinement of deeply trapped energetic particle orbits, thus leading to the expectation that the ripple transport barrier can be substantially lowered in future low aspect ratio configurations, even in the absence of electric fields. This is crucial for low A reactors which must confine alpha-particles.

The configurational optimization is completed by finding a suitable set of modular helical coils to reproduce the physics-optimized bounding magnetic surface. A new modular coil representation is used to directly find coils, subject to various physical restrictions (such as curvature, plasma-to-coil minimum separation), which come closest to minimizing the normal component of the magnetic field on this last closed surface.

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NUMERICAL STUDY OF THE NONLINEAR SATURATION OF DOUBLE TEARING MODES

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The nonlinear saturation of double tearing modes often leads to stationary states with magnetic islands, in the same way as in the case of simple tearing modes. However, due to the fact that the double tearing perturbation has a much larger radial extension than a simple tearing mode, the nonlinear evolution of double tearing modes is more violent and may lead finally to an oscillatory state. Using known results of bifurcation theory for tearing unstable plasmas, we have studied this possibility numerically by looking for nonlinear single-helicity solutions bifurcating from a cylindrical, double-tearing-unstable equilibrium when the Lundquist number S is varied. Starting with very small values of S (< 1000) we show that a stationary solution, characterized by two magnetic island chaines, bifurcates at a critical value S_c. Increasing S to values relevant to fusion plasmas, we find that the stationary solution becomes unstable and an oscillatory solution bifurcates from it.

SOL instabilities and anomalous transport localized in divertor legs

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The presence of a sufficiently strong instability localized in the divertor legs (i.e., not involving the area above the X-point) could help in reducing the heat flux on the divertor plates (by increasing the thickness of the SOL in the divertor legs) without causing any enhanced transport through the last closed flux surface. The possibility for such modes to exist is related to the fact that, for the flute-like modes, extremely strong shear near the divertor X-point [1] makes the communication between the divertor legs and the rest of the SOL very difficult, unless some special conditions are satisfied [2].

In the present paper we analyse drift-type modes with such a localization. The modes are sensitive to the sheath boundary conditions at the divertor plate, and, in particular, to the angle between the plate and the magnetic field. We use a general form of the sheath boundary condition that includes non-steady-state effects and effects of spatial dispersion. We describe the strongly-sheared X-point region phenomenologically, by introducing an "effective resistance". This resistance establishes a link between the cross-field potential difference and the current through the ends of the flux-tube.

We find the mode structure, frequencies and growth rates for the most unstable perturbations and speculate with regard to possible magnitude of the transport induced by these modes. This work was carried out under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

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The Shear Alfvén Wave Spectrum in a Resistive MHD Plasma without Magnetic Shear

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In Ref. [1], Tataronis and Rauf examine the time development of the shear Alfvén wave in a resistive magnetohydrodynamic plasma. The analysis is restricted to a pressureless plasma confined in a planar sheet pinch with a constant equilibrium magnetic field directed parallel to the magnetic surface wave vector. The equilibrium mass density depends on the spatial coordinate x orthogonal to the planar magnetic surfaces, implying that the local Alfvén frequency $\omega_a(x)$ varies with x. Under these conditions, the shear Alfvén mode decouples from the compressional Alfvén mode. Using Laplace transform techniques to solve the governing second order wave equation as an initial value problem, they demonstrate that the shear Alfvén wave solution in a resistive plasma does pass to the singular ideal MHD solution in the limit of zero resistivity. For the configuration studied in Ref. [1], the spatial singularity is a delta function. In the present study, the associated eigenmode problem is treated, with emphasis placed on the limiting spectrum as resistivity passes to zero. In the presence of resistivity, the eigenmodes with frequency ω are governed by the following boundary value problem over the domain $0 < x < a$,

$$\frac{\partial^2 u}{\partial x^2} - i\frac{\mu_0}{\eta}f(x,\omega)u = 0 \qquad \frac{\partial u}{\partial x}(0) = 0 \qquad u(a) = 0$$

where μ_0 is the vacuum permeability, η is the resistivity, $f(x,\omega) = \omega - \omega_a^2(x)/\omega - ik^2\eta/\mu_0$, and k is a wave number. When ω_a is constant in space, the spectrum, which is readily derived, consists of discrete complex eigenvalues with positive imaginary parts. When ω_a depends on x, solution of the eigenvalue problem requires numerical methods coupled with approximate analytic techniques. The limit of small resistivity is addressed with WKB theory. The WKB turning points occur at the zeros of $f(x,\omega)$, which are complex but close to the position of the ideal MHD resonance, $\omega_a(x) = \omega$. In the vicinity of a turning pont, $f(x,\omega)$ can be linearized, producing Airy's equation with a complex coefficient. Matching across the turning point can be accomplished either with phase integral methods or with Airy functions. Numerical solutions of the spectrum are compared to the spectrum obtained with WKB theory. In the limit of small η, the governing eigenmode equation becomes stiff, thereby complicating the numerical analysis. Details of the numerical algorithm that is used will be presented.

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Global Nonlinear Calculations of Ion Temperature Gradient Driven Turbulence*

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There has been considerable interest in the transport associated with ion temperature gradient driven turbulence (ITGDT) in tokamaks. Many linear and nonlinear calculations have been performed using gyrokinetic and gyrofluid models [1]. For the most part, these calculations have been carried out using flux tube or quasi ballooning formulations which are local to a flux surface or a set of flux surfaces. Here we report on results of nonlinear Landau fluid [2, 3], calculations of ITGDT in three dimensions which cover the entire plasma cross section.

Comparisons between fluid and Landau fluid calculations with identical profiles and parameters demonstrate the reduction in linear growth rates and the spatial localization of the linear eigenfunctions expected with Landau damping. Single helicity calculations close to marginal stability further show that spatial localization persists nonlinearly and is not affected by the generation of sheared poloidal flow through Reynolds stress. Corresponding calculations with multiple (but few) helicities show more pronounced profile modification and more sheared flow generation through Reynolds stress. This is similar to what is observed in calculations of resistive pressure gradient driven turbulence [4]. Progress towards development of a full torus model of ITGDT will also be reported.

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1D30

Global nonlinear gyrokinetic simulations with self-consistent E_r shear and pressure profile variation

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The radial force balance equation has been implemented in a global toroidal three-dimensional nonlinear gyrokinetic simulation. This includes both the effects of toroidal shear flow and variation in the pressure gradient. We find that shear in the radial electric field reduces the nonlinear heat flux even in the absence of fluid flow (diamagnetic flow canceling $E \times B$ flow). The variation in the pressure gradient produces two stabilizing effects: E_r shear and variation in ω_*. This is the first time both these effects have been studied together self-consistently. The simulation is collisionless, however poloidal flow would be damped neoclassically, so we simply set the poloidal component of the equilibrium flow to zero. We will present results parameterizing the turbulence suppression from both the toroidal shear flow and the variation in the pressure gradient. This is, in some ways like a numerical co/counter/balanced neutral beam injection experiment. We will also parameterize the ion heat diffusivity as a function of the linear growth rate and the $E \times B$ shearing rate. Additionally, we will show results comparing equilibrium E_r to self-generated E_r. We find that the reduction in the nonlinear heat flux from these two contributions to E_r are additive. A brief comparison between self-generated E_r in global vs. local flux-tube simulations will also be given.

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Experiment-Theory Comparison of Neoclassical Tearing Modes and Extrapolation to ITER

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Recently, neoclassical tearing modes driven by the bootstrap current or pressure gradient have received broad interest due to their degradation of long pulse high-β steady state operation in large tokamaks [1]. In ITER, this effect may imply a reduction in ignition margin. Understanding of the neoclassical tearing modes based on present experiments has become an important research topic for ITER design.

With its unique internal MHD diagnostics, TFTR can provide detailed MHD data to test, validate or benchmark the present theories or models. Using the internal temperature fluctuation measurement, we are able to measure the island width down to the scale of $\sim$ 1cm. Island evolution derived from external magnetic measurement has been found in good agreement with the internal island width measurement. In addition, using the measured $\tilde{T}_e$ profile from a major radius shift experiment, we can estimate the tearing instability index Δ'. It is found that the values of Δ' are negative for m/n =3/2 and 4/3 modes, which is consistent with the neoclassical island saturation model.

The "threshold island" is an important physical concept in the neoclassical tearing theory. Comparison of the two threshold island models, *i.e.*, finite-$\chi_{||}$ model [2] and ion polarization current model [3], with variety of island evolutions as observed in TFTR plasmas shows that the finite-$\chi_{||}$ model gives better agreement with the experiment. Other effects like rotation, velocity shear, multiple helicity islands, interaction with sawtooth crash and collisionality scaling have been studied.

Results from the study on TFTR plasmas are extrapolated to the study of neoclassical tearing modes in ITER. Threshold island width, saturated island width and the effect on the plasma performance based on TRANSP simulations will be presented.

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CORSICA: A Comprehensive Tokamak Simulation Code *

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The CORSICA project has developed a prototype comprehensive simulation code for toroidal magnetic fusion devices. Our goal was to build an efficient simulation on the slow transport timescale by exploiting time and space scale disparities. The project concentrated on three coupling problems: (1) coupling core transport to the quasi-static solution of the free-boundary ideal MHD equilibrium problem (based on the TEQ equilibrium code) and to the evolution of the circuit equations for the poloidal field coils and passive structure; (2) coupling core transport to a 2-D fluid edge transport calculation (the UEDGE code); and (3) coupling core transport to a 3-D turbulence simulation code (the Gryffin toroidal ITG code). In order to solve these coupled systems together in an efficient manner, special coupling algorithms were developed, tested in prototypes, and finally implemented in the CORSICA simulation code. In this paper we will give an overview of the project's accomplishments, discuss applications of the CORSICA simulation code, discuss current work being done by the group, and present our plan for future development in this area.

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Fluid equations for the self-consistent description of fluctuations and transport in tokamak plasmas

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A complete set of equations that describes the evolution of a toroidal plasma in two time scales is developed. The plasma is described as a multifluid medium, where the ion dynamics is the most dominant. These equations include collisional and non-collisional viscosities as well as diamagnetic effects, which are needed when temperature variations are allowed. The fast scale is related to the evolution of fluctuations produced by plasma instabilities driven by the magnetic field curvature (ballooning modes), which ought to be present near the edge region. The fluctuations depend on the equilibrium profiles of the plasma parameters, which in turn evolve in the slow transport scale, determined by the properties of the turbulent fluctuations that drive the transport. The equations are derived in a twisted coordinate system where a coordinate is parallel to the field lines everywhere in the domain considered (the edge). Due to the magnetic shear, a flux bundle is deformed as it moves around but has the advantage of yielding correlation lengths that depend only on the actual nonlinearities, not the computational grid. This set of two-time-scales equations is appropriate to study the formation and evolution of a thermal barrier, resulting by the quenching of fluctuations produced by a sheared average velocity field. Here the contributions from Stringer spin-up and Reynolds stress to plasma sheared rotation are appropriately included. From the complete equations, a simpler model is derived which is amenable to direct numerical solution, and is used to self-consistently simulate the so-called L-H transition observed in toroidal plasmas.

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Theoretical features of relativistic particle gyrokinetic dynamics*

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Basic aspects of relativistic particle gyrokinetic dynamics are investigated, with particular reference to magnetoplasmas exhibiting relativisting flows.

The limits of validity of previous relativistic gyrokinetic theories based on Lie-transform approaches [1, 2] are analyzed under the viewpoint of physical consistency, dictated by the causality requirement. The issue of the possible existence of the *paradox of unphysical iperrelativistic particle guiding-center velocities* is pointed out. The problem of achieving physically consistent formulations of relativistic gyrokinetic dynamics, able to avoid such a paradox, is discussed. Its solution is obtained based on the adoption of a covariant formulation to relativistic gyrokinetic particle dynamics recently developed [3, 4] and in the general case of magnetoplasmas displaying relativistic flows. Consequences on Lie-transform approaches are analyzed.

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TOROIDAL TRANSPORT VIA RADIATIVE COLLISIONALITY

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Momentum transfer via Kirchhoff radiation of electrostatic electron and ion-cyclotron-harmonic waves contributes an enhanced collisionality far in excess of that given by the Fokker-Planck term in the existing neoclassical models. The resultant particle and thermal transport resembles the observed anomalous transport in ohmically heated toroidal plasmas.

The power radiated per unit volume by a plasma in thermodynamic equilibrium is $\eta_E = (T/\pi^2) \int_0^{k_D} \int_0^{k_D} \Im[\omega]\, k_\perp\, dk_\parallel dk_\perp$, where $\Im[\omega]$ is the imaginary part of $\omega(\mathbf{k})$, $k_D = 2\pi/\lambda_D$, and λ_D is the Debye length. The integrations are sensitive to the integration limit k_D and hence to λ_D. Since the plasmon of energy $\hbar\omega$ carries a momentum $\hbar k$, momentum exchange among the particles via the emission and absorption of radiation gives rise to radiative collisionality. The collisionality contribution is derived from first principles.[1]

Radiation-induced electron-electron collision frequency $\tilde{\nu}_{ee}$ is about a hundred times larger than the neoclassical value ν_{ee}; *radiative* $\tilde{\chi}_{ee}$ *exceeds neoclassical* χ_{ee} *by a factor of one hundred*, thereby resolving the most perplexing of the transport anomalies. In contrast, only a nominal enhancement is found to occur for the collisionalities ν_{ei}, ν_{ie}, and ν_{ii}.

$\tilde{\nu}_{ee}$ increases linearly with B_0, while $\tilde{\nu}_{ei}$, $\tilde{\nu}_{ie}$, and $\tilde{\nu}_{ii}$ exhibit a quadratic dependence on B_0. The resultant diffusivities scale as $\tilde{\chi}_e \sim B_0^{-1}$, $\tilde{\chi}_i \sim B_0^0$, and $\tilde{D} \sim B_0^0$. For $B_0 \sim 2T$, $\tilde{\nu}_{ee}/\tilde{\nu}_{ii} \sim m_i/m_e$, so that electrons and ions become equal participants in thermal conduction. $\tilde{\chi}_e$ dominates energy transport below $B_0 \sim 2T$ and $\tilde{\chi}_i$ above $B_0 \sim 2T$.

$\tilde{\nu}$ is found to follow the neoclassical $T^{-3/2}$ dependence. Accordingly, thermal as well as particle diffusivities show a rapid increase towards the plasma edge.

Radiative collisionality displays relative insensitivity to n_e. Thus $\tilde{\nu}_{ee} \sim n_e^{0.6}$, $\tilde{\nu}_{ei} \sim n_e^0$, and $\tilde{\nu}_{ii} \sim n_i^{0.1}$. The crossover of $\tilde{\nu}_{ei}$ and ν_{ei} occurs at $n_e \sim 6 \times 10^{19}\, m^{-3}$. Below this density the electron and ion populations are uncoupled, so that λ_D is determined by the colder ions leading to larger $\tilde{\nu}_{ei}$ at lower densities. The combination of ν_{ei} crossover and electron-ion thermal coupling gives rise to the LOC-SOC ohmic confinement regimes. At higher B_0, and with the accompanying higher temperatures, both the ν_{ei} crossover and the electron-ion coupling shift to higher densities, in accord with observations.

$\tilde{\nu}_{ii} \sim A^{-3/2}$, leading to a $A^{1/2}$ isotope mass dependence of ion energy containment time. Higher isotope mass also results in a poorer electron-ion coupling, pushing the LOC-SOC transition to higher densities, as observed experimentally.

Radiative and neoclassical collisionalities possess fundamentally different characters. Radiative collisions, occurring primarily at low parallel particle velocities, selectively target trapped particles and act as extremely efficient contributors to particle and thermal diffusivities; yet the enhancement in ν_{ei} does not affect Spitzer resistivity.

The implications of radiative collisionality for auxiliary-heated plasma confinement, impurity effects, alpha-particle transport (ash removal), transient transport, profile resiliency, heat pinch, bootstrap current, and ITER scaling are presently being considered.

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Thermal Lattice Boltzmann (TLBE) Simulations of Variable Prandtl Number Turbulent Flows*

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Turbulence simulations are very difficult to perform for complex flows. This has forced most computational schemes into Reynolds averaged (RANS) modeling. Direct numerical simulations (DNS) for simple flows are an important tool to refine RANS modeling so as to allow computations to be performed for realistic geometries.

TLBE is a new form of DNS - with the important advantages of being ideal for multi-parallel processors as well as being able to handle complicated geometries. Since there are many kinetic models that will reproduce the macroscopic nonlinear (compressible) transport equations, TLBE chooses that subset which can be readily solved on a discrete spatial lattice. The lattice geometry must be so chosen that the discrete phase representation of TLBE will not taint the rotationally symmetric continuum equations. For 2D compressible flows, we have performed linear stability analyses which indicate that the hexagonal lattice is optimum.

In all previous TLBE (and incompressible LBE), one solves a linearized Boltzmann equation with the simple Krook-like collision operator. The inherent beauty of the method is that all operations are local: (a) free streaming along lattice links, and (b) collisional relaxation at each nodal site. This makes LBE ideal for multi-parallel processor machines like T3E. What has been lost by going to a higher dimensional phase space is more than recouped by the fact that the nonlocal macroscopic interactions have been modeled by local microscopic ones.

In nearly all lattice Boltzmann literature, the linearized Boltzmann collision operator has been taken to be the simple single-time Krook relaxation collision operator. This scalar collision operator is sufficient to recover the nonlinear transport equations under Chapman-Enskog expansions. However, all previous LBE have suffered from the problem of density-dependent transport coefficients. This poses no problem for incompressible flows - but is one that must be handled for heat flux problems. The other deficiency of the single relaxation time Krook collision operator is that it only allows for fixed Prandtl number flows. It is well known that heat flux to walls is a function of Prandtl number : in certain ranges of Prandtl number, the heat flux it from the walls while in other ranges heat flux is into the walls.

We have generalized the scalar collision operator into a tensor collision operator so that variable Prandtl number flows can now be treated. We have also generalized the relaxation times so that the transport coefficients become independent of density. Explicit solutions of TLBE for the effect of velocity shear layer on a heat front for various Prandtl number are determined.

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Feedback Stabilization of the Resistive Shell Mode in Tokamaks

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Stabilization of the resistive shell mode is a vital component of the so-called *advanced tokamak* scenario. Stabilization of this mode is also necessary in reversed field pinches and spheromaks, otherwise these devices are not reactor relevant. It has been established that feedback stabilization of the resistive shell mode is, in principle, perfectly feasible in a tokamak reactor [1]. It remains to be established that the resistive shell mode can be successfully stabilized in a tokamak using a practical feedback system which employs a relatively small number of coils, which do not necessarily cover the whole surface of the plasma.

The key to analyzing the coupling between a tokamak plasma and a realistic set of feedback coils is the realization that once the interaction between the plasma and the *passive* coils is fully understood, it is relatively easy to add feedback into the problem. Motivated by this observation, a comprehensive theory has been developed in order to determine the effect of a partial resistive shell on the growth-rate of the external kink mode in a low-β, large aspect-ratio, circular flux-surface tokamak. This theory builds on, and considerably extends, the results of a previous investigation [2]. In most cases, it is possible to replace a partial shell by a complete *effective shell* of somewhat larger radius. In fact, the radius of the effective shell can be used to parameterize the ability of a partial shell to moderate the growth of the external kink mode. It is necessary to draw a distinction between *resonant shells*, for which the eddy currents excited in the shell are able to flow in unidirectional continuous loops around the plasma, and *non-resonant shells*, for which this is not possible. As a general rule, resonant shells perform better than similar non-resonant shells. The theory is used to derive some general rules regarding the design of incomplete passive stabilizing shells. The theory is also employed to determine the effectiveness of two *realistic* feedback stabilization schemes for the resistive shell mode, both of which only require a relatively small number of independent feedback controlled conductors external to the plasma.

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Nonlinear Coherent Energization of Magnetized Ions in Two or More Electrostatic Waves

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There are many observations in the Earth's ionosphere of ions getting energized by broadband electrostatic waves propagating across the geomagnetic field. The observed energies of the ions cannot be explained by assuming a wave-particle interaction with a single plane electrostatic wave as the initial ion energies are well below the minimum energy bound of the chaotic phase space.[1] In an attempt to explain the observations, we have studied the ion dynamics in two or more electrostatic waves. An interesting phenomenon of nonlinear coherent energization of the ions takes place for two electrostatic waves separated in frequency by the ion cyclotron frequency.[2],[3] This coherent energization can accelerate low energy ions into the chaotic phase space discussed previously.[1] A detailed Hamiltonian perturbation analysis using Lie transforms gives the dependence of the coherent acceleration on the frequencies, wavelengths, and amplitudes of the two waves. It shows that for an appropriate choice of frequencies and wavelengths, the coherent energization is independent of the amplitude of the waves. Furthermore, the ions can be accelerated or decelerated by a proper choice of the wave characteristics. Our results are applicable for waves in the lower-hybrid range of frequencies for a variety of space and laboratory plasmas, and show that it is possible to selectively heat ions or to selectively remove energy from the ions in a plasma by a judicious choice of the lower-hybrid waves. The results obtained from the perturbation analysis are confirmed by numerical integration of the exact equations of motion. The analytical and numerical details of this coherent acceleration/deceleration process will be presented.

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Neoclassical electron and ion transport in toroidally rotating plasmas

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Neoclassical transport processes of electrons and ions are investigated in detail for toroidally rotating axisymmetric plasmas with large flow velocities on the order of the ion thermal speed [1, 2]. By using the moment expansion method, the complete neoclassical transport matrix with the Onsager symmetry is obtained for the rotating plasma consisting of electrons and single-species ions in the Pfirsch-Schlüter and banana regimes [1]. It is found that the, for the rotating system, the populations of trapped electrons and ions are increased by the poloidal variation of the electrostatic potential and the effective gravity potential due to the centrifugal force, which results in the enhancement of the neoclassical transport coefficients. It is shown that the parallel electric field drives the inward particle flux (Ware pinch) as well as the inward flux of the toroidal momentum.

The flow-dependent neoclassical ion thermal diffusivity for the banana regime in the large-aspect-ratio system ($r/R \ll 1$) is given by

$$\chi_i = 0.678\left(\frac{r}{R}\right)^{1/2}\frac{\rho_{i\theta}^2}{\tau_{ii}}\left(1+0.765\Upsilon-0.631\Upsilon^2+0.280\Upsilon^3\right)$$

where $\Upsilon \equiv m_i V_0^2/(T_e+T_i)$ denotes the square of the toroidal flow velocity normalized by the sound wave velocity and $0 \le \Upsilon \le 1$ is assumed. Here the enhancement factor $(1+0.765\Upsilon-\cdots)$ in the right-hand side is in good agreement with that obtained by Catto it et al. [3] using the variational method (see also [4]). For the plateau regime, we have

$$\chi_i = \frac{3\sqrt{\pi}}{4}\left(\frac{v_{Ti}}{Rq}\right)\rho_i^2 q^2\frac{\left(1+2\Upsilon+2\Upsilon^2+\frac{2}{3}\Upsilon^3+\frac{1}{12}\Upsilon^4\right)}{\left(1+\Upsilon+\frac{1}{2}\Upsilon^2\right)}.$$

The flow-dependent parallel current for the banana regime in the large-aspect-ratio system is written as

$$\begin{aligned}
J_{\parallel} \;=\; & -\left(\frac{r}{R}\right)^{1/2}\frac{c}{B_\theta}\left[2.41\left(1+0.868\Upsilon-0.539\Upsilon^2+0.229\Upsilon^3\right)\frac{dP}{dr}\right. \\
& -1.80\left(1+2.248\Upsilon-1.661\Upsilon^2+0.727\Upsilon^3\right)n_e\frac{dT_e}{dr} \\
& \left.-2.83\left(1+1.494\Upsilon-1.022\Upsilon^2+0.434\Upsilon^3\right)n_i\frac{dT_i}{dr}\right] \\
& +\sigma_S\left[1-1.83\left(\frac{r}{R}\right)^{1/2}\left(1+0.431\Upsilon-0.184\Upsilon^2+0.072\Upsilon^3\right)\right]E_{\parallel}
\end{aligned}$$

where σ_S denotes the Spitzer resistivity.

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Linear Growth Rates and Nonlinear Saturation Amplitudes of TAE Modes Destabilised by ICRF Heating

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TAE (toroidal Alfvén eigenmode) instabilities excited by ICRF heating are due to the resonant coupling of energetic toroidally "trapped" particles. The ICRF heated energetic particle distribution function is likely to be anisotropic in velocity space. We survey TAE growth rates over a wide range of plasma parameters and pitch-angle dependent distribution functions. For distribution functions sharply peaked in pitch-angle, instability can occur even if the wave frequency is greater than the energetic particle diamagnetic frequency . We also investigate the nonlinear saturation of a single unstable mode near threshold when phase-space relaxation is the dominant saturation mechanism. The particle energy loss due to relaxation of the particle distribution function is evaluated, and from global energy conservation , an estimate is obtained of the saturation wave amplitude. We explore the accuracy of these estimates using a simulation code to follow the time evolution of a single unstable TAE mode to nonlinear saturation. For unstable modes with low growth rates, the "nonlinear wave frequency" (proportional to the square root of the saturation amplitude) increases directly proportional to the linear growth rate. At higher growth rates , the perturbed radial particle excursions are restricted by the "internal" radial width of the mode , and the "nonlinear wave frequency" increases more slowly with growth rate. The observed simulation results are consistent with the theoretical estimates of the "nonlinear wave frequency" both in magnitude and variation with linear growth rate .

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Interaction of Self-Generated Phase-Space Holes and Clumps

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Self-generation of a pair of nonlinear BGK waves has been observed in numerical simulation of a single, low-amplitude, weakly-unstable plasma mode. In this case, a hole-clump pair – that is, a local depletion and corresponding accumulation of fast particles – emerges and splits, with the hole moving up the phase-space density gradient, and the clump moving down the gradient. The hole represents a BGK mode shifted upward in frequency (if $f'(v) > 0$, with $\omega, k > 0$) and the clump a mode shifted downward.

When multiple discrete modes exist simultaneously, holes and clumps from initially unstable modes can interact nonlinearly, and can also trigger the instability of modes which are linearly *stable*. Thus, instability scenarios which look rather mild according to the linear picture (*i.e.*, very close to marginality) can evolve nonlinearly to states where a comparatively large amount of free energy is removed from the energetic particle component.

In this work we examine various multiple-mode scenarios in an unmagnetized, one-dimensional plasma using a δf particle code.

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Nonlinear Dynamics of the Fishbone

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The excitation of the $m = 1$ internal kink mode by fast-ions (produced by neutral beam injection or ion-cyclotron resonance heating) has been identified as the mechanism for plasma oscillation bursts known as fishbones [1]. The linear theory of these modes is well-developed [2].

To describe the temporal evolution of the fishbone instability, we present a model based on a WKB-expansion of the plasma energy functional – including the fully nonlinear hot particle contribution. The model takes into account realistic geometry, radial structure of the kink mode ($m = 1, 2$ harmonics) and full fast ion orbit effects. The fast ion current is computed numerically by the δf particle-code FAC [3]. We compute saturation levels, frequency change during the nonlinear pulse, and orbit loss characteristics for fishbone activity in both JET and PDX discharges. In particular, fishbone losses are found to be more severe in PDX than in JET because of the larger normalized width of the trapped-particle orbits. For JET, estimates show that the saturation level of the displacement of the magnetic axis can be as large as 3 cm.

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Abstract

Radial Mode Coupling Saturation of a Flute Mode , A. Ponomarev and A.K. Sen
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We have studied experimentally and theoretically the structure and properties of a centrifugal flute mode driven by **E x B** rotation of a plasma column. This mode appears as a single mode ($m = 1, k_{\parallel} = 0$). Then a puzzling question arises about the possible saturation mechanism of such a single mode with the obvious absence of the usual mode-mode coupling and nonlinear Landau damping. An equally important parallel question is how a single mode can cause experimentally observed particle transport. A partial answer to this question comes from the observation that there is some spectral width of the ($m = 1$) mode of the **E x B** instability. The fact that there is substantial spectral width of this so called "single" mode clearly implies that it is not a single coherent fluctuation and must represent at least several fluctuational components. To investigate this possibility we have performed a bispectral analysis. The auto-bispectrum was used to determine the level of coherence of the various frequency components in the spectrum based on the three-wave interactions. The resulting data clearly indicates strong mode coupling in the spectral width of the mode. We also tracked the amplitudes of individual frequencies across the plasma cross-section, giving the radial structure of different frequency amplitudes. Frequencies with self-similar radial structures are grouped together to belong to the same radial harmonic. Clearly, these radial harmonics contribute to the spectral width. These observations suggest that the nonlinear mode coupling between these radial harmonics is the saturation mechanism, as well as the underlying cause of anomalous transport.

Prompted by the above observations we formulated a 3-wave non-linear coupling model using radial harmonics. A proper treatment of two-dimensional (azimuthal and radial) nature of the polarization drift non-linearity and inclusion of damped radial harmonics to insure a steady state are important. The analysis reveals the generation of damped higher order radial harmonics by the unstable fundamental radial harmonic, which is the saturation mechanism. The resulting RMS fluctuation and levels of higher harmonic generation are in fair agreement with the experimental observations.

The 'moving-contact' plasma-wall instability and the appearance of halo currents

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It is recognized that plasma disruptions and vertical displacement events (VDEs), with the attendant formation of 'halo currents', are a threat to the success of future experiments such as ITER. Halo currents have been observed in some experiments to develop large toroidally asymmetric components, and we propose a model of this that regards the plasma primarily as a movable electrical contact that completes a wall-plasma-wall circuit, with the enclosed evolving magnetic flux providing the driving voltage. The ingredients of the 'moving-contact' instability are the difference in induction and resistance between wall and plasma current paths, the motion of the plasma-wall contact according to force balance, and the transfer of current between inductively coupled current channels. We develop a simple prototype model and perform a linear stability analysis which is then verified numerically. Qualitative conclusions are drawn for the case of the helical halo, and the consequences of requiring the periodicity of the current path while the system obeys force-balance and Ohm's law are pointed out. We discuss the possible implications of our model for the stabilization of such modes.

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Momentum Transport and Radial Electric Field in High Temperature Plasmas

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This work addresses the inference of the radial electric field E_r in the core region of high ion temperature discharges such as TFTR supershots, hot-ion H- and VH-Modes on DIII-D and JET, and high-β_P H-Modes on JT-60U. Underlying issues in momentum transport are successfully addressed, providing experimental evidence to support the neoclassical inference of the poloidal velocity profile in high temperature plasmas for near-balanced neutral beam injection. Improved analytical forms are derived for the neoclassical radial electric field and shown to quantitatively reproduce the results of a full two-species numerical calculation that is comprehensive within the standard framework.[3] They provide the "neoclassical corrections" to the expression $E_r = V_{\varphi x} B_\theta$, where $V_{\varphi x}$ is the measured impurity toroidal velocity, and can be used to self-consistently include the stabilizing effect of radial electric field shear in predictive nonlinear transport codes. These corrections are linear in the gradients of the hydrogenic ion temperature and hydrogenic thermal ion density, and are computed analytically and numerically[3] using the standard neoclassical viscosities.[2]

The theory quantitatively reproduces a large well structure ("notch") in the measured impurity toroidal velocity profile in the core of TFTR plasmas, while at the same time predicting well-behaved, *monotonic* toroidal velocity profiles for the hydrogenic species. This is consistent with the radial transport of toroidal momentum by anomalous diffusion, and with the conservation of toroidal angular momentum by the lowest order neoclassical theory. A similar notch feature has recently been observed in JT60-U toroidal velocity profiles.

The observed notch indicates a similar well structure in the radial electric field profile, localized to the region of enhanced confinement in supershot plasmas.[3] However, using $E_r \simeq V_{\varphi x} B_\theta$ in this region underestimates the well depth in E_r by roughly a factor of two by neglecting residual neoclassical flows. This demonstrates that the assumption of pure toroidal rotation, on the basis of neoclassical poloidal flow damping, is quite wrong in high temperature regimes. This assumption is made in most recent work attempting to include velocity gradients in the linear stability analysis of toroidal drift modes. Outside the half-radius of supershot plasmas, where the local confinement trends are degraded, as well as in L-Mode plasmas, we find this approximation remains reasonable, provided the measured *impurity* toroidal velocity is used to evaluate E_r.

The well in E_r results in a stabilizing shear layer in the radial electric field near the half-radius, separating the region of enhanced confinement from the degraded outer region. The corresponding decorrelation rate[4] is comparable to the linear growth rates calculated by comprehensive gyrokinetic codes in TFTR supershot plasmas.[5] This suggests a potentially nonlinear[6] relationship between the ion temperature gradient and shear in the radial electric field, particularly relevant to transport barrier formation.

Implicit in the pure neoclassical approach is the assumption that all momentum imparted by neutral beams is carried away by anomalous radial momentum diffusion, with no other effect. This is supported by the small interspecies toroidal velocity difference arising classically from the differential beam torque. These effects are important, however, relative to orbit squeezing, which we neglect on the basis that the squeezing parameter is within 5% of unity in the considered plasmas. Performing TRANSP monte-carlo analysis to obtain the poloidal magnetic field and beam source terms, we formulate and solve the more complete system numerically. The more complete treatment with radial momentum diffusion and beam source terms resolves a nonphysical discontinuity in the predicted velocities associated with convectively limited, "clipped" ion temperature profiles. In addition, the toroidal momentum diffusivity can be inferred while consistently accounting for neoclassical viscosity, heat friction, and heat stress.

A fully extensible, modular, portable transport code was developed[3,7] to carry out these calculations. The code reads data prepared in netCDF format from TRANSP output and can perform a variety of related transport calculations for all times in a discharge.

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1D46

Nonlinear Landau damping in plasma and fluid

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The linear Landau damping of plasma waves [1] is well understood by now, although back in sixties it caused some controversy because of the counter-intuitive idea of damping in an ideal Hamiltonian system. In nonlinear formulation, the damping also exists and can be explained in quite natural terms of relaxation to an equilibrium *slightly different* from the unperturbed one. This difference is caused by nonlinearity and leads to a new damping/relaxation law. If the perturbation amplitude is of order ϵ, the linear, exponential damping works for $\omega_p t < \epsilon^{-1/2}$; then, for $\epsilon^{-1/2} < \omega_p t < \epsilon^{-1}$, O'Neil's trapping oscillations [2] take place, and it is widely believed that, at least in 1D, the system settles to a nonlinear BGK wave [3]. It is proposed [4] that this doesn't happen and in fact a new regime of nonlinear damping takes over for $\omega_p t > \epsilon^{-1}$, in which the amplitude of the perturbation decays algebraically, $E \propto t^{-d}$, where d is the dimension of the Vlasov-Poisson problem.

A similar algebraic damping law is also derived for 2D ideal fluid/magnetized non-neutral plasma, where the background shear flow disperses vorticity perturbations and leads to flow relaxation. The difference of the shear damping in fluid from the Vlasov case is that it is algebraic already in linear theory [5]. The nonlinear shear damping in fluid takes over at large time and results in a faster damping law.

The specific damping laws predicted by this theory indicate that the relaxation to a new steady state is so fast that a complete mixing of phase-space/fluid elements is impossible, and therefore the Vlasov and 2D fluid turbulences are non-ergodic, and statistical models of such relaxation are questionable.

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Hybrid MHD-Gyrokinetic Simulations of Drift Alfven-Ballooning Modes

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The resonant excitation of low-frequency MHD waves by energetic ions in an inhomogeneous high pressure plasma has been studied by means of hybrid MHD-gyrokinetic particle simulations. The purpose of the investigation is to identify the instability mechanism for internally excited Pc 4-5 geomagnetic pulsations.

In the model, energetic ring current ions are treated as gyrokinetic particles while the magnetohydrodynamic description is used for the low energy bulk component. The two plasma components are coupled using a current coupling scheme [1]. This approach allows one to self-consistently study the growth and saturation of the low-frequency shear Alfven and compressional type modes which are driven unstable by the hot ion pressure gradient through resonant interaction with energetic ions. The two dimensional numerical scheme with fixed background inhomogeneities in a magnetic field of constant curvature has been developed using a multiple-scale expansion in the gyrokinetic Vlasov equation. A generalized two-weight δf scheme [2] is employed in order to reduce the numerical noise.

The effects of the magnetic field curvature, hot ion pressure anisotropy and the pressure gradient on the growth rate and saturation amplitude of the drift Alfven-ballooning modes are studied for large beta $\beta \sim 1$ and $k_\perp \rho_i \sim 1$. Very good agreement with linear theory in terms of the wave frequency and growth rate is obtained in the simulations. It is found that the effect of the magnetic field curvature is important and results in a larger growth rate and saturation amplitude, as compared to the straight magnetic field approximation. The maximum amplitude of the radial component of the perturbed magnetic field is about several percent of B_0 at saturation. The saturation of the instability is caused by particle trapping in the case of an adiabatically-injected particle distribution. When the hot ion distribution function is taken to be a local Maxwellian with fixed density gradient the steady state still can be achieved, in spite of the absence of quasilinear relaxation of the density gradient. In this case a continuous energy exchange between the competing modes in the saturated state is observed.

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Equilibrium Flux Surfaces in MHH2*

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The PIES code has been used to assess the integrity of the equilibrium flux surfaces in the MHH2 device.[1] Although stellarators are generally designed to have good vacuum flux surfaces, the three dimensional pressure driven currents contain Fourier components which resonate with rational surfaces in the plasma, producing magnetic islands and destroying flux surfaces as the pressure is raised. The PIES code calculates three-dimensional equilibria without making any assumptions about flux surfaces[2], and it can be used to address the issue of the loss of equilibrium flux surfaces. Calculations have been performed for two sets of pressure profiles: $p \propto (1-\psi)^2$ (a peaked profile), and $p \propto 1-\psi$ (a broader profile), where ψ is the toroidal flux normalized to one at the boundary. For both profiles, island chains of increasing width are observed as β is increased. For the peaked profile, flux surfaces are lost across a substantial fraction of the minor radius as β is raised above 2%. This is interpreted as an equilibrium β limit. The equilibrium β limit for the broader profile is about a factor of two higher.

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DISRUPTIONS IN TOKAMAKS

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Disruptions are of great concern for tokamaks, primarily because of the potential for damaging the vacuum chamber, divertor, first wall, and/or other plasma facing components. Disruption damage can be caused by localized thermal deposition on the first wall, as well as structural failure due to $J \times B$ forces arising from induced currents. These problems are expected to be more pronounced in ITER and future reactors due to the much greater thermal energy, high I_p and B_ϕ, and increased conductivity of the vessel structures. Axisymmetric toroidal eddy currents, and the $J \times B$ forces they give rise to, are well understood and modelled with straightforward axisymmetric plasma/circuit models. However, induced poloidal 'halo' currents are not as well understood, despite the fact that they can also give rise to comparable forces on the vessel and internal hardware. In particular, questions about magnitude, scaling, toroidal asymmetry and peaking, radial distribution, temporal behavior, current path, etc. need to be addressed. Partly because of ITER concerns, an extensive effort to study halo currents, as well as other disruption issues such as quench timescales, vertical stability and motion, disruption frequencies, etc. is being carried out on many tokamaks around the world. Generally speaking, there is now a lot of experimental data on disruption and halo current characteristics, but very little theoretical understanding. The result is that we currently have compiled an empirical dataset which is being used to constrain the ITER design, but without the basic understanding of the underlying physical processes involved.

For example, halo current fractions, I_{halo}/I_{p_0}, are typically found to be in the range of 0.1 to 0.3 (although extreme cases can go above 0.5). But larger tokamaks (JET and JT-60U) tend to be at the lower end of this range. Does this mean that ITER, which is $3\times$ bigger than JET, can ignore halo currents altogether? Without a basic theory, we just can't say. Another example of our lack of understanding pertains to the spatial structure of halo currents. Spatially resolved measurements of halo currents on several machines reveal significant toroidal asymmetry, which is usually well characterized as an $n = 1$ helicity superimposed on an $n = 0$ background (although a few examples having $n = 2$ structure have also been seen). The resulting toroidal peaking factors (i.e. peak/average) range from 1 to more than 3. Furthermore, this asymmetric pattern usually rotates toroidally at a few kHz, thus ruling out first-wall non-uniformities as the cause of the asymmetry. The toroidal peaking is fundamentally important because it locally exacerbates the $J \times B$ force due to halo currents. But here again, the lack of a physical understanding for the toroidal asymmetry precludes any reliable prediction of its magnitude in ITER, leading to design constraints that perhaps may be overly stringent, or maybe even too lenient.

Details of our current knowledge of disruption and halo current characteristics will be presented, with emphasis on the areas where development of a theoretical understanding would be most helpful. Attempts at reducing the deleterious effects of disruptions by fast plasma termination (killer pellets) will also be discussed.

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Nonlinear 3D Simulations of Disruptions in NCS Discharges in DIII–D

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Nonlinear simulations of experimentally observed magnetohydrodynamic (MHD) bursts and fast disruptions in DIII–D L–Mode negative central magnetic shear (NCS) discharges were performed with a full 3D nonlinear MHD code NFTC. The effects of plasma rotation in the presence of resistivity and viscosity are included and an effective implicit numerical scheme allows the transport profile to evolve self consistently with the nonlinear MHD instabilities and the externally applied sources and sinks. The simulations follow the MHD bursts and disruptions through the linear and nonlinear phases and identify the connections between the early MHD bursts and the ultimate disruption phase. Specific predictions of the growth and saturation of the modes are directly compared with experimental diagnostic measurements in DIII–D.

Local resistive interchange instabilities are found to be linearly excited when the magnitude of the magnetic shear and pressure gradient locally exceed critical values at rational surfaces in the negative shear region. The resulting modes saturate at a small amplitude if no external heating is applied. With continued auxiliary heating, however, the axis pressure is steepened, while the magnetic shear is reduced near the magnetic axis but steepened at the innermost resonant surface. Initially, while the shear near the axis remains finite, partial reconnection occurs in a small zone near the resonant surface. However, later during the nonlinear evolution, the shear vanishes in a region between the magnetic axis and the innermost rational surface and the entire core magnetic surfaces reconnect. This quasi-saturated state then ultimately collapses. Comparison of calculations with diagnostics from several discharges confirms that the appearance of the central region with zero shear correlates with the onset of the MHD bursts, and leads to a flattening of the current density inside some mixing radius. Continued heating restores the plasma profiles, and the time interval before the appearance of the next burst depends on the heating rate. It is found from the calculations that the peaking rate of the central pressure increases after a burst. This can then lead to a more global instability which can be correlated with the observed major disruption. The major disruption is exhibited in the calculations as the excitation of a double tearing mode coupled with the resistive interchange.

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Fokker-Planck Simulations of Knock-on Runaway Electron Generation in Tokamaks

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The ability to tolerate disruptions is an important issue in high current tokamaks. To minimize the thermal and electro-mechanical stresses that can be produced during current quench in a disruption, it has been proposed to inject pellets or jets to quench the plasma thermally and thus allow a rapid current decay. A serious concern for this method is that high electric fields produce long-lived high energy runaway electrons [1]. Specifically, the presence of trace amount of high energy electrons can produce secondary runaways through large angle knock-on collisions with the bulk electrons and produce an avalanche of runaways in a fraction of a second. This work is the first numerical study that attempts to accurately evaluate the phenomena including realistic effects. To simulate this phenomena, the bounce averaged Fokker-Planck code CQL3D is used. Effects such as trapping, synchrotron radiation and bremsstrahlung are included. Secondary knock-on production is modeled by a source term using Moller cross-section and an approximation that the primary runaways have negligibly small pitch-angles. It is shown that even when the electric field is small for production of Dreicer runaways, knock-on collisions can cause the runaways to exponentiate at a characteristic time constant typically a fraction of a second, and then saturate when the electric field decreases to near or below the critical electric field. The growth rate is shown to be in good agreement with Rosenbluth's analytic theory [1]. Simulations of pellet injection indicate that sufficiently low Z pellets can effectively quench runaways. We will present results of evolution of the electric field and runaways at constant current, as the temperature and density change abruptly during pellet injection. The effect of magnetic fluctuations on runaways and the consequence of removing the approximation of negligible pitch angle for the runaway distribution in calculating the source term will be discussed.

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2C01

NONLINEAR INTERACTION OF THE LOW-FREQUENCY ELECTROMAGNETIC EXCITATIONS IN THE PLASMA EDGE AND ANOMALOUS DIFFUSION

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The interest in the low-frequency (frequencies not exceeding the ion cyclotron frequency) long-wave (wavelengths longer than the ion Larmor radius) electromagnetic plasma fluctuations manifested in the plasma edge (see [1]) is constantly growing due to their relation to the transport anomalies in plasmas [1-2]. The importance of the magnetic drift in the test particle diffusion was revealed in [1-3]. It is believed also [2] that the anomalous transport is determined not only by nonlinear interactions between ponential and magnetic perturbations in a plasma, but by their cross correlations as well.

Making use of the cross-field renormalized statistical approach [2], we obtain the stationary spectra with regard of nonlinear mode interaction. The thermal (fluctuative) parts of the linear solutions may fit to the nonlinear case only in a plasma with isothermal components. This was not noticed in [1] that led the authors to irrelevant conclusions.

In obtaining the diffusion coefficient, we follow the approach elaborated by Sytenko Sosenko [1] with reserve that the calculation carried out in [1], is not correct due to neglecting the linear viscosity and mathematical errors and leads to wrong result.

In the presence of the transverse electric plasma flow, when the nonlinear terms containing the potential component are unimpornant, the diffusion is attenuated.

The parallel external electric field leads to enhanced diffusion, in agreement with [3], and the finite cross correlations between the potential and magnetic excitations produce the similar effect.

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The Shear Alfvén Wave in Asymmetric MHD Equilibria

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The shear Alfvén wave of ideal magnetohydrodynamics (MHD) has received considerable interest and attention in the past because of its potential importance for plasma heating and current drive, and because of its possible effects on plasma stability. The key feature of the shear Alfvén wave that underlies its many applications is its spatial singularity about surfaces of constant pressure. This singularity implies the existence of a continuous spectrum of eigenmodes. What is known about the Alfvén continuum has arisen principally from studies of Alfvén wave phenomena in MHD equilibria with spatial symmetries, such as the one dimensional cylindrical screw pinch and the two dimensional toroidal tokamak. Shear Alfvén wave behavior in asymmetric equilibria has received minimal attention. In the absence of spatial symmetry, existence of MHD equilibria and existence of the shear Alfvén continuum have not been clearly established. This lack of existence proofs and the mathematical difficulties associated with asymmetric geometries have likely impeded studies of Alfvén wave behavior in three dimensional plasmas. Recently, however, a class of asymmetric MHD equilibria, each of which is an exact solution of the ideal MHD equations, has been derived [1]. These particular equilibria are parallel to a straight, infinite, magnetic axis. The magnetic lines of force twist about the axis and form closed magnetic surfaces. The study reported here treats the shear Alfvén wave and continuum in this class of straight asymmetric MHD equilibria. Emphasis is placed on small beta plasmas. Under this condition, an ordinary differential equation along the force lines of the equilibrium magnetic field govern the shear Alfvén continuum mode. The analytic representations of the equilibrium result in expressions for the spatially dependent coefficients of the differential equation. In the vicinity of the magnetic axis, the mode equation can be expressed in an explicit form that can be solved analytically along particular magnetic field lines. The analytic solution reveals that the Alfvén continuum has two components: a continuous component that is characterized by modes defined over the entire magnetic surface, and a discrete component characterized by modes localized with a finite decay length on specific magnetic field lines. The localized modes, which in this study are termed **nonsymmetry induced Alfvén eigenmodes** (NAE), are new. They do not occur in symmetric plasma configurations. Numerical solution of the Alfvén continuum equation on magnetic surfaces further from the magnetic axis confirms the generality of this classification of the continuum modes. Properties and implications of NAE will be described. Although this study is based on a particular asymmetric straight configuration, it is speculated that the results have relevance in asymmetric toroidal plasmas.

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Toroidal Resistive MHD Steady States Contain Vortices

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Resistive toroidal MHD steady states, which are required to obey Ohm's law and Faraday's law as well as force balance, differ considerably from their ideal MHD counterparts. Except in the case of probably unphysical resistivity profiles [1], $\nabla\times(\mathbf{j}\times\mathbf{B})$ is non-vanishing, and so cannot be balanced by the gradient of any scalar pressure. Viscous drag is required for force balance, and gives rise to a characteristic "double smoke ring" pair of toroidal vortex rings [2]. These have no analogue in the straight-cylinder approximation, and are not a consequence of any instability – rather, they are a necessary consequence of the local torque exerted by the difference of the $\mathbf{j}\times\mathbf{B}$ and pressure gradient forces. It is important to appreciate that they have little if anything to do with the familiar "Pfirsch-Schlüter effect" from the 1960s. The magnitude of the flow depends sensitively on the magnitude (and probably the form) assumed for the viscous stress. No streamlines are required to leave the toroidal boundary. Previously [2], the problem was solved for low Hartmann number assuming stress-free boundary conditions. Here, we take advantage of some recent mathematical developments using toroidal coordinates [3], and some novel Green's function techniques for the biharmonic equation, to solve the same problem in the presence of the (more physical) no-slip boundary conditions on the velocity field.

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An Integral Equation Approach to Modelling of the Observed Phenomena of Fast Nonlocal Heat Transport in a Tokamak

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The physics model [1] for the nonlocal (non-diffusive) heat transport by plasma waves of the long mean-free-path (m.f.p.) – of the order and much larger than plasma characteristic size – and the respective formalism [2] of an **integral** equation, in space variables, are shown to provide universal qualitative explanation of major features of recently observed phenomena of the fast non–diffusive heat transport in a tokamak, which being interpreted in formalisms of **differential, diffusion-like** equations give instant jumps of thermal diffusivities in a large part of plasma volume (see, e.g., the survey [3]). The success of the approach [1, 2] arises from self-consistent generation of the **nonlocal inward energy flux** which is lost in diffusion-like approaches. The dominance of the nonlocal contribution of (long m.f.p.) waves to energy transport has been shown, for the first time, for longitudinal waves by Rosenbluth and Liu [4] (anomalous cross-field energy transport (ACFET) by electron/ion Bernstein waves) and, for transverse waves, by Tamor [5] (electron cyclotron radiation (ECR) transport in a tokamak). Nonlocality of heat propagation by the electron Bernstein waves was demonstrated in [6].

The approach developed includes:

(1) Derivation of the integral equation formalism for the ACFET as a statistics of 'ballistic' energy transfer by wave quanta. Here, the approach [1] is extended to the case of describing the local energy balance of the ACFET by the long m.f.p. waves, under conditions of geometrical optics and multiple reflections of wave quanta from/at plasma boundary/periphery. The non-linear (in T_e and n_e) integral (in space) term is obtained which should be added to conventional energy transport equation. This term gives approximate analytic solution of the wave transport problem, for fixed T_e and n_e profiles. The validity of the approach [1] is proved by the results of its application to energy transport by ECR waves in a tokamak (cf. [5, 1]).

(2) Formulation of **inverse problem** of reconstructing major parameters of the above-mentioned integral term. To this end, a model is proposed which is based at phenomenological description of (i) dispersion and emission/absorption characteristics of a non-equilibrium magnetically confined plasmas with respect to emission/absorption of the long m.f.p. waves, and (ii) coefficients of reflection of a wave from/at plasma boundary/periphery.

(3) Modelling, with few phenomenological parameters, of the initial stage of the following phenomena: (i) net inward flux of energy during off-axis heating (similarly to ECRH experiments on DIII-D [7]); (ii) fast "volumetric" response of energy transport to plasma edge behavior during L-H transitions (JET [8], JT-60U [9]); (iii) prompt rise/drop of T_e in the core in experiments on fast cooling/heating of the periphery on TEXT [10] and TFTR [11].

The diagnostic strategy needed to identify the nonlocal inward energy flux is discussed.

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Optimization of the Magnetic Field Structure of EPEIUS[1]: a proposed low-aspect ratio torsatron-tokamak hybrid*

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Although the current EPEIUS design has most of the characteristics desired in a stellarator reactor, low aspect ratio, robust magnetic surfaces, tokamak like rotational tranform profile, and a magnetic well, the asymmetry in the magnetic field geometry (neglecting radial electric field effects) leads to direct losses of some fraction of the trapped particle population. The reduction of these losses has been one of the goals of several recent stellarator design efforts.[2–5] These optimization efforts have focused on achieving some degree of symmetry in the magnetic field by considering the spectrum of Fourier coefficients of the magnetic field in Boozer coordinates.[6]

However, since these configurations may be difficult to obtain at low aspect ratio,[7] another approach will be taken. "Isodynamic" or "omnigenous" equilibria[8–10] are equilibria in which the particle drift surfaces coincide with the flux surfaces and therefore there is no neoclassical transport. Recent calculations[11] have suggested that, since omnigeneity is less restrictive than axisymmetry or quasi-helicity, an approximately omnigenous system may be easier to obtain and provide better transport. In fact, it has been shown that by localizing the ripple in the magnetic field due to its helicity to the inside of the torus, the transport can be reduced by over an order of magnitude.[12]

The approach used[13] is to vary the shape of the last closed flux surface from an initial equilibrium obtained from VMEC,[14] iteratively, coupled with recalculation of the equilibrium and evaluation of a target functional of aspect ratio, rotational transform profile, magnetic well profile, B_{max}, and B_{min}. This loop is driven by a nonlinear least squares minimization algorithm (Levenberg-Marquardt) which attempts to search for the flux surface shape which minimizes the variation of the target functional.

Once the desired shape has been achieved, the final step (under development) in this process is then to work outward from the last closed flux surface to a coil configuration which is consistent with such a shape.

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2C06

Necessary and Sufficient Instability Condition for Inviscid Shear Flow

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We derive a condition that is necessary and sufficient for the instability of inviscid, two-dimensional, plane parallel, shear flow with equilibrium velocity profiles that are monotonic, real analytic, functions of the cross stream coordinate. The analysis, which is based upon the Nyquist method, includes a means for delineating the possible kinds of bifurcations that involve the presence of the continuous spectrum, including those that occur at nonzero wavenumber. Several examples are given.

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FRACTAL AND MULTIFRACTAL PROPERTIES OF EXIT TIMES AND POINCARÉ RECURRENCES

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Systems with chaotic dynamics possess anomalous statistical properties and their trajectories do not correspond to the Gaussian process. This property imposes description of such time-characteristics as distribution of exit times or Poincaré recurrences by introducing a (multi) fractal time-scale in order to satisfy the observed power-like tails of the distributions. We introduce a corresponding phase-space-time partitioning and spectral function for dimensions, and make a connection between dimensions and transport exponent that defines the anomalous ("strange") kinetics. Numerical example is given for the standard map near the accelerator mode regime.

2C08

INDUCTANCE OPERATOR AND FEEDBACK STABILIZATION OF WALL MODES

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The plasma response to currents, $\kappa(\theta,\varphi)$, in a thin shell surrounding a plasma can be represented by an inductance operator $\hat{\mathcal{L}}$, which relates κ and the normal component of the magnetic field, b, on the shell. The current density in the shell is written as $\mathbf{j} = \left(\nabla\kappa(\theta,\varphi,t)\mathbf{X}\nabla r\right)/\Delta$ with the radial coordinate r defined so the shell is at constant r, $r = r_s$. The thickness of the shell is Δ. The normal component of the perturbed magnetic field is chosen so that it has units of magnetic flux, $b \equiv \mathcal{J}\,\mathbf{b}\cdot\nabla r$ with $\mathcal{J}$ the Jacobian of (r,θ,φ) coordinates. In perturbation theory, the current in the shell $\kappa(\theta,\varphi,t)$ and $b(\theta,\varphi,t)$ are linearly related,

$$b = \int_{-\pi}^{\pi} d\theta' \int_{-\pi}^{\pi} d\varphi' \int_{-\infty}^{t+0_+} dt'\, \mathcal{L}(\theta,\theta',\varphi-\varphi',t-t')\kappa(\theta',\varphi',t') = \hat{\mathcal{L}}[\kappa].$$

If feedback currents κ_f are driven in coils behind the shell, $r = r_f$, then the normal field on the shell is the sum of two terms, an inductance and a mutual inductance, $b = \hat{\mathcal{L}}\left[\kappa\right] + \hat{\mathcal{M}}\left[\kappa_f\right]$. A feedback system drives a current κ_f in response to a measured normal magnetic field on the shell, or $\kappa_f = -\hat{\mathcal{G}}[b]$. Combining operators $b = \hat{\mathcal{L}}_{eff}[\kappa]$. The combination of Faraday's law and Ohm's law imply $\partial b/\partial t = -\hat{\mathcal{R}}[\kappa]$. The resistance operator $\hat{\mathcal{R}}$ is positive definite and Hermitian,

$$\hat{\mathcal{R}} \equiv -\mathcal{J}\nabla\cdot\left(\frac{\eta}{\Delta}\nabla r\cdot(\nabla\kappa\mathbf{X}\nabla r)\right).$$

Wall modes are stable with feedback if the equation

$$\hat{\mathcal{L}}_{eff}\left[\frac{\partial\kappa}{\partial t'}\right] = -\hat{\mathcal{R}}\left[\kappa\right]$$

yields no growing solutions. In a cylinder, the eigenvalues of $\hat{\mathcal{M}}$ are $(r_f/r_s)^m$ times those of $\hat{\mathcal{L}}$. Each eigenvalue of $\hat{\mathcal{L}}_{eff}$ can be written as $L_{eff} = L/(1+\alpha L)$ with α proportional to the feedback. A wall mode arises if L is negative but is stabilized if L_{eff} is positive. Supported by U.S. DoE grant DE-FG02-95ER54333.

The M3D (Multi-Level 3D) Project for Plasma Simulation*

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The M3D project aims at extending the capability of predicting plasma behaviors for fusion, space weather forecast, etc., through numerical simulations using multi-levels of physics models.[1] The project has started with a nonlinear MHD code, MH3D, since the MHD physics generally gives the dominant effects, and has added step by step the higher order effects such as the two-fluid effects and the hot particle kinetic effects. This M3D (Multi-Level 3D) code package not only has the options to operate with a selection of different physics, but also with a selection of geometry and grid models ranging from simple to complex. This multi-level approach was adopted in view of the following: 1)Due to the complexity of physics involved, comparing results from various levels is essential both to understand the physics and to ensure the validity of the results, 2)This approach facilitates a step by step path to a more comprehensive simulation code, 3) Depending on the problem at hand, one can choose the best physics, geometry, and grid models. 4)The object oriented modular code design ensures that carrying the multi-level capability in one code package would incur only a minimal overhead for any given run with particular options chosen.

The currently available options of the M3D project are the MHD version MH3D, the particle/MHD hybrid version MH3D-K, the two-fluid version MH3D-T, and the unstructured mesh version MH3D++. Recent applications of MH3D code includes the interpretation of high-β disruption[1, 2] and the off-axis sawteeth[3] in reversed magnetic shear plasmas. The particle/MHD hybrid MH3D-K has been used to find the nonlinear saturation mechanism of TAE modes.[4] The two-fluid MH3D-T has been used to study the diamagnetic effects on tokamak plasmas.[5] The unstructured mesh MH3D++ is currently being used to study DIII-D disruption, ITER pellet injection, and NSTX.

We are further improving M3D by adding step by step more physics, geometry, and grid models, and continue to use these capabilities to study plasma systems. The effects of bulk plasma pressure anisotropy are being implemented in MH3D-T. This will give the bootstrap current and neoclassical tearing modes. The particle/fluid hybrid version will be extended to include the thermal ion gyrokinetic particles. An unstructured 3D grid model will be implemented in MH3D++. This version will be applicable to plasmas of various 3D shape and topology, including space plasmas and stellarators. We are also improving the computer technology side of the M3D, some of them with help from NERSC researchers. The massively parallel T3E version and a high end visualization capability are being developed.

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3D MHD Simulations on an Unstructured Mesh

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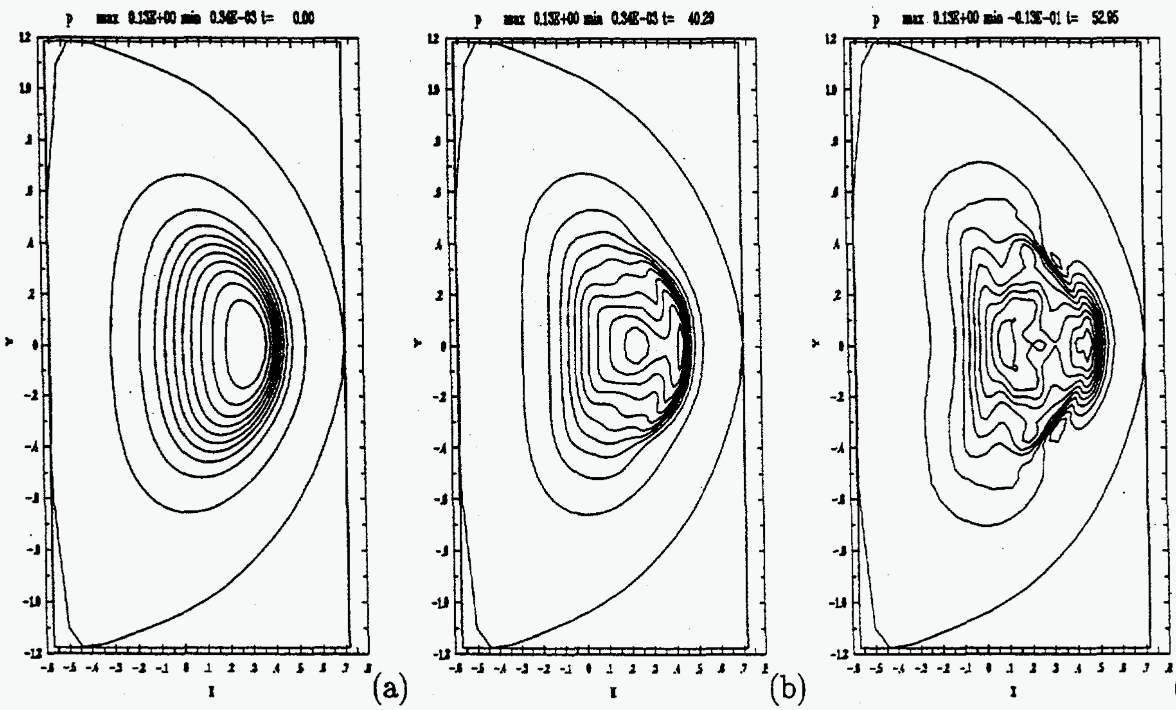
The MH3D++ code has been used to simulate disruptions in DIIID reversed shear discharges, the 3D dynamics of pellet injection, and disruptions in NSTX. MH3D++ is an extension of the PPPL MH3D resistive full MHD code. It employs an unstructured mesh and finite element / Fourier discretization using triangular and quadrilateral piecewise linear elements.

Disruptions in negative central shear DIIID discharges illustrate how secondary MHD pressure driven instabilities can be generated by nonlinear resistive evolution. Equilibria were produced from data of a DIIID-D L-mode negative central shear discharge and were found to be ideally stable but resistively unstable to a 2/1 tearing mode. The plots show pressure contours initially (a) and at later times. Nonlinearly, reconnection occurs at the q=2 surface (b). Then, the pressure peak bursts through the q=2 surface, as if there were an aneurism (c).

Pellet simulations were initialized with ITER - like ideally stable equilibria. The pellet was modeled as a density blob, inserted adiabatically. Simulations show it is favorable to inject pellets on the inboard side. Studies are in progress on the stability of the 3D state containing a pellet.

Simulational studies of NSTX equilibria, linear modes, and nonlinear evolution of disruptions are also in progress.



(a) (b) (c)

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Two-Fluid Toroidal Effects on Tokamak Plasmas*

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The two-fluid initial value code MH3D-T has been developed and tested [1]. The code follows the evolution of 3D perturbations in a toroidal plasma, when the electrons and ions are modelled as separate fluid species, the electrons having zero mass. The closure assumption is the drift ordering [1], generalized to arbitrary perturbation size. The model includes the diamagnetic drifts, the Hall terms and electron pressure gradient in Ohm's law, the gyroviscous force, and parallel and perpendicular thermal conductivities. It has been used to study two-fluid effects on the evolution of low mode number magnetic islands. For cylindrical plasmas, the nonlinear evolution was found to follow previous theoretical and numerical results obtained for simplified geometries, including the reduced torus (aspect ratio expansion). In a full torus, however, results are found to differ significantly from such theories and 3D effects are important. Magnetic islands are found nonlinearly to couple much more easily to modes of different *toroidal* mode number in the two-fluid than in the MHD approximation. The two-fluid coupling can drive island growth at a rate much faster than MHD. A number of processes related to geometrical and two-fluid effects influence the modes and their evolution. One of the most important and complex is the plasma poloidal rotation. The diamagnetic drifts appear in the two-fluid velocities and change as the islands and the associated gradients evolve. There is also a strong global coupling of the poloidal and toroidal ion velocities through the continuity equation due to the toroidal geometry, that includes the excitation of sound waves and the radial propagation of the velocity perturbations. A complete ordering for a two-fluid model also requires the neoclassical collisional viscous forces $\nabla \cdot \mathbf{\Pi}_j$, which introduce damping of the ion poloidal rotation over an ion-ion collision time scale and the boot-strap current and related terms. The viscous forces have been added to MH3D-T. Their effects in a fully toroidal plasma are discussed.

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Three Dimensional Particle/Magnetohydrodynamic Simulation of Energetic Particle driven MHD Modes in Tokamak Plasma*

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The energetic particle driven MHD modes are studied using a particle/MHD hybrid code MH3D-K. In the hybrid model, the MHD equations are coupled with gyrokinetic energetic particles through the pressure tensor (or current density in the current coupling scheme).[1, 2] The plasma is divided into two parts: the bulk plasma, which contains the thermal electrons and ions, and the energetic hot ions. The bulk plasma is described by the ideal MHD equations, whereas the hot ions are described by the gyrokinetic equations. In the pressure coupling scheme, The effects of hot ions couple to the bulk plasma motion through the pressure tensor term in the momentum equation. The hot particle contribution to the pressure tensor is calculated from the hot ion distribution function f represented by an ensemble of particles which follow the gyrokinetic equations with the self-consistent electromagnetic field. The model is fully self-consistent, including self-consistent effects of hot particles on the MHD dynamics and the nonlinear MHD mode coupling.

In the previous work, we had found that wave particle trapping is the dominant mechanism for the TAE saturation[2], using the "double trajectory method" to reduce the simulation noise. In this work, we apply the δf noise reduction scheme, for the first time, to a fully self-consistent 3D electromagnetic problem. The new linear results agree closely with the double trajectory method results, while improved nonlinear saturation results have been obtained for realistic parameters and profiles. Numerical results for the internal kink mode and the toroidal Alfvén eigenmode will be presented.

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Transport modeling for EPEIUS: a small aspect-ratio torsatron-tokamak hybrid*

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Design studies are underway for a proposed small aspect-ratio torsatron-tokamak hybrid experiment (EPEIUS),[1,2] which is based on a concept conceived at ORNL.[3,4] While partial optimization of these low-A configurations is possible,[2,4] the effects of radial electric fields will be crucial for confinement. Here, we present results of neoclassical transport modeling based on analytic expressions of Shaing,[5] and compare with the results of Monte Carlo calculations.[4,6] The analytic model is one-dimensional and takes into account the poloidal and radial drifts of the helically trapped particles by means of simplified flux-surface averages. These include E_r, both self-consistently determined by ambipolarity and externally driven. The model also includes *ad hoc* anomalous transport.

Our studies show that, despite the large helical ripple inherent in such a device, interesting plasma parameters can be achieved with modest heating power. This occurs mainly because the E_r required to achieve ambipolarity has a profound effect on the collisionality at low A, leading to relatively easy access to the ν_{eff} / E_r^2 regime. Initial comparisons with the Monte Carlo code applied to an actual proposed configuration show remarkable agreement.

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2C14

Nonlinear terms of fluctuation-averaged fluid equations as source of plasma rotation

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Several works have derived fluid equations that represent the slow, average part of the plasma dynamics, which gives the transport in the plasma. This is done by averaging the momentum balance equation over the fluctuations that are supported by the plasma, and in doing so some nonlinear terms remain that keep the effect of the fluctuations. When the fluctuations are externally imposed, this terms are usually identified with the ponderomotive force, produced by RF wave injection. For internal turbulent fluctuations those terms are the so-called Reynolds stress, which is known to produce sheared plasma rotation. Here we analize the two effects in a unified way to show that in both cases one can have sheared rotation. We consider the two different mechanisms that have been proposed for the non-resonant production of poloidal plasma rotation by a ponderomotive force: (a) a poloidal drift due to a radial PM force [1], and (b) a radial convection of momentum given by the angular (toroidal or poloidal) PM force [2]. While a physically simple model is initially considered to have a clear understanding, a more realistic model including the effect of viscosity is also developed in order to estimate the expected value for the poloidal velocity.

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Unstructured Adaptive Grid Technique to solve 2D and 3D Elliptic Boundary Problems *

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A technique to solve 2D and 3D differential boundary problems is presented. This technique includes solution of the original problem on an arbitrary unstructured grid and an adaptation of the grid points to the structure of the solution.

A family of special noncorformal finite elements were constructed to produce higher order accuracy. Three sorts of them provide an approximation of 2D(3D) second order differential operator with order $O(h)$, $O(h^2)$, $O(h^3)$ on an arbitrary grid correspondingly. They can be used separately and in a combination to solve a particular problem. A finite support (stencil) for each finite element is a priori unknown and is determined during solution of the problem.

A collocation method is used to reduce an original differential problem to a matrix problem. In this technique residual function is set equal to zero in each grid point.

Only minimal information about topology of a priori unknown solution is used to adapt grid points.

Advantages of this approach are:

- initial problem can easily be approximated on an arbitrary 2D(3D) "cloud" of grid points;
- high accuracy of numerical solution can be reached using appropriate set of finite elements with corresponding order of approximation;
- wide class of differential equations (not only elliptic) can be approximated and solved. In the presented here realization of this technique differential operators with up to forth order can be treated;
- all this features can easily be operated by user.

2D and 3D version of the code had been developed. This approach was extensively tested. Among others 2D analytic Solov'jev's equilibria including equilibria with separatrix, 2D and 3D Poisson fixed boundary elliptic problems served as tests.

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Rotation Damping and ITG Modes

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Recent advances in gyro-fluid simulation of Ion Temperature Gradient (ITG) modes in tokamaks have shown that the predominant saturation mechanism for the instability is the production of $m = n = 0$ primarily poloidal flows which vary with radius and serve to shear-stabilize the instability. Thus the damping of such poloidal flows is critically important in determining the turbulence level to be expected, and the adequacy of gyro-fluid models for calculating the damping is an issue. We solve kinetically a relevant model problem, and suggest it as a benchmark for gyro-fluid simulations. We calculate the linear collisionless damping of poloidal rotation with particular interest in the level of buildup of such rotation as fed by ITG modes. We find that, after a transient of a few ion transit times, the kernel relating the rotation to the nonlinear source asymptotes to a plateau value which would then slowly damp according to neoclassical collisional damping. This plateau value is compared with gyro-fluid predictions. A higher value would imply a stronger shear-stabilizing effect, and hence a lower level of ITG turbulence.

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Study of Confinement and Stability in KSTAR

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The first fully superconducting tokamak, KSTAR (Korea Superconducting Tokamak Advanced Research) has been designed for a year and is expected to have the physics conceptual review by June, 1997. The unique feature can be an active control of both plasma pressure and current profiles with steady-state capability. The current profile will be modified by a combination of FWCD, LHCD, and beam driven current. Unprecedented configuration of NBI has been considered to provide a flexible and localized control of the plasma pressure profile in KSTAR. Various pressure profiles generated in consequence of differently configured NBI can be used to test the proposed transport models based on $\bar{E} \times \bar{B}$ and Shafranov shift and/or Drift reversal and ITG model. Also observed study of correlation of beam fueling profile and plasma performance on TFTR and other tokamaks can be tested to obtain an optimum arrangement of NBI system in KSTAR.

The basic operating modes in KSTAR will be a combination of three distinct pressure profiles, broad, moderate, and peaked, and three kinds of current profiles, peaked, broad, and hollow. Each of the advanced tokamak configuration studied during the design of TPX can be matched by one of basic operating modes in KSTAR with some optimization. Regular high $li(1)$ (> 1.5) and high li (> 1.0) with hollow current modes have been explored through the study of stability optimization and will be presented besides conventional , sawtooth free conventional, and high bootstrap fraction modes. The high li mode may possess the best characteristics against both ballooning and low n kink modes.

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Studies of Kinetic Effects in Highly Radiating Divertor Plasmas with the Monte Carlo Impurity (MCI) Transport Model

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The mission of the Monte Carlo Impurity[1] (MCI) code is to accurately model the effects of realistic wall and divertor structures on the production and transport of impurities in highly radiating divertor and SOL plasmas. MCI uses a plasma flux driven, distributed, physical sputtering model to calculate neutral carbon launch parameters. The physical sputtering model accounts for plasma ion energies, sheath energies, and angular dependencies in the incident ion flux. Neutral carbon is randomly launched from each plasma facing surface with a range of angles and energies which are consistent with a Thompson distribution[2] function. The carbon neutrals are followed until they ionize and then transported along field lines by classical parallel diffusion, thermal gradients, and collisional drag. Perpendicular diffusion is simulated as a random process with a spatially fixed diffusion constant. The MCI model is primarily used to predict the 2D density distributions of each carbon charge state. Line and total radiation rates are calculated from the carbon density distributions and these simulations are compared with an extensive array of 2D imaging and line integrated spectroscopic diagnostics on the DIII–D tokamak. MCI results are also compared with the multi-fluid UEDGE[3] carbon impurity distributions in order to better understand the role of kinetic neutral carbon effects on the divertor plasma.

We find that in plasmas with a detached inner strike point and attached outer strike point, CIII and CIV densities predicted by MCI and UEDGE agree very well near the inner strike point but MCI predicts much lower CIV densities near the outer strike point than UEDGE. Detailed studies of individual carbon neutral trajectories with MCI also show that neutrals sputtered from the outer strike point can cross the private flux region and reach the vicinity of the X–point before becoming singly ionized. These effects are being quantified in order to determine whether they can account for the differences observed with the MCI and UEDGE code. Results from these studies will be discussed and implications relevant to our comparisons with the DIII–D carbon imaging system will be presented

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Nonlinear MHD calculations of coherent modes in weak negative shear discharges *

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Bifurcation of coherent peaks in the frequency spectrum of the density fluctuations has been observed during weak negative central shear discharges in DIII-D. Important ingredients needed to explain these coherent modes are the excitation of resistive interchange and/or infernal modes centered around the 5/2 harmonic and the presence of a large sheared toroidal flow velocity that distorts the frequency spectrum. Calculations using model q profiles to simulate the time evolution of these discharges are performed with a reduced version of the nonlinear resistive magnetohydrodynamic (MHD) stability code FAR [1, 2] which was modified to include sheared toroidal flow velocity. Linear calculations with model pressure and q profiles confirm the existence of multiple resistive pressure driven modes residing at different 5/2 surfaces. In the presence of significant dissipation, the sheared toroidal flow appears to have a stabilizing effect on these linear modes. Nonlinear calculations show the importance of radial coupling between modes at different rational surfaces. Because initial calculations were dominated by the m=0, n=1 component of the poloidal flow generated by the fluctuations through Reynolds stress, this component was zeroed out to permit investigation of the fluctuation spectra. Calculations are now being performed to determine the effects of this self-generated poloidal flow on the nonlinear stability of pressure-driven, coherent modes.

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Nonlinear Simulations of Tearing Modes with a Resistive Wall and Plasma Rotation

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Nonlinear simulations of tearing modes with a resistive wall and plasma rotation in 2D slab geometry will be presented. The resistive wall is treated in the thin wall approximation, and there is an external vacuum region bounded by a conducting wall which may have a field error embedded in it. The regimes of interest include: (1) unstable tearing mode which may exhibit locking to the resistive wall; (2) resistive wall tearing mode slowed but not stabilized by rotation of order the nominal tearing growth rate. In (1), the tearing mode can begin a locking process, during which the plasma flow and the mode both slow, allowing flux diffusion through the wall, and a much greater nonlinear amplitude for the mode. There is a bifurcation between multiple states, called fast and slow modes, or unlocked states and locked states, respectively. This bifurcation exhibits hysteresis. With field errors, the field (but not the plasma rotation) in the slow mode can become completely locked. An important control parameter for the bifurcation is ν, which is the anomalous decay rate of total momentum. With ν large and a source to balance the decay, the range of parameters over which there are multiple states or oscillating states is much smaller, i.e. the hysteresis is much more shallow.

Ripple Induced Stochasticity Arround the Divertor Scrape-Off Layer

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One of the outstanding problems in present day tokamak devices is the one of understanding the transport of helium ashes and impurities across the separatrix of poloidal divertors. A phenomenon that influences the particle confinement, is the stochastisation of the scrape-off layer due to the finite nature of the toroidal field coils. Although this problem has been previously studied for cylindrical geometry [1], and similar studies have been carried out recently in similar contexts by Punjabi et al. [2], [3], Pomphrey and Reiman [4], and Reiman [5], it is necessary to determine the precise role of the finite nature of the coils, as well as the toroidicity effects. For this purpose, a simple 3-D model is proposed in this work, in which the magnetic field due to any arbitary number of toroidal field coils, of circular shape, is numerically computed whithin the toroidal volume, and the magnetic field lines are followed by integration. Since we are interested on the scrape-off layer, where the plasma current is negligible, the poloidal component of the magnetic field is simulated by using an equivalent current concentrated on a single turn coil arround the axis major circle, while the separatrix may be produced by the addition of an excentric coil. In order to better understand the physics, the case in which two coils are placed symmetrically arround the equator, as previously proposed by Boozer and Rechester [6], is studied. In both cases, the Poincaré map is obtained. The code is tested for the axisymmetric case, where no stochasticity is expected. Opposed to the results obtained by Yamagishi [7], cuvature alone cannot yield a stochastic behavior. The ripple effect is studied for a number of examples, where the ratio of the plasma and divertor currents, and the number of toroidal field coils are varied. The width of the stochastic layer is measured for the case of the symmetric coils, by means of the flux function defined by the currents. It is shown that ripples lead to significant stochastisation of the layer near the separatrix. The width of the stochastic layer is rather large for the case of 12 coils, and decreases with increasing number of coils.

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Neoclassical transport in advanced tokamaks configurations *

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A gyrokinetic neoclassical simulation code (GNC) [1] based on delta-f scheme has been developed to realistically assess the neoclassical transport properties in magnetically confined plasmas. It has been successfully applied [2] to resolve the apparent physics contradiction that the measured ion thermal transport level in the enhanced reversed shear regime fall below the "irreducible minimum level" predicted by standard neoclassical theory. Recently, the very important feature of treating general MHD equilibrium has also been implemented in the GNC code. These new computational capabilities enable us to assess neoclassical transport properties in both advanced axisymmetric devices and stellarators. Transport properties relevant to advanced tokamaks such as DIIID and the proposed NSTX are being investigated. These geometric effects include strong shaping, magnetic well, poloidal asymmetry and background profile variations. The implications of this very promising new computational resource for studying advanced magnetic confinement configurations in general geometry will be discussed.

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Routes to anomalous transport in the standard map

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Long flights are observed for different ranges of the stochasticity parameter of the standard map. The study of the phase space structure corresponding to these flights reveals the existence of different mechanisms responsible for anomalous transport. A qualitative and quantitative study of these mechanissms is presented with an emphasis on the link between the topological properties of the phase space and transport.

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Equilibrium Quantities on an Arbitrary Flux Surface — a Generalized $s-\alpha$ Model

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The goal of this work is a parameterization of equilibrium quantities suitable for localized stability studies such as those carried out using the ballooning mode representation of the gyrokinetic equations. Equilibrium information used for studying the stability of localized modes in a tokamak typically comes from one of two sources. One is the shifted circle $s-\alpha$ model which allows easy manipulation of the shear and pressure gradient but is unable to deal with essential equilibrium features such as elongation and triangularity. The other source is numerically generated equilibria which incorporate all of the correct geometry but require recomputation of an equilibrium when parameters are changed. One exception is the generalized $s-\alpha$ model of Greene and Chance[1] which allows modification of the shear or pressure gradient without recomputing the equilibrium. Here we generalize a localized equilibrium model introduced by Bishop *et al.*[2] and characterize exact local equilibria by s, α, elongation κ, triangularity δ, and safety factor q. The variation of κ, δ, and the Shafranov shift with flux surface also help characterize the local equilibrium. An initial equilibrium in the neighborhood of a flux surface may be constructed directly from the above model or may be obtained from a numerical equilibrium which is then represented locally in terms of the above parameters. In either case, using the model, the above parameters can then be individually varied and when input to stability codes can be used to study the effects of each upon stability. Equilibrium and stability examples will be presented.

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The Quasi-Optical Grill (QOG) : Lower Hybrid Current Drive in Tokamaks in the 3-8 GHz Range - IGNITOR and TdeV

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There is an urgent need to develop highly simplified rf launchers in the 3 - 8 GHz range for large tokamaks with toroidal fields ≥ 4 T. The Quasi-Optical launcher for LH waves offers one possible solution to this problem. In our model of the QOG [1,2], the grill is mounted in a hyperguide with the rods situated in one oversized waveguide and irradiated obliquely by a wave emerging in the form of a higher mode from an auxiliary oversized waveguide. For the first time, the proper boundary conditions on the confining walls are taken into account. Unlike previous QOG designs, there are no mirrors and the reflected power can be readily handled by standard waveguide techniques. The QOG structure is compact and highly efficient even if only one row of rods is used. Wave diffraction is readily handled by the full wave representation.

To show the flexibility of QOG LHCD launchers we illustrate their design for 2 very different tokamaks: the advanced high parameter *IGNITOR* and the medium size *Tokamak de Varennes*.

The 13 T field in IGNITOR requires LHCD launchers at 8 GHz - a frequency that is very difficult to reach using standard waveguide grills. However the 8 GHz frequency is well suited for QOG as is the very strong poloidally elongated IGNITOR port. Using our bounded QOG theory for resonant cross sectional rods, we optimize several grill geometries within the hyperguide. The rods in front of the plasma and at the mouth of the QOG are the diffraction elements. These rods are irradiated obliquely by very efficiently generated wavers excited in the form of LSE_{1n} modes from an auxiliary hyperguide hyperguide using (n + 1) tapered waveguides. For IGNITOR one can consider n = 2 and obtain a spatial power spectrum with main peak at $N_{\parallel} = -2$ and weighted directivity $\delta_w = 50\%$. For broader QOG structures, typically 10-30% of the incident power will inevitably be in the higher LSE_{m2} modes (with m = 3, 5, 7) and the coupling of these modes to the plasma will also be considered.

QOG designs for TdeV will also be considered - where now the operating frequency is 3.7 GHz.

In these calculations, the rods follow the poloidal curvature of the plasma surface near the grill mouth. The effect of subcritical plasma density in front of the grill mouth on the grill-plasma distance is also considered.

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Simple Estimate of Bootstrap Suppression of Field-Error-Induced Islands in a Quasi-Toroidal Stellarator

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This paper extends the calculation of Hegna and Callen, Phys. Plas. **1** 3135 (1994), to the case where the bootstrap current "heals" field-error-induced islands in a quasi-toroidal stellarator with positive shear (bootstrap current adds to $\iota \equiv 1/q$, $\iota' > 0$). This work does not treat the more subtle resonant Pfirsch-Schlüter current effects included in a related calculation by Reiman, presented at the most recent APS meeting. However the result is easily expressed in terms that can be estimated quickly for various configurations. A key parameter in the calculation is

$$W_{bs} \equiv \frac{2\mu_0 R j_{bs}}{mB\iota'} \sim \frac{4\iota_{bs}}{m\iota'}$$

where ι_{bs} is the rotational transform due to the bootstrap current, whose current density is j_{bs}, and ι' is $d\iota / dr$.

The result of the calculation is that the saturated full island width is given by:

$$W_{sat} = \left(W_{ext}^2 + W_{bs}^2\right)^{1/2} \pm W_{bs}$$

Where W_{ext} is the full island width due to "external" field errors. In the unfavorable case of negative bootstrap current or ι' (the plus sign) and for $W_{ext} = 0$, $W_{sat} = 2\,W_{bs}$ reproducing the Hegna and Callen result. For the favorable case, with large at W_{bs},

$$W_{sat} \sim W_{ext}\left(\frac{W_{ext}}{2W_{bs}}\right)$$

Since W_{bs} can be of order a, this is a potentially very favorable result. β–limiting "field errors" can arise from equilibrium shifts, and in principle this effect should allow a substantial increase in such field errors and consequently in the equilibrium β limit. The PIES code is currently being upgraded to evaluate this effect numerically.

Island healing should be limited at small island size by lack of pressure flattening, which means - of course - that the island does not require "healing." The effect is also limited at large toroidal mode number, n, by banana toroidal precession, which wipes out toroidal variation in the bootstrap current density. The critical n for this can be estimated at

$$n_{crit} \sim \left[\frac{R}{r}\left(\frac{\nu_{90} R}{v_t}\right)\right]\left(\frac{R}{\rho_\theta}\right)$$

Interaction of converted ion-hybrid waves with neonatal alphas: a modular approach

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Linear conversion of an incoming magnetosonic wave (*a.k.a.* fast or compressional wave) to an ion-hybrid wave can be considered as a *3-step* process in ray phase space. This is demonstrated by casting the cold-fluid model into the Friedland-Kaufman normal form for linear mode conversion. First, the incoming magnetosonic ray (MSR) converts a fraction of its action to an *intermediate* ion-hybrid ray (IHR), with the transmitted ray proceeding through the conversion layer. The IHR propagates in k-space to a *second* conversion point, where it converts in turn a fraction of its action into a *reflected* MSR, with the remainder of its action constituting the *converted* IHR. The existence of the intermediate IHR has important physical consequences as it can resonate with α particles. As a result, the time-integrated damping coefficient may be *large*, thus annihilating the ray between conversions and transferring its energy to the α's. Meanwhile, the transmitted MSR can reflect at the inner edge of the tokamak and cross the conversion layer again, leading to a *different* IHR. We shall describe this basic physical picture, and present a numerical algorithm for identifying and implementing linear conversion in multi-dimensional ray tracing.

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Stability of Pegasus – Ideal MHD and Neoclassical MHD *

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The Pegasus Toroidal Experiment is an Extreme Low-Aspect Ratio Tokamak (ELART, A < 1.3) currently being built to access extreme operational regimes because the ideal MHD β limit is anticipated to increase rapidly as A falls below 1.3. Equilibria that is stable to ideal MHD instabilities, ballooning and low-n instabilites, will be shown. Results will also be shown for a preliminary study of the effect of neoclassical tearing mode [1] behavior in ELART's. Because of the low shear in the center of ELART's, the behavior of the tearing modes depends very sensitively on the profiles. Specifically, the modes are in general more unstable than in high aspect ratio tokamaks, but they also have a greater opportunity to be stabilized by the 'Glasser term'. [2, 3]

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Modular Coil Representation for Optimized Stellarator Devices*

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The procedure that optimizes the confinement properties of stellarator devices usually produces a representation of an outer flux surface as the result of the optimization. The current source that produces the vacuum flux surface of the optimized device is determined after the equilibrium and transport calculations have been completed. This procedure is desirable because the current source (coil configuration) does not have a unique solution for a given flux surface. This division of the optimization into separate problems allows filtering of coil configurations for engineering constraints. We have devised a procedure that allows for a search of a coil configuration that matches the magnetic field components on the outer flux surface. The search is embedded as a minimization problem where a general coil description parameterized by a Fourier description serves as the unknown and the accuracy or target of the minimization is the match of the vector field components on the outer flux surface. Our description allows for multiple coils with different currents per field period, conservation of stellarator symmetry, vertical field coils or fixed coils, trim coils, lead inclusion in the coil model, and restriction of the coil to a winding surface if desired. Engineering constraints such as toroidal variation, total length, maximum radius of curvature, etc., can be imposed as penalty terms for each coils.

We present the results of several calculations with this approach and a comparison with the well known code NESCOIL.[1]

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Synthetic Experimental Diagnostics: A Simulation Example*

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The CORSICA equilibrium, transport, and stability modeling code is being extended to include simulation models of experimental diagnostics. Diagnostic systems are often significant experiments within an experiment. Understanding the performance of fusion experiments is based on conclusions and inferences derived from the diagnostic measurements. Therefore, in order to better understand the physics of the diagnostics, to increase confidence in the inferences based on the diagnostics, to make direct comparisons with experiments easier, and, hence, to model experiments more comprehensively, we are adding simulation models for a suite of selected diagnostics to CORSICA. The first example diagnostic is reflectometry, which is used to infer density and magnetic field spatial profiles. Simulation models of O and X-mode reflectometry[1] are being added to CORSICA as packages. The reflectometry simulation models consist of full-wave solutions for the electromagnetic wave propagation in a cold plasma and geometric optics reconstruction packages to infer the density and magnetic field profiles. Examples of reflectometry simulations for DIIID and the Livermore spheromak experiment (under development) executed from within CORSICA transport simulations are presented.

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2C31

MHD Stability with Kinetic Effects*

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Magnetic equilibria with favorable confinement properties have been identified. Unfortunately, conventional MHD stability calculations indicate that these configurations are ideally unstable. In some cases, the ideal Mercier criterion is strongly violated. However, estimates of the size of kinetic corrections indicate that significant stabilization is likely in some promising cases. We are therefore developing a code to calculate the MHD stability properties of axisymmetric toroidal equilibria, including kinetic corrections (such as the Kruskal-Oberman terms). This code is tightly coupled to existing MHD equilibrium solvers (VMEC, VMOMS and EFIT) and to our gyrokinetic and gyrofluid microinstability and turbulence codes. Preliminary results will be presented.

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Beta Limits in Toroidal-Resistive-Rotating Plasmas Surrounded by a Resistive Shell

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According to standard ideal MHD theory, the external kink modes limit the maximum achievable beta in tokamaks. If the effects of finite wall and plasma resistivity are retained, three additional modes become unstable for lower values of beta: the resistive wall mode (RWM) that grows on the wall magnetic-diffusion-time scale τ_w, the ideal wall tearing mode (IWTM) destabilized by the plasma resistivity ($\gamma_{IWTM} \sim \gamma_\eta \equiv S^{-3/5}\tau_A^{-1}$), and the resistive wall tearing mode (RWTM) destabilized by the combination of plasma and wall resistivity. The stability of these modes depends on the plasma beta, the plasma rotation, the wall/plasma resistivity and the trapped particle compressibility. In the circular-cylindrical limit, the RWM has the eigenstructure of an ideal external kink mode without singular surfaces inside the plasma column. In a torus, the finite pressure and toroidicity of the plasma column induce the coupling of the poloidal harmonics and the mode sidebands have singular surfaces inside the plasma. According to the magnitude of the plasma resistivity at such surfaces, the RWM either behaves as an ideal mode (for small $\gamma_\eta\tau_w << 1$ no magnetic field reconnection takes place) or it reconnects the magnetic field lines and behaves as a RWTM (for $\gamma_\eta\tau_w > 1$). In the first case, it is shown that a large plasma rotation (a fraction of the Alfven frequency) is needed to stabilize the RWM and a stability window in β opens up just below the ideal MHD beta limits. In such a large-rotation window, both the RWM and RWTM are stable[1–4] but the IWTM is still unstable. In the second case, a judiciously chosen slow rotation[3] can do the job. The stabilization at slow rotation only occurs when the rotation frequency is low enough to allow the reconnection of the magnetic field at the rational surfaces. As the rotation frequency exceeds a few tearing mode growth rates, the reconnection is prevented and the RWM becomes unstable again. If the rotation frequency is further increased up to a fraction of the Alfven frequency, the RWM falls into the large-rotation window and becomes stable. The finite thermal trapped particle compressibility causes a shift of the stability thresholds.

A diagram in the β, b/a (wall radius/plasma radius) plane showing the different stability regions induced by slow and fast rotation is constructed and discussed.

The stability analysis is based on a sharp boundary model for the plasma pressure and current. The model includes: toroidicity, toroidal rotation, high-β, plasma and wall resistivities, and thermal trapped ions.

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Single Particle Motion in Axisymmetric Symmetric Systems with Large Safety Factor*

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Near the edge of a divertor tokamak and in many low aspect ratio tokamaks the safety factor is relatively large. In order to study low collisionality transport in such cases it is necessary to modify the usual theory of single particle motion in axisymmetric fields, *c.f.* H. Weitzner, *Phys. Plasmas* **2**, 3595 (1995). We present the necessary modifications which permit the symmetry preserving sequence of canonical transformations of the single particle Hamiltonian. These results allow a study of transport in tokamaks with moderate ion flow and not too large electrostatic potentials. Preliminary transport results will be given.

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Stability of small-wavelength tearing modes in a high-beta toroidal plasma *

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The maximum beta that can be sustained for periods of time comparable to the resistive diffusion time, the so-called long-pulse beta-limit, is determined by the stability threshold for the tearing mode. A key parameter in all the theories aiming to determine this threshold is the Δ' index. This index describes the free energy available for the mode in the bulk of the plasma. Here, we present a method for evaluating Δ' for modes with large wavenumbers in an arbitrary equilibrium configuration. Our results extend the well-known low-beta cylindrical result,[1] $\Delta' \sim -2k_\perp$, to toroidal discharges with shaped cross-sections, finite beta, and arbitrary aspect-ratio.

The stability of resistive modes in a torus is governed by matrices that may be interpreted as scattering matrices for Alfvén waves. The diagonal elements of these matrices constitute the proper generalization of the Δ' index to toroidal geometry.[2] We describe a method for evaluating the elements of these matrices in the limit of short wavelength. This limit depends only on local information of the type used to evaluate the stability of ballooning and interchange modes. It also has the advantage of being considerably simpler to evaluate than the long wavelength limit. Note, however, that Δ' describes modes that reconnect the magnetic field lines on a *single* magnetic surface. The small-wavelength Δ' is thus related in a non-trivial way to the analogous stability index for resistive ballooning modes.

We present the results of a code that implements our method numerically. Our code complements PEST-III,[2,3] which calculates the stability matrices for long wavelength modes. The short wavelength matrices have the advantage of requiring only the knowledge of quantities determined locally near the magnetic surface of interest. This makes it possible to consider the effect of modifying the local gradients, such as the pressure or current gradient, without recalculating the entire equilibrium.

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Particle Simulation for Super Ion-Acoustic Double Layer

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A magnetohydrodynamic (MHD) plasma is a highly nonlinear medium where self-organization can evolve easily. In the MHD self-organization, free energy is provided by a parallel plasma current whereby a current-driven kink instability (global instability) is excited and a global topological change of the magnetic field configuration is caused. In this process, nonlinear energy dissipation arises in a fast time scale, thus, a superfluous entropy (thermal energy) is generated. Suppose that the generated entropy is swiftly removed from the system, then a new stable ordered structure will be established.

In the present work, we attempt to investigate a self-organization process for a kinetic plasma. As a candidate for such a process, an ion-acoustic double layer(IADL) is considered.

An IADL is studied through a one-dimensional electrostatic particle simulation for an open boundary condition. This "open system" model consists of the internal plasma which is continuously and smoothly connected to the surrounding plasma without any rigid electrodes. We have developed a constant current open boundary model in which the surrounding plasma plays a role of both the energy and particle reservoirs, namely, a fresh and constant net flux of electrons is continuously supplied from the upstream boundary and disordered ("dirty") internal particles are discharged from the downstream boundary.

A "super" IADL is discovered through this new particle simulation of the open boundary model. The IADL reaches an unexpectedly large magnitude, which is far above the electron thermal energy, and a superthermal electron beam is generated on its downstream side. It does not persist steadily but eventually subsides with leaving a highly disturbed structure afterwards. Interestingly and importantly, the entropy production rate is found to be maximized in accordance with creation of normal and super double layers.

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Control of Large Events in a SOC System*

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

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Centrifugally Confined Plasmas for Fusion

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Centrifugal forces from rotating magnetized plasmas can be employed to affect confinement parallel to the magnetic field [1]. This additional "knob" allows for axisymmetric configurations for fusion plasmas wherein the magnetic field is completely from external coils, hence steady state and disruption free. An added advantage of such schemes is that the associated velocity shear may suppress instabilities. Two possible configurations are an azimuthally rotating simple mirror and a toroidally rotating multipole. Theoretical studies pertaining to the successful operation of such schemes for fusion are discussed:
(1) MHD equilibrium is demonstrated showing parallel localization of plasma for rotation above Mach 1. (2) MHD numerical simulations are presented suggesting that the most deleterious MHD instability, the flute interchange, may be suppressed by the velocity shear. This stabilization may not be complete, necessitating the addition of a toroidal field. Exactly how much magnetic shear is needed impacts the eventual attractiveness of this scheme. (3) Particle orbits are examined and crossfield "neoclassical" transport is assessed. Toroidal field is unfavorable. (4) Transport parallel to the magnetic field is estimated. The ions are completely confined by the centrifugal potential while the electrons are held in by the self-consistent electrostatic potential drop along the field. This potential drop scales as the square of the Mach number. Operation above Mach 3 is shown to be sufficient to minimize the electron heat loss to below the Lawson Criterion. The requirement of Mach 3 puts a beta limit on the system. (5) The feasibility of attaining such large rotations, with the implied large circulating power in a reactor, are assessed. (6) The drift stability of the device, in view of a fully trapped particle population, is discussed. Fast approving trapped ion modes may be a concern [2].

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2C38

BURGERS TURBULENCE, INTERMITTENCY AND NON-UNIVERSALITY

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A new approach to the problem of strong turbulence is discussed. Recently developed methods of quantum field theory [1] are shown to predict the highly intermittent statistics of velocity fluctuations. Very good agreement between the theory and numerical simulations is demonstrated.

More specifically, the 1D model of turbulence without pressure is considered. The basic equation is the Burgers equation with random Gaussian external force:

$$u_t + uu_x = \nu u_{xx} + f(x,t) \ . \tag{1}$$

This is believed to be the first exactly solvable model, which allows one to test many general ideas applied to fluid and plasma turbulence. The appropriate quantum field theory methods for treating such a problem were developed rather recently by A. Polyakov [1]. They are based on the self-consistent conjectures on the operator product expansion, Galilean and scaling invariance.

In its usual formulation the problem is specified by choosing the force to have zero mean and white in time variance:

$$\langle f(x,t)f(x',t')\rangle = \kappa(x-x')\delta(t-t') \ . \tag{2}$$

This model can be used to describe the stationary turbulence with nonlinear energy transfer over scales from the pumping region (external force) to the dissipative one (shocks). It is assumed that the regions of source and sink are very well separated, i.e. the formal limits of large dimension of the system and small viscosity are considered. This is in accord with the general picture of developed turbulence, first proposed by Kolmogorov in 1941 [2].

We choose the force to be large-scale-correlated, so that the κ function in (2) can be expanded as $\kappa(y) = 1 - y^\alpha$. One can show that in this case the probability density function for velocity differences has rather peculiar structure. It decays exponentially for large positive Δu and has an algebraic tail for $\Delta u \to -\infty$. This accounts for such general phenomenon as intermittency on a rigorous basis: the structure functions $S_n \equiv \langle |u(y,t) - u(0,t)|^n \rangle \sim y^{\beta_n}$ are non-universal, beginning with some n.

These PDFs can be found explicitly for some values of α [3], which agree strikingly well with recent numerical findings [4]. The developed methods can be applied with some modifications to the turbulence with pressure, passive scalar advection, problems of self-organized criticality, etc.

The phenomenon of non-universality with respect to the dissipative regularization discovered in the model [3] is also discussed.

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2C39

Orbit Squeezing and Confinement Improvement in Tokamaks*

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It is well-known that standard tokamak banana orbits can be squeezed by Φ''. [H. L. Berk, and A. A. Galeev, Phys. Fluids **10**, 441(1967)] Here, Φ is the equilibrium electrostatic potential, prime denotes $d/d\psi$, and ψ is the poloidal flux function. The corresponding ion transport flux is reduced from its standard neoclassical value by a factor of $S^{-3/2}$, where S is the orbit squeezing factor: $S = 1 + I^2 e\Phi''/(M\Omega)$, $I = RB_t$, R is the major radius, B_t is the toroidal magnetic field strength, M is the ion mass, e is ion charge, and Ω is ion gyrofrequency. [K. C. Shaing, and R. D. Hazeltine, Phys. Fluids B **4**, 2547(1992)] This demonstrates that transport fluxes in standard neoclassical theory are not irreducible minima. Here, we generalize the theory to potato orbits close to the magnetic axis. [T. H. Stix, Plasma Phys. **14**, 367(1972); T. E. Stringer, Plasma Phys. **16**, 651(1974)] We find that ion potato transport flux is reduced by a factor of $S^{-5/3}$ from its non-squeezed value in flux coordinates. This reflects an increase of the fraction of the trapped particles by a factor of $S^{1/3}$, and the reduction of the orbit size in ψ by a factor of $S^{-2/3}$. Thus, orbit squeezing effect is stronger in the region close to the magnetic axis than in the core region. The reduction of ion transport flux due to squeezed bananas and squeezed potatoes may be responsible for the better than standard neoclassical ion confinement observed in advanced tokamak operations.

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MHD waves and Plasma Transport at the Dayside Magnetopause*

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The Earth's magnetic field creates a huge cavity in the solar wind known as the magnetosphere. The transition region between the solar wind plasma and magnetosphere plasma is of substantial interest because many magnetospheric processes are governed by the transport of particles, momentum and energy across that magnetopause boundary. Abrupt transitions in plasma properties, such as decreases in plasma bulk flow, density, pressure, and increases in temperature and magnetic field, occur over a distance of 10 ion gyroradii.

Large amplitude compressional type waves, with frequencies below the ion cyclotron frequency, are nearly always found in the magnetosheath as well as at the magnetopause where the Alfvén velocity increases by an order of magnitude. Moreover, the polarization of waves observed by satellites during magnetopause crossings changes from primarily compressional in the magnetosheath to dominantly transverse in the magnetopause. As compressional waves propagate to the magnetopause, gradients efficiently couple them with shear/kinetic Alfvén waves near the Alfvén field-line resonance location ($\omega = k_{\|}v_A$) [1]. We present a solution of the kinetic-MHD wave equations for this mode conversion process using a realistic steady-state profile including full ion Larmor radius and magnetic drift effects as well as wave-particle resonance interactions for electrons and ions to model the dissipation. For northward interplanetary magnetic field (IMF) a kinetic Alfvén wave propagates backward to the magnetosheath. For southward IMF the wave remains in the magnetopause but can propagate through the $k_{\|} = 0$ location because the particle magnetic drift significantly alters the wave-particle resonance condition and spatially shifts the region of strong electron Landau damping.

Our theory predicts substantial transport for MHD waves due to particle magnetic drift ($D_{\perp} \sim 10^9 \mathrm{m}^2/\mathrm{s}$). The resulting transport is substantially larger than that originally proposed for kinetic Alfvén waves by *Hasegawa and Mima* [2], who did not consider magnetic drift effects. However, for southward IMF additional transport can occur because magnetic islands form at the $k_{\|} = 0$ location. Due to the broadband nature of the observed waves these islands can overlap leading to stochastic transport. To systematically study plasma transport due to MHD waves at the magnetopause, we investigate the general problem of particle motion in a strongly sheared magnetic field. When the wave amplitude exceeds a threshold, particle orbits become stochastic—both $\mathcal{E}$ and μ are not conserved—leading to substantial transport and heating.

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Alpha Particle Redistributions due to Sawtooth Oscillations*

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The behavior of alpha particles from D-T reactions is a fundamental consideration for the performance of a future D-T reactor. However, in the recent TFTR D-T experiments, both the Pellat Charge Exchange (PCX) [1, 2] and the alpha Charge Exchange Recombination Spectroscopy (α-CHERS) [3, 4] diagnostics indicate that sawtooth oscillations can cause significant broadening of the fusion alpha radial density profile. Investigation of this sawtooth mixing phenomenon was performed by applying a Hamiltonian guiding center approach. A model of time evolution of the Kadomtsev-type sawtooth is constructed. The presence of more than one mode in the nonlinear stage of the sawtooth crash is necessary to cause significant broadening of the alpha density profile. Use of numerical equilibria allows us to perform detailed comparison with TFTR experimental data. The simulation results are in reasonable agreement with α-CHERS and show a broadening of alpha particles similar to that seen in PCX measurements.

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Spectrum of Contained Interacting Modes and their Excitation by High Energy Fusion Products*

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In experiments with fusing plasmas, enhanced emission at the harmonics of the ion cyclotron frequency of the fusion products has been observed.[1,2,3] In fact this radiation is strongly correlated with the neutron flux. A model for this emission has been developed[4,5] based upon the interaction of fusion products with collective modes of the plasma. It is known that in a plasma with inhomogeneous magnetic field, density, and temperature, it is possible to find radially localized solutions,[4] that we call "contained modes," for the perturbed field. The instability related to the interaction between contained modes having frequencies comparable to the ion cyclotron frequency and the fusion products population in a toroidal configuration is studied.

Emphasis is placed on the dependence of the growth rate on finite Larmor radius effects of the fusion products,[6,7] and the characteristics of the particle distribution function.[8] In particular, a sufficient degree of anisotropy in the energetic particle distribution is required in order to have a positive growth rate for realistic parameters. The velocity space anisotropy of the fusion products is a function of the region in which the mode-particle resonance occurs, and thus the spectrum of modes which are driven unstable is strongly dependent on the radial localization of the contained modes.

Only a small region of phase space is involved in the resonant interactions associated with the considered modes. We consider the case where the growth rate is larger than the bounce frequency (local approximation), that is appropriate for plasma parameters corresponding to the experiments and which allows for the straightforward identification of the regions of phase space that are involved in the instability.

The possibility to excite these modes in experiments by an external source is discussed. Pointing out that these modes can be exploited for the transfer of energy from the high energy fusion products to the thermal fusing nuclei, we consider the severity of the limitations on the use of this mechanism.

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Particle Simulation Study of Collisionless Driven Reconnection

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Magnetic reconnection in a collisionless plasma subjected to an external driving flow, "collisionless driven reconnection", is investigated by means of particle simulation [1, 2]. The system is initially in a MHD equilibrium and it evolves dynamically with time due to an external driving flow. Collisionless reconnection is triggered by particle kinetic effects when the system evolves into a kintic region. One of main findings is that magnetic reconnection develops in two steps in accordance with the formation of two current layers, i.e., slow reconnection which takes place in the early stage of the compression when the current layer is compressed as thin as a characteristic spatial scale of ion kinetic effect (ion current layer), and subsequent fast reconnection which takes place in the late stage when the electron current is concentrated into the narrow region with a characteristic spatial scale of electron kinetic effect (electron current layer).

There are two types of particle kinetic effects which lead to collisionless driven reconnection in a sheared magnetic field, particle inertia effect (an effect of collisionless skin depth) and particle orbit effect (an effect of meandering particle motion). The detailed examination of simulation results in the fast reconnection phase reveals that the dominant triggering mechanism changes from an electron meandering motion effect in a weak magnetic field to an electron skin depth effect in a strong magnetic field as a longitudinal field increases.

Energy conversion process between the field and particles through collisionless driven reconnection is also investigated by examining the role of electromagnetic and electrostatic components of an electric field. It is found that an electrostatic field, which is excited as a result of magnetic compression by a divergent reconnection flow in the downstream side, acts as an energy conversion channel from the electrons to the ions in a collisionless plasma. Thus, the total ion energy becomes twice as large as the total electron energy.

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Solution and Application of the Multiple Species Parallel Force Balance Equations for Tokamak Plasmas*

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The multiple species steady state parallel force balance equations coupled with the radial force balance equations for tokamak plasmas are presented and solved using the reduced charge state method in the NCLASS code [1]. The three odd velocity moments for each charge state of each species include neoclassical friction and viscosity contributions as well as allowance for additional source and damping terms from neutral beam injection, charge exchange with neutral atoms and a phenomenological model to simulate the effects of turbulent damping of toroidal rotation. The effects of strong gradients in the radial electric field is included through orbit squeezing in the neoclassical viscosity. Applications to bootstrap current studies in high β_p plasmas, ion energy confinement and minority species transport in reversed shear plasmas and radial electric field and rotation studies in the barrier region of reversed shear plasmas are presented. Progess in the development of a graphical user interface for selection of input options, linkage to experimental profile data and viewing results is summarized.

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Eigenmode Solution of Ballooning Equation with Sheared Rotation[1]

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High-n MHD equations for plasma with sheared rotation in the ballooning space are reduced to a time dependent set of coupled second order differential equations[1, 2]. Earlier, for circular tokamak cross-section, they have been solved as an initial value problem[3], showing bursting behavior of the solution in time. Another, more fundamental approach, involves determination of the eigen functions of these equations. Because in the presence of rotation, the time cannot be eliminated from equations by assuming exponential behavior, these eigen functions remain time dependent, but periodic in time[2]. This implies that the same sweeping technique that has been used in the Sweeping Equilibrium and Stability Code (SESC) for solving Grad-Shafranov equation can be applied also for ballooning modes with sheared rotations.

For this purpose, the solver ballooning equation in SESC has been modified for solving equation for arbitrary number of periodic harmonics associated with the shear flow. Typical results for circular and noncircular tokamak cross-sections will be presented.

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2C46

NEAR THRESHOLD TRANSPORT IN THE STANDARD MAP

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Anomalous transport is investigated for the Standard Map. The transport is found to be related to the stickiness of particular island structures in phase space. The anomalous exponent of the transport is related to the characteristic temporal and spatial scaling parameters of the islands causing orbit sticking.

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Wake Fields in Plasma Channels with Arbitrary Transverse Density Profiles*

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We examine wake fields produced by an intense, short laser pulse propagating in a plasma channel which has an *arbitrary (continuous) density profile.* Previous theoretical studies of plasma wakes in channels have considered either step-function density profiles, for which there is an exact expression for the wake, or, alternatively, parabolic profiles for which the wake is only computed approximately. Modeling the plasma as a cold fluid and averaging over the (fast) driving laser, we solve the linearized equations for the wake taking into full *account* the channel *profile.* A arbitrary channel profile has a spatially dependent plasma frequency; thus in a temporal Fourier decomposition, there exists the possibility of a resonance between a mode (or quasi-mode) frequency and the plasma frequency. This resonance is manifest in the presence of (typically regular) singular points in the differential equation for the wake field amplitude. To obtain an accurate solution for wake, such *singular points* must be handled with care. The Fourier analysis is complemented by numerical solutions, in the time domain, of cold fluid equations. We present detailed analysis of the transverse structure of the wake for a wide range of experimentally accessible channel profiles and we discuss the long time behaviour of the excited modes.

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Magnetic shear reduction and ballooning instabilities during the sawtooth crash

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Experimental studies of a tokamak sawtooth crash [1-3], indicate the generation of a steep pressure gradient across the current sheet [4] of the m=1 magnetic island. We suggest that secondary pressure-gradient-driven ballooning modes may play an important role in the final stage of the sawtooth crash. In the vicinity of the X-point of the island (or Y-points after the large shift of the central core), the local magnetic shear can be reduced and thereby trigger ballooning instabilities below the usual threshold. This process can be understood by an ideal MHD analysis where the relevant ballooning δW is given by [5, 6]

$$\delta W = \int d\rho \left[|\nabla S|^2 |\nabla_{||}\varphi|^2 + \frac{4\pi}{|\nabla\psi|}\frac{dp}{d\psi}\left(\kappa_n - \kappa_g \frac{\nabla S \cdot \nabla\psi}{B}\right)|\varphi|^2 \right]$$

where $|\nabla S|^2 |\nabla_{||}\varphi|^2$ represents the field line bending stabilization term, κ_n and κ_g are the normal and the geodesic curvature, respectively. The reduction of the stabilizing line bending term allows the positive pressure driven contribution to dominate at lower pressure gradient regime in the energy integral δW. This effect arises from the topological change in the magnetic configuration and differs from the effect due to the coupling of the kink free energy to the pressure driven mode [7]. In this work, the local magnetic shear in the presence of a large magnetic axis shift is estimated as well as the δW. In addition, the three dimensional asymmetric structure of the current sheet (Y-ribbon) and the pressure profile have been investigated from numerical results from the FAR code.

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Alfvén Eigenmode Stability and Alpha Particle Transport in JET Tritium Discharges

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A hybrid magnetohydrodynamic-gyrokinetic model based on a Lagrangian formalism for the particle motion was developed for the stability analysis of global Alfvén eigenmodes (AE) in the presence of energetic ions. A weak turbulence description was applied to the nonlinear evolution of the unstable AE and the fast particle redistribution / loss. The power transfer between the waves and the energetic particles is computed in the linear phase by the CASTOR-K code. The non-linear evolution is modelled using the FAC and HAGIS codes. These codes enable the detailed modelling of typical JET plasmas.

The AE excitation experiments at JET - by the Saddle Coils and by RF beat waves - have confirmed the existence of weakly damped AE's. The linear theory, which comprises the usual Alfvén waves as well as the Kinetic Alfvén wave branch, has with success explained the observed spectra together with damping and destabilisation. It has been established that core localised modes exist in the plasma core with very small damping in addition to the global toroidicity-induced AE which extend across the entire plasma.

Alpha particle driven AE's in high performance discharges are analysed in preparation of the JET tritium campaign . It is found that in hot ion H-mode discharges Kinetic Toridicity induced Alfvén Eigenmodes (KTAE) are the most unstable modes in JET tritium (DTE1) plasmas with toroidal wave numbers between n=4 to n=10. Furthermore, the finite orbit width effects of very energetic ions reduce the instability drive by the alpha particles. Due to the level of the alpha particle pressure expected in JET and the various damping mechanisms the AE are predicted to be marginally stable in the JET tritium experiments. In the non-linear evolution the wave saturation amplitude is found to be proportional to the square of the linear growth rate, i.e. $\delta B / B \propto (\gamma / \omega)^2$, with typical values of $\delta B / B \leq 10^{-4}$ being below the alpha-orbit stochasticity threshold in JET DT plasmas. Therefore, no significant alpha particle losses should occur. However, scenarios under which α -driven unstable AE should be observed are outlined. Optimised shear discharges at JET with an internal transport barrier have recently shown very good confinement properties. In these plasmas several core-localised AE's exist in the central low-shear region. Due to the pronounced radial extent of these AE's and due to the low plasma density the expected alpha particle pressure can drive such AE' s weakly unstable. New results of the ongoing modelling of JET tritium discharges are presented.

2-D HIGH-n ANALYSIS OF TOROIDICITY INDUCED ALFVÉN EIGENMODES. *

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A high-n stability code, HINT, has been developed to study the stability of TAE's (Toroidicity induced Alfvén Eigenmodes) in large tokamaks such as ITER where the spectrum of unstable TAE's is shifted toward the medium to high-n modes. The new code includes two versions: a previously developed HINT-W based on the WKB eikonal representation for the radial dependence of the eigenmode envelope, and a new version, HINT-F, based on Fourier transformation in the radial variable. HINT-F solves the $2D$ eigenmode problem by expanding the eigenfunctions in terms of orthogonal basis functions. The eigenmode problem is reduced to a system of coupled $1D$ equations, which is solved numerically by using a SPARSE matrix solver. The numerical method used in this work allows us to include nonpeturbatively non-ideal effects such as: full ion FLR, trapped electron collisional damping, etc. A perturbation theory based on an expansion in the small parameter $1/n$ has also been developed to understand the 2D numerical eigenmode solutions for different radial profiles of equilibrium quantities. The global properties of TAE, KTAE and RTAE modes are investigated. The 2D numerical results will be compared with those previously obtained using the HINT-W version. The results show that TAE's can be driven unstable by alpha particles in ITER with $n = 10 - 20$. The growth rate for the most unstable mode is within the range $\gamma/\omega_A \simeq 0.3 - 0.5\%$. The most unstable modes are localized near $r/a \simeq 0.5$ and have a radial mode width $\Delta r/a \simeq 0.1 - 0.2$.

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2D03

Spontaneous Hole-Clump Pair Creation in a Weakly Unstable Plasma

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Our recent numerical simulations show that an unstable low amplitude wave evolves into a pair of BGK waves when the kinetic instability (such as the bump-on-tail instability or the alpha particle driven Alfvén wave instability) is close to its threshold, *i.e.* when the linear growth rate from the kinetic drive is comparable to the damping rate associated with the background plasma. A hole-clump pair emerges in the fast particle distribution function during this process. The simulation results and the subsequent analysis show that the hole and the clump appear as a result of an explosive phase where the wave amplitude grows to a level independent of the closeness to the instability threshold. The surprise observation is that after saturation is reached and the distribution function flattens near the resonance, the mode does not damp, but remains relatively constant, with the frequency shifting both up and down from the original frequency. The frequency shifts are produced by the phase space hole and clump. The shifting frequency allows power to be extracted from the fast particles, and this power is then dissipated into the background plasma.

The process is described analytically by using particle adiabaticity to calculate the nonlinear power extraction from the kinetic drive. The hole and clump only dissipate if they shift to the edges of the fast particle distribution, or collisions cause the passing particles to mix with trapped particles.

It has been previously pointed out that frequency sweeping has the potential application to energy channelling, where charged fusion products release their energy to waves, rather than to electrons through the drag process. The difficulty appeared to be how to change the frequency continuously. The above theory shows that the hole-clump formation provides a natural mechanism for the frequency to change, so that frequency sweeping does not have to be controlled externally. We are currently investigating this application.

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Detached Divertor Plasmas with Time Variation*

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Detached divertor plasmas are studied using the time-dependent mode of the UEDGE 2-D fluid transport code. The two-fluid Braginskii equations describe the hydrogenic plasma with anomalous cross-field transport and a reduced Navier-Stokes model describes the neutral gas. Impurities are represented by either fixed-fraction or multi-charge state models. Steady-state solutions are generally found for moderate impurity levels. These plasmas can exist with no particle throughput for the system. As the radiation loss from impurities is increased, the plasma particle and energy fluxes to the plate are drastically reduced. As this detached plasma mode becomes more pronounced, an ionization front moves upstream from the plate and steady-state solutions become more difficult to find. We expand our analysis of these detached plasmas to include time-dependent solutions and find two types: One has a small, but finite, particle throughput for the system with inflow from the core and outflow near the divertor plate which produces delicate steady-state solutions when balanced. The second state has no particle throughput and results in periodic temporal oscillations of the plasma which can change from weakly attached to detached over the course of the oscillation. A MARFE under the x-point can play an important role in these oscillations which may be the extension to detached plasmas including impurities of oscillatory divertor-plasma solutions described previously.[1] The general behavior described above is found for either impurity model. The effect of gas puffing and pumping at various locations is analyzed as a means of controlling the detached plasma for the DIII-D and ITER tokamaks.

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3A01

The Dynamo within the Earth

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Any theory of the origin of the Earth's magnetism must provide answers to a number of key questions. First and foremost, (1) Why is the Earth magnetic? (2) Why does the magnetic compass needle point approximately North? (3) Why is the field predominantly dipolar? (4) What determines its strength? (5) What causes the slow "secular" changes in the field? (6) Why do the field patterns on average drift westward? (7) Why has the Earth been magnetic for most of its existence? (8) Why does the magnetic polarity of the field occasionally reverse? (9) Why has the frequency of reversals varied so greatly over geological time? (10) What happens to the field during a reversal? (11) Why was neither field polarity favored over the other in the geological past? (12) Why, when averaged over the recent geological past, do the magnetic and geographical poles coincide? And so on. The first six questions have been asked for centuries; the remainder surfaced more recently through paleomagnetism, the study of the magnetism fossilized in rocks at the time of their creation.

The questions above are most satisfactorily answered when it is supposed that a fluid dynamo operates within the Earth. The electric currents flow in the Earth's metallic core, 3480 km in radius, the central 1222 km of which, the inner core, is frozen solid. As the Earth cools, the inner core grows and latent heat of crystallization is released at the inner core boundary, together with light constituents of core fluid. These provide buoyancy sources that drive the fluid core into convective motion that is sufficiently rapid to maintain the field by dynamo action. Dynamo theory provides natural answers to questions 1, 2, 3, 11 and 12. Recent numerical simulations described in this talk have gone some distance towards answering the remainder, though some intriguing puzzles remain. Geomagnetic dynamo action shares only a few common features with dynamo processes in the RFP; in most respects it is different, and the objectives of the theory are also different. Hopefully it will be made clear why this is so.

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FINITE TEMPERATURE EFFECTS ON COLLISIONLESS MAGNETIC RECONNECTION

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In collisionless magnetic reconnection regimes, electron inertia is responsible for the decoupling of the plasma motion from that of the magnetic field. In the MHD range of frequencies reconnection in collisionless regimes can be analyzed[1] on the basis of a 2D incompressible fluid model for the electrons, which includes the effects of electron inertia and of the perturbed electron pressure gradients along magnetic field lines. Ions are treated with a hybrid fluid-kinetic model, which includes ion Larmor radius effects to arbitrary order.

This system of equations is Hamiltonian, in terms of non-canonical Poisson brackets, and has two infinite sets of conserved quantities (Casimirs) which play the role of topological constraints.

Here we show that the spatial structures of the plasma current density and of the plasma vorticity, which occur in the nonlinear stage of magnetic field reconnection, are related to the form of the the topological constraints.

In particular we investigate the non-linear evolution of magnetic reconnection in the small Larmor radius limit, using a numerical code based on a finite difference scheme with a non-uniform grid. We start from an equilibrium configuration where a single mode is linearly unstable and has a large value of the instability parameter Δ'.

We consider two different plasma regimes, where $d_e = c/\omega_{pe}$ is either larger or smaller than the "sound" Larmor radius $\varrho_s = \sqrt{T_e/m_i}/\omega_{ci}$. The scalelength ϱ_s is associated with the electron pressure gradient in the generalized Ohm law. The set of topological invariants (Casimirs) takes different forms in the two mentioned regimes.

In the small ϱ_s regime[2],[3], the current density is structured in a current sheet of width $2d_e$, however a sublayer of amplitude smaller than d_e is found inside the reconnection region. The conserved quantities are $C_1 = \int d^2x\ h_1(F)$ and $C_2 = \int d^2x\ U\ h_2(F)$ where $F = \Psi + d_e^2 J$ is the generalized flux function, Ψ is the magnetic flux function, J is the current density, U is the plasma vorticity and $h_{1,2}$ are arbitrary functions. When finite ϱ_s values are considered, the invariants C_1 and C_2 are replaced by $C_\pm = \int d^2x\ h_\pm(G\pm)$ where $G_\pm \equiv F \pm d_e \varrho_s U$ and $h_\pm$ are arbitrary functions. The flux surfaces of $G_\pm$ conserve their topology. On the contrary F undergoes reconnection and develops an O-point with a cusp-like structure. The current density is now mainly distributed along the magnetic separatrices. In addition, in this regime, vorticity sheets are formed at the magnetic separatrices.

In both regimes, magnetic reconnection exhibits a quasi-explosive time evolution.

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Decorrelation Dynamics, Spectra, and Transport in Drift-Alfvén Turbulence

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Extensive studies of MHD turbulence and electrostatic drift wave turbulence have examined many facets of the disparate behavior of each of these systems. Much less work has been done on the basic properties of magnetic turbulence which combines the essential features of both systems, specifically on magnetic turbulence in the presence of nonhomogonous electron density, or magnetic turbulence with a significant fluctuating electron density component. Such turbulence characterizes fluctuations in a variety of laboratory plasma experiments, particularly those that tend to relaxed states, and in naturally occurring plasmas.

We examine here a minimum fluid model for drift-Alfvén turbulence, consisting of an Ohm's law equation for the magnetic field, a vorticity equation, and an electron density equation. Electron density dynamics couples through the parallel pressure in Ohm's law and parallel compression in the density equation. This system has reduced MHD and the Hasegawa-Mima equation as limiting subsystems. We consider the turbulent magnetofluid regime, where Alfvénic fluctuations drive the fastest decorrelation, and study basic properties of the turbulence. These include the wavenumber and frequency spectrum, the turbulent response, spectral energy transfer and spectral transfer between different energy components, and the physics of particle transport. Particular attention is given to the turbulent response, which describes the decorrelation of turbulent interactions, and therefore regulates the rate of spectral transfer and governs the wavenumber spectrum falloff rate. Measurement of a statistical ensemble of turbulent responses to impulsive perturbations in direct numerical simulation and statistical closure theory show that the turbulent response and wavenumber spectrum have a fundamentally different structure from that of MHD turbulence. Whereas in MHD turbulence, the spectrum index is set by the faster Alfvénic decorrelation, in drift-Aflvén turbulence it is set by the slower fluid straining decorrelation. While this behavior is reflective of drift wave turbulence, the frequency spectrum and energy partitions evince signatures of magnetic turbulence: the rms turbulent frequency is Alfvénic and robust cross field transfer mediated by Alfvénic interactions equipartitions the magnetic field with the flow and the density. Particle transport is controlled by the slower fluid straining decorrelation, even when external energy injection drives only the magnetic fluctuation and density fluctutations are excited purely by nonlinear energy transfer from the magnetic field. Particle transport is governed by a non invariant cross correlation that is generated by the spectral energy transfer.

These results are applied to two plasmas with magnetic turbulence, the high frequency magnetic fluctuation spectrum in the Madison Symmetric Torus and the interstellar medium. Both have density fluctuations, and neither has the spectral index of MHD turbulence. Drift Alfvén turbulence is able to reproduce the spectra of both types of turbulence, but is too simple to describe all features of these systems. Details of the comparisons will be presented.

Landau-Fluid Equations, The Stochastic Oscillator and Masses with Springs: Model Closure Problems*

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Several interesting physical models are presented that give insight into the nature of the phase-mixing closures used in Landau-fluid equations. The Landau-fluid closures introduce dissipation into fluid moment equations to model the *phase mixing decay* which occurs at the rate $|k|v_t$ where k is the wavenumber and v_t is the thermal velocity [1].

The linearized Vlasov equation is precisely analogous to the stochastic oscillator problem [2, 3] through a simple transformation of variables. This transformation connects fluid moment closures of the Vlasov equation to statistical moment closures of the stochastic oscillator. Following this connection in both directions unveils fresh perspectives on two classic problems. The Landau-fluid closures [4] are transformed into a novel set of linear statistical closures that may serve as a useful guide into extensions of statistical closure theories to higher order moments. Studies of statistical moment closures [3, 5] provide a wealth of ideas for fluid moment closures.

Convergence of the linear response function for fluid moment systems with Landau-fluid closures is studied here. Strong numerical evidence is presented that indicates convergence of the linear response for the closed moment system to the exact kinetic response with increasing numbers of moments. Results are also presented concerning the behavior of the poles of the approximate response.

The fluid moment system for the Vlasov equation linearized about a Maxwellian background has been shown to be equivalent to a semi-infinite mass-spring system [6]. This mechanical system with an infinite number of masses has a continuous distribution of normal modes that become decorrelated with one another over time, leading to the phase-mixing decay of perturbations. A mass-spring system is considered here with a response function that contains a square-root type singularity. The convergence properties of linear closures for this system indicate some of the potential pitfalls in extending toroidal drift closures [7] to systems with larger numbers of moments, since the toroidal response function also exhibits a square-root type singularity.

Finally, the concepts of phase mixing closures for moments are discussed in the context of subgridscale closure models. A summary is presented of ongoing research into the evaluation of subgridscale dissipation models in two and three dimensional drift-wave turbulence simulations.

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Induced Eddy Current Patterns on Tokamak Conducting Shell and Their Implications on Active Feedback Stabilization of External MHD Modes

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The external kink mode is widely believed to be the plasma-beta-limiting instability in most tokamak operating modes including the reversed shear mode. The instability is easily stabilized if an ideal wall is placed close enough to the plasma. The ideal external kink mode will, however, turn to a resistive wall mode in the presence of the actual resistive shell, leading to an instability growing on an L/R time scale. One way to stabilize this mode is to properly mount a system of active feedback coils and other required hardware elements. For a successful implementation of such a system, it is necessary to study the two dimensional patterns of the eddy currents as well as the corresponding normal magnetic field induced on the conducting shell. We have done such calculations using the PEST-VACUUM code. The calculation results for various situations, including different profiles and toroidal mode numbers, conducting shell with and without a midplane gap, and several leading advanced operating modes, will be presented. Preliminary results show well-defined patterns in some systematic ways and the implications will be discussed.

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Changes in the Dynamics of Turbulent Transport in the Presence of a Sheared Flow*

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The fundamental importance of sheared flows in turbulence and turbulent transport has been demonstrated both through experimental observations and theoretical predictions [1, 2]. However, questions exist about the local effect of the sheared flow on both the turbulent dynamics (the local spectral transfer) and the transport dynamics (embodied in the cross field spectral dynamics). Using a wavelet representation of the nonlinearities we are able to directly investigate both of these quantities. Starting with a simple 2-D model in which the polarization drift nonlinearity is the dominant nonlinearity we compare the spatially localized spectral dynamics with and without a sheared flow. This then allows us to build up in complexity to more complete models with multiple fields and multiple nonlinearities. By exploring the dynamics at a local level we are able to make predictions about locally measured quantities in addition to averaged quantities.

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SYMBOLIC ANALYSIS OF CHAOTIC SIGNALS AND TURBULENT FLUCTUATIONS

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Abstract

The symbolic analysis introduced in this paper allows quantitative description of dynamical coupling between different time signals. In order to demonstrate how this method works we applied it to the explicit examples of chaotic signals and turbulent fluctuations. Our results appear to be quite robust when external noise is added.

Experiences Migrating a Large Fortran Plasma Simulation Code to a Parallel Computing Environment Using C++ and Object Oriented Design Methods

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The incorporation of an algorithm to solve the Quiet Implicit PIC (QIP) moment equations into the Generalized Tokamak Simulator (GTS) is near completion. This has involved rewriting approximately 100,000 lines of Fortran 77 code in C++ using an Object Oriented Design (OOD) approach. In addition, the QIP algorithm has been reimplemented to run effectively on parallel computers. One of the motivations for undertaking this project was past experiences trying to implement and maintain a complex computational physics algorithm such as QIP in a modular and extensible fashion using a procedural language like Fortran 77. Future plans for this work included incorporation of an equilibrium flux coordinate system to handle more general tokamak geometries, coupling of the QIP moment equations to the QIP δf particle equations and reorganizing the entire algorithm to perform efficiently on parallel computers. These future plans all introduce considerable additional complexity to an algorithm which is already very complex. Because of past experiences and the prospect of considerable additional complexity, it seemed that migration or adoption of a more modern programming language was called for. Both Fortran 90 and C++ were considered and C++ was chosen.

One of the concerns in choosing C++ was computational performance and whether it would be close to that of Fortran 77 if high levels of abstraction typical of an OOD were used. Another concern was the learning curve associated with changing to another language that was radically different from Fortran 77 and considerably more complex. Finally, another concern was whether the result of this conversion of a large Fortran 77 code to C++ would really result in a new implementation that was really flexible, extensible and easy to maintain. Results from this project will be presented in an attempt to address these concerns as well as others. Finally, a current status of the work will be presented along with plans for future work.

Control of Internal Transport Barriers in Reverse Shear and Weak Shear Discharges*

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Transitions to an enhanced confinement regime in systems with reversed and weak central magnetic shear have been observed in a number of magnetic confinement devices [1, 2, 3]. A simple model [4] incorporating the nonlinear coupling between the turbulent fluctuations and the sheared radial electric field is added to a more complete transport model in order to investigate the dynamics of the transition to the enhanced confinement mode in these discharges. An intrinsically nonlinear radially coupled model is needed to explain the bifurcation to "enhanced confinement" from the regular reversed shear regime. In this simple model by incorporating both the instability growth rate profiles and particle/power deposition profiles a rich variety of transition dynamics are found. Due to the importance of this enhanced confinement regime for fusion devices, a detailed investigation with a more comprehensive transport model is made. Transition dynamics with their concomitant thresholds are examined with these models. In the course of investigating the transitions, the models have illuminated potential methods for triggering and controlling these enhanced confinement regimes. Many of these potential techniques exploit both the hysteresis intrinsic to these transitions and the transient nature of the transition itself. Some of these methods including current profile control, flow control, RF heating, and pellet injection will be discussed.

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Magnetohydrodynamic Stability of Tokamak Discharges with Negative Central Shear*

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The stability properties of tokamak discharges with negative central shear are studied using the linear and nonlinear, ideal and resistive, magnetohydrodynamic (MHD) stability code FAR [1, 2]. FAR solves the full set of MHD equations in toroidal geometry, including shaping, compressibility, fineta beta and finite aspect ratio effects. Linear resistive stability calculations for such discharges (e.g., DIII-D shot #87009 at 1675 msec) [3] show a weak pressure-driven instability in the negative central shear region. These localized interchange modes have growth rates which increase with n. The termination of these discharges is usually associated with the excitation of a global $n = 1$ mode. On the other hand, resistive interchange modes in cylindrical geometry exhibit a nonlinear spectrum which peaks at the lowest n [4]. Here, nonlinear calculations are performed in toroidal geometry to determine whether the interaction of the linearly unstable modes, associated profile modifications, and sheared poloidal flow generation can lead to the fast rise time of the $n = 1$ mode observed prior to termination.

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Optimization and Confinement Properties of Small Aspect Ratio Tokamak/Stellarator Hybrid (SMARTH) Devices*

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Small aspect ratio stellarator/tokamak hybrids offer a number of attractive features, including compact design, lack of disruptions, axisymmetric diverted regions, and lack of low order islands near the plasma edge. However, in order for these advantages to be realized, improved confinement regimes are required [1]. These regimes can be obtained either through control of the ambipolar electric field or through optimization of the magnetic geometry. We have evaluated the effects of electric field control and magnetic optimization using a combination of Monte Carlo transport simulations and simpler criteria such as B_{min}, B_{max}, and J^* contours.

Physics-based magnetic optimizations have been carried out by varying the shape of the outermost magnetic flux surface in such a way as to minimize the variation of B_{min}, and B_{max} around several targeted flux surfaces while reducing ripple and maintaining transform, aspect ratio and V'' well. A separate optimization loop is then used to reconstruct modular coils which will produce the required outer surface shape. We will also examine the use of criteria which target omnigeneity (i.e., no averaged drift away from flux surfaces). This can be achieved either by minimizing the variation of J^* around a flux surface for several values of ε/μ or, equivalently, by equalizing the angular separation between equal mod B contours [2]. We have examined devices with a range of field periods from 1 up to 10. Use of the B_{min}, B_{max} centering optimization procedure seems to work best in the range of 5 to 7 field periods (for aspect ratios around 3) and results in configurations which also approach being quasi-helical. Monte Carlo simulations have confirmed that our optimization procedures lead to improved transport.

Since such optimized configurations possess closed superbanana orbit trajectories, we expect that their confinement properties may also be improved by steepened gradients in the ambipolar electric field which can induce orbit-squeezing effects. Such effects can play a role in transport barrier physics and have not been observed in the un-optimized configurations due to a lack of closed/confined superbanana orbits (unclosed B_{min} contours). We will examine this possibility using orbit trajectory studies.

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Neoclassical Transport in MHH2*

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A numerical and analytic assessment of the transport in one member of the MHH2 class[1] of quasitoroidal modular stellarators has been performed. Monte Carlo simulation results are compared with expectations from established stellarator neoclassical theory, and with some empirical stellarator scalings, used as an estimate of the turbulent transport which might be expected. The numerical results are reasonably well explained by analytic neoclassical theory, though the MHH2 configuration does not strictly adhere to some assumptions made in the theory. From the standpoint of transport, MHH2 may be viewed as either a tokamak with large ($\delta \sim 1\%$) but low-n ripple, or as a stellarator with small ripple. The non-axisymmetric contribution to the heat flux is comparable with the symmetric neoclassical contribution, and also falls in the range spanned by the empirical estimates for turbulent transport. Thus, it appears effort to further optimize the thermal transport beyond the particular incarnation studied here would be of only modest utility. However, the favorable thermal confinement relies heavily on the radial electric field, which we have computed to satisfy the ambipolarity constraint. Thus, the present configuration will have a loss cone for trapped energetic ions. Further optimization may thus be indicated for a large device of this type unless high enough β can be achieved that the additional precessional drift this induces is able to confine these particles as well, similar to what occurs for the Wendelstein-VII-X configuration. Initial finite–β results will be presented.

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Theory of semi-collisional nonlinear kink-tearing modes and sawtooth collapse in tokamaks

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Semi-collisional non-constant- ψ magnetic reconnection, caused by nonlinear m=1 kink-tearing instabilities, is studied analytically using the generalized Ohm's law in a modified MHD model [X. Wang and A. Bhattacharjee, *Phys. Plasmas* **2** (1995), 171]. The model includes the effects of resistivity and electron pressure gradient in the generalized Ohm's law

$$\frac{\partial \psi}{\partial t} + \mathbf{v} \cdot \nabla \psi \approx \frac{a^2}{\tau_R} \nabla^2 \psi + \frac{c \nabla p_e}{ne} ,$$

where ψ is the flux function, $\mathbf{v}$ is the fluid velocity, a is the minor radius, τ_R is the resistive diffusion time, p_e is the electron pressure, n is the electron density, and other symbols have their usual meanings. It is shown that the nonlinear evolution of m=1 semi-collisional kink-tearing islands obey the equation

$$\frac{dX}{d\tau} \cong \frac{1}{4} \left(\frac{\omega_A}{\Omega_i} \right)^{1/2} X^2 (1-X)^{3/2} \left[1 + \left(1 + \frac{16}{S(\omega_A / \Omega_i) X^3 (1-X)^2} \right)^{1/2} \right] ,$$

where $X \equiv w/(2r_s)$ is the dimensionless island width normalized by the diameter $(2r_s)$ of the m=1 rational surface, $\tau \equiv \omega_A t$, and $\omega_A \equiv v_A / r_s$ where v_A is the Alfven speed. This equation predicts near-explosive growth of the island in the nonlinear stage, followed by rapid decay, as seen during sawtooth crashes in JET and TFTR. It is suggested that the electron pressure gradient that drives near-explosive growth of the nonlinear m=1 island causes a strong geometric deformation of the island, producing local regions where the nonlinear current sheet on the separatrix becomes unstable. Electron pressure gradients are then reduced by the instability, quenching the reconnection process, and providing a possible explanation of the incomplete reconnection seen in several observations.

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Low Collisionality Stellarator Steady States*

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Previous work, H. Weitzner, *Phys. Plasmas* 4, No. 3, 1997, is extended to complete the characterization of low collisionality steady states in a non-axisymmetric configuration. It was claimed earlier that the system must have an approximately constant rotational transform, and must also have approximate quasi-tokamak symmetry. It is shown that these conditions are only the first of a increasingly complex set of constraints. Under the assumption that the constraints are satisfied, or that they do not affect the conditions for the steady state, the basic conditions are given for mass and energy conservation, as well as ambipolarity. The relationship between the failure of the constraints and the generation of turbulence is discussed.

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W7-X Equilibria with Magnetic Islands Using the PIES code

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Solving the MHD equilibrium equations $\mathbf{J}\times\mathbf{B}=\nabla p$, $\nabla\times\mathbf{B}=\mathbf{J}$, $\nabla\cdot\mathbf{B}=0$ for finite-aspect-ratio, high-beta, 3-D configurations, leads to a complicated magnetic topology. Due to the absence of symmetries guaranteeing the existence of nested magnetic surfaces, computation of stellarator equilibria requires the treatment of magnetic islands and/or stochastic regions. The PIES code [1], solving the MHD equilibrium equations by an iterative, non-variational technique is able to deal with systems without a nested toroidal flux surface geometry. The algorithm the code uses is a Picard iteration scheme, in which the 'new' fields are used as input to the next iteration. Such methods tend to have slow or even unstable convergence. Furthermore, numerically unstable modes (m,n) (m = poloidal, n = toroidal mode number) may appear near resonant surfaces with $\iota = n/m$. Here, it was found to be useful to blend the Fourier coefficients of coordinates and fields of one iteration with those of the previous iteration, controlled by a blending parameter. Particularly in low shear cases and for higher values of $\langle\beta\rangle$, large values of this parameter are necessary to avoid instability. The consequence is a very slow convergence rate . For instance, several hundred iterations were necessary for a W7-X equilibrium with islands for a value of $\langle\beta\rangle$ of 3.75 % [2]. This convergence rate can be improved using 'Chebychev' periodic sequences of iterations with different blending parameters.
Significant, further progress has been made by using finite beta equilibrium solutions obtained with the VMEC code [3] as initial conditions for the PIES code. The VMEC code locates 3-D equilibria by finding numerical minima of the MHD energy using a variational method assuming the existence of a set of well behaved nested magnetic surfaces. The VMEC code allows the computation of such equilibria complying with this restriction with a minimum of computational effort and a minimum number of poloidal and toroidal harmonics. With these equilibria as input to the PIES code, the number of iterations necessary to converge a PIES run has decreased by nearly one order of magnitude. Fixed boundary W7-X equilibria, with, and without, islands and with $\langle\beta\rangle$ values up to approximately 5 % are shown. The convergence properties are compared with corresponding PIES runs using the vacuum fields as initial guesses.

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Localized Interchange Stability Criterion for a Toroidally Rotating Tokamak

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Toroidal rotations at small fractions of the sound speed have been observed in present day neutral beam injected tokamaks. Substantial rotation shear could result from good confinement of the toroidal angular momentum. Conventional wisdom indicates that MHD modes are stabilized by a weak rotation shear yet destabilized by a strong rotation shear. In DIII–D negative central shear (NCS) discharges with a peaked central pressure, MHD bursts have been observed [1] in the central reversed shear region with good confinement. In this region, based on static MHD theory with no flow, localized MHD interchange [2] and ballooning modes have been predicted to be stable, only the resistive interchange [3] has been found to be unstable, although at a reduced growth rate compared [4] to experimental observation. This work investigates the destabilizing effect of a strong rotation shear on the ideal localized interchange and attempts to resolve this extant discrepancy between theory and experiment.

Stability to localized MHD interchange modes is studied in a tokamak with a small toroidal flow but with a non-negligible shearing rate of the toroidal rotation. We use the variational principle of Frieman and Rotenberg [5] and consider localized plasma motion around a rational surface. Modification to the localized interchange stability criterion is obtained by maximizing the growth rate. The rotation shear couples to both the Alfvén and sound waves and reduces the stabilizing effect of these waves. This coupling allows the plasma motion to tap the energy associated with the flow shear. A new interchange criterion

$$D_{\mathrm{I}} + \frac{1}{4}\left(M_{\mathrm{a}}^2 + A\right) + \frac{\beta_\Gamma M_{\mathrm{s}}^2}{F(\beta_\Gamma - M_{\mathrm{s}}^2)}\left[D_{\mathrm{I}} + \frac{1}{2}\left(\frac{1}{2} - H\right)\right]^2 < 0 ,$$

is obtained. In here, D_{I} is the interchange criterion based on static MHD [2], β_Γ is plasma beta, M_{a} and M_{s} are appropriately defined Mach numbers which measure the rate of shear flow, A specifies the amount of up-down asymmetry, and F and H are flux surface quantities.

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Internal modes in well confined plasmas

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Finding the conditions under which internal modes can be excited and have a serious influence on global confinement is the objective of combined theoretical and experimental effort involving the Alcator C-Mod machine. The effects that these modes can have on the ability of fusion burning experiments to reach ignition is of importance [1]. Specific issues are the relative size of the region where these plasma pressure gradient driven modes are excited, and the amplitude of the resulting sawtooth oscillations. In particular, the combination of the highest values of β-poloidal with the lowest values of the safety factor q_{95} for which the effects of these modes can be considered acceptable is of special interest.

A survey of a large set of relevant discharges has identified three for which: i) $\beta_{pol} \simeq 0.8, q_{95} \simeq 4.5, I_p \simeq 0.8\ MA$; ii) $\beta_{pol} \simeq 0.7, q_{95} \simeq 3.7, I_p \simeq 1.0\ MA$; iii) $\beta_{pol} \simeq 0.6, q_{95} \simeq 3.4, I_p \simeq 1.0\ MA$. These parameters were achieved in ELM-free, or mildly Enhanced-D_α H-modes [2] with $2-3\ MW$ of ICRH power. They represent some of the highest values of β-poloidal obtained so far on Alcator C-Mod. The main machine parameters were in these cases : $R = 0.67\ m, a = 0.22\ m, \kappa \simeq 1.6, B_T = 5.3\ T$. The estimated radius of the $q = 1$ surface is $r_1/a \lesssim 0.27$.

The ideal MHD stability analysis of these relatively high β_{pol} discharges carried out by the PEST code [3], indicates that they are nevertheless below the critical value of β_{pol} for the onset of $n = 1$ internal kink instabilities. The presence of a significant high energy particle population may also have a stabilizing role. Consequently the observed sawtooth activity can be attributed to resistive internal modes.

The contribution of the Alcator C-Mod group in producing the relevant plasmas is acknowledged with special pleasure. In particular, we wish to thank J. Irby, A. Hubbard, P. O'Shea, J. Rice, Y. Takase, and S. Wolfe for providing the experimental data and useful comments.

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Macroscopic Stability of $n = 1$ Internal Modes in ITER Plasmas

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Using the analytical approach[1], we have investigated the magnetohydrodynamics (MHD) stability of $n = 1$ internal modes in plasmas relevant for the proposed International Thermonuclear Experimental Reactor (ITER). As is well known, the ideal MHD potential energy can be reduced to a second order polynomial in the local poloidal beta parameter β_{p1}, whose coefficients depend upon global characteristics of the q-profile. We have computed numerically these coefficients for general q-profiles of the form[2] $q(\rho) = q_0(1 + \alpha_q \rho^{2\nu})^{1/\nu}$ (here ρ is a radius-like dimensionless variable and $\alpha_q = (q_a/q_0)^\nu - 1$), by solving the appropriate initial value problems for the $m = 2$ poloidal harmonic of the plasma displacement. Effects due to shaping of the plasma boundary[3] are also taken into account. We find that, characteristically, instability occurs for values of $\beta_{p1,crit}$ in the range of 0.1 to 0.2 and that, for fixed values of q_0 and q_a, the value of $\beta_{p1,crit}$ is strongly reduced as the radius of the $q = 1$ resonant surface is increased. ITER plasmas are expected to have relatively large values of the $q = 1$ radius, $\rho_1 \approx 0.4 \div 0.5$; we find that they become unstable for values of the central pressure that are typically well below those required for ignition. These results are in fact similar to those obtained in Ref.[4] with the PEST-1 ideal-MHD stability code.

In fusion burning Deuterium–Tritium plasmas, the presence of energetic alpha particles may alter significantly the stability properties of $n = 1$ internal modes[5]. We have therefore included alpha particle effects (in the small frequency limit) in our analysis of ITER plasmas stability. We find that only when the radius of the $q = 1$ surface is kept small, typically $\rho_1 \leq 0.2$, alpha particles can stabilize $n = 1$ internal modes for values of the central pressure of interest for ignition. Moreover, for larger values of the $q = 1$ radius, alpha particles can have destabilizing effects.

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Sawtooth stability of plasmas in Alcator C-Mod

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The issue of the excitation of internal modes is important for both present day magnetically confined plasmas and for proposed new experiments [1]. In order to better understand the regimes relevant to modes involving magnetic reconnection as well to modes described by the ideal MHD approximation, we have analyzed* the characteristics of plasmas produced by Alcator C-Mod, where sawtooth oscillations are nearly always present. By modelling these plasmas with the help of the PEST stability code [2], we have concluded that most, if not all, discharges operate in regimes of ideal MHD stability: β is below the critical value necessary for the ideal internal n=1 kink mode. This situation of ideal stability results, primarily from operation at relatively low values of beta (about 1% on axis) and is helped by shaping, i.e., high values of triangularity. The ratio β/β_{crit} is small enough, < 0.5, that this picture (ideal stability) is relatively insensitive to uncertainties in the q-profile (which is inferred from EFIT reconstructions but not measured directly).

The issue of resistive stability has been considered both in the context of a simple two-fluid description [3] as well as a more complete model which [4] takes into account the effects of finite Larmor radius (FLR: finite ρ_i/r_1) and ion-ion viscosity. The two-fluid model includes the effects of resistivity (necessary in order to break the ideal MHD approximation and allow magnetic reconnection) and finite ion and electron diamagnetic frequencies. The second model goes beyond the two-fluid description by considering a kinetic ion response which includes a particle and momentum conserving term as well as finite ion Larmor radius (i.e., $k\rho_i$ is kept to all orders, where k is the perpendicular wavenumber). A good correlation is found between the absence of well-defined sawteeth and the marginal stability boundary. We also show that stabilization is possible, in principle (namely that a marginal stability boundary exists) even for relatively large values of the normalized FLR parameter, $\rho_i/r_1\epsilon_\eta^{1/3}$ with $\epsilon_\eta = \tau_A\eta_{||}c^2/4\pi r_1^2$, that are typical of RF-heated plasmas in Alcator.

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Assessment of the Theory-Based Multi-Mode Transport Model*

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The current version of the Multi-Mode transport model has been used since the end of 1995 to predict the temperature and density profiles observed in L-mode and H-mode tokamak plasmas within an average RMS deviation of about 15% relative to central values[1, 2]. A modified version of this model predicts the profiles observed in TFTR supershot plasmas[3]. A systematic protocol has been established to set up the input data for simulations of experimental data and to analyse the results. A blind test has been carried out to test this procedure. Simulations using the Multi-Mode model are found to reproduce the experimentally observed scaling with respect to plasma current, density, heating power, and dimensionless parameters such as the normalized gyro-radius (ρ_*).

Since no one transport theory encompasses all the effects that contribute to transport in tokamaks, the Multi-Mode model is constructed using a combination of different theories. The current version of the Multi-Mode transport model uses a combination of four theoretically derived transport models: (1) Weiland model for drift waves, (2) Guzdar-Drake model for drift resistive ballooning modes, (3) kinetic ballooning modes, and (4) neoclassical transport.

In spite of the success of the Multi-Mode model at matching experimental data, we plan to change each part of the model to add new effects and to improve its theoretical foundations. The issues to be addressed include the effects of shear flow, elongation, modes with more spatial structure, the effects of Shafranov shift and triangularity, and a more consistent approach to the transition from one mode to the next. The current version of the Multi-Mode model is assessed and plans for changes are described.

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Modeling of MHD Stability for Tore Supra Discharges with LHCD

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In the last few years, discharges with improved core confinement, Lower Hybrid Enhanced Performance (LHEP) [1], have been achieved on Tore Supra. The improvement in core confinement is due to improved current profile control —the safety factor profile is flattened or reversed in the core. Such current profile modifications are also known to affect the MHD stability of tokamak equilibria. On Tore Supra, the observation is made that the LHEP phase is often terminated by an abrupt transition towards a degraded regime that consists of quasi-periodic *sawtooth-like* relaxations (mainly observed on the electron temperature evolution) [2]. Both the transition and the ensuing *sawtoothing* regime , which are observed to be driven by low-mode-number tearing modes, are analyzed in the frame of the so-called *neoclassical*-MHD model [3]. This model appears to be a leading candidate to explain the phenomenology of this low-collisionality regime –! -such as the existence of various threshold conditions for the nonlinear excitation of the observed low-mode-number tearing modes.

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Forced Reconnection and Mode-Locking due to Time-Dependent Error Fields in Rotating Plasmas

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The problem of mode-locking caused by various time-dependent field-errors in rotating cylindrical plasmas is studied. An analytic description of forced reconnection and mode-locking due to field errors with different time-dependencies is developed. Corresponding locking thresholds are obtained. For error fields that are ramped up on a fast time-scale, the locking threshold is the same as the constant (or sudden) field error case [X. Wang and A. Bhattacharjee, Phys. Plasmas **4**, (1997), to appear]:

$$\frac{b_{s,lock}}{B_\varphi} = \frac{n^{1/5}}{m}\left[\frac{\Omega_0^2 \tau_A^2 \tau_{spV}}{2\lambda_{p,e}\tau_V}\right]^{2/5}\left[\frac{r_s}{R_0}\right]^{1/5} .$$

For error fields that are ramped up with a slower time-dependence, it is found that the constant ψ phase is possibly attained under certain conditions and leads to the locking threshold obtained by Fitzpatrick [R. Fitzpatrick, Nucl. Fusion **33**, 1049 (1993)]:

$$\frac{b_{s,lock}}{B_\phi} = \frac{\Omega_0 \tau_A}{m}\left[\frac{\tau_{LC}}{2\lambda\tau_V}\right]^{1/2} .$$

An oscillating field error, which has been suggested as a possible C-coil experiment on DIII-D, is also considered. It is found that for fast oscillations, islands are suppressed. The predictions of the theory are compared with experimental data from Compass-C and DIII-D.

3C20

NUMERICAL SIMULATION OF THE MRX EXPERIMENT

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

The TRIM code uses an unstructured, adaptive grid of triangular cells to represent the poloidal plane. This allows the exact geometry of the MRX experiment, including the non-simply connected flux cores, to be captured in the simulations. Poloidal and toroidal voltages are applied at the flux core boundaries to simulate "push" and "pull" modes of operation. Both null injection (zero toroidal field) and co-injection (uni-directional toroidal field) cases are studied. Both zero-beta and finite-beta models are used. Comparison with experimental results are given, and a scaling of reconnection rate with Lundquist number is presented.

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Exact Landau Fluid Equations

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We derive a set of exact Landau fluid equations, making no approximation regarding nonlinear kinetic interaction. Prior such equations[1,2] include a model for only *linear* wave-particle resonances. However, there has been concern that this inaccurately treats *nonlinear* kinetic effects, such as wave-particle scattering or trapping.[3,4,5]

We start with the drift kinetic equation in a straight slab with Maxwellian equilibrium,

$$\left(\omega - k_{\|}v_{\|}\right)\widetilde{f}_{\mathbf{k}} - \left[k_{\|}v_{\|} - \omega_{*} + \omega_{*}^{T}\left(\tfrac{3}{2} - \tfrac{1}{2}v^2\right)\right]F_M\widetilde{\phi}_{\mathbf{k}} - \sum_{\mathbf{k}'}\widetilde{\mathbf{v}}_{E,\mathbf{k}''}\cdot\mathbf{k}'\widetilde{f}_{\mathbf{k}'} = 0.$$

Fluid closure is accomplished by expanding $\widetilde{f}_{\mathbf{k}}$ in Hermite polynomials, solving analytically for the higher coefficients in terms of the second coeffiecient, and using this solution to evaluate higher moments in terms of lower. This gives the following temperature equation:

$$-i\omega\widetilde{T}_{\|,\mathbf{k}} - i\omega_{*}^{T}\widetilde{\phi}_{\mathbf{k}} + 2ik_{\|}\widetilde{V}_{\|,\mathbf{k}} + \sum_{\mathbf{k}'}\widetilde{\mathbf{v}}_{E,\mathbf{k}''}\cdot i\mathbf{k}'\widetilde{T}_{\|,\mathbf{k}'} + ik_{\|}\sum_{\mathbf{k}'}G_{\mathbf{k},\mathbf{k}'}\widetilde{T}_{\|,\mathbf{k}'} = 0,$$

where the Landau fluid heat flux is:

$$G_{\mathbf{k},\mathbf{k}'} \equiv -\overrightarrow{e}_{\mathbf{k}}\left[Z_0'''(\overleftrightarrow{W}/\sqrt{2})/\sqrt{2}Z_0''(\overleftrightarrow{W}/\sqrt{2})\right]\overleftarrow{e}_{\mathbf{k}'}$$

Z_0 is the plasma dispersion function, $v_{\mathbf{k}} \equiv \omega/k_{\|}$, and $\widetilde{u}_{\mathbf{k},\mathbf{k}'} \equiv \widetilde{\mathbf{v}}_{E,\mathbf{k}-\mathbf{k}'}\cdot\mathbf{k}'/k_{\|}$, $\overrightarrow{e}_{\mathbf{k}}\overleftrightarrow{W}\overleftarrow{e}_{\mathbf{k}'} \equiv v_{\mathbf{k}} - \widetilde{u}_{\mathbf{k},\mathbf{k}'}$, $\overrightarrow{e}_{\mathbf{k}}$ and $\overleftarrow{e}_{\mathbf{k}'}$ are unit row and column vectors for modes $\mathbf{k}$ and $\mathbf{k}'$. For non-degenerate $\overleftrightarrow{W}$, the operators $Z_0(\overleftrightarrow{W})$ can be evaluated by an eigenvalue representation. To evaluate time evolution of a complicated function of frequency $G_{\mathbf{k},\mathbf{k}'}$, we introduce a numerical scheme where the frequencies are evaluated in terms of the previous time step, $\omega_{\mathbf{k}} \simeq i(\partial_t\widetilde{T}_{\|,\mathbf{k}})/\widetilde{T}_{\|,\mathbf{k}}$.

Work is currently underway to determine whether these equations repair previously discovered discrepancies between Landau fluid and kinetic theories.

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Full MHD simulations of moderate-n ballooning modes with the XTOR code

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The full-MHD initial value code XTOR [1] was entirely rewritten to allow the simulation of tokamak plasma with non-circular poloidal cross sections surrounded by a vacuum region. The actual version of the code solves

$$\begin{aligned}\rho\partial_t\mathbf{v} &= -\rho\mathbf{v}.\nabla\mathbf{v} + \mathbf{J}\times\mathbf{B} - \nabla p + \nu\nabla^2\mathbf{v} \quad (1)\\ \partial_t\mathbf{B} &= \nabla\times(\mathbf{v}\times\mathbf{B}) - \nabla\times\eta\mathbf{J} \quad (2)\\ \partial_t p &= -\Gamma p\nabla\mathbf{v} - \mathbf{v}.\nabla p + \nabla\chi_\perp\nabla p + \mathbf{B}.\nabla[\chi_{||}(\mathbf{B}.\nabla p)/B^2] + H \quad (3)\end{aligned}$$

with $\eta p^{3/2}$ kept constant in time, $H = -\nabla\chi_\perp\nabla p(t=0)$. The metrics and the equilibrium profiles are provided by the CHEASE code in the coordinate system used by XTOR [2]. For the time evolution, XTOR uses a semi-implicit scheme for the ideal MHD part of Eqs.(3), and a fully implicit scheme for the diffusion terms in Eqs.(2) and (3). A particular effort was devoted to the development of a method which ensures variationality of the discretized problem in the limit of ideal MHD. Indeed, previous simulations of the evolution of moderate-n ballooning modes with high-β equilibria [3] suggested that even a minute violation of this condition leads to the numerical destabilization of high-n harmonics.

Simulations performed with the new version of XTOR show that the saturation mechanism of moderate-n ballooning modes is different than the one observed for low-β modes. Indeed, these modes evolve to current singularities, and show certain analogies with Rayleigh-Taylor instabilities. In this study, the influence of the shape of the shear profile on the evolution of these modes is investigated. In particular, effects of shear inversion in the core region of the plasma are addressed.

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On Finite-η_i Shear Alfvén Instabilities in Toroidal Plasmas*

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Abstract

Recently, it has been predicted that shear instabilities may be excited in toroidal plasmas when $\eta_i = \partial \ell n T_i / \partial \ell n N_i$ exceeds a critical value, η_{ic}[1]. The instabilities have the interesting features that they exist in the low-β ideal MHD stable regime and reside within the unstable continuum. Thus, the instabilities, time asymptotically, grow quasi-exponentially. To test these theoretical predictions, we have developed an initial value code based on the gyrokinetic-MHD hybrid simulation scheme[2]. Preliminary simulation results have demonstrated that there does exist shear Alfvén instabilities driven by finite η_i values. Mode structure analyses, however, indicate that the instabilities are discrete eigenmodes rather then continuum modes. Detailed numerical results as well as corresponding theoretical analyses will be presented.

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Kinetic Modeling of Detached Plasmas in the PISCES-A Linear Machine *

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We present results of modeling axial (parallel) electron transport in the PISCES linear divertor simulator [1]. As input parameters for our simulation we use axial profiles of atomic and molecular hydrogen density and ion density (both experimentally measured and reconstructed via fluid modeling). The electron distribution function at the plasma source is assumed to be a sum of two Maxwellians: a majority at lower temperature and a higher energy minority (a Maxwellian beam with a density of order few percent of the majority) to simulate th primary electrons produced in the plasma source.

Our kinetic model is an extension of the model used in our previous work [2]. In addition to Coulomb collisions with electrons and ions, we have added interactions with neutral particles, which can be important for the relatively dense ($n_p \approx 3 \times 10^{13} cm^{-3}$) and cold ($T_p \approx 2eV$) plasma near the target. These include inelastic collisions (electron impact ionization and excitation of atomic hydrogen, and the most important molecular dissociation processes. The required cross-sections are taken from [3]. Elastic collisions of electrons with neutrals are taken into account in the BGK approximation.

The non-stationary kinetic equation with a self-consistent parallel electric field is solved numerically by using the time-dependent 1D2V Fokker-Planck code ALLA [3]. We run the code until equilibration of the distribution function is achieved.

We present results of our simulations, where we study the sensitivity of the electron distribution function to the fraction of minority electrons introduced in the plasma source.

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Relaxation Theory of a Two-Fluid Plasma

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The relaxation of a two-fluid plasma differs markedly from the more restrictive single-fluid model. In particular, it possesses two robust invariants instead of one: the ion and electron self helicities. [In a modified two-fluid (massless electrons) the electron self helicity is equivalent to the magnetic helicity of a single fluid.] The robustness of the electron and ion self helicities in a weakly-dissipative plasma is defended using both cascade and selective decay arguments; key to this approach is the postulate that the flow-field coupling is dominated (at each wave number) by the lowest-energy turbulent mode. Relaxed equilibria are found by minimizing the energy (flow kinetic plus magnetic) subject to constraints on the self helicities. These relaxed states can have finite beta (in contrast to the single-fluid theory which admits only force-free states). Moreover, strongly sheared flows appear in all finite-beta relaxed states. Two-fluid relaxed equilibria are computed that correspond to reversed-shear tokamaks, field reversed configurations (FRC), as well as reversed field pinches and spheromaks. The presence of a relaxed state may explain the internal structure of FRCs and their remarkable stability in experiments. It is also a tantalizing explanation for low transport in reversed-shear tokamaks: although relaxation is impeded there by ideal stability, near-relaxed states may be artificially created; this could turn off anomalous transport because of the absence of free energy.

Outward momentum transport and inward coupled particle flow in accretion disks and laboratory plasmas*

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In order to gain insight into the processes which are responsible for the outward angular momentum transport and the inward particle transport characterizing accretion structures[1] such as disks, a simple plane one dimensional plasma configuration is introduced.[2] Important features of this are: a gravity force directed as the density gradient and perpendicular to a slightly inhomogeneous magnetic field and a plasma flow velocity which is nearly parallel to the magnetic field. The gradient of the plasma flow velocity is perpendicular to it and in the same direction as the density gradient. Collective modes capable of transporting momentum and particles in opposite directions are then found.

The excited modes involve the combined effects of the velocity gradient, of the gravity acceleration, and of the violation of the frozen-in constraint by the effects of a finite diffusion coefficient D_m of the plasma current density. One type of mode has relatively short wavelengths in the direction of the velocity flow. The other, which strongly depends on the magnetic field shear, propagates perpendicularly to the magnetic field on a given mode-characteristic surface and has a frequency and a growth rate proportional to $D_m^{1/3}$. The latter type of mode is applicable to toroidal rotating plasmas where the average magnetic field curvature is in the direction of the density gradient and has a similar effect to that of a "favorable" gravity force.

It is pointed out that a different electrostatic mode due to the combined effects of a favorable gravity force, the plasma diamagnetic velocities and magnetic shear was found earlier [3] for strongly collisional regimes.

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PIES Analysis of DIII-D ITER-Like Discharges

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Mirnov data has implicated tearing modes as the cause of poor performance on some DIII-D, long pulse ITER-like discharges. Performance increased as the density increased, which has led to speculation that the current profile modifications caused by the higher density leads to equilibria more stable to tearing modes. This talk is concerned with determining the correctness of this conjecture by comparing the results of the 3-D equilibrium code, PIES [1], with experimental observations. For this purpose six time slices from five different shots have been analyzed. These cases exhibit three possible states for tearing modes; saturated, nonexistent and onset for both the 3/2 and 2/1 modes. (Here the ratios denote m/n, with, m, the poloidal mode number and, n, the toroidal mode number). Prediction of the state of the 3/2 and 2/1 islands from the PIES code will be compared with the experimental results.

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The Dynamics of Transitions in Models of Internal Transport Barriers*

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The seeming universality of the L to H type transition in fusion confinement devices has led to the development of transport models to explain the experimental features of this transition [1]. It is thought that the sheared radial electric field plays a major role in reducing the turbulence, thus allowing the formation of a transport barrier. In this work, the transition is obtained through the nonlinear coupling between the envelope equations for the density fluctuation level and the radial electric field shear [2]. Building on the experience gained from the work on L-H transition dynamics a model for internal transport barrier formation has been developed [3]. This model consistently evolves the transport equations for the temperatures, particle density and toroidal flow profiles. Any mechanism that promotes a locally larger growth of the electric field shear relative to the ion temperature gradient driven instability can give a local quenching of the turbulence. This, in turn, helps the system stay over the critical values for the transition, but it is found that both these critical values and the fixed points for the model strongly depend on the dynamics of the fluctuation level. This dependence is investigated with various versions of the transition/transport model in order to determine the importance of various effects. Trends with respect to density, power deposition and magnetic field are found to be in agreement with analytic predictions based on dimensional analysis, while high sensitivity is found to the fluctuation dynamics at the triggering of the transition.

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Enhanced flexibility of EPEIUS: a small aspect-ratio torsatron-tokamak hybrid with extra TF and VF coils*

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One major goal in the design of the small aspect-ratio torsatron-tokamak hybrid EPEIUS[1] is to allow maximum flexibility in terms of configurations which can be achieved without modifying its basic coil set. Small vertical and toroidal field coils included in the design, when used with even small plasma current, allow significantly increased flexibility and control at low extra cost. We believe this flexibility is due to the robustness[2] of the optimized[3] low aspect ratio equilibrium we have found in collaboration with ORNL[4,5].

Here we present the results of a systematic study of the wide range of equilibria accessible within the current and power limits of the EPEIUS coil set and power supplies. Our studies, which are conducted using the equilibrium code VMEC[6] and the field line code HOMER[2], show that interesting plasma parameters such as iota profile, helical ripple, major radius, aspect ratio, and beta can each be varied individually while holding most others constant by using the three independent extra controls, viz. plasma current, vertical field, and toroidal field. We show that adding a small amount of plasma current to the basic torsatron equilibrium significantly enhances the flexibility and control. We outline controlled experiments addressing physics issues regarding equilibrium, transport[7], and disruptions which can be conducted on EPEIUS using this enhanced flexibility.

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SELF-ORGANIZED CRITICAL GRADIENT TRANSPORT THEORY — COMPARISON WITH THE STELLAR TRANSPORT

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The stellar energy transport in the opaque stellar atmosphere has been analyzed by the scientists such as Schwarzschild, Prandtl, and Spiegel. The convective instability sets in when the Rayleigh number exceeds the critical Rayleigh number R_{ac}, the Schwarzschild's superadiabaticity. In most stars, when the Rayleigh number exceeds much beyond the critical number, the convective transport becomes too great so that the core temperature cools down, to such an extent that the temperature gradient is maintained very close to the marginality. This is because the cell size of the convectively unstable modes is of the macroscopic scale.

In the (ion) temperature gradient (ITG) instability of tokamak plasmas in which once again the "cell size" of the ITG turbulence is of a "macro-scale"; in this case the "macro-scale" is caused by the toroidicity of the tokamak plasma, which introduces the vortical size typically of the geometrical means of the minor radius and the gyro radius. The effective Rayleigh number of the ITG is defined (a function of kinetic effects such as the gyroradius in this case). The small deviation away from the marginality and its properties of transport are similar in many respects to those of stellar transport, except that the smallness of deviation is less excessive, as the kinetic effects influence here. Intermittent bursty-effects such as the ELM's may again not be so asimilar to those in some of stellar pulsations (including Cepheids, etc.).

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ON THE WAY TO A STELLARATOR-SPHEROMAK*

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An enormous potential payoff of a spheromak as a fusion reactor has sustained the spheromak research for many past years. Spheromaks differ markedly from many other toroidal systems as they do not have any material structures such as magnet coils or conducting walls linking the torus. Another distinguished peculiarity of a spheromak is that the magnetic field structure is self-generated by the large internal plasma currents, and the toroidal and poloidal magnetic field components have comparable magnitudes. Among main advantages of spheromaks are compact and simple magnetic field geometry with a natural divertor, supporting the high energy density plasma, nearly force-free equilibrium minimizing stresses, and a simply connected fusion blanket. However, the experimentally obtained spheromak plasmas are short-living, even when they are confined in flux conservers. For fusion reactor applications, however, it is important to have the long-living spheromak plasma (better if it will be steady-state), and without the flux conserver.

In our work, a novel concept (we call it Stellarator-Spheromak (SSP)) is discussed, which might be able to resolve the above mentioned spheromak problems while maintaining the main advantages of a spheromak. This type of fusion device represents a hybrid between a stellarator and a spheromak. It is clear, of course, that one cannot use the standard stellarator coils in a spheromak as they encircle the plasma in poloidal direction and go through the central hole. However, the opportunity for SSP exists in modifying a Spherical Stellarator (SS) [1-3] device equipped with the Outboard Stellarator Windings (OSW), recently discussed in [4-5]. Here, we present the initial results of calculations for SSP carried out via the field-line tracing code, UBFIELD (see, for example, [6]), and the MHD equilibrium code, VMEC [7], running in its free-boundary mode. In searching for the suitable SSP configuration, we took the following approach. First, we have found an efficient SS coil configuration utilizing OSW and capable of producing the strong stellarator effects, such as existence of closed vacuum flux surfaces with significant enclosed volume and appreciable rotational transform. Transition to the corresponding SSP is made by gradual decreasing of the current in TF coils to zero (removing the TF coils) and adjusting the plasma current magnitude and profile, plasma pressure, and the enclosed toroidal magnetic flux. We were successful in obtaining a 3D low-aspect-ratio equilibrium, $A \approx 1.5$, with central β, $\beta(0) = 90\%$, volume average β, $\langle\beta\rangle = 21\%$, and the total rotational transform $\iota > 1$ everywhere in the plasma.

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3C32

Bounce–Averaged Fast Wave Current Drive Calculations in General Toroidal Geometries*

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In advanced toroidal devices, plasma shaping can have a significant effect on quantities of interest, including the radio frequency(RF) deposited power and current. Most 2D RF modeling codes use a parameterization [1] of current drive efficiencies to calculate fast wave driven currents. This parameterization is derived from a ray–tracing model in a low–beta equilibrium. There are difficulties in applying it to a spectrum of waves, and it cannot account for multiple resonances and coherency effects between the electrons and the waves. We show how the parameterization can be adapted for a spectrum of waves to account for coupling of poloidal modes by the magnetic field's inhomogeneity. To account for trapped particle effects, we introduce a bounce–averaged model. Using real numerical equilibria from the JSOLVER code, we compare the trapped particle model in the parameterization with a direct bounce–averaged quasilinear flux model in general toroidal equilibria.

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Comparison of C++ and Fortran 90 for Object-Oriented Scientific Programming

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Abstract
for 1997 International Sherwood Fusion Theory Conference

C++ and Fortran 90 are compared as object-oriented languages for use in scientific computing. C++ is a full-featured, object-oriented language that provides support for inheritance and polymorphism. Fortran 90 can mimic some object-oriented features through combinations of its TYPE and MODULE syntax elements, but it lacks inheritance and thus does not permit code reuse to the same extent as C++. Each language has other useful features unrelated to object-oriented programming, but the additional features of Fortran 90 can be included in C++ through the development of class libraries. In contrast, including the additional features of C++ in Fortran 90 would require further development of the Fortran 90 syntax. A critical feature missing in Fortran 90 is the template, which allows C++ programmers to build portable, reusable code and to dramatically improve the efficiency of the evaluation of complex expressions involving user-defined types.

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MHD Stability Analysis of Shear Optimised Discharges in JET

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The improved confinement in JET shear optimised discharges leads to very peaked pressure profiles in the L-mode phase without edge pedestals. If the plasma stays in L-mode the discharge usually ends in a disruption. The disruption can be avoided by triggering an L to H transition, thereby broadening the pressure profile by increasing the edge pressure gradient. The SXR data displays a pronounced precursor to the disruption. Tomographic reconstruction of the precursor shows a perturbation in the plasma center with dominant poloidal harmonics $m = 1$ and $m = 2$. The toroidal mode number is $n = 1$. Initially, at small amplitude the mode rotates with a frequency of 25 kHz. As the amplitude increases the mode slows down and locks to the wall leading to a disruption.

The MHD stability of a number of shear optimized discharges has been analysed using the newly developed MISHKA1 [1] ideal MHD stability code. The results show that due to the very peaked pressure profile, an ideal $n = 1$ infernal mode with poloidal mode numbers $m = 1$ and $m = 2$ becomes unstable as β increases and q on axis (q_0) decreases in time. The value of $\beta_p ol$ where the $n = 1$ infernal mode is marginally stable is about 0.6 for $1.2 < q_0 < 1.7$, corresponding to a normalized β_N of 1.3. For lower q on axis this value drops sharply. The critical value of β_{pol} agrees well with the experimental value where the disruption occurs.

Reducing the peaking factor of the pressure profile can stabilise the mode. Adding an edge pedestal to the peaked pressure profile also has a stabilizing effect in agreement with the observed stabilizing effect of an L-H mode transition.

Detailed comparison of the mode structure obtained from tomographic inversion of the SXR data with the calculated $n = 1$ mode structure of the infernal mode shows good agreement.

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Hamiltonian Formulation of Magnetic Field-Lines with Symmetry and Relabeling Symmetry in Fluid Systems

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Magnetic field-line equations are known to have a Hamiltonian formulation that involves representation of the magnetic field in terms of the vector potential [1] or in terms of other scalar potentials. Recently in [2] a new Hamiltonian formulation, which is not based upon a potential representation, was given for the flow lines of divergence-free vector fields. We review this new formulation and introduce an associated noncanonical Hamiltonian formulation.

In the second part of this poster we show that the Lagrangian formulation of an ideal, compressible fluid possessing three thermodynamic variables exhibits relabeling symmetry. This symmetry leads to a conservation law similar to Ertel's theorem for fluids with two thermodynamic variables. Additionally we describe the (non-point) Lie symmetries corresponding to Ertel's theorem [3] and fluid helicity.

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Singular Hamiltonian Equations and Explosive Non-periodic Phenomena*

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Plasmas have been observed to produce bursts, or explosive instabilities, that are events of brief duration and involving large excursions of relevant physical quantities at regular time intervals or in a random fashion. Recently, to model these events, sets of two nonlinear coupled equations (one for the fluctuation amplitude and one for its driving factor) involving characteristic singularities have been introduced. A Hamiltonian function for these equations has been found, and two distinct cases [1] have been considered: one in which a divergence in a physical parameter involves an infinite value for the Hamiltonian, and one in which the parameter can diverge while the Hamiltonian remains finite. The relationship between the process described by these equations and those described by more traditional models of intermittency phenomena [2] is pointed out.

Random bursting can be produced by a set of two nonlinear equations when one of the coefficients entering these equations has a time dependence that is not related to the intrinsic nonlinear period of the system. A specific analysis of this case, starting from the Hamiltonian that is found when all coefficients are time independent, has been carried out. The considerations have been restricted to the case in which an infinite Hamiltonian is connected with the divergence of either the fluctuation amplitude or the driving factor.

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Suppression and Control of Ideal and Resistive MHD instabilities

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The realization of a practical tokamak reactor is dependent on three major physics issues, stability, confinement and power and particle handling. Of these three, stability, especially of the very fast growing MHD modes is of critical importance, both for achieving the plasma parameters of a reactor as well as for safe operation of the machine. While the need for achieving MHD stability has been widely recognised, the means to achieve it has been pursued sporadically, with limited results. We will review the results of past feedback experiments and outline several options for stabilizing both ideal and resistive MHD instabilities in present and proposed experiments. This work was supported in part by DoE Contract No. DE–AC02–76–CHO–3073.

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Boundary Effects on the Alfven Wave Resonance

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We consider a configuration where the magnetic field lines enter the plasma boundary. This situation occurs in the scrape-off layer of divertor tokamaks but is more common in space plasmas. The boundary conditions we impose[1] are not the usual line-tying but rather allow for wall insulation and/or resistivity. Significantly, the boundary conditions affect the different MHD waves differently, with the Alfven waves "feeling" the wall resistivity while the fast mangetosonic waves do not. As a result, the field line resonance phenomenon is modified greatly by the shift in the Alfven spectrum.

It is still possible to solve the resonance problem asymptotically for slowly varying plasma profiles. We use a boundary layer analysis with an "outer" solution describing a fast wave, and an "inner" solution about the (nearly) resonating field line. It is possible to give an exact integral representation to the "inner" problem so that a connection can be made. Interestingly, the amplitude of the excited Alfven wave is much smaller than in the usually treated case.

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Using Adaptive Grids to Simultaneously Simulate Stiff Confinement Models and MHD Evolution in the ONETWO Transport Code

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A characteristic of turbulent confinement models in tokamaks is that the associated transport equations can exhibit a very large and rapid spatial variation in the effective diffusion coefficient over different parts of the plasma as the density and temperature evolve. This stiff behavior can lead to nonphysical numerical simulation results unless modifications of the existing solution schemes are made. An additional complication arises due to MHD equilibrium evolution which must be accounted for if accurate simulations are to be done. In the standard transport formulation the MHD modeling will require a moving grid. Simultaneously to resolve and stabilize the critical gradients in the confinement models, a dynamic grid packing scheme is called for. In the present work we investigate this behavior and show how an appropriately designed adaptive grid strategy can be used to satisfy both the confinement and MHD restrictions. Using unconditionally stable solution methods ensures that no adverse interaction between space and time discretization occurs. Time dependent MHD equilibrium information, obtained from detailed kinetic equilibrium analyses, are incorporated into the solution scheme. Several examples of application to DIII–D discharges are presented.

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Low *n* Kink Stability of Low Aspect Ratio Toroidal Confinement Systems

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The Spherical Torus concept has the potential to achieve stability at high β values. This potential is based on extrapolation of the optimized ideal ballooning and kink β limit (Troyon) scaling with current to low aspect ratio, and on the high current-carrying capacity of a low aspect ratio torus with $q > 2$. Even higher β values are in principle achievable with stabilization of the kink modes by a moderately placed wall. However, numerical calculations at low aspect ratio are generally difficult due to the large number of rational surfaces that are present for conventional current density profiles; even the flat Solov'ev profiles result in a ratio of $q_{edge}/q_0 \sim 100$ at an aspect ratio $A \sim 1.2$, compared to a ratio of order 1 at conventional aspect ratios.

Optimization of the β limit against ideal kink and ballooning modes over the conventional range of current profiles is therefore a numerically daunting task. Another serious issue for the Spherical Torus is the question of driving the large currents in steady state, given the efficiency of the presently available non-inductive current-drive schemes. One approach to solving these two issues simultaneously is to consider profiles that are restricted so that essentially 100% of the current is driven by the neoclassical bootstrap current. With a reasonable parameterization of the pressure profile, this leaves the position of the peak pressure gradient as the single profile parameter, and this can be optimized for ballooning stability iteratively with the equilibrium calculation. The kink stability is then considered by determining the position of the stabilizing wall at which the $n = 0$, 1, 2, and 3 modes are stabilized for the ballooning-optimized equilibria. Numerical accuracy of the low n calculations is maintained by extensive convergence studies with increasing mesh size and extrapolation to infinite resolution.

The Spherical Torus has been optimized using this procedure for a wide range of cross sections. Ballooning optimized β_N values $[\beta_N \equiv \beta/(I/aB)]$ of the order of 7 to 8 are possible for a fully bootstrap driven Spherical Torus with $A \sim 1.4$ and vanishing edge pressure. These optimized equilibria are stable to $n \leq 3$ modes with a conformal wall at 1.2 times the minor radius. This corresponds to β values of $\sim 60\%$. With finite edge pressure, $\beta_N \sim 10$ is possible — this corresponds to $\beta \sim 70\%$. Comparison of these results with other low aspect ratio configurations, such as Spheromaks and low aspect ratio Field Reversed Configurations has also been performed. These configurations can also yield interesting β limits, but preliminary results show them to be significantly lower than the corresponding Spherical Torus limits.

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Global Modeling of Non-Axisymmetric Disruptions and Halo Currents in Tokamaks

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The modeling of halo currents, large currents which flow in tokamak vacuum vessels as a result of contact with bulk plasma during a disruption, is an important aspect of the design of ITER as well as a necessity for ensuring the structural integrity of existing experiments when run at maximum specifications. A new model has been developed to study a class of non-axisymmetric force-free disruptions and the resulting halo and eddy currents, using a nested sheet-current model for the disrupting plasma and chamber wall. By focusing on the global electrodynamic interaction between the wall and plasma instead of trying to capture detailed disruption physics, the model produces complete, time-dependent J×**B** profiles without requiring excessive computation time, lending itself to engineering design studies. A fast, workstation-based code called TSPS-3D has been written to solve the sheet current model; comparisons of simulations with experimental data from the Alcator C-MOD experiment will be presented, along with a set of investigative runs showing that force-free plasmas tend to produce force-free halo currents, and that eddy currents play the dominant role in loading the vacuum chamber.

Development of Implicit 3D Fluid Turbulence Code in SOL Plasmas with X-Point Geometry*

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During to the complication of magnetic shear, we are unable to conduct 3D simulations with real x-point geometry in our simulation code using an explicit time advance scheme. We are currently reprogramming the code by using implicit CVODE/PVODE PDE integrator. CVODE/PVODE is a solver for stiff and non-stiff initial value problems for systems of ordinary differential equation. The robust preconditioned iterative integrator has been demonstrated in the UEDGE transport code. We have tested this PDE integrator in our 2D non-local Hasagawa-Wakatani code for the parameter $\alpha >> 1$ and have obtained saturated states on a reasonable time scale short compared to our previous explicit code. The implementation of real x-point geometry and the electron inertia will be discussed. The effects of magnetic shear and electron inertia on the turbulence will be reported.

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Arnold Diffusion in the Standard Map

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The evolution of any pair of canonical coordinates of an arbitrary Hamiltonian is given by a Hamiltonian of one and a half degree of freedom H(q,p,t). An arbitrary action evolves stochastically if H is aperiodic in time [1]. We use the Standard Map with aperiodic perturbation

$$r_{n+1} = r_n - \frac{k}{2\pi} \sin(2\pi\theta_n)$$

$$\theta_{n+1} = \theta_n + r_{n+1}$$

where

$$k = k_0 + \delta \sin(n).$$

δ is the amplitude of the aperiodic perturbation, and n is iteration number. We are attempting to calculate the number of iterations N as a function of the parameter δ for which a given good surface (of the periodic Standard Map) Arnold diffuses by the same amount when k_0 is held constant. This will tell us how long it takes for the trajectories to Arnold diffuse as the aperiodic perturbation becomes arbitrarily small. We will present the results of this study.

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The Low MN Map for a Single-Null Divertor Tokamak

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The Low MN Map represents the magnetic topology of a single-null divertor tokamak with a stochastic layer including the effects of low MN perturbation [1]. The Low MN Map is given by

$$x_{n+1} = x_n - k y_n \left[1 - y_n - \delta\, y_n \cos\left(\frac{2\pi (n+1)}{N_p} \right) \right]$$

$$y_{n+1} = y_n + k x_{n+1} \left[1 + \delta \cos\left(\frac{2\pi (n+1)}{N_p} \right) \right]$$

where k is the Simple Map parameter [2,3], and δ is the amplitude of low MN perturbation. This perturbation adds the effect of two quadrupoles with opposite helicity of toroidal mode number ±1. N_p represents the number of iterations of the Simple Map which is equivalent to a single toroidal circuit of tokamak for a given q_{edge}. We employ the Low MN Map to calculate the trajectories of the field lines in the stochastic layer of a single-null divertor tokamak with low MN perturbation. We also calculate the footprint of field lines on the collector plate. We keep the width of the stochastic layer and the edge safety factor, q_{edge}, approximately constant. We choose appropriate combinations of (k, δ, N_p) to satisfy these constraints. Here we will present the results of this study.

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Three-Dimensional Computation of Drift Alfvén Turbulence

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A transcollisional, electromagnetic fluid model, incorporating the parallel heat flux as a dependent variable, is constructed to treat electron drift turbulence in the regime of tokamak edge plasmas at the L-H transition. The resulting turbulence is very sensitive to the plasma beta throughout this regime, with the scaling with rising beta produced by the effect of magnetic induction to slow the Alfvénic parallel electron dynamics and thereby leave the turbulence in a more robust, nonadiabatic state. Magnetic flutter and curvature have a minor qualitative effect on the turbulence mode structure and on the beta scaling, even when their quantitative effect is strong. Transport by magnetic flutter is small compared to that by the ExB flow eddies. Fluctuation statistics show that while the turbulence shows no coherent structure, it is strongly enough coupled that neither density nor temperature fluctuations behave as passive scalars. Both profile gradients drive the turbulence, with the total thermal energy transport varying only weakly with the gradient ratio, d log T/d log n. Scaling with magnetic shear is pronounced, with stronger shear leading to lower drive levels. Scaling with either collision frequency or magnetic curvature is weak, consistent with their weak qualitative effect. The result is that electron drift turbulence at L-H transition edge parameters is drift Alfvén turbulence, with both ballooning and resistivity in a clear secondary role. The contents of the drift Alfvén model will form a significant part of any useful first-principles computation of tokamak edge turbulence.

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