1995 International Sherwood Fusion Theory Conference *April 3-5, 1995 Incline Village, Nevada*

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April 3-5, 1995
Incline Village, Nevada

Hosted by
Lawrence Livermore National Laboratory
University of California

1995 International Sherwood Fusion Theory Conference

April 3-5, 1995

Hyatt Regency
Incline Village, Nevada

Hosted by

Lawrence Livermore National Laboratory
University of California
Livermore, CA

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General Information

- 217 papers were submitted, 13 of which were selected for oral presentation. In addition, there are three review papers.
- The review papers will be presented in the Regency Ballroom at 8:30 a.m. Monday through Wednesday.
- The oral papers will be presented in the Regency Ballroom at 9:30 a.m. Monday through Wednesday.
- All poster sessions will be held in the Regency Ballroom, Salons E and F, on Monday from 2:00-6:00 p.m., Tuesday from 7:00-9:00 p.m., and Wednesday from 10:30 a.m. to 12:30 p.m.
- A Reception will be held for all attendees on Sunday evening from 7:00-9:00 p.m. in Lakeside B and C.
- A Companions' breakfast will be held on Monday morning at 9:00 a.m. in the Ciao Mein Trattoria.
- Coffee will be served in the Lower Lobby Monday through Wednesday mornings at 9:15 a.m.
- Soft drinks and beer will be served in the Lower Lobby on Monday afternoon at 3:30 p.m. and Tuesday at 6:00 p.m.
- A buffet will be served in the Lower Lobby on Tuesday at 6:00 p.m. and coffee will be served at 8:00 p.m.
- Requests for special meetings should be made at the Conference Registration Desk.
- Registration for the Numerical Tokamak Workshop will begin at 8:00 a.m. on Wednesday, April 5 in the Upper Lobby. The Workshops will be held on Wednesday afternoon and all day Thursday.

Hyatt Regency Incline Village
April 3-5, 1995

Registration Schedule

Location: Upper Lobby

Sunday	April 2 – 4:00 a.m. - 7:00 p.m.	
Monday	April 3 – 7:30 a.m. - 5:00 p.m.	
Tuesday	April 4 – 8:00 a.m. - 12 noon	
	6:00 p.m. - 7:00 p.m.	
Wednesday	April 5 – 8:00 a.m. - 12 noon	

Oral and Poster Session Schedule

Review and Oral Presentations	Regency Ballroom
Poster Presentations	Regency Ballroom, Salons E and F

MONDAY

8:20 a.m.	Welcome	T.B. Kaiser, Chairman	
8:30 – 9:20 a.m.	1A	Review Paper	M.E. Schlesinger
9:30 – 12 noon	1B	Oral Session	5 30-minute talks
2:00 – 4:00 p.m.	1C	Poster Session	51 poster papers
4:00 – 6:00 p.m.	1D	Poster Session	51 poster papers

TUESDAY

8:30 – 9:20 a.m.	2A	Review Paper	R.L. Berger
9:30 – 10:30 a.m.	2B	Oral Session	2 30-minute talks
10:30 a.m. - 12:30 p.m.	2C	Oral Session	4 30-minute talks
7:00 – 9:00 p.m.	2D	Poster Session	51 poster sessions

WEDNESDAY

8:30 – 9:20 a.m.	3A	Review Paper	G.M. McCracken
9:30 – 10:30 a.m.	3B	Oral Session	2 30-minute talks
10:30 a.m. – 12:30 p.m.	3C	Poster Session	51 poster papers

Coffee	Monday through Wednesday at 9:15 a.m. Tuesday at 8:00 p.m.
Soft Drinks and Beer	Monday at 3:30 p.m. Tuesday at 6:00 p.m.

MONDAY ORAL PRESENTATIONS

Welcome	T.B. Kaiser, Chairman
8:20 a.m.	
Review Paper 1A	R. Waltz, presiding
8:30 a.m.	M.E. Schlesinger, *To Abate or Not to Abate? – That is the Greenhouse Question*
Oral Session 1B	R.G. Kleva, presiding
9:30 a.m.	M.A. Beer, *Bounce-Averaged Electron Fluid Equations: ITG and TEM Driven Transport*
10:00 a.m.	W. Dorland, et al., *Turbulence and Transport Simulations*
10:30 a.m.	A.M. Dimits, et al., *Implications of Gyrokinetic Simulations on the Role of ITG Turbulence in Tokamak Transport*
11:00 a.m.	J.B. Taylor, et al., *Structure of Short -Wavelength Modes in a Toroidal Plasma*
11:30 a.m.	A. Zeiler, et al., *3-D Tokamak Edge Turbulence*

TUESDAY ORAL PRESENTATIONS

Review Paper 2A	T.B. Kaiser, presiding
8:30 a.m.	R.L. Berger, *Plasma Physics Phenomena in ICF*
Oral Session 2B	T.S. Hahm, presiding
9:30 a.m.	W. Park, et al., *Nonlinear 3D Simulation Studies of High-β Disruptions in TFTR*
10:00 a.m.	Y. Wu, et al., *Nonlinear Evolution of the Alpha Particle Driven Toroidicity-Induced Alfvén Eigenmode*
Oral Session 2C	R. Fitzpatrick, presiding
10:30 a.m.	D.J. Ward, *Resistive Wall Stabilization of External Kink Modes in Tokamaks with Partial Poloidal Walls*
11:00 a.m.	A.Y. Aydemir, et al., *Resistive MHD Stability in Small Aspect RatioTokamaks*
11:30 a.m.	B. Rogers, et al., *Nonlinear ω_* - Stabilization of the m=1 Mode inTokamaks*
12 noon	J.M. Finn, *New Parallel Velocity Shear Instability*

WEDNESDAY ORAL PRESENTATIONS

Review Paper 3A	P.J. Catto, presiding
8:30 a.m.	G.M. McCracken, *Experimental Data for Edge Model Validation*
Oral Session 3B	B. Braams, presiding
9:30 a.m.	K. Kupfer, et al., *Kinetic Modeling of SOL Plasmas*
10:00 a.m.	S. Rauf, et al., *Low Frequency Current Drive Utilizing Nonlinear and Spatial Inhomogenieity Effects*

1995 INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE

HYATT REGENCY LAKE TAHOE
INCLINE VILLAGE, NEVADA
APRIL 3-5, 1995

REGISTRATION

Upper Lobby

Sunday,	April 2	4:00 p.m. - 7:00 p.m.
Monday,	April 3	7:30 a.m. - 5:00 p.m.
Tuesday,	April 4	8:00 a.m. - 12 noon
		6:00 p.m. - 7:00 p.m.
Wednesday,	April 5	8:00 a.m. - 12 noon

RECEPTION

Lakeside B-C 7:00 p.m. - 9:00 p.m.

M O N D A Y M O R N I N G

WELCOME

8:20 a.m. - T. B. Kaiser, Local Chairman

1A REVIEW TALK

Regency Ballroom

8:30 a.m. - 9:20 a.m.

Presiding: R. Waltz

1A1. To Abate or Not To Abate?--That is the Greenhouse Question. M.E. Schlesinger.

1B ORAL SESSION

Regency Ballroom

9:30 a.m. - 12 noon

Presiding: R.G. Kleva

1B1. Bounce-Averaged Electron Fluid Equations: ITG and TEM Driven Transport. M.A. Beer.
1B2. Turbulence and Transport Simulations. W. Dorland, M. Kotschenreuther, M.A. Beer, G.W. Hammett, and R.E. Waltz.
1B3. Implications of Gyrokinetic Simulations on the Role of ITG Turbulence in Tokamak Transport. A.M. Dimits, T.J. Williams, J.A. Byers, and B.I. Cohen.
1B4. Structure of Short-Wavelength Modes in a Toroidal Plasma. J.B. Taylor and H.R. Wilson.
1B5. 3-D Tokamak Edge Turbulence. A. Zeiler, J.F. Drake, and D. Biskamp.

MONDAY AFTERNOON

1C POSTER SESSION

Regency Ballroom

2:00 - 4:00 p.m.

1C1. Control of Shear Flow Profiles Via External Velocity Perturbations. R. Fitzpatrick.
1C2. MHD-Vlasov Simulation of the Toroidal Alfven Eigenmode. Y. Todo, T. Sato, K. Watanabe, T.H. Watanabe, and R. Horiuchi.
1C3. Eliminating Locked Mode Instabilities in Tokamaks. J.D. Hanson.
1C4. Application of Hyperviscosity to the Study of Long Wavelength Modes in 3D Gyrofluid Tokamak Turbulence. S.A. Smith and G.W. Hammett.
1C5. Non Perturbative Kinetic Effects on Alfven Eigenmodes in Tokamak Plasmas. A. Jaun, K. Appert, J. Vaclavik, and L. Villard.
1C6. The Neoclassical Method for Calculating Fluctuation Driven Shear Flows in Tokamaks. W. Horton and H. Sugama.

1C7. Transport Fluxes in H-Mode Bifurcated Layer. K.C. Shaing.
1C8. Influence of Momentum Conservation on the Ambipolar Electric Field and the Heat Flux in 2D Fokker-Planck Edge Modeling. N.A. Kuzmichova, A.P. Smirnov, R.W. Harvey, and K. Kupfer.
1C9. An Alternate Nonperturbative Method of Treating Alpha-Alfven Waves for Examining Sensitivities to the Alpha Distribution Function. C.L. Hedrick, J.-N. Leboeuf, M.D. Prochaska, D.A. Spong, and B.A. Carreras.
1C10. Fast Wave Driven Alpha Current and Its Implication to Current Profile Control by FWCD in a Tokamak Reactor. C.S. Chang and D. Van Eester.
1C11. Ideal MHD Analysis of TFTR Discharges. S. Migliuolo, J.P. Freidberg, J. Kesner, and J.J. Ramos.
1C12. Fokker-Planck Simulation of Electron Transport in Scrape-off Layer. A.A. Batishcheva, M.M. Shoucri, O.V. Batishchev, S.I. Krasheninnikov, D.J. Sigmar, and I.P. Shkarofsky.
1C13. The Two Fluid Model and Stabilization of the m=1, n=1 Mode in a Tokamak. L.E. Sugiyama and W. Park.
1C14. Self-Organized Criticality as a Paradigm for Turbulent Transport. D.E. Newman, B.A. Carreras, and P.H. Diamond.
1C15. Investigation of Neoclassical Tearing Instability in TFTR. Z. Chang, E.D. Fredrickson, R.V. Budny, A. Janos, K.M. McGuire, M.C. Zarnstorff, TFTR. Team, J.D. Callen, C.C. Hegna, and M. Zabiego.
1C16. 3D Nonlinear Simulations of Drift-Resistive-Ballooning Modes in the Scrape-Off-Layer in Tokamak Plasmas. P.N. Guzdar and S.V. Novakovski.
1C17. Coupling of Slow Lower Hybrid Waves at the Plasma Edge: pondermotive effects, density cavitons and mode conversion. J. Preinhaelter, L. Vahala, and G. Vahala.
1C18. Electron Acceleration by Super Ion-Acoustic Double Layer. H. Takamaru, T. Sato, R. Horiuchi, K. Watanabe, T. Hayashi, Y. Todo, T.H. Watanabe, and A. Kageyama.
1C19. Slow Linear and Nonlinear Thermal Wave Propagation in Radiative Plasmas. D.Kh. Morozov and J.J.E. Herrera.
1C20. Singular Eigenfunctions for Shear Flow. N.J. Balmforth and P.J. Morrison.
1C21. Stellerator Properties of Tokamaks With Inclined Toroidal Field Coils. P. Moroz.
1C22. A Cure for Locked MHD Modes and Their Feedback Control. A.K. Sen.
1C23. Nonlinear Radiative Condensation in a Divertor Plasma During ELM Activity. P. Helander and S.I. Krasheninnikov.
1C24. Global Gyrokinetic Particle Simulation Studies on Isotope Effects. W.W. Lee, R.A. Santoro, S.E. Parker, and H.P. Furth.
1C25. Stability of the m=1 Top. F.L. Waelbroeck, A.Y. Aydemir, and R.L. Miller.
1C26. Simulation of Divertor Plasmas With a Combined Edge Plasma/Navier-Stokes Neutral Transport Model. D.A. Knoll, P.R. McHugh, S.I. Krasheninnikov, and D.J. Sigmar.
1C27. Resistive Wall Mode Analysis for PBX-M Using the Nova-W Code. N. Pomphrey, D. Ward, J. Manickam, and M. Okabayashi.
1C28. Two-Dimensional Radial Structures of Alfven Modes Excited by Energetic Particles in Tokamaks. F. Zonca and L. Chen.
1C29. MHD Stability of Simulated ITER Discharges in DIII-D. A.D. Turnbull, L.D. Pearlstein, D. Bulmer, L.L. Lao, S.J. Thompson, T.C. Luce, C.M. Greenfield, and M.N. Rosenbluth.
1C30. 2-D WKBJ-Ballooning Approach to High-n TAE Modes. C.T. Hsu, C.Z. Cheng, L. Chen, G.Y. Fu, G. Rewoldt, and W.M. Tang.
1C31. Current Diffusion and Loop Voltage Response to a Noninductive Current Drive in a Tokamak. C. Litwin, N. Hershkowitz, and S. Wukitch.
1C32. Rapid Guiding Center Calculations. R.B. White and A.H. Boozer.
1C33. Divertor Modelling for Reactor. B.J. Lee, B. Merriman, L. Schmitz, and F. Najmabadi.
1C34. 3D Fluid Simulations of Turbulences in Detached SOL Plasmas. X.Q. Xu and R.H. Cohen.
1C35. Ballooning Stability of Supersonic Flows. R. Young and E. Hameiri.

1C36. 1D Model of the Transport of the Plasma and Neutrals in the Divertor Layer. A.S. Kukushkin and S.I. Krasheninnikov.
1C37. Symbolic Analysis of Turbulent Fluctuations. A.B. Rechester and R.B. White.
1C38. Modelling of Neon Puffing and Pumping in ITER Divertor. S. Ohtsu and B.J. Braams.
1C39. Analytical Estimation of NBI Heating Efficiency and Plasma Beta in Heliotron/Torsatrons. S. Murakami, N. Nakajima, S. Okamura, and M. Okamoto.
1C40. Study of a Divertor Plasma in E x B Flow. G. Manfredi, M. Shoucri, I. Shkarofsky, P. Bertrand, A. Ghizzo, S. Krasheninnikov, D. Sigmar, O.V. Batishchev, and A.A. Batishcheva.
1C41. Extensions of the TAE/FL Toroidal Alfven Time Evolution Model to Include Kinetic and Single Particle Effects. D.A. Spong, C.L. Hedrick, M.D. Prochaska, J.-N. Leboeuf, and B.A. Carreras.
1C42. Multidimensional Autoresonant Three-wave Interactions in Space-Time Varying Plasmas. L. Friedland.
1C43. An L-H-Like Transition in a Tokamak SOL. R.H. Cohen and X.Q. Xu.
1C44. Low-Dimensional Representations for the Dynamics of L-H Transitions. W. Horton, G. Hu, and J.A. Krommes.
1C45. Drift-type Microinstabilities in High Beta Tokamaks. M. Artun and S.C. Cowley.
1C46. High Beta, Skin Current Tokamaks. T.H. Jensen, R.L. Miller, and Y.R. Lin-Liu.
1C47. Kinetic Effects on Particle and Heat Fluxes in Detached SOL Plasmas. O.V. Batishchev, X.Q. Xu, J.A. Byers, R.H. Cohen, S.I. Krasheninnikov, and T.D. Rognlien.
1C48. Computer Simulation of an MHD Dynamo. A. Kageyama and T. Sato.
1C49. Analytical and Numerical Solutions of the Tearing Modes Linear Stability Equation. R. Gatto, D. Hua, and S. Migliuolo.
1C50. Equilibrium and Stability Studies of Low Aspect Ratio Tokamaks. E.R. Solano, D.J. Strickler, J. Uglum, and P.H. Edmonds.
1C51. Spectra and Mode Structures of Global Drift Waves in Toroidal Geometry. S. Brunner and J. Vaclavik.

1D POSTER SESSION

Regency Ballroom

4:00 - 6:00 p.m.

1D1. Plasma-Neutral Interaction in Tokamak Divertor: "Gas Box" Model (Knudsen Limit). T.K. Soboleva and S.I. Krasheninnikov.
1D2. Electric Fields and E x B Drifts Including the Tokamak Separatrix Region. T.D. Rognlien, N. Mattor, and R.H. Cohen.
1D3. Tellegen's Theorem Applied to Tearing Modes. S.N. Bhattacharyya and A. Sen.
1D4. Computational Studies of Ultra-short-pulse Reflectometry. B.I. Cohen, B.B. Afeyan, and T.B. Kaiser.
1D5. Semi-ideal Magnetohydrodynamics of a Tokamak Plasma. S. Bazdenkov, T. Sato, and K. Watanabe.

1D6. Considerations on Plasma Transport Barriers. T. Tajima and B. Coppi.
1D7. Advanced MHD Configurations in TFTR. J. Manickam, M. Bell, and R. Budny.
1D8. Normal Mode-Quasilinear-Mixing Length Model Transport Code. R.E. Waltz, W.D. Dorland, G.W. Hammett, and M. Kotschenreuther.
1D9. Electron Cyclotron Heating and Current Drive for Advanced-Tokamak Operation in ITER. A.H. Kritz, G.R. Smith, W.M. Nevins, and M.A. Makowski.
1D10. Three-Dimensional Calculations Using the Quiet Implicit PIC Method. R.A. Nebel, D.C. Barnes, and W.D. Nystrom.
1D11. Interpretive Treatment of Scrape-off-Layer Plasmas. J. Kesner and B. LaBombard.
1D12. Thermodynamic Aspects of Fluid Dynamics and Convariant Onsager Symmetry. J.M. Greene and P.J. Morrison.
1D13. Adaptive Gridding for Primitive MHD Simulations. D.D. Schnack, Z. Mikic, I. Lotatti, and P. Satyanarayana.
1D14. MHD Simulation of Coalescence Process of Spheromaks. T.H. Watanabe, B. Dasgupta, T. Sato, T. Hayashi, and K. Watanabe.
1D15. Broadening of Alpha Energy Spectrum Due to Cyclotron Instabilities. K.R. Chen.
1D16. Effect of Low MN Perturbations on Footprints of Field Lines on the Divertor Plates in Single-Null Divertor Tokamak. A. Verma, A. Punjabi, and A. Boozer.
1D17. RF Tokamak Plasma Confinement in Electron Cyclotron Frequency Range. S.A. Uryupin and V. Stefan.
1D18. Finite-Size Effects and Quasi-Crystallization of Vortices in the Hasegawa-Mima Equation. N. Kukharkin, S.A. Orszag, and V. Yakhot.
1D19. Bootstrap Current in Arbitrary Collisionality and Aspect Ratio Tokamaks. W.A. Houlberg, K.C. Shaing, and S.P. Hirshman.
1D20. Comparison of the Calculations of the Stability Properties of a Specific Stellarator Equilibrium with Different MHD Stability Codes. J.L. Johnson, Y. Nakamura, T. Matumoto, M. Wakatani, S.A. Galkin, V.V. Drozdov, A.A. Martynov, Yu. Yu. Poshekhonov, K. Ichiguchi, L. Garcia, B.A. Carreras, C. Nührenberg, and W.A. Cooper.
1D21. The Modeling of Non-Axisymmetric Halo Currents in Tokamaks. J. McCarrick and J.P. Freidberg.
1D22. Isolated Magnetic Islands in a High Temperature Tokamak Plasma. H.R. Wilson, J.W. Connor, and C.C. Hegna.
1D23. MHH Stellarator With the 2D Symmetry of the HSX Experiment. P.R. Garabedian.
1D24. Noether Derivation of Local Manley-Rowe Relations for Non-Eikonal Wave Fields. A.J. Brizard and A.N. Kaufman.
1D25. Casimir Invariants and Their Applications in Generic Turbulent Transport Problems. G. Hu and J.A. Krommes.
1D26. Generation of Ultra-Intense Magnetic Fields. G.A. Askar'an, S.V. Bulanov, F. Pegoraro, and A.M. Pukhov.
1D27. Aspects of Computational Thermally Collapsed States. G.G. Craddock, A.E. Koniges, J.L. Milovich, and T.D. Rognlien.
1D28. Parallelization of the Generalized Tokamak Simulator. G. Furnish and M.J. LeBrun.
1D29. Nonlinear Bounce-Averaged Kinetic Equation and Neoclassical Polarization Density. B.H. Fong and T.S. Hahm.
1D30. Nonlinear Theory of Collisionless Trapped Ion Modes. T.S. Hahm and W.M. Tang.
1D31. Renormalized Dissipation in Plasmas with Finite Collisionality. S.E. Parker and D. Carati.
1D32. Flux Limiting Due to Electron Impact Excitation Energy Loss. P.J. Catto, S. Krasheninnikov, and R.D. Hazeltine.
1D33. Scaling Laws for Two-Dimensional Fluid Neutral and Plasma Modeling of Divertors. J.W. Connor, P.J. Catto, and S. Krasheninnikov.
1D34. Dynamics of Electric Microfields at a Neutral Point. M. Berkovsky and J.W. Dufty.

1D35. Extraction of Alpha Particle Energy by Waves in the ICRF Range of Frequencies. M.C. Herrmann and N.J. Fisch.
1D36. Stability Analysis of Resistive Wall Kink Modes in Rotating Plasmas. R. Betti and J.P. Freidberg.
1D37. Computations of IBW Spectra and Induced Diffusion Rates in Toroidal Geometry. E.J. Valeo, N.J. Fisch, and D.W. Ignat.
1D38. MHD Simulations of ELMs in Divertor Tokamaks. H.R. Strauss.
1D39. The Extrapolated Performance of Fusion Reactors Based on First Principles Simulations with Kinetic Effects. M. Kotschenreuther and W. Dorland.
1D40. L-H Power Threshold Scalings. J.G. Cordey, W. Kerner, and O. Pogutse.
1D41. On the Existence of Scalar-Pressure Magnetostatic Equilibria. M. Tessarotto, J.L. Johnson, R.B. White, and L.-J. Zheng.
1D42. Analysis of Self-Consistent MHD Stable Operating Scenarios in the Tokamak Physics Experiment (TPX). P.T. Bonoli, M. Porkolab, and C. Kessel.
1D43. Collisional Relaxation of Electron Distribution Function in a Region of Stochastic Magnetic Field Lines. X.Z. Tang and A.H. Boozer.
1D44. Finite-Beta Effects on Toroidal Alfven Eigenmodes Driven by Energetic Particles. R.A. Santoro and L. Chen.
1D45. Toroidal Coupling of Ideal MHD Instabilities. C.C. Hegna, J.W. Conner, R.J. Hastie, and H.R. Wilson.
1D46. Numerical Simulations of the Effect of the ExB Drift on Divertor Plasma Flows. D.R. McCarthy, S.I. Krasheninnikov, and D.J. Sigmar.
1D47. Inertial-Range Dynamics: Scaling Laws and Computational Methods. J.C. Bowman, B.A. Shadwick, and P.J. Morrison.
1D48. Evolution of Trapped Ion Temperature Gradient-Driven Convective Cells with Electric Field Shear. R.D. Sydora and P.H. Diamond.
1D49. Spontaneous Symmetry Breaking in Divertor Scrape-off Layers. G.M. Staebler.
1D50. Relativistic Effects in Energy Extraction From Alpha Particles. A. Fruchtman, N.J. Fisch, M.C. Herrmann, and E.J. Valeo.
1D51. Unstructured Mesh Model of the SOL Using Riemann-Delaunay Triangulation. A. Kuprat.

T U E S D A Y M O R N I N G

2A REVIEW TALK

Regency Ballroom

8:30 a.m. - 9:20 a.m.

Presiding: T.B. Kaiser

2A1. Plasma Physics Phenomena in ICF. R.L. Berger.

2B ORAL SESSION

Regency Ballroom

9:30 - 10:30 a.m.

Presiding: T.S. Hahm

2B1. Nonlinear 3D Simulation Studies of High-Beta Disruptions in TFTR. W. Park, E. Fredrickson, A. Janos, J. Manickam, W. Tang, and L. Zakharov.

2B2. Nonlinear Evolution of the Alpha Particle Driven Toroidicity-induced Alfven Eigenmode. Y. Wu, R.B. White, Y. Chen, and M.N. Rosenbluth.

2C ORAL SESSION

Regency Ballroom

10:30 a.m.- 12:30 p.m.

Presiding: R. Fitzpatrick

2C1. Resistive Wall Stabilization of External Kink Modes in Tokamaks with Partial Poloidal Walls. D.J. Ward.

2C2. Resistive MHD Stability in Small Aspect Ratio Tokamaks. A.Y. Aydemir, R. Fitzpatrick, E. Solano, and F. Waelbroeck.

2C3. Nonlinear omega*-Stabilization of the m=1 Mode in Tokamaks. B. Rogers and L. Zakharov.

2C4. New Parallel Velocity Shear Instability. J.M. Finn.

T U E S D A Y   E V E N I N G

RECEPTION

Regency Ballroom, Lower Lobby   6:00 - 7:00 p.m.

2D POSTER SESSION

Regency Ballroom

7:00 - 9:00 p.m.

2D1. Study of Mode Overlap Resonance for TAE Growth Rates. H.V. Wong, H.L. Berk, and B.N. Breizman.
2D2. Modeling of a High Fusion Power TFTR DT Supershot. R.V. Budny, M.G. Bell, R.E. Bell, C.E. Bush, Z. Chang, P.C. Efthimion, E. Fredrickson, L.C. Johnson, J. Manickam, D.C. McCune, H.K. Park, A.T. Ramsey, M.H. Redi, J. Schivell, S.D. Scott, J.D. Strachan, E.J. Synakowski, G. Taylor, T. Terpstra, and et.al..
2D3. Effects of Magnetic Field Nonuniformity on Energetic-ion Bernstein Waves. A.N. Kaufman, A.J. Brizard, and E.R. Tracy.
2D4. Numerical Simulation of ELM Phenomena. L.A. Charlton, B.A. Carreras, J.-N. Leboeuf, and P.H. Diamond.
2D5. Extended Quasilinear Model Applied to Energetic Particle-Alfven Wave Problem. J. Fitzpatrick, H.L. Berk, and B.N. Breizman.
2D6. Spectrum Study of Microturbulence in Tokamak Plasmas. J.Q. Dong and W. Horton.
2D7. "Continuum Approximation" for Impurity Transport in Tokamak Edge Plasma. D.J. Sigmar, S.P. Hirshman, S.I. Krasheninnikov, N.S. Krasheninnikova, and R.C. Ward.
2D8. Saturation of Toroidal Alfven Eigenmodes via Nonlinear Density Modulation. L. Chen and R.A. Santoro.
2D9. Nonlinear MHD Simulations of RFP Configurations With Thermal Energy Transport. C.R. Sovinec, S.C. Prager, and D.D. Schnack.
2D10. Anomalous Transport and Its Self-Similarity in the Ergodic Layer. G.M. Zaslavsky.
2D11. A Flexible Code Based on a Scalar Representation of Toroidal MHD. E.K. Maschke, G. Urquijo, and R.E. Denton.
2D12. Poloidal Flow Near the Tokamak Scrape-off Layer. H. Xiao, R.D. Hazeltine, P.J. Catto, and H.V. Wong.
2D13. Issues in Gyrofluid Turbulence Simulations. G.W. Hammett, M.A. Beer, W. Dorland, M. Kotschenreuther, and R.E. Waltz.
2D14. Simulations of Delta′ and Neoclassical-MHD Driven Magnetic Islands in a Tokamak Plasma. T.A. Gianakon, J.D. Callen, and C.C. Hegna.
2D15. Accurate Treatment of Impurity Parallel Transport in NEWT1D. S.P. Hirshman and R.C. Ward.
2D16. Ion Cyclotron Absorption and Anomalous Transport in Turbulent Two-Ion Tokamak Plasmas. V. Stefan and S.A. Uryupin.
2D17. Interaction of Mode-Converted Ion-Bernstein Waves With Electrons in Tokamaks. A.K. Ram, A. Bers, S.D. Schultz, and V. Fuchs.
2D18. Transport Barrier in Very High Temperature Plasmas. G. Penn, B. Coppi, and W. Daughton.
2D19. Turbulence Propagation and Correlation Lengths. X. Garbet and R. Waltz.
2D20. A Parallel Gyrokinetic Field Solver for the Generalized Tokamak Simulator. M.J. LeBrun and G. Furnish.
2D21. Simple Current Sheets and Reconnection. S. Cowley, T. Squires, and E. Zweibel.
2D22. Simulation of Current Generation in a 3-D Plasma Model. F.S. Tsung, W.J. Nunan, and J.M. Dawson.
2D23. Some Theoretical Aspects of a "Linear Collider" Open-Ended Fusion Power System. R.F. Post.

2D24. Divertor Plasma Simulation With the UEDGE Code Including an Advanced Neutral Transport Model. F. Wising, D.A. Knoll, and T.D. Rognlien.

2D25. The Ignitor Experiment and Relevance of the Alcator C-Mod Confinement Results. F. Bombarda, B. Coppi, W. Daughton, L. Sugiyama, M. Greenwald, A. Hubbard, J. Irby, C. Fiore, J. Rice, S. Wolfe, and B. LaBombard.

2D26. 1D and 2D Analytical and Numerical Study of the Drift-Resistive-Ballooning Modes in the Scrape-Off-Layer in Tokamak Plasmas. S.V. Novakovski, P.N. Guzdar, J.F. Drake, and C.S. Liu.

2D27. Toroidal Electrostatic Guiding Center Plasmas. X. Shan and D. Montgomery.

2D28. MHD Stability of Reversed Shear Current Profiles. M.H. Hughes, M.W. Phillips, and F. Levinton.

2D29. Magnetic Field Calculation of (m,n) Modes at Mirnov Coil Locations. J-S. Kim, J.M. Greene, A. Turnbull, and M.S. Chance.

2D30. MHD Stability of Advanced Operating Regimes in Tokamaks. M.W. Phillips, M.H. Hughes, and F. Levinton.

2D31. Bifurcations and Intermittent MHD Activity. M. Ottaviani, C. Tebaldi, and F. Porcelli.

2D32. A Multi-Variable Core-Edge Simulation via 1D-2D Coupled Non-Linear Transport Codes. A. Tarditi, R.H. Cohen, G.G. Craddock, J.A. Crotinger, T.D. Rognlien, A.I. Shestakov, and G.R. Smith.

2D33. Scale-Invariant Plasma Motions Near X-Points. F. Pegoraro, B.N. Kuvshinov, M. Romanelli, and T.J. Schep.

2D34. Particle Control in DIII-D and TPX. M.E. Rensink, S.L. Allen, M.E. Fenstermacher, D.N. Hill, G.D. Porter, T.D. Rognlien, and G.R. Smith.

2D35. A New Paradigm in Cyclotron Emission and Absorption. D.G. Swanson.

2D36. Role of Edge Turbulence in Plasma Detachment. F.Y. Gang, S.I. Krasheninnikov, and D.J. Sigmar.

2D37. Multiple Mode Simulations of Energetic Particle-Alfven Eigenmode Dynamics. M.S. Pekker, H.L. Berk, and B.N. Breizman.

2D38. Modelling of TF Ripple Loss of Alpha Particles in TFTR DT Experiments. M.H. Redi, R.B. White, M.C. Zarnstorff, R.V. Budny, D. Darrow, D.C. McCune, J. Schivell, and S.J. Zweben.

2D39. Theory of the Electron Energy Pinch in Tokamak. M.B. Isichenko.

2D40. First Steps in the Development of Adaptive Grid Algorithms for Divertor Tokamak Plasmas. J.L. Milovich and A.E. Koniges.

2D41. Applications of Object Oriented Methods to Self-Consistent Plasma Simulation. J.R. Cary, I. Doxas, S. Hendrickson, J. Loui, R. McLean, S. Shasharina, and P. Stoltz.

2D42. Transport Simulations of Alcator-Cmod Plasmas. W. Daughton, B. Coppi, L.E. Sugiyama, M. Greenwald, F. Bombarda, and Y. Takase.

2D43. Toroidal Velocity Profiles and Core Transport in DT Plasmas in TFTR. C.E. Bush, R.E. Bell, E.J. Synakowski, M.G. Bell, R. Budny, Z. Chang, D. Ernst, P. Efthimion, E. Fredrickson, D. Mansfield, H.K. Park, S.D. Scott, J.D. Strachan, G. Taylor, M.C. Zarnstorff, S. Zweben, and TFTR. Group.

2D44. Intermittent Statistics in Turbulent Plasma Transport. J.A. Krommes and G. Hu.

2D45. Core-Localized Toroidal Alfven Eigenmodes. H.L. Berk, J.W. Van Dam, D. Borba, J. Candy, G.T.A. Huysmans, and S. Sharapov.

2D46. Noncanonical Hamiltonian Perturbation Theory. B.A. Shadwick, N.J. Balmforth, and P.J. Morrison.

2D47. Theory of Parametric Decay of Fast Waves With Finite Pump Wavelength. S.C. Chiu, R.I. Pinkser, and C.C. Petty.

2D48. K-epsilon Modelling of Compressible Neutral Gas Turbulence on a Heat Front in the Divertor Region. L. Vahala, G. Vahala, J. Morrison, S. Krasheninnikov, and D. Sigmar.

2D49. Density Edge Localized Mode in Rotating Plasmas. Y.-T. Lau.
2D50. Lattice Boltzmann Approach to Temperature Driven Turbulence. G. Vahala, P. Pavlo, and L. Vahala.
2D51. Accessibility of High-li, High-beta Advanced Tokamak Operational Mode. Y.R. Lin-Liu, R.L. Miller, T.S. Taylor, and V.S. Chan.

WEDNESDAY MORNING

3A REVIEW TALK

Regency Ballroom

8:30 a.m. - 9:20 a.m.

Presiding: P.J. Catto

3A1. Experimental Data for Edge Model Validation. G.M. McCracken.

3B ORAL SESSION

Regency Ballroom

9:30 - 10:30 a.m.

Presiding: B. Braams

3B1. Kinetic Modeling of SOL Plasmas. K. Kupfer, R.W. Harvey, and O. Sauter.
3B2. Low Frequency Current Drive Utilizing Nonlinear and Spatial Inhomogeneity Effects. S. Rauf and J.A. Tataronis.

3C POSTER SESSION

Regency Ballroom

10:30 a.m. - 12:30 p.m.

3C1. Alfven Instability and Edge Plasma Physics in TFTR. E.D. Fredrickson, Z. Chang, R.V. Budny, C.E. Bush, G.Y. Fu, E. Mazzucato, K.M. McGuire, R. Nazikian, H.K. Park, S.J. Zweben, and TFTR. Team.

3C2. Off-Axis Electron Cyclotron Current Drive in ITER. R.W. Harvey, W.M. Nevins, Y.R. Lin-Liu, and F.W. Perkins.

3C3. Collisionless Magnetic Reconnection in Well-Confined Plasmas. B. Coppi and L.E. Sugiyama.

3C4. Neutral Transport Modeling of the DIII-D Divertor With DEGAS 2. C. Karney and D. Stotler.

3C5. Sawtooth Stabilization and Triggering of High-Beta Disruptions in TFTR. L. Zakharov, J. Manickam, W. Park, and B. Rogers.

3C6. Theory and Simulations of Fluctuation Reflectometry in Multi-Dimensional Inhomogeneous Plasmas. B.B. Afeyan, B.I. Cohen, and T.B. Kaiser.

3C7. Enforcement of Quasi-Neutrality and Momentum Conservation Using a delta-f Monte Carlo Code. M. Sasinowski and A.H. Boozer.

3C8. High Power Radiative Divertor Scenarios for ITER and TPX. B.J. Braams and S. Ohtsu.

3C9. Hamiltonian Description of Toroidal Magnetic Fields in Vacuum. J.W. Bates and H.R. Lewis.

3C10. Robust Multivariable Shape and Stability Control for ITER. L.D. Pearlstein, D.A. Humphreys, S.W. Haney, R.D. Bulmer, and J.A. Crotinger.

3C11. Toroidal Momentum Input to Tokamak Plasmas from Alpha Particles or Neutral Beams. F.L. Hinton and M.N. Rosenbluth.

3C12. Linear Stability of MHD Modes in Toroidally Rotating Tokamak Plasmas. M.S. Chu, J.M. Greene, R.L. Miller, A. Bondeson, and H. Luetjens.

3C13. Log-Additive Parameterisation of JET Electron Temperature, Density and Pressure Profiles. K. Imre, K.S. Riedel, and B. Schunke.

3C14. A Comparison of Monte Carlo and Fluid Approaches to Neutral Transport Modeling in Tokamak Edge Plasmas. D.P. Stotler, C.F.F. Karney, and S.I. Krasheninnikov.

3C15. Thermal Bifurcation of Scrape Off Layer Plasma and Divertor Detachment. S.I. Krasheninnikov, P.J. Catto, P. Helander, D.J. Sigmar, and T.K. Soboleva.

3C16. Linear Electrostatic Drift-Kinetic PIC Code for eta-i Modes in Toroidal Geometry. M. Fivaz, K. Appert, and J. Vaclavik.

3C17. RF Wave Effects on the Neoclassical Electron Distribution Function in Tokamaks. S.D. Schultz, A. Bers, and A.K. Ram.

3C18. The Issue of Internal Modes in Ignition Experiments. B. Coppi, P. Detragiache, and S. Migliuolo.

3C19. On the Noise Response of Chaotic Systems. J. Shaw, A. Joshua, and E.R. Tracy.

3C20. Can Inertial Electrostatic Confinement Work Beyond the Ion-Ion Collisional Time Scale?. W.M. Nevins.

3C21. The Role of Line Emission in Radiation Transport Calculations of Divertor Ablation Mitigated by a Vapor Shield. A.E. Koniges, D.C. Eder, A.S. Wan, B. Bazylev, I. Landman, and H. Wurz.

3C22. Combined Effects of Parallel Viscosity, Resistive Wall, and Toroidal Rotation on External Kink Modes in Tokamaks. R.A. Gerwin and J.M. Finn.
3C23. An Adaptive-hp Finite Element Grad-Shafranov Equation Solver. J.C. Wiley and D.W. Ross.
3C24. Stabilization of Wall Modes by Slow Plasma Rotation. A.H. Boozer.
3C25. Origins and Uses of Plasma Rotation. D. Montgomery and X. Shan.
3C26. MHD Stability of Anisotropic Plasma Containing Fast Drifting Particles. D.D. Ryutov.
3C27. Fast Particle Destabilization of TAE Modes. C.Z. Cheng and C.T. Hsu.
3C28. Existence of Core Localized Toroidal Alfven Eigenmode. G.Y. Fu.
3C29. Mode Structure around an X-point. N. Mattor.
3C30. Emission Above the Ion Cyclotron Frequency in a Nonhomogeneous Magnetic Field. C. Riconda, B. Coppi, and G. Penn.
3C31. The Application of DCON to the Ideal MHD Stability Analysis of the Spherical Tokamak. A.H. Glasser, Y-K. M. Peng, and D.J. Strickler.
3C32. Scaling Law Based Studies of the Performance Capabilities of a Small Aspect Ratio Tokamak. P.M. Valanju, S.C. McCool, D.W. Ross, J.G. Uglum, and A.J. Wootton.
3C33. Time Dependent Studies of Advanced Tokamak Operating Scenarios Using a Theory-based Transport Model. J. Kinsey, A.H. Kritz, P. Bonoli, and M. Porkolab.
3C34. The Spherical Way--Physics and Scaling of Spherical Convergent Ion Focus Fusion Systems. T.N. Tiouririne, J.M. Finn, and D.C. Barnes.
3C35. Canonically Conjugate Phase Space Coordinates Appropriate for the Study of Stellarator Transport. H. Weitzner.
3C36. Three-Dimensional Shell Effects in delta-W Using the PEST-SPARK Code. M.S. Chance, J. Bialek, S.C. Jardin, J. Manickam, and G.H. Neilson.
3C37. The Relaxed-Cusp Configuration as an Approach to Magnetic Confinement. D.E. Baldwin.
3C38. Stabilization of Ballooning Modes With Sheared Toroidal Rotation in a Cylindrical Tokamak. E. Hameiri.
3C39. Pseudo-MHD Ballooning Modes in Tokamak Plasmas. J.D. Callen and C.C. Hegna.
3C40. Incorporation of the Reduced-Ion Impurity Module FMOMBAL into UEDGE. G.R. Smith, T.D. Rognlien, S.P. Hirshman, and D.A. Knoll.
3C41. On Nonlinear MHD-Stability of Toroidal Plasma Confinement Systems. V.P. Pastukhov and V.I. Ilgisonis.
3C42. MHD Stability of High-Beta Tokamak Equilibria. R.G. Kleva and J.F. Drake.
3C43. Turbulence Simulation With Self-Consistent Profiles via Coupled Codes. A. Shestakov, R.H. Cohen, X.Q. Xu, J.A. Crotinger, and L.L. LoDestro.
3C44. Non-perturbative Solution Method for the Gyrokinetic Fokker-Planck Equation. D. Gregoratto, M. Tessarotto, and L.-J. Zheng.
3C45. Equilibrium and MHD Stability of Plasmas with Toroidal Rotation in the DIII-D Tokamak. A.M. Popov, Y. Liu, A.V. Pedorenko, and A.D. Turnbull.
3C46. Tearing Mode Bifurcation: A Way to Control MHD Activity in Tokamak Plasmas. M. Zabiego, J.D. Callen, and Z. Chang.
3C47. Characteristics of LHD Configurations With Multi Layer Helical Coils. K. Ichiguchi, N. Nakajima, M. Okamoto, and O. Motojima.
3C48. Microinstability Analysis of DIII-D High Performance Discharges. G. Rewoldt, L. Lao, and W.M. Tang.
3C49. Transport in Steep Gradient Region. Y-B. Kim.
3C50. Effect of Alfven Resonance on Low-Frequency Fast Wave Current Drive. C.Y. Wang, D.B. Batchelor, M.D. Carter, E.F. Jaeger, and D.C. Stallings.
3C51. Plasma Fluid Model with Finite Larmor Radius Effects. A.I. Smolyakov, I.O. Pogutse, and A. Hirose.

1995 International Sherwood Fusion Theory Conference
Incline Village, Nevada, April 3–5, 1995

To Abate or Not To Abate? — That is the Greenhouse Question

MICHAEL E. SCHLESINGER

Department of Atmospheric Sciences
University of Illinois at Urbana-Champaign

This presentation will examine the question: How quickly must we respond, and by how much, to the threat of Global Warming? The answer depends on how much increasing greenhouse-gas concentrations will change climate — the climate sensitivity — and what the consequences of such a climate change will be — the climate impacts. Yet our knowledge of these climatic changes and impacts is quite uncertain. To provide a basis for understanding why this is so, information will be presented about the greenhouse effect, climate modeling and simulation, and economic and policy analysis.

A sequential-decision strategy for abating climate change will be examined wherein either moderate emissions reduction — energy conservation alone — or aggressive emissions reduction — energy conservation plus switching to non-fossil fuels — is begun now and followed in ten years by a least-cost abatement policy chosen such that the temperature change never exceeds an "optimal" target, defined implicitly as the global warming for which the marginal climate damage cost equals the marginal climate-change abatement cost.

It will be shown that the difference in emission rates and costs between the moderate and aggressive near-term policies is much smaller than the difference in emission rates and costs between the different climate targets and different climate sensitivities. Thus, if future research shows that the damage cost of climate change is high, the optimum climate target will be low and the global consumption of fossil fuels will need to be phased out much earlier than if the damage cost of climate change is low, this regardless of which near-term policy is chosen.

Bounce-Averaged Electron Fluid Equations: ITG and TEM Driven Transport

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The IFS-PPPL transport model[1] predicts temperature profiles in the core ($r/a < 0.8$) of more than 50 TFTR L-mode discharges with encouraging success. This model is based on linear gyrokinetic theory and nonlinear gyrofluid simulations of toroidal ITG turbulence,[2] which find much larger transport and fluctuation levels than in sheared slab geometry. The original IFS-PPPL transport model is based on simulations with adiabatic electrons, which appears adequate to predict ion heat transport for the moderate electron collisionality of most L-modes. However, to extend the model to lower collisionality regimes, and to address key physics issues such as particle transport, the simulations have been improved by including nonadiabatic trapped electron dynamics. This is especially important for supershots, which have a significant convective component in the heat flow.

New fluid equations are derived for the non-adiabatic trapped electron response by taking moments over energy (but not pitch angle) of the nonlinear bounce-averaged drift-kinetic equation,[3] with closure approximations to model the trapped electron toroidal precession resonance. This leads to 3D (non-local) trapped electron "fluid" equations which retain the pitch angle dependence of the precession drift and bounce-averaged potential. This also allows use of a Lorentz collision operator for pitch angle scattering. Retaining the pitch angle dependence of the trapped electron response is important for advanced tokamak regimes in the second stability regime or with reversed magnetic shear,[4] where a major fraction of the trapped electrons have favorable toroidal precession drift, stabilizing the TEM. Because these electron equations are bounce averaged, the fast parallel electron time scale is removed, and nonlinear simulations with trapped electrons are only about two times slower than simulations assuming adiabatic electrons. With these nonlinear simulations, we investigate the transition from ITG driven to TEM driven turbulence.

This work supported by USDoE contract No. DE-AC02-76-CHO-3073, in part by a DoE Fusion Postdoctoral Fellowship administered by the Oak Ridge Institute for Science Education, and used computers at the National Energy Research Supercomputer Center, LLNL.

† In collaboration with G. W. Hammett.

[1] W. Dorland, M. Kotschenreuther, M. A. Beer, G. W. Hammett, *et al.*, IAEA-CN-60/D-P-I-6 (1994); M. Kotschenreuther, W. Dorland, M. A. Beer, G. W. Hammett, APS Invited Talk (1994).

[2] M. A. Beer, Ph.D. Thesis, Princeton University (1994); R. E. Waltz, G. D. Kerbel, and J. Milovich, Phys. Plasmas **1**, 2229 (1994).

[3] F. Y. Gang and P. H. Diamond, Phys. Fluids B **2**, 2976 (1990).

[4] C. Kessel, J. Manickam, G. Rewoldt, and W. M. Tang, Phys. Rev. Lett. **72**, 1212 (1994).

Turbulence and Transport Simulations

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Recently, we showed that simulation-based models of anomalous transport quantitatively describe the thermal transport characteristics of *core* TFTR L-mode plasmas.[1,2] We parameterized results from the Beer-Hammett 6-moment toroidal gyrofluid model[3] (which is the toroidal generalization of an earlier sheared slab gyrofluid model[4]) and comprehensive linear gyrokinetic simulations;[5] quantitative agreement with the experimentally inferred anomalous thermal conduction in TFTR L-modes for $r/a < 0.8$ was obtained.[1,2] Here, we report results from (a) *more stringent experimental tests* of our model and methods, (b) extensions to the theory which describe the thermal transport *all the way to the plasma edge,* and (c) comparisons with nonlinear gyrokinetic simulations. Specifically, (1) A long-wavelength mode (with fluctuation characteristics similar to those reported by Durst *et al.*[6]) likely to be responsible for anomalous thermal conduction for $r/a > 0.8$ in TFTR L-modes has been identified; (2) The role of the carbon-based ITG mode in core supershot confinement has been clarified; (3) TFTR and DIII-D ρ^* scans have been simulated; (4) Off-axis heating experiments in DIII-D and TFTR have been simulated; (5) Experimentally measured fluctuation spectra obtained from Beam Emission Spectroscopy on TFTR in current and power scans have been compared to the predictions from the nonlinear gyrofluid simulations, thus testing our understanding of the underlying mechanism of turbulent thermal transport (complementing our predictions of the gross transport characteristics); and (6) Nonlinear gyrokinetic particle simulation results[7] have been compared with our interpolations of nonlinear gyrofluid simulations. More than 70 TFTR L-modes have been simulated using an approximate interpolation formula estimated from the published particle simulation results and supplemented with linear gyrokinetic calculations. (The purely kinetic results agree reasonably well with the gyrofluid/gyrokinetic predictions.)

[1] W. Dorland *et al.,* 1994 IAEA Conference.
[2] M. Kotschenreuther *et al.,* 1994 APS Conference.
[3] M. A. Beer, PhD Thesis, Princeton Univ., 1995.
[4] W. Dorland, PhD Thesis, Princeton Univ., 1993.
[5] M. Kotschenreuther *et al.,* 1992 IAEA Conference.
[6] R. Durst *et al.,* PRL 71 3137 (1993).
[7] A. Dimits *et al.,* 1994 IAEA Conference.

Acknowledgements: This work was supported in part by two DoE Fusion Postdoctoral Fellowships administered by the Oak Ridge Institute for Science Education, by DOE Contract Nos. DE-FG05-80ET-53088 and DE-AC02-76-CHO3073 and by the HPCC. Computations were performed primarily at NERSC.

Implications of Gyrokinetic Simulations on the Role of ITG Turbulence in Tokamak Transport [1]

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A large number of three-dimensional δf gyrokinetic simulations of fully toroidal ion-temperature-gradient (ITG) turbulence[2] have been completed, spanning a wide range of the ITG-turbulence parameter space. These simulations show that ion thermal transport resulting from ITG turbulence alone is lower by a factor of 2 to 4 than that observed in many tokamak discharges. A power-balance analysis translates this disagreement into predictions for ion temperatures that are systematically at least 50% higher than those seen in the experiments, across large portions of the profile. These results also preclude the use of ITG-transport-based "marginal-stability" arguments as an explanation of the minor-radius dependence of the effective thermal diffusivity. The gyrokinetic simulations provide the only available first-principles-simulation-based test of gyrofluid models and of the resulting gyrofluid-ITG transport models.[3] Significant disagreements are observed, which is not surprising; unlike gyrofluid models, the gyrokinetic equations have a complete treatment of nonlinear kinetic effects. The reduction to the gyrofluid model has never been justified in terms of any parameter that is small for ITG turbulence.

Simulations with toroidal-rotation shear show that destabilization by the parallel flow shear competes with the stabilization by the perpendicular flow shear, so that the existence of a toroidal-velocity-shear bifurcation depends strongly on the magnetic field-line pitch. Results from a bispectral analysis of spectral energy transfer, and measurements of the parallel velocity fluctuations in the simulations will be compared with experimental results of Fonck *et al.* on TFTR.[4] The generalization of the simulations to noncircular cross section will also be discussed and initial simulation results presented.

The inclusion of kinetic electrons, may result in significantly improved agreement with experiments. Initial results from investigations using a bounce-averaged δf electron model will be presented. A theoretical assessment of the effects of "stagnant" electrons, which are not well described by the bounce-averaged model but which can resonate with the turbulent-Reynolds-stress-generated flows, will also be presented.

The combination of δf methods with a quasiballooning-coordinate representation permits fully gyrokinetic simulations with a less-than-twofold increase in computer time over existing gyrofluid simulations with similar spatial resolution.[3]

[1]This work was performed by LLNL for USDoE under contract W-7405-ENG-48.

[2]A.M. Dimits *et al.*, in the Proceedings of the *15th. International Conference on Plasma Physics and Controlled Nuclear Fusion Research, 1994*, paper IAEA-CN-60/D-P-I-5.

[3]W. Dorland *et al.*, ibid. paper IAEA-CN-60/D-P-I-6.

[4]R.J. Fonck *et al.*, ibid., paper IAEA-CN-60/A2/4-P-7.

STRUCTURE OF SHORT-WAVELENGTH MODES IN A TOROIDAL PLASMA

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Short wavelength fluctuations, such as electron-drift (ED) and ion- temperature-gradient (ITG) modes are frequently considered to be a source of the ubiquitous 'anomalous' transport in toroidal plasmas. Consequently it is important to understand the structure and properties of these linear modes, even though transport is presumably a non-linear phenomenon. The well-known, and most unstable, form of ED and ITG modes occur only at isolated plasma radii and do not seem good candidates for ubiquitous transport. A more general class of ED and ITG mode has recently been investigated [1-6]: these have a higher stability threshold than the isolated modes (closer to that for similar modes in a plane slab) but they occur at all plasma radii. In some cases they may have an eigenfunction spanning much of the plasma radius - suggesting large transport and a 'marginal stability' profile for the plasma. More typically, however, the eigenfunction has a smaller width consistant with a Bohm like scaling and an increase in transport with plasma radius. In the presence of a sheared plasma velocity, the mode width (and presumably the transport) decreases, and the stability threshold becomes ever closer to that for modes in a plane slab.

1 J W Connor, J B Taylor and H R Wilson, Phys Rev Lett 70, 1803 1993
2 F Romanelli and F Zonca, Phys Fluids B5,4081 1993
3 J Y Kim and M Wakatani, Phys Rev Lett 73, 2200 1994
4 J B Taylor and H R Wilson Proc ICPP Conference, Iguassu, Brazil 1994
5 J B Taylor, J Connor and H R Wilson, Plasma Phys Cont Fusion 36, 1241 1994
6 J Connor, J B Taylor and H R Wilson, Proc 21st EPS Conference Montpellier 1994

3-D tokamak edge turbulence

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Abstract

3-D simulations of drift resistive ballooning turbulence are presented. The turbulence is basically controlled by a parameter α, the ratio of the drift wave frequency to the ideal ballooning growth rate[1]. If this parameter is small ($\alpha \leq 0.5$, corresponding to Ohmic or L-mode plasmas), the system is dominated by ballooning turbulence, which is strongly peaked at the outside of the torus. If it is large ($\alpha \geq 1.0$, corresponding to H-mode plasmas) field line curvature plays a minor role. The turbulence is sustained even if curvature is removed and all modes are linearly stable due to magnetic shear. An analytic calculation reveals that the source of the turbulence is a nonlinear streaming instability in which radial flows extract energy from the ambient density gradient and drive drift waves which then amplify the radial flow. This nonlinear instability dominates the usual linear drift-wave instability as the source of the turbulence also in the absence of magnetic shear. Thus, the linear stability properties play essentially no role in understanding the nonlinear state of the system. The implications of these results for understanding the L-H transition are being explored. First results concerning the scaling of the transport in the high α regime are presented.

1. P.N. Guzdar et al., Phys. Fluids **5**, 3712(1993)

Control of Shear Flow Profiles Via External Velocity Perturbations

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Recent experiments performed on the DIII-D tokamak have demonstrated the feasibility of controlling the plasma toroidal rotation profile via externally applied helical magnetic perturbations. Changes induced in the rotation shear are found to have a significant effect on transport in VH-mode plasmas. According to theory, the non-linear electromagnetic torques exerted on the plasma develop at so-called rational magnetic flux-surfaces where the perturbed equations of ideal magnetohydrodynamics become singular.

It is well-known that in high Reynolds number, plane Poiseuille flow the perturbed ideal equations of hydrodynamics become singular on surfaces where the phase velocity of the perturbation matches the equilibrium flow velocity. An externally applied velocity perturbation, resonant at a singular surface located within the flow, can exert a non-linear Reynolds stress in the vicinity of this surface and, thereby, modify the equilibrium velocity profile. A chain of vortex islands, centred on the singular surface, is induced in the flow. The Reynolds stress force develops predominantly in a thin boundary layer located on the separatrix of the island chain.

A formalism is developed for calculating the modifications induced in shear flow profiles by external velocity perturbations. This is similar, in many respects, to the formalism used in tokamak physics to investigate the interaction of magnetic perturbations with a rotating plasma. A linear solution in the ideal region is asymptotically matched to non-linear vortex island solutions located at the singular surfaces of the flow. (In general, there is more than one singular surface.) A matrix dispersion relation is obtained. This can be solved to give the widths and phases of the vortex island chains. An expression is obtained for the total Reynolds stress exerted on a given island chain. The localised Reynolds stresses which develop in the flow are balanced against viscous restoring forces. In this manner, the modified steady-state velocity profile can be calculated. Relatively small applied velocity perturbations can drive large vortex islands and, thereby, substantially modify the flow profile.

This effect could be used to control shear flow without the need for any mechanical interaction with the fluid, which would be advantageous if the fluid in question were particularly corrosive or hazardous. Alternatively, the effect could be used to investigate the relationship between fluid turbulence and the equilibrium velocity profile in a controlled manner.

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MHD-Vlasov Simulation of the Toroidal Alfvén Eigenmode

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Abstract

A new simulation method has been developed to investigate the excitation and saturation processes of the TAE modes. In this method, the background plasma is described by the full-MHD model, while the kinetic evolution of energetic alpha particles is represented by the drift kinetic equation. Both the drift kinetic and MHD equations are solved by a finite difference method. It is demonstrated that the $n = 2$ TAE mode is excited, the linear growth rate of which is in good agreement with the linear theory [G. Y. Fu and J. W. Van Dam, Phys. Fluids **B1**, 1949 (1989)].

The saturation of the magnetic field fluctuation can reach to a significant level, e.g. 1.8×10^{-3} of the equilibrium field intensity when the initial beta of alpha particles is 2% at the magnetic axis, which is supposed to lead to a non-negligible alpha particle loss in one slowing time [D. J. Sigmar, C. T. Hsu, R. White, and C. Z. Cheng, Phys. Fluids **B4**, 1506 (1992)]. After saturation, the TAE mode amplitude shows an oscillatory behavior with a frequency corresponding to the bounce frequency of the alpha particles trapped by the TAE mode. The decrease of the power transfer rate from the alpha particles to the TAE mode, which is due to the trapped particle effect of a finite-amplitude wave, causes the saturation. From the linear growth rate the saturation level can be estimated.

ELIMINATING LOCKED MODE INSTABILITIES IN TOKAMAKS*

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The locked mode instabilities which occur in many large tokamak, such as DIII-D and JET, are sensitive to error fields which break the axisymmetry of the magnetic field. Error fields which have large m=2 n=1 resonant components are particularly effective at destabilizing locked modes which can lead to disruptions. One possibility for fixing this problem is using a set of small correction coils to eliminate resonant error fields. Previous work[1] has shown how to compute the various correction coil currents so that resonant fields are minimized.

Recent work has involved the evaluation of coil currents required for expected errors in TPX. Results will be shown for both n=1 errors (shifts and tilts of Poloidal Field Coils) and n=2 errors (shape distortions of the Poloidal Field Coils).

One drawback to the current method is that the rotational transform profile of the axisymmetric equilibrium is not very accurately modeled. Efforts are under way to incorporate magnetic fields from axisymmetric equilibrium codes into the calculation of correction coil currents. Future work will be aimed at coupling the correction coil current calculation to a complete three-dimensional MHD equilibrium calculation.

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Application of Hyperviscosity to the Study of Long Wavelength Modes in 3D Gyrofluid Tokamak Turbulence

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Significant progress has been made recently[1,2] in explaining the anomalous ion heat diffusivity, χ_i, observed in the core of a broad class of L-mode discharges on the Tokamak Fusion Test Reactor (TFTR), through a parameterization of results from toroidal gyrofluid simulations of Ion Temperature Gradient (ITG) driven turbulence.[3] Extending these results will be increasingly computationally expensive, for several reasons. The number of nonlinear simulations required to accurately parameterize the diffusivity increases exponentially with the number of physical parameters considered. Turbulence near the edge ($r/a \sim 0.9$) of a tokamak may be driven by very long wavelength instabilities, rendering infeasible simulations that resolve ion gyroradius scales. Finally, if non-local effects due to radial propagation are important in determining the global transport,[4] larger simulation grids will become necessary.

For a grid with N^3 points, computational costs are $O(N^4)$, (including the number of time steps) so reducing the required resolution by a mere factor of 2 leads to a reduction in computation time by a factor of 16. Subgrid turbulence models have been successfully used in the study of Navier-Stokes turbulence for years[5] to eliminate short wavelength modes from simulations while modeling their effects through simply calculated damping terms. Hyperviscosity, a damping term of the form k^n ($n > 2$), has proved to be a highly effective tool in the study of periodic 2D turbulence[6] and more recently periodic 3D turbulence.[7] Phenomenological k^4 hyperviscosity models have been used in plasma turbulence simulations as well.

We present physical arguments for the scaling of the hyperviscosity, and extend it from 2D to 3D, finding a new $k_{\|}$ dependent damping term. In steady state, barely resolved modes will be sheared by $\mathbf{E} \times \mathbf{B}$ advection to unresolved scales, resulting in a net loss of fluctuation energy from the resolved scales. This net loss is well modeled by a hyperviscosity that scales with the amplitude and scale of the turbulence at long wavelengths. Studies of a simple 2D model for drift wave turbulence indicate that the spatial resolution of simulations can be reduced by more than a factor of 2 without affecting the observed k spectrum or particle flux.[8]

Initially, the minimum resolution required to simulate the Numerical Tokamak Project test case (TFTR L-mode discharge #41309) is determined. We then proceed to study ITG turbulence in regimes of high R/L_t, where long wavelength instabilities are important.

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Acknowledgments: A 2D Navier-Stokes spectral code provided by A. Chekhlov was modified for use in the 2D phase of this study. Many useful discussions were had with Dr. S.A. Orszag of Princeton University and Dr. J. Krommes at PPPL. Computations were performed on a Cray C-90 at the National Energy Research Supercomputer Center, Lawrence Livermore National Laboratory. This work was supported by USDoE Contract Nos. DE-AC02-76CH03073, DE-FG02-93ER54204, and by a graduate fellowship from the Natural Sciences and Engineering Research Council of Canada.

Non Perturbative Kinetic Effects on Alfvén Eigenmodes in Tokamak Plasmas

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The propagation of the shear and the kinetic Alfvén wave (KAW) is investigated in general tokamak equilibria with finite aspect ratio and finite plasma β. Using the bicubic finite element code PENN, Maxwell's equations are solved in terms of the electromagnetic potentials [1] using either a resistive magneto-hydrodynamic (MHD) model or a kinetic model [2] based on a second order finite Larmor radius (FLR) expansion.

Using the kinetic model, the non-perturbative coupling between a global MHD Alfvén eigenmode (GAE) and the KAW is shown to be dominant at low temperatures, while the mode conversion at toroidally coupled surfaces becomes very efficient once the thermal speed of electrons exceeds the phase velocity of the wave.

In the range of toroidicity induced eigenmodes (TAE), kinetic effects result in a considerable change of the spectrum obtained with the resistive model. Different types of kinetic modes are excited below, inside and above the ideal MHD frequency gap. An iterative scheme is used to calculate the wave-particle interaction in a self-consistent manner and shows that the condition for hot particles to enter into resonance with the mode can be satisfied for velocities lower than the Alfvén velocity.

A kinetic analysis of a β induced mode (BAE) in the DIII-D tokamak [3] reveals that the wavefield is different from that expected from ideal MHD models.

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The Neoclassical Method for Calculating Fluctuation Driven Shear Flows in Tokamaks

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The neoclassical method of calculating the poloidal and toroidal mass and thermal flows in tokamaks is used to find the flows induced by broad-band spectrum of electrostatic drift wave fluctuations. The neoclassical-kinetic theory method developed here avoids the individual calculations of the many terms that occur in the ensemble averaged fluid equations, e.g.

$$m_a \frac{\partial}{\partial t}(n_a \mathbf{u}_a + \langle \widehat{n}_a \widehat{\mathbf{u}}_a \rangle_{\text{ens}}) + m_a \nabla \cdot (n_a \mathbf{u}_a \mathbf{u}_a + n_a \langle \widehat{\mathbf{u}}_a \widehat{\mathbf{u}}_a \rangle_{\text{ens}} + \langle \widetilde{n}_a \widehat{\mathbf{u}}_a \rangle_{\text{ens}} \overline{\mathbf{u}}_a + \overline{\mathbf{u}}_a \langle \widehat{n}_a \widehat{\mathbf{u}}_a \rangle_{\text{ens}}$$

$$+ \langle \widehat{n}_a \widehat{\mathbf{u}}_a \widehat{\mathbf{u}}_a \rangle_{\text{ens}}) = n_a e_a \left(\mathbf{E} + \frac{1}{c} \mathbf{u}_a \times \mathbf{B} \right) - \nabla p_a - \nabla \cdot \boldsymbol{\pi}_a + \mathbf{F}_{a1} + e_a \left\langle \widehat{n}_a \widehat{\mathbf{E}} \right\rangle_{\text{ens}}$$

$$+ \frac{e_a}{c} \langle \widetilde{n}_a \widehat{\mathbf{u}}_a \rangle_{\text{ens}} \times \mathbf{B}$$

where $A + \widehat{A}$ are the ensemble averaged and fluctuating part of A. By making the projection of the kinetic equation directly into mean and ensemble fluctuation the calculation is reduced to that of finding the anisotropies driven by the quasilinear operator $\overline{D} = -\left\langle \widehat{\mathbf{E}} \cdot \frac{\partial \widehat{f}}{\partial \mathbf{v}} \right\rangle$. The Legendre expansion $P_\ell(\xi)$ of the mean distribution function for its pitch-angle $\xi = v_\parallel / v$ dependence with the parallel flows given by

$$f^{(\ell=1)} = \frac{2v_\parallel}{v_t^2} \left[u_\parallel + \frac{2q_\parallel}{5p} \left(\frac{mv^2}{2T} - \frac{5}{2} \right) \right] F_{M-B}$$

where in Hirshman's notation $v_1, v_2, u_\theta, q_\theta$ are flux functions and $u_\parallel = v_1 + Bu_\theta, q_\parallel = \frac{5}{2} pv_2 + Bq_\theta$.

The poloidal flows and the quasilinear diffusion from the fluctuations produce anisotropies ($\ell = 2$) that drive surface averaged transport $\langle \mathbf{B} \cdot \nabla \pi \rangle$ and $\langle \mathbf{B} \cdot \nabla \cdot \boldsymbol{\Theta} \rangle$ where π and $\boldsymbol{\Theta}$ are the nondiagonal parts of the momentum and thermal flux tensors. The calculation of the $\ell = 2$ induced anisotropies is difficult except in the plateau regime where the delta-function resonance approximation allows good estimates of the combined neoclassical-fluctuation driven flows.

The method and results are contrasted with those from Shaing, Phys. Fluids (1988).

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Transport Fluxes in H-Mode Bifurcated Layer*

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In the H-mode bifurcated layer, the conventional neoclassical theory is not applicable because the ion poloidal $\mathbf{E} \times \mathbf{B}$ Mach number M_p is of the order of unity and the ion orbit squeezing parameter $\mathbb{S} > 1$. Thus to characterize the transport property in the bifurcated layer, one needs to extend neoclassical transport theory to the $M_p \sim 1$ and $\mathbb{S} > 1$ regime. This goal can be accomplished by employing the plasma viscosity $\langle \mathbf{B} \cdot \nabla \cdot \vec{\pi} \rangle$ and heat viscosity $\langle \mathbf{B} \cdot \nabla \cdot \vec{\Theta} \rangle$ calculated to model the experimentally observed $M_p \sim 1$ and $\mathbb{S} > 1$ H-mode phenomenon. It is found that the viscosity driven ion heat flux decreases exponentially in the banana and plateau regime as expected. The other transport fluxes will also be presented.

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Influence of Momentum Conservation on the Ambipolar Electric Field and the Heat Flux in 2D Fokker-Planck Edge Modeling

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We simulate the electron parallel heat flux (along the magnetic field) to the divertor in the tokamak edge plasma. To model this process, we numerically solve the 2D kinetic Fokker-Planck equation written in self-similar variables for a special class of temperature and density profiles [1,2].

The linearized Fokker-Planck operator contains two terms: a differential term and an integral term. The linearized representation of the electron-electron and electron-ion collision operators in Ref. 2 contained only the differential term, so it did not provide momentum conservation. The aim of this work is to investigate the influence of collisional electron momentum conservation on the heat flux. To do this, we retain the first term of the Legendre polynomial expansion of the integral part of the collision operator. Calculations are performed with and without momentum conservation for a representative set of parameters that define the temperature and density profiles in the divertor region. Calculations show that including the integral term in the electron-electron collision operator leads to an increase of the ambipolar electric field by a factor of 1.4 to 1.9 and an increase of the heat flux by a factor of 1.2 for $Z_{\text{eff}} = 1$ and 2.2 to 3.6 for high Z_{eff} in the range 3 to 10. The main conclusion is that to perform realistic kinetic modeling of parallel electron heat conductivity in the scrape-off layer, momentum conservation in electron-electron collisions must be retained.

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Poster presentation requested

An Alternate Nonperturbative Method of Treating Alpha-Alfvén Waves for Examining Sensitivities to the Alpha Distribution Function*

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Here we present an alternate method of treating Alpha-Alfvén waves (TAE, etc.) that allows incorporation of details of the alpha particle distribution function. At the linear level this method allows comparison of slowing-down distributions and Maxwellian distributions, as well as Landau fluid approximations for these distribution functions. At the nonlinear level this method allows quasilinear "transport" effects to be incorporated simultaneously with other nonlinear effects (e.g., those associated with the parallel and polarization currents). This allows one to simultaneously study the nonlinear saturation effects of sheared velocity flow, flux modification, and distribution function (or pressure) gradient reduction.

The method is an outgrowth of the Landau fluid approach, which has proven to be remarkably robust and flexible. The new method also uses evolution equations, because this approach has been a key part of allowing flexibility and numerical stability in a simple way. The central equation is the vorticity evolution equation (i.e., $\nabla \cdot \mathbf{J} = 0$): the change is to treat a term associated with the alpha particles in the same way that the previous code treated the corresponding term associated with background electrons and ions (S_{ei} -term).

In addition to comparing the new method to the Landau fluid method, a comparison to approaches based on "extended energy principles," or "global dispersion relations" will be made on a term-by-term basis. The term mentioned in the previous paragraph is associated with compressibility in ideal MHD, and, for example, Wu and White's $\delta W_k^{(na)}$ is related to our S_α by

$$\delta W_k^{(na)} = 2\int d^3x \,|\kappa\cdot\xi_\perp|^2\, n_\alpha T_\alpha S_\alpha, \quad S_\alpha = -\int d^3v \frac{\omega}{\omega - k_\parallel v_\parallel}\frac{\omega_{d^2}}{\omega_{d0^2}}\left(\frac{\omega_{*\alpha}}{\omega} L_{n\alpha}\frac{\partial F}{\partial x} + T_{\alpha 0}\frac{\partial F}{\partial \varepsilon}\right)$$

The techniques for mapping guiding centers, or following particles, in the fluctuating fields to determine the quasilinear changes in F used by Berk, Breizman and Ye, and by Wu and White can be used with this method, while simultaneously allowing other nonlinearities.

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Fast Wave Driven Alpha Current and Its Implication to Current Profile Control by FWCD in a Tokamak Reactor*

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A new current drive mechanism generated by magnetic trapping of passing alphas through ion cyclotron resonance heating has been identified. The occurrence of this effect may be unavoidable when electron current drive by fast waves (e-FWCD) is attempted in a deutrium-tritium reactor plasma. The synergistic alpha current can be at a similar efficiency as the e-FWCD but with different radial dependence. The present study suggests that, without a careful choice of the wave properties, the synergism may yield a destructive fast-wave-driven current profile for plasma equilibrium. However, a proper choice can produce a more favorable result than the e-FWCD can alone. The present study shows that, in a bootstrap dominated burning plasma, it may be possible to achieve a reversed shear equilibrium with current profile controlled only by FWCD.

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Ideal MHD Analysis of TFTR Discharges*

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We have analyzed the stability of selected TFTR discharges, including recent shots with D-T plasmas, with the intent to compare theoretical predictions with experimental behavior. The analysis has been carried out within the ideal MHD framework, using the PEST-1 [1] and KINX [2] numerical codes. Input was provided from TRANSP analysis and reconstruction, typically in terms of $q(\psi)$ and $p(\psi)$ profiles.

For discharges with central q below unity, we find that a pressure driven internal mode ($n = 1$ and primarily $m = 1$) is always present, at nominal values of the pressure. Indeed, we find that this instability is encountered whenever $\beta_N \geq 1$ (where $\beta_N = \langle\beta\rangle$ (%) a (m) B (T)/ I (MA)), a threshold much below the experimental disruption limit (typically $\beta_N \sim 2$ in TFTR). There is no apparent evidence of a threshold for external modes being crossed in coincidence with the disruption. An $n = 1$ external is predicted theoretically with a hard threshold for $q_a < m$. A second internal mode is predicted at pressures that are well beyond (e.g., $\beta_N > 6$) the point where TFTR disrupts.

In the case of discharges with $q_0 > 1$, the analysis indicates the existence of a threshold for a mode that has a dominant $m = 2$ component. The computed critical value for β_N is apparently above that where the experiment disrupted.

This analysis points to a fundamental difficulty in the use of linear ideal MHD theory as a predictive tool for disruptions, at least as far as TFTR is concerned. The issue of non–ideal effects is also briefly addressed.

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Fokker-Planck Simulation of Electron Transport in Scrape-off Layer

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Abstract

The efficient numerical method [1] of collisionless plasma transport investigation was extended on non-uniform spatial grid and combined with fast Fokker-Planck solver [2] to apply it for the study of high recycling scrape-off layer tokamak plasmas which characterized by a very strong inhomogeneity along the magnetic field lines.

We present the first results of 3D evolution of electron distribution function for the case of fixed ion background. Ambipolar electric field is taken from Braginskii's electron momentum balance equation. Sheath potential is found from ambipolarity of plasma flow onto the target. The ionization of the neutrals in plasma recycling region is modeled by the source of cold electrons located near the target. The heating of electrons is modeled by prescribed electron function at the midplane. We consider e-e and e-i Coulomb collisions which are described by Maxwellian Rosenbluth's potentials on v, μ grid.

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The Two Fluid Model and Stabilization of the m=1, n=1 Mode in a Tokamak*

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The two fluid model of plasma evolution in a tokamak, that is part of the MH3DK code [1], has been benchmarked against the linear dispersion relation for the $m = 1$, $n = 1$ reconnecting mode in the limit of 'thin' reconnection layer width. In agreement with the dispersion relation, the two–fluid effects are seen to be stabilizing for the resistive mode at low and moderate beta. The model is then applied to the case when the ideal MHD mode has a significant growth rate. It is shown that two fluid effects retain a stabilizing influence on the mode. The relevant parameter is $\omega_*/\gamma_{\eta MHD}$, the ratio of the diamagnetic frequency to the resistive growth rate. Here $\omega_* \doteq v_{*\theta}(a/r_1)$ is a generalized diamagnetic frequency, based on $\mathbf{v}_* = (\mathbf{J}_{\perp B}/en) + \mathbf{v}_{*e}$, where $\mathbf{v}_{*e} \equiv \nabla p_e \times \mathbf{B}/(en_e B^2)$ and r_1 is the radius of the $q = 1$ magnetic surface. Thus finite beta can enhance the stabilizing effect at a fixed value of the two-fluid, or drift, parameter $\Omega_{ci}^{-1}\tau_A$, the ion gyrofrequency normalized to the poloidal Alfvén time. It is shown that as $\omega_*/\gamma_{\eta MHD}$ increases above a critical value, approximately equal to 2, the eigenmode structure changes significantly from the (resistive) MHD one and a relatively strong stabilizing effect appears. The standard assumptions of the analytic theory break down at this point.

The stabilizing influence of the drift effects on the ideal mode may be relevant to the observed sawtooth stability on TFTR, where the ideal mode is calculated to be strongly unstable, and for future ignition experiments. It has been postulated numerically that $\omega_{*i}/\gamma_{\eta MHD} \gtrsim 2$ should lead to quasilinear mode saturation [2], using a simplified model. This effect is investigated in the full two fluid model by calculating the evolution of the mode.

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Self-Organized Criticality as a Paradigm for Turbulent Transport*

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Understanding anomalous transport in magnetic confinement devices has been complicated by the observation that the dominant transport scale lengths have scaled with machine size (Bohm or worse scalings) while the suspected transport mechanisms have much smaller scales (Gyro-Bohm scaling). In order to shed some light on this apparent discrepancy and the effect of sheared flow on these scaling, a model for transport has been developed[1] based on self-organized criticality (SOC) theory.[2] This theory seeks to describe the dynamics of the transport without relying on the underlying local fluctuation mechanisms. It has been found that SOC systems maintain average profiles which are linearly stable (sub-marginal) and yet are able to maintain active transport dynamics in contrast to marginal stability arguments. It is also found that the dominant scales in the transport dynamics are system scales rather than the underlying local fluctuation scales.

The dynamics of such systems are computationally investigated with a cellular automata model. This model allows us to investigate the major dynamical scales and the effect of an applied sheared flow on these dominant scales. It is found that with no sheared flow or sheared flow decorrelation times smaller than the natural system decorrelation times the transport is dominated by the system scale. However the addition of sheared flow into the dynamics leads to a large reduction of the system scale transport and a commensurate increase in the fluctuation scale transport. This is consistent with the transition from Bohm to Gyro-Bohm scaling observed in improved confinement modes.

The dynamics of these models and the potential ramifications for transport will be discussed.

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Investigation of Neoclassical Tearing Instability in TFTR*

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Abstract

A good agreement[1] has been found between the time evolution of the tearing-type modes observed (mainly with $m/n = 3/2$, 4/3 and 5/4) in TFTR high-β DD/DT supershots and the nonlinear neoclassical tearing theory[2], which predicts that when a finite magnetic island is introduced in the low collisionality regime the single helicity island will evolve as:

$$\frac{dw}{dt} = k_1 \frac{\eta_{nc}}{\mu_0} \left(\Delta'(w) + k_2 \frac{\beta_p L_q}{L_p w} \right), \tag{1}$$

where w is the island width, η_{nc} is the neoclassical resistivity, $\Delta'(w)$ is the well-known tearing instability parameter, β_p is the poloidal beta, $L_p^{-1} = -(1/p)dp/dr$, $L_q^{-1} = (1/q)dq/dr$. k_1, k_2 are constants of unity. Recently, theoretical efforts have been addressed on the threshold island calculations[3]. Preliminary comparison with experiments shows that the threshold theory qualitatively agrees with the observation. On the other hand, we found that experimentally the tearing modes are often excited by different internal and external trigger mechanisms. Also, although the most observed tearing-type modes have single helicity (and its companion mode on the $q = 1$ surface), we also see cases where multiple helicities (e.g., the $m/n = 3/2$ and 4/3 modes) coexist throughout the neutral beam phase. It is also found that a sawtooth-like internal crash can cause a large and fast drop on the island width. All these observations may help us to further explore and understand the instability of the neoclassical ∇p-driven tearing modes.

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3D NONLINEAR SIMULATIONS OF DRIFT-RESISTIVE-BALLOONING MODES IN THE SCRAPE-OFF-LAYER IN TOKAMAK PLASMAS*

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We have modified our 3D nonlinear code for Drift-Resistive-Ballooning modes to study their evolution in the Scrape-Off-Layer. The new boundary conditions along the field line demands that the parallel current of the waves match the "sheath" current. We will show results from two extreme cases. One for which the parallel current associated with the waves is significantlty larger than the sheath current. For this case the boundary conditions at the plates are $\partial\phi/\partial z = \partial n/\partial z = 0$, and $v_{||} = 0.$, where z is the field-aligned coordinate. We find that the transport and fluctuation levels are larger than those obtained from our earlier simulations for these modes inside the last-closed-flux-surface. Also the time dependence of the transport is found to be very bursty in character. During the strong transport phase there a significant poloidal asymmetry in the flux. During the quiescent phase the asymmetry is reduced. The opposite limit being currently studied is the case for which the plasma parallel current is much smaller than the sheath current. The relevant boundary conditions along the field-line for this case are $\phi = n = 0$, and $\partial v_{||}/\partial z = 0$ at the plates. Detailed comparison of the structure of the modes and their associated transport for the two limiting cases will be presented.

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COUPLING OF SLOW LOWER HYBRID WAVES AT THE PLASMA EDGE : pondermotive effects, density cavitons and mode conversion

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A complete nonlinear wave propagation analysis is performed to examine the coupling of waveguide launched slow lower hybrid waves with the edge plasma. For the typical launch spectrum of ASDEX, it is found that one must keep the 4 most dominant waves in the electric field representation and so allow for mode conversion at the plasma edge. Previous pondermotive edge plasma theories have restricted themselved to only a 2-wave representation. These theories find a gradual change of the reflection coefficient with incident waveguide power.

With the more general 4-wave representation, for low incident powers, one finds similar behavior in the reflection coefficient as found in the earlier theories. The plasma edge density changes slowly with incident power while density holes/cavitons are formed in the plasma edge layer. However, there is a threshold power density at which there is a sharp reduction in edge plasma density with a correspondingly large increase in the reflection ceofficient. The plasma density caviton depth increases with incident power, and mode conversion occurs in regions where $| \nabla n \ | > 0$. At the plasma-grill edge there is negligible coupling to the short wavelength modes - but by the end of the pondermotive region, mode conversion can account for as much as 40% of the incident power in the short wavelength modes.

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Electron acceleration by Super Ion-Acoustic Double layer

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One-dimensional electrostatic particle simulation have been performed to investigate the formation and sustaining mechanisms of ion acoustic double layers. Double layers spontaneously evolve out of thermal noise when electrons with a subthermal drift velocity ($v_d < v_{th}$) are injected into a long and open system.

Previously, we realized through a particle simulation that a weak shock-like electrostatic structure (ion acoustic double layer) is created as a result of nonlinear development of an ion acoustic instability [1]. The discovered ion acoustic double layer exhibits the following characteristics; a stepwise potential jump of the order of electron thermal energy and a transient life. It is to be noted here that the simulation was based on a periodic model where electrons and ions periodically circulate from the downstream boundary to the upstream and vice versa. As a consequence of this periodic condition the highly disturbed, disordered "dirty" electrons on the downstream side of an ion acoustic double layer turned to be the incoming electrons from the upstream side. Thus, the dirty plasmas would never be swept away from the system. In addition, free energy was given only as an initial condition but never supplied from the external world.

In view of the restriction imposed by the closure nature of the previous model, one may anticipate that a new ordered state would be created if one sets up a model in which an enhanced entropy is automatically released from the system and a flux of free energy is continuously supplied. In this work, our simulation model is so designed that the system is in contact with an ambient plasma such as a current generator.[2]

We have found the following: First, in the early phase of evolution, weak ion acoustic double layers are generated in a stairs-like form. It is repetitive. Each weak double layer has a sharp negative dip followed by a sudden positive rise. Secondly, and most importantly, during the successive evolution of the weak double layers, it happens that a two-stream instability condition is met somewhere and some time in the system. Then, self-feeding condition is satisfied locally and a "super" ion-acoustic double layer is created there. The amplitude of the potential jump in such double layers reaches an unexpectedly large magnitude, which is far above the electron thermal energy, and a superthermal electron beam is generated on the downstream side.

Simulations for different plasma parameters indicate that the self-feeding excitation of the "super" ion-acoustic double layer is a real physical phenomenon, not a numerical artifact. For example, we have found that (1) ion acoustic double layers are generated when $v_d \geq 0.4 v_{th}^e$, (2) a super ion-acoustic double layer is self-excited when $v_d \geq 0.5 v_{th}^e$, and (3) the maximum amplitude of the super double layer has a strong and increasing dependence on the drift speed.

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Slow Linear and Nonlinear Thermal Wave Propagation in Radiative Plasmas

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Impurity seeded, uniform, optically thin radiative plasmas are investigated in linear and nonlinear approximations. The thermal force which acts on the impurity ions, leading to a relative motion between them and the main plasma ions is taken into account. It is shown that for each impurity species, some temperature intervals exist where the slightly damped or slightly unstable thermal waves are able to propagate. These intervals can be wide or narrow depending on the properties of the radiative losses and heat sources. Near the stability boundary, the real part of frequency equals the ion sound frequency multiplied by small factor, and is proportional to the impurity ion charge and a square root of the rate of radiative losses and impurity - main plasma ion collision frequency. When the electron heat conductivity is sufficiently damped by small scale turbulence, small scale weak stochastic magnetic field or strong inelastic collisions, the width of intervals is increased significantly. Some radiative impurities with heat sources independent of temperature and density, and classical heat conductivity are examined. At least for three sorts of impurity (lithium, copper and silver) there is a wide temperature interval that allows the propagation of these waves. It is trivial to generalize the solution for the case of a thermal and density dependent heat source. A nonlinear equation is obtained for a slow thermal wave in the approximation when the relative impurity and main plasma ions is a first order correction. It is shown analytically that the instability is transformed practically into a harmonic wave in the nonlinear stage.

Singular Eigenfunctions for Shear Flow*

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We study the continuous eigenvalue spectra of perturbations to the shearing, plane parallel flow of an ideal fluid using general methods [1] related to Van Kampen's treatment of the oscillations of a homogeneous plasma. We construct singular eigenfunctions of the continuum and establish that, together with any discrete modes, the eigenfunctions form a complete set with which an initial distribution of vorticity can be expanded. In a finite-dimensional linear Hamiltonian systems it is possible to transform to normal coordinates, in which the Hamiltonian is diagonal for stable degrees of freedom. Since the ideal fluid equations are a Hamiltonian system of infinite dimension (see for e.g. [2]), one would expect a similar situation to apply. Indeed, it is shown that the basis of singular eigenfunctions given in [3] is easily related to the normal coordinates of the linear fluid system.

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SHERWOOD INTERNATIONAL FUSION THEORY CONFERENCE
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STELLARATOR PROPERTIES OF TOKAMAKS WITH INCLINED TOROIDAL FIELD COILS.

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Georgievskij et al. [1, 2] have shown that a tokamak with vertically inclined toroidal field (TF) coils possesses closed vacuum flux surfaces with rotational transform. This configuration has the potential for adding stellarator properties to the tokamak configuration while maintaining the simplicity of flat coils. The present report is an extension of previous studies [1-3] of the configuration to the case of arbitrary shaped inclined TF coils. The scaling of the main parameters of the closed flux surfaces with the inclination angle, TF coil number, aspect ratio, coil size, etc. is investigated, and configuration optimization is demonstrated. Parameters of the system are identified which result in large vacuum flux surfaces and appreciable rotational transform. The important role of the poloidal field (PF) coil system is stressed, and the possibility of the compensated PF system (with zero total current) is found. Two sets of closed flux surfaces with opposite helicity have been studied: the internal one and external one. It was found that the external set of flux surfaces is MHD stable (it possesses a magnetic well), and has a larger enclosed volume and rotational transform. The internal set features a magnetic hill. The analysis of the flux surface structure and the helical harmonic spectrum yielded optimization rules. It is found that toroidal inhomogeneity is a key factor and vacuum flux surfaces disappear in the limit of a very high number of inclined TF coils.

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Abstract for International Sherwood Plasma Theory Conference 1995

A Cure For Locked MHD Modes And Their Feedback Control

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The critical problem of the detection of locked MHD modes in tokamaks is addressed in the context of a feedback control scheme. The feedback loop consists of mirnov loops/soft x-ray sensors, amplifiers, phase shifters and modulated neutral beam suppressors. The modulated radial momentum input of appropriate amplitude and phase from a radially injected neutral beam can stabilize a rotating MHD mode. The problem of lo(ked modes is also solved via feedback by imparting a real frequency to these 'ideal' modes in the plasma frame. Simple theoretical models predict modest levels of beam energy, current and power both for control and unlocking of the locked modes for typical tokamaks.

Nonlinear Radiative Condensation in a Divertor Plasma During ELM Activity

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A divertor plasma periodically heated by ELMs and cooled by impurity radiation may be unstable to the radiative condensation instability. The nonlinear stage of this instability is investigated in the present work. Heat conduction is neglected, and the radiation losses are modeled by a term n^2/T^β in the energy equation, where n is the density and T the temperature. Restricting our attention to one dimension, we have found nonlinear solutions describing the formation of cold, dense filaments in the cooling plasma. These solutions have the character of an explosive "collapse", where the density approaches infinity and the temperature vanishes after finite time.

The nature of the collapse depends on the scale length of the initial conditions and the value of β. For $\beta<-2$ the homogenous state is stable. If $-2<\beta<-1$, arbitrarily small perturbations in the initial conditions give rise to a subsonic collapse provided the wavelength is sufficiently small (but still large enough to neglect heat condution). The pressure remains constant and finite throughout the region. The character of this type of collapse depends to a certain extent on $\beta<-3/2$ or not. If $-1<\beta<0$, a collapse of a different nature occurs. Small long-wavelength perturbations result in the pressure first dropping to zero and the density later peaking as a result of wave breaking. Nonlinear condensation collapse behind a shock wave entering the divertor plasma is also considered.

The filamentation demonstrated to result from this instability would have a profound influence on the behavior of the plasma since, e.g., the incoming heat flux from an ELM could be much more effectively radiated than in a homogenous plasma. To observe the filamentation numerically requires a very fine mesh.

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Global Gyrokinetic Particle Simulation Studies on Isotope Effects*

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Three-dimensional global gyrokinetic particle simulation of ion temperature gradient (ITG) drift instabilities in toroidal geometry have been carried out using hydrogenic isotopes for studying their transport properties. The model, which simulates the total core region of a tokamak, includes the perturbed electrostatic potentials associated with the gyrokinetic ions and adiabatic electrons.[1]

The simulation, which has been carried out with TFTR supershot parameters prescribed by the Numerical Tokamak Project,[1] uses a various combination of hydrogenic isotopes. For the simulation with pure H, D, and T ions, the results indicate that the peak of the $k_\theta\rho_s$ spectrum undergoes a downward shift from 0.5 in the linear stage to 0.2 in the turbulent steady state for all species, where ρ_s denotes the ion gyroradius of the species measured in terms of the electron temperature. In addition, the steady state k_r spectra for all species always peak at zero and the time-averaged widths, Δk_r, also stay nearly constant for all species. A closer inspection reveals that the nonlinear Δk_r is primarily prescribed by the spatial variation of the equilibrium scale length. Finally, the measured ion thermal diffusivity, χ_i, at the saturation and in the steady state scales favorably with mass. For the hydrogenic mixtures, this scaling trend persists with the respect to the effective mass. In such a mixture, an enhancement of χ_i for one species due to the presence of the inverted density gradient of the other has also been observed. This is due to the coupling between the ITG modes and the impurity gradient drift instabilities.[2] The implication of these simulation results on the recent D-T experiments on TFTR will be discussed.

Theoretically, the trend for favorable isotope scaling can be understood as follows. The dominant low (m, n) modes at the nonlinear stage of the simulation still maintain, to certain extent, some of the linear properties, specifically, the mode frequency and radial mode structure. The latter, Δk_r, as shown by Tang and Rewoldt,[3] is intimately related to the equilibrium profile variation. As a result, one can show from the Connor-Taylor invariance for the ITG modes,[4]

$$\chi_i \propto (k_r \rho_s)^{-2} (\rho_s/L_T)\, cT_e/eB,$$

that favorable isotope scaling is indeed feasible. Thus, the work presented gives the possible origin of non-gyro-Bohm scaling in tokamaks and also shows the importance of global simulation.

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Stability of the m=1 Top

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Ideal MHD theory has been shown to predict the experimental high-beta limits accurately when the safety factor is greater than one. When the central safety factor is less than one, however, high beta discharges in DIII-D and TFTR generally violate the *ideal* stability criterion for the m=1 "internal kink" mode, with no clearly identifiable consequences. The discrepancy between theoretical and observed behavior of the m=1 instability is an important concern both for present tokamaks, where it limits the achievable beta, and for the next generation of tokamaks, in which this instability may be destructive. We have evaluated the effect of plasma rotation on the ideal stability of the m=1 mode. This mode is shown to consist of the combination of a rigid displacement along, and a tilt about an axis lying in the equatorial plane of the tokamak. It also has a small sausage component that cancels most of the toroidal magnetic field perturbation caused by the first two displacements. In the presence of rotation the Coriolis force has a stabilizing effect on the mode analogous to that found in a spinning Lagrange top. The m=1 mode differs from the top, however, in that the moment of inertia about the tilt axis is dominated by motion in the inertial layer around the q=1 surface. It is found that the mode can be stabilized by sonic toroidal rotation velocities.

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Poster preferred.

Simulation of Divertor Plasmas with a Combined Edge Plasma/Navier-Stokes Neutral Transport Model*

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A two-dimensional combined edge plasma/Navier-Stokes neutral transport model is presented that includes ions, electrons, and neutral atoms which undergo coulomb collisions, electron impact ionization, ion neutral charge exchange, three-body and radiative recombination, and neutral-neutral collisions. The model includes 8 conservation equations: continuity equations for the plasma and neutral components, an energy equation for electrons, a combined energy equation for the ions and neutrals, a parallel plasma momentum equation, and 3 components of neutral momentum. This model is used for the simulation of dense recombining "ITER-like" divertor plasmas as well as for modeling current Alcator C-MOD conditions, including divertor detachment. It is also demonstrated that this model can produce converged steady-state detached solutions, where detachment is defined by the 1 eV electron temperature contour pulling completely off the divertor plate.

The dense divertor simulations show that interesting neutral flow patterns can exist and that these flows can convect significant energy. Additionally, solutions that ignore neutral-neutral collisions are found to be quantitatively different from ones that include neutral-neutral collisions. We consider the effects of overall problem length, as well as divertor width for a fixed problem length. It is also shown that ignoring hydrogen line radiation has a significant effect on the solution.

The model is used to simulate Alcator C-MOD conditions in a simple rectangular geometry resembling the outboard leg of a slot divertor configuration. At these conditions, carbon impurity radiation is shown to bring about divertor detachment. A significant decrease in heat flux, ion saturation current, and plasma density is observed at the divertor plate. The bulk of the plasma momentum is converted into neutral "toroidal" momentum. We compare numerical results to experimental data within the limits of our geometry.

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Resistive Wall Mode Analysis for PBX-M Using the NOVA-W Code

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Attractive advanced plasma configurations (such as the reversed shear scenarios proposed for TPX and ITER) rely on wall stabilization of low-n external kink modes in order to achieve high β_N simultaneously with high bootstrap current fraction. The PBX-M experiment, with its close-fitting conducting plates, is a good experiment for testing our theoretical understanding of resistive wall mode stabilization by plasma rotation. Using the NOVA-W linear stability code, we analyze a PBX-M experimental shot where the bean-shaped configuration is tightly coupled to the conducting plates. The NOVA-W code is run using the actual geometry of the PBX-M passive shell system (i.e., including gaps) and results are compared with those obtained by assuming a poloidally continuous wall. Growth rates and real frequencies calculated by NOVA-W are compared with the experimental observations of MHD activity. Finally, we describe modifications (in progress) to the NOVA-W code which will allow the incorporation of sheared toroidal plasma flow.

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Prefer Poster

Two-dimensional radial structures of Alfvén Modes excited by energetic particles in tokamaks

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An analytic theory of high toroidal mode number (high-n) Alfvén Modes excited by energetic particles has been recently derived,[1–4] leading to a general expression for the local dispersion function of such modes, $F(\omega; nq, \theta_k)$, in terms of frequency ω, radial 'flux' coordinate nq (q is the safety factor), and WKB phase, θ_k, of the mode radial envelope function, $\mathcal{A}(nq) \simeq \exp(i \int \theta_k d(nq))/\sqrt{\partial F/\partial \theta_k}$. It is known that a global stability analysis can be made, starting from such local dispersion function, and that the two-dimensional mode structure can be determined.[5]

In the present work, we analyze the two-dimenesional mode structures of the Alfvén branches, whose frequencies are close to the toroidicity induced Alfvén continuum gap. Relevant resuls are the confirmation of the previous analyses on the radial envelope function of Toroidal Alfvén Eigenmodes (TAE)[5]; the discussion of the radial localization of the corresponding kinetic branch (KTAE), which may be rather extended; and the analysis of the energetic particle continuum mode,[2] whose localization is determined by the spatial dependence of the beam drive and by the resonance condition between the mode characteristic frequency and the beam particles.

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MHD Stability of Simulated ITER Discharges in DIII–D

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A significant β limit margin, above the nominal ITER operating point, is crucial to the prospects for ignition of the ITER device. The operating point has been designed at normalized $\beta\,(\beta_\mathrm{N}) \sim 2$ to provide a good safety margin with respect to the expected Troyon limit of $\beta_\mathrm{N} \sim 3$. Stability calculations using the PRETOR equilibria yielded ideal kink β limits well above the Troyon limit. However, those equilibria were obtained from extrapolating phenomenological transport models from existing small tokamaks and their relevance to ITER could be questioned. Also, the ITER shape is far from optimal for MHD stability and the Troyon β limit in real discharges may be overly optimistic. It is therefore important to resolve this question by obtaining direct β limit information in ITER-like discharges produced in existing tokamaks.

Several discharges have been obtained in DIII–D that were designed to simulate the ITER EDA operating point. The most important parameters from an MHD perspective were successfully matched in several cases. We have undertaken a systematic program of accurately reconstructing the discharge equilibria and computing the ideal MHD stability of several of these discharges with a view to determining the β limit expected for real discharges in the ITER device. The results show more pessimistic β limits than the PRETOR studies predicted, but the kink stability limits are still sufficient to provide a reasonable safety margin; the ideal $n = 1$ kink β limit is close to the Troyon limit. The discharges tend to be limited by high n ballooning stability. Sensitivity studies with respect to variations in several profile and shape parameters are also being done to determine the robustness of the proposed operating point in ITER. These will also be discussed.

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Poster presentation requested

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2-D WKBJ-Ballooning Approach to High-n TAE modes

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It is now generally acknowledged that TAE modes destabilized by alpha particles could cause significant difficulties for fusion ignition devices because of their capacity to produce large particle losses. Preliminary studies of high-n TAE modes based upon the local ballooning formalism have shown that ITER will be unstable. This has motivated the designation of the 2-D high-n TAE modes analysis as an urgent research need for the ITER project. In this work, a two-scale numerical framework based upon the WKBJ-Ballooning formalism will be presented. This formalism reduces the 2-D toroidal eigen-equation into a 1-D ballooning equation on the fast scale and a WKBJ description of the radial envelope function. Note that the formalism can retain all the non-ideal effects non-perturbatively by solving the non-ideal 1-D ballooning equation in the complex plane and using the anti-Stokes line to obtain the eigen-frequency and thus the radial envelope function. Two codes are thus developed accordingly: (1) a 1-D ballooning code in the complex plane to evaluate the local dispersion relation functional $F(\theta_k, \omega, \psi)$, the radial spectrum of the WKB turning points, the shear-Alfvén continuum and the WKBJ ray trajectories; (2) a global WKBJ code to determine the WKBJ anti-Stokes structure, the global eigen-frequency and the continuum resonance damping. We would like to point out here that the 1-D ballooning code developed here will ultimately include most of the dominant non-ideal physics, general geometry, and self-consistent equilibrium. However, the ideal zero beta case, in which the analytical local dispersion relation functional can be obtained to provide a useful benchmark comparison with the numerical results, will be our starting point. In addition, an appropriate variety of plasma profiles will be considered to illustrate the corresponding TAE modes global radial structures. In particular, the recently observed core localized TAE-mode will be investigated.

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☒ Poster

CURRENT DIFFUSION AND LOOP VOLTAGE RESPONSE TO A NONINDUCTIVE CURRENT DRIVE IN A TOKAMAK

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A noninductively driven current in tokamaks is most commonly measured by changes in the inductive loop voltage with the total plasma current held constant. If a steady state is reached then the driven current is proportional to the loop voltage change. In practice, however, a steady state may not be reached: the current drive pulse duration may be shorter than the current relaxation time scale, plasma conditions may evolve or the current source strength may vary in time. Effects of time dependence are often modeled by invoking circuit equations in which the plasma is represented as a resistance and inductance connected in series. A more complete way of describing the plasma response involves solving a full set of transport equations in order to determine the toroidal electric field diffusion in the presence of an external current source. In the present paper we analyze the loop voltage response as determined solely by the resistive current diffusion under conditions relevant to tokamak operation. In this analysis plasma conductivity is taken as known, rather than self-consistently obtained from the energy transport equations, with its spatial profile (but not necessarily magnitude) being constant in time. By employing the WKB approximation we determine times scales governing the loop voltage response for a large class of conductivity profiles and compare them with numerical solutions.

In recent Alfvén wave current drive experiments in the Phaedrus-T tokamak [1] abrupt loop voltage drops, on the time scale much shorter than the "L/R" time inferred from current decay experiments, have been observed following the rf turn-on. The calculated current relaxation time scales are in agreement with the observations. Our analysis also reveals, somewhat surprisingly, that a localized current drive can give rise to a nonmonotonic loop voltage response if it is located outside a certain critical radius, determined by the node of a relevant eigenfunction. Such behavior has often been seen in experiments. By comparing the measured and the calculated loop voltage responses the current drive position is determined.
This work is supported by U.S. DOE grant no. DE-FG02-88ER53264.

[1] S. Wukitch et al., to appear in Phys. Rev. Lett.

Rapid Guiding Center Calculations*

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Previous guiding center codes using numerical equilibria such as *ORBIT*[1] evaluate the local field strength and ripple magnitude using Lagrangian interpolation. Evaluation of these quantities four times per time step (using a Runge-Kutta routine) constitutes the major computational effort of the code. In the present work we expand the field quantities in terms of pseudo-cartesian coordinates. The simplicity of the representation gives four advantages over previous methods:

1. A much more rapid calculation of field quantities.
2. A very compact representation of the field, which allows simple data exchange.
3. A physical interpretation of the coefficients in the representation of B.
4. A convenient means of carrying out sensitivity studies, in particular that of particle loss under equilibrium modification.

The resulting code ORBITX is eight times as fast as ORBIT.

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*This work supported by DoE contract No. DE–AC02–76–CHO–3073.

poster

Divertor Modelling for Reactor

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Injection of both impurity and deuterium for the gaseous target divertor is considered in order to reduce the heat flux to the divertor plate and dissipate the momentum flux effectively to a larger wall area. This scheme creates not only a radiating mantle just inside of the last closed flux surface and SOL but also radiating spots near the divertor. The self-consistently coupled fluid equations[1,2] for plasma and neutrals developed recently are suitable for this system. We considered the effects of charge exchanges, impact ionization, and recombination. The Fluid Modelling System-1D (FMS1D) code[3] developed at UC-San Diego for general purpose modelling was applied to simulate the gaseous target experiments at the PISCES. Compared to the results from ref.[3], the results of this work show better matching with experimental data, especially near the target. Results from the simple impurity model based on the constant fraction of impurities for ITER will also be presented.

Coupled density and momentum conservation equations with main ions for each charge states of impurities are being added into coupled plasma-neutral equations. Boundary condition, e.g. Bohm sheath criterion with impurities and at arbitrary magnetic field geometry, is incorporated.

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3D Fluid Simulations of Turbulences in Detached SOL Plasmas

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It was recently shown by Krasheninnikov et al that detached divertor regimes can achieved when plasma pressure drop along a magnetic field line towards the divertor plate is balanced by a plasma diamagnetic and $\mathbf{E}\times\mathbf{B}$ drift induced nonlinear inertial force. It has been estimated by Gang et al that the turbulence induced Reynolds stress is comparable to the total plasma presure drop. In this paper we report on detailed nonlinear comparisons of various possible linear instability sources using a recently developed 3D fluid code of the reduced Braginskii Equations in field-line-following coordinates. The linear instability sources are conducting-wall mode, curvature-driven mode, Kelvin-Helmhotz mode and $\nabla v_{||}$ mode. The model has edge and scrape-off layer (SOL) regions, and proper sheath boundary conditions are included in the SOL. Comprehensive nonlinear simulations with increasing complexity will be presented, including: magnetic shear, toroidal geometry and shear flows. By varying the axial background electron temperature profiles in the code, we systematically investigate the changes of turbulence properties. The comparisons of plasma pressure drop along a magnetic field line towards the divertor plate with plasma diamagnetic, $\mathbf{E}\times\mathbf{B}$ drift and turbulence-induced Reynolds stress under detached plasma conditions are discussed.

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*Performed by LLNL for USDOE under Contract W-7405-ENG-48

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Ballooning Stability of Supersonic Flows

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Tokamaks heated by unbalanced neutral beams tend to develop large toroidal flows,[1] with Mach number of order unity. A supersonice flow introduces additional difficulties to the stability analysis. In particular, the flow carries all "slow" magnetosonic waves downstream so that no standing wave is possible. Thus, investigation of stability by the standard (discrete) normal mode analysis is not useful. Instead, one needs to follow an initial perturbation for a long time and to determine whether it grows, and at what rate.

We consider a model problem of a flow parallel to the magnetic field, and investigate the ballooning mode which is also localized to the fieldline. Both the equilibrium state and its ballooning stability are known exactly if the flow is subsonic.[2] Using various "energy"-type estimates we find that the supersonic flow is never exponentially unstable, even in a parameter range where the subsonic case grows exponentially. Instead, the instabilty may grow at most algebraically in time. We suspect that this surprising result depends strongly on the model equilibrium state, and that a more tokamak-like equilibrium will allow for exponential instabilities.

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1D Model of the Transport of the Plasma and Neutrals in the Divertor Layer

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A simple, one-dimensional model describing the transport of the plasma and neutral gas in the divertor layer and divertor of a tokamak has been developed for parametric studies of the divertor performance.

The usual fluid equations along the magnetic field are employed for the plasma transport, while the two components of the neutral flow velocity, along and across the magnetic field, are treated in an one-dimensional fluid approach. Thus the momentum balance equations used in the model are

$$\frac{\partial}{\partial t}(MnV) = -b\frac{\partial}{\partial y}\left(MnV^2 + P_p + \pi_{p,\parallel}\right) - MnNK_{iN}\left(V - U_\parallel\right) + MnNK_I U_\parallel , \tag{1}$$

$$\frac{\partial}{\partial t}(MNU_\parallel) = -b\frac{\partial}{\partial y}\left(P_N + MNU_\parallel^2 + \pi_{N,\parallel}\right) - b'\frac{\partial}{\partial y}(MNU_\perp U_\parallel) + \delta MnNK_{iN}\left(V - U_\parallel\right) - \delta MnNK_I U_\parallel - \nu_W^{(m)} MNU_\parallel , \tag{2}$$

$$\frac{\partial}{\partial t}(MNU_\perp) = -b'\frac{\partial}{\partial y}\left(P_N + MNU_\perp^2\right) - b\frac{\partial}{\partial y}(MNU_\perp U_\parallel) + \delta MnNK_{iN} U_\perp - \delta MnNK_I U_\perp - \nu_W^{(m)} MNU_\perp \tag{3}$$

Here y is the poloidal co-ordinate, the factor δ characterises the efficient width of the plasma layer, and terms with $\nu_W^{(m)}$ describe the interaction of the neutrals with the side walls. Similar terms are added to the energy equations, where both $U_\perp$ and $U_\parallel$ are taken into account in the energy transport with neutrals and the energy balance for the plasma allows for the impurity radiation, and to the continuity equations. Such an approach allows to model, within the framework of simple 1D fluid equations, the effects related with the cross-field transport of neutrals and plasma on the divertor performance, in particular, for the detached plasma regimes presently envisaged in ITER.

Symbolic Analysis of Turbulent Fluctuations*

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Tokamak plasma are characterized by many different types of turbulent fluctuations present at the same time. Our understanding of turbulence related to these fluctuations is still very poor. For example, there is still a debate in the plasma physics community about the nature of turbulence responsible for anomalous heat transport. Namely, whether it is magnetic (destroyed magnetic surfaces), electrostatic or a combination of both. We propose a method of how to identify fluctuations related to the same physical processes by direct analysis of these fluctuations. The traditional method of Fourier transform does not work here, first because there are no coherent modes and second, that due to nonlinearities even fluctuations governed by the same physical processes could have a different power spectrum. Our analysis is based upon symbolic representation of the time series. The correct symbolic language is chosen by maximizing metric entropy. Now, if two different fluctuations exhibit the same information content then it is an explicit demonstration that they are governed by the same physical processes. As an example of the application of this method we present symbolic analysis of the Lorenz model.

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Modelling of Neon Puffing and Pumping in ITER Divertor

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Impurity seeding is being considered to remove energy from the electrons in ITER. Good candidates for impurity puffing are neon, argon, and krypton, because these gases will recycle from the first wall. We are using the B2.5 code to compare different scenarios for neon puffing and gas pumping in ITER-CDA divertor. These calculations consider all charge states of hydrogen, helium, and neon in a multi-fluid model. The input power from core plasma is set to 140 MW. The boundary conditions are varied to model different impurity puffing and gas pumping scenarios: puffing through the private flux region, or from the outside wall, or on both sides; and we vary the rate of gas pumping in order to influence the hydrogen flow pattern in the scrape-off layer and divertor.

At any conditions we find that about 30 % of the power is lost by hydrogen radiation and recycling, and about 10 % by that of helium. The remaining 60 % power is shared between neon radiation and heat flux to the target in a ratio determined by the neon concentration. 40% of the energy loss by neon comes from Ne^{6+} and 20% from Ne^{5+} in the divertor region close to the separatrix.

At low pumping speed, a recirculating flow pattern is very effective in mixing the impurity concentration between the divertor region and the core. We attempt to model a situation in which the impurity would be trapped in the divertor by high gas pumping in the divertor. However, this does not lead to a favourable scenario. High pumping causes a lower plasma density near the target and this is unfavourable for the electron cooling by neon. The plasma begins to detach from the target at the lowest neon concentration in the cases where we pump very little plasma, not attempting to influence the hydrogen flow pattern. At the start of detachment more than 100 MW is lost by impurity radiation in the divertor.

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Poster presentation

(1) On leave from Department of Quantum Engineering and Systems Sciences, University of Tokyo.

Analytical Estimation of NBI Heating Efficiency and Plasma β in Heliotron/Torsatrons

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Physics of high β plasma is one of the important issues for developing the efficient future fusion reactor. Many experimental and theoretical studies have been done not only in tokamaks but also in heliotron/torsatrons. Recently the high β experiments in the CHS (Compact Helical System) show the highest averaged β value in heliotron/torsatrons as $\langle\beta\rangle = 2.1\%$. Since the large Shafranov shift occurs in finite β in heliotron/torsatrons it is necessary to take this configuration change into account for evaluating the heating efficiency in finite β. In this paper the efficiency of the NBI heating is analytically derived in finite β using the calculated beam deposition profile and beam particle orbit. Large drift orbit deviation of tangentially injected NBI particle from the original magnetic surface occurs to enhance the prompt orbit loss and diminish the heating efficiency when the strength of magnetic field is small. It is found that the configuration changes due to the finite β effects alter the NBI heating efficiency largely and that the magnetic well or hill condition, which is important for the MHD stabilities, is also an important factor to determine the heating efficiency in a weak magnetic field. By combining the energy confinement scaling law the plasma β is evaluated. It is found that there is the optimum value of the magnetic field to obtain the high plasma β in a point of view of the NBI heating efficiency. Applying our model to the CHS plasma we evaluate the plasma β using consistent configuration with obtained β value. The results agree well with the high β experiments in the CHS. It is found that the effects of beam particle orbits play an important role to determine the reachable β value in the CHS experiments.

Study of a Divertor Plasma in $\vec{E} \times \vec{B}$ Flow

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Abstract

Recent experiments on most diverted tokamaks have found "detached divertor" operating regimes characterized by a vert low heat and particle fluxes to the divertor plates. So far, practically all estimations of edge plasma parameters were done by means of fluid models of tokamak edge plasma. However for edge plasma parameters typical for current tokamaks as well as ITER an the applicability limit of these plasma fluid models is usually violated (especially in "detached divertor" regimes characterized by the steep plasma parameter profiles) and kinetic effects must be incorporated. Perpendicular plasma transport ($\vec{E} \times \vec{B}$ drift in particular) can lead to enhanced suprathermal tails in the SOL plasma due to the radial gradient of the plasma temperature. Moreover, due to the influence of the shear of the self consistent $\vec{E} \times \vec{B}$ drift affecting the inertia term in the plasma momentum balance a strong drop of the total plasma pressure $P_{\sum} = Mnv_{\|}^2 + nT$ along the magnetic field lines can be supported in a manner similar to that observed in detached divertor plasma experiments without any influence of the plasma neutral interaction.

We present in this work an Eulerian Vlasov gyrokinetic code developed for the investigation of the different subjects previously listed. The model consists of a two-components collisionless plasma slab, with a fixed wall, to simulate a plasma divertor. The model is two-dimensional in space and makes use of the gyrokinetic approximation in the plane perpendicular to the magnetic field. The code includes the possibility of biasing the fixed wall to a given potential. Preliminary results indicate that kinetic effects parallel to the magnetic field seems to play an important role in this problem. These results represent one step further in studying consistently the effect of biasing and electric field in a divertor plasma. Vlasov codes have proven to give very good results in plasma simulation, being capable of describing correctly the phase space distribution function even in regions of low density.

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Extensions of the TAE/FL Toroidal Alfvén Time Evolution Model to Include Kinetic and Single Particle Effects

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Stability of fast ion-driven TAE (toroidal Alfvén) modes is an important consideration both for the efficiency of alpha heating in ignited devices as well as for wall heat load limitations caused by enhanced losses of high energy alphas. Two topics will be covered:
(a) Application of the Landau fluid model to ITER and TFTR In the ITER-EDA design high-n TAE instabilities have been analyzed. Although the parameters appear to be close to or below stability thresholds, further analysis is warranted due to the consequences of these modes and the sensitivity of the thresholds to parameter/profile variations. We have demonstrated that our approach is numerically robust up to toroidal mode numbers of n ≈ 30–40 which covers most of the unstable regime in the current design. Also, this model can include most of the growth/damping mechanisms expected to be relevant to ITER. The TFTR-DT experiments have attempted to excite alpha-driven TAE instabilities through a variety of approaches including lowering the ion temperature (to lower the damping rates) and raising the central q value (to increase the drive). Application of our model to a number of these cases will also be discussed.
(b) Extensions of the model Techniques have recently been developed to extend the TAE/FL gyrofluid model to (1) treat more general fast ion distributions, and (2) incorporate stochastic orbit transport effects. Under topic (1) two approaches can be used. The simplest way is to adjust two of the coefficients in the gyrofluid evolution equations (these arise from the two-pole approximation of the plasma dispersion function) so that they fit the resonant response of a distribution other than a Maxwellian (e.g., a slowing-down distribution) over the relevant ranges of phase velocity. The second, and more general approach, is to replace the fast ion gyrofluid response term in the quasineutrality relations (i.e., vorticity equation) by a kinetic integral, S_α (a simplified version of which is given below), over an arbitrary fast ion distribution.

$$S_\alpha = -\int d^3v \frac{\omega}{\omega - k_\parallel v_\parallel}\left(\frac{\omega_d}{\omega_{d0}}\right)^2 \left(\frac{\omega_{*\alpha}}{\omega} L_{n\alpha} \frac{\partial F_\alpha}{\partial r} + T_{\alpha 0} \frac{\partial F_\alpha}{\partial E}\right)$$

If $\gamma/\omega << 1$, as is typical for the TAE, then the imaginary part of this integral is dominant and depends only on the real frequency, ω, which can be calculated dynamically during the time evolution. This approach can then also be employed under topic (2) as a means of coupling this model to particle orbit mapping techniques (eventually to be replaced by a general orbit trajectory model) to allow simulation of the effect of the TAE perturbed fields on the fast ion transport. By averaging over the distribution of particle locations we can form a reduced distribution $F_\alpha(r,E,t)$ which is then used to update our resonant velocity integral, S_α. This model then no longer relies on gyrofluid techniques to treat the fast ions (except possibly as a means for providing a "quiet start" initial condition for the TAE mode structure), but can still retain many of the desirable features of the TAE/FL model, such as adequate radial and Fourier mode resolution, analysis of noncircular cross sections and the retention of nonlinearities such as velocity shear generation and magnetic island formation which arise from the n = 0 components of the vorticity equation and generalized Ohm's law; the latter two equations are still retained in the new model. Such nonlinearities have been found important for the saturation of the TAE in our previous work.

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MULTIDIMENSIONAL AUTORESONANT THREE-WAVE INTERACTIONS IN SPACE-TIME VARYING PLASMAS

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Abstract

Autoresonance is a unique nonlinear phase-locking phenomenon characteristic of resonantly interacting oscillations and waves in adiabatically varying systems. Applications of the autoresonance are known for accelerators [1], atomic physics [2], nonlinear dynamics [3], and one-dimensional resonant wave-wave interactions [4,5]. Following our recent study on three-dimensional autoresonant mode conversion [6], we shall generalize the theory to multidimensional nonlinear three-wave autoresonant interactions for externally launched waves in a weakly space-time varying medium. We shall consider a boundary value problem in which the volume of interest is illuminated by two eikonal waves, which internally (inside the volume) resonantly excite a third (daughter) wave. It will be shown that this excitation process takes place in a thin layer around a two-dimensional resonant surface and, across the layer, the three-wave interaction problem is locally one-dimensional. We shall discuss this problem in the regime when nonlinear four-wave vector shifts are important and find the conditions for the autoresonance in the system, leading to the broadening of the resonant region and enhanced efficiency of the three-wave interaction. The effects of a weak damping and/or nonuniformity of the boundary conditions will be also included in the theory.

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An L-H-Like Transition in a Tokamak SOL*

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Increasing the radial mode number has a stabilizing effect on the conducting-wall and curvature-driven interchange modes in a tokamak scrape-off layer (SOL), arising from the increased polarization response. Such an effect is naturally imposed as the SOL width is decreased, and for a narrow-enough SOL, the stabilizing effect is stronger than the increase in the instability drives. By combining a mixing-length estimate for the thermal diffusivity with energy conservation and heat conduction equations and the condition of continuity of the heat flux at the separatrix, we find that the resultant turbulence-transport system admits two solutions, one stable and one unstable, at different SOL widths. Addition of additional physics can add a second stable root at lower width; we consider $\nabla v_{\|}$ and Kelvin-Helmholtz turbulence as examples. These roots are plausibly identified with SOL behavior in L and H modes. Particularly when a model is introduced for finite-β, finite-$k_{\|}$ effects on the modes, a power threshold for transition to the narrower root is obtained, suggesting a possible L-H transition mechanism. The scaling of this threshold with density, toroidal field, current, geometry, and several other paramters is obtained from a combination of dimensional analysis and numerical experiments, and found to be consistent with data reported for single-null operation of DIII-D.[1] The non-monotonic dependence of the turbulent heat flux vs. SOL width and the possibility of multiple solutions for the equilibrium SOL width are verified with nonlinear turbulence simulations.

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Low-dimensional representations for the dynamics of L–H transitions*

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The resistive-g PDEs are a canonical two-parameter model for the thermal convection and the momentum transport in confined plasmas.[1] For low viscosity and high pressure gradient the coupled vorticity–pressure convection equation show the onset of shear flows with a reduction of the thermal heat flux. We study the bifurcations (second instabilities) to shear-flow states through a 6-ODE model of the system. The structure of the coupled thermal and momentum flux is investigated in terms of entropy production functionals. Closures of the triplet correlation functions are used to reduce the system to three thermodynamic variables $\mathcal{U}$, $\mathcal{W}$, and $\mathcal{F}$ for the mean potential energy $\mathcal{U}$, the turbulent fluctuation energy $\mathcal{W}$, and the shear-flow kinetic energy $\mathcal{F}$. Finally, the dynamics of the 6-ODE system and the thermodynamic model are compared.

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Drift-type Microinstabilities in High β Tokamaks*

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In the high-β plasma equilibrium[1] ($\beta \gg \epsilon/q^2$) the core region consists of straight magnetic flux surfaces (with only major radius dependence) and a boundary layer region of thickness δa where $\delta \equiv \sqrt{\epsilon/\beta q^2}$. The boundary layer region has several interesting equilibrium properties distinctly different from a low-β tokamak while the core region is in many ways similar to a low-β equilibrium. Considering the fact that for drift-type modes at high β electromagnetic perturbations are the same order as electrostatic perturbations, the study of these modes in a high-β equilibrium becomes very interesting. The boundary layer region coincides with the bad curvature region. However, in this region, the ∇B drift is in the opposite direction to what it is in a low β plasma (due to the magnetic well) and the curvature drift is $\mathcal{O}(\delta^3)$ smaller. Furthermore, the connection length and shear length are reduced by $\mathcal{O}(\delta)$ and $\mathcal{O}(\delta^2)$ from their low β values respectively. These issues and the reduced fraction of trapped particles (by $\mathcal{O}(\delta)$) enable us to perform a local analysis of these modes for a large portion of the parallel and perpendicular wavelength spectrum. We show that the η_i branch is significantly stabilized and the instability threshold is approximately given by $\eta_{i\text{crit}} = 3.4 - 2.4e^{-\beta/0.25}$ for a single species equal temperature plasma. Numerical and analytical results from this analysis will be presented. Transport implications of these results will be discussed.

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Request POSTER presentation

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High Beta, Skin Current Tokamaks

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Past experiments have shown that "anomalous" current penetration took place when the current of a toroidal discharge was increased rapidly and yet the expected skin current distribution could not be sustained. It was commonly believed that this was caused by the double tearing mode and therefore skin current tokamaks were dismissed as contenders for fusion reactors. Recently discharges with good confinement and relatively high beta and with non-monotonic q-profiles have been established in DIII–D. It is believed that a shear in a toroidal rotation established by early neutral beam injection has stabilized the double tearing mode. We have considered the extreme manifestation of the non-monotonic q discharge, namely a skin current, high beta tokamak. The first challenge is how to drive the current and maintain the skin current profile for a long time. Arguments are found which suggest that this can be accomplished for certain equilibria by injection of power and mass, for example by neutral beam injection. These equilibria are of very high beta of order unity and stable to ideal ballooning instabilities. If the DIII–D result holds, potential external kink instabilities may be stabilized by toroidal rotation of the plasma relative to a close fitting resistive wall.

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Poster presentation requested

Kinetic Effects on Particle and Heat Fluxes in Detached SOL Plasmas

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Abstract

A comprehensive 1D2V kinetic PIC code W1 [1] for collisional divertor plasma simulation was originally developed on the PC/486 platform. Through a joint effort, W1 has been ported to workstations and to the Cray C90. Optimization through vectorization and parallelization is in process. In order to achieve peak execution speed on C90, we have rewritten part of the program to "in-line" several functions used in the collision algorithm based on stochastic Langevin equations. These new versions will facilitate our ongoing investigation of the effects of impurities and neutrals on detachment phenomena and on axial heat and current fluxes in the presence of strong gradients when fluid descriptions break down.

In this investigation, various neutrals and impurity models are being used. In particular, we present results for Knudsen (long mean-free-path) and "gas-box" models of the neutrals, and an initial impurity model with fixed excitation profiles as functions of space and energy. We compare with solutions from a 1-D version of the UEDGE fluid code and with experimentally observed detachment results on the DIII-D and C-Mod tokamaks.

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Computer Simulation of an MHD Dynamo

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A computer simulation of a magnetohydrodynamic dynamo in a rapidly rotating spherical shell is performed. Extensive parameter runs are carried out changing electrical resistivity. New results which we have obtained are summarized as follows:

1. When the resistivity is sufficiently small, the magnetic energy (ME) generated by the dynamo can become larger than the kinetic energy (KE) of the convection motion. It reaches more than ten times larger than the KE.

2. The KE keeps nearly the same level irrespective of generation of the magnetic field. This is true even for the case when the ME becomes more than ten times larger than the KE.

3. The growth rate of the magnetic field is well represented by a linear function of the logarithm of the resistivity. The physical process is under investigation.

4. The structure of the convection columns become quite different depending on whether the ME is larger than the KE or not.

5. When ME $<$ KE, the convection motion keeps an almost identical motion to that of the convection motion with no magnetic field. The convection motion in this case is so robust that it is not affected by the existence of magnetic field.

6. When ME $>$ KE, the convection motion is strongly disturbed by the magnetic field and becomes turbulent.

7. The generated magnetic field is organized into two concentrated magnetic fluxes with parallel and perpendicular components to the rotation axis (z-axis); B_z–flux concentrated regions and $B_\perp$-flux concentrated regions.

8. The B_z–fluxes are confined in anticyclonic columns.

9. The $B_\perp$–fluxes are confined outside convection columns.

And we have recently found a parameter range in which the dipole moment is dominant in the generated magnetic field.

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ANALYTICAL AND NUMERICAL SOLUTIONS OF THE TEARING MODES LINEAR STABILITY EQUATION

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Since tearing mode activity characterizes much of the history of a typical plasma discharge in tokamaks, it is important to have methods to analyze the resistive stability of various current density profiles. In particular, it would be useful to develop fast and accurate stability methods that could be efficiently connected to transport codes, which then could simulate the evolution of a discharge in a self-consistent way, i.e. taking into account the interaction between the energy balance of a tokamak plasma and the tearing mode instability. In the present work we consider the equations governing the linear evolution of the tearing modes with poloidal number greater than one. To evaluate the stability factor $\triangle' \equiv \triangle(d \ln \tilde{B}_r)$, which characterizes the local stability of the mode around each singular surface, it is enough to deal with a single linear first order ordinary differential equation in the perturbed radial component of the magnetic field. The first step in the calculation of $\triangle'$ is to solve this stability equation in the outer region ($r >> \delta_R$, with δ_R being the width of the resistive layer). This is usually done by using numerical solvers for initial value problems based on predictor/corrector schemes. These procedures could be very time-consuming. Here, we develop a semi-numerical method which runs much faster than previous numerical methods. The second step in the calculation of $\triangle'$ is to obtain an analytical solution of the stability equation in a region closer to the resistive layer ($r \tilde{>} \delta_R$) and matching it with the numerically evaluated solution in the outer region. This is usually done by expressing the solution as a Taylor series that includes a logarithmic singularity at the singular surface[1]. We propose an alternative approach based on the reduction of the stability equation to a Bessel-like equation. As a means of checking numerical solutions of the stability equation in the outer region, we have obtain an exact analytical solution, expressed in terms of the Gauss geometric series, for the case of a linear current density profile. Using our methods, we then calculate the stability factor $\triangle'$ for a few representative tokamak J-profiles and compare with previously obtained results.[2]

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1C50

Equilibrium and stability studies of low aspect ratio tokamaks*

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Low aspect ratio tokamaks, as proposed by M. Peng and D. Strickler[1)], have the potential to elucidate tokamak physics by exploring a little known region of operating space. Initial results from START[2)] are very promising: discharges show good confinement and absence of disruptions. Theoretically, the potential for high β operation has been established.[3)]

Because the ohmic solenoid is as small as possible, and very near the plasma inside boundary, it is difficult to control plasma shape throughout the flux swing. A succession of equilibria at each step of the discharge needs to be carefully tailored.

In the presence of a constant vertical field, low aspect ratio plasmas display natural elongation. This indicates that for that "natural" elongation the plasma up-down position is neutrally stable. For higher elongation, position control requirements will be presented, based on the work of Lazarus and Lister. In-out position stability will also be investigated. Modeling of eddy currents will be necessary both for the stability study and to show that a high order field null can be made for plasma break-down.

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Spectra and mode structures of global drift waves in toroidal geometry.

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To get an overview of drift waves in tokamak plasmas, a fluid code was written so as to easily obtain spectra and mode structures over a wide range of parameters. In particular, the goal of this study was to understand the effect of toroidicity and ellipticity on these waves and whether they can induce new modes. Also, the radial extension and the balooning of these modes was studied for various density and temperature profiles and mode numbers.

In this spirit, the simplest fluid model was chosen: electrostatic approximation, cold magnetized ions, Boltzmann electrons and quasineutrality. The toroidal magnetic geometry is given by a Solovev equilibrium. This model contains radial and poloidal coupling related to polarization and curvature drift which are essential for global drift waves. The resulting partial differential equation was cast into a weak variational form and solved using linear finite elements in the radial direction and Fourier series in the poloidal direction.

Although this model is restricted, as it contains none of the kinetic effects that can lead to instabilities which are of the major interest, it allowed to clarify the properties of global drift waves in toroidal geometry and will also serve as a reference for futur kinetic studies.

Plasma - Neutral Interraction in Tokamak Divertor: "Gas Box" Model (Knudsen Limit)

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Abstract

Recently [1] the main features of plasma-neutral interaction in the recycling region of a tokamak divertor were investigated for the fluid and Knudsen neutral models. These model describe two opposite extremes of neutral transport in the divertor region: short- and long neutral mean free path approximations. In Ref.1 the Knudsen regime of neutral transport was employed for the slot like divertor geometry (Δ_s is the width of the slot). In this paper we assume, that near the target the slot is ended by the "box" (Δ_b and L_N are the width and the length of the "box"; $L_N, \Delta_b \gg \Delta_s$) and consider plasma flow onto the target through the "gas box", the neutrals are in Knudsen regime, and only sustained due to plasma recycling. Thus, our neutral model is a modification of Knudsen neutral model employed in Ref.1 on different divertor geometry. We assumed prescribed upstream plasma pressure, p_u, and heat flux into the "gas box", q_{rc}. We have found that the main results of the plasma-neutral interaction for the "gas box" model are very similar to those, obtained in Ref.1 for Knudsen neutral flow for the slot divertor geometry: a reduction of the heat flux q_{rc} below a critical value leads to bifurcation of the plasma parameters near the target. The bifurcation causes a strong decrease of the plasma particle and heat fluxes onto the target and plasma pressure drop along the magnetic field lines. However, for a very low q_{rc}, the neutral density increases as q_{rc}^3, while for the slot like divertor it can not exceed a maximum density, which is of the order of $(1-2) \cdot 10^{13} cm^{-3}$ for current experiments [1].

This work was performed in part under US DoE grant DE-FG02-91-ER-54109.

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Krasheninnikov S.I., Catto P.J., Helander P., Sigmar D.J., Soboleva T.K.

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Electric Fields and $E \times B$ Drifts Including the Tokamak Separatrix Region *

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A model is given for calculating the electrostatic potential, ϕ, in the edge region of a tokamak that allows a continuous solution from inside the separatrix to outside by solving the $\nabla \cdot \boldsymbol{J} = 0$ equation. Inside the separatrix, the radial current, J_r, is obtained from the toroidal momentum balance equation. Here the radial flux of toroidal momentum is assumed to be carried by an anomalous diffusivity, D_ϕ, in keeping with experimental observations of toroidal momentum damping during neutral beam injection. Off-diagonal momentum transport terms can also be included. The simplest form of the model gives J_r scaling as the second radial derivative of the toroidal velocity, v_ϕ. Because the toroidal velocity has an $\boldsymbol{E} \times \boldsymbol{B}$ component varying as $(\partial\phi/\partial r)B_\theta$, the $\nabla \cdot \boldsymbol{J} = 0$ equation becomes a fourth-order PDE for ϕ. The associated boundary conditions will be discussed. In the region of open B-field lines, the parallel current is dominant, and one has a nearly one dimensional situation with the potential on each field line controlled by forces parallel to B.

This model is being incorporated into the 2-D UEDGE fluid code; the description of $J_{\|}$ is the same as previously used in the code, but the origin of J_r is now quite different. The numerical convergence properties with the new J_r will be discussed. We will also present 2-D solutions obtained with $\boldsymbol{E} \times \boldsymbol{B}$ drifts for a slab geometry that only includes the open field lines. This allows inclusion of the effect of electron temperature asymmetries on the types of solutions investigated analytically for fixed, symmetric temperature profiles.[1, 2]

* Work performed for the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

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TELLEGEN'S THEOREM APPLIED TO TEARING MODES

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In electrical circuit theory it is known that in a circuit with resistive elements only, the current distributes itself so as to minimize the total resistive dissipation. When inductive elements are also present the appropriate generalization is $\delta(D + dW/dt) = 0$, where D is the dissipation rate and W is the magnetic field energy. This is known as Tellegen's theorem. In magnetohydrodynamics (MHD) the concept of minimum dissipation has been used to determine equilibria in the context of RFP relaxation. In this study Tellegen's theorem is used for the first time to study MHD stability in the presence of resistive dissipation. It is shown to predict the correct growth rate for the resistive wall instability, when dissipation occurs in a thin resistive wall, as well as for a tearing mode with one resonant surface. While a simple energy balance cannot be used to predict the growth rate for tearing modes with multiple resonant surfaces, Tellegen's theorem still works. Using this theorem an expression for the growth rate of a double tearing mode has been obtained. Further extension to obtain the growth rate of coupled tearing modes with multiple resonant surfaces in a torus is in progress. This could provide a physical basis for the E-matrix formalism.

Computational Studies of Ultra-short-pulse Reflectometry*

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In ultra-short-pulse reflectometry[1], sub-nanosecond microwave pulses are used as sources of ordinary (O) or extraordinary (X) waves with which one can deduce the profiles for the plasma density and perhaps the magnetic field from measurements of the reflected waves. Many pulses can be launched and detected in time intervals that are short compared to the typical time scales on which the plasma profiles evolve. Proof-of-principle experiments have been undertaken in the last year by the UC Davis Plasma Diagnostics Group, and we have performed the first calculations of ultra-short-pulse reflectometry by solving a one-dimensional (1D) full-wave equation for O-mode reflectometry[2].

Our earlier 1D cold-plasma O-mode calculations have been extended to 1D X-mode and 2D O-mode calculations. The X-mode dispersion properties depend on both the magnetic and density profiles. The time delay vs. frequency data for X-modes cannot be Abel inverted, in contrast to the O-mode case; and the reconstruction of the density or magnetic field profile requires a numerical inversion. The accuracy of a simple linear, extrapolative procedure is demonstrated with a number of examples. The influence of density fluctuations on the profile reconstructions and on the scattering phase shifts in the reflected signals have been studied. The results for X-modes are quite similar to those reported for O-modes[3] in which the density-profile reconstruction accuracy was found to be robust until $(\delta n/n)(kL)^{2/3} \approx 1$, where $\delta n/n$ gives the relative density perturbation at the reflection layer for a typical frequency (with corresponding wavenumber k) in the heart of the pulse spectrum and L is the density scalelength.

An efficient 2D full-wave solver has been constructed and is being used to extend our earlier study of O-mode ultra-short-pulse reflectometry. We are using a splitting algorithm with good dispersion properties and a combination of outgoing-wave boundary conditions and a dissipative boundary layer to minimize reflections from the boundaries. The efficacy of the density-profile reconstruction technique that works well in 1D is being assessed with this new 2D code. We also present a formulation of the straightforward extension of the 2D O-mode algorithm to the 2D X-mode case.

* Performed by LLNL for USDoE under Contr. W-7405-ENG-48

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Semi-ideal magnetohydrodynamics of a tokamak plasma

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Abstract

Analytical model of the fast spatial flattening of toroidal current density and q- profiles at the non-linear stage of $m = 1, n = 1$ kink instability of a tokamak plasma is presented. The flattening is shown to be an essentially multi-scale phenomenon which is characterized by, at least, two magnetic Reynolds numbers simultaneously. The ordinary one, Re_m, is related with a characteristic radial scale-length and plasma velocity, while the other, Re_m^*, corresponds to characteristic scale-length of plasma inhomogenety along the magnetic field line. In the case of well-conducting, $Re_m \gg 1$, plasma inside the initial $q = 1$ magnetic surface, where q value does not differ from unity so much, semi-ideal plasma dynamics with two well-separated magnetic Reynolds numbers $Re_m^* \equiv (1 - q) \cdot Re_m \leq 1 \ll Re_m$ takes place. This dynamics is characterized by two contradictory, at first glance, features:

i) magnetic configuration, i.e. profiles, evolves quickly, on the ideal MHD time-scale corresponding to $Re_m \gg 1$;

ii) simultaneously, magnetic surfaces keep their initial circular form practically undisturbed (freezing-in of a magnetic field line into plasma flow is controled by $Re_m^* \approx 1$ value).

Physical background of such a semi-ideal MHD process is analyzed.

Considerations on Plasma Transport Barriers*

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The observation of a barrier for ion thermal energy transport in record high temperature experiments is described by a transport equation that includes a "normal" diffusion term which depends on the ion temperature gradient (the usual outflow) and by another (arising from the "off-diagonal" in the transport matrix) that can give an energy inflow and is attributed to the shear of the toroidal plasma flow velocity. The latter can give rise to excitation of transport barrier modes. The linear and nonlinear analysis of this effect is carried out.

* This work was carried out in collaboration with Y. Koide and JT-60U experimentalists. Work supported by U.S. Department of Energy and JAERI.

Poster

Advanced MHD Configurations in TFTR

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TFTR has achieved record DT power outputs primarily in the supershot regime. The highest power discharges are limited by MHD activity and or disruptions. Further improvement requires a new class of profiles. We investigate the possibility of improvements through shear reversal in the core of the discharge. Various scenarios of current and pressure profile shaping will be investigated and the ideal MHD stability results are presented.

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Normal Mode-Quasilinear-Mixing Length Model Transport Code

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A fast transport modeling code has been developed which reads data base files with precomputed experimental power and plasma flow profiles and solves a general transport model relating flows to temperature and density gradients. The numerical techniques involve shooting the temperature and density profiles from the edge using a linear Taylor expansion of the model flows in terms of the gradients and are designed to deal with models having strong temperature gradient thresholds. The method is efficient enough to treat models which simultaneously compute linear drift-ballooning modes' stability with general physics at each radius. In particular, normal modes in a ballooning mode representation for finite beta gyro-Landau fluid equations with both passing and trapped electron physics is treated. The leading normal mode combined with a mixing length rule for the turbulence saturation is used to compute the quasilinear ion and electron channel power and plasma flows and anomalous energy exchange. A mixing length rule for the fluctuating potential, $\widetilde{v}_{E\times B}\cdot k_\perp \approx (\gamma^+\gamma^-)^{1/2}$ where γ^+ is the growth rate of the leading normal mode and γ^- is the damping rate of a radial mode ($k_y=0$, $k_x\neq 0$), gives an ion heat diffusion $\chi \approx \gamma^-/k_\perp^2 \cdot \gamma^{+2}/(\gamma^{+2}+\omega^{+2})$ which shows the saturation with large temperature gradient and dependence on radial modes seen in simulations. In addition, a rotational shear stabilization factor with $\chi \propto (1-\gamma_{\rm E}/\gamma^+)$ is included where $\gamma_{\rm E}$ is the Doppler rotational shear rate. The initial application is to modeling the DIII–D ρ_*-scaling experiments, in which we try to show that the stabilization effect from diamagnetic rotational shear at the edge leads to a scaling $\chi \propto \chi_{\rm Bohm}\cdot\rho_*\cdot(1-\alpha\rho_*)$ which may break the intrinsically gyroBohm scaling $[\chi_{\rm Bohm}\cdot\rho_*]$ of the models if the rotational shear stabilization term α is large enough.

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Poster presentation requested

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Electron Cyclotron Heating and Current Drive for Advanced–Tokamak Operation in ITER*

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Electron cyclotron power for heating and current drive is now seriously considered for application in ITER[1]. In previous work, we examined heating and current drive scenarios with EC power launched near the equatorial plane. The TORCH ray-tracing code was used to determine optimum conditions for providing the non-inductive current in ITER both near the magnetic axis of the tokamak (normalized poloidal flux $\psi = 0$) and in a broad region ($0.2 \leq \psi \leq 0.8$). We now examine scenarios where the incident power is launched at poloidal locations between the equatorial plane and the top of ITER and with toroidal directions appropriate for heating and current drive when the toroidal magnetic field is in the range 4.0 to 5.7 T. The power deposition along the ray path is obtained using a fully relativistic calculation[2]. The driven current is computed using the adjoint formalism in which relativistic effects and degradation of the current by magnetic trapping are included[3]. Results are presented for EC power launched with a number of Gaussian beams each appropriately directed so as to achieve heating and current drive in accordance with requirements for plasma stability. An objective of this work is to rapidly survey wave and plasma parameter space as a guide to the more detailed calculations that can be carried out with comprehensive 3D, bounce-averaged Fokker-Planck codes[4].

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THREE-DIMENSIONAL CALCULATIONS USING THE QUIET IMPLICIT PIC METHOD*

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Solution of the time-implicit moment equations for electron and ion species combined with Maxwell's equations is the kernel of the moment-implicit particle method and of the quiet implicit PIC method (a generalized δf method for electromagnetic plasma simulation). Previous implementations have used a variety of direct and iterative approaches for obtaining solutions. These methods have suffered from both excessive computational cost (sometimes negating the advantage of implicit time differencing) and from lack of convergence in some regimes of interest (rendering the method inapplicable). We describe a new formulation of the coupled problem, leading to a symmetric, positive definite system. We also show that this symmetric problem may be efficiently and reliably solved by a conjugate gradient method. A three-dimensional algorithm using a pseudospectral Fourier treatment of the poloidal and toroidal directions, and a finite difference treatment of the radial direction has been constructed. The radially-dependent, poloidal and toroidal averaged operator is used as a preconditioner. Convergence is rapid (typical iteration count of 10 for 10^{-5} convergence).

Application of the two fluid form of this code to an internal m=1 kink mode and m = 2 tearing mode will be presented. Timesteps for this simulation are one radial Alfvén time and exceed the Courant-Friedrichs-Levy numerical stability condition (for implicit algorithms) by five orders of magnitude. Electron inertia, Hall effects, displacement current and Poisson's equation are all included self-consistently. Results show growth (with growth rates close to ideal MHD predictions) and saturation with self-consistent rotation. Anticipated applications for this code are tokamak disruption simulation and transport simulations (numerical tokamak).

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Interpretive Treatment of Scrape-off-Layer Plasmas*

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Tokamak scrape-off-layer plasmas can either exhibit pressure balance along the field lines ("attached" divertor) or sustain a pressure gradient ("detached") between the upstream plasma and the divertor plate. In Alcator C-mod the plasma parameters in the scrape-off-layer are measured at upstream and divertor plate locations [1]. We have formulated a 1-D analytic solution to the heat conduction and pressure balance equations and developed an interpretive scrape-off-layer code [2]. Given the measured temperature and density at the two locations we can determine the average volumetric heating and the amplitude of radiation on each flux tube. For detached discharges we determine the neutral pressure that is required to balance the pressure gradient in the charge-exchange dominated region. In addition we determine the SOL cross-field thermal conductivity. The thermal conductivity appears to rise with increasing radius in the attached state and it is lower and spatially independent during detachment.

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Thermodynamic aspects of fluid dynamics and covariant Onsager symmetry**

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A formalism is presented for the thermodynamics of fluid systems that allow the reversible and irreversible transfer of kinetic, internal, and magnetic energies. Of particular interest is how to represent Onsager symmetry with different choices of variables. This is desirable since dynamical variables need not possess symmetry under time translation. To this end tensor analysis in function space is described and equations are written in manifestly covariant form (which is facilitated by considering the entropy production rate as a scalar). The covariant form leads naturally to a covariant statement of Onsager symmetry. This statement differs from that of previous work in that it allows for a reassortment of fluxes and forces.

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* General Atomics

ADAPTIVE GRIDDING FOR PRIMITIVE MHD SIMULATIONS*

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The numerical simulation of the primitive, three-dimensional, time-dependent, resistive MHD equations on an unstructured, adaptive poloidal mesh using the TRIM code has been reported previously[1]. The toroidal coordinate is approximated pseudo-spectrally with finite Fourier series and Fast-Fourier Transforms. The finite-volume algorithm preserves the magnetic field as solenoidal to round-off error, and also conserves mass, energy, and magnetic flux exactly. A semi-implicit method is used to allow for large time steps on the unstructured mesh. This is important for tokamak calculations where the relevant time scale is determined by the poloidal Alfvén time. This also allows the viscosity to be treated implicitly. A conjugate-gradient method with pre-conditioning is used for matrix inversion. Application to the growth and saturation of ideal instabilities in ITER-like systems has been demonstrated[1].

Recently we have concentrated on the details of the mesh adaption algorithm used in TRIM. We present several two-dimensional results relating to the use of grid adaptivity to track the evolution of hydrodynamic and MHD shocks. Examples relating to imploding Z-pinches and plasma guns are presented. Issues relating to mesh adaption criteria are discussed.

1. D. D. Schnack, Z. Mikić, I. Lotatti *et al.*, *Bull. Am. Phys. Soc.* **39**, 1531 (1994).

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POSTER SESSION REQUESTED

MHD Simulation of Coalescence Process of Spheromaks

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We have investigated the MHD relaxation process seen in merging of two spheromaks. Sato and his co-authors[1] studied the coalescence process of spheromaks with the same polarity of the magnetic helicity (which is called 'co-helicity case'). As a result of the merging, a larger spheromak was generated in the co-helicity case. Their simulation results showed not only that the magnetic energy and helicity relaxed in accordance to the Taylor's simple theory, but also that the dynamic evolution of the system was governed by the driven reconnection of the magnetic field. Importance of the driven reconnection in merging of two spheromaks is also confirmed by laboratory experiments[2]. Here, we will consider the relaxation process in merging of two spheromaks with the positive and negative polarity of the helicity, which is called 'counter-helicity case'. In this case, conservation of the total magnetic helicity requires a relaxed state with zero helicity, such as an FRC-like state. Our purpose of this study is to clarify how the high-beta state may be realized from the coalescence of low-beta spheromaks.

In our simulations, we have solved the resistive full MHD equations in (r, θ, z) coordinates using the finite-difference and RKG methods. We have assumed the axial symmetry of the system. The governing equations are solved in the $r - z$ plane so that unstable modes with $n \neq 0$ are excluded from the simulation. Perfect conducting walls are set at $r = 1.5$ and $z = \pm 1.5$, and two flux-core coils are located at $r = 1.0$ and $z = \pm 1.0$. Changing the current intensity in the flux-core coils, we can generate two spheromaks in the simulation system. After formation of spheromaks, they attract with each other by the Lorentz force, then, start to merge spontaneously. Toroidal magnetic field which had different polarity in each spheromaks annihilates in the coalescence process. Through the reconnection of the poloidal field and the 'annihilation' of the toroidal field, large amount of the magnetic field energy is converted into the thermal energy. Thus, the high-beta state like an FRC is resulted from merging of the two spheromaks with counter-helicity.

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ADAPTIVE GRIDDING FOR PRIMITIVE MHD SIMULATIONS*

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The numerical simulation of the primitive, three-dimensional, time-dependent, resistive MHD equations on an unstructured, adaptive poloidal mesh using the TRIM code has been reported previously[1]. The toroidal coordinate is approximated pseudo-spectrally with finite Fourier series and Fast-Fourier Transforms. The finite-volume algorithm preserves the magnetic field as solenoidal to round-off error, and also conserves mass, energy, and magnetic flux exactly. A semi-implicit method is used to allow for large time steps on the unstructured mesh. This is important for tokamak calculations where the relevant time scale is determined by the poloidal Alfvén time. This also allows the viscosity to be treated implicitly. A conjugate-gradient method with pre-conditioning is used for matrix inversion. Application to the growth and saturation of ideal instabilities in ITER-like systems has been demonstrated[1].

Recently we have concentrated on the details of the mesh adaption algorithm used in TRIM. We present several two-dimensional results relating to the use of grid adaptivity to track the evolution of hydrodynamic and MHD shocks. Examples relating to imploding Z-pinches and plasma guns are presented. Issues relating to mesh adaption criteria are discussed.

1. D. D. Schnack, Z. Mikić, I. Lotatti *et al., Bull. Am. Phys. Soc.* **39**, 1531 (1994).

*Work supported by USDOE under contract DE-FG03-91ER54124.

POSTER SESSION REQUESTED

MHD Simulation of Coalescence Process of Spheromaks

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We have investigated the MHD relaxation process seen in merging of two spheromaks. Sato and his co-authors[1] studied the coalescence process of spheromaks with the same polarity of the magnetic helicity (which is called 'co-helicity case'). As a result of the merging, a larger spheromak was generated in the co-helicity case. Their simulation results showed not only that the magnetic energy and helicity relaxed in accordance to the Taylor's simple theory, but also that the dynamic evolution of the system was governed by the driven reconnection of the magnetic field. Importance of the driven reconnection in merging of two spheromaks is also confirmed by laboratory experiments[2]. Here, we will consider the relaxation process in merging of two spheromaks with the positive and negative polarity of the helicity, which is called 'counter-helicity case'. In this case, conservation of the total magnetic helicity requires a relaxed state with zero helicity, such as an FRC-like state. Our purpose of this study is to clarify how the high-beta state may be realized from the coalescence of low-beta spheromaks.

In our simulations, we have solved the resistive full MHD equations in (r, θ, z) coordinates using the finite-difference and RKG methods. We have assumed the axial symmetry of the system. The governing equations are solved in the $r - z$ plane so that unstable modes with $n \neq 0$ are excluded from the simulation. Perfect conducting walls are set at $r = 1.5$ and $z = \pm 1.5$, and two flux-core coils are located at $r = 1.0$ and $z = \pm 1.0$. Changing the current intensity in the flux-core coils, we can generate two spheromaks in the simulation system. After formation of spheromaks, they attract with each other by the Lorentz force, then, start to merge spontaneously. Toroidal magnetic field which had different polarity in each spheromaks annihilates in the coalescence process. Through the reconnection of the poloidal field and the 'annihilation' of the toroidal field, large amount of the magnetic field energy is converted into the thermal energy. Thus, the high-beta state like an FRC is resulted from merging of the two spheromaks with counter-helicity.

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Broadening of Alpha Energy Spectrum Due to Cyclotron Instabilities*

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In a magnetic fusion plasma, the energy needed to sustain ignition is provided by the isotropic shell-distributed alpha particles produced from thermonuclear fusion reactions. Thus, the behavior of alphas due to collective instabilities, as well as the implications for their confinement, are critically important issues for the performance of a burning fusion reactor.

Here, we investigate a cyclotron instability which may provide a mechanism for anomalous slowing down and energy-broadening of alphas. The instability mechanism is a gyro-phase bunching due to relativistic mass variation. In the low harmonics, slow ions are involved. This makes a two-gyro-stream instability, which causes the fast ions to be anomalously thermalized [1]. The same mechanism also explains [2] the ion cyclotron emissions observed in JET [3,4]. For the alphas, the low harmonics are linearly stable, but the high harmonics can be unstable due to the same relativistic mass variation effect [5]. PIC simulations are used to study the dynamics of fusion-produced 3.5 MeV alpha particles due to self-driven high harmonic cyclotron waves in the lower-hybrid frequency range. The waves grow according to theoretical predictions of a relativistic mass variation effect [5]. The instability is absolute since the growth rate is larger than the absolute instability threshold. Some high harmonic alpha results are similar to the low harmonic proton results [1, 2], but some are quite different. The interaction becomes selective. Only those alphas with large pitch angle (perpendicular velocity) are involved in the energy broadening while there is no effect for those with small pitch angle. We still observe large density perturbations and perpendicular energy spreading. But, the average energy loss is smaller; half of the energy is carried by thermal (not tail) deuterons. The large alpha density perturbation may reduce the drive for TAE and MHD instabilities which depends on the density gradient while the pitch angle change of the alphas may affect particle transport. Since this is due to cyclotron waves, cyclotron wave injection may provide a method to control the process.

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EFFECT OF LOW MN PERTURBATIONS ON FOOTPRINTS OF FIELD LINES ON THE DIVERTOR PLATES IN SINGLE-NULL DIVERTOR TOKAMAK

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ABSTRACT

We investigate the effect of naturally occurring low MN perturbations on the footprint of field lines on the divertor plates of a single-null divertor tokamak. The unperturbed topology of a single-null divertor tokamak is represented by the Simple Map /1,2/. The Simple Map with low MN perturbations is given by

$$x_{n+1}=x_n-ky_n(1-y_n)-\delta y_n\cos\left[\frac{2\pi(n+1)}{N_p}\right],$$

$$y_{n+1}=y_n+kx_{n+1}+\delta x_{n+1}\cos\left[\frac{2\pi(n+1)}{N_p}\right],$$

where k is the Simple Map parameter and δ is the strength of low MN perturbations. The continuous analog is given by

$$x(\phi)=x_0-ky_0(1-y_0)\phi-\delta y_0\cos\left[\frac{2\pi(n+\phi)}{N_p}\right]\phi,$$

$$y(\phi)=y_0+kx(\phi)\phi+\delta x(\phi)\cos\left[\frac{2\pi(n+\phi)}{N_p}\right]\phi.$$

We choose combinations of (k,δ) which keep the width of the stochastic layer constant equal to the width for k=0.6 for Simple Map. We decrease k and increase δ, and observe that the area of the footprint increases. We also calculate the structure of the toroidal and poloidal transits as the field lines traverse from one-side of the divertor plate to the other. Here we will present these and other related results in details. This work is supported by U.S. Department of Energy.

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RF Tokamak Plasma Confinement in Electron Cyclotron Frequency Range*

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A dynamic[1] confinement of Tokamak plasmas by electron-cyclotron rf field is studied. It is based on nonlinear interaction[2] of a driver pump with Tokamak MHD modes. The stimulated scattering of X- and O-mode off MHD plasma modes is considered. A nonlocal character of interaction is treated by use of Bohr-Sommerfeld phase integral method. The Tokamak confinement regimes are controlled by properly chosen interaction geometries and rf field-plasma parameters. The scaling laws for energy confinement times are obtained and analyzed.

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Finite-Size Effects and Quasi-Crystallization of Vortices in the Hasegawa-Mima Equation

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It is generally believed that dual, inverse and direct, cascades are at the origin of the formation of coherent structures, such as isolated long-lived vortices in 2-D Navier-Stokes (NS) turbulence [1]. In contrast to unbounded systems, where inversely cascaded quantities can expand to larger and larger scales, dynamics of vortices can change significantly if a system has a characteristic length scale which interferes with the inverse cascade [2],[3].

Here, we report a numerical study of the driven-damped Hasegawa-Mima (HM) equation

$$\frac{\partial}{\partial t}(\nabla^2\phi - \phi/\rho^2) - [(\nabla\phi \times \hat{\mathbf{z}}) \cdot \nabla](\nabla^2\phi) = D + F, \tag{1}$$

that demonstrates a phenomena of general importance: any dynamical mechanism leading to decrease of otherwise constant energy flux ($\Gamma = const$ for $l \leq \rho$, ρ is a characteristic length scale) can lead to energy pile-up at scales $l \simeq \rho$ and creation of an ordered vortical phase. While it may not be surprising that the presence of a characteristic length scale in the HM equation (Larmor radius ρ) leads to the emergence of coherent vortices, we show here that it also results in the formation of a vortical "quasi-crystal".

We are particularly interested in the driven-damped case when the forcing is applied at $l_f < \rho$, so that energy is transferred towards the region $l > \rho$. In this case the flow passes through a transitional (between NS and degenerate HM) regime, when both terms $\Delta\phi$ and ϕ/ρ^2 in (1) are important. In this regime the characteristic length scale ρ interferes with the upscale energy cascade and serves as a kind of "shield" for it. Energy starts piling up at $l = O(\rho)$, thus promoting the formation of long-lived coherent vortices due to finite-size effects. These vortices are less isolated and less movable in comparison with their counterparts in NS turbulence, while the calculation of moments of the potential vorticity increments shows the appearance of the long-range order in the medium, indicating formation of a vortical "quasi-crystal".

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Bootstrap Current in Arbitrary Collisionality and Aspect Ratio Tokamaks

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We use a new formulation of the velocity-dependent viscosity [1] in a numerical evaluation of the bootstrap current that is more general and complete than previous models. The viscosity is valid for all aspect ratios, including the ultra-low aspect ratio limit where the bootstrap current does not vanish in the Pfirsch-Schluter regime. Impurities are included by using the reduced charge state formalism [2]. The computational model should provide a more reliable evaluation of the bootstrap current near the edge of tokamak plasmas (particularly H-mode and VH-mode) where finite aspect ratio, collisionality and impurity effects become important. It should also provide a more reliable evaluation of the bootstrap current profile in ultra-low aspect ratio, high beta-poloidal, and other situations. Comparisons with other models are made.

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1D20

Comparison of the Calculations of the Stability Properties of a Specific Stellarator Equilibrium with Different MHD Stability Codes*

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A particular configuration of the LHD stellarator with an unusually flat pressure profile has been used as a test case for comparison of the MHD stability property predictions of different three-dimensional and averaged codes for the purpose of code comparison and validation.

We were able to carry through the comparison of two or more codes for each of several pressure distributions that were used, so that some understanding of the output of each code has been obtained. We were pleased to see that all of the codes found the same relatively localized $n = 2$ and $n = 3$ modes near where they should be expected to be the most unstable modes, with the eigenvalues Λ having the same behavior as β_0 is changed. The behaviors of the displacement vector found by the different codes are also similar. It is useful to observe that the codes show the same change in behavior of the mode as β_0 is increased. For example, an unstable $n = 3$ mode has a strong $m = 4$ component which peaks at $\beta_0 \approx 6\%$ and then falls off. An $m = 5$ dominated mode starts growing as β_0 is increased to even higher values.

We conclude from this study that all of the tools that have been developed for stellarator stability studies are capable of treating this LHD stellarator model accurately. This is a strong test of the codes since the standard LHD equilibrium is stable, or close to stable, so that a pressure distribution with ∇p localized to the outer region had to be assumed to even find an unstable mode. Thus, the tools that are available for study of stellarator stability are quite extensive.

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1D21

"The Modeling of Non-Axisymmetric Halo Currents in Tokamaks"

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Abstract

Recent experiments have firmly established the existence of non-axisymmetric modes of plasma disruption in tokamaks. The resulting halo currents driven in the vacuum chamber present a possible threat to components not designed to withstand the corresponding non-axisymmetric **J**x**B** forces. An understanding of the halo currents is necessary to insure the safety of existing tokamaks and to properly design future high-performance experiments. We have developed a model of the disrupting plasma and halo currents based on a representation of the plasma by non-axisymmetric, nested current sheets in an axisymmetric vacuum chamber. The current sheet model is more sophisticated than existing filament models in that it allows both toroidal and poloidal non-axisymmetric currents, but computationally more efficient than simulations which require flux-surface reconstruction at every time step. We will present the formulation for how a disrupting plasma in this form can drive halo currents; the method for achieving a numerical solution will also be presented.

ISOLATED MAGNETIC ISLANDS IN A HIGH TEMPERATURE TOKAMAK PLASMA

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A theory for the existence of non-interacting small scale ($w \sim \rho_i$) 'drift' magnetic islands in a high temperature 'sheared slab' model of the tokamak plasma is presented. This situation contrasts with that discussed by Rebut and Hugon [Plasma Physics and Controlled Fusion **33** 1085 (1991)] which involves a background 'sea' of magnetic turbulence caused by island overlap. The islands are driven by the effect of finite ion Larmor radius on the particle drifts and they propagate with a velocity comparable to the diamagnetic velocity. In contrast with the work of Smolyakov [Plasma Physics and Controlled Fusion **35** 657 (1993)] collisions are assumed to be rare. 'Drift' surfaces, which have the same form as the island flux surfaces, can then form around the electron Landau resonance position and lead to plateaux in the distribution function. The result is that there is no energy transfer from the particles to the wave as a result of Landau damping. However, when a low level of collisions is introduced, the plateaux partially relax to a Maxwellian which then restores a residual Landau damping, giving rise to dissipation proportional to the collision frequency ν_e. This dissipation determines the island propagation frequency at low collision frequency.

An estimate is made of the anomalous heat transport which results from the fluctuations in the electrostatic potential associated with these magnetic islands. The predicted thermal diffusivity has several, but not all, of the characteristics of the Rebut-Lallia-Watkins transport model.

Toroidal effects, resulting from ion polarisation drift associated with the finite trapped ion banana width and bootstrap current are being investigated. The interest here is in deriving a threshold condition for the existence of larger islands ($m \leq 3$) of width comparable to the poloidal ion Larmor radius.

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MHH STELLARATOR WITH THE 2D SYMMETRY OF THE HSX EXPERIMENT

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A Modular Helias-like Heliac (MHH) coil set has been chosen for the U.S. Stellarator Power Plant Study that was designed by extensive runs of high performance equilibrium, stability and transport codes. After reduction of the bootstrap current a better configuration with four field periods has been found that is not only stable and robust, but also has a virtually two-dimensional (2D) magnetic field strength suitable for the HSX experiment at the University of Wisconsin. The coils are rather easy to construct despite the awkwardness of 3D geometry. Transport calculations including a mechanism to provide for quasineutrality show that the confinement is excellent in this new stellarator, which seems theoretically to have more favorable engineering properties than the ITER tokamak.

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NOETHER DERIVATION OF LOCAL MANLEY-ROWE RELATIONS FOR NON-EIKONAL WAVE FIELDS*

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The wave-action conservation laws associated with resonant three-wave interactions are of fundamental importance for such processes. These laws, known as Manley-Rowe relations, are usually obtained with great difficulty from the nonlinear evolution equations. Here, we derive them directly from a Noether symmetry of the appropriate Lagrangian.

In this work, we identify the symmetry operation as a phase shift of a *complex representation* of the wave fields [1]. The Lagrangian density for this representation is obtained by performing a Whitham average [2] of the real-field Lagrangian, based on a separation of time scales. This approach allows us to generalize the applicability of the Manley-Rowe relations to non-eikonal conditions, i.e., conditions for which the eikonal approximation is invalid, such as when wavelengths become comparable to the background gradient scale length. Hence, we allow the background medium to have arbitrary spatial variation, so that the concept of local wave-vector need not be valid, and a slow temporal variation, as expected physically from the ponderomotive effects of the waves. The slowness is required for the utility of the complex representation for the wave fields. In addition, we do not require the waves to satisfy local dispersion relations, thus allowing for strong turbulence.

As examples, the Lagrangian formulations for one-dimensional models of stimulated Raman scattering and stimulated Brillouin scattering are presented, and local Manley-Rowe relations, valid in nonuniform media even for non-eikonal wave fields, are derived by the Noether method. A discussion on the eikonal limit of our results, as well as other Lagrangian systems of relevance to magnetic fusion plasmas, will be presented.

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Casimir invariants and their applications in generic turbulent transport problems*

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For a broad range of nonlinear kinetic and fluid models in plasma physics, the entropy balance equation (EBE) can be shown to have the following form[1]:

$$d\mathcal{S}/dt = \mathcal{D} - \kappa\Gamma$$

where $\mathcal{S}$ is the entropy functional, $\kappa\Gamma$ and $\mathcal{D}$ are the positive-definite gradient-flux term and dissipation term, respectively. In steady state, the EBE plays the important role of directly relating the flux to the dissipation. The entropy functionals are found to be the Casimir invariants of the nonlinear interactions.[2] They describe properties of the singular Poisson brackets of the noncanonical Hamiltonian part of the system and physically arise from an underlying relabeling symmetry. We will demonstrate that this symmetry is broken by the transport and dissipation in generic forced-dissipative turbulence. The dissipation (as in the case of Coulomb collision) increases the entropy and the transport decreases the entropy, so the resulting EBE provides a quantitative measure of how far the system is driven away from equilibrium. Finally, through two specific fluid models (Hasegawa–Wakatani and the resistive-g), we will illustrate the importance of the Casimir invariants in the conceptual understanding of the turbulent transport.

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GENERATION OF ULTRA-INTENSE MAGNETIC FIELDS

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The interaction of superintense laser pulses with matter is accompanied by numerous nonlinear processes, self-focusing being one of the most impressive. When the radiation intensity exceeds a critical value, matter is ionized almost instantaneously and nonlinear plasma effects become dominant.

Propagating in such high conductivity media, pulses can excite both high and low frequency waves, and even zero frequency **(quasi-static) magnetic fields with strengths up to 10^5T.**

The mutual attraction of the currents inside the self-focused channels makes them interact magnetically and coalesce into a single one with strongly enhanced electromagnetic energy density. Finite length laser pulses produce a wake of two rows of magnetized regions with opposite polarity. Due to the screening of the magnetic field at distances larger than the skin depth, the observed velocity of propagation of the vortex row is much smaller than the rotation velocity of the electrons inside the vortices, contrary to the von Kàrmàn vortex row in classical hydrodynamics.

Aspects of Computational Thermally Collapsed States

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We examine a numerical (UEDGE) high-recycling thermally collapsed divertor state [T. Rognlien, et al., Contr. Plasma Phys., **34**, 362 (1994)] for sensitivity to various physical effects and for numerical robustness. The goals of this work were to obtain a minimal set of equations to describe this state and to guide the building of a fast time depemdent code to look at the stability of the collapsed state. The collapsed state near equilibrium was found to be relatively insensitive to viscous terms in the ion thermal evolution and neutral diffusion. Strong sensitivity was found in the radial plasma density diffusion, radial electron thermal diffusivity, flow, parallel electron thermal conductivity, hydrogen radiation, and the ionization source in the density equations. Thus, it seems, the collapsed state is strongly dependent on the somewhat less known physics of radial transport (turbulence) and atomic sources/sinks at low Te. To characterize the collapsed state we ploted variations of the sensitve parameters individually (holding all others fixed) against charcteristics of a collapsed state, such as Te along the separatrix at the plate. For these scaling studies, we remained close to equilibrium and thus did not run UEDGE in a time dependent mode. In all cases, the location of the ionization peak (layer) was changed by variations of the sensitive terms. Further, the radial electron thermal diffusivity and radial particle diffusivity had opposite effects on the collapsed state (simultaneous variation of the diffusivities weakly pushed the plasma away from a collapsed state) while the atomic physics terms tended to push the plasma towards a deeper collapsed state. We also attempted to run UEDGE in a time dependent mode to ascertain the collapsed state behaviour with larger variations of the sensitive physical parameters. As to the overall goals, the basic set of equations to describe this collapsed state involve almost all the the physics of UEDGE. This suggests that the fast time dependent code can be simplified little and that naive 1-D analytic solutions can not duplicate the collapsed state here. Even more troublesome is the fact that this state depends strongly on physics we know the least.

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1D28

Parallelization of the Generalized Tokamak Simulator*

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The Generalized Tokamak Simulator (GTS) is a relatively new kinetic PIC code under development at the IFS. GTS provides an environment for kinetic plasma simulation of microturbulence and related effects of relevance to the Numerical Tokamak Project. GTS is based on the preceeding Toroidal Particle Code (TPC), and extends it in numerous ways including support for more physics models, integrated GUI, powerful diagnostics, and parallel execution on local area multicomputers or massively parallel computers . This work will discuss the effort to parallelize GTS and will emphasize aspects of its object oriented design which have facilitated this work.

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Nonlinear Bounce-Averaged Kinetic Equation and Neoclassical Polarization Density*

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Beam-emission spectroscopy measurements on TFTR[1] and the results from a comprehensive kinetic code[2] have indicated the importance of long wavelength fluctuations in the trapped ion regime. In this work, we derive a set of nonlinear bounce-averaged Vlasov and Poisson equations using the action variational Lie perturbation method.[3] The symplectic structure of the original phase space is preserved so that the equations are readily suitable for numerical simulations of the trapped particle driven modes. In the bounce kinetic Poisson equation, the difference between the trapped ion and banana center positions across the magnetic field line must be considered. In analogy to the polarization density[4] in the gyrokinetic Poisson equation, which has made significant progress in gyrokinetic simulations possible, we call the resulting term the "neoclassical polarization density." We elucidate the physical relationship to the more familiar "neoclassical polarization drift."[5]

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Place next to "Nonlinear Theory of Collisionless Trapped Ion Modes"
by T. S. Hahm and W. M. Tang.

Poster Session (not on Wednesday).

Nonlinear Theory of Collisionless Trapped Ion Modes*

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Transport scaling trends closer to Bohm rather than to gyro-Bohm, have been prominently observed in experiments such as TFTR.[1] This is very suggestive of the importance of long wavelengh low frequency fluctuations. Indeed, Beam Emission Spectroscopy measurements on TFTR[2] and the results from the studies using a comprehensive 2-D kinetic code[3] have shown the existence of significant density fluctuations in the trapped ion regime. In the present work, we have developed a simple two field ($\delta P, \delta\phi$) nonlinear model of collisionless trapped ion mode turbulence from bounce-averaged kinetic equations. The radial correlation length is determined by the asymptotic balance of the equilibrium profile variation and the finite banana width reduction of the potential, leading to a nearly Bohm-like scaling of thermal diffusivity. Furthermore, the partial nonlinear shielding associated with the "neoclassical polarization density"[4] introduces an isotope-dependent modification to this Bohm-like diffusivity, which is in rough qualitative agreement with trends recently observed in TFTR D-T experiments.[5]

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Place next to "Nonlinear Bounce-Averaged Kinetic ..." by B.H. Fong and T.S. Hahm

Poster Session (not on Wednesday).

Renormalized Dissipation in Plasmas with Finite Collisionality

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A truncation procedure for Fourier-Hermite expansion of Boltzmann-type plasma equations is presented which is used to eliminate fine velocity scale, taking into account it's effect on coarser scales. The truncated system is then transformed back to (x, v) space which results in a renormalized Boltzmann equation. The resulting equation may allow for coarser velocity space resolution in kinetic simulations. This procedure requires no knowledge of the linear plasma dispersion equation. Also, the renormalized equation has the property that it reduces to the original Boltzmann equation when fine velocity scale is resolved. To illustrate the procedure, renormalized equations are derived for one dimensional electrostatic plasmas in which collisions are modeled by the Lenard-Bernstein operator. The collision frequency is renormalized in a straight-forward way and a new mode coupling term appears in the renormalized equations. The form of the resulting renormalized kinetic equation in in (k, v) space is

$$\partial_t \bar{f}_k + ivk\bar{f}_k - \sum_{k'} E_{k'}\bar{f}_{k-k'} = \nu_0 \partial_v (v\bar{f}_k) + \nu_0 \partial_v^2 \bar{f}_k$$
$$+\lambda_N^{4r}\left[\partial_v(\partial_v + v)\right]^{2r+1}\left\{|k|\lambda_N \bar{f}_k - i\sum_{k'}\bar{\gamma}(\lambda_N, k, k')E_{k'}\bar{f}_{k-k'}\right\},$$

where λ_N is the velocity scale cut-off, and the the bar signifies solving for f neglecting velocity scales finer than λ_N. For example, in a Vlasov simulation with a velocity space grid, one would set $\lambda_N \approx \Delta v$. The terms on the first line of the equation are identical to the original Boltzmann equation. The first term on the second line is dissipative and models transfer from coarse to fine velocity scale by phase mixing. The second term approximates the nonlinear coupling between coarse and fine velocity scale. The larger the value of $(2r + 1)$ the more accurately the original discrete truncation is represented.

Flux Limiting Due to Electron Impact Excitation Energy Loss*

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Abstract

Steepening of the electron temperature profile caused by energy loss due to line radiation can be modeled by including an inelastic impact excitation collision operator in the electron kinetic equation. Line radiation is modeled as being due to electrons exciting impurities which then instantaneously radiate the energy away without re-absorption. The Boltzmann collision operator form of the impact excitation collision operator is expanded to obtain a Fokker-Planck form by assuming the characteristic excitation energy loss is small compared to the electron thermal speed. We consider the energetic tail electrons and employ a high speed expansion of the electron-electron collision operator which attempts to drive the electrons towards a Maxwellian to counteract the non-Maxwellian influence of the inelastic scattering. When excitation loss is strong enough the tail can be depleted by inelastic scattering and the tail contribution to the parallel heat flux and current reduced. To obtain a qualitative estimate of whether a substantial flux limit is possible we assume that the charge state of the impurities is high ($Z >> 1$) so that the lowest order electron distribution function is isotropic. By then adopting a simple analytic model for the excitation cross section we can estimate the effect of the radiation loss on the fluxes. These estimates indicate that while order unity decreases in the electron heat flux are possible, it is unlikely that large decreases can occur within the framework of this model.

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ADJACENT POSTER REQUESTED

1D33

Scaling Laws for Two-Dimensional Fluid Neutral and Plasma Modeling of Divertors*

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Abstract

To model detached divertor operation in short mean free path regimes, fluid neutral descriptions must consider neutral momentum and energy conservation, rather than employing a diffusive neutral model. This more complete, but complicated, description allows the plasma pressure to be balanced by the neutral pressure near the target plates while exhibiting the observed drops in temperature, particle flux, and energy flux. Analytic progress in fluid neutral and plasma systems has only been possible in one-dimension in special circumstances. To gain insights in two-dimensions, we employ similarity techniques to investigate whether model systems of equations plus boundary conditions admit any scaling transformations that leave the system unchanged. To find scaling transformations we adopt models of the divertor region which ignore anomalous processes and then cast the models into dimensionless forms which show densities and inverse lengths must scale linearly with the upstream pressure. As usual, the more approximations made, the greater the number of scaling transformations allowed, and the fewer independent dimensionless parameters that need be varied. The technique illustrates the need to retain the constraints imposed by boundary conditions, and that the simplifications of dealing with the total momentum and energy conservation equations may outweigh the advantages of dealing with separate species fluid conservation equations in two-dimensional divertor codes.

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ADJACENT POSTER REQUESTED

1D34

Dynamics of Electric Microfields At A Neutral Point

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The complex dynamics of electric plasma microfields at a neutral point (atom) is studied via a model of non-interacting "quasi-particles". The simplicity of the model allows reduction of the many-body problem to effective single particle analysis - all properties of interest can be reduced to quadratures. Attention is focused on the dynamics of the conditional electric field: the field value at time t for a given initial value of the field. In addition to the relevant linear response function (electric field time correlation function), this property provides the complete non-linear response of the electric field to arbitrary initial field perturbations. The static properties (distribution of electric fields and field time derivatives) and the electric field time correlation function have been known for some time for this model. We compare these results and the new result for the conditional electric field with molecular dynamics simulations *including* interactions. The comparisons suggest that the model provides a quantitative representation of electric field dynamics in real plasmas, except at strong coupling. The exact theoretical results are compared also with those obtained by modeling the electric field as a stochastic variable obeying a Kangaroo process. The latter can be constructed to yield both the exact stationary distribution and the exact electric field time correlation function. However, we find that the conditional field is never well-approximated by this process. An alternative representation of the joint distribution for electric fields, consistent with the exact stationary distribution, field correlation function, and conditional electric field, is suggested. Applications to the line shape analysis are discussed.

Extraction of Alpha Particle Energy by Waves in the ICRF Range of Frequencies*

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Abstract

Amplifying injected waves in magnetic fusion plasmas at the expense of the charged fusion product distribution might have important implications for economical fusion reactors. In particular, for DT tokamak reactors, the energy diverted from the alpha particle distribution to waves could be used for current drive or for heating of the fuel ions, either of which is a significant benefit. The ideal set of waves extracts alpha particle energy in a time short compared to the alpha particle slowing down time and with minimal injected power. In addition, no particles would be ejected with their birth energy intact. To identify the suitability of moderate frequency ($\omega \approx \Omega_i$) waves for accomplishing these goals, the wave-particle interaction is simulated in a tokamak geometry. Extending previous work[1], we treat the waves as imposed, and use an analytic calculation for the resonant interaction of the alphas with the waves. An advantage of the present treatment is that the particle trajectory may be quickly calculated between interactions with the wave and thus the wave effect on the full distribution of particles can be efficiently simulated.

*This work supported by DoE contract No. DE-AC02-76-CHO-3073 and the Fannie and John Hertz Foundation

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Stability Analysis of Resistive Wall Kink Modes in Rotating Plasmas

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Abstract

The stability analysis[1] of external magnetohydrodynamic modes is carried out for a cylindrical plasma in the presence of a resistive wall, plasma flow and coupling to the sound wave continuous spectrum. It is found that the resonance of the mode with the sound continuum produces an effective dissipation. The combined effects of dissipation and plasma flow open up a window of stability in b/a to the external kinks (b is the wall radius and a is the plasma minor radius). For sufficiently large dissipation (typical of a torus) and wall time, the window size is only dependent on the plasma rotation, the mode wavenumber, the Alfvén speed and the safety factor at the plasma edge. Interestingly, the stability window in b/a at fixed plasma parameters transforms directly to a corresponding window in β when b/a is fixed. However, to gain access to the high β stable window, one must first pass through a window of unstable β's as the plasma is heated. In principle, sufficient rapid heating is required to quickly pass through the region of unstable β. Furthermore, as the dissipation decreases, there is a critical minimum rotation frequency (Ω_c) below which the window does not exist. The magnitude of Ω_c is inversely proportional to a power of the dissipated energy. This theory helps to explain the numerical results of A. Bondeson and D.J. Ward[2].

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Computations of IBW Spectra and Induced Diffusion Rates in Toroidal Geometry†

by

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The generation of Ion Bernstein Waves at the ion-ion hybrid resonance in a reacting plasma has been proposed as an intermediary through which it may be possible to effect the *in situ* channeling of fusion alpha energy for purposes such as current drive and/or maintenance of a hot-ion plasma mode of reactor operation[1]. We extend previous, planar computations of IBW propagation to toroidal geometry. The numerically computed spectra are incorporated into calculations of energy and spatial diffusion coefficients for both fuel and fusion products.

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MHD Simulations of ELMs in Divertor Tokamaks

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ELMs in divertor tokamaks were modelled with 3D RMHD simulations. The model ELMs consisted of moderate mode number pressure driven ideal ballooning instabilities. The computations were done using FEMHD, a three dimensional unstructured mesh finite element dissipative RMHD code. The magnetic geometry modelled a divertor tokamak with a single magnetic null.

Numerical equilibria were first produced with a 2D version of FEMHD. Using these equilibria, the linearized equations were time advanced to get the growth rates and eigenmodes with toroidal mode number $n \leq 4$. This was done both with circular cross sections, to verify previous results with other codes, and in single null divertor geometry. The equilibrium and linear modes were used to initialize 3D nonlinear runs. The modes saturated and relaxed the driving pressure gradient. Evidence of plasma flow into the divertor will be presented. The figure shows an example of nonlinearly saturated pressure contours at the time of saturation of the modes.

The FEMHD code was parallelized using pvm3 message passing. The figure was produced by running the code on workstations connected by a network.

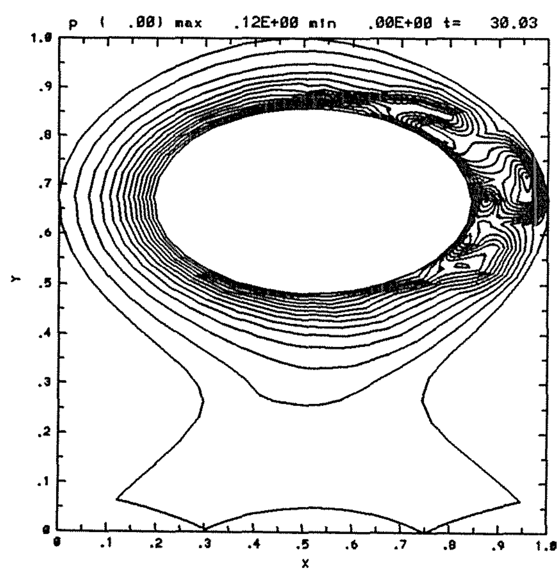

Figure 1: a) Pressure contours at $\zeta = 0$, t $=30\ \tau_A$.

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The Extrapolated Performance of Fusion Reactors based on First Principles Simulations with Kinetic Effects

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Until now, estimates of the performance of future tokamak fusion reactors has been based on empirical extrapolations (e.g. ITER89-P), without insight into the physics controlling χ and how that physics may be different for reactors. Recently, first principles calculations of χ from ITG turbulence have become available and accurately describe the core transport in TFTR and other devices.[1-3] Since the methods are based on fundamental physics, they may be confidently extrapolated to predict the χ from ITG turbulence in proposed devices such as the International Tokamak Experimental Reactor. The methods are used here to address a number of questions central to the design of reactors. The methods show that the present empirical scaling of τ_E with current, power and probably ellipticity cannot be reliably extrapolated to reactors, and more accurate scalings are given. The ITG model is sometimes overoptimistic about the edge confinement (since there is an additional instability present in the edge which it neglects), but it can nonetheless supply an upper bound on L-mode performance which is firmly physics based. This is computed for ITER and other devices, and using this, a lower bound on the confinement enhancement above L-mode needed for ignition (the H factor) will be calculated. Furthermore, it will be shown that some types of enhanced confinement (such as arise in hot ion modes) will not arise in reactor scenarios, so "H factors" based on such discharges in present devices are not applicable. However, confinement enhancement from velocity shear stabilization of ITG modes (a widely hypothesized mechanism for H-modes) may be possible. Using first principles simulations, a quantitative assessment will be given of the heating power required to obtain a significantly stabilizing level of velocity shear.

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ABSTRACT
For the 1995 Sherwood Theory Meeting

L-H Power Threshold Scalings.

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The near separatrix region in tokamaks which combines the properties of closed and open field line regions provides a new length scale parameter $x_0 = (-d \ln P_0 / dx)^{-1}$. This parameter is typically of the order of several Larmor radii.
The edge gradients can drive modified drift and interchange instabilities which depend, in addition, on the conditions at the target plates. The related turbulence gives rise to perpendicular transport and regulates the width x_0. Dimensional analysis is applied to determine the scaling of the transport coefficients.
The H-mode is set up when x_0 becomes sufficiently narrow and the shear flow stabilises these instabilities leading to the condition $\rho = \rho_i / x_0 > c_1$ where c_1 is of order unity. This condition is the more stringent version of the physically natural condition: $V_0^{'} > \gamma$, where $V_0^{'}$ is the shear of the flow velocity and γ the maximum growth rate of the instability.
The L-H power threshold depends strongly on the longitudinal loss mechanism. Classical thermal conduction provides a threshold scaling similar to the experimentally observed dimensionally correct scalings: $P \propto n_0^{0.75} B_0 S$ (or $P \propto n_0 B_0 R^{2.5}$), where n_0 is the average density, S the surface area, B_0 the toroidal magnetic field and P the power heating. The free-streaming loss yields a cubic dependence on B_0, which could match the observed threshold in high edge temperature, low density plasmas.

On the existence of scalar-pressure magnetostatic equilibria§

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The problem whether weakly non-axisymmetric solutions of the *static scalar-pressure magnetostatic equilibrium problem* with nested magnetic surfaces exist is still unanswered. Although equilibrium solutions have only been obtained for models with special symmetry, with current sheets on only isolated magnetic surfaces (weak solutions), or in asymptotic calculations, there is considerable experimental evidence that good magnetostatic confinement is achieved in weakly non-axisymmetric tokamak as well as stellarator configurations. Grad, in a number of papers [1,2], raised the question whether non-symmetric solutions exist to such a problem and pointed out the conjecture [1] that it is very unlikely that there exists a general class of toroidal equilibria with toroidal nested magnetic surfaces and smooth pressure profiles and that only "highly symmetric" solutions should be expected. The purpose of this paper is to point out that arbitrary, non-symmetric and smooth scalar-pressure equilibria with nested magnetic surfaces, when expressed in terms of an appropriate canonical coordinate system, must necessarily fulfill suitable periodicity constraints, i.e., be *quasi-symmetric.* As a consequence, it is proven, in particular, that a generalized Grad-Shafranov equation can be obtained for 3-D *quasi-symmetric, scalar-pressure equilibria.* These results are, therefore, potentially useful for the investigation of stellarator confinement systems and point out that observed confinement equilibria could correspond to quasi-symmetric, scalar-pressure equilibria.

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§ Work supported by the Italian National Research Council, the "Consorzio di Magnetofluidodinamica", Trieste University, Italy, and the United States Department of Energy.

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POSTER PRESENTATION

1995 International Sherwood Fusion Theory Conference

Analysis of Self-Consistent MHD Stable Operating Scenarios in the Tokamak Physics Experiment (TPX)*

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An interface has been written between the ACCOME[1] current drive and MHD equilibrium solver and the JSOLVER/PEST[2,3] equilibrium and stability code. The ACCOME code is used to analyze operating scenarios in the proposed TPX device where the plasma current is sustained through a combination of neutral beam injection (NBI), lower hybrid current drive (LHCD), fast wave current drive (FWCD), and bootstrap effects. An MHD equilibrium consistent with the driven current densities is computed by ACCOME. The JSOLVER/PEST package is then used to analyze the ACCOME equilibria for stability to high-n ideal ballooning modes and for stability to the low$-n$ external kink modes.

MHD stable operating modes are achieved by iterating between the PEST results and ACCOME. For example, an unstable ACCOME equilibrium is modified along guidelines suggested by the PEST stability analysis, where the stability analysis utilizes the driven current densities predicted by ACCOME. Results will be presented for a high bootstrap fraction operating mode in the first stability regime (ARIES-I), where $I_p \lesssim 1.5$ MA, $f_{BS} = I_{BS}/I_p \gtrsim 0.50$, $B_0 = 4.0$ T, $q(0) \gtrsim 1.20$, $\beta_t \approx 2\%$, and $\beta_N = \beta_t/(I_p/aB) \lesssim 3.0\%$. Stability results will also be presented for a reverse shear operating mode where $B_0 = 3.0$ T, $q(0) \gtrsim 2.5$, $q(min) \gtrsim 2.0$, $I_p \gtrsim 1.7$ MA, $f_{BS} \gtrsim 0.75$, $\beta_t \gtrsim 4.0\%$, and $\beta_N \gtrsim 4.5\%$.

*Work supported by the US Department of Energy Contract No. DE-AC02-78ET-51013 and Contract No. DE-AC02-76-CHO-3037.

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Collisional Relaxation of Electron Distribution Function in a Region of Stochastic Magnetic Field Lines

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The collisional relaxation of the electron distribution function $f(\mathbf{x}, H, \mu, t)$ in a region of stochastic magnetic field lines can be described by the drift kinetic equation

$$\frac{\partial f}{\partial t} + \mathbf{v}_p \cdot \nabla_p f = -\nabla_p \cdot \Gamma_c \tag{1}$$

where $\mathbf{v}_p = (\mathbf{v}_g, \dot{H}, \dot{\mu})$ is the phase space velocity of the guiding center with $\mathbf{v}_g$ the guiding center velocity in real space, Γ_c is the collisonal diffusive flux in phase space, ∇_p is a gradient operator on both spatial coordinates $\{x, y, z\}$ and the other two degrees of freedom in the phase space, the electron energy H and the magnetic moment μ. The collisonal flux due to scattering has the form $\Gamma_c = -\mathbf{D}_0 \cdot \nabla_p f$ with $\mathbf{D}_0$ a generalized tensor diffusivity in phase space. Passing electrons move along the stochastic magnetic field lines with $\mathbf{v}_g \approx v_\| \mathbf{B}/B$, so they generally follow a chaotic motion. The drift kinetic equation is an advection-diffusion equation in a five dimensional phase space. The collisional relaxation of an electron distribution function in a region of stochastic magnetic field lines is equivalent to the transport of a passive scalar in a chaotic flow.

Our study is based on Lagrangian coordinates, ξ, which are defined by $\mathbf{x}(\xi, t=0) = \xi$ and $(\partial \mathbf{x}/\partial t)_\xi = \mathbf{v}_p(\mathbf{x}, t)$. If the drift kinetic equation, Eq. (1), is transformed into Lagrangian coordinates $\{\xi^i\} = (x_0, y_0, z_0, H_0, \mu_0)$, one obtains the ordinary diffusion equation with a new tensor diffusivity $D^{ij} \equiv \nabla\xi^i \cdot \mathbf{D}_0 \cdot \nabla\xi^j$,

$$\left(\frac{\partial f}{\partial t}\right)_\xi = \sum \frac{1}{J_0} \frac{\partial}{\partial \xi^i} J_0 D^{ij} \frac{\partial f}{\partial \xi^j} \tag{2}$$

where $J_0 = J_p = B/v_\|$ the Jacobian of the Lagrangian coordinates.

The diffusive transport due to collision is determined by the spatial-temporal distribution of the finite time Liapunov exponent $\omega(\xi, t)$. The collisional relaxation occurs rapidly along the direction in which neighboring points asymptotically converge, the so-called $\hat{\mathbf{s}}_\infty$ direction. A field line of the vector $\hat{\mathbf{s}}_\infty$, the so-called $\hat{\mathbf{s}}$ line, has sharp bends due to the nonhyperbolicity of the system, which affects the finite time Liapunov exponent. For example, the finite time Liapunov exponent $\omega(\xi, t)$ of a 2D divergence-free plasma flow can always be written as $\omega(\xi, t) = \tilde{\omega}(\xi)/t + f(\xi, t)/\sqrt{t} + \omega^\infty$ with $\hat{\mathbf{s}}_\infty \cdot \nabla_0 f(\xi, t) = 0$ and ω^∞ the infinite time Liapunov exponent. The spatial dependence of the finite time Liapunov exponent is related to the topology of the $\hat{\mathbf{s}}$ line through $\tilde{\omega}(\xi)$ by $\hat{\mathbf{s}}_\infty \cdot \nabla_0 \tilde{\omega}(\xi) + \nabla_0 \cdot \hat{\mathbf{s}}_\infty = 0$. In regions of large curvature κ of the $\hat{\mathbf{s}}$ line, $\omega(\xi, t_0) \propto -\ln \kappa/t_0$. These regions are transport barriers, even when the plasma motion is far from integrable.

Finite-β Effects on Toroidal Alfvén Eigenmodes Driven by Energetic Particles

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Recently, due to the powerful plasma heating schemes employed in fusion research and the approach of the deuterium-tritium ignition experiments, there has been increasing attention both theoretically and experimentally on the issues related to the effects of energetic ions/alpha particles on the magnetohydrodynamic (MHD) stability of tokamak plasmas. In this current study we will use a *non*-perturbative approach to determine the effects of the energetic-particle dynamics on the MHD modes. In addition, we will investigate the effects that the finite size of energetic-particle orbits have on these MHD modes. Anticipating that the most relevant modes will be those with large toroidal mode number (high-n), a ballooning formulation is used. An initial value problem formulation is developed for easy extension to the nonlinear regime. A solution to the initial value problem is obtained through the application of a hybrid numerical scheme in which a set of MHD fluid equations[1,2] are solved along with a gyrokinetic vlasov equation for the energetic particles[2]. Special attention is paid to the high-β regime which will be relevant for future fusion reactors. Finite-β effects are found to be strongly stabilizing on the toroidal Alfvén eigenmodes (TAE) when the finite-orbit effects are weak. However, as the finite-orbit effects become more pronounced this finite-β stabilization vanishes. The results will be discussed for a wide range of tokamak parameters.

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Toroidal Coupling of Ideal MHD Instabilities*

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A theoretical framework is introduced to describe the ideal MHD stability properties of toroidal plasmas. The ideal mode is described as a set of poloidal harmonics in configuration space. The energy functional, δW, is then given by a matrix whose elements are computed from the harmonic interaction integrals, by analogy to the resistive MHD version of this problem [1]. In particular, the stability of finite-n ballooning modes in an s-α model equilibrium is studied. The analysis can be extended to include the toroidal coupling of a free-boundary kink eigenfunction to the finite-n ideal ballooning mode. A unified stability condition is derived which describes the external kink mode, a finite-n ballooning mode and their interaction. The interaction term plays a destabilizing role which lowers the instability threshold of the toroidally coupled mode. Hence, it is possible that an instability may be present when the fixed boundary ballooning mode and the cylindrical external kink mode are independently stable.

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NUMERICAL SIMULATIONS OF THE EFFECT OF THE ExB DRIFT ON DIVERTOR PLASMA FLOWS; D. R. McCarthy, Southeastern Louisiana University, Hammond, LA 70402, S. I. Krasheninnikov and D. J. Sigmar, Massachusetts Institute of Technology, Plasma Fusion Center, Cambridge, MA 02139

Recently it was shown analytically [1] that self-consistent shear of the $E \times B$ affecting divertor plasma flows can result in a strong plasma pressure variation along the magnetic field lines, similar to experimental observations of the "detached divertor" regimes. The typical radial scale length of plasma parameter variation such that the drift becomes important is of the order of the poloidal ion gyroradius. In this paper we investigate this problem numerically using a more sophisticated model of the tokamak divertor plasma. We consider slab geometry and include a plasma continuity equation with the source terms (which model plasma recycling), plasma parallel momentum balance equation, and parallel Ohm's law (we assume no electric current). Plasma temperature profile, which can be affected by energy loss due to impurity radiation, is prescribed. We impose boundary conditions on the target: electrostatic potential drop in the sheath, and Bohm relation for plasma velocity. A 2-D axisymmetric finite differencing code is evolved until a steady state is reached. Preliminary numerical results and their relation to the theory [1] are presented.

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Inertial-Range Dynamics: Scaling Laws and Computational Methods*

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Inertial-range scaling laws for two- and three-dimensional turbulence are reexamined within a unified framework. A new correction is derived for Kraichnan's logarithmically corrected two-dimensional law that removes the unexpected divergence at the injection wavenumber. A related modification is found to Kolmogorov's well known $k^{-5/3}$ energy cascade law. The theory is also extended to incorporate a linear frequency such as the drift-wave term in the Hasegawa–Mima equation. The significance of the new corrections has been illustrated with steady-state energy spectra from recent high-resolution closure computations of the Realizable Test-Field Model.[1]

In search of a more direct verification, a recently proposed mode-reduction technique[2] is implemented for the Navier–Stokes equations. Conventional numerical discretizations of a conservative system yield a secular drift in the total energy; for this reason a "numerical" viscosity is often added to the dynamical equations. We demonstrate that this remedy does not properly describe the modal energy evolution. We present a nontraditional time evolution algorithm that exactly conserves energy and enstrophy to *all orders* in the time step and faithfully reproduces the modal dynamics.[3] In addition, it solves for the evolution on the linear time scale exactly, which allows small-scale dissipative regions to be evolved without violating the Courant condition, in contrast to more conventional treatments.

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Evolution of Trapped Ion Temperature Gradient-Driven Convective Cells with Electric Field Shear*

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Scaling studies of transport coefficients using dimensionally similar tokamak discharges have revealed Bohm-like ion transport and gyro-Bohm electron transport. The radial correlation length of the fluctuations has been measured to be roughly the square root of the product of the minor radius and the ion gyroradius. We advance a fluctuation-based model which can partially account for these observations. It is based on the trapped ion temperature gradient-driven instability coupled with nonlinear trapped electron dynamics and the inclusion of self-consistently evolved electric field shear. Nonlinear simulations results are presented as well as a comparison with analytic results.

Simulations are performed using a 3D electrostatic gyrokinetic particle-in-cell model in toroidal geometry. Gyrokinetic ion and drift-kinetic electron dynamics are used, including the $E \times B$, curvature and gradient-B drifts as well as the parallel electric and mirror force and a gyrokinetic Poisson equation is solved at each time step[1]. A nonlinear characteristic method for the perturbed distribution is employed to reduce noise effects[2]. Using parameters which are above the linear instability threshold for the trapped ion temperature gradient mode we show, by scaling studies, that a Bohm scaling is recovered for the ion thermal transport. The electron thermal transport is lower and has a gyro-Bohm scaling[3]. When the purely radial electric field is spontaneously generated via mode coupling, we find electrostatic potential up-down assymetries develop in the ballooning angle. When the flows damp via trapped ion orbit averaging the up-down symmetry is recovered. Details of the saturated fluctuation spectrum dynamics and fluxes will be given with some physical interpretation and analytical analysis as well as the effects of toroidal rotation effects.

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Spontaneous Symmetry Breaking in Divertor Scrape-off Layers

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It has been widely observed that the heat flux to the divertor target plates in tokamaks is asymmetrical. Several theories for the asymmetry have been proposed with some qualitative success. These theories have sought an explicit parity breaking term such as the $E \times B$ drift, in order to predict the direction of the asymmetry. In this work it will be shown that, even if there are no terms in the transport equations which explicitly break parity, the solution to the scrape-off layer (SOL) transport equations can spontaneously break parity and become asymmetrical. The direction of the asymmetry is arbitrary in this case. Either radiation or recycling can cause the symmetric solution to become thermodynamically unstable under certain conditions. If both ends of the SOL are taken into consideration, a new asymmetrical solution is present which is thermodynamically stable. The critical point for the spontaneous symmetry breaking to occur is the point at which the symmetrical solution becomes unstable. The radiated power fraction at which the asymmetrical solution appears is calculated analytically for a general but simple radiation model. The inclusion of explicit parity breaking terms picks out a particular direction for the asymmetry. A strong asymmetry is only found to exist above the critical point for the ideal parity conserving case. The effects of parallel currents and $E \times B$ drifts on the divertor asymmetries are computed with a 1-D SOL transport code.

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Poster presentation requested

Relativistic effects in energy extraction from alpha particles

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Ion Bernstein waves can be excited in tokamaks,[1] with the requisite characteristics to diffuse fusion α particles both in energy and position. Because the diffusion in space is coupled to the diffusion in energy, such waves can produce an α channeling effect,[2] where the wave is amplified as energy is extracted from α particles as they diffuse to the plasma periphery. Recently, K. R. Chen has suggested that there may be favorable and large relativistic effects in amplifying the IBW, based on relativistic gyrophase bunching.[3] The relativistic effects will preserve the coupling between the guiding center displacement and the energy change of the particle, and so will compete directly with the diffusive effect.

We examine whether these relativistic effects are important in a practical geometry. It turns out, however, that in an inhomogeneous plasma, such as a tokamak, the relativistic instability plays only a minor role. The equations of motion are expanded in powers of the electric field amplitude, and the energy change of the particles averaged over initially random gyrophases is calculated, recovering previous results in appropriate limits.[3,4] As it usually is, we find that to first order in the wave amplitude, the average energy change, the drag, is zero. To second order, in an infinite homogeneous plasma, we recover that an instability may result from the relativistic gyrophase bunching.[3] In the second order, however, both the diffusion and the drag enter.

For the mode converted IBW wave, the main plasma nonuniformity, as indicated by ray tracing calculations,[1] is that the component of the wave vector along the magnetic field varies rapidly. Other nonuniformities, such as a varying intensity of the magnetic field,[5] have similar effects on the interaction. We show that these inhomogeneities spoil the coherent effects, so that, for the purpose of channeling energy from alpha particles, the diffusion in energy space dominates the coherent energy extraction resulting from relativistic effects.

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Unstructured Mesh Model of the SOL Using Riemann-Delaunay Triangulation

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Rather than accepting the limitations on geometry due to use of a flux coordinate system, we model the tokamak scrape-off layer (SOL) and divertor regions using a finite element unstructured triangular grid. Previous work focussed on resolving time-dependent behaviour in a simple "toy" PDE using the Moving Finite Element Method. We now concentrate on obtaining steady-state solutions in realistic geometry using a more complete physical model with more dependent variables.

Mesh generation in our complex multiply-connected geometry is accomplished through use of a "Riemannian metric Delaunay triangulation". The stretched, non-Euclidean metric distorts the normally equiangular Delaunay triangles to (1) align with the magnetic field in the scrape-off layer, (2) concentrate to correctly resolve the X-point, and (3) concentrate near the divertor plates to resolve any boundary layer that may exist. Moreover, the generality of this approach suggests its applicability to solving large classes of PDEs on complicated geometries.

In addition, we hope to present results on a standardized "ASDEX" problem that was discussed at the December 1994 Adaptive Grid Workshop (held in Pleasanton CA). This problem was agreed upon as the first phase in a testing regimen for assessing the relative strengths of several emerging adaptive SOL codes of both the finite element and finite volume variety. Future phases will include standardized problems of increasing, more "ITER-like" geometrical and physical complexity, and will probably result in a reduction in the multiplicity of adaptive grid approaches currently seen.

PLASMA PHYSICS PHENOMENA IN ICF*

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Compression and heating of deuterium and tritium filled capsules to ignition with a 2 MJ 500TW laser is the goal of the proposed National Ignition Facility (NIF). The primary approach is indirect drive, wherein the capsule is driven by x-radiation from the laser light converted in a high-Z hohlraum. Indirect drive puts fewer demands on the laser-beam spatial uniformity necessary to control hydrodynamic instabilities (Rayleigh-Taylor). However, advances in laser beam smoothing techniques, the inherent higher hydrodynamic efficiency of direct drive, and the high thresholds for laser-plasma instabilities in direct drive make it an attractive option. We will introduce the basic designs of the hohlraums, capsules, and the laser anticipated for the NIF and in place on Nova, the existing 50kJ, 30TW laser at LLNL. We will also review the achievements to date and in what sense these test the physics models that are involved in the NIF designs. Our emphasis will be on the laser-plasma parametric instabilities such as stimulated Brillouin and Raman scattering and filamentation which can scatter the light and degrade the uniformity of the laser light heating within the hohlraums. We will also discuss experiments and theory on the effects of laser-beam smoothing on parametric instabilities.

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Nonlinear 3D Simulation Studies of High-β Disruptions in TFTR*

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In the DT experiments in TFTR, performance is limited by the onset of MHD instabilities leading to disruptions. A detailed theoretical picture of these high-β disruptions has been developed utilizing the nonlinear 3D MHD code, MH3D. In addition to demonstrating the onset of toroidally localized ballooning modes from a non-axisymmetric 3D equilibrium state, these calculations have simulated ECE signals in good agreement with experimental measurements. The healing of magnetic surfaces after the thermal quench phase is also obtained.

Beginning with a standard 2D toroidal equilibrium calculated from the relevant experimental profiles, an unstable low-n internal mode is found and is followed nonlinearly to saturation. The resultant helically distorted 3D equilibrium contains a steep localized pressure gradient in the bad curvature region. The MH3D code is newly modified to be able to obtain a mixed-n linear eigenmode evolving from such 3D equilibria. A fast growing linear ideal mode with a broad high-n spectrum of $n = 5$ *to* 14 is found to be excited exhibiting a strong toroidal localization in the steep pressure gradient region.

In following the nonlinear evolution of this new mode, it is seen that the steep localized pressure gradient which gives rise to this mode becomes even more steep nonlinearly. This causes it to be increasingly localized and strongly driven until most of the plasma region becomes stochastic, which will result in a thermal quench. [We note that such a thermal quench could be prevented by a sawtooth crash with the mixing radius encompassing the localized pressure bulge thereby relieving the driving pressure gradient. A fishbone event can also cause a similar relaxation for the hot component.]

Comparisons between the simulated ECE signal with the experimental ECE data give good agreement. In particular, the high-n mode "bursts" seen in the experiment just before a high-β disruption correspond to the calculated signals which are due to a steadily growing localized high-n mode driven by the local steep pressure gradient generated by a low-n mode. The high-n mode is seen in the ECE signal only when the toroidally localized mode structure comes into view of the ECE detector, thereby giving the bursting behavior.

After the thermal quench, a 90% reduction of pressure in the simulation causes the magnetic flux surfaces to heal but with magnetic islands. This indicates that there exists some pressure confinement in the post thermal quench phase and can be understood by the fact that with a small β, the plasma is stable to ideal modes while unstable to resistive modes if the perturbation is large enough. The likely final phase of a major disruption is that when the loop voltage in the experiment is not large enough to sustain the plasma current for the post thermal quench cold plasma with a high Z_{eff}, the current quench phase sets in to terminate the discharge.

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Nonlinear Evolution of the Alpha Particle Driven Toroidicity-induced Alfvén Eigenmode

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Abstract

Energy conservation is used to self-consistently study the interaction of high energy particles with a Toroidicity-induced Alfvén Eigenmode (TAE). A Hamiltonian guiding center code is used to simulate the alpha particle motion and nonlinear δf scheme is employed. The code is benchmarked using the bump-on-tail problem and simulation results agree with analytical estimates. For a single TAE mode, the saturation level is about

$$\frac{\delta B_r}{B} = \frac{\Omega}{V_a R}\left(\frac{r\gamma_L}{msq\omega}\right)^2$$

and the induced particle radial excursion is

$$\Delta = 2qR\sqrt{\frac{2V_a}{\Omega R}\frac{\delta B_r}{B}}$$

which is much less than the spacing between the poloidal harmonics for ITER parameters. For the case of more than one mode, the resonant particle orbits are most likely stochastic near the central region. The resonant particles lose their energy to the wave and then become trapped. Due to the large machine size compared to the particle orbit size however, the trapped particles will stay in the machine. Modification of the particle distribution leading to mode saturation is observed.

Resistive Wall Stabilization of External Kink Modes in Tokamaks with Partial Poloidal Walls

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Stability calculations have demonstrated[1,2] that complete stabilization of low-n pressure-driven external modes in tokamaks with resistive walls and toroidal rotation is possible. Two types of modes occur: those that are nearly locked to the wall (resistive wall mode) and those that rotate with the plasma (plasma mode). For the resistive wall modes the stabilizing effect of rotation increases with increasing wall distance. This leads to a window of stability between the threshold wall distance for a given rotation speed and the marginal wall position for the ideal plasma mode. This stabilizing effect has also been demonstrated for advanced tokamak configurations with bootstrap fractions of $\approx 100\%$.[2]

Close fitting conductors that completely surround the plasma are very inconvenient in advanced tokamak experiments and reactor designs. Stability calculations are presented that show the effect of removing poloidal sections of the resistive wall (which remains toroidally continuous). Calculations are performed using the NOVA-W code both with and without rotation.

For the pressure-driven external kink in a reversed-shear,[3] advanced tokamak equilibrium, the mode structure is concentrated on the outboard side. Therefore, outboard gaps in the wall have a very large effect on the growth rate, while removal of the inboard side has very little effect. The eigenfunction is also affected by these gaps in that it is modified in such a way that the stabilizing eddy currents are reduced in the regions where there are conductors, as compared to the eigenfunction in the case with a complete wall. This effect is similar to that which has been demonstrated for the $n = 0$ instability.[4]

Stabilization of resistive wall modes by rotation using resistive walls with poloidal gaps can be *more* effective in that the stabilizing rotation velocity is lowered for fixed walls, or the resistive wall mode stability boundary is moved closer to the plasma for fixed rotation velocities. This moves the stability region (in terms of wall position) closer to the plasma, and it can widen the stability region if the ideal boundary is not strongly affected.

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Resistive MHD Stability in Small Aspect Ratio Tokamaks

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Early experimental and theoretical results with small aspect ratio tokamaks indicate the possibility of operating at high β with relatively quiescent plasmas. We have started a comprehensive investigation of this interesting parameter regime using our nonlinear MHD code **CTD** (Computational Toroidal Device); it can be used to generate equilibria of arbitrary aspect ratio and cross section, with self-consistent toroidal equilibrium flows if desired, which then can be checked for linear and nonlinear stability against resistive and ideal modes.

Earlier studies of small aspect ratio tokamaks have focused on determination of β limits set by external kink and ballooning modes. Our initial investigations instead have focused on stability of the familiar $n = 1$ internal kink mode, which is expected to be unstable in some of the high current, low-q, scenarios under consideration. At low-β, with a circular boundary, decreasing aspect ratio is highly stabilizing for the resistive $n = 1$ mode, even for an equilibrium profile that is quite unstable at a more typical value of $A \equiv R_0/a = 3$. However, the gains of a small A are nearly erased with increased elongation (κ), a natural tendency of small-A equilibria, with the growth rates approaching to those seen at $A = 3$ in circular geometry, as $\kappa \to 2$ at $A = 1.4$. Triangularity is again found to be stabilizing, with a weaker effect on the growth rate than elongation or aspect-ratio variations have. With moderate shear at the $q = 1$ surface, the mode becomes ideally unstable at $\beta_{pol} \simeq 0.2$, corresponding to β values much below the optimized limits for external kinks; significant growth rates coupled with a large radius for the $q = 1$ surface, a typical result in this regime with high-currents, can make this a potentially dangerous mode at the high β values envisioned for small-A devices, necessitating a nonlinear study of the mode under these conditions.

Since the resistive stability boundaries are typically much lower than those of the ideal modes, in the immediate future, we intend to examine resistive modifications of the widely-calculated optimized, ideal β-limits for external kinks and extend our earlier work on rotation stabilization of the resistive wall modes to this parameter regime.

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Nonlinear ω_*-Stabilization of the $m = 1$ Mode in Tokamaks*

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Recent analysis[1] of sawtooth oscillations in TFTR (Tokamak Fusion Test Reactor) supershots has revealed a fundamental contradiction between conventional linear theory and experiment: the theory predicts fast instability due to a nearly ideal $m = 1$ mode in stable, sawtooth-free discharges. A theoretical resolution of this problem was consequently proposed[2], which is based on nonlinear ω_* stabilization of the linear mode. This explanation is consistent with the observation[1] that sawteeth in TFTR are suppressed in all known regimes at certain levels of ω_*; these levels, which seem too small to stabilize the mode linearly, correspond to the stability threshold of the collisionless $m = 1$ reconnecting mode[1].

Here, the early nonlinear evolution of the $m = 1$ mode is simulated numerically with a two-fluid MHD model. A new, efficient approach for the reconnection problem is developed that simulates the singular layer (including the island) separately from the external regions, while an arbitrary ideal $m = 1$ growth rate is taken into account by a boundary condition. We confirm the theoretical prediction[2] that the mode can saturate nonlinearly, provided the ion and/or electron drift-frequencies ω_* are somewhat above the reconnecting mode threshold mentioned above. On the other hand, it is found that the amplitudes at saturation seem higher than those observed in experiments. This suggests additional, stabilizing effects outside the present model are also important.

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NEW PARALLEL VELOCITY SHEAR INSTABILITY

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Plasma flows parallel to the magnetic field are of potential importance in tokamaks because of their impact on various instabilities. It has been noted that sheared parallel flows in the tokamak edge are driven by nonuniform particle transport[1]. These flows are associated with lack of uniformity of the pressure on flux surfaces and can approach the sound speed in magnitude. These flows typically have shear and can be unstable to the electrostatic $v_{\parallel}'$ instability[2,3], the significance of which is its possible effect on edge fluctuations and transport. For sheared parallel flows driven by neutral beam injection, there is a stabilizing influence on resistive MHD modes in toroidal geometry due to differing doppler shifts between the main and sideband rational surfaces of the modes[4], and between the rational surfaces and a resistive wall, but the effect of parallel velocity shear in the resistive layers of such electromagnetic modes has not been studied.

Analytic and numerical results on the linear theory of a new instability driven by shear in the parallel velocity $v_{\parallel}'$ will be presented. This instability exists in the presence of parallel velocity shear, field line curvature and either parallel viscosity (full Braginskii tensor) or parallel compression. It exists in an electromagnetic version, where it can enhance the growth rate of an unstable resistive MHD mode or cause an otherwise stable resistive mode to grow. In its electromagnetic form it is global (matches to an ideal MHD outer region) and can influence modes responsible for disruptions; it can also lead to anomalous transport by stochastic field lines as well as by $\boldsymbol{E}\mathrm{x}\boldsymbol{B}$ advection. The mode also exists in an electrostatic form for short wavelengths. For most reasonable parameters the effect of parallel compression dominates that of parallel viscosity. The properties of this mode, specifically its growth rate and localization width in both electrostatic and electromagnetic versions, will be compared with those of the usual $v_{\parallel}'$ mode.[2,3] The importance of this mode in the edge and on more global resistive MHD modes with and without a resistive wall will be presented.

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Study of Mode Overlap Resonance For TAE Growth Rates*

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We have investigated the resonant interaction of energetic alpha-particles with Toroidal Alfvén Eigenmodes (TAE) in the high-n ballooning limit. The condition for resonant interaction is $\omega + k_{\parallel}\bar{v}_{\parallel} + \ell\,\omega_b = 0$ where $\omega \sim \frac{1}{2}\frac{V_A}{qR_o}$ is the mode frequency. For given values of ω, $k_{\parallel}$, ℓ this equation defines a 'resonance' surface in the particle phase space (E, μ, P_{ζ}) or for a fixed value of μ , a 'resonance' line in the E - P_{ζ} phase plane. The particle-mode interaction is large in the neighborhood of this 'resonance' surface, the width of which is proportional to the growth rate of the unstable mode. We calculate the rate of energy transfer (from passing and trapped particles) to the TAE modes and the corresponding mode growth rates. We can then map out the 'resonance' lines in the E - P_{ζ} phase plane corresponding to modes with a typical range of values of ω, $k_{\parallel}$, ℓ, and thereby assess whether the instabilities have growth rates large enough to produce mode overlap and global particle diffusion.

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

Poster

Abstract for the 1995 International Sherwood Fusion Theory Conference
Lake Tahoe, NV, April 3-5, 1995

Modeling of a High Fusion Power TFTR DT Supershot*

R.V. Budny, M.G. Bell, R.E. Bell, C.E. Bush, Z. Chang, P.C. Efthimion, E. Fredrickson, L.C. Johnson, J. Manickam, D.C. McCune, H.K. Park, A.T. Ramsey, M.H. Redi, J. Schivell, S.D. Scott, J.D. Strachan, E.J. Synakowski, G. Taylor, T. Terpstra, L. Zakharov, M.C. Zarnstorff, and S.J. Zweben

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Experiments with mixed deuterium-tritium neutral beam injection in TFTR have generated supershots with high fusion powers. One of these, with a peak fusion power of 7.5MW, is of considerable interest since it was close to the MHD stability limit, but did not disrupt. It exhibited Mirnov activity in the Alfvén range of frequencies (~300kHz). Lithium pellets were injected before and after the auxiliary heating phase.

The TRANSP plasma analysis code [1] is used to model the time evolutions of plasma parameters of this discharge with a total current of 2.5MA. Measured profiles of the plasma density and temperatures and plasma boundary are used. Five thermal ion species (H, D, T, He^4, and Li), a heavier impurity (~C), and three fast ion species (beam D, T, and fusion alphas) are modeled. The calculated q profiles are in approximate agreement with the locations of coherent MHD activity. The calculated total pressure is in approximate agreement with the Shafranov shifts of the measured profiles. The calculated neutron emission profiles are also in approximate agreement with measurements.

The particle and energy transport is studied. Several alternative transport models for the hydrogenic species mixing are evaluated by comparing neutron emission simulations with the measured profiles. The resulting transport coefficients are compared with those measured in experiments with He and T gas puffing into supershots.

Several uncertainties add challenges to the evaluations of the transport of the thermal species and of the distributions of the fast ions. One is in the Z_{eff} profiles. We compare simulations of the impurity profile with measurements of the carbon density, which is the dominant impurity. Another uncertanty is in the mixing during the post neutral beam phase sawteeth crashes. We compare results from alternative assumptions about the mixing.

Calculations for the alpha parameters are given. These include their distributions in energy and pitch angle.

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1995 International Sherwood Fusion Theory Conference
Incline Village, NV, April 3-5, 1995

Effects of Magnetic Field Nonuniformity on Energetic-ion Bernstein Waves*

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We study the effects of magnetic field nonuniformity on the energetic-ion Bernstein waves in the presence of a thermal majority-ion species. Since the magnetic field nonuniformity causes the Bernstein wave to propagate in $\mathbf{k}$-space, as well as in $\mathbf{x}$-space, a careful analysis of this wave must be carried out in ray phase space $(\mathbf{x}, \mathbf{k})$.

Bernstein waves associated with an inverted energetic-ion population (e.g., alpha particles in fusion plasmas) have attracted special attention recently [1]. In a *uniform* magnetic field, the sign of the energy of a Bernstein wave would be either positive or negative. However, in a *nonuniform* magnetic field, the propagating wave crosses the gyroresonance layer and changes the sign of its energy. We shall present our interpretation of this process.

In a uniform magnetic field, the linear stability analysis of the wave interaction between a negative-energy Bernstein wave and a positive-energy magnetosonic wave reveals an instability known as the magnetosonic-cyclotron instability [1]. A *nonlinear* saturation mechanism is often invoked to explain experimental observations. In contrast, we investigate the process of *linear* conversion between these waves in a *nonuniform* magnetic field, resulting in convective saturation.

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NUMERICAL SIMULATION OF ELM PHENOMENA*

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After an L-H transition, an initial quiescent period is often followed by sharp spikes in the D_α strength (ELM's) and a reduction in confinement times. A 1-D model for so-called Giant or Type I ELM's has recently been developed[1] which includes two components: an ideal ballooning mode instability which drives the D_α spike, and a background drift wave turbulence. This model is being extended by including a 3-D MHD calculation of the basic ideal ballooning mode. The development of the ideal ballooning instability with time and its coupling to the background turbulence will be followed. Ultimately, these simulations will be used to model the time evolution of the ELM behavior. The goal of this effort is to better understand the phenomena with a view toward controlling it (or at least predicting its consequences for more advanced devices such as ITER). At present, only the linear and nonlinear development of the ideal MHD ballooning mode is being studied. Results of this work will be presented.

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Extended Quasilinear Model Applied to Energetic Particle—Alfvén Wave Problem

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The response of energetic particles to Alfvén-like waves depends critically on whether mode overlap conditions are fulfilled; this in turn depends upon the finite mode amplitude being large enough to cause overlap. The usual formulation of quasilinear theory does not describe a triggering effect of the mode amplitude for the onset of global diffusion. Here we develop a quasilinear model that takes into account this trigger effect of a finite amplitude wave. Results of a quasilinear code will be presented, together with examples that show, upon variation of parameters, both steady and pulsating responses and local as well as global diffusion. Attempts are being made to correlate with experimental data.

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Poster

SPECTRUM STUDY OF MICROTURBULENCE IN TOKAMAK PLASMAS

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ABSTRACT

The microturbulence driven by parallel velocity shear and ion temperature gradient is studied with fluid and kinetic theories. The emphasis is put on the mode real frequencies (rotation direction) instead of the growth rate. It is found that the mode rotates in the electron diamagnetic drift direction for $T_i << T_e$ and turns to the ion direction when $T_i \geq T_e$. The quasilinear formulas for the momentum and thermal fluxes are investigated in regard to both the ratio and the magnitude of the anomolous diffusivities for momentum and thermal energy. A comment on the experimental evidence indicating that the measured micro-fluctuations in tokamak plasmas are driven by the parallel velocity shear and the ion temperature gradient is made. The correlations between theory and experiment will be discussed.

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"Continuum Approximation" for Impurity Transport in Tokamak Edge Plasma.

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Abstract

To model impurity transport in tokamak edge plasma it is necessary to solve a cumbersome coupled system of equations describing the evolution of the impurity distribution over ionization states Z_j. In view of the complexity of the equations (which makes numerical solutions quite time consuming) and the large uncertainty in the anomalous transport coefficients, and even in the rate constants of the elementary processes involving complex ions we have derived a simpler semianalytical model. Following [1], we employ the differential analog of the system of discrete equations describing the evolution of the impurities in terms of their ionization states where Z_j is a continuum variable. Then, expanding the distribution function of the impurity over ionization states in Hermite polynomials yields the equations for the coefficients of this expansion. In the simplest case one can use the first three coefficients to describe the impurity distribution over ionization states. Combining this differential analog with the reduced charged state approach [2] we obtain a simple set of equations describing impurity transport in the tokamak edge plasma. The code module CONIMP using this simplified approach was developed and coupled to NEWT-1D code. In this paper we report the first results from the CONIMP & NEWT-1D package.

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Saturation of Toroidal Alfvén Eigenmodes via Nonlinear Density Modulation

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The low frequency density modulation of the core plasma due to toroidal Alfvén eigenmodes (TAE) is investigated as a saturation mechanism for the TAE in high-β plasmas. This density modulation has poloidal asymmetry and can effectively close the TAE gap and lead to the stabilization of the mode. In this study we concentrate on the magnetohydrodynamic (MHD) properties of high-n (large toroidal mode number) TAE, namely the linear dynamics and the nonlinear MHD saturation. Since our main objective is to study the saturation of the TAE due to MHD nonlinearities, we model the energetic particle drive with an effective growth rate, γ, in order to simplify the problem. The scaling of the saturation amplitude of the TAE with inverse aspect ratio ($\epsilon \equiv a/R_o$) is determined both numerically and analytically. Results will be presented for a variety of plasma parameters. In addition, the derivation of the nonlinear equation will be presented as well as an analytical estimate of the saturation amplitude. Connections to recent theories[1,2] will be examined.

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Nonlinear MHD Simulations of RFP Configurations with Thermal Energy Transport*

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Experimental measurements of fluctuating parallel heat flux in the reversed field pinch (RFP) show that magnetic fluctuations are responsible for transport in the RFP core.[1] A new version of the DEBS 3D magnetohydrodynamics (MHD) code[2] evolves pressure self-consistently—including anisotropic thermal conduction—and permits numerical investigations of RFP thermal transport. Profiles of $\langle Q_{||} B_r \rangle$, where $Q_{||}$ is the fluctuating parallel heat flux and $\langle \rangle$ is an average over the poloidal and toroidal coordinates, show that the transport results from parallel conductivity in the stochastic field region (within r/a=0.9), consistent with experimental results. This produces a pressure profile that has a weak gradient in the interior and a strong gradient near the wall. Magnetic energy spectra are compared with spectra from β=0 simulations, showing that the pressure has little impact on the fluctuations.

Additional current drive mechanisms such as DC helicity injection[3] and RF current drive[4] are being developed to improve RFP confinement. These current drive schemes are modeled in the code with an ad hoc electron force that enhances parallel current near the reversal surface. Results showing improved energy confinement are reported.

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

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1995 Sherwood Theory Conference
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Anomalous Transport and Its Self-Similarlity in the Ergodic Layer*

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The material for this work is based on the results [1,2]. General properties of the motion in the ergodic layer (EL) are considered analytically and numerically. It is shown that the fine structure of the EL, its resonances and subresonances, are responsible for the anomalous kinetics inside the EL. The self-similar pattern of the phase space of chaotic motion has been described and its influence on the anomalous diffusion has been displayed. A new property of self-similarity of chaotic dynamics, inside the EL, has been proved and demonstrated by the fine symplectic simulation. The chaotic dynamics is shown to have "wrinkles of memory" and "fractal time" as a general intrinsic property which can be expressed in a more visual way as a possibility to design the Maxwell's Demon operation inside the EL. Such kinds of operations could separate particles of different kinds inside the EL. This gives a new view on the realistic picture of the dynamical chaos and its possible utilization.

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*This work was supported by the U.S. Department of Energy, Grant No. DE-FG02-92ER54184.

A FLEXIBLE CODE BASED ON A SCALAR REPRESENTATION OF TOROIDAL MHD

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Starting from an exact scalar representation of toroidal MHD in terms of stream functions and potentials, one can derive systems of reduced MHD equations of various complexity corresponding to the problem to be investigated. We use this feature of the scalar representation to develop a modular code for the nonlinear evolution of solutions of arbitrary reduced systems or of the complete MHD system. The equations are written in general toroidal flux coordinates r, θ, ζ, and we use finite differences in r and Fourier series in θ, ζ. In the present phase of development the code solves three evolution equations for the vorticity density w, the flux ψ and the pressure p in toroidal or cylindrical geometry. We present first results on tearing modes in configurations with hollow current profiles, as they are observed in tokamak discharges with Lower Hybrid current drive.

2D12

Poloidal Flow Near the Tokamak Scrape-off Layer*

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The scrape-off layer is characterized by a balance between poloidal motion to the divertor plate and radial diffusion from the plasma interior. This balance contradicts conventional tokamak orderings, and requires diffusion to be included in the lowest order drift-kinetic equation. Using a self-consistent ordering, the kinetic equation with diffusion is analyzed rigorously. It is found that radial diffusion allows poloidal flow, unlike the situation in the plasma core. Explicit expressions for the poloidal flow velocity are obtained for two cases: Coulomb collisional diffusion and a simple model for anomalous diffusion.

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[1]Lodestar Research Corp.

2D13

Issues in Gyrofluid Turbulence Simulations

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Major progress has recently been made in realistic gyrofluid simulations of tokamak turbulence[1], resulting in encouraging comparisons with TFTR L-mode experiments[3]. These results will be primarily described in other presentations at this conference. In the present talk we will discuss some of the details in the nonlinear simulations and the comparisons with experiments. Some of these issues will be the resolution requirements for nonlinear plasma turbulence simulations, and the neoclassical behavior of the existing gyrofluid equations. Another of these is the issue of Bohm vs. gyro-Bohm scaling. The differences between flux-tube and full-torus[4] simulations have suggested[5] the existence of transitions in ρ_* scaling. Indeed, recent experiments on DIII-D have seen a transition from super-Bohm ions in L-mode to gyro-Bohm ions in H-mode[6,7]. $E \times B$ sheared rotation has been an important paradigm for understanding H-modes and the nonlinear dynamics of many types of plasma turbulence. Here we explore the possibility that a generalized shearing rate (effectively including radial gradients of $\omega_*(r)$, $\eta_i(r)$ etc. as well as of the $E \times B$ rotation) may be an important parameter in controlling transitions in ρ_* scaling. [The resulting model has similarities to recent work by Staebler et.al.[8].] At present, this generalized shearing model for causing ρ_* transitions is still under development, and needs testing by direct numerical simulations and comparison with experiments. Although a gyroBohm scaling would appear favorable for scaling to larger machines, one needs to be cautious because of marginal stability effects, which, for example, can couple the core transport scaling to edge parameters[2,3]. These complications might be particularly important if the core and edge plasmas are in different ρ_* regimes.

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Simulations of Δ' and Neoclassical-MHD Driven Magnetic Islands in a Tokamak Plasma*

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A set of incompressible, reduced-MHD equations for the poloidal flux ψ, the velocity stream function ϕ, and the plasma pressure p, have been implemented in a modified version of the fully three dimensional, toroidal, initial value FAR[1] code. The set of equations are composed of a toroidal Ohm's Law, a toroidal vorticity evolution equation, and a pressure evolution equation. The Ohm's law and the vorticity evolution include neoclassical viscous-stress effects ($\nabla \cdot \vec{\vec{\pi}}$) based on analytical kinetic closures[2].

To verify the veracity of the implementation for the study of single-helicity tearing instabilities, detailed analysis of Δ' unstable modes without viscous stress effects has been completed which check features of island size and growth rate spanning a time range from the initial exponential growth rate, through the Rutherford regime, and finally into mode saturation. Variations in magnetic Reynolds number S, inverse-aspect ratio ϵ, and plasma pressure β have been considered. Additionally, pressure profile features have been investigated for disparate values of perpendicular $\chi_\perp$ and parallel $\chi_{||}$ heat diffusivities to confirm the flattening of the profile across the island region and to study the variation in the plasma pressure along magnetic field-lines.

The addition of neoclassical effects through the viscous stress tensor term introduces the bootstrap current into Ohm's law, which can then lead to destabilization of tearing modes which are Δ' stable[3], and a viscous term in the momentum balance. Parameter scans of magnetic Reynolds number S, inverse-aspect ratio ϵ, and plasma pressure β will be presented to study both the growth rate and also the mode saturation of this tearing instability.

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Accurate Treatment of Impurity Parallel Transport in NEWT1D*

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The reduced-ion description for computing the parallel forces and heat fluxes in a fluid-regime impurity plasma has been encoded in a module FMOMBAL for use in plasma edge transport codes. This module has been incorporated into the one-dimensional transport code NEWT1D to compute impurity entrainment effects in the presence of gas puffing and recycling at the divertor plate. Comparison with the average-ion model[1] originally in NEWT1D will be made, and the effects of an improved parallel viscosity model are studied.

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Ion Cyclotron Absorption and Anomalous Transport in Turbulent Two-Ion Tokamak Plasmas*

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The anomalous absorption and transport in turbulent[1] two ion Tokamak plasmas in the ion-cyclotron frequency range is studied. The frequency missmatch between the fast magnetosonic mode and the local plasma ion-cyclotron frequency is assumed to be both much larger and much smaller then the anomalous collision frequency for electrons. It is shown that the absorption and transport strongly depend on the level of ion-acoustic turbulence[2] and on the ion-composition of plasmas. The absorption power is evlaluated for different interaction geometries and plasma parameters. A novel spectrum for ion-acoustic turbulence is obtained due to enhanced nonlinear Landau damping on ions in two-ion plasmas.

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1995 INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE

INTERACTION OF MODE-CONVERTED ION-BERNSTEIN WAVES WITH ELECTRONS IN TOKAMAKS*

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Recent experimental observations in ICRF-heated discharges in TFTR and Tore Supra have shown that mode-converted ion-Bernstein waves (IBW) can lead to localized electron heating. In light of these results we are studying the role of IBW's in present and future experiments. Previously, theoretical analysis has shown that the IBW's can interact effectively with electrons in tokamak plasmas [1, 2]. The interaction of IBW's with lower-hybrid current drive generated electron distribution functions has been shown to lead to an enhancement in the current drive efficiency [1]. The damping rate of IBW's on electrons is larger than that for the fast Alfvén waves (FAW) for the same plasma conditions so that the damping of IBW's can be essentially "single pass." Furthermore, the damping of IBW's is localized to be near the mode-conversion region in a plasma. These properties make IBW's good candidates in tokamak plasmas for depositing incoming ICRF power onto electrons. An important issue related to these studies is to determine the optimum scenarios for which the power mode converted to IBW's from the incoming FAW's can be maximized. Towards this end, we have developed a theoretical model [3, 4] that allows us to determine the optimum operating regimes for a given ion mix that would lead to enhanced mode conversion. The theoretical model has been applied to typical TPX equilibria to determine advanced scenarios where mode-conversion to IBW's could be maximized. In this paper we discuss the various mode-conversion scenarios, and the propagation and damping of IBW's in tokamak plasmas.

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† Centre Canadien de Fusion Magnetique, Varennes, Québec, Canada.

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TRANSPORT BARRIER IN VERY HIGH TEMPERATURE PLASMAS

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Plasmas with high ion temperatures have been produced featuring a transport barrier well within the plasma column [1]. The position of this has been associated with that of the q = 3 surface. The proposed interpretation is that the barrier involves the excitation of a dissipative mode driven by the shear of the toroidal flow velocity that is induced [2] in the relevant plasma. The needed dissipation could be associated with a pre-existing state of macroscopic turbulence for which the q-integer surface, that is closest to the surface where the toroidal flow velocity is maximum, is particularly suited. A new purely growing instability [3] of this kind has been found for which the onset criterion is

$$\frac{k_\perp}{k_\|}\frac{1}{\Omega_{ci}}\frac{dV_\|^F}{dr} > 1 + \frac{T_i}{T_e}$$

and the growth rate

$$\gamma < k_\| V_{thi}.$$

Here $V_\|^F$ is the longitudinal flow velocity, Ω_{ci} the ion cyclotron frequency, $k_\|$ and $k_\perp$ the components of the wave number, and V_{thi} the ion thermal velocity. It is argued that this instability is turned off by the steepening of the ion temperature gradient as the relevant mode cannot be found when $|d\ln T_i/d\ln r| \geq |d\ln V_\|^F/d\ln r|$. This steepening can be allowed to occur by the inflow of thermal energy resulting from the enhanced rate of viscous dissipation that the same instability can produce.

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2D19

TURBULENCE PROPAGATION AND CORRELATION LENGTHS

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Recently, transport analysis in Tokamaks have led to surprising results. First, many devices show fast modifications of transport coefficients. For instance, an increase of the central temperature is observed in discharges where a cold pulse is produced in the tokamak edge plasma. This change occurs within a time scale smaller than a diffusion time [1]. Second, several local analysis have shown that the scaling of the ion thermal diffusivity is Bohm-like or Goldston-like [2]. At first sight, these results seem to be in contradiction with usual transport models, which are expected to be diffusive and to exhibit a gyroBohm scaling. However, a detailed analysis is needed before stating such a conclusion. The purpose of this work is to know whether standard instability models can explain these observations.

A 3D simulation of a tokamak turbulence over a large radial scale is a difficult task, essentially because of storage and computation time constraints. Here, a simplified 2D code is used [3]. The simplification relies upon a quasi-ballooning representation, which assumes that each Fourier m,n harmonic exhibits a given radial shape, whose width scales as an ion Larmor radius. This radial shape is a combination of even and odd functions. This code covers the basic physics of ion and electron drift waves. It also includes the dynamics of radial modes. It will be shown that a turbulence can propagate radially faster than a diffusion process. The group velocity is of order of the curvature drift, as expected [4]. However, this is only true if the dissipation is low enough. More precisely, the propagation range, of the order of the group velocity divided by the average damping rate, has to be smaller than the machine size. Some results on the scaling of correlation lengths will also be presented.

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2D20

A Parallel Gyrokinetic Field Solver for the Generalized Tokamak Simulator*

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In this work we present an algorithm, implementation, and discussion of a parallel, gyrokinetic field solver developed for use with the Generalized Tokamak Simulator (GTS). GTS is based on the Toroidal Particle code (TPC), and was developed as part of the Numerical Tokamak project in order to study plasma confinement and instabilities in a general toroidal metric. By utilizing many of the latest advancements in software design such as object-oriented programming, this code is able to far exceed TPC as concerns flexibility, robustness, portability, visualization, physical relevance, and its ability to be run on a variety of parallel architectures. GTS at present is a kinetic simulation code that uses particles for time evolution of the plasma distribution. Such codes have particular challenges dealing with parallelization, notably, how to distribute the particles and field quantities across compute nodes effectively. Further, the general metric imposes significant additional complexity on the solution of the gyrokinetic Poisson equation. The poster will present a discussion of these issues and tests of the resulting field solver, including convergence properties and performance in a parallel computing environment.

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2D21

Simple Current Sheets and Reconnection *

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We consider a simple model of current sheet formation and evolution. Initially a field, $\mathbf{B} = x\mathbf{y}$ is supported by pressure. The field is embedded in a perfectly conducting circular ($x^2 + y^2 = 1$) wall. The plasma is cooled rapidly compared to the reconnection time. A current sheet forms on the line $x = 0$. The current sheet disappears as reconnection evolves the field towards the final equilibria with no current $\mathbf{B} = (x\mathbf{y} + y\mathbf{x})/2$. During reconnection most of the plasma, except close to the current sheet, is in equilibrium. We have solved for all the single current sheet equilibria (multiple current sheet equilibria do exist). These equilibria are specified by two parameters: the length of the current sheet and the amount of reconnected flux. The dynamical evolution between the different states determines the time dependence of the two parameters. Various aspects of the evolution will be discussed.

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Request POSTER presentation

Simulation of Current Generation in a 3-D Plasma Model

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Transport phenomena can significantly increase the toroidal current over that driven directly by ohmic heating electric field. The bootstrap current theory accounts for the effect of collisional diffusion of banana orbits on toroidal current, but the effect is not confined to that transport regime, or even to toroidal geometry. Initial calculations in a $2\frac{1}{2}$-D electromagnetic PIC simulations have demonstrated that Maxwellian plasmas in static toroidal and vertical fields spontaneously develop significant toroidal current, even in the absence of the "seed current" as required by the bootstrap theory.[2]

Simulations in both cylindrical and toroidal geometries, show that if the plasma column is centrally fueled, then an initial current increases steadily. Such results in straight, cylindrical plasmas show that self generated, parallel currents arise without banana orbits. In 2-1/2 D, the fundamental mechanism seems to be the conservation of particles' canonical momenta in the direction of the ignorable coordinate. Bootstrap current driven by banana diffusion is one example of this effect, but the total current drive does not fall to zero at infinite aspect ratio, as the standard bootstrap theory suggests. Our simulations indicate that fueling, coupled with fusion heating may drive all of the tokamak's toroidal current.

Work has begun to study three-dimensional effects in transport driven current. A parallel 3-D electrostatic PIC code has been developed to study perpendicular diffusion of particles and the current associated with such diffusion. In addition, a parallel 3-D electromagnetic PIC code is being developed to reproduce results seen in our 2-1/2 D calculations. We will present our simulation results.

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2D23

Some Theoretical Aspects of a "Linear Collider" Open-Ended Fusion Power System

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This paper represents continued studies of a concept discussed in a previous Sherwood Theory conference [1]. The idea is to permit the achievement of useful net fusion power by the combination of high-efficiency ion sources, injecting into a linear solenoid reaction region, followed by a multi-stage direct converter. The efficiency of such a direct converter is inversely proportional to the energy spread of the captured ions. However, the probability of fusion and the energy spread (about the instantaneous mean) induced in an energy-modulated beam both scale in the same way with the interaction time. Thus net fusion power can in principle be achieved with small fractional burnups, provided injector efficiencies are high. As a specific example of such a system we consider a "linear collider" wherein two dissimilar-energy, co-propagating, energy-modulated, ion beams are injected into a long, graded-field, solenoidal magnetic field the highest intensity region of which coincides with the bunching distance of the beam. In this way both magnetic convergence and klystron-like bunching act to compress the beam ions to high density in the central region of the solenoid, so that "one-pass" net fusion power becomes a theoretical possibility. The main plasma physics issues here concern the possibility of beam-induced instabilities and the physics of the electron cloud in interaction with the beams. In the paper a preliminary analysis of the beam kinetics and of these instability and electron physics issues is presented.

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Divertor Plasma Simulation with the UEDGE Code Including an Advanced Neutral Transport Model

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We have added an advanced neutral transport model to the 2-D edge plasma fluid code UEDGE, which can be used in place of the previous neutral diffusion model. The new model features an additional fluid equation, for the parallel neutral momentum, and should thus be able to describe divertor plasma detachment more accurately. The radial neutral transport remains diffusive while the poloidal neutral transport is both convective and diffusive.

The neutral and plasma parallel momentum equations are fully coupled through charge exchange, ionization, and recombination. This coupling provides the ability to convert parallel plasma momentum into parallel neutral momentum, which is transported across the magnetic field through neutral viscosity. The previous ion energy equation is now used as a combined ion+neutral energy equation. The neutral viscosity and thermal conductivity include the effects of charge exchange.

The new model is benchmarked against a more complete neutral transport model (3D Navier Stokes neutrals) developed for a simple rectangular geometry. It is also used for simulations of the divertor plasma in the complex geometry of Alcator C-Mod. We observe a drop in the ion saturation current and plasma density at the plates, along with a strongly reduced heat flux when carbon impurity radiation is added.

The Ignitor Experiment* and Relevance of the Alcator C-Mod Confinement Results*

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Ignitor is the first experiment designed to reach ignition conditions. For this it relies on the favorable confinement and purity properties of the high density plasmas produced by the compact, high field line of experiments represented by the Alcator A, C and C-Mod machines at MIT and the FT and FTU machines at Frascati.

The dependence of the transport properties on the plasma current observed by the Alcator C-Mod machine, can be described with a type of diffusion coefficient [1], linearly dependent on the current, that reproduces fairly well the measured electron temperature profile, loop voltage and confinement time of ohmic plasmas. The relevant simulations have been carried out by the BALDUR code. The nature of the diffusion coefficients that are found to reproduce the plasma parameters of a series of C-Mod discharges are discussed, with regard to the density, current, and magnetic field dependence, and their implications for the Ignitor project are analyzed.

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

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1D AND 2D ANALYTICAL AND NUMERICAL STUDY OF THE DRIFT-RESISTIVE-BALLOONING MODES IN THE SCRAPE-OFF-LAYER IN TOKAMAK PLASMAS*

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We have developed a theory for Drift Resistive Ballooning Modes in the Scrape-Off -Layer of tokamak plasmas. The stability and mode structure of these modes along the field is determined by two dimensionless parameters. The first parameter is $\lambda = (m_e/m_i)^{1/2}\nu_{ei}qR/v_{Te}$, which is the strength of the sheath current compared to the parallel current associated with the mode. The second parameter is the dimensionless poloidal mode number $\hat{m}=mL_0/a$[1].For $\lambda<<1$and $\hat{m}< 1$, the modes are flute-like and have been studied by various authors[2]. However for $\lambda<<1$and $\hat{m}>> 1$ The modes are strongly ballooning and are 'uneffected' by the limiter on the inside. On the other hand , for $\lambda>>1$and $\hat{m}< 1$, the modes are strongly stabilised and only the high poloidal modes are unstable. The intermediate regime for $\lambda \sim O(1)$ has been studied numerically. We have also developed a 2D code to complement the 1D analytical work. We find that the radial variation in the diamagnetic frequency localises the modes and the flute like modes are stablilised even for the case $\lambda<<1$. Detailed stability curves for the modes as a function of the above-mentioned parameters as well as $\hat{s}$ will be presented.

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TOROIDAL ELECTROSTATIC GUIDING CENTER PLASMAS

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The transition to true toroidal geometry from straight-cylinder approximations to it is known to be drastic because of the loss of poloidal symmetry. For example, resistive MHD equilibria, relatively straightforward to determine in a periodic cylinder, do not exist (under a standard set of assumptions and symmetries) in a torus [1]. Any approach to toroidal plasma theory that aspires to get beyond the ideal (Grad-Shafranov) framework must take the transition seriously, one step at a time. We consider an electrostatic guiding center plasma in axisymmetric toroidal geometry, with all field components independent of the azimuthal coordinate. A vacuum toroidal magnetic field falls off as 1/R inside a perfectly conducting toroidal vessel with square cross section. The plasma moves with guiding center dynamics (the ExB drift) perpendicularly to the magnetic field in the self-consistently generated electrostatic field, E. The walls of the vessel are held at ground potential. This is a natural generalization of the familiar 2D guiding center plasma, but is not incompressible flow. There is no reason to assume that its vortex-forming properties and related cross-field transport are close to those of the 2D guiding center plasma with straight magnetic field lines. We have written a spectral-method dynamical code which uses eigenfunctions of the Laplacian as an expansion basis. Fourier series are used in the z direction, multiplied by linear combinations of Bessel functions and Neumann functions in the radial direction. The computation proceeds entirely in the spectral space. Charge density can be followed directly, without division into positive and negative components, until diffusion is introduced. Preliminary numerical results will be presented. The computation is considered as the first step towards robust, resistive, nonlinear MHD in toroidal geometry.

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MHD Stability of Reversed Shear Current Profiles

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Abstract

Tokamak plasmas with a reversed magnetic shear profile, that is where the current density distribution possesses off-axis maximum, are of interest to the TPX project. There is some experimental evidence from both DIIID and TFTR that such current density profiles result in plasmas having improved confinement properties. Moreover, the diffusion driven (bootstrap) current, essential for steady state tokamak operation since this can represent a large fraction of the toroidal current at high β_p, is expected to result in distributions exhibiting reversed shear in the plasma core. It is long known that safety factor profiles with elevated values of the central safety factor with a reversed shear core have desirable properties[1] for stabilizing the large toroidal node number, 'balloooning', instabilities and facilitate the transition to the second region of ideal (infinite conducivity) MHD stability. Here, we study the small toroidal mode number MHD stability properties of this class of profiles with emphasis on plasmas with finite resistivity.

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Magnetic Field Calculation of (m,n) modes at Mirnov Coil Locations

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The Mirnov coil signals measured in the presence of an (m,n) mode have different amplitudes depending on their locations. In order to analyze Mirnov signals properly, we may need the mode magnitudes at the coil locations. For instance some applications of the Singular Value Decomposition (SVD) method applied to Mirnov data[1] may require preconditioning the Mirnov coil data with the field information to obtain the poloidal mode structure properly.

Utilizing the Green's second identity, and assuming vacuum between the resonance surface and the vacuum wall, the magnetic field at the coil locations may be expressed in an integral equation. A code such as the VACUUM code [2] that solves the integral equation will be used to obtain magnitudes of the magnetic field of an (m,n) mode at DIII-D coil locations.

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MHD Stability of Advanced Operating Regimes in Tokamaks

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Several MHD stability issues applicable to advanced operating modes in tokamaks are investigated. Low central shear and reverse shear can permit access to the second ballooning stability region in the center of a tokamak plasma. These profiles may develop naturally in plasmas with large bootstrap fraction. Reverse shear profiles have been obtained in TFTR and stability analysis of these experiments is presented. Analysis of one particular shot indicated that when reverse shear was obtained the central pressure gradient was well into the second region. The beta in such plasmas is typically limited by infernal and external kink instabilities. Comparisons of the stability boundaries of these instabilities with the experiment will be shown. In addition, a separate study of the effect of various wall boundary configurations on external modes is presented.

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Bifurcations and Intermittent MHD activity

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Intermittent enhancement of MHD activity is a common experimental observation in laboratory plasmas. In tokamak plasmas, this class of phenomena comprises the sawtooth collapse, the various types of so called edge-localized modes (ELMs) occurring in high confinement regimes and obviously disruptions that lead to the termination of the discharge. Often these events are preceded by a well identified *precursor*, namely the occurence of a slowly growing magnetic island inside the plasma.

The theory of bifurcations in dynamical systems naturally provides a conceptual framework with a number of scenarios in which abrupt changes of an observable quantity can occur.

In this work we show that intermittent behavior is a natural property of a basic model of plasma magnetic activity, resistive reduced magnetohydrodynamics (RRMHD). Specifically, we employ a numerical code to analyze the sequence of equilibria occurring in a slab version of two-dimensional (single helicity) RRMHD as a function of the stability parameter Δ'.

As expected from tearing mode theory, the first bifurcation is a symmetry-breaking occurring at $\Delta' = 0$. Above this threshold the system develops a neighbouring equilibrium with a small magnetic island. The first bifurcation is "soft": no dramatic event can be observed.

When Δ' is further increased to a value $\Delta'_{\rm crit} \sim 1/a$, (where a is the system size) a saddle-node (or tangent) bifurcation occurs. This type of bifurcation is characterized by the confluence of a stable and an unstable equilibrium. Above $\Delta'_{\rm crit}$ no equilibrium with a small island exists. The system jumps (virtually disrupts) to a new state with an island size of order a with explosive dynamics, and a burst of magnetic activity is observed. Additional physics (not included in the RRMHD model) would dictate whether the cycle can be repeted (like in ELMs) or whether a true disruption would occur.

A nice side result of this scenario is that the existence of the precursor is naturally predicted, since it corresponds to the state of slighlty broken simmetry occurring between the first bifurcation and the second bifurcation.

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A Multi-Variable Core-Edge Simulation via 1D-2D Coupled Non-Linear Transport Codes

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A code for modeling the nonlinear transport between the core and the edge plasma of toroidal magnetic fusion devices has been constructed by coupling a 2D axisymmetric edge model (UEDGE) to a 1D model for the radial core transport in toroidal flux coordinates (the transport module from the CORSICA 1.0 code).

In the present version of the code the ion density and electron and ion temperature profiles are coupled. The electron density is determined by imposing quasi-neutrality, both in the core and in the edge. The scheme allows the coupling of multiple ion species density profiles with one average ion temperature profile. (CORSICA 1.0 can also evolve the q profile and a free-boundary MHD equilibrium, but these are kept "frozen" in the present model.)

The coupling has been implemented with a single ion species for the simulation of a DIII-D plasma and will be extended by including tritium and helium ash for ITER case studies. Both transport modules share the same magnetic field configuration computed by the MHD equilibrium at the beginning of the run.

The density and temperature core profiles are joined to the corresponding 2D profiles (averaged in the poloidal direction) on a flux surface sufficiently inside the magnetic separatrix that the profiles are approximately independent of poloidal angle.

The self-consistency of the simulation is guaranteed by imposing that the transport equations be satisfied at the interface, as well as in both core and edge domains, simultaneously. For this purpose, a few different algorithms, each of which maintains a substantial structural independence of the 1D and 2D transport modules, are being tested for their relative efficiency. These algorithms are based on a predictor-iteration cycle of the transport equations or on a linear decomposition between the 1D and the 2D domains of the linearized set of equations. The code that perform the coupling is now entirely written in LLNL's BASIS interpreter language.

Besides refinement of the coupling algorithms, work in progress includes runs with DIII-D parameters (modeling experimental results and investigation on the density limit problem). Simulations on ITER plasmas and the insertion of the MHD equilibrium module coupled with the transport are also being considered.

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SCALE-INVARIANT PLASMA MOTIONS NEAR X-POINTS

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The Hamiltonian structure of the two-fluid equations that describe nonlinear low-frequency phenomena in a plasma with large thermal ion gyroradius is investigated.
When the system is energetically closed, the energy functional is the Hamiltonian and non-canonical Poisson brackets can be defined. The system possesses two infinite sets of invariants (Casimirs) that arise from the structure of the equations.
The plasma dynamics in the neighbourhood of critical points (X- and O-points) of the magnetic configuration is investigated in terms of scale-invariant equations. Such solutions correspond to open systems which, in general, do not have well defined Casimirs. However, the scale-invariant members of the families of Casimirs of the closed system survive. These surviving elements are not related to simple power expansions in the fields. They reflect the invariance of the topology of the configuration.
When the fields are analytical, they can be expressed as polynomials and the system has a finite number of degrees of freedom. The corresponding magnetic configuration has either three or one real separatrix lines. This truncated system is Hamiltonian and integrable. Most of the initial structures lead to a collapse of the magnetic separatrices with a velocity that grows as $(t - t_0)^{-1}$.
The spatial connection between these solutions, which are valid in the limit of large ion gyro-radii, and the global 2D RMHD solutions is also discussed. The aim is to construct a full nonlinear solution for the dynamics of a magnetic configuration around an X-point that is valid from the MHD scales down to the scale of the ion gyroradius and of the electron skin depth. On the MHD scale X-points have two real separatrices. Thus, in these global solutions, an MHD X-point must split into two large-ion-gyroradii X-points connected by four (real or imaginary) separatrices. A structured current layer on the ion gyroradius scale is formed between these large-ion-gyroradii X-points.

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Particle Control in DIII-D and TPX*

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The DIII-D Radiative Divertor Program (RDP) design accomodates high performance advanced tokamak operating modes that form the basis of the TPX design. The overall plasma size, plasma current and plasma density of the two designs are similar, and the RDP maximum input power (20 MW) is comparable to the "day-one" TPX input power, but there are significant differences in divertor surface shapes and particle pumping configurations. The RDP divertor has a shaped baffle that defines the slot entrance while TPX uses a vertical re-entrant divertor plate. Here we compare particle flows in these designs by modeling the scrape-off layer and divertor plasmas with the UEDGE code. Preliminary results show that the core ionization probability (α_d) for neutrals that originate at the divertor plates is much larger for TPX (.071) than for the RDP (.013), mainly due to the factor-of-two lower operating plasma density in TPX. For comparable densities, the TPX divertor confines neutrals better than the RDP (α_d = .006 vs .013) because of its longer slot length (53 cm for TPX versus 23 cm for the standard RDP slot configuration used in this preliminary comparison). To identify specific features of the divertors that affect the core ionization, we will examine neutral source profiles, ionization mean free path distributions and in/outboard asymmetries for the two designs.

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A NEW PARADIGM IN CYCLOTRON EMISSION AND ABSORPTION

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The effects of mode conversion theory (or full wave theory) on electron cyclotron emission have led to some surprising results. The classical expressions were originally derived from models which did not include mode conversion or its attendant reflection. When mode conversion was included, the first surprise was that the transmission coefficient is totally independent of absorption and due exclusively to tunneling. The other surprise is that the observed emission arises from two distinct sources, one direct, and one from an indirect Bernstein wave source which is partially converted in the cyclotron layer to outgoing electromagnetic waves, with the net result that mode conversion effectively cancels out for the electron cyclotron case. The only corrections to electron cyclotron emission are then due to reflection effects, and these have been shown to be small for fusion plasmas, leading to the validation of the classical formula, but via an entirely new paradigm in its interpretation. While the emission formulas may be validated for fusion plasmas, there exist reasonable tokamaks where the classical formulas may be in significant error (up to 120% in the amount of emission, up to 40% error in the inferred termperature). Even when the emission formula is validated, the interpretation that everything not transmitted is absorbed is not validated, so that on the high field side, this simple assumption may be off by more than a factor of two. The discrepancy in the estimate of absorption is made up by the indirect emission from a Bernstein wave source partially mode converted out along with the reduced direct emission so that the net emission follows the classical formula. Empirical formulas for the reflection coefficient on the low field side and for the conversion coefficient on the high field side are presented for weakly relativistic electrons. For ions, the classical emission formulas fail rather badly in many cases, since the indirect emission may often fail to compensate for the reflected and converted energy. Again, empirical formulas are presented permitting one to estimate potential errors in interpreting ion cyclotron harmonic emission. This paper includes a discussion of the spatial emission source distribution.

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ROLE OF EDGE TURBULENCE IN PLASMA DETACHMENT

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Detached plasma regime is crucial for the design of ITER divertor. One of the important features of such regime is the significant pressure drop along field lines towards the divertor plate. Here we investigate the role of edge turbulence in producing such a pressure drop. We focus on turbulence induced parallel momentum transport in open field line geometry. We find that for sonic parallel flows, the most important effect is the turbulent viscosity. For sub-sonic flows, additional force arising from the spatial variation of the fluctuation along the field lines also becomes important. Using electron-temperature-gradient turbulence model as a paradigm, a closed expression for the turbulent transport of parallel flow is obtained. Coupled equations describing evolution of plasma pressure and parallel flows are derived and solved using appropriate boundary conditions at the material plate. The implications of the result on plasma detachment is discussed.

Multiple Mode Simulations of Energetic Particle—Alfvén Eigenmode Dynamics*

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New numerical simulations are presented on the self-consistent dynamics of energetic particles and a set of unstable discrete shear Alfvén modes in a tokamak. Our code developed for these simulations has been previously tested in the simulations of the bump-on-tail instability model. The code has a Hamiltonian structure for the mode-particle coupling, with the superimposed wave damping, particle source and classical relaxation processes. In the alpha particle-Alfvén wave problem, we observe a transition from a single mode saturation to the mode overlap and global quasilinear diffusion, which is qualitatively similar to that observed in the bump-on-tail model. We quantify the conditions of resonance overlap and the criterion for the pulsating nonlinear regime versus a steady-state regime. We also demonstrate the effect of global diffusion on the energetic particle losses, including the bursts in the outgoing particle flux.

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Poster

Abstract for the 1995 International Sherwood Fusion Theory Conference

Modelling of TF Ripple Loss of Alpha Particles in TFTR DT Experiments*

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Estimates of the stochastic ripple loss of alpha particles in DT experiments on TFTR [1] are being carried out with a Hamiltonian-coordinate particle following code (ORBIT) as well as with a faster simple model within the TRANSP data analysis code, benchmarked against ORBIT. Initial simulations with the guiding center code showed that collisions enhance the stochastic TF ripple losses at TFTR by about a factor of 2 [2]. A careful statistical analysis of the Monte Carlo noise with runs of varying particle number, simulation time and initial random number generator seed is being carried out as part of validation of a new faster version of ORBIT [3].

The simple stochastic domain model for TF ripple loss in TRANSP analysis follows Monte Carlo ions so that at each bounce point the TF ripple is compared to a threshold $\delta_s = M\,(\varepsilon/(N\pi q))^{3/2}(1/\rho q')$, proportional to the Goldston, White, Boozer stochastic ripple diffusion threshold model [4]. M is evaluated by comparison with ORBIT simulations. The variation of M is thought to result from collisional stochastization of ripple-induced stochastic banana drift diffusion. With the new model, TRANSP includes the effects of ripple and collisions in a selfconsistent dynamic equilibrium. Typical TF collisional ripple loss predictions are about 10% loss of alphas for TFTR D-T experiments at $I_p = 0.9$-1.8 MA and $R = 2.52$ m .

The benchmarking of the new TRANSP ripple loss model, with the results of the guiding center code statistical analysis, and applications to a variety of TFTR experiments will be presented and compared to data obtained from the midplane lost alpha detector.

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Theory of the electron energy pinch in tokamak*

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The particle pinch effect in all major tokamaks consistently shows up via the plasma density peaking. The need for a convective energy transport to describe the observed tokamak temperature profiles was not as clear, until the electron energy transport was directly measured in DIII-D [1]. We propose a theoretical explanation of the electron energy pinch based on the same premises that led to the explanation of the tokamak particle pinch [2]. The basis of the theory is that drift-wave-type electrostatic fluctuations with frequency below the electron bounce frequency induce electron transport in the radial direction at conserved adiabaltic invariants J and μ. The formal description of bounce average electron kinetics involves the turbulent diffusivity in the action space, specifically over the poloidal magnetic flux coordinate ψ:

$$\partial_t f(\psi, J, \mu, t) = \partial_\psi D^{\psi\psi}(\psi, j)\partial_\psi f + C[f].$$

Here $j = J(\mu m)^{-1/2}$ is the pitch angle coordinate, $D^{\psi\psi}$ vanishes for passing electrons $[j > j_c(\psi)]$, and the collisional diffusion operator $C[f]$ accounts for the change in J and μ only (neoclassical diffusion neglected). A formal Chapman-Enskog perturbation theory applied to the turbulent diffusion term leads to the following electron particle and energy density (per unit flux ψ) balance:

$$\partial_t N_e = -\partial_\psi \Gamma_e, \quad \partial_t W_e = -\partial_\psi q_e + Q_{te} + Q_{ie}.$$

The term Q_{ie} describes the usual collisional ion-electron energy exchange, and the flux-surface-integrated electron particle flux Γ_e, energy flux q_e, and the energy exchange between the turbulence and the electrons Q_{te} are as follows:

$$\Gamma_e = -Dn' + Vn, \quad q_e = -(3/2)D(nT)' + (5/2)VnT, \quad Q_{te} = -V(nT)' + UnT.$$

Here $n(\psi)$ and $T(\psi)$ are the electron density and temperature on the flux surface, prime denotes differentiation with respect to ψ, and the kinetic coefficients $D(\psi)$, $V(\psi)$, and $U(\psi)$ depend on the turbulence via $D^{\psi\psi}(\psi, j)$:

$$D = (\sqrt{2}/4)\int D^{\psi\psi}u^{-3/2}dj, \quad V = (3\sqrt{2}/8)\int Du'u^{-5/2}dj < 0, \quad U = (15\sqrt{2}/16)\int Du'^2u^{-7/2}dj,$$

The function $u(\psi, j) = \varepsilon/\mu$, where ε is the particle energy, is uniquely defined by the magnetic geometry, which can be arbitrary.

The expressions for the electron particle and energy fluxes contain both diffusive and convective terms. A comparison with experiment will be presented.

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First Steps in the Development of Adaptive Grid Algorithms for Divertor Tokamak Plasmas. *

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ABSTRACT

Recently, the modeling of tokamak edge plasmas, carried out by state of the art computer codes, have shown the existence of detached state solutions for gas-fueled divertor models.[1] These computational tools have been designed to study steady-state phenomena on long time scales. Consequently, implicit methods have been the algorithms of choice in most of the development so far. The obvious limitation is the size of the computational grid needed to accurately model the physical processes in the divertor in a reasonable time. Furthermore, the physical phenomena leading to the formation of such interfaces as well as the stability properties (such as acceleration-driven Rayleigh-Taylor or ELM-driven Richtmeyer-Meshkov) cannot be described accurately by present simulations. These limitations make the use of these codes nearly impossible in regimes where non-steady situations or fine spatial structure develops giving rise to long execution times and in some cases failure to reach convergent solutions. Consequently, we have drawn from the CFD literature,[2] where adaptive grid techniques are commonly used to deal with small spatial structures that arise during simulations. The first step in accurately representing the solutions is identifying the wave structure associated with the hyperbolic part of the relevant equations. Among the several techniques used, Roe's[3] method seems to be the most widely adopted. In here, we discuss the feasibility of this method as applied to a one-dimensional set of Braginskii equations for a single and multiple ion species edge plasma. The addition of the particle diffusion, heat conductivity and sources is also discussed. Preliminary results and description of the numerical methods are presented.

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Applications of Object Oriented Methods to Self-Consistent Plasma Simulation*

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We have written an object oriented C++ code for plasma simulation. Included in the code are prototype classes of a simulation, a plasma, particles, and waves. The object-oriented structure allows portions of the code to be reused as one changes models for particle motion and field dynamics. Objects keep data that naturally belongs together inside a single structure, making portability to other kinds of simulations possible. This code has served as a model for beam instability and free-electron laser simulations as well.

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Poster

Transport Simulations of Alcator-Cmod Plasmas*

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A detailed series of transport simulations of ohmic and ICRF plasmas obtained by the Alcator C-mod machine at M.I.T. has been performed. The electron thermal transport coefficient used in the simulations is based on profile consistency and has reproduced the observed temperature profiles and energy confinement for ohmic plasmas in detail[1]. The diffusion coefficient predicts a scaling for the energy confinement time increasing with plasma current and independent of the plasma density which is in agreement with experiment. The range of parameter space for ohmic discharges is extended to include a larger range of density and current. The ohmic simulations show good agreement over the range of parameter space for the electron temperature profile, the energy confinement time and the loop voltage. The thermal transport model is extended to reproduce discharges with significant ICRF heating. The model predicts certain dependences on the global parameters in addition to the confinement time; these are investigated for the experimental database.

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2D43

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Toroidal Velocity Profiles and Core Transport in DT Plasmas in TFTR*

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Correlations between features in the V_ϕ and T_i profiles and the core confinement and transport have been investigated in DD and DT plasmas in TFTR. There is a significant change in the V_ϕ profile with time after NBI heating begins and as internal confinement improves. In supershots, a localized region of strong velocity shear develops at a radius $r \sim a/3$ where dT_i/dr is large, as expected from neoclassical theory. Inside this radius, confinement is enhanced, transport is reduced, and the density and pressure profiles are strongly peaked. The region of peak velocity gradient is located at a smaller minor radius (by > 10 cm) than that for the peak in the temperature gradient. Models in which V_ϕ and T_i profiles play a role are discussed as to cause and effect relative to the observed enhanced confinement. Some of the best performance supershots have been obtained when conditioning using lithium pellets to reduce wall recycling is combined with use of co-dominated NBI for plasma heating. $\tau_E > 300$ ms has been obtained in DT supershots with a relatively modest amount of unbalanced NBI power, $P_b \sim 15$ MW, that resulted in a very high central plasma velocity, V_ϕ , of > 800 km/s. The TRANSP simulation of the experimental data is used to determine values of the relevant transport parameters in order to compare the results with various models. The V_ϕ and T_i profiles used in the TRANSP simulation are measured by the charge exchange recombination spectroscopy (CHERS) diagnostic using the C^{5+} 5292 Å line (n = 7-8). Care must be taken in the highly rotating plasmas on TFTR to ensure that features in the V_ϕ and T_i profiles are due to actual radial variation of the transport, by compensating for the velocity dependence of the charge exchange cross-section for the C^{5+} line emission. This is especially important in determining differences in transport between DD and DT supershots and for comparing experimental results with theories which attempt to describe a dependence upon the ion mass.

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Intermittent statistics in turbulent plasma transport*

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It has frequently been speculated that intermittent non-Gaussian effects should significantly affect the levels of steady-state turbulent transport in plasmas. Such a conclusion is too strong, as Hu, Krommes, and Bowman have recently demonstrated[1] that second-order closures can both qualitatively and, in particular, quantitatively accurately predict the steady-state particle flux in the Hasegawa–Wakatani (HW) and similar paradigms even though such approximations do not take into account the details of coherent structures and other intermittent phenomena. Nevertheless, intermittency does manifest itself through non-Gaussian shapes of experimentally observable probability density functions. The development of such non-Gaussian statistics is studied through several approaches: (1) the direct-interaction approximation for the kurtosis; (2) analytically solvable models of random straining; (3) statistical analysis of direct numerical simulations (DNS) of both passive and self-consistent advection. A unifying observation is that substantial non-Gaussian behavior can arise from purely random straining, even in the absence of coherent structures. This motivates a scenario that qualitatively explains relative values of kurtoses observed in HW simulations. An attempt is made to quantify the relative importance of coherent structures and random straining in those DNS.

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Core-Localized Toroidal Alfvén Eigenmodes

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A surprising recent result from NOVA code simulations[1] of a certain D-T discharge in the TFTR tokamak[2] was the finding of a core-localized toroidal Alfvén eigenmode (TAE), at plasma pressure gradient values considerably higher than would have been expected theoretically. An explanation for this result has been given by Fu[3] from an analytic solution of the finite-frequency ballooning equation with finite aspect ratio terms carefully included.

Here we show that finite aspect ratio effects ($\varepsilon \equiv r / R$) also lead to the existence of a second core-localized ideal TAE within the Alfvén continuum gap. Whereas the core-localized mode that Fu considered (with frequency near the lower end of the gap) is the finite-ε, finite-β generalization of the usual ideal TAE at low shear, the mode with frequency near the upper gap edge is a new mode, which exists when $\alpha < \varepsilon + 2\Delta' - s^2$, and hence finite aspect ratio is essential. We also show how both core-localized modes convert to kinetic toroidal Alfvén eigenmodes (KTAE)[8-10] when the parameter values for shear, pressure gradient, and aspect ratio are varied.

When , the ordering for the analytic boundary layer theory is not satisfied. However, direct numerical integration of the coupled TAE equations for a model tokamak equilibrium shows that both core-localized TAE modes can still exist.

Furthermore, for the realistic equilibrium corresponding to TFTR discharge #76770, the CASTOR code[7] was used, with $n = 5$. Both the upper and lower core-localized modes were found, associated with the same central gap near the center of the plasma and having opposite polarizations. Both modes approach the Alfvén continuum with increasing pressure, the upper mode arriving first. These results also agree qualitatively with the analytic predictions.

Because the new core-localized mode at the high end of the gap has negligible radiation damping, it may be experimentally observable at moderate beta values when the lower mode is suppressed by radiation damping.

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2D46

Noncanonical Hamiltonian Perturbation Theory*

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Using the rigid body as a prototype, we develop a formalism of Hamiltonian perturbation theory for *noncanonical* Hamiltonian systems. Typically, to study the behavior of a system about an equilibrium of interest, one considers the linearized theory about that equilibrium. In canonical perturbation theory, the nonlinear corrections to this linear theory arise soley from the Hamiltonian. By contrast, in a noncanonical Lie-Poisson system, the cosymplectic form (Poisson bracket) contributes to the nonlinear corrections. Since the rigid body has a Lie-Poisson type bracket it is an appropriate "toy" model which captures the salient features of Eulerian theories of matter[1] such as those of plasma physics (*e.g.*, the Vlasov–Poisson equation and MHD) and inviscid fluid dynamics.

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Theory of Parametric Decay of Fast Waves With Finite Pump Wavelength

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In DIII–D fast wave current drive experiments, it appears that there is a certain amount of parasitic absorption in the edge region competing with the bulk plasma absorption which is strongly peaked at the core. When the bulk absorption mechanism is weak, this parasitic absorption is particularly evident and can become dominant [1]. During experiments, parametric decay spectrum was routinely detected, and an inverse correlation between bulk heating and the parametric decay amplitudes was established [2]. Thus, parametric decay is a prime candidate for parasitic absorption. A dipole pump approximation was commonly used in the theory of parametric decay of fast waves. In this approximation, the wave number of the pump wave is assumed to be negligible. In this work, we present a theory of parametric decay with finite pump wave numbers. The formulation closely follows and extends the classical dipole approximation so that in the limit of zero pump wave number, dipole theory is recovered. We show that finite wave number effect can be important in the electron drift as well as in the matching of parallel wave numbers. It can be shown that, at densities and temperatures characteristic of the tokamak edge, these corrections are nontrivial. Analytical and numerical results of growth rates will be presented and compared with dipole theory. Work to correlate with experimental observations is in progress.

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Poster presentation requested

K-ε Modelling of Compressible Neutral Gas Turbulence on a Heat Front in the Divertor Region

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It is well known that (i) the projected localized heat loads on the first wall and divertor plate in ITER-like tokamaks poses a severe problem, and (ii) turbulent transport coefficients are orders of magnitude greater than the corresponding laminar coefficients.

Here we investigate the role of turbulence in the neutrals in the divertor region in dissipating this heat load to acceptable values. It is important to note that one must treat the turbulence in 3D - since the energy cascade directions are totally different from those in 2D. This makes direct numerical solutions nearly impossible in realistic geometries of interest in divertor physics.

Reynolds and density-weighted (Favre) averages are taken of the conservation equations for compressible flow. For a two-equation model, the Reynolds stress tensor τ_{ij} takes the usual Boussinesq form and one determines evolution equations for the turbulent kinetic energy K and the turbulent dissipation rate ε. Closure is achieved for this turbulence model by resorting to ensemble average factorization and gradient transport hypothesis. A numerical code, *ISAAC*, solves the resulting set of equations in realistic geometries and has been benched-marked in aerodynamic situations with NASA experimental windtunnel data. Thus even when the mean flow is 2D, the 3D turbulence effects are being correctly handled in real geometries.

A strong temperature gradient (T_{max} = 1 eV, T_{wall} = 0.025 eV) is incident in toroidal cavity geometry with Mach Number = 1.2 and 1 torr pressure with a Reynolds No. R_e = 1770. We find a very substantial broadening in the temperature profile due to the turbulence as well as an increased heat flux to the toroidal walls as the pulse propagates down the cavity over the case when the flow is assumed laminar. This effect is just what one is looking for in reducing strong localized heat loads to the walls and divertor plate.

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Density Edge Localized Mode in Rotating Plasmas

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The paper presents a linear analysis for the density edge localized mode with realistic tokamak edge plasma and electric field profiles. The mode is localized by the density pedestal. It is unstable under the observed levels of sheared plasma rotation because of its narrow radial width. Its mode frequency, growth time, poloidal mode number, and direction of rotation are all found to be comparable to those of the precursors for small (Type III) edge localized modes (ELMs) observed in DIII-D and ASDEX. We conclude that the density edge localized mode is a promising candidate for the precursors.

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Lattice Boltzmann Approach to Temperature Driven Turbulence

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Lattice Boltzmann (LBE) techniques are proving to be an excellent tool to solving nonlinear macroscopic problems in realistic geometries. LBE methods are ideal for parallel processors [in dedicated SPP runs on the 16-processor C90, our 2D thermo-LBE code has a 15.37 CPU/wallclock time ratio at 600 MFlops] and can readily handle real geometries because of the utilization of the 'molecular' collision rules.

Given a set of nonlinear macroscopic equations, one derives a model linear kinetic equation with a Krook-like collisional relaxation such that on using Chapman-Enskog techniques one recovers the given macroscopic system on taking appropriate moments.

Here, we consider the effect of 2D velocity shear turbulence on a sharp temperature gradient in periodic geometry. Considerable difference occur in the vortex structure due to the presence of the initial temperature gradient as it is smoothed out by the turbulence.

Work has also begone on a 3D TLBE code [which has been timed at 15.01 CPU/wallclock and 538 MFlops - but with no i/o slowdown].

LBE codes (both for 2D fluid dynamics and 2D MHD) have been developed[1] and benched-marked against the standard spectral codes.

Theoretical work is now centered on the role of higher order nonlinearities[2,3] introduced in the moment equations of LBE due to the chosen form of the relaxed state distribution function. Methods have been devised that eliminates these spurious terms (which seem to play an important role for high Mach number flows). On the otherhand, renormalization group (RNG) theory[4] of fluid turbulence has indicated that cubic nonlinearities are a natural byproduct of the renormalized moment equation and play an important role in determining the transport coefficients. Thus, with generalized relaxed state distribution functions, it is hoped to be able to accurately model these RNG-induced cubic nonlinearities.

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Accessibility of High-ℓ_i, High-β Advanced Tokamak Operational Mode

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The goal of advanced tokamak operation is simultaneous achievement of high beta and high confinement in a steady-state discharge. Discharges with peaked current profiles produced by rapid elongation ramp and/or current ramp on DIII–D and other tokamaks show improvement in confinement relative to conventional empirical scaling. The confinement enhancement over L–mode scaling, $H = \tau_{\mathrm{E}}/\tau_{\mathrm{E}}^{\mathrm{ITER89P}}$, is proportional to the internal inductance ℓ_i. The MHD stability database on DIII–D also indicates that in the first stability regime the maximum achievable normalized beta scales with ℓ_i, $\beta_{\mathrm{N}} = \beta\,(\%)\,B_{\mathrm{T}}\,(\mathrm{T})\,a\,(\mathrm{m})/I\,(\mathrm{MA}) \leqslant 4\,\ell_i$. While these experiments are transient in nature, they suggest a possible high-ℓ_i high-β advanced tokamak operational mode provided auxiliary heating and non-inductive current drive can sustain the peaked current profile in the core of the discharge; current in the outer region of the discharge would be supported by the neoclassical bootstrap effect. The broad profile of the bootstrap current, coupled with the fact that the central safety factor $q(0)$ cannot be arbitrarily small, limits how large ℓ_i can be in a steady-state high-β discharge. A heuristic analytic model based upon a large aspect ratio approximation predicts a maximum ℓ_i of 1 to 1.2. Results of numerical studies in realistic tokamak geometry will be compared with the analytic prediction.

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Poster presentation requested

Abstract for the Intenational Sherwood meeting, Lake Tahoe , CA. April 3-5, 1995

Experimental data for edge model validation

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A large extrapolation is required from existing tokamak experiments to the ITER reactor design. Thus it is important that we have models to predict ITER conditions and that these models are validated over as wide a range of operating conditions as possible. Edge modelling is of particular importance because it is a critical area for the engineering design and because we are still at a primitive stage in our understanding of the complexities of the 3-dimensional structure of the edge. Since the amount of experimental data which can be obtained is limited it is important to ask the question, what are the most important data required to validate the models? This question needs to be addressed by theoreticians and experimentalists jointly to decide what is the best use that can be made of existing facilities.

In this talk the range of experimental data available either now or in the near future will be reviewed. Some attempt will be made to address the question of whether it is sufficient to test existing models and to discuss data that are desirable but not yet available. Four main topics will be considered: the description of the plasma and plasma edge transport, the neutral density distribution, the impurity transport from the plasma boundary to the core and the phenomenon known as divertor detachment. Emphasis will be placed on the results from the Alcator C-Mod tokamak, where high density, high power in the SOL and divertor geometry come close to simulating the expected conditions in the ITER divertor.

Measurements of radial profiles of n_e and T_e at two points along field lines are now available. From these profiles estimates of cross field transport coefficients can be made.Using simple 1-D models of parallel conduction also enables this data to be interpolated to obtain n_e and T_e at all points on the field line. Additional data from edge Thomson scattering systems will soon be available on both DIII-D and C-Mod. Having obtained estimates of n_e and T_e the neutral density distribution can be unfolded from the local Hα emissivity, now available from the deconvolution of arrays of H_α detectors. The use of the neutral density should in principle allow estimates of the spatial distribution of the ion source function and the local flow velocity. Injection of impurities at different points in the boundary is yielding data on impurity transport.

Divertor detachment is characterized by a sudden reduction in n_e and $T_e$at the target relative to the value upstream. The extent of detachment depends on the amount of power crossing the separatrix and on the geometry of the divertor target relative to the strike point. It is also correlated with the neutral density measured in the divertor. Experiments showing how the critical density for detachment can be lowered by low Z impurity injection will be described.

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Kinetic Modeling of SOL Plasmas

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Kinetic effects play an important role in the transport of particles and heat in the diverted scrape-off layer (SOL) of a tokamak. This occurs when the mean free path of energetic electrons or ions (at roughly three times the thermal velocity) is comparable to the scale length of the parallel temperature gradient. To treat this problem, we have developed the Fokker-Planck Edge Transport code (FPET), a fully kinetic parallel transport code which solves for $f(v_\perp, v_\parallel, z)$, the gyro-averaged distribution function along the magnetic field line. For the case of a fixed ion background, the code accurately recovers classical electron transport in the short mean free path regime, when $\lambda_{\rm MFP}/L_{\rm T} \lesssim 5\times 10^{-3}$. Here $\lambda_{\rm MFP}$ is the mean free path of thermal electrons and $L_{\rm T}$ is the temperature gradient scale length. For larger temperature gradients, FPET calculations of the electron heat flux show a departure from classical transport theory, as expected from earlier Monte Carlo simulations, which indicated the presence of a "flux limit" [1,2]. In this case, the electron distribution function near the target plate has an exaggerated high energy tail due to parallel convection from the hotter plasma upstream. This gives rise to an increase in the sheath potential and, therefore, the sheath energy transmission factor. Furthermore, the non-Maxwellian tail leads to a dramatic increase in the local rate coefficients for impurity ionization in cases when the ionization potential I is much larger than the local temperature of the bulk electrons (*i.e.*, when $I \gtrsim 10\,T_{\rm e}$). Comparisons are made between FPET results and various local (and non-local) fluid transport models. In these comparisons, we specify the temperature at the target, the total heat flux, and the parallel current density, but the temperature profile and the electrostatic field are allowed to evolve self-consistently. Comparisons are also made to available DIII–D data and UEDGE simulations. We present some initial results on coupled electron/ion kinetic simulations.

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Low Frequency Current Drive Utilizing Nonlinear and Spatial Inhomogeneity Effects*

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Conventional current drive schemes are generally based on the interaction of a select group of charged particles with neutral beams or plasma waves[1]. Making use of the fact that plasma acts as a fluid at low frequencies, this paper self-consistently explores a variety of new and nontraditional low frequency current drive mechanisms. The fundamental goal is to show that plasma nonlinearity, spatial inhomogeneity and geometry play critically important roles in steady-state current production at low frequencies. These factors give rise to a host of new macroscopic phenomena that can be effectively utilized in current drive schemes. Many of these phenomena only emerge from a fully self-consistent treatment, and are not addressable by standard quasi-linear techniques.

The first new current drive mechanism that is treated in the paper is based on a certain class of low-β, low frequency, nonlinear waves[2]. These include one dimensional solitary waves as well as two dimensional forced waves. Each shares the interesting characteristic that the wave structure has a d.c. current in the steady-state. This paper describes the characteristics of these waves in detail and addresses issues related to their excitation. Steady-state currents can also be produced in a plasma by nonlinear mixing of linear Alfvén waves[3]. The characteristics of the steady-state current produced in this manner are strongly dependent on geometry. To keep the solutions analytically tractable and still retain finite geometry effects, the paper studies nonlinear wave mixing in a bounded plasma slab surrounded by current sheet antennas. It is demonstrated that sufficiently large steady-state currents can be generated in this manner using waves with modest amplitudes.

Spatial inhomogeneity of the plasma medium introduces additional mechanisms that can either generate steady-state currents on their own or enhance the current that has been produced by other means. One such mechanism is the resonance associated with Alfvén waves in an inhomogeneous plasma. This paper shows that steady-state current produced via nonlinear wave mixing is significantly enhanced in the vicinity of the Alfvén resonance layer in a plasma with both resistivity and viscosity. The current also increases with a reduction in dissipation, which is an attractive scaling as far as large tokamaks are concerned. Quasi-steady currents can also be generated when waves undergo shearing in an inhomogeneous plasma[4]. This effect is opposite to that of dissipation. It is demonstrated in the paper using the example of finite amplitude Alfvén waves.

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1995 International Sherwood Fusion Theory Conference, April 3-5, Incline Village, NV

Alfven Instability and Edge Plasma Physics in TFTR*

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Abstract

An Alfven frequency mode (AFM) is often seen in TFTR neutral beam heated plasmas characterized by quasi-coherent peaks observed in the frequency spectrum of Mirnov coils. The best toroidal mode number obtained is $n = 0$. The mode amplitude is $\tilde{B}_\theta \lesssim 8 \times 10^{-4}$ Gauss ($\tilde{B}_\theta / B_0 \lesssim 10^{-8}$). Due to its amplitude enhancement seen in the high fusion power DT plasmas, this mode has been considered as a candidate of the alpha-driven TAE mode. Recently, more detailed data analysis shows that the AFM is localized near the plasma edge ($r/a > 0.8$). The observation of the mode location clarifies many puzzles previously related to this mode. For example, this mode has very weak interaction with sawtooth, fishbone and tearing mode activities, but has very strong interaction with H-mode transition, ELMs and gas puff and impurity influx (or edge plasma recycling). Also, the AFM can be excited in the Ohmic discharges after a pellet injection. The calculated edge Alfven frequency ($\omega_{Alfven} = V_A/qR$) from the TRANSP code agrees well with the AFM frequency. The statistical data analysis shows that the AFM amplitude is proportional to the plasma edge density and q, and inversely proportional to plasma current. The observed amplitude enhancement during a DT discharge can be mainly attributed to an increase in the edge recycling.

The strong interaction between the AFM and ELMs can be used as a new tool to study the H-mode and plasma edge physics. Some interesting observation will be discussed. At present, there is no theoretical explanation of the driving mechanism. Discussions on the TAE gap structure, instability threshold and scaling will be presented.

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Off-Axis Electron Cyclotron Current Drive in ITER

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Electron cyclotron (EC) waves can provide current drive in ITER at efficiencies as great as $\gamma = 0.3$ [10^{20} A/(m^{2}W)] [1]. This is obtained for a full toroidal field ITER equilibrium for O–mode at 220 GHz, with toroidal launch 40° from perpendicular in the outside equatorial plane of the tokamak. The driven current is peaked near the magnetic axis ($0.2\,a$). As the toroidal launch angle is further increased to 50 deg, the current drive (CD) shifts outwards to $0.45\,a$, and efficiency decreases to 0.15. These results are obtained in a 30 keV plasma, using the TORAY code combined with the CQL3D [2] Fokker-Planck/rf quasilinear code. An extensive survey of off-axis current drive will be reported.

The possibility of enhancement of the off-axis ECCD efficiency by electron tail formation, similar to lower hybrid tail formation, is being studied. Simple models of purely perpendicular and parallel quasilinear diffusion have been added to CQL3D. For a flux surface at $0.75\,a$, it was found that perpendicular diffusion in the region of velocity space $v_\parallel = [4\,v_{\mathrm{Te}}, 7\,v_{\mathrm{Te}}]$, $v_\perp = [0., v_{\mathrm{Te}}]$ produces an efficiency enhancing tail much like the lower hybrid-like tail produced by parallel diffusion in the same region, and with 80 percent as efficient current drive. Consideration of the full tokamak geometry shows that a plateau can be formed, starting at a given flux surface, by combined outside launch of EC power at multiple frequencies and launch angles.

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‡ Princeton Plasma Physics Laboratory (currently seconded to ITER, San Diego).

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Poster presentation requested

Collisionless Magnetic Reconnection in Well–Confined Plasmas*

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Magnetic reconnection processes under collisionless conditions are of great relevance to space plasmas and to magnetically confined laboratory plasmas. Their occurrence in laboratory plasmas gives the possibility of testing the theoretical models that can be formulated. The effects of electron inertia, in both space plasmas and in experiments carried out by the TFTR machine at record high values of the electron temperature ($T_{eo} > 10$ keV), introduce very short spatial scales that have been shown to be insufficient to explain a realistic rate of reconnection and width of the region over which it takes place [1]. In TFTR, we refer in particular to the modes with dominant poloidal and toroidal mode numbers $m = 4$, $n = 3$ and $m = 3$, $n = 2$, whose excitation must necessarily involve magnetic reconnection. The existence of these modes leads us to postulate that a state of microscopic turbulence must pre-exist the triggering of the macroscopic instability. In particular, we assume that the turbulence introduces a diffusion of the longitudinal electron momentum. In the case when the electron temperature is much lower than the ion temperature, as in TFTR, the predicted real frequency becomes $\omega \simeq (1/3)\omega_{*i}^{p}$, the ion diamagnetic drift frequency, and the growth rate becomes $\gamma \simeq (\mathcal{L}_*(\omega_A')^2/a_J^2)^{1/3} I_o^{2/3} > \omega$, where $\mathcal{L}_* = D_*(c/\omega_{pe})^2$ and D_* is the turbulent diffusion coefficient for the electron longitudinal momentum, $a_J = 1/\Delta'$ is the inverse of the mode driving factor, $(\omega_A')^2 = (\mathbf{k}\cdot\mathbf{B})'^2/4\pi n m_i k^2$, and I_o is a numerical coefficient. The layer width is then $\delta_R \sim (\mathcal{L}_*/\omega_A')^{2/9} a_J^{-1/9}$. The mode is expected to be relatively well localized to the center of the plasma, inside the corresponding rational surface, although toroidal effects may extend it beyond this radius. Interaction with a fast ion population, created for example by neutral beam injection, via the resonance $\omega \simeq \omega_{Di}(\mathcal{E}, \mu)$, the precession drift of the fast ions, can scatter the fast ions out of the center of the plasma, by a mechanism similar to that for $m = 1$, $n = 1$ fishbone modes.

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Neutral Transport Modeling of the DIII-D Divertor with DEGAS 2*

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DEGAS 2 [1] is a Monte Carlo neutral transport code used to simulate tokamak divertors and other plasma devices. In this paper, we describe the application of DEGAS 2 to the DIII-D divertor. This is in preparation for coupling DEGAS 2 to the UEDGE fluid plasma code.

These simulations will be carried out with a minimal set of atomic physics reactions. A general mechanism for treating the atomic physics is presently being designed and incorporated into the code. The input format for the reactions and their associated data (cross sections, rates, as well as higher moments) has already been established. In conjunction, a stand-alone package has been developed to extract data from the IAEA Atomic and Molecular Data Information System in the ALADDIN format [2], compute the required reaction rates, and write the results into netCDF files which can be read by DEGAS 2.

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*This work is supported by the U.S. Department of Energy under Contract No. DE–AC02–76–CHO–3073.

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Sawtooth Stabilization and Triggering of High-β Disruptions in TFTR[1]

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TFTR experiments have challenged MHD theory in the explanation of sawtooth stabilization in supershots and the occurrence of high-β disruptions, which have only a very short precursor, if any. While conventional MHD fails in explaining both phenomena, the two-fluid nonlinear analysis of collisionless reconnection has led us to a new concept which describes the sawtooth stabilization in variety of TFTR regimes, including both DD and DT plasmas, irrespective of the plasma current or NBI and ICRH heating. Now, this concept also gives us a consistent picture of the events leading to the "abrupt" disruptions in TFTR:

- As the central β reaches the level determined by the criterion
$$1.4\beta_{1/1}^{2/3}\left(\frac{m_i}{2Z_{eff}m_p}\right)^{1/6}\left|\frac{n'R}{n}\right|_{1/1}^{2/3}\left|\frac{p'R}{p}\right|_{1/1}^{1/3} > q'r_{1/1}$$
sawtooth oscillations become stabilized by nonlinear ω_*-effects.

- While the ideal $m = 1$ mode (coupled toroidally with other modes) is unstable in this state, it exhibits itself only as a saturated $m = 1$ perturbation inside the $q = 1$ surface and disturbs the pressure profile
$$\xi = \xi(r)\cos(\theta-\phi), \quad p = p(r+\xi\cos(\theta-\phi)).$$
The pressure gradient is thereby significantly enhanced in the singular layer at the $q = 1$ surface
$$p' = p'_r[1+\xi'\cos(\theta-\phi)], \quad \xi' \simeq 1$$

- When the pressure gradient reaches locally (in both radial and azimuthal directions) the ballooning threshold, the high-m/n modes are excited.

- Ballooning modes at the $q = 1$ surface presumably destroy the local pressure gradient $p' \propto \omega_*$ needed to stabilize the $m = 1$ mode, and thus trigger a large sawtooth crash and major disruption.

Although many details of the theory need to be elaborated, this theoretical picture may provide a useful guide for disruption avoidance schemes.

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Theory and Simulations of Fluctuation Reflectometry in Multi-Dimensional Inhomogeneous Plasmas *

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In order to resolve the localization paradox of fluctuation reflectometry, we have performed analytic calculations and numerical simulations of microwave scattering caused by density fluctuations in multi-dimensional inhomogeneous plasmas. S-Polarized O-modes are used in this work, and the density fluctuations are represented by localized wavepackets with one or more modulation wavenumbers. In the simplest case, the background density profile is inhomogeneous in one direction only but the density fluctuations have 3-D structure. By moving the location and orientation of the fluctuations with respect to the illumination field, we can identify the 3-D nature of the influence of a given fluctuation packet on the scattering phase shift.

When the finite extent of the microwave source and receiver antennae is taken into account, additional interference phenomena are identified, besides the usual 1-D Bragg scattering picture,[1] which tend to make the reflected signal appear to be emanating from a highly spatially localized region. These path-length-difference induced interferences may be a contributing factor to the experimentally observed localization paradox, where correlation reflectometry is used to gauge the differences between signals received at slightly offset frequencies, which presumably would have arisen from scattering events taking place at slightly offset densities.

The analytic calculations are based on the Born approximation and background density models which are tractable (separable, smooth, etc.). Asymptotic techniques are used to evaluate the multidimensional integral representations for the phase shifts, thus generalizing the Bragg resonance picture to multi-dimensional inhomogeneous plasmas.[2]

* Performed by LLNL for USDoE under Contr. W-7405-ENG-48

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Enforcement of Quasi-Neutrality and Momentum Conservation Using a δf Monte Carlo Code

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We have developed a Monte Carlo code which efficiently calculates the ion and electron bootstrap and Pfirsch–Schlüter currents given the magnetic field strength $B(\theta,\phi,\psi)$, the toroidal and poloidal currents $g(\psi)$ and $i(\psi)$, and the rotational transform $\iota(\psi)$ with θ and ϕ the poloidal and toroidal angles and ψ the toroidal magnetic flux enclosed by a pressure surface. We calculate the deviation δ of the distribution function $f \equiv F_M(\psi,H) + \delta(\partial F_M/\partial\psi)_H$ from the Maxwellian, with $H = mv_{\|}^2/2 + \mu B + e\Phi(\psi,\theta,\phi)$ the drift Hamiltonian, by solving $d\delta/dt + \mathbf{v}_{\mathrm{g}} \cdot \nabla\psi = C_L(\delta) - \nu u B\lambda/v_{th}$, with $\mathbf{v}_{\mathrm{g}}$ the guiding center velocity, C_L the Lorentz collision operator, ν the collision frequency, B the field strength and $\lambda = v_{\|}/v$ the pitch. The flow velocity u gives momentum conservation; $u = 3v_{th}/2B \int \lambda\delta d\lambda = 3j_{\|}/eB = 3/e\left[\langle j_{\|}/B\rangle + 2\sum'_{m,n}\langle j_{P.S.(m,n)}/B\rangle e^{i(n\phi-m\theta)}\right]$, where $j_{\|}/eB$, the local parallel current, is Fourier decomposed in θ and ϕ with the first term corresponding to the bootstrap current and the summation corresponding to the various components of the Pfirsch–Schlüter current. The kinetic equation is solved by starting a large group of particles in a narrow ψ annulus and following their drift trajectories. During each time step, δ is updated using $\Delta\delta = -\int(d\psi/dt + \nu u B\lambda/v_{th})dt$. Then a Monte Carlo equivalent of C_L is used to change the pitch of each particle.

We are studying the variation of the electrostatic potential within the surface due to the enforcement of quasi-neutrality. The density fluctuations on the magnetic surface for each species are Fourier decomposed in θ and ϕ; $(\Delta n/n)_s = \sum_{n,m}(N_{n,m})_s e^{i(n\phi-m\theta)}$ with $(N_{m,n})_s = \int \delta_s e^{i(n\phi-m\theta)} d\theta d\phi$. The electron deviations from the home flux surface are in general much smaller than the ions deviations and can be approximated by the Gibb's distribution $(\Delta n/n)_e = e^{(|e|\Phi(\psi,\theta,\phi)/T_e)}$. This gives a Fourier representation for the electrostatic potential. The quasi-neutrality condition can then be explicitly enforced by inserting $\Phi(\psi,\theta,\phi)$ with $(N_{n,m})_i$ into the Hamiltonian for the next iteration and calculating $(\Delta n/n)$ and $\Phi(\psi,\theta,\phi)$ again. Repeating this procedure will eventually force $(N_{m,n})_i = (N_{m,n})_e$ thereby explicitly enforcing the quasi-neutrality condition. Some preliminary results for non-axisymmetric systems indicate enhanced transport across the magnetic flux surface when the quasi-neutrality condition is explicitly enforced.

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HIGH POWER RADIATIVE DIVERTOR SCENARIOS FOR ITER AND TPX

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The scrape-off layer and divertor plasma in ITER and TPX is modelled using the B2.5 code. For the case of ITER, it is required to introduce a radiating impurity in order to reduce the divertor heat load to an acceptable level. We have investigated neon and argon as candidate recycling impurities. In order to radiate most of the power in the divertor it is found necessary to operate at an edge density of around $6.0 \times 10^{19}/\mathrm{m}^3$ and an edge neon concentration of about 1% or an edge argon concentration of about 0.5%; this is when cross-field transport is modelled by a particle diffusivity of $0.5\,\mathrm{m}^2/\mathrm{s}$ and electron and ion heat diffusivities of $1.0\,\mathrm{m}^2/\mathrm{s}$. In order to decide whether this scenario is acceptable it is necessary to investigate further the role of core plasma radiation, and to understand the scrape-off plasma power threshold for H-mode confinement.

For the case of TPX we concentrate on the high-power scenarios, having 45 MW power input into the plasma. Without impurities, in order to arrive at a divertor peak power load below 12 $\mathrm{MW/m}^2$ normal to flux surfaces, it is necessary to assume an unrealistically high edge density of above $1 \times 10^{20}/\mathrm{m}^3$. On the other hand, when 0.5% neon is included in the calculation we obtain power load below 12 $\mathrm{MW/m}^2$ (normal) at an edge density of $6 \times 10^{19}/\mathrm{m}^3$; for 1% neon the required edge density is about $4 \times 10^{19}/\mathrm{m}^3$.

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Poster presentation

HAMILTONIAN DESCRIPTION OF TOROIDAL MAGNETIC FIELDS IN VACUUM

by
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1995 International Sherwood Fusion Theory Conference
April 3-5, 1995

Abstract

It is well known that the flow of magnetic field lines constitutes a Hamiltonian system. Based on this fact, an investigation of vacuum magnetic fields in toroidal geometry has been initiated. In previous work by Cary,[1] the general form of the magnetic scalar potential for vacuum magnetic fields regular at the poloidal axis was given. In the present study, Cary's results have been expanded to obtain the magnetic scalar potential in a vacuum region that may surround a toroidal current distribution. Using this generalized magnetic scalar potential in conjunction with Boozer's canonical representation of a magnetic field,[2] a field-line Hamiltonian for nonaxisymmetric vacuum fields has been derived. In the case of axisymmetry, a simple transformation to canonical coordinates has been found which permits the explicit construction of a field-line Hamiltonian. Examination of nonaxisymmetric fields using a perturbation theory based on Lie transforms is in progress. In addition, recent results in Hamiltonian mechanics [3,4] – which permit any magnetic field to be expressed in terms of a specified field-line invariant – are being explored for their utility in this problem.

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Robust Multivariable Shape and Stability Control for ITER

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The nominal approach to shape and stability control design for the present ITER EDA outline configuration involves multivariable adjustment of the voltage applied to six poloidal field (PF) coils to regulate the spacing of six plasma-wall gaps. Achievement of adequate performance with such multivariable plasma control algorithms requires highly reliable plasma response models and some measure of robustness in the design. The present study describes plasma models, controller designs, and control scenario simulations for a fiducial ITER end-of-burn (EOB) plasma equilibrium. A nonrigid, flux conserving, linear plasma response model implemented in the Corsica code and based on trial function minimization of the ideal MHD Energy Principle is used for the design. Corsica is a time-dependent, resistive axisymmetric MHD and transport simulation code which includes constrained equilibrium, linear vertical stability, and ballooning mode packages. Validation results for the response model are presented. Controller designs based on this model and derived using linear quadratic Gaussian (LQG) and robust methods are presented along with results of time-dependent simulations. In linear simulation the LQG controller is demonstrated to provide 95% settling times below 5 seconds for all gaps. PF coil power supply voltage demands are found to be below 6 V for restoration of an initial condition corresponding to finite-time growth of the unstable mode with maximum initial gap displacement of 10 cm. Maximum power demand for this scenario is found to be 40 MVA in the highest-demand coil (PF2), and 65 MVA for the sum of all active shape-controlling PF coils. Linear and nonlinear time-dependent simulation of the closed-loop response using the Corsica code demonstrates adequate nominal stabilization and gap regulation following a 1 cm vertical displacement of the magnetic axis or a 25% beta-collapse.

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Toroidal Momentum Input to Tokamak Plasmas from Alpha Particles or Neutral Beams

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Analytical calculations are presented of the momentum input to a tokamak plasma from fusion alpha particles or neutral beams. The transfer of toroidal angular momentum from the fast ions to the thermal ions and electrons takes place either by $j \times B$ forces involving the plasma return current response to the fast ion radial current, or by collisional friction. These are closely related, because of canonical angular momentum conservation. Four distinct contributions to toroidal torque have been identified: (1) a transient current, (2) a frictional current, (3) zeroth-order frictional torque, and (4) first-order frictional torque, where the order refers to an expansion in the poloidal gyroradius. In the case of alpha particles, contributions (2) and (4) cancel exactly, contribution (3) is absent (neglecting prompt losses), and contribution (1) is zero in a steady-state. Consequently, the toroidal angular momentum transferred to a plasma from the birth of alpha particles is too small to affect MHD stability or microturbulence. If prompt losses are allowed, a significant amount of toroidal angular momentum can be transferred, but the efficiency is much less than low energy neutral beams. That is, much more power is lost by alphas for a given torque than would be required by neutral beam injection. The differences between neutral beam and alpha particle momentum injection will be discussed, in particular the effect of directed versus isotropic injection, the role of pitch-angle scattering, and the existence of transient currents.

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Poster presentation requested

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Linear Stability of MHD Modes in Toroidally Rotating Tokamak Plasmas

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A self-consistent computational study of the effect of toroidal plasma rotation on the stability of the MHD modes in tokamaks is presented. This work is motivated by experimental observations that toroidal rotation has been found to be crucial for tokamak stability yet is usually ignored in the conventional MHD analysis, resulting in some apparent discrepancies.

In our self-consistent study, the MHD equilibrium (including the effect of toroidal flow) is obtained from the solution of the generalized Grad-Shafranov equation. The stability problem, which is a non-self-adjoint eigenvalue problem in the growth rate, is solved by a generalization of the MARS code [1].

Computational results show stability of the plasma is affected most by the Doppler shift of the rotation frequency at different resonant flux surfaces. Systematic results have been obtained for the resistive wall mode present for ideally unstable plasmas enclosed by an external resistive wall. At high beta, the general stability diagram shows interesting structures not predicted by the usually assumed simple cubic. The code has also been applied to DIII–D experiments. Using realistic density, pressure, and rotation profiles obtained from detailed equilibrium reconstruction, numerical computations give stability predictions in agreement with observation.

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Poster presentation requested

3C13

Log-Additive Parameterisation of JET Electron Temperature, Density and Pressure Profiles†

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We parameterise the electron temperature, density and pressure profiles as measured by the LIDAR Thomson Scattering Diagnostic of the Joint European Torus for different confinement regimes to obtain scaling-law like expressions for the profile shapes. We adopt simple log-additive models assuming that the profiles can be represented as functions of the normalised flux radius $\bar{\Psi}$ and the plasma parameters $(I_p, B_t, q_{95}, \bar{n}, V_{\mathrm{loop}}, Z_{\mathrm{eff}}, \kappa, \ldots)$: $\ln[n, T, p(\bar{\Psi})] = f_0(\bar{\Psi}) + f_1(\bar{\Psi})\ln[I_p] + f_B(\bar{\Psi})ln[B_t] + \ldots$. The fit functions $f_1(\bar{\Psi})$ are estimated using smoothing splines. The statistical analysis is performed on large sets of L-mode, H-mode and Ohmic data using a penalised least squares regression technique. The Rice selection criterion is used to determine which of the parameters to include in the models. The density profiles are normalised to the line average density $\bar{n}$, the temperature profiles are fitted both in shape and in absolute value. We find it is necessary to use different parameters to fit the profiles in the different confinement regimes. The normalised Ohmic density profile depends primarily on $\bar{n}/B_t$, with a weak dependence on I_p. The profile broadens if either parameter increases $\bar{n}$ and κ are the most important parameters for describing the L-mode normalised density profile. For higher $\bar{n}$ the profiles flatten, while for higher κ the L-mode density profile decreases rapidly near the edge. I_p is the most important parameer for the normalised H-mode density profile, with a weaker dependence on κ. For high I_p the density profiles become hollow, while increasing κ extends the flat reginon of the profile, resulting in sharper edge gradients. The Ohmic temperature profile depends primarily on I_p, B_t, $\bar{n}$ and q_{95}, where q_{95} really represents the geometric part of the safety factor as the I_p and B_t dependence are already accounted for. For the temperature profiles we often find that $f_i(\bar{\Psi}) =$ constant with acceptable precision, which means that this parameter influences the magnitude but not the shape of the profile. The L-mode temperature shape can be modelled using only a B_t dependence, with the magnitude depending on P_{aux} and $\bar{n}$. The result can be interpreted as $T_e^{\mathrm{L-mode}}(0) \sim$ (Power per particle)$^{1/3}$. The H-mode temperature shape depends primarily on q_{95}, with the magnitude depending on Z_{eff}, P_{aux} and I_p. The power exponent is small: $T_c^{\mathrm{H-mode}}(0) \sim P_{\mathrm{aux}}^{12}$, showing that when the H-mode power threshold is exceeded, additional heating only weakly increases the temperature. Results for pressure profile shapes will also be presented.

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3C14

A Comparison of Monte Carlo and Fluid Approaches to Neutral Transport Modeling in Tokamak Edge Plasmas*

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It is crucial that the neutral transport model used to predict the performance of the divertor in next-step devices such as ITER be as accurate as possible. Here we consider two different numerical approaches to neutral transport modeling: Monte Carlo [1] and fluid [2]. Although Monte Carlo methods allow flexibility in the problem geometry and the physics to be included, they may not be very efficient for dense plasmas. Moreover, they presently are missing effects such as the coupling of ion-neutral heat flux and viscosity [2]. Also, reproducing the neutral-ion thermal force requires either that the mesh spacing Δ be much smaller than the neutral mean free path l or that the ion distribution function be interpolated within the mesh.

On the other hand, the validity condition for simple neutral fluid models $l \ll L$, where L is the plasma scale length, may be violated in some regions even in dense plasmas. Also, the treatment of boundary conditions at material surfaces for the neutral fluid equations can be problematic.

In this paper we present the preliminary results of a benchmarking of DEGAS [1] against the neutral fluid model described in Ref. [2]. A simple slab geometry of length L is used; the plasma density and temperature variations are prescribed. A fixed flux of hydrogen atoms through the slab is assumed. For simplicity, ionization is not included. The ratios l/L and l/Δ are varied.

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Thermal Bifurcation of Scrape Off Layer Plasma and Divertor Detachment

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Abstract

Models to investigate the main features of plasma - neutral interactions in the recycling region of a tokamak divertor are developed for the two opposite extremes of fluid and Knudsen neutrals. Both neutral models show that a reduction of the heat flux into the hydrogen recycling region, q_{rc}, below a critical value q_{rc} [MW/m^2] < 0.5 P_u [10^{20} m^{-3} 100 eV], leads to bifurcation of the plasma parameters near the target (P_u is the upstream plasma pressure). For small q_{rc} this bifurcation causes behavior in the scrape off layer which is in agreement with all of the main features of detached divertor regimes in current tokamak experiments: i) strong decrease of the plasma temperature near the target to about 1 eV, ii) plasma pressure drop in the recycling region, and iii) strong decrease of the target heat load and plasma flux onto the target. The physical mechanisms responsible for the decrease in the plasma flux onto the target and plasma pressure drop along magnetic field lines in the recycling region depend on the neutral gas regime of interest. For fluid neutrals, the neutral pressure influence on the plasma flow is responsible, while for Knudsen neutrals, friction between the plasma flow onto the target and the neutral gas scattered by the sidewalls causes these reductions. It is also shown that in the Knudsen limit, bifurcation causes a much stronger decrease of the target particle flux and heat load due to energy transport to the sidewalls by neutrals, and that the neutral density in the divertor region cannot exceed a maximum density, which is of the order of $1\text{-}2 \times 10^{13}$ cm^{-3} for current experiments.

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3C16

Linear electrostatic drift-kinetic PIC code for η-i modes in toroidal geometry

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Unstable drift modes could be responsible for anomalous transport in tokamaks We present a model which describes the linear physics of these modes in toroidal geometry, taking full banana effects into account. We believe that linear models, as opposed to fully nonlinear ones, are useful in several ways. Their numerical convergence is easier to obtain and their results are easier to interpret. They should permit to understand the characteristics of drift modes, and in particular to determine the stability conditions. They can be used both to map interesting regions in parameter space and to provide validation benchmarks for nonlinear codes.

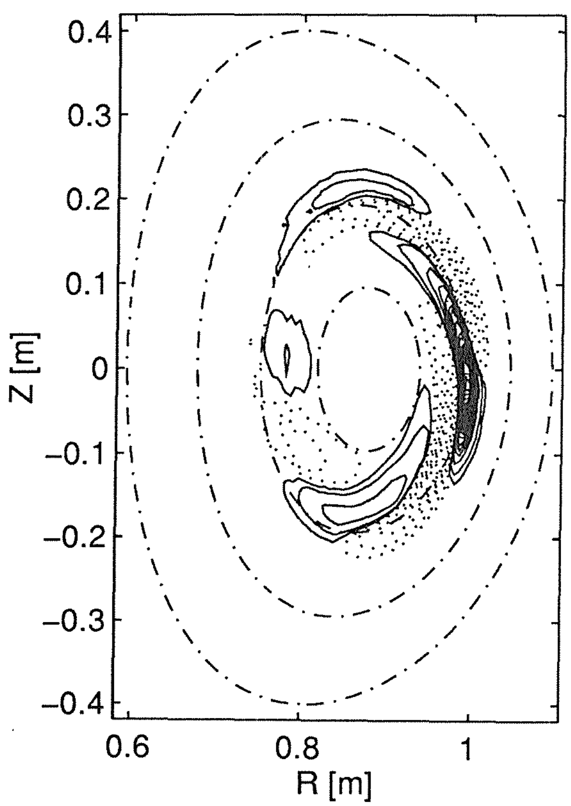
The code evolves in time a perturbation of an arbitrary equilibrium distribution using a linear Particle-In-Cell approach ("δf" type) with drift-kinetic particle ions, Boltzmann electrons and the quasineutrality condition. A Solovev MHD equilibrium provides the magnetic structure which determines the particle (i.e. guiding center) trajectories, including the full banana orbits. The three particle constants of motion are conserved exactly by the time integration scheme.

The perturbation is Fourier-expanded in the toroidal angle; one (complex) toroidal coefficient only needs to be retained. The resulting problem has therefore two dimensions in configuration space and the particles carry a complex weight. A Particle-In-Cell finite element formulation with bi-quadratic spline elements on a (Ψ,θ) i.e. (magnetic surface, poloidal angle) mesh is used and shown to be numerically stable.

The code runs efficiently on the CRAY-T3D massively parallel computer. It can be used to study η-i modes, which belong to the class of drift waves, in full toroidal geometry. The most unstable mode dominates after evolution from arbitrary initial conditions.

Unstable η-i mode

n=1, aspect ratio = 2.7, ellipt. = 1.6



1995 INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE

RF WAVE EFFECTS ON THE NEOCLASSICAL ELECTRON DISTRIBUTION FUNCTION IN TOKAMAKS*

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In advanced steady-state tokamak scenarios, a substantial fraction of the necessary plasma current will be provided by the bootstrap current. This current was initially predicted by the neoclassical theory of transport in toroidal plasmas [1], and is driven by the diffusion of electrons or ions against the plasma pressure gradient. We consider the possibility of enhancing the bootstrap current using radio frequency (RF) waves. The velocity-space distribution function for electrons at steady state is assumed to be gyroaveraged and independent of the toroidal angle. This distribution satisfies the drift kinetic equation, which includes radial drifts due to magnetic field gradient and curvature. RF waves are then included by adding a quasilinear diffusion operator [2] to the drift kinetic equation.The resulting bootstrap current is then found by taking the usual velocity-space moment of the RF-modified electron distribution. Solutions of the drift kinetic equation will be found analytically using several different techniques, including an expansion in small parameters. Different types of RF waves, including lower hybrid waves, fast Alfvén waves, and electron cyclotron waves, will be studied. The analytic solutions will be compared to numerical solutions of the drift kinetic equation.

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THE ISSUE OF INTERNAL MODES IN IGNITION EXPERIMENTS

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The regimes under which ignition conditions can be achieved have a rather well-defined set of characteristics that severely constrain the design parameters of the machines conceived to reach this goal [1]. The considered peak plasma pressures, for instance, range from $p_o \simeq 12 \times 10^{15} k_e V/cm^3$ for the Ignitor experiment [1] to $p_o \simeq 25 \times 1.5 \times 10^{14} keV/cm^3$ for the Iter concept [2]. To confine these pressures, considerable values of the mean poloidal field $\bar{B}_p$ have to be obtained. For this reason and in order to ensure the needed values for the confinement parameter $n\tau_E$, these devices have been designed with the capability of producing high plasma currents. We point out that it is not possible [1] to comply with the need to have high currents and low safety factors (such as $q_\psi < 3$ in the case of Iter) and at the same time satisfy the condition for ideal MHD stability against m = n = 1 modes when $q_o < 1$ and $\beta_p = 8\pi < p > /\bar{B}_p^2$ is relatively high, e.g. $\gtrsim 0.5$. To avoid this problem, the plasma pressure profile should be relatively flat over the entire radius where $q(\psi) \leq 1$, which can exceed half the plasma radius in the case of Iter and of Ignitor. Since the requirement on the flatness of the pressure profile cannot be prescribed with the needed reliability for a well confined plasma, a solution to this dilemma is to adopt high magnetic field technologies, as exemplified by the Ignitor experiment where ignition can be achieved with $\beta_p < 0.3$.

In the case of ITER, assuming $B_T \simeq 5.25T$ at $R = 8.1m$, $a \simeq 3m$, $I_p \simeq 22MA$, and $k \simeq 1.55$, we have $q_\psi \simeq 2.8$ at the edge of the plasma column and values of β_p which produce m = 1, n = 1 modes with such high growth rates that these modes are not affected by finite ion Larmor radius effects nor by the possible presence of a large α-particle population. This assumes also that the pressure profile is not flat within a/2. We note that even with $B_T \simeq 5.25T$ the value of the magnetic field at the inner edge of the toroidal cavity is quite high ($\simeq 12T$) given the state of superconductory technology. Another drastic option to be considered is to decrease the plasma current to the point where the q = 1 surface radius is relatively small (such as a/4, that is a typical value for regime of operation regime of TFTR with record high ion temperatures) or to the point where $q_o > 1$. On the other hand, if we take $q_\psi \simeq 4.2$ and $I_p \simeq 15MA$, for instance, β_p would become relatively high. Then another set of issues on the possibility to reach this regime, on the nature of confinement in the second stability region, etc. has to be dealt with. On the basis of these and other considerations, it appears that a good scenario for the fusion program is to separately develop the technology of high field superconductors, for use in future reactors, and, at the same time, to explore the physics of burning plasmas with the high field normal conducting technology that is available at present.

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

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On the Noise Response of Chaotic Systems

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The response of dissipative chaotic systems to substantial amounts of noise driving is considered. Two 2-D models, the Hénon ($(x', y') = (1 - ax^2 + by, x)$) and Ikeda ($(z' = a - bz exp(i\kappa - i\eta/(1+|z|^2)))$; z complex) maps, are examined. Additive noise ($\delta-$ correlated in time) is used to drive both systems. The noise response of these two systems is markedly different. The Hénon system, with its familiar horseshoe attractor, is unstable to even relatively small levels of noise due to the close proximity of the basin boundary (on the other side of basin boundary the system exits to infinity). The Ikeda system can, for certain values of the parameters, exhibit multiple attractors as well but the evolution of the system is bounded, hence it settles into a steady state even with large amplitude noise driving.

Both of these systems are *nonhyperbolic* , meaning that there exist points on the attractor where the stable and unstable manifolds of the orbit intersect tangentially [1]. The dynamics in the neighborhood of such points is structurally unstable, hence even small amounts of noise can produce substantial effects. It is believed that most chaotic systems are nonhyperbolic, but the literature on this topic is surprisingly sparse.

Two basic issues are considered: a) how to find 'minimum bias' partitions, *i.e.* partitions of the 2-D plane such that the symbol sequence statistics is least affected by noise [2,3]; and b) the role of invariant manifolds of the deterministic system in guiding the noise response of the driven system. (See [4] for a discussion of related issues in Hamiltonian systems.)

The authors would like to acknowledge very helpful discussions with X.-Z. Tang and Michael Lane. Andrew Joshua and Michael Lane were supported by the NSF Research Experience for Undergraduates (REU) program.

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Can Inertial Electrostatic Confinement Work Beyond the Ion-Ion Collisional Time Scale?*

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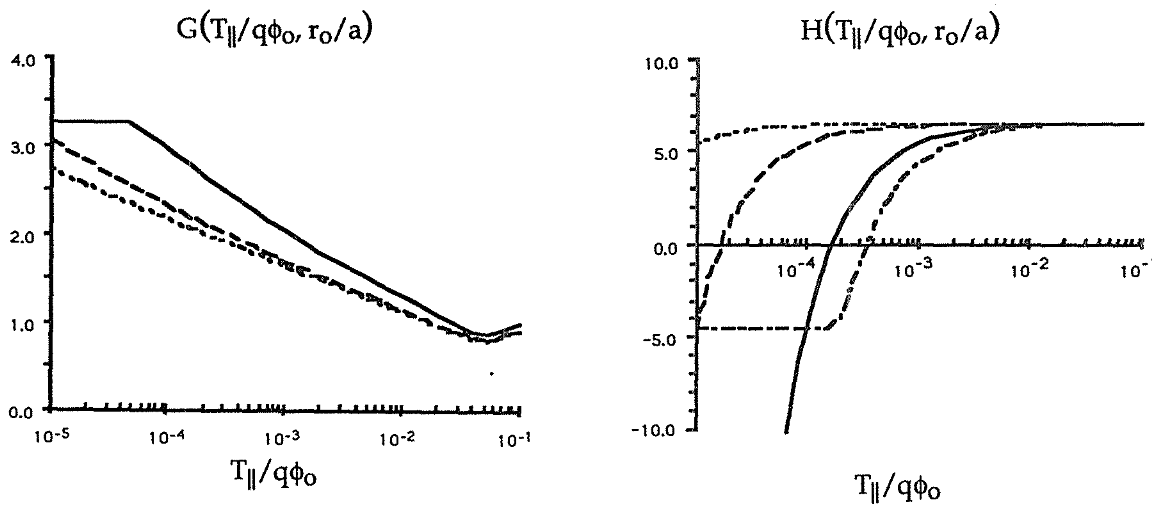
Inertial electrostatic confinement (IEC) systems are predicated on a non-equilibrium ion distribution function. These distributions can be characterized by a convergence ratio, r_o/a (where r_o is the core radius and a is the plasma radius), the longitudinal velocity dispersion $T_{||}/q\phi_o$ (where ϕ_o is the potential well depth). Coulomb collisions between ions is analyzed, and the parameters characterizing the IEC ion distribution function are shown to satisfy

$$\frac{d}{dt}\left(\frac{T_{||}}{q\phi_o}\right) = \frac{4}{3}\, G(T_{||}/q\phi_o, r_o/a) \left(\frac{a}{r_o}\right) q\,\phi_o \langle\nu_o\rangle_{Vol}\,.$$

$$\frac{d}{dt}\left(\frac{r_o}{a}\right) = -\frac{2}{3}\left(\frac{a}{r_o}\right) H(T_{||}/q\phi_o, r_o/a)\ \langle\nu_o\rangle_{Vol}$$

where $\langle\nu_o\rangle_{Vol}$ is the ion-ion collision frequency evaluated at the volume-averaged in density, and the functions H and G are shown in the figure below for $r_o/a = 2\times10^{-2}$ (dash-dot line), 10^{-2} (solid line), 10^{-3} (long dashes) and 10^{-4} (short dashes).



Ion-ion collisions cause the ion distribution function to relax toward a Maxwellian on the ion-ion collisional time-scale, thus destroying the IEC configuration. The power required to prevent this relaxation and maintain the IEC configuration for times beyond the ion-ion collisional time scale is shown to be greater than the fusion power produced. It is concluded that IEC systems show little promise as a basis for the development of commercial electric power plants.

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The Role of Line Emission in Radiation Transport Calculations of Divertor Ablation Mitigated by a Vapor Shield*

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Abstract

The vapor emitted from a surface has the natural property of partially shielding the surface from subsequent ablation provided that a significant fraction of energy incident on the vapor is converted into radiation. This is because the vapor near the surface tends to be cold and dense with very large optical depths while the outer vapor is often hot with a sufficiently low density such that outwardly directed radiation can escape the vapor. The large energy fluxes calculated for disruptions in ITER require substantial vapor shield to have the acceptable lifetimes for plasma surfacing components. However, details in the calculation of the energy transport in this vapor shield can significantly effect its predicted ability to shield the surface. Our initial studies of Be ablation under ITER disruption conditions have shown that line emission can have a large effect on the amount of ablated material. The effect of line emission can be indirect, for example, absorption of line emission in the vapor near the surface can result in enhanced ionization and population of excited states, which can lead to enhanced continuum emission that strikes the plate. The temperature and density spatial profiles have an important effect on the ratio of line to continuum emission and the relative importance of having atomic populations and opacities that are self-consistently calculated with the radiation field. We will discuss benchmark calculations for nonhomogeneous Be vapor shields where optimized multigroup calculations are compared to calculations with self-consistent line transfer.

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Combined Effects of Parallel Viscosity, Resistive Wall, and Toroidal Rotation on External Kink Modes in Tokamaks

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In earlier work (APS, 1994), we examined the influence of parallel viscosity (including fluctuating magnetic fields) on ideal external (global) kink modes in a straight cylindrical tokamak situated within a concentric conducting wall. A cubic equation for the growth rate was derived into which parallel viscosity entered in order ε^2 (where $\varepsilon = a/R$) but also contained a possibly large factor λ_{ii}/a. For wide ranges of the principal parameters (dimensionless viscosity, plasma-to-wall radius ratio, internal q-value), the marginal points proved to be unchanged from their ideal MHD values, and the growth rates experienced quantitative but not qualitative reductions due to parallel viscosity. The new work explores the additional effects of toroidal rotation in the presence of a resistive wall. As before, the derivation of the dispersion relation for this situation will be outlined and numerical results for the complex growth rates for the global kink modes will be presented, emphasizing the comparison with non-viscous results.

An Adaptive-hp Finite Element Grad-Shafranov Equation Solver

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Adaptive-hp finite element methods[1] have been used successfully to solve elliptic boundary value problems in continuum mechanics and other fields. Their advantage is that, for certain problems, exponential rather than polynomial decreases in the solution error can be achieved as a function of increasing resolution. Whether these methods can compete in solving the Grad-Shafranov equation for fixed problem sizes and regular domains for which fast solvers are available is questionable; however, for free boundary problems and irregular domains, the combination of adaptivity and hp refinement may be attractive, especially where high resolution in certain regions such as near an X-point are required. We report on an hp finite element method which, by using a method given by Lackner,[3] extends the work of Blum[2] to the free boundary problem without requiring an artificial Dirchlet bounding surface. We use adaptive-hp quadrilateral elements instead of Blum's linear triangles with the nonlinear terms treated with a Newton's method similar to that used by Blum.

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Stabilization of Wall Modes by Slow Plasma Rotation

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Wall modes are MHD perturbations that would be stable if the plasma were surrounded by a perfectly conducting wall and unstable without a wall. If the plasma is not rotating, wall modes grow on the resistive time scale of the wall. Rotational stabilization divides wall modes into three classes: perturbations not stabilized by rotation, perturbations stabilized by a slow rotation (of order the wavelength divided by the resistive time of the wall), and perturbations stabilized by a rapid rotation (of order the poloidal Alfvén speed). Perturbations can be stabilized by a slow plasma rotation if they form magnetic islands. A magnetic perturbation **b** causes an island to open during the slow development of a wall mode unless **b** satisfies two constraints on each rational surface $q=\mu/n$ with μ and n integers. First, the resonant Fourier component of $\mathbf{b}\cdot\nabla\psi$ must vanish. Second, the surface current in the rational surface $K_s \equiv [\mathbf{B_o}\cdot(\nabla\psi X\mathbf{b})]/B_o^2$ must vanish. The Ohmic power dissipated by a surface current is proportional to $\eta_{||}K_s^2/\Delta$ with Δ the thickness of the current channel. Ohmic dissipation rapidly opens a magnetic island with the current channel Δ equal to three quarters of the island half-width. Perturbations that satisfy these constraints are robustly ideal. The instabilities found by ideal MHD codes satisfy only one constraint, $\mathbf{b}\cdot\nabla\psi=0$, and typically drive islands. The amplitude of the current in a thin axisymmetic wall is given by $\Sigma_m \kappa_m e^{i(n\varphi-m\theta)}$. The energy required to drive that current and distort the plasma equilibrium is $\delta W = \Sigma_{mm'}\, \kappa_m{}^*\mathcal{L}_{mm'}\kappa_{m'}/2$. A wall mode is unstable unless the inductance $\mathcal{L}_{mm'}$ is positive definite. The plasma near the divertor separatrix is ignored in most MHD codes, so $\nabla X\mathbf{b}=0$ in that region. To make the perturbation **b** consistent with robust ideal stability near the separatrix, one must impose a new constraint for each rational surface, which has the form $\Sigma_m \mathcal{C}_{\mu m}\kappa_m=0$ We have derived the form of the matrix $\mathcal{C}_{\mu m}$ in the two-wire model of the separatrix. The stabilizing influence of the separatrix can be assessed by minimizing δW while imposing this constraint on each rational surface. Unstable perturbations that are robustly ideal require rapid plasma rotation for stabilization, if they can be stabilized at all. But, it is unclear that unstable wall modes that are robustly ideal exist in any of the desired tokamak operating regimes.

ORIGINS AND USES OF PLASMA ROTATION

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We examine the microscopic, kinetic-theory sources of toroidal and poloidal flow in confined magnetofluids and the effects of such flow on macroscopic MHD stability. We consider the most likely sources to be the combined effects of electric fields and departures from local charge neutrality. These and wall friction can serve as sources and sinks for angular momentum, often in interactive ways. The drift approximation sometimes deals poorly with angular momentum, since the guiding center velocity sometimes differs from the true fluid velocity. Also, MHD deals poorly with angular momentum, since it has contributions from the vector potential which vanish for strict charge neutrality, but reappear prominently when there is any departure from local charge neutrality, for whatever reason. In spite of this, the representation of angular momentum sources as model drift terms in the MHD equations of motion seems the only feasible way to include the effects of angular momentum in global, nonlinear computation [1].

The loss of charged particles at effectively different radii is a source of poloidal angular momentum, even in the axisymmetric straight cylinder. Wall friction with limiters or divertors is a sink. The competition between these two can determine a radial poloidal velocity profile which can be stabilizing. Toroidal flow can result from the simultaneous presence of a toroidal voltage and non-zero local charge density; the resulting acceleration may be braked by wall friction. An oversimplified analytical problem is found which can be analyzed for stability in the presence of simultaneous toroidal and poloidal flow in the equilibrium. Evidence is found for MHD stabilization by poloidal rotation, but not by toroidal rotation.

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poster format requested

MHD STABILITY OF ANISOTROPIC PLASMA CONTAINING FAST DRIFTING PARTICLES

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Abstract

In magnetic mirrors and field reversed configurations one can often meet a situation when the plasma contains a population of particles whose curvature-driven drift around the magnetic axis occurs faster than characteristic time of development of the MHD instabilities. The energy principle for this case was formulated in Ref.[1]. In Ref.[2], it was pointed out that, somewhat paradoxically, in a low beta limit, the perturbation of potential energy presented in [1], becomes zero; the solution of this paradox consists in that the energy perturbation acquires a form of the kinetic energy. The energy principle alone does not allow to obtain the necessary and sufficient stability criterion, as it doesn't take into account the possible stabilizing role of the charge uncovering phenomenon (see, e.g., [3]). Whence some kind of the mode analysis is required to obtain a definitive conclusion regarding stability. First steps in this direction were made in papers [3] and [4].

In the present communication, we describe a model which covers in a unified way all types of macroscopic perturbations and allows to reach a better understanding of the interplay of such phenomena as flute instability, ballooning mode, negative inertia mode, charge uncovering stabilization, etc. The model is based on the assumption that hot particles are anisotropic and occupy a relatively short stretch of the system (a common situation in modern mirror experiments). Magnetic field can be non-axisymmetric, with a quadrupole minimum B. In the framework of this model, a relatively simple set of equations for the eigenmodes is obtained. The correspondence between the present analysis and the earlier works by H.L.Berk, N.A. Krall and others is discussed (for the survey of these earlier works see Ref.[5]).

Present communication contains two examples of using the aforementioned equations for solving concrete problems. The first is the optimization of density of hot particles in the mirror machine for the best MHD stability. The results are compared with experimental data from the tandem mirror GAMMA-10 and a reasonable agreement is reported. The second is the assessment of the stabilizing role of the particles that are mirror-trapped near the X-points in the FRC configuration and which experience a fast drift motion because of the high curvature of the magnetic field lines. It is concluded that this particles can have a strong stabilizing effect on the whole configuration.

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1995 Sherwood Theory Conference

Fast Particle Destabilization of TAE Modes*

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Most calculations of the stability of fast particle driven TAE modes make use of a regular perturbation analysis; the growth rate due to fast particles is assumed to be much smaller than the real frequency, and the real frequency is calculated either from the ideal MHD theory for TAE modes [1] or by including the thermal ion finite Larmor radius (FLR) effect for KTAE modes [2]. For TAE modes most nonideal MHD effects are smaller than the ideal MHD contribution and thus a regular perturbation analysis is reasonably accurate. However, the KTAE modes exist essentially due to the nonideal FLR effect, its frequency and growth rate are determined with the FLR effect treated nonperturbatively. Since the nonideal effect from fast particles can be as large as the thermal ion FLR effect, the fast particle contribution to the KTAE stability must be treated with the FLR effect on equal footing and thus can not be treated perturbatively. Thus, similar to the existence of KTAE modes due to the nonideal thermal ion FLR effect, new branches of nonideal TAE modes due to the fast particle contribution may also exist.

In this paper we present a new branch of nonideal TAE modes, called the resonant TAE mode (RTAE), due to the fast particle contribution with its frequency determined mainly by the wave-particle resonance condition and its growth rate being maximum when its frequency is about the same as the ideal MHD TAE mode frequency. Numerical results and analytical analysis on the stability of these nonideal TAE modes, RTAE and KTAE modes, will be presented and compared with the ideal TAE mode stability.

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Existence of Core Localized Toroidal Alfvén Eigenmode*

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A core-localized toroidicity-induced Alfvén eigenmode (TAE) is shown to exist at finite plasma pressure due to finite aspect ratio effects in tokamak plasma [1]. The new critical beta for the existence of the high-n TAE mode is given by $\alpha = 3\varepsilon + 2s^2$, where $\varepsilon = r/R$ is the inverse aspect ratio, s is the magnetic shear and $\alpha = -Rq^2 d\beta/dr$ is the normalized pressure gradient. In contrast, previous critical α is given by $\alpha = s^2$. In the limit of $s^2 << r/R$, the new critical α is greatly enhenced by the finite aspect ratio effects. This analytic result has been confirmed by a global calculation using the stability code NOVA [2].

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Mode structure around an X-point

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This work examines mode structure on the edge of a diverted tokamak with realistic X-point geometry. We focus on an apparent paradox:

1. Theoretically, modes should not propagate past an X-point. This follows from the commonly used "eikonal in the perpendicular direction" ansatz (EIPD),

$$\tilde{\phi}(\mathbf{x}) = \hat{\phi}(\mathbf{x}) \exp\left[iS(\mathbf{x}_\perp)\right],$$

   where $\mathbf{x}_\perp$ is the coordinate perpendicular to the magnetic field, and $\hat{\phi}$ and S are slowly varying functions. When EIPD modes pass an X-point there is a large increase of $k_\perp$, which would quickly damp the mode.[1]
2. Experimentally, modes do propagate past an X-point (implied by ASDEX probes[2]).

This paradox can be resolved with a new notion that EIPD breaks down in certain regions. This follows on general grounds from a differential equation of the form:

$$\left[\nabla_\parallel^2 + \epsilon^2 f\left(\nabla_\parallel, \nabla_\perp, \mathbf{x}\right)\right] \tilde{\phi} = 0,$$

where $\epsilon \ll 1$ is a small parameter and f is some differential operator. Many waves in magnetized plasmas are described by equations of this form. To test the validity of EIPD, this equation is examined with *ray tracing.* Taking $\tilde{\phi} = \hat{\phi} \exp[iS]$ (with no directional assumptions), expanding to eikonal order, and factoring gives

$$H_\pm \equiv k_\parallel \pm \epsilon\sqrt{f\left(k_\parallel, k_\perp, \mathbf{x}\right)} = 0,$$

where $\mathbf{k} = \nabla S$. The rays follow parametrized paths $\mathbf{x}(\lambda)$ defined by

$$\frac{d\mathbf{x}}{d\lambda} = \frac{\partial H_\pm}{\partial k_i}\mathbf{e}_i = \mathbf{b} \pm \epsilon \frac{1}{2\sqrt{f}} \frac{\partial f}{\partial k_i}\mathbf{e}_i,$$

where $\mathbf{b}$ is the magnetic field direction. When f is large enough, $\mathbf{b}$ dominates, and the ray follows the magnetic field, giving the EIPD solution. However, when $f \lesssim O(\epsilon^2)$, rays can deviate from $\mathbf{b}$, violating EIPD. Specifically, properly quantized waves can propagate *around* the X-point, and avoid the blowup of $\mathbf{k}_\perp$ experienced by EIPD waves.

The region where the EIPD solution is violated represents a new kind of boundary layer present in plasmas with curved field lines. It has new implications not only for mode structure near an X-point, but in other regions of the plasma as well.

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Emission above the Ion Cyclotron Frequency in a Nonhomogeneous Magnetic Field

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An important source of information on the distribution of α- particles in DT fusing plasmas is the spectrum of radiation emission in the range of the α-particle cyclotron frequency and above.

Localized magnetosonic-whistler modes are thought to lie[1] behind this emission, observed at JET[2] and TFTR[3].

These modes would interact resonating with the harmonic of the α-particle cyclotron frequency, giving rise to a growth rate.

We investigate the effects related to the nonhomogeneity of the magnetic field: particularly we wish to emphasize how the growth rate is affected by toroidicity[4] for frequencies at or above the ion cyclotron frequency, in the resonant case (i.e. $\omega \sim p\Omega_\alpha$).

Moreover, studying the spatial structure of the magnetosonic-whistler wave, it is found that two classes of toroidal modes exist. One class [1] is radially localized within a narrow shell near the outer edge of the plasma column. The distance of the shell from the axis of symmetry is found to be close to that estimated from the experiments[2]. The other class, that propagates almost perpendicularly to the field, can extend radially to well inside the plasma column.

For this second class the whistler component of the mode becomes important: this happens above some critical frequency, $\omega > p_{crit}\Omega_\alpha$.

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The Application of DCON to the Ideal MHD Stability Analysis of the Spherical Tokamak

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The Spherical Tokamak concept has been developed over the last few years into a promising new approach to a practical magnetic fusion reactor.[1] While much has already been done to determine its stability to localized interchange and high-n ballooning modes, the extreme conditions characteristic of this concept have made it an elusive target for most low-n stability codes. DCON is a new type of stability code, based on a recently developed toroidal generalization of the Direct Criterion of Newcomb, with extensions to free-boundary modes.[2] The use of cubic spline fits of equilibrium quantities and an adaptive ODE solver for perturbed quantities provide speed, accuracy, and ease of use, allowing successful treatment of the extreme conditions of the Spherical Tokamak. An initial systematic study has been carried out to determine near optimal stable equilibria for the Spherical Tokamak. Sequences of equilibria are generated with the FBEQ free boundary direct equilibrium code, emphasizing extreme low aspect ratio (around 1.2), high average toroidal β (order unity), high pressure-driven current fraction (around 90%) well aligned with the net plasma current, high natural vertical elongation (around 2.3), and high edge safety factor (around 20). These equilibria are screened for Mercier and high-n ideal ballooning stability, using the BAL code. They are then tested for low-n unstable ideal internal and external modes with DCON. Comparison of results from GATO and ERATO for representative equilibria near marginal stability will also be presented. Our study provides strong evidence that the Spherical Tokamak provides a promising vehicle for advanced regime tokamak operation in small size plasmas requiring modest toroidal fields.

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Scaling Law based Studies of the Performance Capabilities of a Small Aspect Ratio Tokamak

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The success of the START spherical toakamak (ST) has clearly demonstrated the promise of small aspect ratio machines, and made it attractive to build the next stage machine. This next machine needs to be a significant but economical step in the march towards an attractive ST reactor. Since high beta and high bootstrap fractions are the two main advantages of spherical tokamaks, this machine should be able to test the high beta limit at reactor relevant beta values. It should also be flexible enough to resolve differences between different scaling laws so that a reliable extrapolation can be made to an ST reactor. The proposed ETG tokamak at University of Texas is being designed with these aims in mind.

We describe a new design tool developed for this task, and the results obtained from it. Since the various aspects of the design are closely interrelated, it is important to create a custom-made design-prediction tool which incorporates our latest biases, and is modular enough to allow us to add more information as it becomes available. The program includes most of the known theoretical, experimental, and engineering information as well as the uncertainties. It incorporates eleven scaling laws, detailed engineering models for coil capabilities, and phenomenological formulae for many physical quantities such as the plasma shape, bootstrap current etc. The effect of simultaneous variation of the six basic machine parameters (aspect ratio, major radius, plasma current, toroidal field, auxiliary power, and density) on various quantities is studied to find the optimum range of design parameters in this six dimensional design space. A machine design is chosen to allow a wide range of parameters. A minimal set of experimental conditions are found which can maximally distinguish between various scaling laws and allow reasonably accurate prediction of ST reactor scenarios.

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Time Dependent Studies of Advanced Tokamak Operating Scenarios Using a Theory-based Transport Model*

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Results are presented for the time evolution of particle density, temperature, and current density using conceptual design parameters for the proposed Tokamak Physics Experiment (TPX). We incorporate the heating and deposition profiles predicted by the ACCOME radio-frequency heating and current drive code[1] into the BALDUR 1-1/2 D transport code in order to consider various scenarios of fast wave, lower hybrid, and neutral beam heating and current drive. We compare results when different models for radial particle and energy transport are employed. In particular, we use the calibrated multiple mode model[2] and a version employing the Nordman–Weiland formulation for the ion-temperature gradient mode, including effects of trapped particles and impurities[3], replacing the Dominguez-Waltz description of drift waves[4]. Predictions of density and temperature profiles for these models are compared with data from plasma discharges in several tokamaks. We present results for TPX illustrating the dependence of the ion temperature on the division of auxiliary heating power between electrons and ions. The sensitivity of these results on transport modeling is illustrated.

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THE SPHERICAL WAY—PHYSICS AND SCALING OF SPHERICAL CONVERGENT ION FOCUS FUSION SYSTEMS

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Recent advances in the theory of SCIF devices are described.

Previously reported studies of streaming instabilities in nonneutral plasmas with turning points[1] are extended by numerical calculations using both fluid and particle simulation methods. These methods are applied to the previous one-dimensional slab model of a single-species beam plasma confined by an externally applied potential. The previous stability diagram is amended to include a stable region at low mean density when turning points are present in the domain. A quadratic form is developed and applied to this stability transition, and agreement is found between this analysis and the numerical results.

A physics based scaling path to extend the present one-Debye-length experiment (PFX:Penning Fusion eXperiment) to useful sized systems is identified. A nonneutral, electron rich edge is confined near the Brillouin density limit by combined magnetic and electrostatic fields. The space charge of this edge plasma forms a virtual cathode which recycles beam ions back toward a central focus. A new edge equilibrium is identified and its stability discussed.

Space charge effects on ion energy scattering in the central focus and ion beam stability are also discussed.

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Canonically Conjugate Phase Space Coordinates Appropriate for the Study of Stellarator Transport

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Methods previously applied to study tokamak steady states and transport, which are based on coupled Fokker-Planck equations for electrons and ions (*Phys. Plasmas* **1**, 3942 (1994)), depend on the existence of relatively simple canonically conjugate coordinates without intricate period conditions on the coordinates. In order to study stellarator steady states and transport, it is necessary to construct such coordinates. Those proposed originally by Gardner, *Phys. Rev.* **115**, 791 (1959), are appropriate for a single particle or in the small, but the periods of the coordinates are far from trivial. If one considers the electric and magnetic fields to consist of leading order fields, which admit magnetic surfaces, plus small, additional terms which typically destroy magnetic surfaces, then one can start by a study of canonically conjugate coordinates in a time-independent system with magnetic surfaces. If one writes $\mathbf{B} = \nabla\psi \times \nabla\beta$, where ψ is single-valued and β multiple-valued, then in terms of toroidal coordinates ρ, θ, ϕ, where ρ is a radial coordinate, θ a toroidal angle and ϕ a poloidal angle, then $\beta = \beta_\rho(\rho, \theta, \phi) + \theta Q_1(\psi) + \phi Q_2(\psi)$, where $\beta_\rho(\rho, \theta, \psi)$ is periodic of period 2π in θ and in ϕ. It is then possible to take ψ, β_ρ, and θ as the basic coordinates and develop a guiding center Hamiltonian to all orders, and without significant periodicity problems. Perturbation methods of the type used in *Phys. Fluids* **24**, 2280 (1981) permit an examination of the transport induced by the fields which destroy the symmetry. Preliminary results of such a calculation will be given.

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POSTER

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Three-Dimensional Shell Effects in δW Using the PEST-SPARK Code*

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One method to obtain quantitative estimates of MHD stability from the non-axisymmetric portions of the enclosing metallic shell in present and envisioned tokamak devices is to combine our present $2D$ VACUUM code with the SPARK electromagnetics code which is designed to calculate the eddy currents generated in non-axisymmetric conducting shell configurations due to pervading magnetic perturbations. If the latter are MHD perturbations, then the magnetic field which arises from the eddy currents can be used in conjunction with the magnetic field of the perturbations themselves to obtain the vacuum energy which contains the $3D$ nature of the shell:

$$\delta W_{\rm v} \;=\; -\int_{S_p} \mathcal{J} d\theta\, d\phi\, [\chi^{p*}\mathbf{B}\cdot\nabla\xi_\psi + \xi_\psi\hat{\mathbf{B}}\cdot\delta\mathbf{B}_s^*]. \tag{1}$$

Here, χ_p is the scalar potential for the plasma perturbation, and the parallel magnetic perturbation, $\hat{\mathbf{B}}\cdot\delta\mathbf{B}_s$, stems from the eddy current contribution of SPARK. One needs also the normal component because of the boundary condition that the normal component of the *total* magnetic perturbation is continuous across the plasma-vacuum interface. We note that several harmonics in the toroidal angle, ϕ, are required for a $3D$ shell. We either spectrally filter these or perhaps adopt a minimizing procedure in the ϕ coordinate. These latter ideas are still being worked out. The procedure for interfacing the codes involve several stages: a) the vector potential needs to be obtained form the scalar potential of the PEST perturbations for input to SPARK. b) The method is checked against a semi-analytic long wavelength cylinder. c) It was also checked against a $2D$ TPX wall configuration. d) The eddy current patterns of the PEST and SPARK codes were compared. e) Finally, results from $3D$ calculations are obtained. The details of these steps as well as results will be presented.

– Prefer POSTER

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

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The Relaxed-Cusp Configuration as an Approach to Magnetic Confinement*

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Spheromaks have their primary appeal in not requiring toroidal-field coils, thus permitting a quasi-spherical plasma chamber, simpler first-wall designs, etc. As a relaxed Taylor[1] state, the equilibrium is stable against internal current-driven modes. However, nearby conducting walls appear to be required for stability against tilting in the external field. Spheromaks also have rather modest calculated beta limits to ballooning due to finite pressure, depending on the assumed current profile[2]. Apart from these stability issues, Fowler[3] has argued that the core energy confinement of earlier spheromak experiments may have been better than thought and that spheromaks should, therefore, be reconsidered.

As a possible approach to avoiding the tilt without requiring nearby walls, we have considered the Taylor states appropriate to a spindle-cusp geometry. These equilibria retain the advantages of simpler spheromaks and they *may* have superior stability to tilt, owing to the antisymmetry of the external field. In addition, their deep magnetic-well character should provide stability to pressure-driven modes and, therefore, provide significantly higher beta limits. (Cusp configurations have been mentioned in passing by Sudan[4]. However, they do not appear to have been given serious consideration as confinement geometries.) Analytical zero-pressure equilibria in model fields can be obtained readily. Results from an energy-principle analysis of current-driven tilt modes will be presented.

Also presented is a novel approach to helicity injection using rotating sectors of conducting endwalls. Although, in practice, this technique might not be superior to conventional voltage-driven helicity injection, it offers both conceptual and certain practical advantages.

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Stabilization of Ballooning Modes With Sheared Toroidal Rotation in a Cylindrical Tokamak

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In a tokamak with sheared toroidal rotation, it was shown[1] that a new class of Floquet-type ballooning instabilities exists generated by the poloidal periodicity of the equilibrium state. However, the growth rate of these instabilities is much slower compared to a typical ballooning time. This fact makes attractive modelling the tokamak as a circular cylinder which does not admit the Floquet instabilities but is, otherwise, much easier to analyze.

We carried out the stability analysis for this case. The most remarkable result is that a sufficiently large flow shear (but not too large) will stabilize the ballooning mode. This agrees with a recent calculation[2] for a more realistic equilibrium state which shows direct acces to be second stability regime using large flow shear.

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Pseudo-MHD Ballooning Modes In Tokamak Plasmas*

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There are a number of experimental indications that plasma confinement scales with ideal MHD stability parameters (e.g., $\beta_\theta, \ell_i, \kappa$). Also, as the β limit is approached the plasma pressure profile seems to evolve toward one that is marginally stable to MHD ballooning modes across the entire plasma. Further, observations of very low k_θ fluctuations in tokamak plasmas indicate MHD-like growth rates ($\gamma > 1/50\ \mu sec$) — for ELM precursors and striations observed via visible light imaging. Finally, a recent bispectral analysis of BES fluctuation data [1] indicates rapidly growing ($\gamma > \omega_{*i}$) modes at very low $k_\theta \rho_i (< 0.05)$.

However, for typical plasma parameters the ideal MHD ballooning modes are stable, and resistive MHD ballooning modes grow feebly and induce negligible anomalous transport. Regular MHD modes are stable or only weakly growing because the pressure gradient free energy accessible via magnetic field curvature effects is smaller than the perturbed magnetic energy due to the field line bending. Ballooning-type modes could be unstable if the pressure gradient term were larger (but two-fluid and nonlinear analyses usually indicate reductions) or the field-line-bending term were smaller. We explore the latter avenue. Specifically, we allow for adiabatic regime electrons ($\omega, \nu_e \ll k_\| v_{Te}$) and focus on the effects of parallel electron flow compressibility $[T_e \nabla_\| \tilde{n} \rightarrow T_e \nabla_\|^2 (\tilde{J}_\| / e\gamma) \rightarrow T_e \nabla_\|^2 (\nabla^2 \tilde{A}_\| / e\gamma\mu_o)]$ in the parallel Ohm's law. (Linearized kinetic closures that have been recently derived from a rigorous Chapman-Enskog-like formalism [2] are used to take account of parallel electron viscosity and $\nabla_\| \tilde{T}_e$ effects which lead to electron Landau damping effects in fluid models, but these effects are smaller and mostly negligible.) Then, the effective parallel electrical resistivity is $\eta_\| \simeq (m_e/n_e e^2)(\nu_e + k_\|^2 v_{Te}^2/\gamma)$, which is much larger than the classical collisional resistivity in the adiabatic electron regime. This parallel electron compressibility effect strongly reduces the $\tilde{J}_\|$ induced by $\nabla_\| \tilde{\phi}$ and hence the field-line-bending. It thus makes possible new hydrodynamic-type ballooning instabilities which we call pseudo MHD ballooning modes.

The equations used to describe pseudo MHD modes are an electron density conservation equation which includes parallel electron compressibility effects, an extended parallel electron momentum balance (or Ohm's law), a parallel flow equation, and the current continuity equation $[(\mathbf{B} \cdot \nabla)(J_\|/B) + \nabla \cdot \mathbf{J}_\perp = 0]$. In appropriate limits these equations describe ideal and resistive MHD modes, electron drift waves (including electron Landau damping), and sound waves, as well as our new pseudo MHD modes. A two length scale analysis similar to that developed for resistive MHD ballooning modes [3] is used to explore the properties of pseudo MHD ballooning modes, which involve a mix of hydrodynamic and adiabatic electron responses. Like their resistive MHD counterparts, these new modes extend along magnetic field lines many times around the tokamak and are driven by geodesic curvature effects. However, these new modes have much larger, hydrodynamic-type growth rates that scale with ideal MHD ballooning mode parameters ($\gamma \simeq \omega_A [\alpha q (\beta/2)^{1/2} (k_\theta \rho_s)]^{1/3} \simeq \sqrt{2} c_s (k_\theta \rho_s)^{1/3} / (r_p R_o{}^2)^{1/3} >> \omega_{*i}$) for parameters where they are robustly unstable and easily derived — $k_\theta \rho_s < [\alpha q (\beta/2)^{1/2}]^{1/2} / s^{3/2}$. For relevant TFTR parameters, these modes have $\gamma \sim 10^5/s$ for $k_\theta \rho_s \sim 0.02$, and could explain the very low k_θ growing modes observed via BES [1].

Since these "ubiquitous" new modes are analogous to Rayleigh-Taylor fluid instabilites, they are almost purely growing, interchange-type, low dissipation modes. Presumably they will saturate via mode coupling effects that transfer energy to marginally stable, higher k_θ modes for $\Delta_r \sim \tilde{V}_x/\gamma \sim 1/sk_\theta \sim$1–3 cm. The (reversible) turbulent mixing they could induce ($D_{mix} \sim \gamma \Delta_r^2 \sim 40\ m^2/s$) is quite large, but the net transport fluxes would be much smaller (and determined by dissipative effects). These new pseudo MHD ballooning modes could represent the underlying cause of the rapidly growing very low k_θ fluctuations observed on TFTR via BES. They offer the hope of explaining many key aspects of anomalous transport in tokamaks — MHD-like scalings, transient transport much greater than equilibrium, evolution towards pressure profiles uniformly stable to ideal MHD balloning modes, etc.

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Incorporation of the Reduced-Ion Impurity Module FMOMBAL into UEDGE*

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The reduced-ion description for multiple charge states of an impurity ion, as implemented in FMOMBAL,[1] is incorporated into the two-dimensional, edge-plasma transport code UEDGE. The parallel velocities and heat fluxes of individual charge states are obtained without solving a momentum-balance equation for each charge state. Instead, a single mass-averaged momentum equation, derived by summing over electrons and all ion species, is solved for an average parallel velocity. FMOMBAL uses that velocity and parallel gradients of temperatures, pressures, and potential and solves a spatially local matrix problem to compute parallel velocities, heat fluxes, and friction forces for the individual charge states. Those velocities are used in continuity equations solved by UEDGE, which obtains densities of all of the charge states. Consistent with their use within FMOMBAL, the friction forces are used in energy equations solved by UEDGE. FMOMBAL has been previously tested in the one-dimensional code NEWT1D. Initial results with the reduced-ion description within UEDGE are presented and compared with results from the average-ion model.[2]

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ON NONLINEAR MHD-STABILITY OF TOROIDAL PLASMA CONFINEMENT SYSTEMS*

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A Lyapunov functional for analyzing ideal MHD-stability of plasma equilibria in toroidal magnetic fields is suggested. The equilibria can be found by a variation of the Lyapunov functional chosen as the potential energy expressed in terms of three independent Lagrangian invariants $\{\lambda_i\}$: $\partial_t \lambda_i + \mathbf{V}\nabla\lambda_i = 0$. The stability criterion results from the consideration of higher order variations of the functional. Contrary to earlier papers using the Lyapunov formalism, our approach strictly accounts for all the constraints inherent in the varied functions under the integral due to frozen-in, continuity and adiabatic equations. Therefore, this approach leads to the general class of plasma equilibria and enables one to derive a general nonlinear sufficient and necessary stability criterion. The second variation of the Lyapunov functional is found to coincide precisely with the well-known energy principle derived from the linear stability theory. However, there are some plasma displacements which do not change the system energy in the framework of the linear theory (the "neutral displacements"). Therefore, the neutral displacement amplitude can considerably exceed the amplitudes of other components of the displacement, and one might expect that the nonlinear coupling of such a neutral displacement with another components of the displacement can change the system energy in higher order terms. Adding the higher order variations of the Lyapunov functional we have found that there is no such coupling as mentioned above and that the corresponding nonlinear stability criterion can be reduced to linear one by redefining the neutral displacements. This fact results from the existence of a finite neutral transform (coordinate relabeling) whose explicit form for general toroidal confinement systems has been found using our approach. The presence of such the finite neutral transform is evidence of a latent symmetry of the MHD-equations. Using this symmetry we have generalized our approach to find general equilibrium states with stationary plasma flows and to analyze their stability.

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MHD Stability of High-Beta Tokamak Equilibria*

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The MHD stability of high-beta tokamak equilibria with $\epsilon\beta_p > 1$ is studied using a numerical code which solves the compressible MHD equations in toroidal coordinates. Here, the poloidal beta β_p is the ratio of the thermal pressure to the poloidal magnetic pressure and ϵ is the inverse aspect ration. The computed high-β_p equilibria are characterized by an outer boundary layer surrounding an inner core in which the magnetic flux is a function solely of the major radius R, in agreement with the analytic prediction of Cowley et al.[1]. These high-β_p equilibria are shown to be unstable to low n MHD kink modes, where n is the toroidal mode number. The growth rate of the kink mode increases as $\epsilon\beta_p$ increases above unity. Details of the structure of the growing modes will be presented.

*Research supported by DOE.
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Turbulence Simulation with Self-Consistent Profiles via Coupled Codes*

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Turbulence causes evolution of background profiles (which in turn alters the turbulence drives) on a time scale which can be much longer than that for developing saturated turbulence. Furthermore, turbulence simulations are typically done on a restricted grid, with artificial boundary conditions and either no or unrealistic sources, which means that codes that evolve equilibrium quantities are often not doing so in a realistic way. An efficient way to address this problem is to formally separate the fundamental nonlinear equations into fluctuating and averaged components, and solve each on its own timescale (and in fact in its own independently developed code). The necessary quantities (*e.g.,* turbulent fluxes and driving profiles) are passed back and forth, and the combined system is solved by a form of relaxation. The resulting algorithm allows the averaged equation to be solved implicitly, with numerical stability at long (even approaching infinitely long) time steps and convergence in a time of order of that required for the turbulence code alone to reach a saturated state. We demonstrate this algorithm for non-local versions of the Hasagawa-Wakatani equations, with the averaged density evolved either within the turbulence code or separately. We find good agreement between results obtained from the coupled codes and the stand-alone turbulence code, a speed advantage which can be significant even for cases where the turbulent eddy size is not negligible compared to the equilibrium gradient length. We have begun applying the scheme to coupled toroidal transport and 3-D gyrofluid turbulence codes. Here, multiple fields are being coupled. We report on tests of the coupling algorithm for two coupled fields using analytic (nonlinear) model fluxes and the transport module from the Corsica 1.0 code, and on the status of coupling to a turbulence code.

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Non-perturbative solution method for the gyrokinetic Fokker-Planck equation §

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Despite its relevance for numerous transport theory applications and linear stability analyses, the problem of determination of accurate solutions for the gyrokinetic Fokker-Planck equation, especially for weakly collisional toroidal magnetoplasmas is still substantially an open question. For configurations with large aspect ratio, several techniques have been adopted based either on variational approaches [1,2], approximate collision operators [3,4] or expansions in eigenfunctions [5,6]. However, the accuracy of such approaches for magnetostatic equilibria having finite aspect ratios appears questionable. In this paper we intend to propose a new non-perturbative and non-variational, direct solution method, based on a suitable "N-th order approximation" for the Fokker-Planck collision operator, allowing, in principle, the accurate evaluation of arbitrary moments of the distribution function for arbitrary aspect-ratio. In contrast, most of previous approaches, based either on variational [1] or direct solution methods using approximate collision operators [3,4] or suitable eigenfunction expansions [5,6] involve the adoption of second-order approximations for the F-P operator. A fundamental problem, for most of such approaches and in the case of weakly collisional magnetoplasmas, concerns their accuracy for magnetostatic equilibria exhibiting finite aspect ratio. Goal of this paper is to develop an accurate solution approach, which in contrast to the "perturbative-variational" solution method earlier pointed out [2], is non-perturbative and non–variational, i.e., it relies neither on a perturbative expansion for the construction of the approximate solution nor a variational principle for the evaluation of the relevant moments of the gyrokinetic distribution function.

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Equilibrium and MHD Stability of Plasmas with Toroidal Rotation in the DIII–D Tokamak

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A new approach to finding toroidally rotating steady-states of a tokamak plasma is proposed. The model is based on the nonlinear dynamic MHD equations and is incorporated in the Flow Equilibrium Code (FLEC) which computes both the steady-states and the axisymmetric stability for given sheared toroidal and poloidal flow. The steady-states are then analyzed for compressible $n = 1$ stability using the Nonlinear Fully Toroidal Code (NFTC). Both codes use a straight field line flux coordinate system with metric elements calculated, for real DIII–D discharges, directly from the reconstructed equilibria computed from the EFIT code. FLEC uses an implicit finite difference scheme in the radial direction with a very large time step compared to an Alfvén time.

An investigation of the stationary state solutions and their MHD stability was performed. With rigid toroidal rotation, the region of existence of steady-states is described in terms of the Mach and Reynolds numbers. The influence of the rotation profile is then studied. It is found that two solutions of steady-states can exist, one axisymmetrically stable and the other unstable. For sheared toroidal rotation, the solutions can have considerably different profiles as well as magnitudes. The two branches merge as the toroidal rotation frequency is decreased. One branch has the opposite sign to the observed toroidal flow and the evolution of plasma equilibrium to this branch can explain mode locking.

The linear $n = 1$ stability of a fixed boundary equilibrium with rotation is also investigated. A new rotating pressure-driven mode is found. Depending on the values of the toroidal rotation frequency and viscosity, however, this mode can be suppressed by coupling with Alfvén tearing modes; the suppression is sensitive to the conditions just inside the $q = 2$ surface, which depend on the magnitude and profile of the toroidal velocity. In summary, this investigation shows that locked modes can be explained by the evolution of the plasma equilibrium to the unstable toroidal rotation branch. Destabilization leads to a new rotational mode. This rotating instability may be stabilized by the rotational velocity profile.

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Poster presentation requested

Tearing mode bifurcation: a way to control MHD activity in tokamak plasmas

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Tearing modes with low mode numbers are known to affect tokamak performance, by degrading confinement [1] and stability [2]. As a result, understanding their behavior and monitoring their evolution are challenging issues.

Evolution and saturation of magnetic islands associated with tearing modes in TFTR supershots [1] seem to agree with the predictions of the so-called neoclassical ∇p-driven tearing mode model [3] (instability driven by bootstrap current). However, the latter does not predict a threshold condition (to be overcome by a mode before it can grow). This is in contradiction with experiment, since any mode should be unstable in the absence of a threshold condition, while only few are indeed observed (m/n=3/2, 4/3 and 5/4, with m (n) the poloidal (toroidal) mode number). Two mechanisms have recently been proposed that could remove this discrepancy:

1) Transverse conductivity $\chi_\perp$, together with considering large but finite longitudinal conductivity $\chi_{//}$, may prevent electron pressure from equilibrating on perturbed magnetic surfaces. This is found to modify the source of instability: the required pressure flattening inside the island only occurs for island width w larger than a threshold w_{th} scaling as $(\chi_\perp/\chi_{//})^{1/4}$ [4].

2) Ion polarization drift effects (ion inertia and finite Larmor radius) provide a stabilizing contribution, potentially dominant for island widths of the order of the ion Larmor radius ρ_i, but rapidly decreasing for larger islands [5], thus introducing a threshold width $w_{th} \approx$ a few ρ_i.

These mechanisms provide the previously missing threshold condition: an island can only grow if its width w overcomes a threshold value w_{th}. The qualitative island dynamics may be described in a plane (w/w_{th}, C), where C is a control parameter, depending on various local plasma parameters related to pressure and current profiles, and also $\chi_\perp/\chi_{//}$ for the first of the above mentioned mechanisms. The dynamics is characterized by a *universal* stability boundary $C=C_s(w/w_{th})$, which consists of an unstable (stable) branch related to threshold (saturation). The key point is that C_s has a minimum C_{bif} for a critical width w_{crit} (corresponding to the larger possible threshold). As a result, the dynamics exhibits a bifurcation at that point: islands are intrinsically stable (i.e., w_{th} is infinity) for C less than C_{bif}.

This outstanding feature implies that it may be possible to get rid of the undesirable MHD activity by monitoring the control parameter C so as to make it fall down to the bifurcation value C_{bif} for each dangerous mode. The current channel seems to provide the easiest *knob* to control C, by doing local current drive in the vicinity of the mode resonant surface. Various scenarios are proposed that could be tested experimentally.

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Characteristics of LHD configurations with Multi Layer Helical Coils

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Abstract

The Large Helical Device (LHD) is $\ell = 2$ heliotron/torsatron device and each helical coil is composed of three layers. It is designed so that the current in each layer should be controlled independently. Hence, we can change the combination of the layers in which the current flows for each operation. The change of the combination of the layers corresponds to the change of the effective radius of the helical coil, which enlarges the flexibility of the operation.

The properties of the plasmas for several combinations of the layers are investigated numerically. In the configuration called the standard configuration, all three layers are used. The coil radius becomes large when only the outer layer of the coil is used, while the coil radius becomes small when only the inner layer is used. In the vacuum configurations, it is obtained that the combination of the layers which leads to the large coil radius has the large outermost surface. In this case, shallow magnetic well appears in the vicinity of the magnetic axis even in the vacuum configuration, which cannot be obtained in the standard configuration. The Mercier mode in the finite beta equilibrium calculated by the VMEC code is completely stabilized by the magnetic well. However, the equilibrim beta limit is degradated by the large Shafranov shift due to the small rotational transform. On the other hand, the magnetic hill is enhanced in the case of the combination for the small coil radius, therefore, the Mercier mode is destabilized.

Microinstability Analysis of DIII-D High Performance Discharges*

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As part of a collaboration between General Atomics and the PPPL Theory Division, the kinetic stability properties in a number of high performance discharges from the DIII-D experiment have been analyzed utilizing a comprehensive kinetic eigenvalue code[1,2]. Instabilities considered are the toroidal drift mode (trapped-electron-η_i mode) and the kinetic MHD ballooning mode. This code has been interfaced with equilibria specific to DIII-D plasmas. Experimentally measured kinetic profile data, along with MSE data and external magnetic data, was used, and the corresponding MHD equilibria were computed numerically. In particular, a high-l_i H-mode case and a VH-mode case have been analyzed, and a high-β_p case and a low-to-negative magnetic shear case are in progress, as well as an L-mode shot for reference and comparison purposes. For the H-mode and VH-mode cases, only relatively narrow regions of instability were found. An assessment of the influence of velocity-shear flow on these instabilities has also been initiated.

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Transport in Steep Gradient Region

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Global confinement scaling in H–mode is often dominated by the edge region of the width of thermal ion poloidal gyroradius. Establishing the boundary conditions on a solid theoretical basis will complement and strengthen existing analytical and computational work on core transport. As opposed to L–mode, the effect of turbulence on transport in this region is believed to be small in H–mode because of turbulence suppression by electric field shear. Even the standard neoclassical theory is not valid there because of the violation of small poloidal gyroradius ordering. In H–mode, the edge pedestal determines the boundary conditions for the core transport. The scale length of this edge pedestal is also comparable to neutral particle penetration length. We report on a study of these two effects on collisional transport in the edge region: (1) neoclassical transport in the plasma edge with steep gradient and sheared electric field, and (2) effects of neutral particle charge exchange damping on transport and rotations.

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Poster presentation requested

Effect of Alfvén Resonance on Low-Frequency Fast Wave Current Drive*

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The Alfvén resonances may occur on the low- and high-field sides for a low-frequency fast wave current drive scenario proposed for the International Thermonuclear Experimental Reactor (ITER). At the resonance on the low-field side, the fast wave may be mode-converted into a short-wavelength slow wave, which can be absorbed by electrons at the plasma edge, before the fast wave propagates into the core area of the plasma. Such absorption may cause a significant parasitic power loss.

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Plasma Fluid Model with Finite Larmor Radius Effects*

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The hierarchy of fluid moment equations cannot be truncated for finite values of the Larmor parameter even in the low frequency approximation $\omega < \omega_B$. We formulate exact linear closure, which is based on direct calculations of higher moments (viscosity and heat flux) from the linear kinetic equation in the regime $k_\perp \rho \geq 1$. Our set of moment equations consists of the equations for plasma density, velocity and pressure with the linear closure relations for the heat flux and viscosity expressed through perturbed electrostatic potential. These closure relations fully retain effects of the Larmor radius in all orders and, in general, for arbitrary ratio ω/ω_B. By expansion in small parameter $\omega/\omega_B < 1$, reduced expressions for the heat flux and plasma viscosity in the low frequency limit are obtained in terms of the modified Bessel functions. Unlike the gyrofluid approach, our equations are written in the particle space, so that no transformation from guiding center moments to particle moments is required. In our approach nonlinearity has the standard hydrodynamic form. Though not all nonlinear terms are retained in large orders in $k_\perp \rho$, these inaccuracies may be partially compensated in nonlinear calculations, where the amplitude of the harmonics decreases toward large $k_\perp \rho$. In the linear limit the plasma parameters such as density, velocity and pressure obtained from this system are identical to those calculated from the kinetic equation with the full Larmor radius effects. Further simplification of the closure relations using the Padé approximants will be discussed.

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