Sherwood '94

1994
International Sherwood Fusion Theory Conference

March 14-16, 1994
Dallas, Texas

Hosted by
The University of Texas at Austin ~ Institute for Fusion Studies

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Cover
Courtesy of the Dallas Convention and Visitors Bureau

General Information

- 228 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 Fairmont Hotel Regency Ballroom, Banquet Level, 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 and at 7:00 p.m. on Tuesday evening.
- All poster sessions will be held in the Regency Ballroom on Monday from 2:00 p.m. to 6:00 p.m. and on Tuesday 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 p.m. to 9:00 p.m. in the Fairmont Hotel Regency Ballroom Foyer, Banquet Level.
- A Companions' breakfast will be held on Monday morning at 9:00 a.m. in the Garden Room, Terrace Level.
- Coffee will be served in the Regency Ballroom Foyer Monday through Wednesday mornings at 9:15 a.m.
- Soft drinks and beer will be served in the Regency Ballroom Foyer on Monday afternoon at 3:30 p.m.
- Fajitas and beer will be served in the Regency Ballroom Foyer on Tuesday evening at 6:00 p.m. and coffee will be served inside the Regency Ballroom at 8:00 p.m.
- Requests for special meetings should be made at the Conference Registration Desk.
- Registration for the Numerical Tokamak Workshop and the SOL and Divertor Theory Workshop will begin at 2:00 p.m. on Monday, March 14, 1994 at an adjacent table. The Workshops will be held on Wednesday afternoon and on Thursday.

Fairmont Hotel, Dallas, Texas
March 14-16, 1994

Registration Schedule

Location: Regency Ballroom, Banquet Level
Sunday, March 13 — 4:00 p.m. to 9:00 p.m.
Monday, March 14 — 7:30 a.m. to 5:00 p.m.
Tuesday, March 15 — 8:00 a.m. to 12 noon and 6:00 p.m. to 7:00 p.m.
Wednesday, March 16 — 8:00 a.m. to 12 noon

Oral and Poster Session Schedule

Review and Oral Presentations — Regency Ballroom
Poster Presentations — Regency Ballroom

Monday

8:20 a.m.	Welcome	P.J. Morrison and J.W. Van Dam, Co-Chairmen	
8:30 - 9:20 a.m.	1A	Review Paper	K. McGuire
9:30 - 12 noon	1B	Oral Session	(5 30-minute talks)
2:00 - 4:00 p.m.	1C	Poster Session	(54 poster papers)
4:00 - 6:00 p.m.	1D	Poster Session	(54 poster papers)

Tuesday

8:30 - 9:20 a.m.	2A	Review Paper	W.W. Heidbrink
9:30 - 10:30 a.m.	2B	Oral Session	(2 30-minute talks)
10:30 a.m. - 12:30 p.m.	2C	Poster Session	(54 poster papers)
7:00 - 9:00 p.m.	2E	Oral Session	(4 30-minute talks)

Wednesday

8:30 - 9:20 a.m.	3A	Review Paper	N. Zabusky
9:30 - 10:30 a.m.	3B	Oral Session	(2 30-minute talks)
10:30 a.m. - 12:30 p.m.	3C	Poster Session	(54 poster papers)

Monday Oral Presentations

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

Welcome 8:20 a.m.		**P.J. Morrison and J.W. Van Dam, Co-Chairmen**
Review Paper 8:30 a.m.	**1A**	**L. Chen, presiding** K. McGuire, *Initial D-T experiments on TFTR*
Oral Session 9:30 a.m.	**1B**	**S. Cowley, presiding** G.Y. Fu et al., *Linear stability analysis and nonlinear hybrid simulation of TAE modes with application to TFTR D-T experiments*
10:00 a.m.		R.L. Miller et al., *Stabilization of MHD ballooning modes by sheared toroidal rotation*
10:30 a.m.		T.D. Rognlien et al., *CORSICA: A comprehensive tokamak simulation code*
11:00 a.m.		C.T. Hsu et al., *Particle dynamics in chirped-wave and its application to tokamak plasmas*
11:30 a.m.		V.P. Pastukhov et al., *Linked mirror neutron source concept*

Tuesday Oral Presentations

Review Paper 8:30 a.m.	**2A**	**J. Freidberg, presiding** W.W. Heidbrink, *Fast-ion driven Alfvén instabilities in tokamaks*
Oral Session 9:30 a.m.	**2B**	**K. Shaing, presiding** A.D. Turnbull et al., *Stabilization of ideal kink modes in DIII-D by a resistive wall*
10:00 a.m.		R. Fitzpatrick, *Effect of a non-uniform resistive wall on the stability of tokamak plasmas*
Oral Session 7:00 p.m.	**2E**	**M. Chu, presiding** R.N. Sudan et al., *Small scale magnetic flux averaged magnetohydrodynamics*
7:30 p.m.		M. Artun, *Shear flow effects on low-frequency drift-type tokamak microinstabilities*
8:00 p.m.		F. Porcelli et al., *Nonlinear collisionless magnetic reconnection*
8:30 p.m.		K.-R. Chen et al., *Anomalous thermalization of fast ions in magnetized plasma due to two-gyro-stream instability*

Wednesday Oral Presentations

Review Paper 8:30 a.m.	**3A**	**J. Van Dam, presiding** N. Zabusky, *Collapse, intensification and reconnection in vortex dominated flows: Visiometrics and modeling*
Oral Session 9:30 a.m.	**3B**	**J. Van Dam, presiding** M. Yagi et al., *Nonlinear simulation of the current diffusive interchange mode*
10:00 a.m.		D. Boucher et al., *Predictive transport modeling*

1994 INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE

Fairmont Hotel, Dallas, Texas
March 14-16 , 1994

REGISTRATION - Regency Ballroom Foyer, Banquet Level
Sunday, March 13 - 4:00pm - 9:00pm

RECEPTION - Regency Ballroom Foyer, Banquet Level
- 7:00pm - 9:00pm

REGISTRATION - Regency Ballroom Foyer, Banquet Level
Monday, March 14 - 7:30am - 5:00pm
Tuesday, March 15 - 8:00am - 5:00pm
Wednesday, March 16 - 8:00am - 12noon

MONDAY MORNING

WELCOME - 8:20am - P.J. Morrison and J.W. Van Dam, Local Chairmen

1A REVIEW TALK - Regency Ballroom
8:30am - 9:20am
Presiding: L. Chen

1A1. Initial D-T experiments on TFTR. K. McGuire.

1B ORAL SESSION - Regency Ballroom
9:30am - 12:00noon
Presiding: S. Cowley

1B1. Linear stability analysis and nonlinear hybrid simulation of TAE modes with application to TFTR d-t experiments. G. Y. Fu, C. Z. Cheng, W. Park, and R. Budny.
1B2. Stabilization of MHD ballooning modes by sheared toroidal rotation. R. L. Miller, A. B. Hassam, F. L. Waelbroeck, and R. E. Waltz.
1B3. Transition to a thermally collapsed divertor plasma. T. D. Rognlien, D. A. Knoll, M. E. Rensink, and G. R. Smith.
1B4. Particle dynamics in chirped-wave and its application to tokamak plasmas. C. T. Hsu, C. Z. Cheng, P. Helander, D. J. Sigmar, and R. B. White.
1B5. Linked mirror neutron source concept. V. P. Pastukhov, V. I. Ilgisonis, H. L. Berk, and V. Wong.

MONDAY AFTERNOON

1C POSTER SESSION - Regency Ballroom
2:00pm - 4:00pm

1C1. Low-frequency short-wave-length electromagnetic fluctuations in a plasma: the general renormalized statistical approach with cross-field correlations. M. O. Vakoulenko.
1C2. Theory of low-frequency electromagnetic fluctuations in multicomponent plasmas: magnetic effects on the short-wave-length convective cells. P. P. Sosenko and M. O. Vakoulenko.
1C3. Nondissipative two-fluid theory of singular modes in toroidal geometry. L. J. Zheng and M. Tessarotto.
1C4. Monte Carlo operators for collisional transport theory. M. Tessarotto, R. B. White, and L. J. Zheng.
1C5. Tearing modes with multiple rational surfaces. M. Persson, R. L. Dewar, E. K. Maschke, and G. Urquijo.
1C6. Fast nonlinear growth of magnetic islands due to parallel electron pressure gradient. X. Wang and A. Bhattacharjee.
1C7. Stability of tearing modes in finite-beta plasmas. R. Iacono, A. Bhattacharjee, C. Ronchi, J. Greene, and M. H. Hughes.
1C8. Pressure-induced islands in three-dimensional toroidal magnetohydrodynamic equilibria. A. Bhattacharjee, T. Hayashi, N. Nakajima, and T. Sato.
1C9. Noether's theorem revisited: generalized symmetries and conservation laws for plasma fluid models. R. Acevedo and P. J. Morrison.

1C10. Statistical analysis of turbulence in the tokamak scrape-off-layer. S. Benkadda, T. D. De Wit, M. Endler, X. Garbet, A. Sen, and A. Verga.
1C11. The fluid approach to describe plasma rotation in non-axisymmetric systems using general toroidal flux coordinates. M. Coronado.
1C12. The influence of fluctuations on the plasma rotation in tokamaks. I. A. Voitsekhovitch, M. Coronado, and J. J. Martinell.
1C13. Fluctuation effects of the tokamak edge energy balance. J. J. Martinell.
1C14. Minimum ohmic dissipation states in plasmas sustained by DC helicity injection. R. Farengo and J. R. Sobehart.
1C15. ITER divertor: regimes with recombining plasma. T. K. Soboleva, S. Krasheninnikov, D. J. Sigmar, O. V. Batischev, and A. B. Kukushkin.
1C16. Path integrals, turbulence, and numerical tokamak. M. B. Isichenko.
1C17. Current drive and rf dynamo in two-fluid theory. C. Litwin.
1C18. Poloidal rotation of tokamak plasmas at super-poloidal-sonic speeds. A. B. Hassam.
1C19. New hamiltonian formulation for multi-fluid electrodynamics. J. Larsson.
1C20. Charge and current neutralization in the formation of ion rings in a background plasma. B. V. Oliver, D. D. Ryutov, and R. N. Sudan.
1C21. Gyrokinetic Vlasov equation for rotating axisymmetric tokamak plasmas. A. Brizard.
1C22. Theory of toroidal Alfven eigenmode saturation via nonlinear coupling to continuum. T. S. Hahm and L. Chen.
1C23. Reconstructing phase space dynamics from MHD fluctuations data in tokamaks. A. B. Rechester and R. B. White.
1C24. Feasibility studies of lower hybrid current drive in the MST reversed field pinch. E. Uchimoto, M. Cekic, S. A. Hokin, C. Litwin, S. C. Prager, J. S. Sarff, C. R. Sovinec, and R. W. Harvey.
1C25. Magnetohydrodynamic simulation on an unstructured, adaptive mesh. D. D. Schnack, Z. Mikic, I. Lotatti, P. Satyanarayana, and A. Turnbull.
1C26. Plasma boundary conditions. E. Hameiri.
1C27. Analytic results in the theory of reflectometry in multi-dimensional plasmas. B. B. Afeyan, B. I. Cohen, J. A. Crotinger, and E. A. Williams.
1C28. Progress in toroidal gyrokinetic simulations. J. A. Byers, A. M. Dimits, T. J. Williams, and B. I. Cohen.
1C29. Effect of electric drift on sheath structure near, and flows into, a toroidal limiter. D. D. Ryutov and R. H. Cohen.
1C30. Symmetric DC biasing effects on SOL instabilities. R. H. Cohen.
1C31. Implementation of a delta f implicit moment algorithm. B. I. Cohen, A. M. Dimits, X. Xu, and J. Stimson.
1C32. Rayleigh-Taylor mode equations for inverted-flow gas-target divertors. L. L. LoDestro, R. H. Cohen, and L. D. Pearlstein.
1C33. Drift wave propagation as a source of plasma edge turbulence II: nonlinear theory. I. Raskolnikov and N. Mattor.
1C34. Equilibrium current profile of a reversed field pinch. V. Smerdyakov and N. Mattor.
1C35. A core-edge time-dependent simulation through coupled 1D and 2D non-linear transport codes. A. Tarditi, R. H. Cohen, T. D. Rognlien, and G. R. Smith.
1C36. Fluids simulations of nonlocal dissipative drift-wave turbulence. X. Xu, R. H. Cohen, J. A. Crotinger, and A. I. Shestakov.

1C37. Large-gyroradius resonance processes: wave emission and absorption by hot alphas in nonuniform magnetic field. Y-M. Liang and A. N. Kaufman.
1C38. Energy partition among ion species in degenerate gyroresonant absorption. A. N. Kaufman, Y-M. Liang, A. Brizard, and E. R. Tracy.
1C39. Modelling of current profile control in the TPX and Alcator C-MOD devices. P. Bonoli and M. Porkolab.
1C40. Fokker-Planck simulation of radiative divertor plamsas. L. M. Montierth, D. A. Knoll, and V. A. Mousseau.
1C41. Impurity transport and radiation in radiative divertor plasmas. D. A. Knoll and P. R. McHugh.
1C42. Disruption-free toroidal confinement. L. C. Steinhauer.
1C43. An adaptive-hp finite element method for tokamak fluid transport. J. C. Wiley and D. W. Ross.
1C44. The radial structure of ion temperature gradient driven modes. F. Romanelli and F. Zonca.
1C45. Finite orbit effects on kinetic toroidal Alfven eigenmodes excited by energetic particles. S. Briguglio, G. Vlad, F. Zonca, F. Romanelli, and C. Kar.
1C46. Test particle diffusion in 2D turbulent flows; an explicit symplectic numerical scheme. I. Doxas, S. Tian, and W. Horton.
1C47. Propagation of the relativistic fusion-product ion cyclotron instabilities in tokamaks. V. Wong, W. Horton, and K. R. Chen.
1C48. Transport code simulations of recent experiments in large tokamaks. J. Weiland, H. Nordman, and G. Bateman.
1C49. Enhancing lower hybrid current drive with ICRF waves. A. K. Ram, A. Bers, V. Fuchs, and S. D. Schultz.
1C50. A comparative study of the effects of electric field shear on correlation and transport properties of turbulence. V. B. Lebedev and P. H. Diamond.
1C51. A kinetic theory ordering for the development of transport theory in the divertor. W. M. Stacey.
1C52. Revisiting charge-exchange effects on plasma flow. E. R. Solano, R. D. Hazeltine, and P. M. Valanju.
1C53. Isotope scaling and eta-i mode with impurity in tokamak plasma. J. Q. Dong and W. Horton.
1C54. Mathematica as a data analysis tool. W. H. Miner, H. Y. W. Tsui, J. C. Wiley, and A. J. Wootton.

1D POSTER SESSION - Regency Ballroom
4:00pm - 6:00pm

1D1. Optimal extraction of alpha particle power by waves. Z. H. Wang, M. C. Herrmann, and N. J. Fisch.
1D2. Reactor implications of diverting alpha-power to fuel ions. M. C. Herrmann and N. J. Fisch.
1D3. Spectra and correlation functions in toroidal ITG turbulence. M. A. Beer, G. W. Hammett, S. Cowley, and W. Dorland.
1D4. KTAE boundary layer procedure for modifying MHD shooting codes. H. L. Berk, M. Chu, and M. N. Rosenbluth.
1D5. Inertial-range scaling of 2D turbulence. J. C. Bowman.
1D6. Gyrokinetic simulations of rotation shear effects on toroidal ballooning modes. M. Kotschenreuther.
1D7. Lyapunov exponents, correlation functions, and transport coefficients. D. M. Barnett and T. Tajima.
1D8. Basic principles approach for studying nonlinear Alfven wave-alpha particle dynamics. B. N. Breizman, H. L. Berk, and M. Pekker.
1D9. Anisotropy and spectral indices for the driven-damped drift wave problem. W. Horton and W. Dorland.
1D10. Direct numerical simulation of inverted density profile ITG turbulence. W. Dorland, W. Horton, and G. W. Hammett.
1D11. Eta-i mode in neoclassical regime and neoclassical closure. M. Yagi, M. Azumi, J. P. Wang, and J. D. Callen.
1D12. Low beta MHD equilibrium and stability for anisotropic pressure closed field line plasma confinement systems. V. P. Pastukhov, V. I. Ilgisonis, and A. A. Subbotin.
1D13. Finite beta plasma equilibrium in toroidally linked mirrors. V. I. Ilgisonis, V. P. Pastukhov, and H. L. Berk.
1D14. Toroidal gyrokinetic simulation of eta-i mode fluctuations and transport in a radially sheared electric field. M. J. LeBrun, T. Tajima, W. Horton, and Y. Kishimoto.
1D15. Jitter stabilization of electrostatic drift waves. M. G. Prahovic, R. D. Hazeltine, and A. Thyagaraja.
1D16. Time dependent studies of advanced tokamak operating modes. A. H. Kritz, P. Bonoli, and M. Porkolab.
1D17. Ion orbit loss and the poloidal electric field. H. Xiao, R. D. Hazeltine, and P. M. Valanju.
1D18. Exploring the limits of the low q fusion power regime. R. F. Post.
1D19. Alfven wave analysis for Phaedrus-T. N. Hershkowitz and P. E. Moroz.
1D20. ICRF fast-wave analysis for TPX. P. E. Moroz, D. B. Batchelor, R. W. Harvey, and M. Porkolab.
1D21. Multi-species, self-consistent particle simulation of neoclassical transport. Z. Lin, W. W. Lee, W. Tang, and S. E. Parker.
1D22. Stability analysis of ionization fronts of gaseous divertor plasmas. J-S. Kim, P. H. Diamond, and J. Greene.
1D23. Ballooning stability of poloidally rotating plasma with a velocity shear. M. V. Medvedev and P. H. Diamond.

1D24. Divertor radial electric fields and the inboard-outboard asymmetry of DIII-D divertor legs. R. T. Ratt, A. V. Gruzinov, and P. H. Diamond.

1D25. Finite-time singularities in hydrodynamic plasma models. A. V. Gruzinov.

1D26. Turbulence suppression and drag reduction by external magnetic field. W. Zhang and P. H. Diamond.

1D27. Mode structure and stability of TAE modes in ITER and TFTR DT plasmas. J. Candy and M. N. Rosenbluth.

1D28. Pseudo-MHD ballooning modes in tokamaks. J. D. Callen and C. C. Hegna.

1D29. The effect of MHD tearing modes on the stability and transport properties of g-modes in the RFP edge. C. C. Hegna, J. D. Callen, S. C. Prager, and P. W. Terry.

1D30. Progress in the development of a 3D neoclassical-MHD simulation of a tokamak plasma. T. A. Gianakon, J. D. Callen, and C. C. Hegna.

1D31. Turbulent transport across invariant flux surfaces. J. B. Hollenberg and J. D. Callen.

1D32. Radial structure and stability of resistive ballooning modes in the presence of poloidal flow-shear in edge region of tokamak. C. S. Liu, S. V. Novakovskii, P. N. Guzdar, and J. F. Drake.

1D33. New unstable branch of the resistive ballooning modes. S. V. Novakovskii, P. N. Guzdar, J. F. Drake, C. S. Liu, and F. L. Waelbroeck.

1D34. 3D simulations of the resistive ballooning modes-revisited. P. N. Guzdar, J. F. Drake, and A. B. Hassam.

1D35. Truncated model study of the 2D Rayleigh instability. K. Hermiz, P. N. Guzdar, and J. M. Finn.

1D36. Rotation and toroidal effects on resistive wall kink modes. J. P. Freidberg and R. Betti.

1D37. Marfes in tokamaks. J. Kesner.

1D38. A 2D kinetic model of the scrape-off layer of a diverted plasma with a private flux region. J. W. Connor and P. J. Catto.

1D39. 2D kinetic modeling of a tokamak scrape-off layer with recycling. P. J. Catto, P. Helander, and R. D. Hazeltine.

1D40. Fluid equations for the neutral component in a partially ionized plasma. P. Helander and S. Krasheninnikov.

1D41. Simplified description of high-Z impurity transport in tokamak edge plasma. D. J. Sigmar, S. Krasheninnikov, and S. P. Hirshman.

1D42. Dense ITER divertor plasma modelling with Navier-Stokes neutrals. S. Krasheninnikov, D. J. Sigmar, D. A. Knoll, and P. R. McHugh.

1D43. On divertor plasma detachment. N. Krasheninnikova, S. Krasheninnikov, and D. J. Sigmar.

1D44. Bursting processes in plasmas and relevant non-linear model equations. B. Basu and B. Coppi.

1D45. Heat pinch and current diffusion resulting from coupled electron energy and current transport. R. Gatto, B. Coppi, F. Pegoraro, and L. E. Sugiyama.

1D46. Separation of plasma pressure and magnetic field evolution in a two fluid m = 1 reconnection process. L. E. Sugiyama and W. Park.

1D47. Hamiltonian formulation of low-frequency, nonlinear plasma dynamics. F. Pegoraro, T. J. Schep, and B. N. Kuvshinov.

1D48. Vertical instability analysis in noncircular deformable plasmas for the Ignitor experiment. M. Nassi, B. Coppi, S. Graziadei, C. Rita, and M. Roccella.

1D49. Growth rates of the ion cyclotron emission instability. C. Riconda, N. Asherie, and B. Coppi.
1D5Ø. Structure of compressional Alfven modes in cylindrical geometry. N. Asherie, B. Coppi, and C. Riconda.
1D51. Analysis of m = 1 mode stability in D-T plasma with fusion alpha particles. S. Migliuolo, B. Coppi, B. Rogers, and L. Zakharov.
1D52. Advanced fusion in ICRF heated plasmas. P. Detragiache, B. Coppi, S. Migliuolo, M. Nassi, and B. Rogers.
1D53. Anisotropic pressure effects on advanced operating regimes in tokamaks. M. W. Phillips, M. H. Hughes, and R. Budny.
1D54. MHD stability analysis of D-T plasmas in TFTR. M. H. Hughes and M. W. Phillips.
1D55. Self-organized critical gradient transport and L-H transition in the presence of ITG mode. T. Tajima, M. J. LeBrun, W. Horton, J. Q. Dong, W. Dorland, and Y. Kishimoto.

TUESDAY MORNING

2A REVIEW TALK - Regency Ballroom
8:3Øam - 9:2Øam
Presiding: J. Freidberg

2A1. Fast-ion driven Alfven instabilities in tokamaks. W. W. Heidbrink.

2B ORAL SESSION - Regency Ballroom
9:3Øam - 1Ø:3Øam
Presiding: K. Shaing

2B1. Stabilization of ideal kink modes in DIII-D by a resistive wall. A. Turnbull, T. S. Taylor, S. J. Thompson, E. J. Strait, J. R. Ferron, L. L. Lao, A. Bondeson, O. Sauter, and D. J. Ward.
2B2. Effect of a non-uniform resistive wall on the stability of tokamak plasmas. R. Fitzpatrick.

2C POSTER SESSION - Regency Ballroom
10:30am - 12:30pm

2C1. Alpha particle effects on the internal kink mode. Y. Wu and C. Z. Cheng.
2C2. 3D wall calculations for delta-W stability analyses. M. S. Chance, S. C. Jardin, J. Bialek, J. L. Johnson, and J. Manickam.
2C3. Steady-state transport in generic dissipative drift-wave turbulence. G. Hu and J. A. Krommes.
2C4. Stability of TAE modes in TFTR d-t experiments. C. Z. Cheng, G. Y. Fu, R. Budny, E. Fredrickson, S. J. Zweben, and Group. TFTR.
2C5. Numerical simulation of an experiment to test the feasibility of ponderomotive feedback stabilization for control of external kink modes .... S. C. Jardin, M. S. Chance, E. J. Valeo, D. A. D'Ippolito, and J. R. Myra.
2C6. Ponderomotive feedback stabilization of external kink modes in tokamaks. D. A. D'Ippolito and J. R. Myra.
2C7. Edge biasing and electron heating in RF fields. J. R. Myra, D. A. D'Ippolito, and R. Majeski.
2C8. An analysis of the nonlinear generation of sheared flow via E x B Mode coupling of the 2D ITG instability. J. C. Cummings, W. W. Lee, and R. A. Santoro.
2C9. Numerical study of stability of ultra high-beta equilibria. V. Drozdov, J. Manickam, L. Zakharov, and S. Cowley.
2C10. The validity of the extended energy principle. J. L. Johnson, R. M. Kulsrud, and M. S. Chance.
2C11. Ideal MHD analysis of single-divertor configurations in ITER. J. Manickam, D. A. Monticello, and M. W. Phillips.
2C12. Use of the PIES MHD equilibrium code for stellarator studies. D. A. Monticello, J. L. Johnson, and A. H. Reiman.
2C13. Study of effect of plasma rotation on external modes in tokamaks using the Princeton MH3D code. N. Pomphrey, W. Park, and D. J. Ward.
2C14. Linear and quasilinear analysis of toroidal drift modes in high-power TFTR DT shots. G. Rewoldt and W. Tang.
2C15. DEGAS modeling of the H-alpha spectrum on TFTR. D. P. Stotler, C. H. Skinner, R. Budny, H. Adler, and A. T. Ramsey.
2C16. Selfconsistent study of alpha-particle driven TAE mode. Y. Wu and R. B. White.
2C17. Rotating magnetic islands in a tokamak with applied resonant magnetic perturbations. A. I. Smolyakov, E. Lazzaro, J. D. Callen, and G. Re.
2C18. Study of sawtooth-stabilization on TFTR. Y. Zhao and R. B. White.
2C19. Gyrokinetic Vlasov simulation of eta-i modes. Q. P. Liu and C. Z. Cheng.
2C20. The effects of artificial hyper-viscosity and hyper-resistivity in MHD simulations of RFPs. C. R. Sovinec and D. D. Schnack.
2C21. Nonlinear frequency shifts in trapped electron driven drift wave turbulence. A. S. Ware and P. W. Terry.
2C22. Advanced tokamak scenarios in ITER and TPX. W. M. Nevins, J. Manickam, L. D. Pearlstein, R. H. Bulmer, and S. Haney.

2C23. Theory issues for TPX. R. J. Goldston and W. M. Nevins.
2C24. The direct criterion of Newcomb for the stability of an axisymmetric toroidal plasma. A. H. Glasser.
2C25. Psi-version of the DCON stability code. L. Zakharov and V. Drozdov.
2C26. Inertial-electrostatic confinement studies. T. N. Tiouririne, R. A. Nebel, D. C. Barnes, L. Turner, J. M. Finn, W. D. Nystrom, G. H. Miley, J. Javedani, and A. Satsangi.
2C27. Implementation of the quiet implicit PIC method in toroidal geometry. W. D. Nystrom, D. C. Barnes, and R. A. Nebel.
2C28. Penning fusion experiment and higher order multipoles-design, theory, and scaling. D. C. Barnes, T. N. Tiouririne, L. Turner, and R. A. Nebel.
2C29. Generalized two stream instabilities in Penning traps. L. Turner and J. M. Finn.
2C30. Rotation generation and damping mechanisms in tokamaks. J. M. Finn.
2C31. Comparison of fluid and non-fluid neutral models in divertor plasma transport simulations. K. A. Werley and R. Maingi.
2C32. New stellarator reactor concepts. J. A. Rome.
2C33. The performance of fluid codes on a dedicated Cray Y-MP C90. V. E. Lynch, B. A. Carreras, J. N. Leboeuf, and B. C. Curtis.
2C34. Parallel ion flow gradient-driven instability and the L-H transition. L. A. Charlton, B. A. Carreras, V. E. Lynch, and P. H. Diamond.
2C35. Full-wave ICRF modeling of electron heating and current drive by mode converted slow waves in tokamaks. E. F. Jaeger, M. Murakami, C. Y. Wang, D. B. Batchelor, R. Majeski, C. K. Phillips, and J. R. Wilson.
2C36. 3D modeling of RF current drive arrays. M. D. Carter, D. B. Batchelor, T. S. Bigelow, G. L. Bell, and D. J. Hoffman.
2C37. The dynamics of front-like and uniform transitions from L to H or VH modes. D. E. Newman, B. A. Carreras, and P. H. Diamond.
2C38. Fast wave poloidal flow generation in a plasma. C. Y. Wang, E. F. Jaeger, D. B. Batchelor, and K. L. Sidikman.
2C39. Nonlinear calculations of dissipative trapped electron modes with ion magnetic drift. K. L. Sidikman, C. L. Hedrick, and J. N. Leboeuf.
2C40. Shock formation in poloidally rotating helically symmetric plasmas. M. Wakatani and K. C. Shaing.
2C41. Effects of orbit squeezing on poloidal mass flow and bootstrap current in tokamak plasmas. K. C. Shaing, C. T. Hsu, and R. D. Hazeltine.
2C42. A high density, low temperature ignition regime for ITER. W. A. Houlberg and S. E. Attenberger.
2C43. Fitting eigenfunctions and suppressing noise in a Landau fluid approach to dissipative trapped electron modes. C. L. Hedrick, J. N. Leboeuf, and K. L. Sidikman.
2C44. Excitation of TAE/GAE shear Alfven modes by an energetic alpha population in the TFTR DT experiments. D. A. Spong, C. L. Hedrick, and B. A. Carreras.
2C45. Toroidal Alfven eigenmode growth and particle transport. M. Chu, C. Z. Cheng, and C. T. Hsu.
2C46. Effect of orbit squeezing on poloidal rotation in tokamaks. F. L. Hinton and Y-B. Kim.
2C47. Thermal runaway and momentum and energy transport by fast ions. Y-B. Kim and F. L. Hinton.
2C48. Channeling energy from alpha particles into RF waves in a reactor plasma. K. Kupfer, S. C. Chiu, and V. S. Chan.

2C49. New enhanced confinement modes predicted by a flow shear suppression model. G. M. Staebler, F. L. Hinton, and J. C. Wiley.
2C50. Shear flow generated by radiofrequency forces across resonant layers. V. S. Chan and S. C. Chiu.
2C51. Resonant and non-resonant effects due to RF. S. C. Chiu and V. S. Chan.
2C52. Electron cyclotron current drive for ITER. R. W. Harvey, W. M. Nevins, and G. R. Smith.
2C53. Incorporation of the NFREYA neutral-beam heating package into the EFIT equilibrium analysis code. B. J. Lee and L. L. Lao.
2C54. Stability of the internal kink mode with energetic circulating ions. R. Betti and J. P. Freidberg.

TUESDAY EVENING

RECEPTION - Regency Ballroom Foyer
6:00pm - 7:00pm

2E ORAL SESSION - Regency Ballroom
7:00pm - 9:00pm
Presiding: M. Chu

2E1. Small scale magnetic flux averaged magnetohydrodynamics. D. Pfirsch and R. N. Sudan.
2E2. Shear flow effects on low-frequency drift-type tokamak microinstabilities. M. Artun.
2E3. Nonlinear collisionless magnetic reconnection. F. Porcelli and M. Ottaviani.
2E4. Anomalous thermalization of fast ions in magnetized plasma due to two-gyro-stream instability. K. R. Chen, D. B. Batchelor, J. N. Leboeuf, V. Wong, and W. Horton.

WEDNESDAY MORNING

3A REVIEW TALK - Regency Ballroom
8:30am - 9:20am
Presiding: J. Van Dam

3A1. Collapse, intensification and reconnection in vortex dominated flows: visiometrics and modeling. N. Zabusky.

3B ORAL SESSION - Regency Ballroom
9:30am - 10:30am
Presiding: J. Van Dam

3B1. Nonlinear simulation of the current diffusive interchange mode. M. Yagi, K. Itoh, S. I. Itoh, A. Fukuyama, and M. Azumi.
3B2. Predictive transport modeling. D. Boucher and J. Wesley.

3C POSTER SESSION - Regency Ballroom
10:30am - 12:30pm

3C1. Spectral estimation of plasma fluctuations II: nonstationary analysis of ELM spectra. A. Sidorenko, K. S. Riedel, N. Bretz, and D. J. Thomson.
3C2. Anomalous kinetics of particles in the ergodic layer. S. S. Abdullaev and G. M. Zaslavsky.
3C3. Pseudo-spectrum of the resistive MHD operator: resolving the resistive Alfven paradox. D. Borba, K. S. Riedel, W. Kerner, G. T. A. Huysmans, M. Ottaviani, and P. J. Schmid.
3C4. Radiating edge plasma studies for ITER and TPX. B. Braams and D. Rayevski.
3C5. Convective drift-acoustic instabilities in the presence of sheared flows. F. L. Waelbroeck, J. Q. Dong, W. Horton, and P. N. Yushmanov.
3C6. Empirical models of plasma profiles and transport: a hierarchy of models. K. Imre, K. S. Riedel, and B. Schunke.
3C7. Shock waves in the tokamak edge plasma. D. Rayevski and B. Braams.

3C8. MHD simulations in divertor geometry. H. R. Strauss.
3C9. Low collisionality tokamak steady states. H. Weitzner.
3C10. A new method for the ergodic layer width estimation. G. M. Zaslavsky.
3C11. Turbulent transport in the presence of a strong rotation shear. P. N. Yushmanov.
3C12. Analytical aspects of dynamical processes in gas target divertors. G. G. Craddock, A. E. Koniges, and P. H. Diamond.
3C13. Gyrokinetic simulation of turbulent transport. W. W. Lee, R. A. Santoro, and S. E. Parker.
3C14. Properties of theory-based transport models. G. Bateman, J. Weiland, H-G. Gustavsson, J. Kinsey, and C. Singer.
3C15. Spontaneous seed current in tokamaks. S. Ma, J. M. Dawson, and F. Tsung.
3C16. Stable high beta tokamaks, reverse D tokamaks. S. Cowley.
3C17. Structure of Alfven waves with transverse scale on the order of the skin depth. G. J. Morales, R. Loritsch, and J. E. Maggs.
3C18. Computer simulation of transport driven current in tokamaks. W. J. Nunan, J. M. Dawson, and F. Tsung.
3C19. Evolution of trapped electron and ion temperature gradient-driven drift instabilities in the collisionless regime. R. D. Sydora and J. M. Dawson.
3C20. Analytical and numerical studies of plasma stability using a scalar representation of MHD. E. K. Maschke and G. Urquijo.
3C21. A numerical study of high-beta tokamak equilibria. R. G. Kleva, J. F. Drake, and A. B. Hassam.
3C22. Hamiltonian cell dynamics. B. A. Shadwick and P. J. Morrison.
3C23. DIII-D radiative divertor simulations. M. E. Rensink, M. Fenstermacher, G. D. Porter, and T. D. Rognlien.
3C24. A renormalization group approach to transition to chaos in an area preserving non-twist map. D. Del-Castillo-Negrete, J. Greene, and P. J. Morrison.
3C25. Ion impurities effects on anomalous transport in tokamak parametrically driven plasmas at electron cyclotron frequency. V. Stefan.
3C26. Monte Carlo calculation of the bootstrap current. M. Sasinowski and A. Boozer.
3C27. Disintegration of ion banana orbits in tokamak edge plasmas. Y. T. Lau, J. F. Drake, P. N. Guzdar, and A. B. Hassam.
3C28. Lower hybrid wave propagation in large aspect ratio tokamaks. L. Vahala, G. Vahala, and P. Bonoli.
3C29. Lattice Boltzmann approach to turbulence. G. Vahala, L. Vahala, and H. Chen.
3C30. Lack of magnetic confinement in a tokamak. N. A. Salingaros.
3C31. Global thermal transport and indications from the Alcator-CM experiment. B. Coppi, L. E. Sugiyama, and M. Greenwald.
3C32. Spectrum of radiation emission induced by fusion reaction products. B. Coppi, N. Asherie, and C. Riconda.
3C33. Generalized two-fluid theory of nonlinear magnetic structures. T. J. Schep, F. Pegoraro, and B. N. Kuvshinov.
3C34. Transport analysis of results in gyrokinetic tokamaks. H. E. Mynick and S. E. Parker.
3C35. Numerical evaluation of high energy particle effects in magnetohydrodynamics. R. B. White and Y. Wu.
3C36. Three-dimensional calculations using the quiet implicit PIC method. R. A. Nebel, D. C. Barnes, and W. D. Nystrom.

3C37. A numerical study of the neoclassical bootstrap current using adjoint functions. Y. R. Lin-Liu, F. L. Hinton, C. F. F. Karney, and S. P. Hirshman.

3C38. Progress on the simulation of toroidal ITG turbulence. R. E. Waltz, G. D. Kerbel, J. Milovich, and G. W. Hammett.

3C39. Chaotic transport analysis in hamiltonian systems. S. Benkadda, Y. Elskens, B. Ragot, and J. T. Mendonca.

3C40. Bootstrap current in non-axisymmetric tori. S. G. Shasharina, P. N. Yushmanov, and J. R. Cary.

3C41. Alpha current and radial transport driven by ICRH in a DT tokamak reactor. C. S. Chang and S. J. Moon.

3C42. Feedback control of tokamak instabilities. A. K. Sen.

3C43. A set of tokamak edge plasma fluid equations from first principles. R. B. Campbell.

3C44. Nonlocal theory of excitation of Trivelpiece-Gould mode in a plasma filled waveguide by plasma return current. N. K. Jaiman and V. K. Tripathi.

3C45. Neoclassical grad p-driven MHD instability in TFTR supershots. Z. Chang, J. D. Callen, E. Fredrickson, R. Budny, K. McGuire, S. Scott, and Team. TFTR.

3C46. A generic gyrokinetic PIC simulation code for parallel computers. T. J. Williams.

3C47. CORSICA: a comprehensive tokamak simulation code. J. A. Crotinger, R. H. Cohen, S. Haney, L. L. LoDestro, A. I. Shestakov, G. R. Smith, L. D. Pearlstein, T. D. Rognlien, A. Tarditi, and X. Xu.

3C48. Mode structure in the vicinity of an X-point. N. Mattor, R. H. Cohen, and X. Xu.

3C49. Toroidal simulations of ion-temperature-gradient turbulence. A. M. Dimits, J. A. Byers, T. J. Williams, and B. I. Cohen.

3C50. Transitions in rotating magnetofluids. X. Shan and D. Montgomery.

3C51. Three kinds of MHD equilibria. D. Montgomery and X. Shan.

3C52. Gyrofluid vortex cell structure and evolution. G. D. Kerbel and R. E. Waltz.

3C53. Semi-Lagrangian advection in tokamak gyrofluid turbulence simulations. D. E. Shumaker and G. D. Kerbel.

3C54. Parallel fully implicit algorithms for ITG gyro-Landau fluid tokamak turbulence simulations. J. Milovich, G. D. Kerbel, and R. E. Waltz.

Initial D-T Experiments on TFTR*

K. McGuire and the TFTR Group
Princeton Plasma Physcis Laboratory

The deuterium-tritium (D-T) experimental program on the Tokamak Fusion Test Reactor (TFTR), has begun. The initial phase of this program has achieved the goals of 1) demonstration of greater than 5 MW of fusion power, 2) measurement of escaping alpha particles, 3) testing of diagnostics for confined alpha particles and 4) the measurement of tritium transport. The fraction of tritium used in the neutral beam injectors was increased from less than 2% to 100% for a series of discharges during this initial phase. The highest fusion power achieved in this phase was 6.2 MW. Comparisons of the D-T discharges with similar D-D shots indicate that plasmas with significant tritium content exhibit higher plasma stored energy (W_{tot}), ion and electron temperatures ($T_i(0)$ and $T_e(0)$) and energy confinement time (τ_E) than the D-D plasmas. With 30 MW of neutral beam heating power (10 MW D and 20 MW T), the W_{tot} rose from 4.2 to 4.7 MJ, $T_i(0)$: 27 $\rightarrow$ 37 keV, $T_e(0)$: 9.5 $\rightarrow$ 10.3 keV and τ_E: 0.15$\rightarrow$ 0.18 s. Measurements indicate that the tritium influx at the plasma edge is quite low so that the tritium concentration in the plasma is lower than the tritium fraction of the neutral beams used to fuel the plasmas.

No instability behavior (e.g. TAE modes or kinetic ballooning modes) was observed in the D-T discharges, which could be attributed to the presence of alpha particles. The normalized Beta, β_N, of the D-T discharges was higher than that in the comparison D-D plasmas. The alpha particles appear to be well-confined and alpha-particle loss measurements are consistent with no anomalous particle loss.

Detailed analysis is underway to ascertain the relative importance of the power deposition profile, tritium transport, tritium and deuterium recycling and alpha particle heating in the changes observed for the D-T plasmas. Initial analysis indicates an isotopic scaling in the energy confinement time and are consistent with the expected α-heating.

In the second phase of D-T experiments on TFTR, the fusion power and alpha particle density will be increased in order to study alpha particle heating and transport and to study instabilities driven by the alpha particles. Up to 12 MW of ICRF power will be used to study the coupling in D-T plasmas, the interaction of RF with alpha particles, and to increase the alpha particle density. Early results of this second phase of experiments will be discussed.

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Linear Stability Analysis and Nonlinear Hybrid Simulation of TAE modes with Application to TFTR D-T Experiments

G. Y. Fu, C. Z. Cheng, W. Park and R.V. Budny

Princeton Plasma Physics Laboratory, Princeton University

Realistic kinetic calculations have been carried out to determine the linear stability of the toroidicity-induced Alfvén eigenmode (TAE) driven by energetic particles and its nonlinear saturation in a tokamak plasma. Recent experiments have shown that the TAE mode can be strongly destabilized by energetic ions. This can in turn lead to large losses of energetic particles. At present, D-T experiments in TFTR are being carried out to study influence of fusion alpha particles on the TAE modes. Thus, it is of interest to realistically determine the threshold conditions for exciting instability.

In the first part of this work, the stability thresholds of the TAE modes are calculated [1] using the global kinetic stability code NOVA-K [2] in tokamak equilibria with finite aspect ratio and finite beta. The effects of hot particle finite orbit excursion due to magnetic drift, and the collisional damping of trapped electrons are included, in addition to the usual Landau dampings of thermal ions and electrons. Continuum damping effects are also assessed using the resistive MHD code NOVA-R [3]. Our results show that the calculated stability threshold agrees within a factor of two with the measurements in TFTR experiments involving NBI-heating and ICRF heating, when the radiation damping is excluded. For the parameters of the recent TFTR D-T experiments, it is found that TAE modes are marginally stable, even in the absence of radiation damping.

In the second part, we use the MH3D-K code [4] to study the linear and nonlinear evolution of TAE modes driven by hot particles. This is a hybrid code which treats the thermal particles as a fluid and the hot species as gyrokinetic particles. The calculated growth rate of the TAE mode agrees reasonably well with that of NOVA-K results. In addition to the excitation of the TAE mode, our results indicate that a new $n=1/m=0$ global Alfvén eigenmode mode is induced by the hot particles with frequency about three times the TAE frequency. In the nonlinear regime, it is found that the wave particle trapping is important for the saturation of the TAE modes. Finally, the dependence of the energetic particle loss on the TAE mode amplitude will be presented.

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*Supported by DoE Contract No. DE-AC02-76-CHO-3073

[1] G. Y. Fu and C. Z. Cheng, Phys. Fluids B5, 4040 (1993).
[2] C. Z. Cheng, Phys. Reports 211,1 (1992).
[3] T. R. Harley et al., J. Comput. Phys. 103, 43 (1992).
[4] W. Park et al., Phys. Fluids B4, 2033 (1992).

1994 International Sherwood Fusion Theory Conference
Dallas, Texas, March 14–16, 1994

Stabilization of MHD Ballooning Modes by Sheared Toroidal Rotation

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Stabilization of MHD ballooning modes by sheared toroidal rotation is demonstrated using a shifted circle equilibrium model. A ballooning mode representation is used to generate a set of MHD fluid equations which are equivalent to the equations of Waelbroeck and Chen [1] and Grassie and Krech [2]. An initial value ballooning mode code solves these equations for the shifted circle equilibrium model. The $s - \alpha$ diagram of ballooning mode theory is extended to include rotational shear, s_{v}. In this ballooning mode representation, the modes convect with a velocity proportional to the toroidal shear rotation and inversely proportional to the magnetic shear. Stability improves with increasing mode velocity and direct stable access to the second stability regime occurs when the mode convection is approximately one-third to one-half the Alfvén velocity. The $s - \alpha$ curve for fixed toroidal rotation shear is modified in two ways depending upon the magnetic shear: at low enough magnetic shear complete stabilization occurs and for higher values of magnetic shear the unstable region is eroded on both the first and second stable sides of the $s - \alpha$ boundary. While enhancement of balloon stability in highly rotating discharges is predicted, direct comparison with experiments such as DIII–D will require a full geometric treatment; this full geometry work is in progress.

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[†]University of Maryland.
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[1] F.L. Waelbroeck and L. Chen, Phys. Fluids B **3** (1991) 601.
[2] K. Grassie and N. Krech, Phys. Fluids B **2** (1990) 536.

Transition to a Thermally Collapsed Divertor Plasma *

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The 2-D fully implicit fluid code UEDGE is used to study the transition to the thermally collapsed state of the plasma in the vicinity of the divertor plates of a tokamak. The physical model of the plasma is given by the Braginskii equations with the addition of anomalous transport across the magnetic field lines. The neutral gas is described by a 2-D diffusion equation from charge-exchange collisions for the neutral pressure with the addition of convection at the plasma velocity. These charge-exchange neutrals are found to dominate the Franck-Condon neutrals in the collapsed state. Ionization and recombination are included with temperature and density dependences. The plasma and gas equations are solved simultaneously on a 2-D flux-coordinate mesh for the complete scrape-off layer with either steady-state or time-dependent implicit algorithms.

The thermally collapsed state is characterized by high neutral densities in excess of plasma densities with low electron and ion temperatures near 1 eV. In this low-temperature state, poloidal energy transport is dominated by thermal convection over thermal conduction. The collapsed state can be produced by gas injection on the edge of the plasma or by increasing the impurity concentration. As the gas or impurity concentration is raised, the plasma solution exhibits a bifurcation from a moderately high-recycling state to the collapsed state. There are intermediate equilibria, but these are shown to be unstable by running the code in the time-dependent mode. Because gas pumping on the side walls is just the inverse of gas injection, it too influences the bifurcation.

We discuss the correspondence between the collapsed state and the so-called detached state observed in DIII-D, Alcator C-mod, and other tokamaks during gas injection. Common features include spreading of the heat profile, enhanced radiation, the inner divertor collapsing first, and a density build-up near the x-point. The relation to 1-D bifurcation models is presented.

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Particle Dynamics in Chirped-wave and Its Application to Tokamak Plasmas

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A common characteristic of an evolving nonlinear system is that the wave frequency excited in the system also evolves in time. Such behavior, referred to as frequency chirping, can be found in nonlinear optics, developing turbulent systems, and unsaturated systems with nonlinear wave-wave and/or wave-particle interaction. In particular, beam driven activities in tokamak plasmas, especially instabilities with bursting behavior such as *fishbone* oscillations[1], usually exhibit strong frequency chirping. It is therefore worthwhile to study particle dynamics in a chirped frequency fluctuation[2]. A one dimensional (1-D) Hamiltonian system with finite frequency chirping is used to illustrate (i) the formation of a phase space **bucket** which holds the trapped particle while convecting in phase space; (ii) the resonant kick for untrapped particles when they collide with the bucket; (iii) the existence of adiabatic invariance with finite frequency chirping. This investigation is then extended to the axisymmetric toroidal plasma system in which the motion in phase space due to chirped-wave is shown to result in radial convection. The applications of this new mechanism to the tokamak plasmas will be discussed. In particular, a scheme by launching controllable electromagnetic waves with chirped frequency to selectively redistribute charged particles radially in tokamak plasmas for the purpose of α-ash removal will be investigated.

1. M.F.F Nave, et al., Nuclear Fusion **31**, 697 (1991).
2. C.T. Hsu, , C.Z. Cheng, P. Helander, D.J. Sigmar, and R.B. White, (submitted to Phys. Rev. Lett.)

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Linked Mirror Neutron Source Concept*

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H.L.Berk and H.V.Wong
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Previous studies of mirror based beam-target neutron sources [1] have emphasized that the proven high beta containment inherent in mirror systems is highly advantageous for testing materials in a fusion environment. However, generally low electron temperature arises in open-ended mirror systems and reduces considerably the power efficiency of the source. Recently, we have proposed a toroidally linked mirror system (LMS) [2] which allows a target plasma electron temperature T_e of up to 2 keV due to the exclusion of end losses and correspondingly enhances the power efficiency of the source Q, which is proportional to $T_e^{3/2}$, up to 30%. The improved efficiency provides the possibility of an increase of the neutron exposed test surface to 2-3 m^2 for a given injection power, $P_{inj} \sim 50\,\mathrm{MW}$, and neutron wall loading $F \sim 5\,\mathrm{MW/m^2}$.

For the concept analysis we discuss the following problems: low beta MHD equilibrium and stability; toroidal beta limits arising due to FLR ballooning modes and finite pressure distortions of equilibrium plasma column; particle drift orbits, radial electric field and rotational stability; the cooling and the scattering of the hot ions, the relaxation of warm passing (scattered) ions; cross-field transport. The recent toroidal beta limit analysis and advanced theoretical study of the low beta MHD equilibrium and stability generally confirm the previous estimates [2] and enhance the reliability of the concept.

*Work supported by USDoE.

[1] H.L. Berk and D.D. Ryutov, Comments Plasma Phys. Controlled Fusion, **13**, 173 (1990).
[2] V.P.Pastukhov and H.L.Berk, Nucl. Fusion, **33** (1993).

LOW-FREQUENCY SHORT-WAVE-LENGTH ELECTROMAGNETIC FLUCTUATIONS IN A PLASMA: THE GENERAL RENORMALIZED STATISTICAL APPROACH WITH CROSS-FIELD CORRELATIONS

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The low-frequency (frequencies not exceeding the ion gyro-frequency) short-wave (wavelengths smaller than the ion gyro-radius) potential, cross-field and magnetic fluctuation spectra in a current-carrying plasma, are obtained within the new general renormalized statistical approach that accounts for correlations between potential and magnetic excitations. In general, there may exist stationary plasma states corresponding both to zero and constant fluxes of motion invariants along the spectrum. The cross-field correlations may break down the thermal solutions. The finite correlations between electric and magnetic fluctuations influence the relevant renormalized damping coefficients (renormalized widths), thus affecting the anomalous electron heat conductivity.

Partial support of this work was provided by a Soros Foundation Grant awarded by the American Physical Society.

THEORY OF LOW-FREQUENCY ELECTROMAGNETIC FLUCTUATIONS IN MULTICOMPONENT PLASMAS: MAGNETIC EFFECTS ON THE SHORT-WAVE-LENGTH CONVECTIVE CELLS

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A theory of low-frequency (frequencies not exceeding the ion Larmor frequency) electromagnetic fluctuations in plasmas was applied to obtain the short-wave (wavelengths smaller than the ion gyroradius) stationary spectra of potential and magnetic perturbations in a finite-pressure plasma. The growth of gasokinetic plasma pressure results in a decrease of the potential (density) spectrum amplitude. An additional broadening of this spectrum is provided by magnetic nonlinearities that are dominating in a plasma with finite electron beta. Thus the renormalized width of the convective spectrum exceeds much the value calculated within the potential approximation, and the coefficient of anomalous electron heat conductivity calculated is reduced.

Nondissipative two-fluid theory of singular modes in toroidal geometry

L.-J. Zheng and Massimo Tessarotto*

Braginskii's two-fluid equations, with collisional effects neglected and electron fluid assumed to be isothermal along the magnetic filed lines, are employed to obtain the singular mode equations. The parallel ion acoustic wavelength is assumed to be of the order of the curvature radius of magnetic field lines R, instead of order $-nq'x/(Rq)$ as adopted by Glasser [Phys. Fluids B, **3**, 2078 (1991)]. Our ordering assumption is shown to be more proper to describe the parallel motion of the ion fluid.

Three different frequency regimes are considered in our paper: the low, the comparable and the intermediate frequency regimes. They are distinguished by comparing the frequency of the modes to the parallel ion acoustic frequency. In contrary to common opinion, it is shown that, in the intermediate-frequency regime, the stabilizing FLR effect dominates over other nondissipative two-fluid effects. Therefore, to reveal the destabilizing two-fluid effects, especially those arising from the parallel electric field, the comparable frequency regime is pointed out to be the only relevant one. This conclusion is also true of the ballooning-mode theory. The other significant conclusion we want to emphasize here is that using the simplified equilibrium models, such cylindrical or slab ones, to describe the nonideal-MHD singular modes in the low- and intermediate-frequency regimes are inappropriate.

Our detailed results are described as follows: In the low-frequency regime, the FLR effect is recovered from taking into consideration the diamagnetic motion and gyroviscous tensor of the ion fluid. The toroidal effect is shown to give rise not only to the apparent mass effect, but also to an enhancement of the FLR effect. The toroidal FLR effect is even more important than that in the cylindrical model. In the intermediate-frequency regime, the parallel-electric-field-induced destabilizing effect is shown to be negligible as compared to the stabilizing FLR effect. The two-fluid description in this frequency regime actually applies only to the edge localized modes. The results show that the peeling modes (i.e., the free-boundary localized modes at the plasma edge) can be substantially stabilized by the FLR effect. In the comparable-frequency regime, the parallel ion acoustic wave with parallel-electric-field modification is coupled to the vorticity equation for singular modes. This induces a term in the singular mode equation which may resonate when the frequency of the modes is comparable to the parallel ion acoustic one. It is interesting to note that, due to the parallel electric field, this coupling could be destabilizing. This destabilizing effect could be important driving forces to the internal kink modes, the interchange modes, and so on. Since this effect has a similar origin as the apparent-mass effect in the low-frequency regime, it can be concluded that a proper description of this effect should rely on the toroidal geometry.

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MONTE CARLO OPERATORS FOR COLLISIONAL TRANSPORT THEORY

M.Tessarotto*, R.B.White∓ and L.J.Zheng*

A Monte Carlo approach for investigating the dynamics of quiescent collisional magnetoplasmas is presented. Its basic feature is that the Monte Carlo collision operators here obtained fullfill all the required conservation laws, i.e., linear momentum and kinetic energy conservation, and in addition that they take into account correctly also off-diagonal diffusion coefficients.

The purpose of this paper is to discuss a direct construction approach for Monte Carlo operators, describing the dynamics of a collisional magnetoplasma, and to compare it with methods based on approximate solutions of the discretized gyrokinetic Fokker-Planck equation [Tessarotto, White and Zheng, PPPL-2950 (1993); Phys. Fluids B, in press (1994)]. In particular, we aim to construct operators which fulfill the conservation laws characteristic of the exact Fokker-Planck collision operator, i.e., particle number, linear momentum and total kinetic energy. As an application, the case of a strongly rotating toroidal magnetoplasma close to local thermal equilibrium, recently investigated by Tessarotto and White [Phys.Fluids <u>B4</u>,859 (1992); Phys.Fluids <u>B</u>5,3942 (1993)] has been considered.

The Monte Carlo collision operators here obtained extend in several ways Monte Carlo collision operators previously constructed by other authors from kinetic theory, i.e., by Shanny et al. [Phys. Fluids <u>10</u>,1281 (1967)], Boozer and Kuo-Petravic [Phys.Fluids <u>24</u>,851 (1981)], Xu and Rosenbluth [Phys.Fluids <u>B3</u>, 627 (1991)]. Our results differ from previous ones in two main respects: a) momentum and energy conserving terms have been included in the present operators, describing the plasma response to the interaction of the test particles; in contrast, previous operators do not fulfill momentum and energy conservation; b) the Monte-Carlo operators are represented in terms of an arbitrary set of $\underline{v}$-space non-orthogonal coordinates and reproduce correctly also the off-diagonal diffusion coefficients in velocity-space. As a consequence, the neoclassical particle fluxes, carried by the discretized gyrokinetic distribution function, are strictly ambipolar. This property is particularly relevant, since for axisymmetric magnetic configurations it is a test of accuracy for particle simulation codes. A further important feature of the present Monte Carlo operators with respect to the particle-in-cell algorithm due to Takizuka and Abe [J.Comput.Phys. 25,205 (1977)], is that the present one is susceptible of applications to δf discretization schemes [Tajima and Perkins, Sherwood Meeting, (1983); Kotchenreuther, Bull.Am.Phys.Soc. <u>34</u>, 2107 (1988)]. The present operators are thus potentially useful for describing the dynamics of a multi-species toroidal magnetoplasma.

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Tearing modes with multiple rational surfaces

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Abstract

The linear stability and nonlinear evolution of tearing modes with multiple rational surfaces are discussed. Special attention is given to configurations with differential plasma rotation. It is shown that in such configutrations the nonlinear growth might be larger than exponential. The stability of finite size magnetic islands is also analyzed. It is demonstrated that there are configurations that are linearly stable which can be unstable to finite size perturbations. The effect of a wall of finite conductivity on linear stability and nonlinear evolution is also discussed.

Fast Nonlinear Growth of Magnetic Islands Due to Parallel Electron Pressure Gradient

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The main theme of this paper is that the presence of a parallel electron pressure gradient has a dramatic effect on the nonlinear evolution of tearing modes. We demonstrate[1] that for the m=1 instability, this effect can lead to a near-explosive growth of an m=1 island that can account for the *onset* (or fast trigger) of sawtooth oscillations which has been, heretofore, an unexplained feature of tokamak observations[2]. For m=2 instabilities, we show that the presence of this effect can change the dynamics of the island from a slow, algebraic Rutherford growth to exponential growth.

For the m=1 instability, there are three distinct nonlinear phases : a slow growth phase in which the island width w grows as t^2, a near-explosive phase in which w grows as $(t_c - t)^{-1}$, and a rapid decay phase in which w reduces rapidly after the island width becomes of the order of r_s, the radius of the singular surface. We derive a master equation that can account for the nonlinear dynamics of the island in all three phases. Using the constraint of helicity conservation[3], we describe the geometrical structure of the island separatrix as it evolves from a *Y*-point to nearly an *X*-point. These results are consistent with numerical results[4] based on the four-field model. The predictions of the model in the near-explosive phase are shown to be quantitatively consistent with X-ray emissivity data from JET.[2]

A crucial difference between the m=1 and the m=2 instability in tokamaks is that the former is characterized by current sheets in the early nonlinear phase. In the nonlinear regime, the m=2 island is generally believed to exhibit Rutherford-type behavior, with the island width w increasing linearly with t. We show that the presence of parallel electron pressure can change that to rapid exponential growth of the island (which should be contrasted with the near-explosive growth for m=1). Implications for major disruption phenomena in tokamaks will be discussed.

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Stability of tearing modes in finite-beta plasmas

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The linear stability of classical tearing modes in a finite-beta plasma is revisited. The different regimes of tearing mode instability are delineated by means of critical Lundquist numbers. The well-known criterion $\Delta' > \Delta_c$ due to Glasser, Greene and Johnson (Phys. Fluids **18**, 875 (1975)) can be simply viewed as defining a critical Lundquist number above which the plasma is stable. However, the physical importance of this Lundquist number is diminished by the fact that there is another critical Lundquist number, which is typically an order of magnitude smaller, above which the mode changes qualitatively in that the growth rate scales *linearly* with resistivity, and eventually becomes indistinguishable from resistive diffusion.

The effect of parallel viscosity is also considered. For large parallel viscosity, which diminishes the stabilizing effect due to the sound wave, it is shown that Δ_c tends to zero. Thus the stability criterion $\Delta' > \Delta_c$ for a finite-beta plasma is simply replaced by the criterion $\Delta' > 0$.

The analytical results stated above were motivated, in part, by computational results from the code ARES, with which they are shown to be in good agreement.

Pressure-induced islands in three-dimensional toroidal magnetohydrodynamic equilibria

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Recent analytical and computational results for pressure-induced magnetic islands in three-dimensional equilibria of currentless stellarators are compared. The role of singular currents in three-dimensonal toroidal equilibria and their resolution by magnetic island formation is discussed from both analytical and computational points of view. Earlier analytical results are extended to include small vacuum islands. In currentless stellarators, the formation of islands is determined by a combination of the resistive parameter D_R and the integrated effect of global Pfirsch-Schlüter currents. It is shown by a case-study that the "magnetic healing" effect, recently discovered computationally, is consistent with the predictions of analytical theory.

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Noether's Theorem Revisited: Generalized Symmetries and Conservation Laws for Plasma Fluid Models.

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We study generalized symmetries for systems of differential equations, namely, infinitesimal transformations of the most general kind that leave the system invariant, and use this information to construct conservation laws and possible reductions of the number of degrees of freedom. For systems arising from a Lagrangian formulation there exists a fundamental theorem due to E. Noether(1) who proved that for every infinitesimal transformation which is admitted by the action integral one can constructively find a conservation law. Finding conservation laws of a system is often the first step towards finding its solution. We present a detailed analysis of generalized symmetries and new conservation laws for some plasma fluid models for which we have studied the Lie point symmetries and analytic solutions induced by symmetry reduction(2).

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Statistical analysis of turbulence in the tokamak scrape-off-layer

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Langmuir probe data from Asdex tokamak and Aditya tokamak are treated with a variety of statistical tools. In particular, the observed fluctuations are analysed with the biorthogonal decomposition method. This enables us to test for the first time the experimental evidence of coherent structures in the SOL. Besides, bispectral analysis of these data is used to characterize the non linear coupling in turbulence. Preliminary results from numerical simulations of turbulence driven by interchange instability in SOL are compared to these experimental statistical properties observed.

THE FLUID APPROACH TO DESCRIBE PLASMA ROTATION IN NON-AXISYMMETRIC SYSTEMS USING GENERAL TOROIDAL FLUX COORDINATES

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The fluid approach to neoclassical transport theory and in particular to study the plasma rotation in non-axisymmetric systems has traditionally made use of the Hamada coordinates. In this paper it is shown that an equivalent formulation of the problem is also possible in general toroidal flux coordinates, such as the Boozer coordinates. Here the results from a previous work for the radial electrical conductivity and the evolution of the plasma rotation in presence of an external biasing with consideration of momentum damping due to viscosity and collisions with neutrals [1] are derived in general flux coordinates. This work results of practical use, since Hamada coordinates are not so widely known and employed as Boozer coordinates.

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THE INFLUENCE OF FLUCTUATIONS ON THE PLASMA ROTATION IN TOKAMAKS

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In this work the influence of the fluctuations on the plasma toroidal and poloidal rotation is discussed. This problem is of relevance for the L-H transitions and for the short stage before H-VH transitions, where simultaneously a change in the level and spectrum of fluctuations and in the magnitude of the rotation is seen.

To analyze the problem we use the quasilinear hydrodynamic approach including neoclassical and fluctuation effects.[1] The model considers the continuity and momentum balance equations for the average fluid variables and for the fluctuations as well as the ambipolarity condition for the full particle fluxes. The temperature of the plasma is assumed to be constant and the properties of the electromagnetic fluctuations are supposed to be given. The momentum balance equation includes the rotation damping due to the neoclassical viscosity and collisions with neutrals. The analytical solution of the quasilinear equations for the fluctuations provides expressions for the fluid fluctuations in terms of the electromagnetic fluctuations and the plasma parameters, such as density, ambipolar electric field and rotation. Using these expressions in the average momentum equation one can analyze the behavior of the plasma rotation for the different types of fluctuations.

In this work we treat the case of electrostatic fluctuations in a steady-state plasma, where the average momentum balance contains only the fluctuations and the collisions with neutrals. Having in mind the characteristics of the fluctuations in the L and H modes we analyze the dependence of the rotation on the level and spectrum of fluctuations assuming different models for them.

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FLUCTUATION EFFECTS OF THE TOKAMAK EDGE ENERGY BALANCE

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An analysis of the energy balance near the edge of a tokamak plasma including the relevant proceses expected during the L-H transition, can give information about the required conditions for a transition in the temperature gradient, as it has been recently shown [1]. It is also possible to gain an insight on the underlying transport processes as characterized by the temperature scaling of the thermal conductivity. In the present study the presence of fluctuations is explicitly considered in the energy balance equation in order to evaluate its effect on the allowed thermal equilibrium states. The conditions for the existance of multiple equilibrium states with different temperature gradients are determined for a given radial position (the LCFS). An evaluation of the radial variation of the temperature in the edge region is also discussed. As the size of fluctuations is changed the equilibrium temperature and its gradient vary as a result, and this can be used to determine the kind of fluctuations that can give rise to a transition. The results depend on the model used for fluctuations quenching and the resulting rotation reduction.

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MINIMUM OHMIC DISSIPATION STATES IN PLASMAS SUSTAINED BY DC HELICITY INJECTION.

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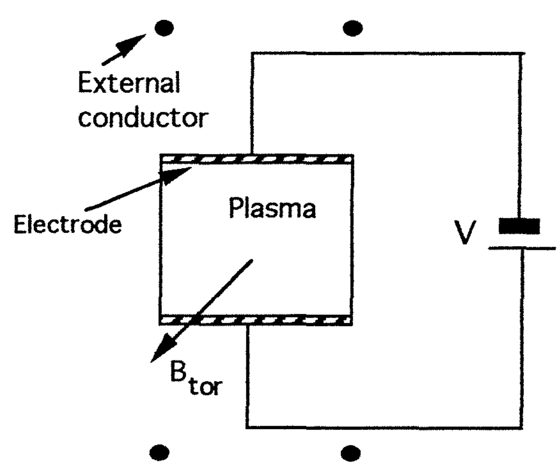
The current and magnetic field profiles of a steady-state, tokamak-like, plasma sustained by DC helicity injection are determined by assuming that it relaxes to a state where the Ohmic dissipation rate is minimum[1,2]. A 2D model is employed and helicity balance is impossed as a constraint.

The situation considered is shown in the figure. Two electrodes, insulated from the sides, are used to apply a DC electric field to the plasma while the external conductors provide the "magnetization" flux needed for helicity injection. The position and current of the external conductors are specified and their contribution to the total field is calculated self-consistently. An external, "toroidal" field is also included.

Closed flux surfaces are obtained indicating the possibility of good confinement in plasmas sustained by DC helicity injection.



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ITER divertor: Regimes with Recombining Plasma

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The possibility to establish regimes with a dense recombining hydrogen plasma in a divertor of ITER scale tokamaks is considered. It is shown that due to the large difference between effective heat transmission coefficients of neutral gas and plasma, the bifurcation of plasma parameters occurs near the target, resulting in the appearance of a cold neutral gas layer between the divertor plate and the plasma. An approximate criterion for establishing this regime is found to be: q_∞ [kW/cm^2] $< 1.5 n_{[14]}(T_e + T_i)_{[100eV]}$, where q_∞ is the heat flux coming to the plate from mid plane of SOL plasma, $n_{[14]}$ is the mid plane plasma density measured in 10^{14} cm^{-3} and $(T_e + T_i)_{[100eV]}$ is the sum of electron and ion temperatures measured in 100 eV.

It is shown that if the heat flux through the neutral gas layer is owing to a heat conduction mechanism, then the flame front separating the neutral gas layer and the hot plasma region can only be located far from the target, if the heat flux coming to the target from the SOL mid plane is practically completely reradiated. For ITER relevant parameters the reradiation of about 90% of the incoming energy will move the flame front to a distance of about few centimeters from the target. It may be assumed that exciting of large scale turbulent structures within a neutral gas layer may increase the effective heat conduction coefficient of a neutral gas, and hence, the distance between the target and the flame front.

Path integrals, turbulence, and numerical tokamak*

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All mathematical models of tokamak plasma used for simulation—fluid, gyrokinetics, etc.—belong to the class of partial (integro-)differential equations exhibiting chaotic behavior, or turbulence. The principal manifestation of the chaos is the sensitivity to the initial conditions, or the Lyapunov exponentiation of neighboring orbits in the infinite dimensional phase space of the system. Therefore any initial inaccuracy, which may be due to finite grid size, time step, or roundoff error, is exponentially enhanced by the dynamics, and there is very little hope, whatever the available computer power, to have quantitatively accurate predictions in terms of *individual orbits*, as far as many exponentiation time scales are concerned. The general attitude towards the results of computer simulation, then, is that they correctly represent certain *average quantities*. This work is an attempt to specify criteria for this optimistic attitude to be justified.

Addressing this issue requires understanding some general properties of the statistics of turbulence, on the one hand, and the statistics of its discretized, computer-code representation, on the other hand. As far as the high-temperature plasma is concerned, the dissipative effect are small, and the chaotic attractors describing the plasma dynamics are extremely multi dimensional. To this end, the phase space of tokamak turbulence can be considered essentially infinite dimensional, of which the computer code samples, and makes its predictions based upon, only a thin slice of its own finite dimensional representation.

A necessary requirement to be imposed on any physical probability functional $P[f]$ describing infinite dimensional turbulence is that any sequence of finite dimensional approximations (in terms of truncated Fourier modes, grid arrays, macro particles, etc.) converge to the same statistics. Contrary to the intuitive perception, based on the experience of integration in finite dimensional spaces, this requirement is far from formal and is in fact very restrictive. It is only fulfilled for Wiener probability functionals of the form

$$P[f] \propto \exp\left(-\alpha \int \left([(\partial_x)^n f(x)]^2 + F((\partial_x)^{n-1} f, (\partial_x)^{n-2} f, ..., f, x)\right) dx\right),$$

where the highest (nth) derivative of the field variable $f(x)$ enters the integral in the exponential quadratically. Otherwise, the result of averaging will significantly depend on the sequence of disretizations chosen to solve the path integral $\langle ... \rangle = \int ... P[f] \mathcal{D} f$.

The most familiar and physically motivated probability functional is the Gibbs ensemble, whereby a linear combination of all invariants of motion appears in the Boltzmann exponential. Then two distinct kinds of Hamiltonian systems are to be distinguished: (a) those with invariants quadratic in the highest-order-derivative variables and (b) those with invariants higher than quadratic in those variables. Of the plasma models in their respective small-dissipation limits, to the first category belongs only reduced MHD; to the second one belong all others, including η_i-type fluid equations, Vlasov-Poisson based models, and gyrokinetics. The first kind has well-behaved statistics, which can be correctly approached by any discrete model in the corresponding high-resolution limit. The second kind has statistics sensitive to the arbitrarily chosen discrete model, and one cannot rely on the simulation unless the grid (or whatever) samples the entire dimensionality of the multi dimensional attractor.

This state of affairs raises serious doubts in the very principle of the high-resolution computation of turbulent plasma adopted in the Numerical Tokamak Project, at least until the statistical nature of the tokamak turbulence is better understood.

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Current drive and rf dynamo in two-fluid theory

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Dynamo effect of propagating Alfvén waves can give rise to an electromotive force and resulting plasma current. In the MHD this effect is small, being proportional to the resistivity. It has been suggested that the inclusion of thermal effects can enhance the dynamo effect. We investigate them in the two-fluid theory. We find that, with the diamagnetic flow neglected, the dynamo effect is solely due to frictional forces. With the diamagnetic flow included, a collisionless dynamo effect arises. We discuss consequences of these effects for low-frequency current drive experiments.

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POLOIDAL ROTATION OF TOKAMAK PLASMAS AT SUPER-POLOIDAL-SONIC SPEEDS

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Tokamak plasmas rotating poloidally at speeds in excess of the poloidal sound speed are studied. The work is motivated by the propositions that perpendicular plasma flow shear could suppress turbulence[1,2] and improve confinement and that the poloidal sound speed is the critical speed to exceed for flow profiles spread out over the minor radius[2]. For such rapidly rotating plasmas, the corresponding Grad-Shafranov Equation is studied, the damping rate of the rotation is calculated, particle orbits in strong radial E fields are obtained, and a preliminary MHD stability study is done. It is found that for rotation speeds exceeding the poloidal sound speed but less that the poloidal Alfven speed no deleterious effects can be expected from the rapid rotation as regards the MHD equilibrium or stability. The damping rate of the poloidal rotation, for all collisionality regimes, is shown to fall off over the peak rate as u_p^{-2}, where u_p is the poloidal speed. This feature makes more efficacious the external driving of such poloidal flow, for example by Neutral Beam Injection, and allows favorable extrapolation to reactor-relevant regimes. Finally, it is shown that the fraction of trapped ions is significantly depleted in this regime, suggesting a reduction in the neoclassical heat transport as well. The efficacy of using NBI to attain such rotating states will also be discussed.

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New Hamiltonian Formulation for Multi-fluid Electrodynamics*

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Hamiltonian perturbation calculations for plasma theory is a goal with this research. It would be attractive to manifestly preserve the underlying Hamiltonian structure in the reduction to simpler models using asymptotic expansions in small parameters. The use of phase-space Lagrangians for this purpose have been suggested by Allan Kaufman[1]. For the Vlasov-Coulomb and the Vlasov-Maxwell models convenient Hamiltonian formulations has been found[2] in terms of phase-space Lagrangians for *extended* dynamical systems with the physical dynamics associated with *invariant subsets* of the phase-space of fields. The invariant subset has the interpretation as the dynamically accessible states. An illustration of the convenience of the new method is obtained by considering the small amplitude expansion. In particular, a very simple derivation of the pseudo-Hermitian structure of the linearised equations[3] is then obtained.

The convenience of the phase-space Lagrangian formulation is further illustrated in the derivation of the corresponding structure for ideal multi-fluid electrodynamics. This formulation was found by first considering the cold limit of the kinetic formulation. The pressure terms could then be inserted heuristically in a quite obvious way.

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Charge and Current Neutralization in the Formation of Ion Rings in a Background Plasma**

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Abstract

For typical field-reversed ion ring experiments, an intense ion beam is injected across a plasma-filled magnetic cusp and propagated into a solenoidal field downstream. The characteristic time τ satisfies $2\pi/\Omega_e \ll \tau \leq 2\pi/\Omega_i$ and the background plasma can be modeled as an electron magnetohydrodynamic (EMHD) fluid. In the nearly collisionless regime, such that $\nu_e \ll \Omega_e$, the plasma response is governed by the whistler mode. The role of the wall boundaries in such experiments to control the charge and current neutralization of the injected beam is considered for axisymmetric $\frac{\partial}{\partial\theta} = 0$ geometry. It is found that for close enough conducting walls, such that the whistler transit time to the wall is short compared to the beam transit time, effective control of the return currents can be established such that current neutralization can be suppressed while maintaining good charge neutralization.

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GYROKINETIC VLASOV EQUATION FOR ROTATING AXISYMMETRIC TOKAMAK PLASMAS*

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The gyrokinetic Vlasov equation is derived in a particle phase-space frame moving with the equilibrium fluid velocity $\mathbf{u}(\mathbf{r}) \equiv \int d^3v\ \mathbf{v}\ F(\mathbf{r},\mathbf{v})/N(\mathbf{r})$, where F is the equilibrium Vlasov distribution and N is the equilibrium density. Our work is based on the Phase-space Lagrangian Lie-transform approach, originally used by Littlejohn [1] to study guiding-center theory in the absence of equilibrium flows. Although our derivation considers equilibrium flows in general magnetic geometry, we focus our attention on incompressible equilibrium flows in axisymmetric tokamak geometry. The ordering used for these equilibrium flows is consistent with experimental observations of primary-ion rotation velocities in H-mode DIII-D plasmas [2], which show that $\mathbf{u} \equiv K\ \nabla\zeta\times\nabla\psi - W\ R^2\nabla\zeta$, where $W \equiv \omega - KI/R^2$ denotes the toroidal rotation frequency and $K(\psi) \equiv u_\theta/B_\theta$ denotes the strength of the equilibrium poloidal rotation velocity. Here, $\omega(\psi) \equiv c\ [\Phi'(\psi) + P'(\psi)/eN(\psi)]$ is the perpendicular rotation frequency, where Φ is the equilibrium electrostatic potential, and N and P are the equilibrium density and pressure, respectively. Also, in contrast to earlier works [3], the equilibrium rotation velocity has a nonvanishing poloidal component ($K \neq 0$) as a result of non-standard neoclassical effects due to orbit squeezing associated with sheared radial electric fields [4].

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Theory of Toroidal Alfvén Eigenmode Saturation via Nonlinear Coupling to Continuum†

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We investigate a novel nonlinear saturation mechanism of TAE mode analytically. Since a discrete TAE mode has a frequency very near $\left(\sim r/R \cdot \omega_A\right)$ to the Alfvén continuum, it can nonlinearly couple to the continuum via Compton scattering off back ground thermal ions when $(r/R)^2 \lesssim \beta_i$. A TAE mode saturates when the nonlinear pumping rate due to ion Compton scattering reaches the linear continuum damping rate. For typical large tokamak parameters, our results indicate $\delta B_\theta / B_\phi \lesssim 10^{-3}$.

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Reconstructing Phase Space Dynamics from MHD Fluctuations Data in Tokamaks *

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Symbolic dynamics provides a means of partitioning phase space so that information concerning the underlying dynamics is embedded in the partioning [1,2]. We attempt to reconstruct the phase space dynamics using only time record of Mirnov coil data of MHD fluctuations from PBX-M tokamak. To accomplish this we first descretize output data and present them in symbolic form. Maximizing metric entropy we are able to determine the most appropriate symbolic language. The second step is to use this symbolic presentation for partitioning the phase space. We choose one, two, etc., time delayed variables and then perform symbolic coarse graing in such restricted phase space [2]. We first tested this method for the "data" generated from well known models.

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Feasibility Studies of Lower Hybrid Current Drive in the MST Reversed Field Pinch*

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Magnetic stochasticity produced by nonlinear interactions of large amplitude resistive tearing instabilities is believed to be the primary cause of the anomalous transport in a reversed field pinch. The amplitudes of these instabilities can be reduced by modifying (i.e., flattening) the poloidal current profile in the outer region ($0.6a < r < a$) of the plasma and this would in turn increase the energy confinement time. Such an improvement has been observed in the pulsed poloidal current drive experiment[1] and also in numerical results[2] utilizing the 3-D resistive MHD code DEBS. To sustain an improved confinement state, it is desirable to employ an active control method which is noninvasive and nontransient. To this end, we are studying the use of radio frequency current drive in the poloidal direction.

One promising candidate is found to be lower hybrid current drive (LHCD) in a frequency range of $2\sim3f_{LH}$. Analytic estimates, neglecting toroidal magnetic shear, suggest that, in a typical MST discharge, the slow wave of frequency f = 200~300 MHz with $n_{||}$ ~10 would penetrate to $r \sim 0.6\text{-}0.7a$ after making two to three poloidal turns. In this zone the electron temperature T_e = 150~200 eV and electron density $n_e = 6\sim8\times10^{12}\text{cm}^{-3}$, and significant electron Landau damping can be expected. The current drive efficiency could be as high as 0.4 A/W.

To refine our analysis, we are modifying a version of Brambilla's ray tracing code for the tokamak to accommodate the reversed field pinch configuration. Preliminary ray tracing results, suppressing toroidal magnetic field variations, are consistent with the analytic estimates. Ray tracing results will be coupled to the 3-D Fokker-Planck code CQL3D and to the 3-D resistive MHD code DEBS. Effects of a driven current on the large amplitude tearing fluctuations will be examined.

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MAGNETOHYDRODYNAMIC SIMULATION ON AN UNSTRUCTURED, ADAPTIVE MESH*

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Progress in the numerical solution of the primitive, three-dimensional, time-dependent, resistive MHD equations on an unstructured, adaptive poloidal mesh is reported. 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 exactly conserves mass, energy, and magnetic flux. Two-dimensional results pertaining to both hydrodynamic[1] and MHD[2] shocks have been previously reported[3]. Here we present results pertaining to dynamical adaption and local refinement of the mesh when computing moving discontinuities in both hydrodynamics and MHD.

We have also developed a semi-implicit method 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. Performance of the method on three-dimensional problems relating to the equilibrium and stability of a model ITER plasma will be presented.

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Plasma Boundary Conditions

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When a magnetic field intersects the plasma boundary, as in the scrape-off layer of a tokamak or in many astrophysical situations, the electrical properties of the wall affect the plasma behavior through the inducement of boundary conditions different from the usual tokamak conditions. We have developed a number of boundary conditions appropriate for various situations such as hard walls with finite resistivity or the presence of a cold plasma layer near the boundary (as in the lower solar atmosphere). The method of solution is to find asymptotically the general solution of the relevant electromagnetic field equations within the wall or boundary layer, to impose the conditions appropriate deep in the boundary, and to use these restrictions on the general solution evaluated at the plasma edge as boundary conditions. A relatively simple example for this procedure may be found in Ref. 1. One of the difficulties in this method is that the resulting boundary conditions may be *nonlocal*, relating different boundary values at different points and times. This is caused by wave motion and multiple reflections within the boundary layer. To simplify matters it is necessary to approximate the boundary conditions by either Taylor or Padé expansions. However, some of these simplifications may give rise to ill-posed initial-boundary value problems[2], and care must be exercised in choosing the right approximation.

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Analytic Results in the Theory of Reflectometry in Multi-Dimensional Plasmas*

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Whereas earlier efforts to model reflectometry have concentrated on 1-D models of plasmas, their success in matching experimental signatures has been limited.[1] Recent careful measurements of reflectometry signals from controlled plasmas reveal the extent of these discrepancies quite clearly.[2]

In an attempt to assess the role played by multi-dimensional effects on these measurements, we have developed analytical models that allow the density fluctuations as well as the microwave field to have 2 and 3-D structure. In addition, the background plasma is allowed to have inhomogeneity in more than one dimension.

Green's function techniques are used to evaluate the reflected field due to density fluctuations in first Born approximation.

The effects of structures in the transverse directions of the density fluctuations alone and of the input field pattern itself are studied individually, and non-one-dimensional behavior is thus isolated and shown. Attempts will also be made to compare these theoretical results to UCLA experiments and numerical simulations of the full wave equations.

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Progress in Toroidal Gyrokinetic Simulations.[1]

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Our three-dimensional toroidal gyrokinetic code uses a quasiballooning-coordinate formulation[2] which gives uniformly optimal spatial resolution and allows a seamless implementation of toroidal periodicity conditions. We report on several developments towards the incorporation of realistic physical effects into the code. (A) Our formulation allows a straightforward inclusion of arbitrary poloidal-angle dependences of the magnetic field strength and local magnetic shear. This is of particular importance for the simulation of tokamaks such as DIII-D and ITER, which have noncircular cross-sections and divertors and for which the constant-shear circular-cross-section model is inadequate. We will give the details of this inclusion and show simulation results for toroidal ion-temperature-gradient turbulence that address the importance of these effects. (B) Because our formulation does not rely on a radial Fourier representation for the smoothing and field solves, we have been able to include a generalization which we have developed of Kotschenreuther's offset-periodic radial boundary condition to allow simulations with externally driven sheared flows, and without quasilinear profile relaxation. (C) A like-particle δf collision operator[3] has been incorporated into the code. As a check of this operator in the toroidal setting, we show that it does not result in neoclassical particle transport. Details of the diagnostics needed to determine rates of neoclassical poloidal flow damping will be presented, along with results. The effects of realistic magnetic geometry and orbit squeezing, due to radially varying radial electric fields, on neoclassical processes will be investigated. (D) A new interpretation of quasiballooning coordinates in toroidal-poloidal Fourier space is given, based on a formula previously derived.[2] The transformation from toroidal-poloidal coordinates to quasiballooning coordinates corresponds to a shift of the quasiparallel wavenumber into the lowest Brillouin zone. This shift is easily accomplished in practice with a wavenumber table and offers very simple method for the implementation of quasiballooning coordinates. This method will be valuable for implicit-moment-PIC codes and Landau-fluid codes where parallel wavenumber representation is most economical.

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Effect of Electric Drift on Sheath Structure Near, and Flows into, a Toroidal Limiter *

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We consider the effect of an electric drift on the sheath structure and flows into a toroidal limiter or poloidal divertor. We consider a simple model of a magnetic field obliquely incident on absorbing parallel plates, with an $\boldsymbol{E} \times \boldsymbol{B}$ drift contributing to a flow toward one of the plates, and describe the plasma by fluid equations. We demonstrate that, at the plates, the velocity normal to the plates (projection of parallel flow plus drift) must equal or exceed the normal projection of sonic flow along field lines. The density asymmetry associated with the $\boldsymbol{E} \times \boldsymbol{B}$ drift is shown to drive a parallel current through the SOL; this current can be an appreciable fraction of the ion saturation current for realistic parameters. For the case where the $v_{\mathbf{E}} \times \boldsymbol{B} > 2c_s \sin\theta$, where θ is the angle between the field and the plates, the plasma "detaches" from one plate, with only a tail in the ion distribution providing connection to that plate. In this limit, we develop a description of the sheath structure and particle orbits at the opposite plate. In particular, when the limit where the electron gyroradius is large compared to the Debye length, an electron with energy too low to escape over the Debye sheath reflects off of it many times before leaving the sheath region, and as a result makes a radial excursion of order $\rho_e / \sin\theta$. This is a potentially significant source of electron transport in the SOL.

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Symmetric D.C. Biasing Effects on SOL Instabilities*

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We consider the effect on scrape-off layer instabilities of a symmetric DC bias, in which conducting plates at either end of a field line are biased together with respect to ground. Such biasing has been demonstrated experimentally to have an appreciable effect on turbulence levels.[1] Nedospasov noted that the equilibrium parallel current set up in response to the driven radial current alters the sheath impedance, and considered the resulting effect on curvature-driven interchange modes.[2] Ryutov, Tsidulko and Berk[3] noted that two additional significant effects, the change in the radial electric field in the plasma and the electric field between the biased an unbiased portions of the end wall, tend to cancel. There are at least four additional effects: a radial gradient in the equilibrium parallel current, which modifies the dispersion relation by introducing a distinction between Eularian and Lagrangian current perturbations; perturbation of the process giving rise to the equilibrium radial current (which is modeled as a cross-field mobility term); change of the Kelvin-Helmholtz drive from shear in the $\boldsymbol{E} \times \boldsymbol{B}$ rotation; and, competing with the latter at the nonlinear level, change in the reduction of eddie size by velocity shear.[4] We assess the sign and relative importance of these effects for situations where the curvature or conducting wall drives dominate. In addition, we note that the perturbation of the radial mobility term can lead to instability even in the absence of the other drives, and even in the presence of only the naturally occuring radial electric field. If the mobility is due to ion-neutral collisions, the growth rate increases with neutral density, which is of potential importance for gas-target divertors.

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Implementation of a δf Implicit Moment Algorithm*

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An implicit δf electrostatic algorithm has been developed for gyrokinetic ions and drift-kinetic electrons. The basic algorithm presented is generally applicable to diverse particle simulation models. The methodology is derived from the recent work of Dan Barnes and co-workers[1] and extends earlier work on orbit-averaged implicit particle codes.[2] A δf particle description[3] (in this case for the electrons) is used to close the continuity and momentum conservation fluid equations by providing a kinetic pressure tensor. The particle equations of motion are advanced explicitly and can be subcycled in time with respect to the field equations (and the gyrokinetic ion advance in this case). The accumulation of the pressure tensor can be numerically orbit averaged to ease the statistical constraints on the orbit-averaged kinetic species. By adding and subtracting an isothermal fluid approximation to the pressure tensor, and evaluating the added fluid pressure implicitly, as was done in previous work on the implicit moment algorithm,[4] an additional improvement in stability and convergence is achieved.

The fluid equations are implicitly differenced in time and solved simultaneously with the gyrokinetic Poisson's equation using a combination of Fourier methods and a one-dimensional periodic tri-diagonal matrix solve in the direction of the shear variation of the magnetic field. The requisite Bessel functions have been replaced with a Pade approximation. Care must be taken to ensure that solutions of the matrix equation remain well behaved because one of the matrix eigenvalues is zero. In the companion work of Xu and co-workers, these methods are extended to include electromagnetic effects.

Dispersion analyses and supporting simulation results illustrate the desirable properties of this algorithm. We will check the new algorithm against published results of simulations of ion-temperature-gradient instability with kinetic ions and electrons.[5]

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"Rayleigh-Taylor" Mode Equations for Inverted-Flow Gas-Target Divertors*

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Gas-target divertors employ a region of cold high-density gas with the aim of absorbing much of the core-plasma flux before it reaches the plate. Two-dimensional simulations indicate that such steady-states can exist, and indeed flow patterns with $v_{\|}$ reversed along some field lines have been observed.[1] It has recently been proposed, however, that such configurations are intrinsically unstable to a Rayleigh-Taylor-like mode, driven by the braking forces parallel to the magnetic field and in the direction of decreasing density.[2]

In this paper we develop an equation to describe such modes using the finite-Larmor-radius paraxial Lagrangian formalism of Newcomb,[3] to which we add a density- but not momentum-conserving Krook collision operator modelling charge exchange with neutrals. The ordering scheme is that of Rosenbluth and Simon,[4] and we order $\nu_{col} \sim \partial/\partial t$. A fully nonlinear, arbitrary β, arbitrary (but paraxial) 3D geometry, fluid-like equation is obtained for the field-line motion. No assumptions (apart from the assumed orderings) to obtain closure for the fluid moments are required. We compare to a linearized, electrostatic, straight field-line calculation, and to the linearized Braginskii equations in the $\nu_{col} \ll \Omega_c$ regime.

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Drift Wave Propagation as a Source of Plasma Edge Turbulence II: Nonlinear Theory

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In a recent work,[1] we hypothesized that edge turbulence in magnetized plasmas is caused by drift waves generated in the core and propagating to the plasma edge, where they reach the observed amplitudes. This previous work used linear ray tracing to analyze of drift wave propagation. Here, we make a first attempt to develop nonlinear corrections to this theory.

Nonlinear drift wave propagation obeys the wave kinetic equation,[2] which is a continuity equation for wave action,

$$\frac{\partial}{\partial t} N_{\mathbf{k}} + \nabla \cdot (N_{\mathbf{k}} \nabla_{\mathbf{k}} \omega_{\mathbf{k}}) = \gamma_{\mathbf{k}}^{\mathrm{lin}} N_{\mathbf{k}} + \gamma_{\mathbf{k}}^{\mathrm{CS}} N_{\mathbf{k}} + D_{\mathbf{k}} \nabla^2 N_{\mathbf{k}} - S_{\mathbf{k}},$$

where $N_k = E_{\mathbf{k}}/\omega_{\mathbf{k}}^{\mathrm{local}}$ is the wave action, $E_{\mathbf{k}}$ is the wave energy, $\omega_{\mathbf{k}}^{\mathrm{local}}$ is the frequency in the plasma rest frame, $\gamma_{\mathbf{k}}^{\mathrm{lin}}$ is the linear growth rate, $\gamma_{\mathbf{k}}^{\mathrm{CS}}$ is the nonlinear ion Compton scattering rate, and the remaining terms represent fluid-like resonances, which may not be accurately described weak turbulence theory.

As a preliminary scenario, we consider the following. In the plasma core, wave amplitudes are determined by the balance of linear growth and Compton scattering, which couples unstable long wavelength modes to stable modes at much shorter wavelength but comparable frequency.[3] This determines a saturation amplitude, which generally is low enough that fluid wave resonance is subdominant. As waves approach the edge region (characterized by low density and temperature), $\tilde{n}/n_0$ grows to a point where fluid wave resonance becomes more important, allowing drift wave breaking. The specific nature of wave breaking (subscale instability, soliton formation, *etc.*) will be addressed.

This preliminary scenario is analogous to surface waves in the ocean.[3] In the deep sea, wave instability saturates by coupling to stable capillary waves at short wavelength, which are damped by surface tension. As these waves approach the shore, they approach a different regime, steepen, and break.

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Equilibrium Current Profile of a Reversed Field Pinch

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In a reversed field pinch (RFP) the profile of J_0/B_0 generally is peaked on axis, not a constant as predicted by the Taylor minimum energy theory.[1] Kadomtsev has recently noted[2] that the observed J_0/B_0 profile is generally about midway between the Taylor profile and the profile of the older "paramagnetic model."

Here, we offer a possible explanation for this situation. The equation describing $\mathbf{B_0}$ is the equilibrium Ohm's/Faraday's Law in a cylinder

$$\frac{\partial}{\partial t}\mathbf{B_0} = \nabla \times \left\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \right\rangle + c\nabla \times E_z^{\text{induced}} + \frac{\eta c^2}{4\pi}\nabla^2 \mathbf{B}_0. \tag{1}$$

Here, we assume constant resistivity, η, noting that varying η itself can produce a peaked J_0/B_0 profile. The essence of the present theory is the treatment of the term $\nabla \times \left\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \right\rangle$, which describes the action of the dynamo and is necessary for the maintenence of field reversal. This term may be viewed as the end result of an inverse cascade of helicity, bringing with it a minimum amount of energy. The dynamo thus acts as a *source* term, continually supplying magnetic field, $\delta\mathbf{B}$, in the Taylor profile. This motivates the following "source model" for the dynamo term:

$$\nabla \times \left\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \right\rangle = \gamma \left(\mathbf{B}^{\text{Taylor}} - \mathbf{B}_0\right),$$

where γ is the inverse cascade rate, $\mathbf{B}^{\text{Taylor}} = B\left(J_0(\mu r)\hat{z} + J_1(\mu r)\hat{\theta}\right)$, and γ, B and μ are constants to be determined by the constraints of energy and flux conservation.

Once Eq. (1) is modelled, the equations can be closed with the usual Ampere's Law and force free assumption, $(4\pi/c)\,\mathbf{J}_0 = \nabla \times \mathbf{B}_0 = \lambda(r)\mathbf{B}_0$, of course with nonconstant λ. Thus, the last two terms in Eq. (1) contain the essence of the paramagnetic model, in which inductive drive balances resistive dissipation. Viewed this way, the dynamo is a *source,* driving toward the Taylor profile, while resistivity is the *sink,* driving toward the paramagnetic profile; the net profile should generally be midway between source and sink profiles.

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A Core-Edge Time-Dependent Simulation through Coupled 1D and 2D Non-Linear Transport Codes

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The non-linear transport code UEDGE for 2D-axisymmetric modelling of the tokamak edge plasma has been coupled to a 1D non-linear code that simulates the radial transport within the core region in the slab approximation. The coupling has been performed for the electron density and temperature equations, for each one independently, and then for both simultaneously. In this last case the 2D code is coupled to two copies of the 1D code, one for each variable: the 1D code is still in fact a single variable code.

The coupling is realized through a domain decomposition algorithm that allows each simulation domain to be solved directly without iteration. The core density or temperature 1D profile is joined to the corresponding 2D profile in a region close to the magnetic separatrix, but yet far enough from it that the 2D effects remain negligible. The constant, imposed boundary condition for the inner surface of the 2D code thus becomes a time-varying value that results from the simultaneous and self-consistent solution of the 2D and 1D transport equations.

The method allows one to consider different spatial and temporal scales in the two models (as well as different number of spatial dimensions): the coupled codes are in effect independent codes that share some common physical quantities.

The solution, already obtained in the equilibrium state [1], is here followed in the time-dependent mode. The non-linear 2D solver (a preconditioned Krylov package for ODE's) has been rearranged in a way to allow a direct coupling at the stage of the linear solution that is performed at every iteration step. The time evolution of the profiles towards the equilibrium is reproduced through a variable step size scheme (controlled by the 2D solver).

The results show evidence of the reciprocal influence between the core and edge region of a density perturbation (*e.g.*, gas puffing on the edge) or of a temperature perturbation (*e.g.*, core plasma heating). Such effects cannot be seen by simulating a single plasma region, core or edge. The coupling scheme enhances the overall realistic character of the simulation with respect to the case of the 2D edge model with fixed core boundary values and appears to be a versatile tool for the effort in progress towards the development of more elaborate models.

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Fluids Simulations of Nonlocal Dissipative Drift-Wave Turbulence

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A $2d(x, y)$ fluid code has been developed to explore nonlocal dissipative drift-wave turbulence and the anomalous transport.[2] In order to obtain a steady state turbulence, we force the ensemble averaged fluctuation density $<n>$ to be zero in simulations, thus avoiding the difficulty of choosing proper sources and sinks in turbulence simulation codes. For $L_n > L_c$ and $L_k > L_c$, where L_c is the turbulence correlation length, L_n the density gradient, and L_k is the curvature of density profile $(L_k^{-1} = (L_n/n_0(x))(d^2n_0(x)/dx^2))$, we have shown that local turbulence simulations give reasonable results. While $L_n \sim L_c$ or $L_k \sim L_c$, turbulence eddy size is comparable with variations of background density profile, we found that local turbulence codes overstimate the flux. For a family of hyperbolic tangent background density profiles, $n_0(x) = n_m + n_1 \tanh\left(\frac{2x-L_x}{2\Delta_n}\right)$ with $n_1 < 0.5n_m$, we have demonstrated that the non-locality of the turbulence leads to a transition from local Gyro-Bohm[3] ($\chi^{local} \simeq 5.5(T_e/eB)(\rho_s/L_n(x))(\alpha/0.01)^{-1/3}$) to nonlocal Gyro-Bohm transport scaling ($\chi^{nonlocal} \simeq 0.043(T_e/eB)(n_1\rho_s/n_m\Delta_n)$) for $\alpha < 1$, where $\alpha = k_{||}^2\chi_e$. The impact of velocity shear on the transition will be discussed.

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LBL-35144a

Large-Gyroradius Resonance Processes: Wave Emission and Absorption by Hot Alphas in Nonuniform Magnetic Field*

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In the traditional approach to gyroresonance processes in a nonuniform magnetic field $\boldsymbol{B}_o = \hat{z}B_o(x)$, a wave equation for the electric field is formulated in x-space, with $k_x \rightarrow -i\partial / \partial x$ in the local dielectric tensor. While this method produces a finite-order differential equation when the Bessel functions can be expanded for small argument, it produces an integral equation when the argument $k_\perp r_g$ is not small, as for hot alphas. This difficulty is overcome by working in k_x-space[1], with $x \rightarrow +i\partial / \partial k_x$. We analyze the standard gyroresonance processes in k_x-space, obtaining absorption and emission rates.

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Energy Partition Among Ion Species in Degenerate Gyroresonant Absorption*

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If two species (a,b) share a local gyroresonance $\left(l_a\Omega_a = l_b\Omega_b\right)$, energy can be transferred between the species by their non-resonant self-consistent electric field. For example, in a DT plasma, when minority ^3He is gyroresonantly excited at its fundamental $\left(\omega = \Omega_{He}\right)$, its energy can be transferred to tritium $\left(\Omega_{He} = 2\Omega_T\right)$ even when the tritium was not itself excited at its second harmonic $\left(\omega = 2\Omega_T\right)$. This process is analyzed (for a slab model) in terms of gyroballistic waves propagating in k_x-space[1]. Our analytic results will be compared with numerical solutions of the traditional approach.

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Modelling of Current Profile Control in the TPX and Alcator C-MOD Devices*

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In recent years, tokamak operating modes exhibiting very high energy confinement time have been observed in several experiments including the DIII-D and JET devices.[1,2] These so-called advanced tokamak equilibria are characterized by peaked pressure profiles, relatively high bootstrap current fractions ($I_{BS}/I_p \gtrsim 0.7$), on-axis values of the safety factor $q(0) > 2$, and nonmonotonic profiles of $q(\psi)$ (reverse shear mode). We have developed a current drive and MHD equilibrium (ACCOME)[3,4] to study the possibility of achieving such scenarios through current profile control. The ACCOME code computes self-consistent MHD equilibria in the presence of driven currents due to neutral beam injection, lower hybrid waves, ICRF fast waves, and bootstrap effects.

Time dependent access to these operating regimes is studied using a O-D model for plasma transport and heating in conjunction with the ACCOME code. The O-D model is used to determine the auxiliary heating power required to reach a combination of current, temperature, and density corresponding to various times during a discharge evolution. The ACCOME model is then used to study the rf current drive requirements for maintaining this current in a reverse shear type profile at these times. Results will be shown for advanced physics scenarios (reverse shear modes) in the proposed Tokamak Physics Experiment (TPX) and the Alcator C-MOD device.

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Fokker-Planck Simulation of Radiative Divertor Plasmas*

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It has long been recognized that kinetic effects play an important role in the edge plasma. Flux limiting of parallel electron thermal conductivity in fluid codes is evidence of this. With the recent interest in radiative/gaseous divertor concepts for ITER we have encountered an additional reason to study kinetic effects. Flame front solutions produced by fluid simulations can show electron temperature gradients which are on the order of a Coulomb collisional mean free path. This implies that non-Maxwellian electron distribution functions may effect the energy flow into and across this flame front. It also implies that the energy loss in the flame front due to inelastic collisions of electrons with neutrals or impurities may have important kinetic effects, since fluid codes use Maxwellian averaged cross-sections to represent these energy losses. We are modifying an existing 1D 2V Fokker-Planck code [1] to study electron kinetic effects across a flame front. The flame front will initially be produced by a set of fluid equations with gas puffing. The electron Fokker-Planck simulation, which includes inelastic collisions of electrons with neutrals, will be done on the fixed ion/ neutral background. We will also discuss the advanced numerical solution algorithm being developed to solve a coupled system of Fokker-Planck equations.

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Impurity Transport and Radiation in Radiative Divertor Plasmas*

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A radiative divertor produced via injected impurity line radiation may provide a mechanism for dissipating the large energy flows expected in the ITER divertor. The ability to remove significant energy from the edge plasma via impurity injection has been demonstrated in a number of experiments, but many questions remain to be answered before this concept can be assumed viable. The development and application of detailed computational tools for the edge plasma, which include multicharge state impurity transport and radiation, can assist in the study of ITER's radiative divertor concept. For a computational tool to be effective in this role it must: 1) be exercised on existing tokamak experiments in order to asses the correctness of the physical models; and 2) produce clearly converged solutions to the discretized system of partial differential equations based upon these physical models. As part of the UEDGE code collaboration, we are developing and applying a 2-D code with multicharge state impurity transport and radiation capabilities. The current physical model and numerical methods will be described. We will present results from our work modeling carbon transport and radiation in Alcator C-Mod as well as results simulating radiative divertor scenarios for ITER. Additionally, we will use a model geometry to asses solution sensitivity to boundary conditions and grid refinement. We will clearly demonstrate convergence of all results presented.

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DISRUPTION-FREE TOROIDAL CONFINEMENT*

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Disruption in toroidal plasmas appears when magnetic islands overlap. This arises when resistive modes at adjacent rational surfaces grow to sufficient size. A magnetic configuration without rational surfaces would not be subject to such disruption. A toroidal plasma with no toroidal field has no rational surfaces (except in a degenerate sense) is called a field-reversed configuration (FRC). The only global mode threatening disruption in an FRC is the $n = m = 1$ mode. However, unstable *tilting* may not appear because of a unique property of axisymmetric plasmas with only a poloidal field: they have no parallel component of current. Thus the one and only instability drive in ideal-MHD theory is bad curvature. Consequently fast local modes (high toroidal mode number, n) and tilting are both driven by the same force. The macroscopic result of local-MHD activity is a continuous rapid restructuring of the equilibrium to keep it marginally stable (e.g. by producing hollow current profile). If the consequent equilibrium is marginally stable to saturated local modes then it should be fully stable to tilting. An $n = 1$ mode, tilting is always more stable in ideal-MHD theory than local modes ($n \rightarrow \infty$). Circumstantial evidence for the restructuring activity of local modes is offered by the observation of profile consistency in FRC experiments.[1]

The objective of this study is to determine the dependence of local mode stability on equilibrium, particularly the current profile. The *double-adiabatic* (DA) stability theory as originally developed by Bernstein et al.[2] is specialized to local modes in FRCs. DA theory is employed because in typical weakly collisional plasmas, there is insufficient time for the disturbance to isotropize on the time scale of the fluctuation. DA theory differs from ideal-MHD theory only by the appearance of an additional stabilizing term. The equations are separable allowing each flux surface to be treated independently. Thus, the problem is one dimensional, the only variable being the distance coordinate along a magnetic flux line. Stability is determined by solving the equivalent variational problem using the Rayleigh-Ritz technique. Preliminary stability results and the trend with equilibrium parameters will be presented. The DA results will also be compared with the the predictions of ideal-MHD theory.

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An Adaptive-hp Finite Element Method for Tokamak Fluid Transport

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We discuss an object-oriented approach to an adaptive-hp finite element method. Adaptive-hp methods are those which locally modify the element size, h, and polynomial order, p, using a refinement control strategy driven by a local *a posteriori* error estimate. The result is an unstructured mesh in which each node may be associated with a different polynomial order. Adaptive-hp finite element methods can achieve exponential as compared to polynomial decrease in the solution error for increasing resolution for certain problems.[1] While these methods have great promise, they are not widely used. One reason is that the data structures needed to support the adaptive hp method are complex. Object oriented design strategies and languages like C++ help control the complexity of these modern methods.[2,3]

We intend to apply these methods to 2-D fluid models of transport in tokamaks. We have begun exploring simple model problems both to characterize the numerics and to understand the characteristics of the fluid models and their boundary conditions.

We present a discussion of the object class structure of our program and its applicability to tokamak transport. We also present the results of our model studies and discuss their relationship to plasma edge transport equations and their boundary conditions.[4-6]

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The Radial Structure of Ion Temperature Gradient Driven Modes

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An analysis of the radial structure of the ion temperature gradient driven mode (ITG) is presented, using a theoretical formalism previously developed for the study of the two-dimensional structure of Toroidal Alfvén Eigenmodes. The importance of correctly describing the fully two-dimensional character of ITG modes is evident, especially considering that the radial correlation length L_r of the turbulence, possibly induced by these instabilities, influences the thermal conductivity of the plasma χ. A crude estimate of $\chi \approx L_r^2/\tau_c$, τ_c being the autocorrelation time of the turbulence, with an evaluation of $L_r \approx \rho_i$ as the ion Larmor radius, typical of one-dimensional "local" theories, leads to the well known discrepancy between the radial dependences of the experimental and the theoretically predicted diffusion coefficients. Indeed, theoretical models predict a decrease in the conductivity as the plasma edge is approached, in contrast to the experimentally observed monotonic increase.

The present analysis shows how such a disagreement is largely due to the incorrect estimate for the characteristic step size of the turbulence induced diffusion process. In a two-dimensional toroidal system, the linear mode-coupling between different poloidal mode numbers, due to the presence of a finite curvature, causes the radial extent of the mode to involve also a macroscopic lenth L, yielding, e.g., $L_r \approx (\rho_i L)^{1/2}$. The estimate of L_r as the radial extent of the linear eigenmode structure is also incorrect, since the nonlinear mode-coupling tends to tear these linear structures apart. Nevertheless, the present analysis suggests that, at saturation for the ITG instability, linear and nonlinear mode-coupling compete at the same level, which makes the linear estimate of L_r reasonable, at least qualitatively. This hypothesis is further justified by the experimental evidence of radially elongated turbulence, in contrast to the isotropic turbulence expected in the case of dominant nonlinear mode-coupling.

An important result of the present analysis is in the obtained dependence of L_r on parameters such as the magnetic shear. In particular, it is found that L_r decreases algebraically with increasing shear for moderate to large shear values, while it decreases exponentially with decreasing shear for low shear values. These results seem in qualitative agreement with several experiments, which observe a strong reduction of the transport coefficients close to the magnetic axis, where the magnetic shear is smallest [1]. The importance of other parameters, relevant to the macroscopic plasma equilibrium (as, e.g. the poloidal beta and ellipticity), in determining L_r and , thus, the radial mode structure, will be also discussed.

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Finite Orbit Effects on Kinetic Toroidal Alfvén Eigenmodes Excited by Energetic Particles

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It has been shown that discrete, global modes, induced by toroidicity, exist in the gaps of the continuous Alfvén spectrum. These Toroidal Alfvén Eigenmodes (TAE's) can be destabilized, e.g., by the resonant interaction with the parallel motion of energetic ions, like fusion-produced alpha particles, and, in turn, enhance their losses.

When resistivity, finite Larmor radius, parallel electron dynamics or kinetic effects associated to electron Landau damping are included, the singular character of local oscillations of the shear-Alfvén continuum is removed. Correspondingly, the ideal continuous spectrum is replaced by a closely-spaced set of discrete modes, called Kinetic Alfvén Waves (KAW's). The existence of KAW's coupled by toroidicity gives origin to a new mode, the Kinetic TAE (KTAE), with two distinct branches: the first branch, weakly stabilized by resistivity, with complex frequency close to the upper bound of the gap; the second one, strongly stable, close to the lower bound. The mode structure of the KTAE is similar to TAE, but with opposite phase between the coupled poloidal harmonics.

Besides originating the KTAE, the existence of KAW's can significantly affect both the stability and the structure of the TAE. As long as the equilibrium effects yield TAE frequency well inside the gap, dissipative and kinetic effects can be treated perturbatively. The small coupling with KAW's then introduces a perturbative 'radiative' damping, associated to an outward energy flux. In the purely resistive case (kinetic effects neglected), the TAE comes out to be less damped by resistivity and more sensitive to the resonant drive than KTAE. Consequently, in this perturbative regime, TAE attracts more interest as a potential scattering mechanism for fast ions. When the effect of magnetic shear or plasma pressure gradient causes the TAE frequency to be sufficiently close to the continuum, the coupling with KAW's becomes very strong, leading to a relevant radiative damping and the break-down of any perturbative approach. Correspondingly, the mode structure becomes more peaked and similar to that of a KAW. In such regimes, the TAE merges into the lower branch of the KTAE and can remain stable even in the presence of resonant drive. The upper KTAE branch results, in this case, to be the most unstable shear-Alfvén mode.

Among the other kinetic effects, those associated to the finite deviation ρ_{dH} of energetic-particle drift orbits from the magnetic flux surfaces are particularly relevant in the non-perturbative regime, because the more peaked, KAW-like character of the eigenfunctions and the significant value of ρ_{dH} contributes to make $k_\perp \rho_{dH} \sim 1$. In order to fully retain these non-perturbative finite-ρ_{dH} effects an initial-value hybrid fluid-particle simulation code has been developed, which solves the set of MHD equations for the fluctuating electromagnetic fields, coupled to the gyrokinetic equations for the phase-space trajectories of an energetic-particle population.

The occurrence, for typical equilibrium parameters, of the non-perturbative regime, with stable TAE and unstable upper KTAE branch is shown. The dependence of the KTAE growth rate on the ratio between the typical hot-particle velocity and the Alfvén velocity is also considered. At fixed value of β_H, defined as $\beta_H \equiv 4\pi n_H T_H / B^2$, with n_H and T_H being the hot-particle density and temperature respectively, the growth rate is maximum at values of the typical hot-particle velocity of the same order of the Alfvén velocity, consistently with the resonant character of the energetic particle drive. These results are shown to be in satisfactory qualitative agreement with the findings of an analytical treatment.

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TEST PARTICLE DIFFUSION IN 2-D TURBULENT FLOWS; AN EXPLICIT SYMPLECTIC NUMERICAL SCHEME*

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Low order explicit symplectic integration schemes [1,2] have recently been shown to be more efficient in treating simple hamiltonian systems not only compared to more traditional integrators like Runge-Kutta, but also to higher order symplectic methods [3]. For systems with more complicated exact solutions, where the cost of computing the force explicitly may be comparable to the cost of computing it through the equations of motion, higher order schemes are expected to be more efficient. An example of such a system is the 2-D turbulent flow described by the hamiltonian

$$H(x, y, t) = \sum_n A_n \, sin(k_n x + \alpha_n) \, cos[q_n(y - u_n t) + \beta_n]$$

for $1 \leq n \leq M$. The problem of calculating the stochastic diffusion along with error estimates is investigated by comparing symplectic and nonsymplectic integrations. The accuracy of the trajectories is further assessed by introducing techniques based on the decomposition of the hamiltonian into M hamiltonians of the form $H_n = \sin(k_n x) \cos(q_n y)$ by a sequence of Galilean transformations and then using the exact solutions which are given in terms of the Jacobi elliptic functions [4]. We compare the relative computational speeds of low and high order explicit methods for this system with Runge-Kutta and implicit symplectic schemes.

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PROPAGATION OF THE RELATIVISTIC FUSION-PRODUCT ION CYCLOTRON INSTABILITIES IN TOKAMAKS*

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In a homogeneous plasma the energy dependence of the fusion-ions cyclotron frequency gives rise to resonant negative mass type instabilities.[1,2] The unstable cyclotron wave occurs in the narrow frequency gap between the down shifted fast ion cyclotron frequency $\ell_f \omega_{cf}(1 - v^2/2c^2)$ and the thermal ion cyclotron frequency $\ell_i \omega_{ci}$. Here we investigate how these resonant negative mass or gyrophase bunching instabilities propagate in inhomogeneous, sheared magnetic fields. For finite toroidal-poloidal mode numbers (n,m) the sheared $\underset{\sim}{B}$ couples the modes to electron plasma waves which determine the $k_{||}$ and thus the electron and ion cyclotron Landau damping of the modes. Criteria are derived for the strength of this effect. For m=n=0 modes the magnetic shear is not effective and we introduce a low beta-theta pinch model $B_z(r/L_B)$ to study the radial mode structure. Here a complete solution is obtained in terms of a matrix eigenvalue problem derived from the Fourier-Bessel function expansion of the field. The growth rate makes a transition from the beam instability $\gamma/\ell\omega_{cf} = C_f\left(v_f^2\omega_{pf}^2/c^2\omega_{pi}^2\right)^{1/3}$ form to the resonant form when $L_B < L_{crit}$. Finally, we report a set of 2D model linear partial differential equations suitable for solving the initial value problem with modifications of existing drift wave codes.

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*Work supported by the U.S. Department of Energy.
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Transport Code Simulations of Recent Experiments in Large Tokamaks.

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Abstract

Results from simulations of shots from JET, TFTR and D-III-D , using a reactive drift wave transport model are presented. Good agreement is found regarding general trends in radial profiles and ratio of χ_e/χ_i. The significance of off-diagonal components of the transport matrix is discussed, including also components due to auxiliary ion species.

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ENHANCING LOWER HYBRID CURRENT DRIVE WITH ICRF WAVES *

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Experiments on JET and subsequent theoretical models have shown that the lower hybrid current drive (LHCD) efficiency can be significantly enhanced in the presence of ICRF waves. This enhancement is primarily due to an interaction of the mode converted ion-Bernstein waves (IBW) with the suprathermal electron population generated by LHCD [1,2].

We examine conditions for optimizing the interaction of LHCD with ICRF waves and explore its applicability to higher temperature, reactor-grade, tokamak plasmas. For this we study the propagation and mode conversion of fast Alfvén waves in such toroidal plasmas and the subsequent propagation of IBW's. Results for optimized scenarios in general, and for TPX, in particular, will be presented.

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

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A Comparative Study of the Effects of Electric Field Shear on Correlation and Transport Properties of Turbulence

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The two-point correlation function of fluctuating velocity and the transport flux due to random-force-driven turbulence are calculated in the presence of electric field shear. The relative importance and sensitivity to E_r' of fluctuation amplitude, correlation time and length scales for momentum and particle transport is discussed in detail. The nonlinear dependence of transport on E_r' coupled with electric field dependence on the momentum transport can lead to temporal oscillations in hysteresis - like behavior in the good confinement region. The relevance of this to ELM phenomena will be discussed.

A KINETIC THEORY ORDERING FOR THE DEVELOPMENT OF TRANSPORT THEORY IN THE DIVERTOR

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It is demonstrated that the Chapman-Enskogg type procedures that have been developed for solving the ion and electron kinetic equations in the plasma core can be adapted to the divertor. A "maximal" ordering is defined by establishing limiting values of neutral and impurity densities and of radial gradient scale lengths for which the leading order solutions of the ion and electron kinetic equations are shifted Maxwellians. It is shown that this ordering is applicable to most of the conditions encountered in present and anticipated divertors. Ordered hierarchies of kinetic equations are derived for this "maximal" ordering in the divertor. Since the gyroradius ordering parameter in the divertor region is about 10^{-1}, the terms that are retained at each order are quite different than for the core plasma, where the gyroradius parameter is about 10^{-3}. In particular, equations for higher order corrections to the distribution function which account for the effects of high impurity density, charge-exchange, ionization and recombination, strong radial gradients and strong electric fields are obtained.

Revisiting Charge-Exchange effects on Plasma Flow.*

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Research into the H-mode points out the close relationship between changes in edge plasma rotation and changes in plasma confinement. For this and other reasons, edge plasma rotation deserves careful study.

Previous work[1)] has shown that the ion and impurity parallel flows are slowed down by friction with neutrals. That work considered the ion, impurity and neutral equations. Neoclassical and classical plasma impurity flows are known in the absence of neutrals[2)]. A simplified model of the effect of impurity-electron friction on the plasma impurity and main ion flows exists[3)], but it also ignores the charge exchange interaction between ions and edge neutrals. We now include the electron equation in our formalism, as well as the ion, impurity and neutral equations.

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Isotope scaling and η_i Mode with Impurity in Tokamak Plasma

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Abstract

The ion temperature gradient driven instabilities, or η_i modes, are studied for discharges with hydrogen, deuterium or tritium in a toroidal magnetic configuration. Impurity effects on the modes and the instabilities which are driven by the presence of impurity ions (impurity modes) are studied as well. It is found that the maximum growth rate of η_i mode scales as $M^{-\frac{1}{2}}$ for pure hydrogen, deuterium or tritium discharges, where M is the mass of the working gas ion. With inclusion of impurity ions the growth rates of η_i mode decrease in all three kinds of plasmas and hydrogen plasma still has the highest maximum growth rate, tritium the lowest and deuterium in between. For the impurity mode the situation is similar to that of the η_i mode with impurity ions. However, the isotope effects are weaker and scale as $M_{eff}^{-\frac{1}{2}}$ with the presence of impurity ions, where M_{eff} is the effective mass of each ion. Experimental database shows that the plasma confinement time scales as $\tau \sim A^{\frac{1}{2}}$ in clean plasmas, with A being the mass number of ions. The correlation of the theoretical results with the experimental confinement scaling is discussed.

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SHERWOOD THEORY MEETING 1994

Mathematica™ as a Data Analysis Tool*

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A database of experimental data taken in the edge of several different tokamaks has been stored in the Magnetic Fusion Energy Database (MFEDB)[1]. Although there are several tools currently available, such as the *Mathematica*™[2] Database Interface (MDI)[3] and a Mosaic server, for retrieving and graphing these datasets, they are limited in their ability to easily perform more sophisticated tasks such as applying complex constraints to the data and performing elaborate statistical analysis such as nonlinear multivariate regression. In order to facilitate these tasks, two new *Mathematica*™ packages have been developed. The first package, which relies heavily on MDI, allows the user to select data sets from the MFEDB and write them to a local file in a tabular form. The second package takes advantage of several of the Standard *Mathematica*™ Packages[4] and a package developed by Maeder[5] which provides standard database functionality. The second package reads in the table of data written by the first and creates a table or a relation in database terminology. This relation can now be restricted in both dimensions using the *Projection* operation to narrow the relation or the *Selection* operation to shorten the relation. Once the dataset has been appropriately restricted, each column may be treated as a single variable which can be manipulated with any *Mathematica*™ operator. Examples will be given.

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Optimal Extraction Of α Particle Power By Waves *

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Abstract

There is considerable free energy in the energetic population of α particles in a reactor that in principle, could be extracted by waves. These waves could then direct this power to fuel ions or to current drive.[1] Different waves extract energy best from different populations of the energetic α-particles, i. e. , some waves best tap the perpendicular energy, some best tap parallel energy, and some best extract energy from the more energetic α-particles. Through analytical and numerical calculations, we address how the extraction of energy from α-particles can be optimized.

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

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Reactor Implications of Diverting Alpha-Power to Fuel Ions*

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Abstract

It has been recognized that there are advantages in operating fusion reactors in regimes in which the ion fuel temperature exceeds the electron temperature[1] or in which there is a significant non-thermal component to the ion distribution function.[2,3] If alpha particle power could be diverted by waves to the tail of the ion distribution function, both of these effects might be accomplished at once.[4] The reactor implications of these effects are explored, with particular attention paid to the regime of high power diversion concurrent with small electron confinement time.

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Spectra and Correlation Functions in Toroidal ITG Turbulence

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We present nonlinear simulations of ITG turbulence in toroidal geometry using gyrofluid equations including models of parallel resonances and FLR,[1] toroidal drift resonances,[2] and some trapped ion and neoclassical effects. Our simulations use a field-line coordinate system which efficiently represents microinstability driven turbulence, where the perpendicular correlation lengths are much shorter than the correlation length in the parallel direction. This allows the simulation volume to be small (several correlation lengths) in the perpendicular directions, but elongated along the field line. We typically find perpendicular correlation lengths on the order of 10 ρ_i, indicating that the box only needs to be about 100 ρ_i in the perpendicular directions, which corresponds to a small fraction of the minor radius for typical TFTR parameters. We examine the correlation function along the field line to investigate the $k_{\|}$ spectrum and determine the required parallel box length.

For typical TFTR L-mode parameters, the poloidal spectrum peaks at $k_\theta \rho_i \sim .15$, at significantly larger scale than the fastest growing wavelength, at $k_\theta \rho_i \sim .4$. The radial spectrum is peaked at $k_r \rho_i = 0$, with a width of about .15. These results are similar to BES and reflectrometry measurments. Further work needs to be done to determine what controls the width and position of these long-wavelength spectral features, but simulations have been done in larger boxes to verify that the long-wavelength features are not just tied to the box size.

The dominant saturation mechanism is the nonlinear generation of sheared poloidal ExB flow; details of the neoclassical damping (due both to collisions and to collisionless averaging over banana orbits) of this flow are investigated further.

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KTAE Boundary Layer Procedure for Modifying MHD Shooting Codes*

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Numerical evaluation of modes in MHD eigenvalue codes, that contain no geometrical expansions is complicated by the presence of the MHD continuum , even when there are gaps through most of the profile. A technique based on analytic continuation has been developed to calculate eigenmodes and eigenvalues, and model codes have been used to exhibit continuum damping. However, the continuum description that uses analytic continuation always breaks down when the mode frequency is sufficiently close to the envelope of the continuum. To describe this region physically we have developed a boundary layer method that takes into account additional physics to ideal MHD based on finite ion Larmor radius and finite parallel resistivity. Though the ideal equations in arbitrary geometry are given by a set of 2-N equations describing the coupling of N poloidal harmonics with N in principle a large number, the layer equations are given by a single second order differential equation (a Legendre equation). The matching conditions through the boundary layer are formulated. Model solutions will be exhibited and the procedure of how the boundary layer problem could be implemented in large MHD codes will be discussed.

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Inertial-Range Scaling of Two-Dimensional Turbulence

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In 1941, Kolmogorov proposed his famous $k^{-5/3}$ scaling law for the inertial-range energy spectrum of homogeneous and isotropic three-dimensional turbulence. Since then, this result has been subjected to extensive numerical and experimental confirmation. Kolmogorov's argument was extended to two-dimensional turbulence by Kraichnan, who in 1971 suggested the scaling $k^{-3}[\log(k/k_1)]^{-1/3}$, where k_1 is the lowest wavenumber in the (enstrophy) inertial range. However, the true inertial-range behaviour of two-dimensional turbulence is still a subject of much controversy.

A new analytical approximation, the realizable test-field model (RTFM), has recently been developed and implemented for two-dimensional turbulence. A type of *statistical closure*, the RTFM provides us with a tool for investigating high Reynolds number turbulence. An important property of this approximation is that, unlike the related test-field model, the RTFM is guaranteed to predict positive energies even in the presence of drift waves. In contrast to the direct-interaction approximation and the realizable Markovian closure,[1] this approximation is invariant to random Galilean transformations; it is therefore expected to obey Kraichnan's inertial-range scaling.

Dramatic advances in the implementation of statistical closures have recently made it possible to compute energy spectra over 7 wavenumber decades (i.e. $10^7 \times 10^7$ modes), a task that will clearly remain outside the realm of conventional numerical simulations for the foreseeable future.[2] Kraichnan's logarithmically-corrected inertial-range scaling has thereby been confirmed within the context of this approximation. In addition, the effect of changing the usual Laplacian viscosity to an enhanced "hyperviscosity" (as is often done for numerical reasons) can now be quantitatively assessed. The application of these techniques to anisotropic drift-wave turbulence is also discussed.

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GYROKINETIC SIMULATIONS OF ROTATION SHEAR EFFECTS ON TOROIDAL BALLOONING MODES*

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A fully gyrokinetic ballooning grid code has been constructed which is extremely complete and very fast. New linear and nonlinear results are reported here. The code includes velocity shear and is unique in that it includes the stabilizing effects of poloidal rotation shear for toroidal modes with toroidal curvature and trapped particles (e.g. ITG, trapped particle modes). Destabilizing parallel velocity shear is also included. Data from D-III VH modes will be analyzed to see if velocity shear effects on linear growth rates can account for the observed confinement improvement. The code has been run for TFTR experimental L-mode data for beam scans with increasing rotation shear. The code finds that the destabilizing parallel velocity shear effects overwhelm the stabilizing perpendicular velocity shear effects, and strongly destabilize the modes. Surprisingly, the experimental χ did not increase. Nonlinear effects due to the buildup of microscopic ambipolar potentials[1] have been found to be a crucial effect in gyrofluid simulations, and this nonlinear effect is being included in this kinetic code. However, present gyrofluid models have potentially substantial inaccuracies in the treatment of this physics, which are corrected here. Preliminary results from multi-mode simulations will be reported.

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Lyapunov Exponents, Correlation Functions, and Transport Coefficients*

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Stochastic perturbation theory is used to derive a proportional relationship between the largest Lyapunov exponent of a many-body system and the correlation function of the second derivative of the inter particle potential. Two limiting cases are examined: (1) a weakly coupled gas (binary collisions only) in 3 dimensions, with a coulomb gas as a particular example; (2) A 1-dimensional monatomic lattice with non-linear nearest neighbor coupling.

If one combines the Lyapunov exponent formulae with Green-Kubo relations, connections with transport coefficients can be established.

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Basic Principles Approach for Studying Nonlinear Alfvén Wave-Alpha Particle Dynamics*

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An analytical model and a numerical procedure are presented which give a kinetic nonlinear description of Alfvén-wave instabilities driven by the source of energetic particles in a plasma. The steady-state and bursting nonlinear scenarios predicted by the analytical theory are verified in the test numerical simulation of the bump-on-tail instability. A mathematical similarity between the bump-on-tail problem for plasma waves and the Alfvén wave problem gives a guideline for the interpretation of the bursts in the wave energy and fast particle losses observed in the tokamak experiments with neutral beam injection. At present a simulation code has been developed that describes a nonlinear state of a single mode driven by a weak source. The code contains background dissipation and particle sources and sinks. The numerical technique allows for a continuous evolving simulation without any evidence of numerical instability. The results are in excellent agreement with theory. Under current development is a multi-mode case and preliminary results will be given. The procedures that are being developed here provide a background for the quantitative self-consistent description of the collective alpha particle transport in an ignited plasma.

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Anisotropy and Spectral Indices for the Driven-Damped Drift Wave Problem

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We compare spectral distributions obtained from standard drift wave simulation models of the forced Hasegawa-Mima equation and the $i\delta_k$ dissipative $\mathbf{E}\times\mathbf{B}$ nonlinearity equation with predictions from the weak turbulence wave-kinetic equation. In particular, we compare the scaling exponents for the saturated spectrum $W(k_x, k_y)$ predicted for the $k_\perp \rho_s \gg 1$ and $k_\perp \rho_s < 1$ regimes based on the scalings of the linear frequency $\omega(k_x, k_y)$ and the nonlinear matrix element V_{k,k_1,k_2} derived by Balk *et al.*[1] and Novakovskii *et al.*[2] These theories predict $W_k = |k_x|^{-\nu_x}|k_y|^{-\nu_y}$ with $(\nu_x, \nu_y) = (2, 3/2)$ and $(3, 3/2)$ for high and low $k_\perp \rho_s$ respectively. Generally speaking, the high $k_\perp \rho_s$ exponents are in reasonable agreement, while at small $k_\perp \rho_s$ the spectral indices are larger and more isotropic with $3 < \nu_x \sim \nu_y \leq 4$. The low $k_\perp \rho_s$ field appears to contain a significant component of "coherent structures," contributing to the steeper spectra. To understand better the role of the long-lived vorticies, we will attempt to compare the simulations with high resolution 2D-Euler simulations which also yield steep spectra and coherent structures.

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Direct Numerical Simulation of Inverted Density Profile ITG Turbulence

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A gyrokinetic weak-turbulence theory of ion-temperature-gradient modes for inverted density profile ($\eta_i < 0$) plasmas exists.[1] Set in sheared slab geometry, this theory predicts that the thermal diffusivity associated with $\eta_i < 0$ modes is much lower than strong-turbulence (mixing-length) estimates of the more conventional $\eta_i > 0$ modes. In this work, we seek to test the details of this prediction from within the sheared-slab gyrofluid[2] paradigm. First, we extend the earlier linear analysis to arbitrary $k_\perp \rho_i$ by employing the gyrokinetic integral code of Linsker[3] and compare these results with the gyrofluid predictions; excellent agreement between the full gyrokinetic and gyrofluid theories is found. Next, the corresponding gyrofluid weak-turbulence theory[4] is developed and shown to reproduce the gyrokinetic predictions with reasonable precision. Although the dominant nonlinearity is found to be three-wave coupling, Landau damping is shown to be important. We then integrate the gyrofluid equations directly to compare with the theoretical predictions, making no assumptions about the important nonlinear processes or the relevance of the weak-turbulence expansion beyond those necessary to derive the gyrofluid equations. Preliminary runs indicate that at least qualitative agreement is found with the theoretical predictions; the predicted thermal diffusivity is small compared to $\eta_i > 0$ simulations. The simulations are characterized by a large number of modes with substantial energy, and hence cannot be described well by a three-mode theory. Refinements of the analytic theory based upon the simulation results are suggested.

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η_i Mode in Neoclassical Regime and Neoclassical Closure

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We have extended the *Hamaguchi/Horton* model [1] to investigate neoclassical effects on η_i modes. First, using the *Callen/Shaing* model [2] in which has not been taken into account the compressibility effect on Π and Θ, and consistent with the *Hirshman/Sigmar* relation [3], we checked the effect of $\nabla \cdot (\mathbf{B} \times \nabla \cdot \Pi/B^2)$ and $\nabla \cdot (\mathbf{B} \times \nabla \cdot \Theta/B^2)$ on the stability of the η_i mode. Next, taking into account the compressibility in Π and Θ, we have modified the *Sundaram/Callen* model[4] consistently. Using a new model, we studied the η_i mode and compared it to the result obtained from the *Callen/Shaing* model. We found that if we retain not only the Π term but also the Θ term in model equations, the stabilization effect which comes from $\nabla \cdot (\mathbf{B} \times \nabla \cdot \Theta/B^2)$ overcomes the destabilization effect, which is derived from $\nabla \cdot (\mathbf{B} \times \nabla \cdot \Pi/B^2)$, so that η_i mode is stabilized by the neoclassical effect. This means if we investigate the neoclassical effect on the fluctuations, the term $\nabla \cdot (\mathbf{B} \times \nabla \cdot \Theta/B^2)$ can not be negligible in the system, although only the term $\nabla \cdot (\mathbf{B} \times \nabla \cdot \Pi/B^2)$ was used in the previous analysis [5].

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Low Beta MHD Equilibrium and Stability for Anisotropic Pressure Closed Field Line Plasma Confinement Systems*

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General formalism is developed to analyze the MHD equilibrium and stability of low beta anisotropic pressure plasmas contained in closed field line magnetic confinement systems. The formalism allows to consider rather general magnetic systems with nonuniform axis curvature and longitudinal profiles of toroidal and quadrupole poloidal field. It also allows having a strong pressure anisotropy corresponding to enhanced plasma pressure in mirror cells of the system. As an example of such the system we consider the recently proposed linked mirror neutron source [1].

We obtain that under the paraxial (near axis) approximation the equilibrium plasma column is completely described by the following parameters: Δ — displacement of the column axis from the magnetic axis of the system and plasma column ellipticity. The displacement Δ is determined by the closure condition of the dipole component of the Pfirsch-Schlüter current. The displacement Δ, can vanish with proper bending of the magnetic axis. The plasma column ellipticity (at some fixed cross-section) is determined by the quadrupole Pfirsch-Schlüter current closure condition which takes the form $J_1 - J_2 = 0$, where $J_{1,2}$ are some integrals along the axis. This condition is closely related with the stability condition which takes the form $J_1 + J_2 > 0$. J_1 and J_2 depend on longitudinal pressure and magnetic field distributions, and as a rule they do not vanish simultaneously. This circumstance causes a nonconventional situation when stable and unstable equilibrium regions in parametric space are separated by a zone where the equilibrium is absent.

Application of the above formalism to the linked mirror neutron source analysis confirms most of the preliminary results [1], however, we obtain a considerable reduction of mirror cell axis curvature and an appreciable ellipticity of plasma cross-section in the mirror cell midplane. We have also optimized the longitudinal pressure and magnetic field distribution.

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Finite Beta Plasma Equilibrium in Toroidally Linked Mirrors*

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The problem of finite pressure plasma equilibrium in a system with closed magnetic field lines consisting of quadrupole mirrors linked by simple toroidal cells with elliptical cross-sections is analyzed. An appropriate analytical procedure is developed, that uses conformal mapping techniques, which enables one to obtain the magnetic field structure for the free boundary equilibrium problem. This method has general applicability for finding analytic solutions of the two dimensional Dirichlet problem outside of an arbitrary closed contour. Using this method, the deformations of the plasma equilibrium configuration due to finite plasma pressure in the toroidal cell are calculated analytically to the second order in λ-expansion, where $\lambda \sim \beta/\epsilon E$, β is the ratio of plasma pressure to the magnetic field pressure, ϵ — the inverse aspect ratio and E — the ellipticity of the plasma cross section. The outer displacement of the plasma column is shown to depend nonlinearly on the increase of plasma pressure, and does not prevent the achievement of substantial $\beta \sim 10\%$ in the toroidal cells.

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Toroidal Gyrokinetic Simulation of η_i-mode Fluctuations and Transport in a Radially Sheared Electric Field*

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In this work we present gyrokinetic simulation results of the effect of radially sheared electric fields on fluctuations and transport due to the η_i instability, via the Toroidal Particle Code (TPC). Our treatment utilizes a (r, θ, ζ) coordinate discretization and retains all metric-dependent terms without approximation. The integral gyrokinetic Poisson equation including radial dependencies is simplified by employing a Padé approximant for the modified Bessel term (correct to $\mathcal{O}(k_\perp \rho_i) \gtrsim 1$). The parameter regime employed by the runs is such that this term is relevant. This results in a second order differential equation which is solved by iterative application of a rapid elliptic solver. Preliminary simulation runs show that the presence of a sheared electric field reduces the growth rate and transport, and changes the radial structure of the potential vortices (or streamers). A theoretical model to explain these observations is discussed.

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Jitter Stabilization of Electrostatic Drift Waves*

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An investigation is made into the possibility of stabilizing electrostatic drift waves by adding an oscillating, or "jittering," component to the parallel wave number $k_{\|}$ for the mode. The drift model,[1,2,3] a generalization of MHD, provides the context for the present work. Our local study neglects the effects of radial mode structure. A perturbation analysis that uses the ratio of the drift frequency to the jitter frequency as a small parameter shows that jitter modifies the classical local dispersion relation: the growth rate of the classical resistively destabilized mode is multiplied by a factor incorporating the effects of jitter. It is found that this factor can become very small—effectively stabilizing the drift mode—for certain values of the jitter frequency and amplitude.

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Time Dependent Studies of Advanced Tokamak Operating Modes*

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An important question in the study of advanced tokamak operating modes is whether regimes can be accessed where bootstrap current provides most of the plasma current. To address this question, we are developing a time dependent model which combines BALDUR, a 1.5-D transport and MHD equilibrium code,[1] with a fast wave current drive package (FWCD).[2] The FWCD package incorporates a full wave calculation of the power deposition (FISIC code[3]) and a parameterization of the current drive efficiency.[4] The neutral beam and bootstrap current drive modules are already present in the BALDUR code. The addition of the FWCD package will allow us to study access to advanced operating modes characterized by peaked pressure profiles and long energy confinement time (such as those observed in JET and DIII-D). We believe that discharges of this nature could be achieved using FWCD to provide a source of on-axis current density. With the coupled transport and FWCD code, we can follow the effect of the radio frequency power deposition on the evolution of the equilibria as well as the effect of evolving plasma on the radio frequency power deposition. In the results presented here, we use the BALDUR code, and we input model profiles for radio frequency current density and electron power deposition based on the predictions of the fast wave current drive package.[2] With this modeling of the FWCD, we examine the subsequent evolution of the equilibrium. Preliminary results will be presented for parameters characteristic of the proposed Tokamak Physics Experiment (TPX) [$a = 0.5\,\mathrm{m}$, $R_o = 2.25\,\mathrm{m}$, $B_o = 4.0\,\mathrm{T}$, $I_p = 1.6 - 2.0\,\mathrm{MA}$].

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Ion Orbit Loss and the Poloidal Electric Field

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Monte-Carlo simulation studies for the ion orbit loss in limiter tokamak show that the ion loss pattern is non uniformly distributed in the poloidal direction due to the different ion drift direction. If electron loss to the limiter is uniformly distributed due to its tiny orbit width, the non uniform ion loss could cause a poloidal electric field which make the ion loss to the limiter tend to be uniformly distributed. A simple analytical derivation of poloidal electric field and the discussion of effects of poloidal electric field on the ion movement and transport are also presented.

Exploring the Limits of the "Low Q" Fusion Power Regime*

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In earlier papers [1] the fusion power balance potentialities of low Q open-ended systems were discussed. The present paper is aimed at further exploring the limits (in the direction of lowered reactivity) of hypothetical driven fusion power systems. These limits are set by constraints of a thermodynamical nature that are associated with the injection and the energy recovery processes associated with the fusion fuel. Ideally, regimes could be found where these constraints arise in the main from collisional processes, and where collective effects play a minor role. Plasma theory provides guidelines for finding such regimes, and defines experiments that could be used to confirm their existence. Assuming that such regimes can be attained, the issue of calculating the lower limits on Q for net fusion power can be reduced to a classical problem. The concept here is to shift the emphasis away from a concentration on the need for ever-better plasma confinement aimed at ignition, and toward an emphasis on the efficiency of the injection and energy recovery processes. The analogy is the development of the gas turbine, where success hinged on the achievement of adequately high efficiencies from the compressor and the turbine components.

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SHERWOOD INTERNATIONAL FUSION THEORY CONFERENCE
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ALFVEN WAVE ANALYSIS FOR PHAEDRUS-T*

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Alfven wave plasma heating and current drive experiments are in progress at the Phaedrus-T tokamak. Preliminary experimental results suggest non-symmetry in wave penetration along the torus relative to the direction of the ohmic current. To theoretically analyze this feature it was found necessary to include the poloidal magnetic field effects into the consideration. This report is devoted to the numerical analysis of the experimental situation in the Phaedrus-T tokamak. For these purposes, the full-wave code, FASTWAC[1,2], has been amended to include the poloidal magnetic field effects. The theoretical and numerical results on Alfven wave dispersion relation, 2D distribution of wave fields, and absorbed power inside the plasma will be presented. The non-symmetry in wave field structure for the waves penetrating in opposite directions along the torus (opposite toroidal wave numbers) has been obtained in calculations. The final goal of these studies is to find the most promising regimes for Alfven wave current drive in tokamaks.

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ICRF FAST-WAVE ANALYSIS FOR TPX*

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Past studies[1] of fast wave current drive (FWCD) in TPX, the Tokamak Physics Experiment[2], with the full-wave codes, FASTWAC and PICES, and a ray-tracing code, CURRAY, showed that ion absorption at the fundamental or harmonic ion cyclotron resonances was one of the main factors limiting current drive efficiency. On the other hand, these ICRF regimes are most efficient for plasma heating and correspond to the high antenna loading resistance and full single pass absorption. This report is devoted to a more detailed analysis of such ICRF regimes in the TPX tokamak from the point of view of optimizing current drive. In this situation a significant part of the total input power is absorbed near resonant surfaces and non-Maxwellian ion distribution function is formed. Numerical calculations of the ion distribution function (2D in velocity space) in the tokamak plasma are presented. For these purposes, CQL3D[3], a RF quasilinear bounce-averaged Fokker-Planck code, and FASTWAC, the full-wave code, were partially integrated to calculate power deposition profiles and the corresponding ion distribution function. These calculations are the basis for numerical estimation of minority ion current drive in a tokamak. The final goal of these studies is to find the most promising scenarios for the efficient current profile control and current drive in TPX.

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Multi-species, Self-consistent Particle Simulation of Neoclassical Transport*

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Abstract

A time varying weighting (δf) scheme for gyrokinetic particle simulation is applied to the steady state simulation of neoclassical transport. If the code is exercised in the familiar non self-consistent mode, results for the two species(ions and electrons) including like and unlike particle collisions agree well with neoclassical theory. In the self-consistent case, an ambipolar potential is free to build up if there is an imbalance between ion and electron fluxes. Building on the advantage of the present approach, (e.g., multi-species capability, fully dynamical approach, low noise), we intend to explore significant modifications of neoclassical transport which are usually inaccessible by conventional calculation processes; e.g. energetic particle effects, finite gyroradius dynamics, shear flow, etc. Based on Dimits and Cohen's approach[1], accurate collision operators conserving momentum and energy for both inter-species and like-species collisions are developed and implemented. A new Poisson solver suitable for general geometry will also be presented.

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

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Stability Analysis of Ionization Fronts of Gaseous Divertor Plasmas

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The dynamics of ionization fronts in gaseous tokamak divertors have been examined in a model of a reaction-diffusion system.

$$\partial_t n_e + \vec{v}_e \cdot \nabla n_e = D_e \nabla^2 n_e + n_e n_n < \sigma v >_{ionz}$$

$$\partial_t n_n + \vec{v}_n \cdot \nabla n_n = D_n \nabla^2 n_n - n_e n_n < \sigma v >_{ionz}$$

$$\partial_t (n_e T_e) + \vec{v}_e \cdot \nabla (n_e T_e) = \kappa_T \nabla^2 (n_e T_e) - E_0 n_e n_n < \sigma v >_{ionz}$$

The variables have the usual notaion: n for densities, v for velocities, and D for density diffusion coefficients with subscripts e for electrons and n for neutrals, T_e for electron temperature, κ_T for thermal conductivity normalized by the electron density, and E_0 for energy released per neutral ionization. In a 1-D equilibrium with x perpendicular to divertor plates, and assuming the ionization occurs in a narrow region due to sensitive temperature dependence we write

$$< \sigma v >_{ionz} \propto \sqrt{1 + F_y^2}\, e^{+N_1/T} \delta(x - F) \approx \sqrt{1 + F_y^2}\, e^{+N(1-\tilde{T})} \delta(x - F)$$

where $F=F(y,t)$ is displacements of the front, F_y is its derivative with respect to y, N is an activation rate, and $\tilde{T}$ is perturbed normalized front temperature. Note the + sign of the exponent due to the endothermic reaction opposite from the Arrhenius' equation.

First, with proper boundary conditions, a shock equilibrium is obtained. Then linear stability with respect to perturbation perpendicular to the front is analyzed. (Toroidal coordinate is y.) For us the ratio of thermal conduction to mass diffusivity, L, is much greater than 1. For large L, unlike the usual flame fronts[1], instability is found for some cases of long wavelength waves. There exists a cutoff wavelength k_c such that $k>k_c$ the modes are stable. Similar analysis is applicable for recombination fronts.

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† Research supported by DOE Contract No. DE-FG03-88ER53275.
†† Research supported by DOE Contract No. DE-AC03-89ER-5114.

BALLOONING STABILITY OF POLOIDALLY ROTATING PLASMA WITH A VELOCITY SHEAR .

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Fast poloidal rotation of plasma is observed in some regions of tokamak discharges that exhibit L-H transitions. The characteristic velocity for this rotation is usially less than or comparable to the sound speed. The rotating layer is very thin (of order of 1-3 cm.), thus, the poloidal velocity shear is also very strong. An analytical criterion for ballooning instability in a toroidal axisymmetric configuration for this case is derived. It has been shown that pure poloidal rotation destabilizes the plasma, shifting the instability zone toward smaller pressure gradient. The value of this effect is of the order of $\Delta\alpha \sim (v_{\Theta}/v_{\text{Alfvèn}})^2 q^2 R/a \sim \beta q^2/\epsilon$. The velocity shear has a stabilizing influence that can be roughly viewed as an "effective" ellipticity of the plasma column. This effect is of order of $(a/\Delta l)^2\beta^2$, where Δl is the thickness of rotating layer. Ballooning instability during poloidal rotation with shear likely plays an important role in the dynamics of ELMs. The term, describing ballooning effect, can be involved to the simplified model of ELMs dynamics, which consists of coupled equations for ∇p, $\mathbf{E}_r'$ and magnetic fluctuations. It appears that ballooning instability plays different roles in the dynamics of "giant" ELMs (primarily via poloidal rotation) and "grassy" ELMs (primarily via velocity shear).

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Divertor Radial Electric Fields and the Inboard-Outboard Asymmetry of DIII-D Divertor Legs

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Strong asymmetry in radiation losses from the two divertor legs was found in DIII-D experiments.[1] The asymmetry is reduced when D_2 puffing is turned on. We use the recently developed minimal Divertor Model[2] to understand the phenomenon. Also incuded are the effects of radial electric fields which exist in the divertor region due to the dependence $\phi(x) = \Lambda T_e(x)/e$.[3]

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1D25

Finite-time Singularities in Hydrodynamic Plasma Models

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A new class of finite-time singularities (Taylor singularities) in hydrodynamic models is presented. Among the systems which demonstrate Taylor singularities are some plasma-physical ones: 2D microtearing, 3D electron MHD, plasma convection between conducting plates, degenerate Hasegawa-Mima equation.

Turbulence Suppression and Drag Reduction by External Magnetic Field

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ABSTRACT

Imposition of a DC magnetic field on some systems, such as turbulence boundary layers, can result in turbulence suppression and drag reduction. These phenomena are investigated theoretically. We note the magnetic Reynolds number R_m in these systems is smaller than unity. The analysis indicates that although the fluctuating magnetic field is weak $\left(\langle\tilde{b}^2\rangle << \rho\langle\tilde{v}^2\rangle\right)$, the energy dissipated by resistivity is not negligible as compared to the energy dissipated by viscosity. Suppression of turbulence and momentum transport is caused by the enhanced energy dissipation via resistive dissipation of Alfvén excitations. For such a turbulence quench process, $M^2/R>1$ is required (M is the Hartmann number and R is the Reynolds number). Another important phenomenon we noticed in both shear and homogeneous flow is the anisotropy induced by the magnetic field. Turbulent eddies tend to have extended vorticity along the magnetic field. The 2D-ization of the flow tends to offset the effect of magnetic field (a factor of two in the experimental region). Finally, comparison of our results with experimental work is performed.

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Mode Structure and Stability of TAE Modes in ITER and TFTR DT Plasmas*

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The small-inverse-aspect-ratio boundary layer approximation, used previously to describe the analytic structure of α-driven nonideal TAE modes[1], is applied to a numerical analysis and stability calculation for the TAE in ITER and TFTR DT plasmas. Away from TAE gaps (singular layers), zero-β cylindrical MHD determines the generic structure of outer solutions. Within each gap, a detailed kinetic treatment is used to include (i) modifications to fluid equations arising from $E_{\|}$ and FLR, (ii) stabilization from electron curvature damping and ion Landau damping, and (iii) drive from finite-orbit-size fusion α-particles and zero-orbit-size neutral beam particles. The model is valid for arbitrary toroidal mode number, and predicts the growth/damping rate of (among others) the most dangerous TAE. Comparison with experimental estimates of critical fast particle β is quite good, although disagreements with other TAE codes persist; specifically concerning relative magnitudes of continuum, kinetic, ion Landau and electron curvature damping[2]. A discussion of these discrepancies, along with possible suggestions for future experiments, is included.

* Work supported by U.S. DOE Contract No. DE-FG03-88ER-53275 and Grant No. DE-FG03-92ER54150.

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Pseudo-MHD Ballooning Modes In Tokamaks*

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There are a number of indications from experimental measurements in tokamaks that MHD-like ballooning-type modes might be responsible for the turbulence that induces anomalous plasma transport -- scaling of τ_E with β-limit parameters (e.g., l_i, κ) in DIII-D, ohmic equilibria limited to $\beta_p \sim$ 0.1 - 0.3, ballooning character of fluctuations, etc. However, for typical plasma parameters the ideal MHD ballooning modes are stable and resistive MHD ballooning modes should be so feebly growing that the anomalous transport they induce should be negligible, except at the plasma edge where the plasma resistivity is high. These regular MHD modes are stable or only weakly growing because the pressure-gradient free energy accessible via the curvature drive term is smaller than the perturbed magnetic energy embodied in the field-line-bending term. The field-line-bending term reflects the fact that modes localized to the outer, bad curvature region of the tokamak have $\partial\tilde{\phi}/\partial\ell \neq 0$ and thus induce via an Ohm's law a parallel current $\tilde{J}_{||}$ which in turns induces a parasitic $\tilde{\mathbf{B}}_{\perp}$. Ballooning-type modes could become more unstable if the pressure-gradient-drive term were larger or the field-line-bending term were smaller. It should be noted that recent BES measurements [1] on TFTR indicate that the turbulence apparently responsible for anomalous transport has $\Delta_r \sim 2$ cm, $k_\theta \sim 1$ cm^{-1}, which for $L_s \sim 200$ cm implies a typical mode $k_{||}(\Delta_r) \sim 1/(100 \text{ cm}) << 1/R_0 q \sim 1/500$ cm. For an inferred growth rate $\gamma \gtrsim 3 \times 10^4$/sec the turbulent modes apparently would satisfy $\omega_{bi} < k_{||} v_{Ti} \lesssim \gamma \lesssim \nu_e << k_{||} v_{Te}$. Thus, the electrons would be relatively adiabatic but the ions could be fluidlike. Previous attempts to extend MHD ballooning mode theory using an adiabatic electron, fluid ion kinetic (FLR) theory [2] or via two-fluid equations [3] have generally reduced the pressure-gradient-drive term and effectively converted the modes into drift-type modes. In these previous studies the field-line-bending term was not significantly affected because it was assumed that either $\tilde{E}_{||}$ vanishes [2] as it does in ideal MHD or the parallel electron response was assumed fluidlike [3].

In this work we take advantage of the recently derived kinetic closures for the fluid-moment equations [4], and in particular of a parallel Ohm's law in the adiabatic electron regime, to significantly reduce the field-line-bending term. Specifically, the effective parallel resistivity can be written approximately as $\eta \simeq (m_e/n_e e^2)(\nu_e + k_{||}^2 v_{Te}^2/\gamma)$. For the adiabatic electron regime ($k_{||}^2 v_{Te}^2 >> \gamma \nu_e$) this effective resistivity is much larger than the classical resistivity and thus allows ballooning-type instabilities with interchange-mode type growth rates, $\gamma \sim c_s/r_p^{1/4} R_0^{3/4}$. We call these instabilities pseudo-MHD ballooning modes because while they are derived from the current continuity equation $(\mathbf{B} \bullet \nabla)(J_{||}/B) + \nabla \bullet \mathbf{J}_{\perp} = 0$ with fluid ions, the electrons are assumed to be adiabatic and dramatically reduce the field-line-bending term through an enhanced resistivity. The radial eigenmode structure is being investigated and will be discussed along with the other properties of these new modes and the turbulence they might induce.

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The Effect of MHD Tearing Modes on the Stability and Transport Properties of g-Modes in the RFP Edge*

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A standard view of the Reversed Field Pinch (RFP) is that it is characterized by a core region dominated by stochastic magnetic fields produced by resistive tearing mode turbulence, and an edge region where temperature gradients exist. In the edge region, resistive g-modes are often suggested to determine the plasma transport properties. However, theories of resistive pressure-gradient-driven turbulence predict fluctuation levels and transport coefficients that are much too small to explain experimental observations in RFPs [1,2]. In the present study, we attempt to model the effect of the dynamo-producing tearing modes on RFP edge micro-turbulence. In particular, we examine the stability properties of short wavelength resistive g-modes in "equilibria" that are populated by a collection of long wavelength, slow time-scale magnetic fluctuations. A random phase approximation is invoked to derive an eigenmode equation for the g-mode. The background magnetic fields produce a dynamo term in the renormalized Ohm's Law. It is found that for sufficiently strong magnetic fluctuation levels, the linear growth rate of pressure gradient/curvature-driven modes is enhanced over the resistive-MHD prediction [3]. Correspondingly, the nonlinearly saturated g-mode fluctuation level and anomalous transport coefficients exceed the resistive-MHD prediction.

* Research supported by U. S. DOE grant nos. DE-FG02-86ER53218 and DE-FG02-85ER53212.

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Progress in the Development of a 3-D Neoclassical-MHD Simulation of a Tokamak Plasma*

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The introduction of neoclassical viscous effects into a resistive-MHD-like simulation of a tokamak plasma requires the formulation of a set of resistive-MHD-like equations in a fully three dimensional toroidal geometry. Numerous representations (and associated computer codes) have been developed which begin with a density, momentum, and an Ohm's Law formulation to describe a portion of the required set of equations in terms of the magnetic potential, vorticity, and plasma compressibility. However, for neoclassical-MHD simulations additional representations are required for the viscous stress tensors, as well as the pressure evolution. The optimum choice from a computational viewpoint for such a set of equations relies primarily on four features: 1) the evaluation of the equilibrium metric elements must be highly accurate, 2) the evaluation of the operator $B \cdot \nabla$ should be simple, accurate, and fast to compute, 3) the neoclassical-MHD terms should be easily representable, and 4) the overall accuracy and speed of the simulation for the large number of modes to be considered suggest a pseudo-spectral formulation. This set of equations will be presented and discussed.

Additionally, progress in the development of a nonlinear, three-dimensional, toroidal resistive/neoclassical MHD computer simulation based on this set of equations will be presented. This computational development seeks to take advantage of the distributed computing capacity of the newly created CPTC FDDI-cluster of workstations. Discussion of our preliminary experience in this heterogeneous environment composed of 1 SUN-10/41, 2 DEC-Alphas, and 4 IBM-RS6000's connected via a fiber optic network will be outlined.

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Turbulent Transport Across Invariant Flux Surfaces*

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We investigate net transport due to a combination of Coulomb collisions and turbulence effects in a plasma using a fluid moment description which allows for kinetic and nonlinear effects via stress tensor closure relations. A closed, nested flux surface model is considered. This model allows for turbulent fluctuations which distort but preserve the topology of species-dependent $\mathbf{B}_{\#}$ or canonical flux surfaces, where $\mathbf{B}_{\#} \equiv (1/q)\nabla\times[m\mathbf{u} + q\mathbf{A}]$ in which $\mathbf{u}$ is the flow velocity of the fluid species. For the surface motion, the closed surface assumption yields a canonical flux invariance condition. Net transport equations are found for the total number of particles and total energy enclosed by a moving canonical flux surface. The corresponding transport fluxes are calculated using a toroidal axisymmetry approximation for the surfaces. The resulting transport fluxes include classical, neoclassical, and anomalous contributions and show for the first time how these various contributions should be summed to obtain the total transport fluxes. The particle flux includes a contribution from $\tilde{n}\nabla\tilde{\alpha}_k$, where $\tilde{\alpha}_k$ is a species-dependent scalar potential. For electrons with $m_e \approx 0$, this term is equivalent to $\tilde{n}\nabla\tilde{\phi}$ in the electrostatic limit, but more generally it also includes electromagnetic and parallel inertial effects. Because the surfaces are closed in this model, flow along the field produces no net transport and the ambipolar contributions of $\tilde{\alpha}_e$ to particle transport result primarily from the fluctuating parallel electric field, which is in turn induced by fluctuations in the electron parallel pressure gradient, viscous force, and friction force. These latter quantities can all be related in lowest order to fluctuations in the density and temperature.

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Radial Structure and Stability of Resistive Ballooning Modes in the Presence of Poloidal Flow-Shear in Edge Region of Tokamak*

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The radial structure and stability of resistive ballooning modes (RBM) in the presence of flow-shear (FS) of poloidal rotation in the edge region of tokamaks is studied. The problem is treated both as a two-dimensional eigenvalue system, where a set of coupled equations for different poloidal harmonics is solved, and also by means of an explicit initial value code. The effective strength of interaction between harmonics and global radial structure is determined. The transition from weak to strong ballooning regime, accompanied by change in topology of modes is observed as function of magnetic shear, poloidal numbers, etc. The influence of sheared flow on the stability of RBM is discussed.

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New Unstable Branch of the Resistive Ballooning Modes*

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Resistive ballooning modes (RBM) are studied for present-day tokamak edge plasmas. We have derived a ballooning mode equation for RBM, corresponding to the "optimal ordering" [1]. It is constructed by choosing the length and time normalizing units such that make the three terms in the vorticity equation to be of the same order. We have determined the regions of validity of the weak and strong ballooning approximations for RBM. Furthermore we have shown that there exist two unstable branches of the RBM with different properties. Numerical investigation of the conventional, slab-like RBM shows that this branch is stabilized when magnetic shear rq'/q is of the order of unity. We have found a new unstable branch, which has a stronger ballooning structure compared to the conventional RBM branch. It is less unstable for weak shear, but is the only one which is robustly unstable for shear of the order of unity.

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THREE-DIMENSIONAL SIMULATIONS OF THE RESISTIVE BALLOONING MODES - REVISITED*

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We have modified our three-dimensional fluid code for Drift Resistive Ballooning Modes (DRBM). The Reduced Braginskii equations are now solved in the fully 'twisted' coordinate system. Also in the radial direction we have now introduced periodic boundary conditions. The transformation to the twisted coordinate system allows us to use significantly larger time steps for realistic shear rq'/q=1-2. The periodic boundary condition prevents the quasilinear flattening of the density since the outgoing flux at the right boundary equals the incoming particle flux at the left boundary. In the fieldline direction we have introduced Neumann boundary conditions for the density and potential and Dirichlet conditions for $v_{\parallel}$ .With these two modifications we have found that in the absence of the quasilinear flattening, the particle flux is significantly larger than that obtained in our earlier simulations. The levels are now consistent with experimental values. Also we observe a strong localisation of the turbulence along the fieldline, consistent with the strong ballooning character reported in our earlier simulations. The levels of density fluctuations are typically between 25-30% a factor of 2-3 larger than in our ealrlier work. These results further support our point of view that DRBMs are a very promising candidate for edge fluctuations in tokamak plasmas.

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TRUNCATED MODEL STUDY OF THE 2D RAYLEIGH INSTABILITY*

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The 2D nonlinear evolution of the Rayleigh-Taylor instability, with periodic boundary conditions in the x direction and hardwall boundary conditions in y, can be studied by using a truncated fourier model, for Rayleigh numbers Ra of the order of 10^2. Such a model was first proposed by Howard and Krishnamurti, J. Fluid Mech.170,385(1986). This truncated system of equations succeeded in modelling the symmetry breaking leading to tilted convective rolls which arises from the generation of shear flow. However the model does not preserve the average vorticity as dictated by the vorticity equation. This aspect was found to have important consequences on the generation of shear flow in our earlier work on driven vortices.(Finn et. al. Phys. Fluids B 4,2758,1992). Thus we have extended the H-K set to include an additional fourier harmonic which leads to conservation of the average vorticity. We have derived a new criterion for the Critical Rayleigh Number (as a function of the elongation $\alpha=2L_x/L_y$, of the vortices and the Prandlt Number) for the onset of the shear flow instability. For low Prandlt numbers, we find that the shear flow instability occurs for a much larger Ra for than predicted by the H-K equations. Also comparing our full 2D simulations with the H-K simulations for small $\alpha < 0.49$ we find nonlinear evolution significantly different from the H-K equations. This is because for this elongation the second harmonic mode in the periodic direction has is unstable for a lower Ra than the first harmonic. Thus the validity of the H-K system of equations is more restrictive than anticipated.

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Rotation and Toroidal Effects on Resistive Wall Kink Modes

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The effect of plasma rotation and finite beta on the resistive wall kink mode have been investigated for a high aspect ratio tokamak. An eigenvalue equation for the radial eigenfunction retaining toroidal corrections is derived. The coupling of the kink mode to the sound wave is retained by ordering the parallel and perpendicular components of the displacement to be the same order of magnitude ($\xi_{\parallel} \sim \xi_{\perp}$). It is shown that for a purely growing mode with dominant poloidal component m, a resonance occurs between the plasma rotation frequency and the sound frequencies of the sideband components ($m+1$ and $m-1$). At the point of resonance, the radial eigenfunction can become logarithmically singular. There are two possibilities concerning the effect of the singularity. First, in an ideal MHD plasma, such a singularity is removed if the mode rotates with the plasma. However, for a rotating mode the wall looks perfectly conducting and the destabilization mechanism (due to the resistivity of the wall) disappears (no resistive wall mode exists with a finite frequency). Thus, the second possibility prevails in which the singular mode represents the only possible solution to the eigenvalue problem. Its stability as a function of the plasma parameters and the wall position is investigated and preliminary results will be presented.

Marfes in Tokamaks*

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Marfes are radiation condensation instabilities that appear in tokamaks as a density limit is approached. They are manifested as a dense, cool region of radiating plasma which form a poloidally localized and toroidally symmetric ring which are usually located near an outer flux surface on the high field side of the torus. We show that the Braginskii fluid equations yield several equilibrium solutions which may be divided into two classes: 1) those that exhibit a constant temperature along the field line and 2) Marfe-like solutions which vary along the field. The transition from a constant temperature to a Marfe-like solution can take place if the former solution becomes linearly unstable. We find that the initial constant temperature equilibrium is usually stable and we hypothesize that temperature fluctuations can cause a constant temperature equilibrium to "jump" into the Marfe-like solution (even if the initial equilibrium is stable) when these two equilibrium approach each other. This model for the transition can explain a number of observed phenomena including the tendency of Marfes to form on the inside of the torus and the tendency of Marfes to locate themselves at an x-point if one is present. The transition threshold depends on the connection length (qR) and the edge temperature and we present necessary conditions for the transition to occur.

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A 2-D Kinetic Model of the Scrape-Off Layer of a Diverted Plasma with a Private Flux Region*

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Earlier two dimensional (radial and poloidal angle), analytically tractable ion kinetic models of the scrape-off layer were unable to make a distinction between limited and diverted plasmas [1,2]. The model presented removes this limitation while still remaining amenable to a Wiener-Hopf solution procedure. In this improved model, diffusion into the private flux region and the additional diffusion in an extended divertor channel can be evaluated. The boundary conditions employed at the diverted plate allow for partial reflection in order to model ion recycling. A steady state is achieved by balancing the streaming loss of ions to the divertor plates with the radial diffusion of ions from the core into the scrape-off layer.

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[2] P. Helander, P. J. Catto, MIT Plasma Fusion Center report PFC/JA-93-33, December 1993.

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Two-Dimensional Kinetic Modeling of a Tokamak Scrape-off Layer with Recycling*

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A two-dimensional (radius and poloidal angle), analytically tractable kinetic model of the ion behavior in the scrape-off layer of a limiter or divertor plasma in a tokamak is presented. An earlier model [1] assuming perfectly absorbing walls is extended by allowing for ion recycling at the limiter or divertor plates by an effective ion reflection coefficient [2]. The model desecribes the balance between radial diffusion and streaming along the magnetic field, and the structure of the resulting scrape-off layer is found to depend on the reflection coefficient. The particle and heat loads on the limiter or divertor plates are calculated, as well as the boundary conditions on the density and temperature gradients of the core plasma. By assuming that electrons have a Maxwell-Boltzmann distribution, the radial variation of the plasma potential is determined, and the potential of the Debye sheaths formed at the limiter or divertor plates is estimated.

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[2] P. Helander, P. J. Catto, MIT Plasma Fusion Center report PFC/JA-93-33, December 1993.

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1D40

Fluid Equations for the Neutral Component in a Partially Ionized Plasma*

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In partially ionized hydrogen plasma, the neutral particles interact with the ions by charge-exchange, ionization and recombination. Because this couples the ion and neutral distribution functions to each other, the transport of both species are affected by these processes. In this work, the short mean free path transport coefficients for the neutrals are derived. The electron distribution function is assumed to be unaffected by the presence of neutral particles, and collisions among the latter are neglected. The neutral kinetic equation is solved by means of a Chapman-Enskog-like procedure, using a more exact charge-exchange operator than previously employed [1,2]. This gives rise to new terms in the momentum and energy equations, representing the thermal force and the thermo-diffusion effect.

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Simplified description of high-Z impurity transport in tokamak edge plasma

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Abstract

In order to determine the magnitudes and profile of the radiation losses in a tokamak it is necessary to know how the impurities are distributed over their ionization states Z_j. However, the complexity of the equations describing their evolution and the large uncertainty in the anomalous transport coefficients and even in the rate constants of the elementary processes involving complex ions make it useful to derive simpler semianalytical models of the evolution of the impurity distribution by ionization states. In the limit of $Z_j >> 1$ we have employed a differential analog of the system of discrete equations describing the evolution of the impurities in terms of their ionization states Z_j. Expanding the distribution function of the impurity over ionization states in a series of Hermite polynomials yields the equations for the coefficients of this expansion. In the simplest case one can use the three first coefficients to describe the impurity distribution over ionization states. We use classical equations to describe impurity transport along the magnetic field and assume that impurity transport across magnetic field is described by pinch velocities and diffusion coefficients.

Dense ITER divertor plasma modelling with Navier-Stokes neutrals

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Abstract

The gas blanket operating regime of the ITER divertor, characterized by a cold gas layer near the divertor plates and the sidewalls and reduced heat load on the targets, is one of possible solutions of the ITER divertor problem. In hydrogen plasmas such regimes can only be established for ITER relevant conditions in the case of dense divertor plasma [1,2]. Regimes with dense recombining hydrogen plasma in the ITER divertor were investigated in [3,4] with 2D fluid plasma codes (based on Braginskii-like plasma equations) coupled with different neutral models (Monte-Carlo and diffusion approximation) where only charge-exchange, ionization and recombination was taken into account. However, in the recombining ITER divertor plasma the neutral density is so high ($\geq 10^{21}$ m^{-3}) that neutral-neutral collisions must be taken into account for proper neutral gas modeling, since the neutral-neutral collision mean free path is of the order of a few millimeters. This circumstance is crucially changing the two very important features of the ITER divertor modeling: a) heat transport through the gas layer is due to not only thermal conductivity but also by neutral gas convective structures which become very important and b) plasma momentum transfer to the sidewalls is governed by neutral gas viscosity.

In this paper the coupled plasma/neutrals set of the equations as well as a boundary conditions are formulated and simplified analytic estimations of plasma/neutrals parameters are discussed. The first results of dense ITER divertor plasma modeling based on the coupling of the 2D UEDGE fluid plasma code with the Navier-Stokes neutrals are presented.

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On Divertor Plasma Detachment

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Abstract

The different regimes of the neutral gas influence on plasma flow in a tokamak Scrape-off Layer (SOL) are discussed. It is shown that the detached divertor regimes found recently on JET, DIII-D, Alcator C-Mod, ASDEX/U, JT-60U might be related to the thermal bifurcation of divertor plasma parameters. This bifurcation is described by the low temperature SOL plasma flow interaction with the curtain of the neutrals for the case when the SOL width is transparent for the neutrals. The plasma flow through the curtain and the curtain formation are treated self-consistently. The criterion of the SOL plasma thermal bifurcation is obtained.

Bursting Processes in Plasmas and Relevant Non-linear Model Equations

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Important intrinsic plasma instabilities manifest themselves in the form of periodic bursts of fluctuations rather than as a state of stationary fluctuations which a conventional application of quasilinear theory would lead to expect. A set of coupled non-linear equations [1] for the time evolution of the fluctuation amplitude and of the driving factor of the relevant instability is shown to have the features necessary to reproduce the variety of bursts that are observed experimentally [2]. These are the periodicity, the duration, and the shape of the bursts, special consideration being given to the excitation of modes by energy particle populations [3],[4] in thermalized plasmas. A model is introduced which is relevant to the case where the spatial dependence of the mode amplitude is important. The application of the given analysis to the case of spatially distributed bursts in space is given.

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Heat Pinch and Current Diffusion Resulting From Coupled Electron Energy and Current Transport*

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It has been proposed that, in regimes where the applied electric field drives the plasma current and at the same time heats the plasma, the transport of the electron thermal energy and the redistribution of the toroidal current density are strongly coupled [1] and can be described by a matrix equation. The degradation of the energy confinement that occurs when auxiliary heating becomes dominant can be interpreted in terms of the breaking of the symmetry of the transport matrix [2]. This matrix equation contains, besides the thermal conductivity, a "thermo-viscous" coefficient that accounts for the energy and current density transport driven by the deviation of the relative shapes of their profiles from an ideal relation. The thermo-viscous coefficient causes a thermal energy inflow, associated with the gradient of the current density, that provides a natural formulation for the so-called "heat pinch".

Using a 1D transport code [3], we have verified the effect of the thermo-viscous term on the current density and electron temperature profiles for several TFTR ohmic discharges. Assuming a Coppi-Mazzucato-Grüber type of electron thermal diffusion coefficient, $\chi_e \propto I_\phi/(r^2 n_e^{0.8} T_e)$, where I_ϕ is the toroidal current within the flux surface of radius r, we have taken the thermo-viscous coefficient of the form [1] $L = \lambda[c_0(c_0-1)](n_e\chi_e)(T_e/J_\phi^2)$, where c_0 is a constant related to the ideal shape of the temperature and current density profiles, J_ϕ is the current density, and λ is a control parameter. As expected, the new term in the Ohm's law eliminates the typical "cusp" of the current density profile at the magnetic axis, caused by neoclassical resistivity. The smoothing effect saturates at a moderate value of λ. The steady state temperature profile is not strongly affected by the new terms. In the central part of the plasma column the thermo-viscous energy flux is inward and much smaller than the usual outward thermal diffusion in the ohmic steady state.

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Separation of Plasma Pressure and Magnetic Field Evolution in a Two Fluid $m = 1$ Reconnection Process*

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The independence of the motion of the electron and ion components of a plasma that is allowed by the addition of an electron fluid to the one fluid MHD description introduces several new effects into the evolution of the $m = 1$ kink and magnetic reconnection. The symmetry of MHD description in the poloidal/toroidal angles is broken by the new terms that are introduced, the Hall term ($\mathbf{J} \times \mathbf{B}$) and the gyroviscous stress tensor. The motion along the magnetic field lines becomes an important factor. Numerical simulation of the nonlinear evolution using a version of the code MH3DK [1] that has been extended to the two fluid model shows that, even in the cylindrical plasma where the disturbance maintains a strict $m = 1$, $n = 1$ helical symmetry, the electron pressure and the magnetic field can become decoupled over a wider region around the reconnection layer, at an earlier stage of the nonlinear evolution than in MHD (measured, e.g., by the amplitude of the perturbation or the displacement of the central plasma column from its equilibrium position).

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HAMILTONIAN FORMULATION OF LOW-FREQUENCY, NONLINEAR PLASMA DYNAMICS

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The system of equations describing the nonlinear, low-frequency dynamics of a plasma in a strong magnetic field (Schep, Pegoraro and Kuvshinov at this conference) can be cast, in the limit of infinite plasma conductivity, in noncanonical Hamiltonian form. In terms of the field variables $\xi_1 = \Psi_e$, $\xi_2 = d_e\beta_e^{1/2}\ln n/n_0$, $\xi_3 = -d_e\beta_e^{1/2}\left[\ln n/n_0 + \tau_i(1-\Gamma_0)\Phi\right]$, the Hamiltonian functional and our set of equations become

$$H = \frac{1}{2d_e^2}\int d^3x\left[-\xi_1\frac{d_e^2\nabla^2}{1-d_e^2\nabla^2}\xi_1 + \xi_2^2 + \frac{1}{\tau_i}(\xi_2+\xi_3)\frac{1}{1-\Gamma_0}(\xi_2+\xi_3)\right], \qquad (1)$$

and

$$\partial\xi_i/\partial t = \{\xi_i\ , H\}, \qquad i = 1,2,3. \qquad (2)$$

where $\{\}$ denotes the noncanonical Poisson brackets.

In the general 3-D case, three global constants of the motion exist, besides the Hamiltonian and the fields momentum: $Q_i = \int d^3x\ \xi_i$, $i = 1,2,3$. These constant functionals (Casimirs) are independent of the form of H and follow simply from the form of the Poisson brackets. In the cold ion limit the "ion" Casimir becomes an infinite set: $C_3 = \int d^3x\ G(\xi_3)$. In the 2-D limit two infinite set of "electron" Casimirs are found: $C_\pm = \int d^2x\ F_\pm(\xi_1 \pm \xi_2)$.

The existence of these infinite sets of conserved global functionals in the 2-D limit implies that $\xi_\pm$ (and ξ_3 in the cold ion limit) are the quantities that are locally conserved, instead of the magnetic flux Ψ or of the generalized flux Ψ_e. This indicates that magnetic reconnection in Ψ and/or Ψ_e can occur in the presence of an infinite set of conservation laws. The critical points, such as the X-points, of the conserved ξ fields are preserved (and advected together with their field) and the area inside separatrices is constant. The relationship with the better known conservation laws of reduced MHD can be seen from the fact that the Casimirs $C_\pm$ are generalizations of the Casimirs $C_1 = \int d^2x\ F(\Psi)$ and $C_2 = \int d^2x\ \Omega\ G(\Psi)$ (where Ω is the fluid vorticity) that exist in the limit of zero electron mass and cold ions and when diamagnetism is omitted. An analogous connection with the conservation law of the generalized flux Ψ_e can be established in the cold electron limit by retaining the effect of electron inertia.

The existence of the Casimir invariants restricts the possible plasma motions to hypersurfaces in the infinite dimensional phase space where the Casimirs are constant. This restriction can be used to describe the stationary solutions of Eq.(2) with the help of an "isotopological" variational principle (Arnold). Further, if the second variation (again at constant Casimirs) of the Hamiltonian functional is positive, these stationary solutions are stable. This variational principle allows us to perform a stability analysis of the shear-Alfvén vortices and of the nonlinear perturbations of a sheared magnetic field which are described by Eqs.(1, 2).

Vertical Instability Analysis in Noncircular Deformable Plasmas for the Ignitor Experiment†

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The effect of plasma deformability on the vertical instability growth rate has been studied in the presence of external passive conductors and active feedback coils by means of numerical simulation codes and an appropriate analytical model. The used model describes the elongated, triangular plasma as a system of toroidal coils with variable sizes and currents, in equilibrium with external poloidal coils producing the vacuum magnetic field. It is demonstrated that a deformable plasma does undergo instabilities with higher growth rates than a rigid one.This model has been applied to the Ignitor machine, a compact, high magnetic field experiment whose main goal is to reach thermonuclear burn conditions. [1] The results of this model have been verified against numerical simulations carried out using both the free boundary equilibrium code TF9 and the transport and MHD free boundary code TSC. These analyses have shown that an active feedback system, provided with proportional and derivative control, can stabilize vertical modes in a wide range of gain parameters. Finally, a study of the dependence of the growth rate and safety factor on the relevant plasma displacement is presented taking into account the effects on the equilibrium by the currents induced on the passive structures.

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Growth Rates of the Ion Cyclotron Emission (ICE) Instability*

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We present an analysis of the linear growth rate, γ^α, of the ICE instability that results from the interaction of fusion produced alpha particles with a characteristic mode that is radially non-convective and is spatially localized near the periphery of the plasma column [1]. The features of these modes make them the most appropriate driving factor for the radiation emission at the harmonics of the cyclotron frequency of the fusion reaction products observed in experiments carried out by the JET [2] and TFTR [3] machine. In particular, the perpendicular velocity gradient of the fusion products, $\partial f/\partial v_\perp$, determines whether the mode is unstable or not. We explore the relation of γ^α to n_α, the density of the fusion products. Considering that, in general, $\gamma^\alpha/\omega_r \propto (n_\alpha/n_e)^\nu$, we find that $\nu \simeq 1$ corresponds to the modes that can be realistically excited. The role of the finiteness of the longitudinal mode number is analyzed and the combined effects of the confinement geometry and of the particle distribution function are illustrated.

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Structure of Compressional Alfvén Modes in Cylindrical Geometry*

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Localized compressional Alfvén modes are thought to lie [1] behind the ion cyclotron emission observed at JET [2] and TFTR [3]. We have developed an analysis that is valid in the frequency range with $\omega \sim p^o \Omega_i$, where p^o varies from unity up to relatively large values. Since, to lowest order in the relevant parameters, it is appropriate to adopt the cold plasma approximation, we use a set of MHD equations that includes the Hall term in generalized Ohm's law to study the mode structure in this frequency range. We obtain a second order differential equation, for the radial structure of the mode, which admits localized solutions. The position of the region in which these modes are localized agrees with experimental results.

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Analysis of m=1 Mode Stability in D-T Plasma with Fusion Alpha Particles*

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An analysis of the stability of D-T plasmas, against m=1 internal modes (sawteeth and fishbones) driven by pressure gradients, is performed for selected equilibria of recent TFTR experiments. The plasma equilibrium profiles p(r) and q(r) are evaluated by the TRANSP code and the resulting two-fluid [1]-[2] stability parameters (λ_H, ω_*) are obtained. A numerical code [3] is employed to analyze the linear stability boundaries for sawteeth and fishbones, as functions of the alpha particle parameters (number density and pressure profile).

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Advanced Fusion in ICRF Heated Plasmas*

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Fusion burning of a D-^{3}He mixture in a high density, high magnetic field, compact toroidal experiment (Ignitor) heated by ion cyclotron radio frequency (ICRF) waves is investigated. The use of a minority (5-15%) population of ^{3}He permits efficient creation of a suprathermal tail (with central energies exceeding 1 MeV) capable of incurring substantial fusion rates with the Deuterium nuclei. The Ignitor [1] experiment is uniquely suitable to study advanced fusion burning, due to its high plasma current ($I_p \lesssim$ 12 MA) and high density (n_o up to $10^{21} m^{-3}$); it confines the 14.7 MeV fusion protons and its energy replacement time exceeds the slowing-down time of fusion products. Numerical simulations are performed using the FPPRF code [2] that combines a ray-tracing package (for the wave propagation and energy deposition) with the numerical solution of the Fokker-Planck equation for the minority species. The fusion reactivity is also evaluated from an analytical form [3] of the minority distribution function so as to identify the optimal parameters that maximize the total fusion power. Results indicate that D-^{3}He fusion powers of the order of 1 MW should be attained. [4]

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Anisotropic Pressure Effects on Advanced Operating Regimes in Tokamaks

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The effects of anisotropic pressure distributions on the stability of TFTR plasmas and advanced operating modes in TPX are investigated. Anisotropic pressure has little effect on the first region stability boundary of ballooning modes. However, there is a substantial effect on the second region boundary and the transition region. Thus, anisotropic pressure is also likely to have a significant effect on the infernal mode stability limits as well. Some of the MHD activity observed in TFTR high beta plasmas have characteristics that correlate with infernal mode stability limits and mode structure. Anisotropic pressure distributions arise as a result of auxiliary heating - in TFTR as a result of neutral beam heating. Pressure distributions for TFTR are derived from TRANSP simulations of experimental data. Equilibrium and ballooning stability codes including anisotropic pressure effects have been developed for this study. Progress on a low-n MHD code with anisotropic pressure will also be reported.

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MHD Stability Analysis of D-T Plasmas in TFTR*

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Data is available from recent experiments at TFTR where a limited number of plasmas have been created using tritium and D-T fuel. The supershot plasmas for these experiments were produced at higher currents than previously. This has significantly altered the observed MHD behaviour of these plasmas. In the high current plasmas slowly growing, coherent MHD modes are observed usually with an m/n=4/3 structure rather than the 3/2 instabilities which occurred most frequently in the past. Using pressure and current density profile data obtained from TRANSP analysis of these D-T experiments we study the predictions of both ideal and resistive MHD theory and compare these with the experimental observations.

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SELF-ORGANIZED CRITICAL GRADIENT TRANSPORT AND L-H TRANSITION IN THE PRESENCE OF ITG MODE*

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A series of runs of the toroidal particle simulation of ITG mode (by TPC) has shown that (with single or multi-n modes): After the initial fast evolution and in the quasi-steady state the time-averaged amplitude of the radially extended potential streamers is nearly independent of r and the temperature gradient scale length L_T becomes nearly independent of r over the domain of ITG activities. During this period the waves remain weakly unstable to sustain the transport and necessary ExB trapping width. Because of these properties we can describe this nonlinear state as the self-organized critical state, since the global vortices organize the relaxed temperature landscape, and any small deviation away from which is quickly transported away. This physical picture provides two coupled equations that describe the global parameters (not a volume averaged) of $|\phi|^2$ and L_T both of which are r-independent because of the global self-organization. These equations produce results that are consistent with many known experimental transport characteristics of the L-mode. We generalized this system to include shear flows (both toroidal u_t and poloidal u_p), leading to the four state variables, $|\phi|^2$, L_T, u_p, u_t. Dynamical equations for these four state variables (and their extension to four fields when the shear flow profile is independent of the temperature) produce the L-H transition, the critical momentum input power, the L-H transport ratio χ_H/χ_L among other things. For example, they yield

$$\chi_L \sim 5\chi_H \sim \left[\overline{T}_i / T_i(r)\right]^2 (\rho_i v_i) a^{1/2} L_T^{1/2} / R$$

We show the comparison of this theory and shear flow TPC simulations.

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Fast-Ion Driven Alfven Instabilities in Tokamaks

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ABSTRACT. Global Alfven modes are observed in a number of tokamaks, including TFTR and DIII-D. Instabilities occur during neutral-beam injection and during fast-wave ICRF heating. Identification of toroidicity-induced Alfven eigenmodes (TAE) is based primarily on the scaling of the real frequency of the mode. Measurements of the mode structure are consistent with theoretical predictions, but the uncertainties are large. The stability properties of TAE modes seem to agree (to within a factor of two or three) with theoretical predictions; detailed comparisons are given. The changes in the stability properties of Alfven modes near the beta limit are also discussed. Global Alfven modes can cause large losses of fast ions, but detailed comparisons between experimental observations and theoretical predictions have not yet been performed. Phenomenologically, beam-driven Alfven modes usually "saturate" through bursts that expel beam ions, while modes observed during ICRF approach a steady saturation amplitude. The implications of the observed saturation mechanisms for alphas in a reactor are considered.

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Stabilization of Ideal Kink Modes in DIII–D by a Resistive Wall

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The most promising advanced tokamak scenarios envisaged in DIII–D and TPX require wall stabilization on a steady state time scale in order to reach even moderate beta values. With wall stabilization, the gain in the beta limit for these scenarios can be up to a factor 2. However, for a resistive wall, simple theoretical models predict an instability which grows on an L/R time scale when the plasma is ideally stable with a perfectly conducting wall but unstable for no wall, irrespective of the plasma rotation. Stability analysis of many DIII–D discharges over the past several years, however, has hinted that the DIII–D vacuum vessel stabilizes the ideal kink for times much longer than the wall L/R time — the observed discharges are more consistent with the theoretically predicted stability boundaries computed with wall stabilization. Convincing evidence of wall stabilization has now been obtained by detailed equilibrium and stability analyses for several DIII–D discharges — specifically at high β_p, high β_N, and at high β. These include several recent high β, low ℓ_i discharges in which the observed β is much higher than the expected β limit; the profile dependence of the β limit has been shown in earlier studies to be consistent with β_N proportional to ℓ_i, so these are expected to have correspondingly lower β limits. Wall stabilization, however, is expected to be most effective at low ℓ_i. The detailed stability analysis confirms that the high beta observed in these discharges is most likely due to stabilization by the DIII–D vacuum vessel. Taken together, the results from all the detailed studies provide clear evidence of stabilization of the external kink mode by the resistive wall in DIII–D on long time scales. More recent theoretical analyses have now suggested that the simplest MHD theory, which was for a straight cylinder with periodic end boundary conditions, is inadequate for a finite aspect ratio, finite beta torus; complete wall stabilization is possible under some circumstances if the plasma is rotating at a small but significant fraction of the sound speed. The DIII–D discharges were strongly neutral beam heated and were consequently rotating, consistent with the more recent theories. Work on confirming the details of the newer theory for these DIII–D discharges is continuing and will be discussed.

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Effect of a Non-Uniform Resistive Wall on the Stability of Tokamak Plasmas

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A general formalism is developed for investigating the influence of a non-uniform resistive wall on the stability of MHD modes. The analysis is performed in the cylindrical tokamak limit, assuming that the wall lies in the 'thin-shell' regime. The dispersion relation for wall modes reduces to a matrix eigenvalue problem. The eigenvalue determines the mode growth-rate, and the eigenvectors determine the Fourier harmonics of the magnetic flux in the wall. In general, the dispersion relation requires numerical solution. However, an analytic solution is obtained in the special case of a toroidally non-uniform wall where the variation scale-length of the resistance is much larger than the poloidal spacing of the eddy current vortices.

The influence of toroidal gaps on wall mode stability is investigated. For the case where only one of the coupled modes has a wall stability index which differs appreciably from the vacuum value, it is found that if the mode is stable the perturbed poloidal flux tends to concentrate in the metal sections of the wall, if the mode is marginally stable the flux becomes evenly distributed between the metal and gap sections, and if the mode is unstable the flux tends to concentrate in the toroidal gaps. In fact, if the stability index exceeds a critical value the flux becomes entirely concentrated in the gap regions, and the mode can then 'explode' through the gaps with an ideal growth-rate.

The above result has obvious implications for the design of tokamaks with incomplete stabilizing shells. Clearly, the structure of an unstable mode interacting with such a shell cannot be assumed *a priori*, but must instead be solved for in a self-consistent manner along with the growth-rate. There are also ramifications for the design of MHD feedback systems, since an incomplete resistive wall is equivalent to a low-gain feedback system with finite coils. It seems likely that a sufficiently unstable non-rotating mode could completely defeat a feedback system by 'squeezing' between the coils. This is not a 'phase instability', but rather a 'spectrum instability' in which the mode changes its structure under the influence of the applied feedback signals. This effect cannot easily be counteracted, since it is a function of the number and extent of the feedback coils rather than the strength or phasing of the feedback signals.

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Alpha particle effects on the internal kink mode*

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Abstract

The effects of α-particles on the stability of internal kink modes are studied analytically by employing Solovev equilibria. Finite inverse aspect ratio, plasma β, and plasma shaping effects can significantly enhance the trapped particle drift reversal domain in the pitch angle space. Since the trapped α-particles have a uniform pitch angle distribution, its averaged magnetic drift frequency can be greatly reduced. The α-particles have a small effects on sawteeth. But, the fishbone mode can be excited at a much lower β_α threshold than that predicted by the previous model [1]. The fish bone can be excited even when the total plasma β is below the ideal kink threshold. The core ion diamagnetic drift effect can significantly reduce the stable domain in the presence of α-particles.

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Three Dimensional Wall Calculations for δW Stability Analyses*

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The enclosing metallic shell in present and envisioned tokamak devices is usually inherently three-dimensional in nature because of the access through the shell for beams and diagnostics, etc., and the need to have as much conducting material in the crucial outer major radius side of the plasma as is feasible for contributing to the stabilization of the external kink mode. The PEST-VACUUM codes are limited to studying $2D$ axisymmetric configurations, but an effective method to incorporate the $3D$ nature of shell is to treat the plasma as $2D$, but use the vacuum $\delta W_{\rm v}$ which incorporates the $3D$ boundary conditions of the shell. We do this by interfacing with the $3D$ SPARK electromagnetics code, which is suitably modified to calculate the perturbed magnetic field from the induced shell currents using the PEST perturbations as its driver. Several steps are involved. First, we decompose all possible boundary displacements from PEST into Fourier harmonics on the surfece. Then for each harmonic the SPARK code is used to find the $3D$ magnetic perturbation, $\delta\mathbf{B}_s$ which, when driven by the fields obtained from χ_p, both combine together to satisfy the appropriate boundary conditions at the $3D$ shell. Using the continuity of the normal component of $\delta\mathbf{B}$ to relate to the radial plasma displacement, $\xi_\psi = \boldsymbol{\xi}\cdot\nabla\psi$, at the plasma-vacuum interface the vacuum energy becomes,

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

This requires the parallel component of $\delta\mathbf{B}_s$ in addition to the normal component from SPARK, because of the boundary condition. These are spectrally filtered for input to the PEST codes in the form of a modified vacuum energy in terms of ξ_ψ:

$$2\delta W_{\rm v} \;=\; \sum_{ll'} (l - nq)(l' - nq)\mathcal{R}_{ll'}\xi_{l'}^* \xi_l.$$

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Steady-state transport in generic dissipative drift-wave turbulence*

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Various two- and three-field fluid models have been proposed to study forced, dissipative drift-wave turbulence. Although many physical details have been included, even the generic nonlinear behavior of such multi-field models is not yet well understood. We concentrate here on the two-field Hasegawa–Wakatani (HW) model,[1] which is well known to exhibit both an adiabatic regime ($\alpha \gg 1$, where $\alpha \doteq k_{\parallel}^2 v_t^2 / 2\nu_{ei}\omega_{ci}$) and a hydrodynamic regime ($\alpha \ll 1$). Koniges et al. have suggested[2] that transport in the hydrodynamic regime is suppressed by the formation of "coherent structures" that are not captured by standard Eulerian statistical theories. We critically analyze this assertion. By consideration of a simple model for the dominant statistical interactions in k space, we show that the steady-state transport can be explained both qualitatively and quantitatively by a simple Markovian closure that makes no reference to, and does not capture the details of, coherent structures. The analytic work is supported by detailed numerical calculations of the Realizable Markovian Closure[3] for the HW model; preliminary results will be presented.

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1994 Sherwood Theory Conference

Stability of TAE Modes in TFTR D-T Experiments*

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Stability analysis of low-n TAE modes in the TFTR D-T experiments has been performed by using the NOVA-K code [1, 2], and the results are compared with the TFTR D-T experiments. The NOVA-K code contains linear physics such as ion Landau damping, electron Landau damping, collisional damping of trapped electron, neutral beam ion drive, ICRF fast minority ion drive, alpha particle drive, and finite ion orbit excursion from the flux surface, etc. If the TAE mode suffers the continuum damping, the continuum damping can be computed from a resistive stability code, NOVA-R[3], and is then added to other damping effects computed from the NOVA-K code.

For the present plasma parameters of TFTR D-T experiments, the ion Landau damping is the dominant stabilizing mechanism on the TAE stability due to high thermal ion temperature and beta. The experimentally produced volume averaged alpha beta values in steady state operations are still smaller than the theoretically computed critical volume averaged alpha betas for the TAE instability, and so the TAE modes are stable as indicated in the experiments. However, there are operational regimes where TAE instability can be unstable. Detailed results will be presented.

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* The work is supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

Numerical Simulation of an Experiment to Test the Feasibility of Ponderomotive Feedback Stabilization for Control of External Kink Modes and Disruptions in Tokamaks†

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It has been suggested that an active feedback system utilizing the ponderomotive force produced by several IBW antennas can stabilize external kink resistive wall modes in advanced tokamak regimes.[1,2] We propose a simple precursor experiment that could be carried out with minimal modification of PBX-M that would test many of the physical principles required for this feedback stabilization to work. In this experiment, both the vertical field strength and the IBW power amplitude are modulated with a sinusoidal frequency ω and a relative phase difference ϕ. Measurements of the variation of the amplitude of the plasma major radius oscillation with ϕ and ω will give information about the efficiency of the coupling of the IBW ponderomotive force to the bulk motion of the plasma. These measurements can be compared directly with corresponding simulations presented here using the TSC code[3] and with the axisymmetric ponderomotive calculation of Myra[4]. The coupling coefficients measured in this manner can then be used to benchmark the ponderomotive feedback stability calculations[2]. In this way, we will determine the feasibility of using IBW to stabilize the external kink mode in future experiments.

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† This work supported by the U.S.Department of Energy Contract No. DE-AC02-76-CHO 3073 and by SBIR Grant No: DE-FG05-93ER81587.

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Ponderomotive Feedback Stabilization of External Kink Modes in Tokamaks

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One of the important challenges facing the tokamak concept is that of developing active means of stabilizing MHD modes near their instability boundaries. The control of external kink modes is important for disruption control and for maintaining "advanced tokamak" operating regimes with high "bootstrap current" fractions and high values of the plasma beta. Here, we re-examine the original proposal[1] to stabilize external kink modes using the ponderomotive force (PF) exerted on the plasma by a system of radiofrequency (rf) antennas, incorporating now the idea[2] of using of a feedback system to reduce the required rf electric fields and rf power for stabilization. The PF feedback coupling term in the kink equation is derived assuming that the antennas are modulated in response to the signal from an array of MHD mode detectors. For a finite number of antennas and detectors, the rf term induces MHD mode coupling, with the form of the matrix depending on the exact feedback scheme. The properties of two feedback models will be discussed, and it will be shown that multiple-mode stabilization is possible in principle. The parametric dependences of the stability boundaries for n = 1, m > 1 external kink modes will be illustrated in the Shafranov cylindrical tokamak stability model. Work is underway at PPPL to model a near-term experiment that could test this proposal on PBX-M and benchmark the results of the present model for realistic PBX-M plasma equilibria.[3] Estimates of the required rf fields and rf power for typical antenna systems will be given for PBX-M. Extrapolations to TPX and ITER will also be discussed.

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Edge Biasing and Electron Heating in RF Fields*

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Motivated by the Faraday screen glow seen in some circumstances during ICRF heating experiments on TFTR,[1] we have developed a theory of electron interaction with rf fields in the vicinity of conducting surfaces. The theory incorporates the physics of both rf sheaths and the electron jitter that gives rise to the ponderomotive force by piecing together these previously disjointed regimes. Because the electron physics depends only on electron inertia and acceleration in the space and time varying rf fields, the results are expected to be applicable to a wide range of wave frequencies, including but not limited to ICRF. The crucial parameter is $v_e \sin\theta / \omega \Delta$, which determines whether the electron response is Maxwell-Boltzmann (MB) across the rf sheaths of width Δ. (Here θ is the grazing angle of the B field with respect to the surface.) Electron heating arises from the Fermi acceleration that results when the electrons bounce off the sheaths.[2] In the low frequency MB regime, we recover the usual processes of rf rectification, rf-driven impurity sputtering, power dissipation and convective cells.[3] In the opposite limit where ponderomotive effects would be expected to enter, the rectification effect, and all of its consequences, are reduced, suggesting a possibility for improvement of ICRF antenna performance through reduced θ. While a rich and largely unexplored parameter space exists, the present beginning of a unification of sheath and ponderomotive effects may also have implications for proposed ponderomotive rf limiter schemes,[4] and for understanding the relationship of ponderomotive and sheath effects in IBW experiments.[5]

* Work supported by USDOE contracts DE-FG03-93ER54212, DE-FG02-88ER53263 and DE-AC02-76-CHO-3073.

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An Analysis of the Nonlinear Generation of Sheared Flow via E × B Mode Coupling of the 2D ITG Instability*

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Abstract

Much attention has recently been given to the role that nonlinearly generated sheared flows may play in suppressing pressure-gradient-driven instabilities and reducing the associated thermal flux. [1,2] Here we apply a simple mode-coupling analysis, as was done by *Lee et al.*, [3] along with 2D gyrokinetic simulations in a detailed exploration of the generation mechanisms responsible for the appearance of sheared flow ($k_{||} = 0$) modes and the effect of these modes on the ITG instability. The effects of electron dynamics, finite-β and magnetic shear on the development of sheared flow modes are also considered.

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Numerical study of stability of ultra high-β equilibria[1]

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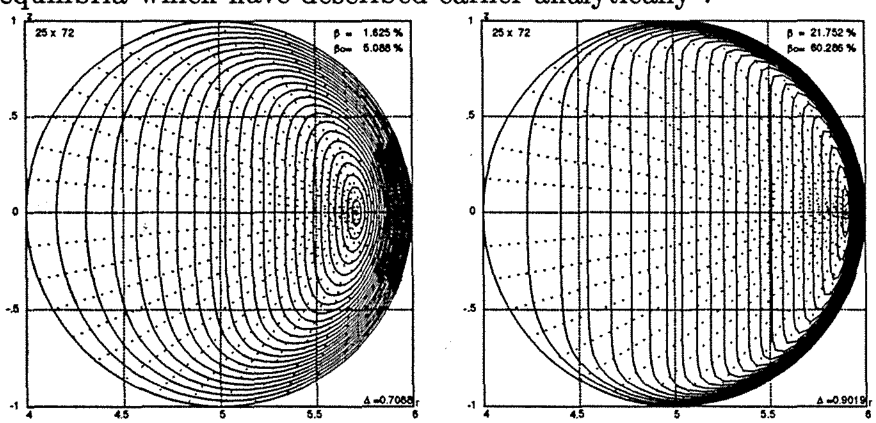
The numerical code POLAR, developed in the Keldysh Institute of Applied Mathematics (Moscow, Russia), has been used to calculate the ultra high-β tokamak equilibria which have described earlier analytically[3].



Shafranov shift $\Delta_0/a = 0.71$ $\Delta_0/a = 0.90$, $q_a = 10$, $R/a = 5$

Those configurations were predicted[4] to be stable against Mercier and high-wave number ballooning modes. These results have been checked numerically. The stability of such equilibria with respect to the low-n free boundary modes is currently under investigation with use of the PEST code and the results will be reported.

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The Validity of the Extended Energy Principle*

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A recent analysis[1–3] of plasma stability based on modifications of the extended energy principle for magnetohydrodynamic stability[4] led to conclusions that are too optimistic. The original interpretation of this principle is indeed applicable. We first show that the functional $\delta W_B(\xi, \xi)$ that is used by Bernstein *et al.*[4] for "improper" perturbations ξ which do not satisfy pressure balance at the plasma-vacuum interface provides a satisfactory test of stability by demonstrating that if an "improper" perturbation ξ which makes $\delta W_B(\xi, \xi)$ negative can be found, a nearby "proper" one $\tilde{\xi}$ which does satisfy pressure balance can be constructed with $\delta W_B(\tilde{\xi}, \tilde{\xi})$ having the same value. We then show that the functional $\delta W_L(\xi, \xi)$ which Lehnert proposes for "improper" ξ's does not possess this property and demonstrate how it differs from $\delta W_B(\xi, \xi)$. Finally, we consider an extended energy principle in which there is a finite surface mass at the interface, such that acceleration of the surface can sustain a pressure imbalance, and show that self adjointness can again be demonstrated and that this approach also leads to the functional $\delta W_B(\xi, \xi)$. A comparison of the results of the two models provides justification for believing that the eigenfunctions that are obtained from a minimization of the extended energy principle with the proper kinetic energy norm are a good representation of what would be achieved with an exact treatment. This strengthens the acceptance of the results from the PEST code[5] as a valid description of the linear behavior of ideal MHD instabilities in tokamaks.

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Ideal MHD analysis of single-divertor configurations in ITER

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International Tokamak Engineering Reactor, ITER, is designed to have a single divertor in the lower-half plane. This geometry no longer has up-down symmetry. The PEST[1,2] codes have been modified to account for this lack of symmetry. This requires keeping both the real and imaginary parts of the displacement vector. In a symmetric case, these are identical with different parities and it is sufficient to retain one of them. Stability analysis of ITER relevant equilibria will be presented.

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2C12

Use of the PIES MHD Equilibrium Code for Stellarator Studies

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Considerable work[1–3] has been done to verify that the PIES[4] and VMEC[5] codes find the same equilibrium properties in stellarators. This work is continuing and application of the PIES code to stellarators is now being done. We report favorable results for a comparison that was made for an ATF configuration which has been used in experimental studies. We describe work that is in progress for a new Modular Helias-like Heliac which has been proposed as a candidate for a Stellarator Power Plant Study which is being undertaken by the ARIES team. The work with the PIES code should be valuable at high values of β where magnetic islands may be found.

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Study of Effect of Plasma Rotation on External Modes in Tokamaks using the Princeton MH3D Code*

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The MH3D code is a fully toroidal, non-linear resistive, free-boundary, 3D initial-value MHD code, which, in the past, has been used extensively to investigate the physics of internal modes in tokamak plasmas.[1] A recent extension of the MH3D code capabilities allows the study of external modes, including the effect of a resistive wall.[2] Since the MH3D plasma model includes poloidal and toroidal flows, the code is well suited to study the influence of toroidal plasma rotation on external modes. In this poster, we describe some early stages in a systematic effort to investigate toroidal flow effects on external modes. In particular, we will describe (1) some careful benchmarking of MH3D against analytic calculations of external kinks in the presence of resistive walls without plasma rotation, and (2) MH3D calculations of kink mode stabilization, comparing cases when the wall is rotated[3] with cases where the plasma itself has rotation.

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Linear and Quasilinear Analysis of Toroidal Drift Modes in High-Power TFTR DT Shots*

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Recent TFTR experimental discharges have employed tritium neutral beam injection and tritium gas puffing to obtain comparable fractions of deuterium and tritium. This has led to the production of large amounts of neutron power, up to 6.8 MW in one shot. These recent discharges are analyzed with a comprehensive kinetic linear instability code[1,2] to study the properties of the high-n toroidal drift mode, destabilized by the combined effects of trapped-particle dynamics and of ion temperature gradients. The effects of magnetically trapped and untrapped fractions of electrons, deuterium and tritium background ions, hot deuterium and tritium beam ions, and of hot fusion alpha particles, as well as of helium ash ions and of carbon impurity ions, can be included in the calculation. Also, for the hot species, the sensitivity of the results to the equilibrium distribution function, which can be a Maxwellian distribution, a slowing-down distribution, or a general function of energy and pitch-angle from a Fokker-Planck calculation, is investigated. In particular, the scaling with mass for the different ionic species is investigated, with respect to the linear growth rates and real frequencies, as well as to the associated quasi-linear transport of particles and energy for each species.

* Work supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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1994 International Sherwood Fusion Theory Conference
Dallas, Texas

DEGAS Modeling of the H_α Spectrum on TFTR*

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Reliable predictions of the performance of divertors are crucial for the design of next-step devices such as ITER. Given that high density, low temperature regimes are the primary focus of these designs, it is especially important that the neutral gas models used be as accurate as possible. The spectrum of Balmer-α emissions make for an excellent benchmark for kinetic neutral gas models such as the DEGAS Monte Carlo neutral transport code [1] in that it yields direct information about the velocity distribution of hydrogenic atoms. Comparisons of measured and simulated spectra provide insight into the atomic and molecular physics as well as the wall reflection and recycling properties which govern the hydrogen atom velocity distribution.

Here, we will present DEGAS simulations of the Balmer-α spectrum measured in TFTR via a Fabry-Perot interferometer [2]. The existing set of H_2 dissociation energies in DEGAS has allowed to us to obtain good agreement between the calculated and measured spectra in H-D plasmas. However, some of the H_2 dissociation models may need to be refined; this is a topic of current investigation. We will also discuss the modeling of deuterium-tritium discharges in TFTR. The measured spectra in conjunction with the DEGAS modeling should provide insight into the T recycling source at the edge.

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Selfconsistent study of α-particle driven TAE mode*

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Abstract

The interaction of high energy particles with an Alfven eigenmode is investigated self-consistently by using a realistic dispersion relation. The toroidal mode number is $n = 1$ but all important poloidal mode numbers and their radial mode profiles calculated with the NOVA-K code are included. A Hamiltonian guiding center code using a fourth-order Runge-Kutta integration is used to simulate the alpha particle motion. The numerical simulations include particle finite orbit width, full nonlinear particle dynamics and the effects of modes on the particles. Modification of the particle distribution leading to mode saturation is observed, along with some induced particle loss.

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ROTATING MAGNETIC ISLANDS IN A TOKAMAK WITH APPLIED RESONANT MAGNETIC PERTURBATIONS *

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In this work we consider the dynamics of low m (poloidal mode number) nonlinear tearing modes in a tokamak plasma. We focus on rotating magnetic peturbations such as those typically observed in experiment. Two-fluid magnetohydrodynamic equations are used to derive nonlinear equations for the evolution of the island width and the toroidal rotation frequency. The structure of a perturbed flux function outside the island is investigated without the vacuum field approximation for the region between the rational surface and the plasma boundary. The effect of a finite plasma current on the penetrating magnetic field induced by external coils is considered. Using the radial momentum balance equation for ions, the profile of the toroidal plasma velocity in the presense of a magnetic island is determined. It is shown that the evolution of the island rotation is governed by the balance of the plasma momentum in the toroidal direction which is subject of external forces associated with the applied resonant magnetic perturbations and viscous damping. The effect of the neoclassical (parallel) viscous force on the damping of the island rotation is estimated. It is shown that for sufficiently large magnetic islands, when the viscosity can be neglected the frequency of the island rotation decreases inversely with the island width. The effect of plasma viscosity in the Rutherford-type evolution of the island width is reconsidered and found to be different from that in Ref. 1. The stabilizing effect of plasma inertia is considered allowing for an ion FLR effect.[2] New expressions for a critical magnitude of the magnetic field leading to a nonlinear island instability are derived. Implications for feedback stabilization of MHD activity in tokamaks are discussed.

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Study of Sawtooth-stabilization on TFTR*

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Abstract

The stabilizing effects of high-energy particles on the sawtooth mode are investigated for the case of TFTR experiments. This study is based on the analysis of the interaction between high energy ions and magnetohydrodynamic modes. A variational dispersion relation including the contribution from the inertial(resistive) layer is employed. Both analytical and numerical equilibrium are used to approximate the plasma shape and particle orbits. Monte-Carlo simulation generates the particle distribution. Good approximations of equilibrium and distribution are important since stability of sawtooth mode is sensitive to the details of particle distribution, aspect ratio and q-profile. Comparisons are made with experimental data from TFTR.

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1994 Sherwood Theory Conference

Gyrokinetic Vlasov simulation of η_i modes[1]

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Issues in the gyrokinetic Vlasov simulation of η_i modes as well as η_i turbulence are discussed. It will be important that both the linearly unstable and stable harmonics be numerically resolved when carrying out a nonlinear simulation. The gyrokinetic Vlasov simulation is successfully benchmarked for the unstable modes.

Linear two-dimensional modes using higher order terms in the ballooning formalism are studied. The growth rate of the global two-dimensional mode can be larger than those of the lowest-order one-dimensional modes. This is possibly due to the fact that the higher order terms represent a radial variation in the driving terms, allowing the mode to couple to a stronger source than allowed in the lowest order representation.

Preliminary investigations of the nonlinear simulation show that the fluctuation amplitude in the quasi-saturation stage continues to grow at a much slower rate than the linear growth rate. For example, in a time of $100L_n/v_i$, the total fluctuation energy increases by a factor of 3—4. The shape of the k_θ spectrum remains approximately stationary. The amplitude of the fluctuations in the nonlinear quasi-staturated state is $|e\phi/T|^2 \sim 0.1$—$1.0\rho_i^2/L_n^2$, which is similar to typical gyrokinetic particle and gyrofluid results. But the heat flux is $\chi_i \sim 0.2$—$0.5\rho_i^2 v_i/L_n$, which is an order of magnitude lower than typical gyrokinetic particle and gyrofluid results.

[1]This work supported by DoE contract No.DE–AC02–76–CHO–3073.

The Effects of Artificial Hyper-viscosity and Hyper-resistivity in MHD Simulations of RFPs*

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The 'steady' state of a typical RFP discharge is a saturated state of interacting resistive MHD modes. Simulating the complex behavior at realistic Lundquist numbers remains a numerical challenge due to the resolution requirements. Artificial hyper-dissipation mechanisms are being explored to lessen them. Radial resolution is necessary for the sharp gradients near the mode resonance surfaces, and the RFP safety factor profile produces many m=1 resonant surfaces. Also, nonlinear interactions can produce gradients that are not physically significant but cause numerical aliasing instabilities if unresolved. Physical dissipation mechanisms (proportional to k^2) control these instabilities by truncating the radial spectrum, but artificial hyper-resistivity and hyper-viscosity (proportional to k^4) can more effectively serve the same purpose. While excessive artificial dissipation can distort results, linear scalings and full nonlinear simulation results from the DEBS code[1] show that hyper-dissipation can be used to reduce resolution without sacrificing accuracy. This opens the possibility of simulating less resistive, hence more realistic, conditions than previously practical.

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

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Nonlinear Frequency Shifts in Trapped Electron Driven Drift Wave Turbulence*

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Theories of drift wave turbulence have typically predicted the spectrum only as a function of the wave number S(k) due to the difficulties associated with predicting the frequency spectrum.[1] Recent numerical simulations of dissipative trapped electron driven turbulence, however, have seen large frequency shifts,[2] which are not predicted by theories limited to calculation of the wave number spectrum. Also, experimental measurements of plasma turbulence often predict the spectrum as a function of only the frequency $S(\omega)$, and not the wavenumber.

A two-time, two-point theory for dissipative trapped electron driven turbulence is presented. Equations describing both the mean and relative time evolution are derived. By solving the mean time equation, the imaginary part of the incoherent contribution is obtained, which corresponds to frequency broadening.[3] In previous theories of clump emission processes, only this term has been considered. It is shown, however, that the real part contributes a nonlinear frequency shift. This nonlinear frequency shift is obtained by solving the relative time equation using an expansion in a large effective Reynold's number. The frequency shift can affect both stability and transport by altering the phase between the trapped electron response and the electrostatic potential.

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* Supported by US DOE contract No. DE-FG02-89ER-53191

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Advanced Tokamak Scenarios in ITER and TPX*

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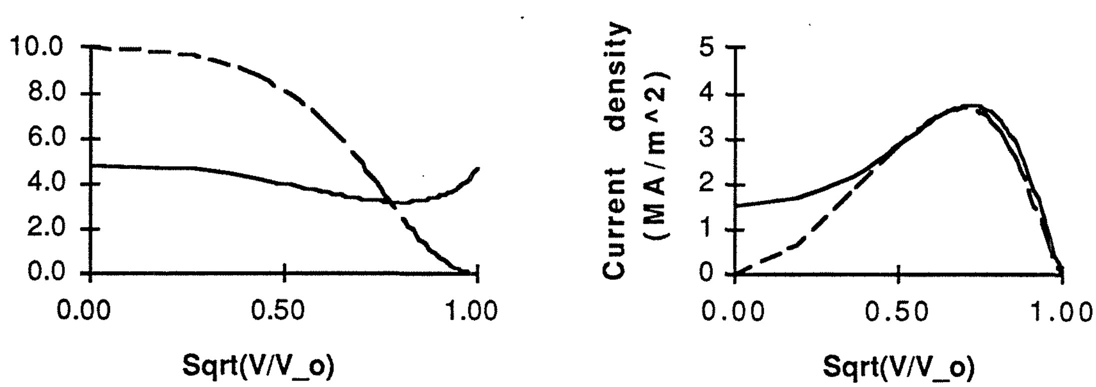
The ultimate attractiveness of tokamaks as fusion reactors may well hinge on successful development of high-Q, steady-state operation. The key to achieving High-Q, steady-state operation will be the development of operating scenarios with very high bootstrap current fractions ($f_{BS} \geq 90\%$) in which the radial profile of the bootstrap current density is well aligned with that of the total plasma current density, and for which the MHD β-limit exceeds $\beta_n{}^* = 0.05$ T–m/MA. Such advanced steady-state operating scenarios have been developed in connection with the TPX project. and Steady State Tokamak Reactor. These operating scenarios are based on the PEP mode observed in JET and other tokamaks. A key feature of this operating mode is a non-monotonic current profile, such that the q-profile has a minimum off axis. This leads to a region of reversed shear between the minimum in the q-profile and the magnetic axis, which is in the second stable regime to high-n ballooning modes. The Rebut-Lallia-Watkins and other transport models transport models predict excellent confinement in the region of reversed shear,. A strong reduction in transport was observed in the reversed shear region of JET PEP-mode discharges. We will review these operating modes as proposed for TPX, and show how similar modes can be accommodated in the ITER device. Radial profiles for such an operating mode in ITER are shown below.



*Work performed under the auspices of the U.S. Dept. of Energy under contracts Nos. W-7405-Eng-48 and DE-AC02-CHO-3073.

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Theory Issues for TPX

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The key theory issues that need to be addressed for TPX fall into four categories:

- **Divertor modeling**
  Improved models of impurity radiation, neutral collisions, pumping, and drifts need to be incorporated into codes capable of representing realistic divertor and pump geometries.
- **Advanced RF physics**
  Further work is needed on ICRF-LH synergy, on alpha-current drive (using an ICRF-driven tail for tests), and on new ideas for profile control (e.g., IBW, MCCD). In addition improved understanding of operational limits for FWCD antennas is needed.
- **MHD physics**
  Work is needed to improve understanding of the stabilizing properties of three-dimensional, but otherwise ideal, walls on kink modes, and more generally on the stabilization of non-ideal plasmas by non-ideal walls. Work is needed on feedback control of kinks and tearing modes by magnetic coils, NBI, ponderomotive forces, and ECCD
- **Advanced tokamak modes**
  New modes of operation could be proposed which combine high beta limits with high bootstrap fractions and enhanced confinement. Modeling codes need to be developed which can handle the time-dependent transport, MHD, and current-drive physics in TPX and in an Advanced Tokamak Reactor.

Development of DCON: The Code

The Direct Criterion of Newcomb for the Stability of an Axisymmetric Toroidal Plasma

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A new method has been developed for determining the MHD stability of an axisymmetric toroidal plasma.[1] Existing methods, used in well-known codes like PEST, ERATO, and GATO, expand the linear equations of ideal MHD in a set of 2D basis functions, reducing the original 2D PDE to a large matrix eigenvalue problem. They are used to determine the entire ideal MHD spectrum, both stable and unstable. They suffer from inadequate convergence of the basis functions, particularly near singular surfaces for marginally stable modes. Eigenvalues and eigenvectors are often not of interest when the practical question concerns merely the stability of the equilibrium. Newcomb[2] developed a method for determining the stability of a cylindrical plasma, reducing the task to solving an initial-value problem for a 2nd-order real ODE. Newcomb's approach has been extended to an axisymmetric toroidal plasma, reducing the task to solving an initial-value problem for a $2M$th-order coupled system of complex ODEs of the form $\mathbf{u}' = \mathbf{L}\mathbf{u}$, with primes denoting derivatives with respect to the flux surface label and

$$\mathbf{L} = \begin{bmatrix} -\mathbf{F}^{-1}\mathbf{K} & \mathbf{F}^{-1} \\ \mathbf{G} - \mathbf{K}^{\dagger}\mathbf{F}^{-1}\mathbf{K} & \mathbf{K}^{\dagger}\mathbf{F}^{-1} \end{bmatrix}.$$

The solution $\mathbf{u}$ is a complex $2M$-vector whose first M components Ξ are the Fourier coefficients of the radial component of the displacement vector and whose last M components are $\mathbf{F}\Xi' + \mathbf{K}\Xi$. The $M \times M$ complex matrices $\mathbf{F}$ and $\mathbf{G}$ are self-adjoint, the $2M \times 2M$ matrix $\mathbf{L}$ is Hamiltonian, and the $2M \times 2M$ fundamental matrix of solutions $\mathbf{U}$ is symplectic. Singular surfaces, where $m = nq$ for some Fourier component m, are characterized by the vanishing of $\det \mathbf{F}$. Frobenius expansion about a singular surface has been worked out, allowing for the correct coupling of singular and nonsingular components to all orders in the expansion. Fast, accurate numerical methods have been developed for evaluating the Fourier integrals of equilibrium quantities appearing in $\mathbf{F}$, $\mathbf{G}$, and $\mathbf{K}$, for storing these matrices as cubic splines for smooth interpolation, and for integrating the ODEs with an adaptive method which resolves the behavior near a singular surface. The generalization of Newcomb's sign-change criterion has been derived, allowing for the correct treatment of coupling between independent subintervals by nonsingular components. The behavior near the singular surfaces can be used to compute jump conditions for resistive modes. It is expected that this code will be sufficiently fast to provide accurate, reliable results between experimental shots and to allow rapid scanning of families of equilibria. Details of code design and performance will be presented.

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ψ-version of the DCON stability Code*

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January 25, 1994

Abstract

The idea of using Newcomb's approach to determine MHD stability in toroidal plasma (the DCON code) has been proposed by A.Glasser[2] as an alternative to the existing MHD stability codes. This approach allows one to solve the Euler equations by an adaptive technique and is able to guarantee a prescribed accuracy in the determination of critical plasma stability parameters without need for the time consuming convergency studies.

The current ψ-version of DCON uses the Pogutse-Yurchenko[3] choice of the test functions in the W. This significantly simplifies the Euler equations and leads to the tearing mode form of $W = W(\psi, \lambda)$ based on the perturbation of the vector potential ψ instead of the plasma displacement ξ. The second test function λ in W is a perturbation of the toroidal magnetic field. It can be easily determined numerically in terms of ψ and typically gives only small corrections of the order of B^2_{pol}/B^2_{tor}, $\beta \ll 1$ to the major terms.

Although even the full version of DCON$_\psi$ has considerable advantages in storage requirements and in the number of calculations with respect to other approaches, it also allows several fast versions corresponding to different orders of expansion with respect to the above mentioned parameters of the Reduced MHD.

The development of DCON$_\psi$ code is currently under progress and the first results are expected for this meeting.

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[1]Permanent address: Keldysh Institute of Applied Mathematics, Miusskaya Sq.4, Moscow, 125047, Russia

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Inertial-Electrostatic Confinement Studies*

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Inertial-Electrostatic Confinement is one of the earliest plasma confinement concepts, having first been suggested by P. T. Farnsworth in the 1950s. The concept involves a simple apparatus of concentric spherical electrostatic grids and intricate physics. An electrostatic structure is formed from the confluence of ion beams with a background of electrons that are provided by the grid.

A detailed comparison between single grid systems and three grid systems with dispenser cathodes will be presented. Observed neutron yields will be compared with simulation predictions. Basic physics of two stream instabilities in IEC systems will also be discussed and numerical results presented.

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IMPLEMENTATION OF THE QUIET IMPLICIT PIC METHOD IN TOROIDAL GEOMETRY*

– W. D. Nystrom, D. C. Barnes & R. A. Nebel –

LOS ALAMOS NATIONAL LABORATORY

The quiet implicit PIC method of Barnes and Nebel[1] has been implemented in toroidal geometry for a circular cross section torus. The implicit two-fluid equations are solved using a predictor-corrector scheme for the current density. This implementation uses a pseudospectral Fourier representation of the poloidal and toroidal coordinates and a finite difference treatment of the radial coordinate. The electric field is decomposed into transverse and longitudinal components. The resulting equations for the electric field are a coupled system for the transverse electric field and the electrostatic potential which is solved using a block tridiagonal system as an approximate inverse and a Picard iteration scheme. The block tridiagonal solution is vectorized over the Fourier modes to give an efficient algorithm. It is possible to configure this code as a straight cylinder torus and make direct comparisons to an existing straight cylinder code[1]. Results from the two codes are currently being compared for a variety of two fluid simulation runs representing the ideal internal m=1 mode. It is expected that toroidal runs will be made and compared to the appropriate straight torus runs after there is good agreement between the two codes. These results will be presented if available along with a comparison of the two codes with regard to performance issues such as the robustness of the electric field solution in different parameter regimes.

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* Work supported by US DOE

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PENNING FUSION EXPERIMENT AND HIGHER ORDER MULTIPOLES – DESIGN, THEORY, AND SCALING*

– D. C. Barnes, T. N. Tiouririne, L. Turner, & R. A. Nebel –

LOS ALAMOS NATIONAL LABORATORY

We describe the physics basis of the design and operation of PFX (Penning Fusion eXperiment), currently under construction at Los Alamos as part of the Innovative Research initiative of the MFE program. This experiment will construct and operate a small (6 mm diameter) Penning trap with a radially convergent electron beam velocity distribution[1] to produce a dense ($n \geq 10^{21} m^{-3}$) thermonuclear core plasma. PFX will demonstrate: 1) Ultra-high applied electric fields ($E \sim 10^8 V/m$); 2) Maintenance of a radial beam distribution; and 3) Ion confinement in a partially charge-neutralized core plasma. We also describe scaling possibilities based on this demonstration to systems of size relevant for production of fusion power. These concepts are based on recent work on higher order multipole traps[2] which are relatives of the Penning trap. They are also related to the Polywell[3] concept. In such large systems, a high order multipole provides confinement of a pure electron plasma near the boundary. These electrons, in turn, produce an internal virtual cathode which confines a convergent *ion* distribution in a nearly spherical system. In contrast to the polywell, such multipole systems are expected to exhibit excellent confinement of the electron edge plasma and nearly complete spherical symmetry, without additional self-consistent high-β effects. The equilibrium and transport properties of such systems and their scaling are described and shown to provide an alternative path toward the development of fusion power systems of small size.

* Work supported by US DOE

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GENERALIZED TWO STREAM INSTABILITIES IN PENNING TRAPS*

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In Penning traps for fusion applications, the design involves a relatively cold spherically symmetric beam of ions with nearly zero canonical angular momentum, giving a large density enhancement at the center. These ions are absolutely confined by the external electric and magnetic fields and have turning points in radius, where $v_r = 0$. In the Larmor frame, the confinement appears to be due to an attractive spherical parabolic potential well or, equivalently, to an effective uniform charge density background.

We have investigated two-stream-like instabilities in a slab model for a Penning trap. Equilibria are characterized by two dimensionless parameters, n_0 and v_0. These are, respectively, the density and velocity at the center, with $0 \leq n_0 \leq 1$. For $n_0 = 1$, the ion density is uniform and equal to the effective background charge. In this case, there are no turning points and particles are reflected off walls at $x = \pm L/2$. Analytic results for $n_0 = 1$ show that modes with the electric field, E(x), odd about x = 0 correspond to the usual two stream modes. Modes with E(x) even, however have a richer structure, including the usual two stream instabilities plus other modes which are unstable due to the interaction of positive and negative energy (fast and slow) beam modes. These modes are unstable over a larger range of v_0 than the ordinary two stream modes. We have also investigated the effect of thermal spread on these modes. Stability in the range $0 < n_0 < 1$ has been studied numerically with a cold fluid code and compared with particle code results.[1] Results show that odd and even modes are unstable over a range in (n_0, v_0) space slightly larger than the range in which turning points occur in $-L/2 < x < L/2$. For $n_0 << 1$, the stability boundary appears to occur exactly when the turning points are at the wall. Implications of these instabilities on the performance of the Penning trap and possible improvements will be discussed.

*Work supported by USDOE.

1. N. Tiouririne et al., this conference.

ROTATION GENERATION AND DAMPING MECHANISMS IN TOKAMAKS*

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Several sheared rotation generation/sheared rotation damping mechanisms related to MHD activity will be discussed from the point of view of relevance to H-modes with and without ELM's and disruptions. These mechanisms are (i) Reynolds stress/eddy viscosity[1], which drives sheared rotation for modes of wavelength shorter than their radial extent and damps sheared rotation otherwise, (ii) propagation of sound waves along chaotic field lines[2] due to large scale modes or external perturbations and (iii) rotation damping due to overlapping tearing modes of different helicities. The last mechanism involves damping of the relative rotation of the plasma at the rational surfaces of the tearing modes and has an analog for single helicity double tearing modes[3].

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2C31

Comparison of Fluid and Non-Fluid Neutral Models in Divertor Plasma Transport Simulations†

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Improved accuracy and reliability of edge-plasma models are increasingly important as magnetic fusion energy experiments push into higher power regimes where protecting the plasma and material walls from each other becomes more difficult. The two-dimensional, multi-fluid edge-plasma transport code, B2.5, of Braams[1] is used widely for simulating experiments and for designing future fusion devices. This B2.5 model describes the transport of particles, energy and parallel momentum for electron, ion and neutral particles of both background and impurity species. Versions of the B2.5 model use different neutral-particle transport models. These neutral models include a fluid treatment, a semi-analytic 3-species kinetic approximation[2], and coupling to a monte-carlo kinetic treatment[3]. While the latter (monte-carlo) model provides the most complete physics description, computational requirements are too restrictive for many applications.

The present work incorporates the fluid and 3-species neutral models into the same B2.5 version so that direct comparisons can be made. A 4-species model that combines the fluid and 3-species models is also examined. The various models result in large quantitative differences in predicted values of the divertor plasma temperature, density and flow patterns. The physics underlying the differences in the models are examined. The role of boundaries, the choice of cross-field diffusivities, and the effect of model assumptions on the numerical convergence of the solution algorithm are also studied.

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†This work was supported by the U.S. Department of Energy under Contract No. W-7405-ENG-36.

2C32

New Stellarator Reactor Concepts

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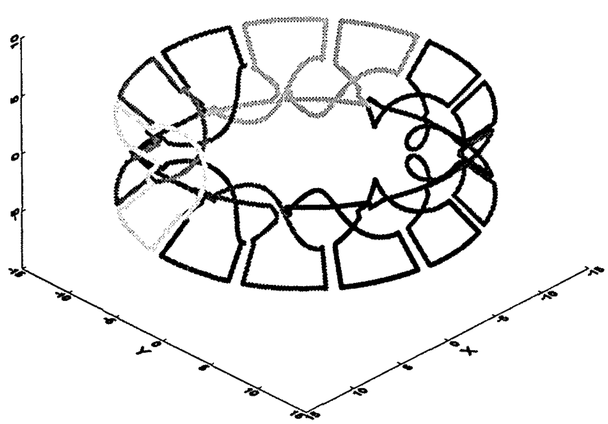
(For the Stellarator Reactor Study Group)

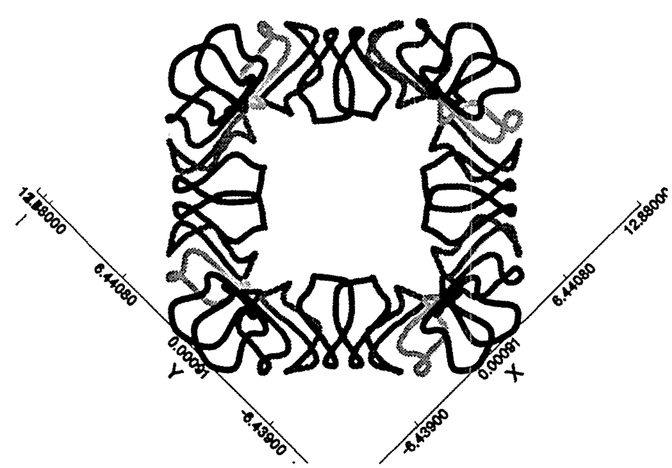
Using modern design techniques, it is possible to optimize stellarator configurations so that their physics and engineering properties are more desirable than ever before possible. The ARIES design team has been tasked to study a modern stellarator reactor during FY '94, so the US stellarator community has been generating new stellarator reactor designs with an average major radius of 10 meters. Four different configurations were considered, but only two of these were new.

- A modular version of ATF (MATF, developed by James Rome, ORNL) is based upon the symmotron concept but with the added flexibility of being able to place the windbacks at any poloidal angle. In addition, the segments connecting the modularized helix to the windbacks can go outward from the plasma, thus minimizing its contribution to the fields. The resulting configuration has physics properties similar to ATF, but with large gaps for access and a plasma-coil spacing of at least 1.2 m.
- A modular helias-like heliac (MHH, developed by Paul Garabedian, NYU and David T. Anderson, University of Wisconsin, Madison) has improved orbit transport and reduced plasma currents. It is based upon a helias with a highly modulated hard core, but has many of the quasi-helical properties of W7-X (Garching, Germany). The plasma-coil spacing in MHH is also about 1.2 m in a 10-m machine.

Both configurations have <β> of 4—5%, but the transport properties of MHH are much superior to those of MATF. It was decided to concentrate the study on the MHH configuration.



MATF oblique view.
Two sets of vertical field coils are also required.



MHH top view

† Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta, Inc.

The Performance of Fluid Codes on a Dedicated Cray Y-MP C90*

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Physically realistic and experimentally relevant calculations of plasma turbulence and transport at the core and edge of magnetic fusion devices using state-of-the-art, three-dimensional, nonlinear, initial value gyrofluid models have been tested in dedicated, multi-CPU mode[1] on NERSC's Cray Y-MP C90. Microtasking compiler directives were added to three memory- and CPU-intensive fluid codes: the FARDTEM code for trapped-particle instabilities at the tokamak core, the TAEFL code for core instabilities driven by energetic particles and/or fusion products, and the KITE code for tokamak edge turbulence studies. All three codes use a spectral representation in poloidal and toroidal mode number space and finite differences in radius. The linear part of the calculations results in a block tri-diagonal matrix system, while the nonlinear part gives rise to convolutions over modes. For the slab geometry FARDTEM and cylindrical geometry KITE, the parallelization is effected over the poloidal and toroidal mode pairs, while the inner loops over the number of equations and radial grid points are vectorized. For TAEFL, parallelization of the block tri-diagonal matrix can only be effected over the toroidal mode number since poloidal modes for each toroidal mode are coupled by the toroidal geometry. Dedicated microtasking tests of FARDTEM resulted in an average overlap of 14.5 out of 16 processors and a speed of 5 Gflops for 25 minutes of wallclock time. Access to dedicated multi-processors and the full 200 Mword memory of the Cray Y-MP C90 for production use by these codes would provide the resolution and realistic parameters needed to permit more meaningful comparisons with experiments.

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*Research sponsored by the Office of Fusion Energy U. S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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Parallel Ion Flow Gradient-Driven Instability and the L-H Transition*

L. A. Charlton, B. A. Carreras and V. E. Lynch, ORNL, P. H. Diamond, UCSD, San Diego, CA.

Simple model equations for the L-H transition have been proposed[1]. They incorporate the features of the nonlinear evolution of many instabilities as found by numerically following the time evolution of much more complicated equations governing each separate instability. The parallel ion flow gradient-driven instability has been found to well reproduce the features of the simple model. It is a good paradigm for flow profile modification and the corresponding effect of fluctuation suppression by the average poloidal flow as may take place during an L-H transition. Nonlinear calculations which use the full equations and follow the nonlinear evolution show the existence of two distinct nonlinear regimes. One is characterized by strong poloidal flow damping with the saturation of the fluctuations caused by nonlinear coupling to high-k modes plus dissipation (L-mode). The second nonlinear regime is characterized by the shear poloidal flow controlling the steady-state saturation level of the instability (H-mode). The main dynamic features of this instability are well-described by the simple equations of Ref. 1. The present numerical results are local (single helicity). Full three dimensional calculations are underway and may show the effect of H-mode propagation into the plasma interior. Results will be shown, if available.

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*Research sponsored by the Office of Fusion Energy U. S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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Full-Wave ICRF Modeling of Electron Heating and Current Drive by Mode Converted Slow Waves in Tokamaks*

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Recently it has been suggested[1] that the damping of mode-converted slow waves in tokamak plasmas may provide an efficient means of direct electron heating and current drive. One advantage over direct Landau damping of the incident fast wave is that the mode conversion layer is quite narrow and therefore allows easy profile control for both the heat deposition and driven current profiles. The balance between these two competing mechanisms for electron heating will be studied in the upcoming ICRF experiments on TFTR with D-T-^{3}He and D-T plasmas (experimental proposals DT21 and 28 respectively). Here we consider D-H operation in DIII-D geometry with f = 30 MHz and B = 2.0 T. Numerical results are calculated using both the 2-D reduced order full-wave code, PICES and the 1-D 6th order single pass scattering code, ORION. As the hydrogen concentration is increased from 5% to 50%, there is an increase in the separation between the hydrogen fundamental cyclotron resonance layer ($\omega = \Omega_{c,H}$) and the mode-conversion layer ($n_{\|}^2 = S$). At the same time, there is a transition from simple minority ion heating at $\omega = \Omega_{c,H}$ for low fractions of H to significant mode conversion heating at $n_{\|}^2 = S$ for high fractions. One interesting characteristic of the 2-D result is that off-axis ion heating occurs near the intersection of the mode conversion and resonant surfaces. Current drive efficiencies will be calculated for the mode-conversion case and compared to those found for the conventional fast wave case at 60 MHz where damping is on the incident fast wave.

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*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

Three Dimensional Modeling Of RF Current Drive Arrays*

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Three-dimensional (3D) modeling is necessary for a complete understanding of the RF power spectrum launched by fast wave current drive arrays. Return currents in the antenna sidewalls and septa are not properly handled by two dimensional models. Results from the RANT3D code for the TPX 12 strap array will be presented. These results indicate that the present design produces a good spectrum, but that the phase velocity of the launched waves cannot be significantly increased without degradation in the spectrum caused by 3D effects. Extensions to RANT3D to handle septa with different heights will also be discussed. Comparisons with experimental vacuum measurements will be shown using RANT3D and the MRFI code, which calculates the launched power spectrum using measured magnetic fields on a poloidal-toroidal plane. The MRFI code is especially useful for analyzing complex launching structures such as the folded waveguide for current drive applications in ITER. Both the RANT3D and MRFI codes are written in the object oriented FORTRAN 90 language.

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*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

The Dynamics of Front-like and Uniform Transitions from L to H or VH modes*

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The phase transition model for the L to H transition[1] is extended to allow for radial non-uniformity and nonlinear diffusion. This model is analyzed computationally and analytically in order to map out its phenomenology in parameter space. The radial non-uniformity and nonlinear diffusion lead to the existence of a set of transition solutions which display front like behavior. Depending on the details of the model used, the shear in the radial electric field can propagate radially inward with very little diffusive behavior and with a propagation velocity that agrees very well with simple analysis. In the simplest model the propagation velocity is proportional to $(P - P_{th})^{1/2}$ where P is the power and P_{th} is the threshold power. For this model the critical point is at $P = P_{th}$ where the front velocity goes to 0. In cases in which spatially non-uniform parameters are used the fronts adapt to the local values and propagate at the local velocity. When the parameters become sub critical the fronts stop.

The model has been extended to a variety of levels of complexity. The simplest being the 2 field (fluctuation energy and velocity shear) model derived in reference 1 with the addition of a nonlinear diffusion term. To this model an external torque term is added and finally a third field (pressure gradient evolution) is added.[2]

With these extensions the models exhibit more varied behavior. With an external torque applied to the system, a transition to a zero fluctuation level solution is seen for values of shear larger than a critical shear and with the 3 field model in addition to fronts, uniform transitions are seen. A variety of these solutions and their possible connections to experimental results will be presented.

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Fast Wave Poloidal Flow Generation In A Plasma*

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Fast wave poloidal flow generation at the plasma edge of a tokamak is studied with a 1-D slab model. In the absence of mode conversion the poloidal flow can be generated by spatial change of plasma velocity and current density profiles due to strong minority ion power absorption at the minority ion cyclotron resonance. The electromagnetic force plays a more important role in the flow generation than the plasma Reynolds stress. In the presence of mode conversion the flow is mainly generated by interference between the long wavelength transmitted fast wave and short wavelength ion Bernstein wave (IBW) from mode conversion. Sheared flow generated in the presence of mode conversion varies spacially with a scale length similar to the IBW wavelength. The plasma Reynolds stress becomes more important in the flow generation than the electromagnetic force with mode conversion. For both cases, the plasma Reynolds stress and the electromagnetic force are out of phase so that the resultant flow shear is smaller than either one. Possible turbulence suppression at the plasma edge is also discussed.

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Nonlinear Calculations of Dissipative Trapped Electron Modes with Ion Magnetic Drift.*

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Dissipative Trapped Electron Mode (DTEM) turbulence is a relevant model for the study of core fluctuations. Experiments suggest that long-wavelength modes play an important role in the core, and this is also true for DTEM turbulence. Our initial formulation — one equation for perturbed ion density — yielded much physical insight, but was based on a closure relation that assumed an unrealistically large ion collision frequency. Recently, this formulation has been extended to two equations (perturbed electrostatic potential and parallel velocity) so that more realistic damping mechanisms can be included.

New closure relations have been chosen to incorporate damping mechanisms that arise from linear kinetic effects. Since a linear eigenmode is strongly localized around the rational surface, where Landau damping is weak ($k_{||} \sim 0$), the ion magnetic drift resonance must be included as well. The coefficients in these closure relations have now been chosen to:

(1) accurately reproduce the frequencies and radial profiles of the eigenfunction solutions to the kinetic dispersion relation

and

(2) produce proper damping of non-eigenfunction fluctuations, such as those generated through nonlinear interactions, away from the rational surface.

The resulting evolution equations have been used as the basis of an initial-value fluid code called DTEM. Single-helicity calculations will explore the nonlinear saturation levels and energy spectra obtained in the absence of collisional dissipation, through the action of the "kinetic" dissipation terms.

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SHOCK FORMATION IN POLOIDALLY ROTATING HELICALLY SYMMETRIC PLASMAS*

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A flow pattern is derived for a compressible flow in a nonsymmetric torus. This general expression is applied to a poloidally rotating helically symmetric plasma. It is found that when the poloidal **E** x **B** velocity is of the order of v_t (B_p/B) $(|m-nq|/m)$, a shock can form. Here, v_t is the ion thermal speed, B_p is the poloidal magnetic field strength, B is the magnetic field strength, m(n) is the poloidal (toroidal) mode number of the helical system, and q is the safety factor. At a fixed toroidal angle, the shock will occur at m equally spaced poloidal locations. The structure is extended in the helically symmetric direction. Both shock viscosity and compressible viscosity are calculated to illustrate that incompressible viscosity does provide a qualitatively accurate description of the nonlinear behavior.

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EFFECTS OF ORBIT SQUEEZING ON POLOIDAL MASS FLOW AND BOOTSTRAP CURRENT IN TOKAMAK PLASMAS*

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Based on the solution of the collisional kinetic equation in the banana regime in tokamak plasmas, it is found that the parallel (poloidal) viscosity coefficient is modified by the effects of the orbit squeezing by a factor of $S^{-3/2}$ where $S = 1 - (\rho_{pi}\ d \ln E_r/dr)\ (cE_r/B_p v_{ti})$, ρ_{pi} is the poloidal ion gyroradius, E_r is the radial electric, c is the speed of light, B_p is the strength of the poloidal magnetic field, v_{ti} is the ion thermal speed, and r is the local radius. However, the driving terms of the parallel (poloidal) viscosity are still the poloidal mass flow and the poloidal heat flow, which are not affected by the orbit squeezing. The asymptotic values of the poloidal mass flow and the bootstrap current in the banana regime are, therefore, the same as those in the conventional neoclassical theory. At the transition between the banana and plateau regimes, the values of the poloidal mass flow and bootstrap current are different from their conventional ones because ν_{*i} is reduced by a factor of $S^{-3/2}$. The theory is not applicable to a region which is within a few banana widths away from the boundary, because the equilibrium distribution is not Maxwellian and more importantly, the fact that particle orbit intersects the boundary is not taken into account. However, it does provide a better understanding of the ion orbit loss mechanism. One can conclude that the large poloidal mass flow observed in the edge region of the DIII-D H-mode plasmas cannot be explained by the effects of orbit squeezing. However, the orbit loss mechanism seems to provide a plausible explanation.

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2C42

A HIGH DENSITY, LOW TEMPERATURE IGNITION REGIME FOR ITER*

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An attractive high density, low temperature ignited operating regime has been found for the ITER EDA. This regime is made accessible by deep pellet injection in L-mode confinement (no enhancement over ITER89-P confinement). WHIST time-dependent transport simulations show thermally stable operation (1500 MW fusion power) at density-averaged plasma electron and ion temperatures of 4–5 keV and $\langle n_e \rangle = 2.3 \times 10^{20}$ m^{-3} and central values of 10 keV and 3.5×10^{20} m^{-3} (with strong sawtooth activity causing axial temperatures to fluctuate between 8 and 12 keV). When the density profiles are extremely peaked by deep pellet injection ($\geq 60\%$ of the minor radius) the plasma ignites without any auxiliary power even when the confinement is L-mode. The dynamics of pellet penetration appears to enhance thermal stabilization. The Troyon factor is ≈ 1.5, $\approx 50\%$ of the power is radiated, the plasma collisionality at the separatrix was well above unity and therefore likely to remain in L-mode, so it provides a very attractive mode for divertor operation and is unlikely to exhibit deleterious alpha particle instabilities. The regime is accessible with pellet velocities of 3–5 km/s at less than 1 Hz, which can be provided by two-stage light gas guns. We report on analysis of the physics of this regime and its impact on ITER start-up and operating scenarios.

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Fitting Eigenfunctions and Suppressing Noise in a Landau Fluid Approach to Dissipative Trapped Electron Modes.*

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Velocity dependent ion magnetic drift is necessary to stabilize Dissipative Trapped Electron Modes (DTEM) at high poloidal mode numbers. Incorporating velocity dependent magnetic drift in the Landau Fluid approach requires a careful selection of fitting criteria in order to adequately treat DTEM with a small number of evolution equations, and suppress spurious noise which can arise in numerical nonlinear computations. Here we discuss the selection and application of criteria at the linear level. More computation is required at the linear level than has heretofore been the norm -- in order to reduce the complexity of nonlinear numerical computations. This is especially important if one wants to include a large number of modes and follow them to saturation in the nonlinear calculations. Our most recent work has centered on the suppression of spurious noise encountered in nonlinear computations. This will be discussed in detail. We are also upgrading a number of the details incorporated in the model, and progress in this area will also be reported.

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2C44

Excitation of TAE/GAE shear Alfvén modes by an energetic alpha population in the TFTR DT experiments

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The excitation of toroidal (TAE) and global (GAE) shear Alfvén waves by an energetic alpha component is of substantial relevance to the ongoing DT experiments on the Tokamak Fusion Test Reactor (TFTR). The gyrofluid model with Landau closure has proven a useful tool for analyzing such instabilities. We have applied it to a number of specific TFTR cases based on profiles from TRANSP simulations. Due to the relatively dilute level of the alpha component (peak $\beta_\alpha \leq 0.003$), many of the cases examined have been below the threshold for TAE/GAE instabilities and, as a result, are stable. Using the gyrofluid model, we shall systematically explore the effect of varying a number of parameters and profiles which could lower the linear stability thresholds and allow TAE/GAE instabilities to be more readily observed. We will examine effects of variation in q-profile, ion density profile, β_α profile, ion/electron temperature, and $v_\alpha/v_{Alfvén}$. The q and ion density profiles control the gap structure and level of continuum damping. The β_α profile controls the level of instability drive; in particular, growth rates can be influenced by the radial location of the peak gradient in β_α relative to the various gap locations. The ion/electron temperatures control Landau damping of the Alfvén modes, ion FLR effects, and finite β continuum damping effects. Finally, due to the resonant nature of the TAE/GAE instabilities, the level of $v_\alpha/v_{Alfvén}$ can influence growth rates; however, due to poloidal mode coupling effects (i.e., sideband coupling) these resonances tend to be fairly broad (for example, our model has shown weak levels of TAE instability even for $\langle v_\alpha \rangle / v_{Alfvén} \approx 0.3$).

In addition to these linear effects, the gyrofluid model has also proven useful for nonlinear studies. This approach is especially well suited for studying nonlinear mode coupling effects such as generation of sheared velocity flows, and localized current generation which modifies the q-profile. We find that such effects can cause a saturation in the TAE instability growth. The relation between TAE stability and velocity shear generation can lead to methods for controlling TAE mode turbulence and also have implications for L-H mode transition physics in future DT tokamaks. Analysis of these and other nonlinear effects will be discussed.

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Toroidal Alfvén Eigenmode Growth and Particle Transport

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The stability of Toroidal Alfvén Eigenmodes (TAE) in DIII–D has been analyzed by applying the NOVA-K [1] code to experimentally obtained DIII–D data [2] with toroidal mode number up to $n = 5$. Aside from Alfvén waves localized on particular singular surfaces, a large number of extended TAE modes with different mixtures of poloidal harmonics have been computed. Modes with higher poloidal mode content are in general located more toward the outer (edge) portion of the plasma and with a lower frequency; while modes with lower poloidal mode content are located more toward the center with a higher frequency. TAE modes with larger growth rates have their frequencies clustered around experimentally observed values. The growth and damping mechanisms included are excitation by the beam particles, ion Landau damping, and electron damping processes. $n = 1$ modes have been found to be stable. Energetic particle transport due to the excited TAE modes is also investigated using the Hamiltonian guiding center ORBIT code [3].

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Effect of Orbit Squeezing on Poloidal Rotation in Tokamaks

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Ion poloidal flow in tokamaks near the plasma edge has been calculated by extending neoclassical theory to allow for gradient lengths comparable to the ion poloidal gyroradius. Orbit squeezing, which is the reduction of the ion banana widths due to radial electric field shear, allows the poloidal flow velocity to be a significant fraction of the ion diamagnetic velocity, which can be much larger than the standard neoclassical value (proportional to the ion temperature gradient). The reason is that the pressure gradient-driven ion parallel flow is reduced by orbit squeezing, and its poloidal component no longer cancels the diamagnetic flow, resulting in a large poloidal flow. The radial electric field can be calculated self-consistently, using the ion radial force balance equation, in which both poloidal flow and pressure gradient appear. The resulting profiles of poloidal flow velocity and radial electric field are compared with experimental results for main ion poloidal rotation in the DIII–D tokamak.

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Thermal Runaway and Momentum and Energy Transport by Fast Ions

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In NBI heated plasma, in addition to direct collisional heating of the bulk plasma, there can be an additional thermodynamic force associated with momentum transfer from fast ions to the background plasma. This momentum input can transport background ions inward (or outward) similar to Ware pinch phenomena. This pinch flux can be significantly larger than the standard neoclassical diffusive heat flux. In the core region, this inward heat pinch can generate a thermal runaway condition with a singular ion temperature profile in the case of co-injection [1]. The main cause of this runaway of central temperature is that the beam-driven inward heat pinch is dominant over standard conduction close to the magnetic axis. We conjecture that this thermal runaway in the case of co-injection may be the principal reason for the rapid increase of central temperature, the peaked ion temperature profile in the core region and the very low inferred ion thermal diffusivity in the Hot Ion H–modes in DIII–D.

Transport fluxes carried out by slowing-down fast ions will be discussed. Since fast ions have much larger effective toroidal rotation velocity and energy than background thermal ions, small radial transport of these fast ions can lead to much larger effective transport coefficients. Roles of fast ion toroidal and parallel viscosity, radial flux of fast ions due to collisions with background plasma in steady state will be discussed.

Qualitative comparison between theory and experiments will be presented.

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Channeling Energy From Alpha Particles into RF Waves in a Reactor Plasma

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The possibility of channeling free energy from alpha particles to rf waves for the purpose of either enhancing the effective current drive efficiency, or controlling the alpha particle heat deposition could bring significant advantages in the development of a commercially attractive tokamak reactor. It has been suggested that strong quasi-linear diffusion due to intense lower-hybrid waves may accomplish this purpose [1]. In this work we consider the linear theory of alpha particle absorption and amplification of rf waves. Assuming waves of arbitrary polarization and frequencies far above the ion cyclotron frequency, our calculations show the following: (i) radial gradients of the alpha particle distribution function can lead to amplification of waves when the wavevector is properly oriented in the poloidal direction and (ii) amplification requires that the radial gradient term dominate the velocity gradient term, which accounts for the usual Landau damping. For a classic slowing down distribution, the velocity gradient term tends to dominate and there is no amplification, only absorption. Alternatively, if the alpha particle distribution were to remain peaked near the birth speed, then the radial gradient term tends to dominate and amplification is possible. Thus, free energy can be channeled into high frequency waves if the alpha particles do not achieve a slowing down distribution. Radial transport is a natural mechanism which tends to displace alpha particles outward before they can slow down. However, solution of the alpha particle Fokker-Planck equation, assuming a constant radial diffusion coefficient in cylindrical geometry, shows that the distribution function still tends to be absorbing. In effect, the only way of channeling energy from alpha particles to high frequency waves is by dominating the collisional slowing down with quasilinear diffusion, as suggested in Ref. 1, thus extracting avaliable energy before the alpha particles slow down. The problem with this idea is that under ordinary conditions the quasilinear interaction saturates (flattens the distribution function along the diffusion paths), unless the diffusion paths intersect an absorbing boundary, a situation which may be difficult to achieve. At lower frequencies, just below the alpha particle gyrofrequency, one may find a more favorable scaling for the transfer of energy to waves.

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*Oak Ridge Associated Universities Postdoctoral Research Fellow.

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New Enhanced Confinement Modes Predicted by a Flow Shear Suppression Model

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A transport model which includes the suppression of turbulence by sheared flow has been successful in reproducing the phenomenology of the L/H transition. The VH–mode naturally follows from the model at high power. Other enhanced confinement modes are also predicted by the model. These new enhanced confinement modes and the conditions under which they occur are discussed in this poster. For very low plasma density, the predicted H–mode power threshold increases until it equals the VH–mode threshold. This qualitatively agrees with the observation of a low density limit for obtaining H–mode at a given power. For low recycling and high power, a transport barrier region can form in the plasma interior first and then propagate to the edge. This phenomenon is similar to the high β_p mode on JT–60U. If there is strong impurity radiation at the edge, the H–mode can be prevented, but at sufficiently high power a transport barrier forms inside of the radiating mantle, giving a VH–mode interior with an L–mode edge. If the magnetic shear is weak near the center and the recycling is low at the edge, a transport barrier can form in the core but not at the edge. These model discharges are similar to supershots.

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Shear Flow Generated by Radiofrequency (RF) Forces Across Resonant Layers

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It is becoming clear that plasma rotation and rotational shear can enhance the confinement and stability of tokamak plasmas by suppressing micro- and macro-turbulence. Neutral beam injection can impart significant momentum into a tokamak to rotate the plasma. It remains a question that rf waves used for auxiliary heating and current drive can be equally effective. This study examines the force generated by rf waves in the presence of collisional and collisionless damping across a resonant layer. Under appropriate conditions, this force can act on ions, resulting in localized plasma rotation. A self-consistent force balance equation is derived to determine the resultant rotational shear. It appears possible to produce significant rotational shear across an Alfvén resonant layer with reasonable rf power. The interplay between collisions and viscosity will be discussed.

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Resonant and Non-Resonant Effects Due to RF

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Non-resonant rf-induced forces are of interest in tokamaks for various reasons. In current drive [1–3], they are closely connected with helicity injection and have the plausible property that the efficiency is independent of density, Recently [4], it was demonstrated that non-resonant rf forces can be of interest as a means of inducing plasma rotation. In a periodic system, the non-resonant force which is proportional to the gradient of a potential vanishes on the average. The averaged parallel force in a straight magnetic field was derived in detail in Ref. 4 for low frequencies ($\omega \ll \Omega_i$). Here this restriction is removed so that it is appropriate for considering waves in the ion cyclotron frequency range. Using the Vlasov-Maxwell equations, the quasilinear operator due to the influence of rf wave field is derived using a $k_\perp \rho$ expansion. In contrast to the usual procedure of keeping only the resonant wave particle interactions, the nonresonant terms are kept. It is shown that the effect of nonresonant terms may be of significance in singular layers. The resonant and nonresonant parallel forces are obtained by taking the appropriate moments. The effect of shear will be discussed.

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Electron Cyclotron Current Drive for ITER

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Electron cyclotron waves (ECW) as a source of auxiliary power for heating to ignition can be injected into the ITER tokamak through a simple launching structure. Absorption can be strong and localized near the plasma center, even in high density and temperature operation.

The ECW can also provide rf current drive. Current drive efficiency to values $\gamma = 0.35$ (10^{20} A/m^{2}W) are obtained at frequency 220 GHz, injecting 35 deg from perpendicular to the toroidal magnetic field for a full magnetic field equilibrium with central electron temperature of 30 keV. Present high power gyrotrons operate at frequencies $\sim$ 140 to 160 GHz. At these lower, technologically more advantageous frequencies, the current efficiency efficiency peaks at angles closer to perpendicular, and is lower in magnitude. At 160 GHz, the peak efficiency is 0.17 at approximately 10 deg from perpendicular.

These results have been obtained with the CQL3D Fokker-Planck code [1]. The rf power densities are sufficiently low that the distribution function remains closely Maxwellian [2]. The Fokker-Planck code incorporates effects of momentum conserving electron-electron collisions which contribute typically $\sim$ 20% to the increased efficiency compared to models which omit the current carried by the bulk electrons due to collisions with the tail. Parasitic overlap of the second harmonic absorption [3] with that of the primary first harmonic has been accounted for in the code. Interestingly, the second harmonic contributes a small *positive* component to the current drive [4].

Results of modeling calculations will be presented showing current drive dependencies on EC launch angle, antenna divergence, plasma temperature, density, and magnetic field.

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Incorporation of the NFREYA Neutral–Beam Heating Package Into the EFIT Equilibrium Analysis Code

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For the study and understanding of MHD stability and transport, it is essential to obtain information on the internal plasma profiles such as the shape of the toroidal current density distribution, J_T, and the shape of the safety factor, q. Since an important component of J_T is driven by the pressure gradient, an accurate reconstruction of these profiles requires a knowledge of the plasma pressure, P. The thermal component of P can be obtained from information on plasma densities and temperatures. However, when there is a fast population of ions due to neutral–beam heating, their contribution, P_f, must be added to P. In DIII-D, n_e is obtained from CO_2 interferometry and Thomson scattering measurements, T_e is obtained from Thomson scattering and electron cyclotron emission, T_i is obtained from charge exchange recombination spectroscopy, and n_i is inferred from the quasi–neutrality constraint. In this work, we describe the initial results obtained by incorporating the NFREYA neutral beam package[1,2] into the equilibrium analysis code EFIT to self-consistently compute P_f, rather than obtain it from a separate transport analysis. From a neutral beam source, P_f contribution to P is computed assuming the fast ions are thermalized locally using the magnetic geometry at that particular equilibrium iteration. The Grad-Shafranov equation is then inverted to obtain a new set of magnetic surfaces. The process is then repeated until it converges.

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STABILITY OF THE INTERNAL KINK MODE WITH ENERGETIC CIRCULATING IONS

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1994 Sherwood Fusion Theory Conference

ABSTRACT

A complete treatment of the interaction between energetic circulating particles and the $m = 1, n = 1$ ideal internal kink mode is carried out including the fluid as well as the kinetic particle response. The limit of particle radial orbit excursion $(qv_{\|}/\Omega_c)$ larger than the thickness of the mode inertial layer is considered, and the interaction between the particles and the radial component of the mode electric field in the inertial layer is also included. It is found that the leading order energetic particle fluid and "real" kinetic contributions to the plasma potential energy (δW) exactly cancel. The resulting net effect is the resonant interaction between the energetic circulating ions and the high frequency branch of the internal kink mode (with frequency ω_{*i}). In addition to the resonant interaction between the particles and the poloidal component of the wave electric field inside the $q < 1$ region, it is shown that the modulation of the particle poloidal velocity leads to a new resonance between the energetic particles and the radial electric field in the inertial layer. The energy exchange in the layer is opposite to the one in the $q < 1$ region and leads to a less effective destabilization when the shear at the $q = 1$ surface is less than unity. For realistic q profiles the growth rate is of the same magnitude of the trapped particle induced fishbone mode.

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SMALL SCALE MAGNETIC FLUX AVERAGED MAGNETOHYDRODYNAMICS*

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Abstract

By relaxing exact magnetic flux conservation below a scale λ a system of flux-averaged magnetohydrodynamic equations are derived from Hamilton's principle with modified constraints. An energy principle can be derived from the linearized averaged system because the total system energy is conserved. This energy principle is employed to treat the resistive tearing instability and the exact growth rate is recovered when λ is identified with the resistive skin depth. A necessary and sufficient stability criteria of the tearing instability with line tying at the ends for solar coronal loops is also obtained. The method is extended to both spatial and temporal averaging in Hamilton's principle. The resulting system of equations not only allows flux reconnection but introduces irreversibility for appropriate choice of the averaging function. Total energy and momentum are conserved over times much longer than the averaging time τ but not for less than τ. This averaged system is applied to electron magnetohydrodynamics and in one-dimensional geometry predicts solitons and shocks in different limits.

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Shear Flow Effects on Low-frequency Drift-type Tokamak Microinstabilities*

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The influence of sheared equilibrium flows on the confinement properties of tokamak plasmas is a topic of much current interest. A proper theoretical foundation for the systematic kinetic analysis of this problem has been provided by a derivation of a set of nonlinear electromagnetic gyrokinetic equations in the presence of toroidal sheared flows. This represents the incorporation of the important dynamics associated with subsonic sheared flow into the nonlinear gyrokinetic equations of Frieman and Chen.[1] The physical significance of the new terms are explained, and the general result is also cast in a phase-space conserving continuity equation form readily applicable to gyrokinetic particle simulations. The formalism has been applied to investigations of the influence of velocity shear on ion temperature gradient (ITG) driven modes with comprehensive linear results obtained for the familiar sheared slab geometry.[2] Applications to toroidal geometry have also been carried out and results obtained. This has involved developing a sheared-flow-modified version of the finite element code[3] used to carry out a fully two-dimensional toroidal analysis of the Trapped Ion Mode (TIM) in the long wavelength limit ($k_r \rho_{bi} < 1$). The primary result from the systematic studies including trapped-particle dynamics, magnetic drifts, and poloidal mode coupling effects is that global modes with radial extent over many rational surfaces can be significantly stabilized by realistic levels of sheared toroidal rotation for TFTR-like parameters. Since both the mode width and the growth rate tend to decrease with sheared rotation, heuristic estimates of the associated energy transport would suggest a favorable impact on tokamak core confinement. Possible implementations of these important dynamics in nonlinear gyrokinetic and gyrofluid simulation studies will be discussed.

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†Work performed in collaboration with W. M. Tang and G. Rewoldt

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NONLINEAR COLLISIONLESS MAGNETIC RECONNECTION

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Magnetic reconnection in collisionless regimes, where electron inertia is responsible for the decoupling of the plasma motion from that of the magnetic field, can now be observed in Tokamak plasmas such as JET and TFTR. Indeed, at the high temperatures attained in these experiments, internal plasma (*sawtooth*) relaxations can occur on a time scale shorter than the electron-ion collision time. The linear theory of m=1 kink-tearing modes, recently extended to the experimentally-relevant regimes, has indicated that these modes can remain virulent at high temperatures with an initial growth rate which compares favourably with the observed reconnection rate[1].

To investigate the nonlinear evolution, we present the numerical and analytic solution[2] of the following set of equations in 2D [(x,y) slab with periodic boundary conditions and aspect ratio $\varepsilon = L_x / L_y$]:

$dU / dt = \partial_t U + [\varphi, U] = [J, \psi]$ vorticity equation $U = \nabla^2\varphi$; $J = -\nabla^2\psi$

$dF / dt = \partial_t F + [\varphi, F] = 0$ collisionless Ohm's law $F = \psi + d^2 J$

where U is the fluid vorticity, $\mathbf{v} = \hat{\mathbf{z}} \times \nabla\varphi$, J is the current density, F is the fluid canonical momentum along z (the ignorable coordinate), d is the normalized skin depth and $[A, B] = \hat{\mathbf{z}} \cdot \nabla A \times \nabla B$.

The relevant instability scenario corresponds to large values of the familiar Δ' parameter of tearing mode theory, such that macroscopic flow cells develop with a scale size $L_{cell} \sim L_x$. During the early nonlinear phase, characterized by $d << w_{isl} << L_{cell}$ (w_{isl} is the magnetic island width), reconnection proceeds faster than exponentially. The fluid displacement into the island X-point, ξ, reaches a macroscopic size on a time of the order of the linear growth time, $\gamma_L^{-1} \sim (\tau_A d)^{-1}$, with τ_A the relevant Alfven time. Physically, the electromagnetic torque, $\oint_C J d\psi$, intensifies and drives the flow rotation through the magnetic island (along the contour C) during this phase. The current density across the X-point is mainly distributed over a distance of order d. Within this distance, a very narrow current spike of width $\delta_s(t) \sim d \exp(-\xi(t)/d)$ develops, shrinking with time as a consequence of the conservation of F on moving fluid elements and the hyperbolic flow pattern around the X-point.

These results are compared with the published literature[3-6]. Also, the behavior of the current spike is investigated in the presence of weakly collisional processes. Other effects, such as the finite ion Larmor radius, density and pressure gradients, 3-D, etc. must be taken into account to describe realistic experimental conditions. Nevertheless, it is believed that the present analysis opens the possibility of understanding the rapidity of relaxation processes in low collisionality plasmas.

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Anomalous thermalization of fast ions in magnetized plasma due to two-gyro-stream instability*

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A novel instability concept, namely, a two-streaming process in gyrospace, has been proposed [1]. This leads to a two-energy-stream cyclotron instability even without beams in real space, where fast ions drive electrostatic ion Bernstein waves unstable. The instability comes from the coupling of the fast and slow ion Bernstein branches due to a weak relativistic effect. The mechanism gives an explanation [2], supported by numerical simulations and analytical theory, for the harmonic cyclotron emission induced by fast ions in tokamak plasmas---in particular, for the emission observed at low harmonics in deuterium-deuterium and deuterium-tritium experiments in the Joint European Torus. It is shown that the first proton harmonic, whose field energy amplitude scales as the 0.84 power of the proton density, is one of the highest spectral peaks whereas the first alpha harmonic is weak. The relative spectral amplitudes of different harmonics are compared. The results are consistent with the experimental observations. The simulations verify that the instabilities are caused by the relativistic mass effect.

As shown on both PIC simulations and a gyro-averaged model, the two-gyro-stream instability excites a novel anomalous process causing the perpendicular energy of fast ions to be thermalized and lost on average to bulk ion heating, instead of classical slowing down and bulk electron heating. More than half of the fast ions are slowed down to the thermal ion level, although some are heated to twice their birth energy. The fast ion density perturbation is so large that this process may also cause anomalous transport. PIC simulation also shows that a sinusoidal nonuniform magnetic field (e.g., a poloidal magnetic field) leads to no appreciable change in the growth rate and saturation amplitude of the waves; however, localized cyclotron eigenmodes are observed when the nonuniformity is large. After the fast ions have been thermalized and the waves are saturated, new-born fast ions are added into the simulation. They experience the same process in a shorter time scale such that the process may continually occur in a burning plasma. The implications for fusion ignition and fast ion confinement are assessed.

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Collapse, Intensification and Reconnection in Vortex Dominated Flows: Visiometrics and Modeling *

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We examine the dynamics and topology of interacting, collapsing and reconnecting tube-like regions of vorticity. This generic process undoubtedly plays a role in high-Reynolds number intermittent phenomena. We present visualizations and quantifications from studies of incompressible-homogeneous, incompressible-stratified and compressible domains obtained with pseudospectral, Biot-Savart (single-and multifilament) and Godunov (TVD) algorithms.

We juxtapose results and quantify the similarities and differences for initially:(1) orthogonally-offset tubes,(2) a "Lissajous-elliptic" vortex ring; and (3) a sinusoidally perturbed shock-driven interface (the Richtmeyer-Meshkov environment). In all cases we find the final states of collapse associated with antiparallel vortex tubes or filaments and maximum strain intensification off the tubes and in regions where reconnection will occur. In (2) we characterize the collapse phenomena via geometrical and motion invariant quantities and observe a near self-similar 500-fold increase in strain intensification, suggesting a near-singular event for the Euler equations. We present "local diagnostics" in the collapse region of the filament, including line densities of energy(which approach zero locally). These diagnostics provide a rational basis for filament surgery algorithms. Finally, in (1) we quantify the properties of the shocklet entrained in a strong compressible dipolar vortex flow and the important consequences of dilitationally-generated vorticity.

A second theme of the talk discusses insights obtained from cogent visiometrics, the process of visualizing and quantifying the content, shape, topology and interactivity of evolving amorphous objects (or coherent structures) within massive space-time data sets. This includes techniques for object tracking two and three dimensions. This process will allow the prepared investigator to pose problems whose solution can reveal quintessential (reduced-degree-of -freedom) physical phenomena.

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Nonlinear Simulation of the Current Diffusive Interchange Mode

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Recently, a new theoretical approach to study the anomalous transport coefficient was developed[1]. In this new approach, effects of the anomalous transport process on the mode stability itself are incorporated through convective nonlinearity in the electron inertia term. We found that convective nonlinearity in the electron inertia term drives nonlinear instability and can be rewritten as the current diffusivity term by means of mean field approximation. Originally, the anomalous viscosity was considered on the generation of dynamo but only few theories were developed, noting that convective nonlinearity in the electron inertia term plays a similar role as the anomalous viscosity in tokamaks. It was also recognized that electron inertia plays an important role for the dynamics of re-organization of the magnetic field. We have done direct simulation to investigate nonlinear instability driven by electrons. Although the toroidal effect is important quantitatively, we paid attention to the electrostatic interchange mode for simplicity because we focus on the nonlinear mechanism itself. The Ohm's law which we used is given by

$$\frac{\partial j}{\partial t} + [\phi, j] = -\nabla_{\parallel}\phi + \lambda^L \nabla_{\perp}^2 j$$

where we normalized this equation using the poloidal Alfvén time. The electron collisionless skin depth for time and space, [,] is the Poisson bracket, and λ^L is the current diffusive term caused by the Coulomb collision. But we regard this term as artificial in investigating the nonlinear mechanism relating to the saturation of the fluctuation and its evolution, also a cooperative effect. We used the vorticity equation and assumed cold ion. Comparing the analytical result with the numerical result, we confirm the mean field approximation is applicable in the evolution phase of the nonlinear instability. Furthermore we observed the nonlinear evolution of this instability and the self-organization of the turbulence in these simulations. The novel point is that the steady state is sustained by the cooperative effect between the effective dissipation caused by the normal cascade of the energy to the short wave length region and linear dissipation.

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Predictive Transport Modeling

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Results of predictive transport modeling are presented supporting the view that this method is an effective way to reach an objective phenomenological description of a Tokamak plasma. Indeed, by self-consistently taking into account such ancillary effects as equipartition between ions and electrons, sawteeth activity, ohmic heating, plasma geometry, power deposition profile or particle sources, one can unambiguously exhibit properties of either transport coefficients or specific terms of energy or particles conservation equations. Examples of perturbative simulations, detailed time dependent simulations of entire discharges of Tokamaks of various sizes and for different regions of the operating space are presented to illustrate how transport coefficients can be constructed to reproduce and explain experimental observations.

The predictive modelling tool thus calibrated against experiments can be used to study the properties of a plasma where most of the heating comes from the slowing down of fusion born alpha particles. The important role of fuel dilution is highlighted leading to the concept of fusion power control by fuel injection. The properties of a plasma where the power is maintained constant by such a method are derived analytically and through simulations. Examples of the method and results and implications for the ITER EDA design will be presented.

SPECTRAL ESTIMATION OF PLASMA FLUCTUATIONS II: NONSTATIONARY ANALYSIS OF ELM SPECTRA

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Abstract

Several analysis methods for nonstationary fluctuations are described and applied to the edge localized mode (ELM) instabilities of limiter H-mode plasmas. The microwave scattering diagnostic observes poloidal k_θ values of 3.3 cm^{-1}, averaged over a 20 cm region at the plasma edge. A short autoregressive filter enhances the nonstationary component of the plasma fluctuations by removing much of the background level of stationary fluctuations. Between ELMs, the spectrum predominantly consists of broad-banded 300-700 kHz fluctuations propagating in the electron diamagnetic drift direction, indicating the presence of a negative electric field near the plasma edge. The time-frequency spectrogram is computed with the multiple taper technique. By using the singular value decomposition of the spectrogram, it is shown that the spectrum during the ELM is broader and more symmetric than that of the stationary spectrum. The ELM period and the evolution of the spectrum between ELMs varies from discharge to discharge. For the discharge under consideration which has distinct ELMs with a 1 msec period, the spectrum has a maximum in the electron drift direction which relaxes to a near constant value in the first half millisecond after the end of the ELM and then grows slowly. In contrast, the level of the fluctuations in the ion drift direction increases exponentially by a factor of eight in the five milliseconds after the ELM. High frequency precursors are found which occur one millisecond before the ELMs and propagate in the ion drift direction. These precursors are very short ($\sim 10\mu$secs), coherent bursts, and they predict the occurrence of an ELM with a high success rate. A second detector, measuring fluctuations 20 cm from the plasma edge with k_θ values of 8.5 cm^{-1}, shows no precursor activity. The spectra in the ion drift direction are very similar on both detectors, while the "electron" spectrum level is significantly larger on this second detector.

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Anomalous Kinetics of Particles in the Ergodic Layer

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The problem of particle kinetics in the ergodic layer is important for the general plasma edge problem. We are studying the model equation to show that the kinetics strongly depend on the fine phase space structure of the ergodic layer, which can be modified by parameters of the system. It is shown that the particle distribution function P obeys the self-similar law $P = P(x^\alpha/t^\beta)$ with $\alpha \neq 2$ and $\beta \neq 1$ in the generic case. It is found for the mean displacement $\langle x \rangle \sim t^\mu$ with $\mu = \alpha/\beta > 1$ that corresponds to the anomalous acceleration along x. The variable x can be considered as the poloidal coordinate. Strong intermittency of particles motion was observed simultaneously with the anomalous kinetics. This phenomenon can influence a strong poloidally localized energy dissipation. The fifth-order optimal simplectic integrator has been used to provide high order resolution and accuracy of simulations.

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PSEUDO-SPECTRUM OF THE RESISTIVE MHD OPERATOR: RESOLVING THE RESISTIVE ALFVÉN PARADOX

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Abstract

The Alfvén spectrum of resistive magnetohydrodynamics (RMHD) consists of discrete, exponentially damped modes, and the corresponding eigenvalues lie on specific curves in the complex plane with spacing of $O(\eta^{\frac{1}{2}})$, where η denotes the resistivity. These curves are independent of resistivity for small resistivity. The 'Alfvén Paradox' is that as resistivity decreases, the exponential damping is independent of the resistivity, and the discrete eigenmodes do not converge to the generalized eigenmodes of the ideal Alfvén continuum.

To resolve the paradox, the ϵ-pseudospectrum of the RMHD operator, $\mathbf{L}_\eta$, is considered. λ is in the ϵ-pseudospectrum if there exists a function, $\mathbf{u}$, such that $||\mathbf{L}_\eta \mathbf{u} - \lambda \mathbf{u}|| \leq \epsilon$ and $||\mathbf{u}|| = 1$. It is proven that for any ϵ, the ϵ- pseudospectrum contains the Alfvén continuum for sufficiently small resistivity. Formal $\epsilon - pseudoeigenmodes$ are constructed using the formal Wentzel-Kramers-Brillouin-Jeffreys solutions, and it is shown that the entire stable half-annulus of complex frequencies with $\rho|\omega|^2 = |\mathbf{k} \cdot \mathbf{B}(x)|^2$ is resonant to order ϵ, i.e. belongs to the $\epsilon - spectrum$. In this frequency half-annulus, the norm of the frequency response Green's function is proportional to $\exp(R_M^{\frac{1}{2}})$, where R_M is the magnetic Reynolds number.

RADIATING EDGE PLASMA STUDIES FOR ITER AND TPX

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Divertor scenarios involving line radiation by naturally present or deliberately introduced impurities have often been considered as a candidate solution to the heat load problem, but to make such scenarios credible it is necessary to model accurately the transport of the impurities in the scrape-off plasma and to assess the associated impurity concentration in the core. We are using the B2.5 edge plasma code to simulate the edge and divertor plasma in ITER and TPX, for a plasma composed of a mixture of hydrogen, helium, and alternatively carbon, neon or argon. The nature of the impurity dynamics (frictional forces scaling as Z^2, electric field force as Z, inertial force independent of Z) makes it highly desirable to model each charge state as an individual species, as was recognized already in the one-dimensional (along the magnetic field) modelling of Neuhauser et al. [1] and as is done in the present work. We are now implementing the formulation of Boley et al. [2] of the full multispecies parallel transport theory developed by Hirshman [3] and by Zhdanov, Igitkhanov and Yushmanov [4]. Our aim is to compare the effectiveness of the various impurity species for creating a radiating layer away from the divertor.

Discussions with Yu. Igitkhanov have been very helpful in making the multispecies transport theory accessible to us. This work was supported by U.S. DoE Grant No. DE-FG028ER53223.

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Convective Drift-Acoustic Instabilities in the Presence of Sheared Flows

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Shear in the plasma flow velocity, when directed perpendicular to the magnetic field, has a stabilizing effect on drift-acoustic eigenmodes. Generally, eigenmodes are of interest because their *standing-wave* nature endows them with infinite linear coherence-time. In systems with small shear, however, *propagating* wave-packets may retain coherence during many periods of oscillation, as the spatial variation of the dielectric permittivity is weak. In such systems, it can be argued that the stability of propagating waves is of greater relevance than that of eigenmodes. This stability has traditionally been investigated by neglecting entirely the spatial variation of the permittivity, in a procedure referred to as the local analysis. The spatial variation of the permittivity *does* play a role, however, in limiting the time during which a travelling wave-packet remains in resonance and receives energy from the plasma. We have evaluated the amplification of propagating disturbances in a plasma with a sheared equilibrium flow. We find that the maximum amplification is attained precisely at the threshold for stabilization of the eigenmodes, when the flow-shear is such that the poloidal phase-velocity is constant in the rest frame. This occurs when the radial variation of the sound wave's phase-velocity, in a frame moving with the plasma, is compensated by the variation of the plasma velocity.

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Empirical Models of Plasma Profiles and Transport: A Hierarchy of Models

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1 We present two families of statistical models of increasing statistical complexity which generalize global confinement expressions to plasma profiles and local transport coefficients. The temperature or diffusivity is parameterized as a function of the normalized flux radius, r, and the engineering variables, $\vec{u} = (I_p, B_t, \bar{n})^t$. The log-additive temperature model assumes that $\ln[T(r,\vec{u})] = f_0(r) + f_I(r)\ln[I_p] + f_B(r)\ln[B_t] + f_n(r)\ln[\bar{n}]$. The unknown $f_i(r)$ are estimated using smoothing splines. The Rice selection criterion is used to determine which terms in the log-linear model to include. A 50 profile JET Ohmic dataset is analyzed and good fits are obtained. The wall material has a very strong influence on the plasma temperature. Beryllium tiles reduce the temperature relative to the earlier Carbon tile discharges. The total plasma current is more important than the edge safety factor in determining the JET Ohmic temperature profile. Our results differ from earlier "profile consistency" results because we fit both the the temperature shape and magnitude simultaneously i.e. we do not normalize the data.

Our second class of models is log-additive diffusivity models where $\ln[\chi(r,\vec{u})] = g_0(r) + g_1(r)\ln[I_p] + g_2(r)\ln[B_t] + g_3(r)\ln[\bar{n}]$. These log-additive diffusivity models are useful when the diffusivity is varied smoothly with the plasma parameters. We describe a penalized nonlinear regression technique to estimate the $g_i(r)$.

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SHOCK WAVES IN THE TOKAMAK EDGE PLASMA

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One of the major problems of future thermonuclear reactors is removal of heat and of helium ash. This problem is handled in modern tokamaks by means of special magnetic configurations where magnetic flux lines are intercepted by a neutralizing plate [1].

In large tokamaks typical core plasma parameters are $T_e, T_i \sim 5-10\text{keV}$, $n_e, n_i \sim 0.5-1\times 10^{20}/\text{m}^3$, while near the plate the temperature falls to tens of eV and the density may grew by an orders of magnitude, which reduces the mean free path for ionization to a few centimeters. The latter justifies fluid dynamics approach in the form of multifluid (not MHD) reactive flow [2,3]. Nonsteady Navier-Stokes equations with source terms representing ionization, charge exchange, radiation, heat conduction and other significant processes for multiple atom species including neutrals are treated in 2D implicit code. Boundary conditions are of Dirichlet type at the core boundary (T_e, T_i and n_e, n_i specified). For the neutralizing plate Bohm criteria are imposed assuming Mach number of ion flow greater or equal then unity.

In the present paper we study high density regimes which are dominated by charge exchange between ions and neutral hydrogen. Strong charge exchange frictional coupling causes the collapse of electron temperature and thus very unstable flow pattern near the plate. Under certain conditions extreme radiation cooling and ionization losses lead to the appearance of supersonic zones followed by shock waves, with flow Mach number up to 6. The possibility of supersonic regimes was pointed out in [3]. This process leads to enormous growth of ion and neutral density near the plate, which is very important since it stimulates energy dissipation.

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MHD Simulations in Divertor Geometry

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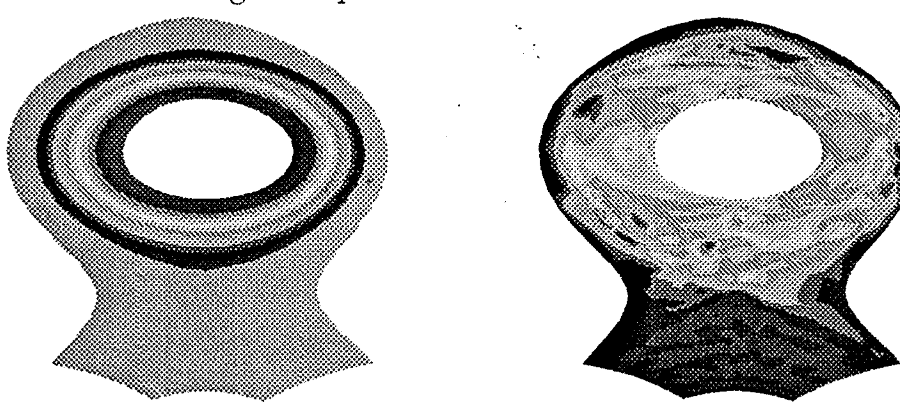
Two and three dimensional, unstructured mesh, finite element dissipative reduced MHD codes are being developed. They are being applied to the simulation of MHD activity in a divertor tokamak with a magnetic null. Two applications are presented.

Poloidal rotation inside the separatrix is a feature of the H mode. One possible cause of spin up is poloidal variation of diffusive loss caused by the presence of the magnetic x point. Two dimensional simulations illustrate this and related effects.

ELMs may be caused by ballooning modes near the plasma edge. Using the three dimensional nonlinear finite element MHD code, moderate mode number ballooning modes were obtained in a magnetic separatrix geometry. The modes, predominantly m = 3 to 8, cause a rapid flattening of the pressure across the separatrix. High pressure plasma flowed along the separatrix into the divertor.



(a) (b)

Figure 1: a) Initial pressure distribution in a poloidal cross section. b) Pressure distribution after a ballooning disruption, showing pressure flowing along the separatrix to the divertor.

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Low Collisionality Tokamak Steady States

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In the low collisionality limit, the usual neoclassical expansion does not necessarily apply. A variant expansion is developed for this case. It is possible to obtain the conditions for the existence of a steady state without the usual intermediate steps of calculation of transport coefficients and their use in moment equations. The procedure is applied to Ohmically driven tokamaks. It is shown that Ohmic drive alone, without any other energy sources or sinks, does not lead to a possible steady state. Provided an additional energy source of appropriate magnitude is present it is possible to find steady state solutions by formal expansion to all orders in the expansion parameter. The procedure also applies when the Ohmic current is comparable in magnitude to the bootstrap current. Although no direct calculation of perpendicular electron heat flow is necessary, it can be calculated, and it scales differently from the usual neoclassical formula in the low collisionality limit.

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A New Method for the Ergodic Layer Width Estimation

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The width of the ergodic layer has been calculated for the large amplitude high frequency perturbation. New analytical results are obtained by applying the averaging method in the complex time plane.

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Turbulent transport in the presence of a strong rotation shear

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It is generally accepted that suprathermal electromagnetic fluctuations cause anomalously-rapid energy losses in the magnetic confinement systems. The purpose of this study is to explore the plasma transport in the presence of two-dimensional electrostatic turbulence with the strong shear of rotation velocity. The diffusion coefficient and other important characteristics of transport are determined both numerically and analytically. It is shown that the diffusion is suppressed at high rotation shear even if the fluctuation amplitude remains constant. The main effect of the velocity shear on transport is the transition from saturated (percolational) to quasilinear regime.

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3C12

Analytical Aspects of Dynamical Processes In Gas Target Divertors

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The divertor is a key aspect of ITER design. The plasma in the divertor is 3-D [T. Evans, et. al, Bull. Am. Phys. Soc. **38**, 2060 (1994)] and it is not always in equilibrium due to episodic influx of particles and heat from the main plasma, especially during H-mode where ELM's are present.

In this work, we examine the divertor in the 2-D plane consisting of the direction along a field line down the slot and in the toroidal direction. In this vein, the ignored direction (including the private flux region as a boundary) is a thin layer whose width is smaller that both the slot length and the the major radius. Various mechanisms for the source of fluctuations are considered in this geometry. One novel candidate, is a corrugation or Raleigh-Taylor instability. In the case of a divertor, the hot, less dense, high momentum plasma at the x-point impinges on the cold, dense, low momentum plasma at the plate. The transition region between these two plasmas is equivalent to an interface, which is unstable to toroidal perturbations. The growth rate is estimated locally to be $V_{\|} k_y / k_{\perp} \sqrt{L_v L_n}$ where $V_{\|}$ is the ion flow down the leg, L_v is the scale length of the flow, L_n is the density scale length, k_y is the toroidal wavenumber, and $k_{\perp}$ is the wavenumber in the 2-D plane. This mode is investigated in with nonlocal theory, including model profiles (to be used in a 3-D fluid code). In the nonlinear regime this mode results in bubbles of hot plasma falling on the plate, as well as enhanced mixing of neutrals and plasma. We also examine other modes in this geometry including modes driven by the flow itself [parallel flow instability, A. S. Ware and P. H. Diamond, Phys. Fluids B **5**, 2125 (1993)] modes driven by shear flows parallel to the interface (Kelvin-Helmholtz instability), and modes associated with radiation [condensation, D. R. Thayer and P. H. Diamond, Phys. Fluids **30**, 3724 (1987).] Finally, we discuss the impact of main plasma dynamics, especially the connection of H-mode flows, ELM's, and particle/heat input to the flow driven instabilities.

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Gyrokinetic Simulation of Turbulent Transport*

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Three-dimensional gyrokinetic particle simulation studies of ion temperature gradient drift instabilities (ITG modes) in toroidal geometry have been carried out with focus on the issues of transport scaling, isotope effects and impurity inward pinch. The model, which simulates the total core region of a tokamak, includes the perturbed electrostatic potentials along with the full gyrokinetic dynamics for the ions and the adiabatic response for the electrons.[1]

In the area of transport scaling, we have carried out simulations with different minor radius similar to the ρ^* scan in the experiments.[2] Based on the TFTR supershot parameters used by the Numerical Tokamak Project,[1,4] the results indicate that the $k_\theta\rho_s$ spectrum remains unchanged with a peak around 0.15. While the $k_r\rho_s$ spectrum always peaks at zero, its width, $\Delta k_r\rho_s$, decreases with the minor radius. As argued by Perkins et al.,[2] this is the signature for non-Gyro-Bohm scaling. This scaling trend can also be understood by the Connor-Taylor invariance analysis,[1,3]

$$\chi_i \propto (\rho_s/L_{Ti})\,(k_\perp\rho_s)^{-p}\, cT/eB,$$

with $p \approx 2$ as given by the simulation results.

A consequence for such a non-Gyro-Bohm scaling is that it will lead to a favorable isotope scaling for the thermal diffusivity, i.e., a reduction of χ_i with an increase in mass. This is borne out by the simulation. Specifically, by changing from deuterium to tritium, we have seen a 10% reduction in χ_i at saturation and a 25% reduction shortly aferwards. With an increase of the tritium temperature by a factor of 2, the total reduction in comparison with the deuterium case becomes 15% and 45%, respectively. This favorable scaling trend is similar to that observed in the recent D-T experiments on TFTR.

In recent impurity transport studies, the Z/m dependence for the pinch velocity observed in the slab simulation is found to be somewhat reduced in the toroidal case. This is attributed to the modification of the $E_{||}$ acceleration by the toroidal effects on the ExB advection. Comparisons with the recent trace tritium experiments on TFTR[5] will be presented.

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Properties of Theory-Based Transport Models

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Various combinations of theoretically derived transport models have been used in the BALDUR transport code to predict the temperature and density profiles in tokamak experiments.[1,2] Recent work has concentrated on the Nordman-Weiland transport model[3–5] for η_i and trapped electron modes (including impurities and finite Larmor radius effects) which is combined together with transport from resistive ballooning modes, kinetic ballooning modes, neoclassical MHD, and neoclassical models. The Nordman-Weiland model is used to compute a full 4×4 matrix of coefficients for the transport of ion heat, hydrogen ions, electron heat, and impurity ions. The scaling of this model with respect to the gradient scale lengths and other plasma parameters will be explored and compared with experimental data.

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Spontaneous Seed Current in Tokamaks*

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Particle orbits in an axisymmetric tokamak configuration are examined near the magnetic axis. Self-consistent field effects on particle dynamics are ignored in the study. The equations of energy, angular momentum, and magnetic moment conservation are solved to determine the drifting surfaces on which particles move. Radial excursion for a trapped particle occurs depending on the particle's parallel (toroidal) velocity. When a particle carries a current in the same (opposite) direction of the plasma current that gives rise to the poloidal magnetic field, inward (outward) excursion takes place. As the drifting surface moves closer to the magnetic axis, the outward (inward) radial excursion greatly increases (decreases). It is argued that when Coulomb collisions or anomalous effects are taken into account, the outward excurting particles are rapidly transported away from the axis than the inward excurting particles, resulting in an effective net current at the axis. This current can act as a seed current required by the standard bootstrap theory[1,2] to make a completely bootstrapped tokamak possible. The calculation of the current will be presented.

* Work supported by DOE.

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3C16

Stable High ß Tokamaks, Reverse D Tokamaks

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The MHD stability of high ß tokamaks to global (kink) modes is examined. At high ß ($\beta >> \varepsilon/q^2$) global stability (like local ballooning stability) is sensitive to curvature and local shear. An analysis of δW shows that the instability drive, when present, is localized in the neighborhood of the zero (local) shear points. By shaping the boundary as a reversed D, we can put all the zero (local) shear points firmly in the good curvature region. At high ß, the reversed D configuration has no internal sources of MHD instability. With a nearby conducting wall reversed D configurations are stable. Stability without a conducting wall is under investigation. This new configuration, while desirable at high ß, is known to be undesirable at low ß; i.e., it has a low first stability boundary. Thus, the experimental realization of this configuration may take some ingenuity.

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3C17

STRUCTURE OF ALFVÉN WAVES WITH TRANSVERSE SCALE ON THE ORDER OF THE SKIN DEPTH*

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This study examines the spatial structure of Alfvén waves whose scale across the confining magnetic field is on the order of the electron skin-depth. This physical situation is motivated by the increasing interest in the spontaneous filamentation of magnetized plasmas, axial relaxation of transport currents, and effect of the long-scale divergence of Alfvén-disturbances in the divertor region. The mathematical formulation consists of a disk exciter that modulates field aligned currents at frequencies below the ion cyclotron frequency. It is found that the radiated patterns exhibit a spreading cone structure whose angle is determined by the ratio of the frequency to the cyclotron frequency. The modulated axial currents remain confined within the spreading cones. Far from the excitation region a radial diffraction pattern develops because the finite parallel electric field induces a coaxial current system on adjacent field lines. The effect of electron collisions is considered as well as the modifications caused by global drift motion surrounding the filament. Comparisons are made with experimental observations in the LAPD device.

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Computer Simulation of Transport Driven Current in Tokamaks[1]

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Plasma transport phenomena can drive large currents parallel to an externally applied magnetic field. The Bootstrap Current Theory accounts for the effect of Banana diffusion on toroidal current, but the effect is not confined to that transport regime, or even to toroidal geometry. Our 2-1/2 D, electromagnetic, particle 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" which the Bootstrap Theory requires.

Other simulations, in both toroidal and straight cylindrical geometries, and without any externally imposed electric field, show that if the plasma column is centrally fueled, then the toroidal current grows steadily. Such results in straight, cylindrical plasmas show that self-generated, parallel currents arise without banana orbits. The more fundamental mechanism seems to be the conservation (or the near conservation due to collision and turbulences) of particles' canonical momenta in the direction of the ignorable coordinate (axial or toroidal). 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 states. We show that a central plasma source also results in a central current source.

When the plasma is fueled at the edge rather than the center, the current drive still exists, but is less strong; however, near central fueling is probably needed in a reactor for particle control reasons. Our simulations indicate that such fueling, coupled with central heating due to fusion reactions may establish conditions in which transport driven current would eliminate the need for any external current drive in tokamaks, except simple ohmic heating for initial generation of the plasma.

Recently, works have begun to investigate current generated by heat conduction. Such runs will require calculating particle moments on the grid; therefore many more particles are required. The 2-1/2 D code has been ported to run on a 64-node SP1 at Cornell. We will present the results of the new runs at the meeting.

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Evolution of Trapped Electron and Ion Temperature Gradient-Driven Drift Instabilities in the Collisionless Regime *

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The radial variation of the experimental power balance conductivity disagrees with the theoretical turbulent conductivity for many models of microturbulence generation. This conflict suggests that theories underestimate the fluctuation levels which are measured to increase strongly with radius. Attempts to obtain the increase of $\chi_i(r)$ with r/a by adding effects of finite-β drift wave-MHD mode coupling and trapped electron resonances are being made. We report here on progress in examining the latter mechanism.

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]. The ∇T_i and collisionless trapped electron instabilities are present in the simulation when nonuniform electron and ion density and temperature profiles are initialized. The trapped electron-driven turbulence produces $E \times B$ turbulent diffusion of ions and electrons. This instability is dispersive in the linearly unstable wavenumber range and Ion Compton scattering and trapped electron scattering are important nonlinearities in the saturation of the fluctuations[2]. The ion thermal flux is enhanced due to the presence of the trapped electron instability. The analysis is complicated by the fact that poloidal flow generation occurs via mode coupling and this is an additional saturation effect during the spectral evolution. Details of the saturated fluctuation spectrum versus minor radius and fluxes will be given with some physical interpretation and analytical analysis.

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ANALYTICAL AND NUMERICAL STUDIES OF PLASMA STABILITY USING A SCALAR REPRESENTATION OF MHD

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A general scalar representation of MHD , which we have introduced previously, is used to formulate sets of "reduced" systems of MHD equations of various complexity. The most complex system is equivalent to the complete system of MHD equations.

We describe a nonlinear toroidal evolution code, the structure of which is particularly well adapted to the description in terms of reduced equations of various complexity. First results concerning the tearing instability are presented.

The representation is also well suited for analytical investigations, since the velocity field is represented with respect to a stationary but otherwise arbitrary reference field (e.g. an axisymmetric toroidal equilibrium field). This feature facilitates the description of geometrically complex situations, as for instance non-axisymmetric plasma edge layers in which the magnetic field and the position of obstacles are given by the experimental conditions.

A Numerical Study of High-Beta Tokamak Equilibria

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In order to minimize the cost of the magnets which confine the plasma in tokamak discharges, it is advantageous to reduce the magnitude of the magnetic field B. Therefore, the equilibrium and stability of high $\beta \equiv 8\pi nT/B^2$ tokamak discharges are of interest. We have developed an MHD code written in toroidal coordinates. We present a study of high-β equilibria in toroidal geometry, obtained using this code. The code can be used to investigate equilibria in small, as well as large, aspect ratio (R_0/a) tokamaks. Our numerical results are compared with the analytic theory of S. C. Cowley, P. K. Kaw, R. S. Kelly, and R. M. Kulsrud [Phys. Fluids B **3**, 2066 (1991)] for high-beta equilibria in large aspect ratio tokamaks. We confirm their prediction that high-β equilibria are characterized by an outer boundary layer surrounding an inner core in which the poloidal flux is solely a function of the major radius R.

Hamiltonian Cell Dynamics*

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We present a new algorithm for computing the time evolution of a noncanonical Hamiltonian field theory.[1] By partitioning the system's phase space into many regions (called cells), we are able to approximate the field theory by a finite dimensional system that is *exactly* Hamiltonian. Each cell contains a Hamiltonian system which is coupled to the other cells by an appropriate approximation of the original Hamiltonian. This method preserves many of the important characteristics of the original system and explicitly exploits its Hamiltonian structure. We apply this algorithm to the one dimensional pressureless fluid equation and to the Vlasov–Poisson system.

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DIII-D Radiative Divertor Simulations*

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The UEDGE fluid model edge-plasma code is used to simulate gas puffing and impurity radiation in a new radiative divertor configuration for DIII-D. We validate the model by simulation of specific DIII-D shots. Anomalous radial transport parameters are chosen by fitting UEDGE solutions to experimentally determined midplane density and temperature profiles. The resulting divertor plate heat flux profiles are consistent with measured IRTV data and bolometer measurements of radiated power if impurity radiation is included in the simulations. For the proposed radiative divertor design we vary the magnitude and location of the hydrogen gas puffing and pumping, demonstrating plasma detachment from one or both divertor plates as observed in recent radiative divertor experiments on DIII-D. The effect of possible divertor baffle structures on neutral gas leakage to the core plasma is assessed via the DEGAS Monte Carlo code, simulating neutral transport in a fixed plasma background provided by the UEDGE code. We find that recycling off the top of a "gas bag" baffle can significantly increase the ionization source in the core plasma. Other more favorable baffle configurations are being studied. Carbon impurity radiation can lead to multiple solutions, similar to the effects of gas puffing, with either high divertor temperatures (greater than 10 eV) or thermally collapsed plasmas near the divertor plates.

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A RENORMALIZATION GROUP APPROACH TO TRANSITION TO CHAOS IN AN AREA PRESERVING NON-TWIST MAP

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The transition to chaos due to the destruction of invariant circles (KAM curves) in area preserving maps exhibits universal critical behavior that can be analyzed using Renormalization Group methods. The basic idea is to define, in the infinite dimensional space of maps, a function called the Renormalization Group Operator (RGO). The study of the existence of a given KAM curve is then translated into the study of the dynamical system generated by the RGO in the space of maps. Of particular importance are fixed points of the RGO, i.e., maps that are invariant under renormalization. These fixed points have very large basins of attraction and define universality classes for the destruction of the KAM curve. The linearization of the RGO at the fixed points gives the universal scaling exponents. In the present work we apply these ideas to study the destruction of KAM orbits in a map for which the twist condition is violated (i.e. the periodic variable is *not* a monotonic function of the other variable). Maps of this type appear often in physical situations, an example being magnetic field configurations with nonmonotonic q-profiles. The problem is quite interesting since, due to the violation of the twist condition, most of the well-known results and ideas, including KAM theory, can *not* be applied. We present numerical evidence of the existence of a period-6 fixed point of the RGO governing the destruction of the inverse golden mean KAM curve located in the region where the twist condition fails. This defines a new universality class.

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Ion Impurities Effects on Anomalous Transport in Tokamak Parametrically Driven Plasmas at Electron Cyclotron Frequency*

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Anomalous transport induced by current-driven ion-acoustic turbulence[1] (IAT) in Tokamak plasmas is addressed. The theory is based on self-consistent approach including quasilinear scattering of electrons off IAT spectrum and nonlinear scattering of IA modes off ions in the presence of a driver-pump in electron cyclotron (EC) range of frequencies[2]. It is shown that EC parametric absorption leads to appearance of a strongly non-Maxwellian distribution of electrons. Anomalous collision frequency, describing nonlinear power dissipation of EC driver pump, is evaluated in the presence of carbon ion-impurities. Modified (parametric and ion-impurities effects included) Sagdeev's equations[3] are rederived and analyzed.

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Monte Carlo Calculation of the Bootstrap Current

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We have developed a δf Monte Carlo code, which can efficiently calculate the bootstrap current. The method can also be used to determine the parallel heat flux in a divertor. The distribution function is written as $f = f_m(\psi,H)\exp(f)$ with f_m a local Maxwellian, ψ the toroidal magnetic flux enclosed by a pressure surface, and H the drift Hamiltonian. We solve

$$df/dt + \partial \ln(f_m)/\partial\psi \, d\psi/dt = C_L(f) - \nu K B \lambda$$

with df/dt the derivative along the trajectory of a drift orbit, B the field strength, and $\lambda \equiv v_{\|}/v$ the pitch. The collision operator C_L is the Lorentz operator and ν is the collision frequency. The function K gives momentum conservation; $K = 3\int \lambda f d\lambda / 2B$. The equation is solved by following the drift trajectories of a large group of particles with the change in f in a time step $\Delta f = -\int\{\partial \ln(f_m)/\partial\psi \, d\psi/dt + KB\lambda\}dt$. After each time step the pitch λ of each particle is changed using the Monte Carlo equivalent of the collision operator. The function K is evaluated using averages over the particles $\langle\ldots\rangle$. In a tokamak with $B=B_0(1 - \varepsilon\cos\theta)$, one has $K(\psi,\theta,H)=K_0+K_1\cos\theta+\ldots$ with $K_0=3\langle\lambda f/B\rangle$ and $K_1=6\langle\lambda f\cos\theta/B\rangle$. The parallel current is given by the same averages, $j_{\|}= 2e\int KBv \, f_m d^3v/3$. The bootstrap current is given by K_0 and the Pfirsch-Schlüter current by K_1.

We have evaluated the bootstrap current in a tokamak as a function of inverse aspect ratio ε and collisionality ν_* ignoring the momentum conserving K-term. Our results accurately fit the formula

$$\langle j_b/B\rangle = a_o \, \varepsilon^{1/2} \, (1+\varepsilon)(1 - \nu_*^{1/2})$$

over the range $0.003 < \nu_* < 0.08$ and $0.005 < \varepsilon < 0.2$ with the coefficient a_o given by the analytic theory in the limit as $\varepsilon \to 0$ and $\nu_* \to 0$. The Pfirsch-Schlüter current is more robust than the bootstrap current and agrees with the analytic answer. Supported by DoE grant DE-FG05-84ER53176.

Disintegration of Ion Banana Orbits in Tokamak Edge Plasmas

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The ion orbit loss mechanism for plasma rotation relies on the fact that, in the absence of fluctuations, ions will be preferentially lost because of their large banana orbit widths compared to those of the electrons. A radial ambipolar electric field then forms to hold back the ions. Here we investigate the orbits of ions and electrons in toroidal edge plasmas in the presence of low frequency turbulent transport. We find that at fluctuation levels well below those inferred from observations, ion banana orbits are washed out by the turbulent transport and transport becomes intrinsically ambipolar. The angular momentum deposited to the limiter or divertor by the ions is also shown to be negligible at these fluctuation levels. Ion orbit loss is therefore not a viable mechanism for driving poloidal rotation at the L-H transition in tokamaks.

LOWER HYBRID WAVE PROPAGATION IN LARGE ASPECT RATIO TOKAMAKS

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The recent trend in designing future tokamaks is to large aspect ratio devices, i.e., devices with inverse aspect ratio $\varepsilon = a / R_0 \leq 2/9$. It has been shown[1], for circular flux surface equilibria and in the absence of scattering from fluctuations, that the accessibility of lower hybrid (LH) waves to the plasma center is a strong function of ε. In particular, if $\varepsilon \geq 0.2$, it was shown that there was sufficient toroidal upshift in $n_{||}$ to form ergodic LH rays, which were accessible towards the plasma center.
We examine the effect of fluctuations on LH wave propagation in large aspect ratio tokamaks. It is seen that the effects of LH wave scattering from fluctuations play a major role in wave accessibility, electron power deposition as well as current dirve profiles. The wave energy density F satisfies the wave kinetic equation

$$\left[\frac{dF}{dt} \right]_{ray} = \sum \int_0^{2\pi} d\beta \left[F(\phi+\beta) - F(\beta) \right] \left[S^n(\kappa)\, K^n(k_\perp',\beta) \; + \; \mathbf{S}^B \mathbf{:}\, \mathbf{K}^B(k_\perp',\beta) \right]$$

where K^n and $\mathbf{K}^B$ are density and magnetic fluctuation scattering kernels, κ = perpendicular fluctuation wavenumber [$\kappa = | \mathbf{k}_\perp' - \mathbf{k}_\perp |$], and S^n and $\mathbf{S}^B$ are the fluctuation spectra. It is shown for TPX parameters that the electron power deposition profiles are strongly dependent on the initial Gaussian $n_{||0}$ spectrum if fluctuation scattering is neglected. However, even for 1% edge density fluctuations (typical for divertor plasmas), these deposition profiles now exhibit weak dependence on the initial $n_{||0}$ spectrum. For JT-60 like parameters, one finds a very large effect on deposition profiles on varying ε if fluctuation scattering is ignored. However, this strong dependence on ε is removed if scattering is taken into account. Future work includes incorporating scattering into the Fokker-Planck/LH current drive module of the ACCOME code.

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LATTICE BOLTZMANN APPROACH TO TURBULENCE

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In the numerical solution of nonlinear macroscopic problems with non-trivial boundaries, one is faced with the problem of resolution. This is particularly true in the area of turbulence in bounded systems as well as in compressible flows. The lattice Boltzmann approach (LBE)[1-4] to solving these problems is to replace the macroscopic nonlinear system by a microscopic linearized Boltzmann equation with a Krook collision operator. This microscopic system is solved on a lattice grid so that the kinetic velocities are discretized. The lattice grid is so chosen that after averaging over the allowed lattice directions, one recovers macroscopic continuous rotational symmetry. Averaging the LBE system over the lattice directions, for sufficiently small microscopic propagation velocities, will recover the original nonlinear macroscopic system on following the standard Chapman-Enskog procedures. The choice of the local equilibrium distribution, in the Krook operator, is critical. For various 2D flows, we examine the effects of various choices of local equilibrium distributions and compare the effects of compressibility vs. incompressibility. In particular, some forms of equilibrium distribution functions can give rise to cubic nonlinearities[4] - and this level of nonlinearity is what is recovered by some renormalization group techniques[5] on originally quadratically nonlinear systems. Thus LBE techniques may allow for solution of such nonlinear systems, when standard transform methods face considerable difficulties.

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LACK OF MAGNETIC CONFINEMENT IN A TOKAMAK. N. A. Salingaros, *University of Texas at San Antonio.* A rigorous analysis based on the MHD generation mechanism shows that an externally-imposed magnetic field does not lead to complete confinement. The toroidal field in a tokamak actually creates a "magnetic drag" on the plasma current. This is a velocity-dependent reaction force on lateral motions, but it is not a position-dependent reaction force. That means that disruptive plasma motions are slowed down but are not counter-balanced. Any growing perturbation will continue to grow exponentially. Increasing the toroidal field increases the apparent time scale of fluctuations, yet the stability cannot be improved in a controllable manner. Two possible sources of disruption in a tokamak are identified. First, a sudden increase in the plasma resistivity will drive normally controllable sinusoidal oscillations to the wall. Attempts to Ohmically heat the plasma can therefore turn benign oscillations into disruptions. Second, an exponentially increasing solution will not be counteracted by the toroidal field, but will grow to the wall in a characteristic time. For large tokamak operating conditions, this time is on the order of $<200\mu sec$. These results revise the traditionally optimistic expectations for the controlled release of fusion energy in magnetic devices.

Global Thermal Transport and Indications from the Alcator-CM Experiment*

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High field, compact experiments have a well demonstrated ability to produce a relatively large variety of plasma regimes. The early operation of the Alcator-CM (CMOD) machine has indicated the possibility that the confinement parameters of plasmas that are subjected to ohmic heating only can be distinguished into two categories: i) one where the energy confinement time increases with density and is consistent with the neo-Alcator scaling, and ii) another, corresponding to a lower density range, where the confinement time is higher than predicted by the neo-Alcator scaling and increases with the plasma current. The latter feature is similar to the so-called L-regime obtained by injected heating. In the case of Alcator-CM, the parameter that is found to differ the most from one regime to the other is ν_{*e}, the degree of collisionality of the trapped electron population. Thus a global transport coefficient is introduced that is inspired by the theory of the collisionless ("ubiquitous" [1]) trapped electron mode and yields the plasma current scaling for lower values of ν_{*e} and the neo-Alcator scaling for higher values. This can be represented by the electron thermal conductivity $\kappa_e = n_e(r)D_c(r)$, where

$$\kappa_e \propto \frac{cp_{eG}}{eB_\theta}\left(\frac{r_G}{r_{p*}}\right)^2 \frac{\rho_c}{R_o}\frac{1}{F_\Omega}\left(\frac{Z_{eff}}{\overline{A}_i}\right),$$

$B_\theta(r)$ is the poloidal magnetic field, away from the magnetic axis $r_{p*} = r_p$, $1/r_p \equiv -(T_i/T_e)dlnn/dr - dlnp_e/dr$, $r = r_G$ is the surface where $1/r_p$ is maximum, $p_{eG} = p_e(r_G)$, p_e is the electron pressure, $F_\Omega = 1 + g(\nu_{*e})\beta_{p*}q(r)(Z_{eff}/\overline{A}_i)^{1/2}$, $\beta_{p*} = [(\int_0^{r^2} dr^2 p(r)) - p(r)]/B_\theta^2)$, $g(\nu_{*e})$ is a "transition" function of ν_{*e}, $\rho_c \equiv c/(\Omega_{\theta e}\Omega_{\theta p})^{1/2}$, where $\Omega_{\theta_j} = eB_\theta/(m_j c)$ and m_p is the proton mass, and all other symbols are conventional. Thus when $g << 1$ we obtain the scaling $\tau_E \propto (n/P_H)^{1/2}I$, where I is the current and P_H is the heating power. When $g > 1$, the scaling $\tau_E \propto n$ is obtained. This model would indicate that the transition to scalings for τ_E that depend strongly on the plasma current, that have been observed in the past during the application of injected heating, is related to the transition to a regime of weak collisionality of trapped electrons.

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Spectrum of Radiation Emission Induced by Fusion Reaction Products*

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The radiation emission in the range of the cyclotron frequency of fusion reaction products and above has been observed to have a spectrum characterized by a discrete part and a continuum [1]. The discrete part corresponds to the harmonics of the cyclotron frequency evaluated near the outer edge of the plasma column and is explained [2] by the excitation of toroidal magnetosonic modes that do not propagate in the radial direction and are localized [3] in a narrow shell near the outer edge of the plasma column. The distance of this shell from the symmetry axis, as predicted by the theory, agrees quite well with that estimated from the observed emission "lines" of the discrete spectrum. Then, it is argued that this part of the spectrum carries information on the degree of confinement of the fusion products as its amplitude is related to the number of fusion products with large orbits that reach the mode excitation shell. The continuum component of the spectrum is related to the theoretically demonstrated [4] existence of non-normal modes, for frequencies well above the first harmonic, that can extend well inside the plasma column toward the central part of it. If the spatial variation of the magnetic field is taken into account this feature implies that the excited modes can have overlapping bands of frequencies. The class of extended non-normal modes owes its existence to the finiteness of magnetic shear that generates a finite longitudinal wave number and involves an incipient transition of magnetosonic modes into whistler modes. The range of frequencies above which this class of "modes" appears is consistent with that inferred ($\omega \gtrsim 8\Omega_c$) from the spectrum observed in the experiments carried out by the JET machine [2]. Then we may expect that by varying the plasma current in order to vary the number of high energy particles that reach the outer edge of the plasma column, a variation of the discrete component of the spectrum, relative to the continuum should be observed. Since the relevant mode particle resonances involve mostly a change of the particle transverse energy, we expect that the affected particles will acquire better confined orbits as a result of the mode excitation. Thus external means to interact with the resonating particles by affecting the excited modes can be envisioned.

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

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GENERALIZED TWO-FLUID THEORY OF NONLINEAR MAGNETIC STRUCTURES

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A system of equations is introduced and discussed that describe the nonlinear dynamics of magnetic perturbations in a magnetized, high-temperature plasma. Electron and ion diamagnetism, ion gyro-radii effects to all orders and finite electron mass are taken into account. These equations govern Alfvén as well as electrostatic waves and vortices and describe the nonlinear evolution of reconnecting modes. In particular, they are the nonlinear generalization of equations that describe collisional and semi-collisional modes. The electron fluid is described by the continuity equation and by the parallel momentum balance. The latter includes electron inertia.
The following model equation is adopted for the ion response

$$\frac{\partial}{\partial t}\left[\ln\frac{n}{n_0}+\tau_i(1-\Gamma_0)\Phi\right]+a\left[\Phi,\ \ln\frac{n}{n_0}+\tau_i(1-\Gamma_0)\Phi\right]+aL_j\left[L_j\Phi,\ \ln\frac{n}{n_0}\right]=0.$$

This is a nonlinear generalization of the linear Vlasov response and of the nonlinear fluid model to all orders in the thermal ion gyro-radius ρ_i. Here $\tau_i = T_e/T_i$, $\Phi = e\phi/T_e$, $a = cT_e/(eB_0)$, the brackets denote $[f,\ g] = \vec{e}_z \cdot \nabla f \times \nabla g$, and $\Gamma_0 = \exp\left({\rho_i}^2\nabla_\perp^2\right)I_0(-{\rho_i}^2\nabla_\perp^2)$, I_0 being the Bessel function of the first kind. The operator $\vec{L}$ is such that $L^2 = \Gamma_0 - 1$ with $\vec{L} \to \rho_i\nabla$ for $\rho_i \to 0$ and $L_j \to i/2^{1/2}$ for $\rho_i \to \infty$.
Our system of equations does not conserve either magnetic fluxes or generalized fluxes (which correspond to the canonical electron momentum). Instead new conserved quantities are given.
Two-dimensional equilibrium solutions in the form of stationary propagating structures in a sheared magnetic field are discussed. In the small-ρ_i limit, the current density J and the magnetic flux function Ψ are singular when approaching a separatrix. Near the singularity the large-ρ_i limit applies. In the non-collisional regimes of interest the inertia of the electrons resolves this singularity in the current density that tends to develop at magnetic separatrices. The positions of the X- points of the conserved quantities are mirror-symmetric and at a distance of order of the electron skin-depth from the resonant surface.
The set of equations admits an energy integral ($\beta_e = 4\pi n_0 T/{B_0}^2$ and $d_e = c/\omega_{pe}$)

$$H=\frac{1}{2}\int d^3x\left[|\nabla_\perp\Psi|^2+{d_e}^2J^2+\beta_e\ln^2\frac{n}{n_0}+\beta_e\tau_i\Phi(1-\Gamma_0)\Phi\right]$$

that plays the role of the Hamiltonian and the equations can be cast in noncanonical Hamiltonian form (see Pegoraro, Schep, and Kuvshinov at this conference).

Transport Analysis of Results in Gyrokinetic Tokamaks

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The transport in gyrokinetic (gk) tokamaks is governed by much of the same physics as in real tokamaks, but the gk 'experiment' is far simpler and diagnostic information is far more readily obtained than in real experiments. Accordingly, we take as our objective the development of a reliable theory of transport in gk machines, being guided by the gk data at each step in the development of a theory, to test the validity of assumptions, suggest appropriate approximations, *etc.*. A complete turbulent transport theory can be specified by an expression for the fluxes, *e.g.*, the ion heat flux Q_i as a function of the spectrum $\{\phi_k\}$ of potential amplitudes (the current gk results are purely electrostatic), plus a nonlinear theory properly predicting the steady-state values of the $\{\phi_k\}$. The gk data indicate[1] that $Q_i[\{\phi_k\}(t)]$ has an approximately quadratic dependence $Q \propto \sum_k |\phi_k|^2(t)$, suggesting that a weak-turbulence treatment may be appropriate. To lowest nonlinear order, the $\{\phi_k\}$ are then governed by the mode-coupling equations $\partial_t \phi_k = L_k \phi_k + \frac{1}{2}\sum_{0=k+p+q} M_{kpq}\phi_p^* \phi_q^*$. Using a method earlier applied[2] to data from real experiments, we infer both the linear frequencies L_k and the mode-coupling coefficients M_{kpq} from the gk data. The data indicate that, of the thousands of k's and p's which could in principle be needed for a proper description, only a modest number ($N_k \sim 10$) of k dominate the transport, and for each, only a handful ($N_p \sim 5$) of couplings appear to be significant, greatly simplifying the above mode-coupled system. Once obtained, these numerical M_{kpq} may be compared with the weak-turbulent analytic prediction, and used to evolve the reduced mode-coupled system, to see if its time evolution and saturated state properly models the full gk system.

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[Oral presentation requested]

NUMERICAL EVALUATION OF HIGH ENERGY PARTICLE EFFECTS IN MAGNETOHYDRODYNAMICS

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A numerical code has been developed for the analysis of the effects of high energy particles on MHD modes[1,2]. The contribution of the particles is calculated by performing orbit averaging using guiding center equations in analytic or numerically generated equilibria. This correctly gives the toroidal precession rates in the finite beta, shaped equilibria as well as including non-linear particle dynamics. The high energy particle contribution is used in a linear dispersion relation to solve for the complex mode frequency, which can be followed as a function of equilibrium independent parameters such as dia-magnetic frequencies, plasma resistivity, high energy particle beta, etc. A few thousand particles suffice to give an accurate determination of the high energy particle effects. The use of numerical equilibria allows the investigation of the effects of elongation, magnetic well, plasma rotation, etc. The analysis is linear in the MHD phenomena, and the time scale of interest is assumed short compared to changes in the plasma equilibrium. Equilibrium parameters and the linear form of the eigenmode, obtained with a MHD code or with a linear kinetic-MHD code such as NOVA-K[3] are input data. The particle distribution is generated by Monte-Carlo methods so that realistic high energy particle distributions are easily realized. Computing requirements are modest, allowing scans of plasma parameters. The analysis includes sufficient detail to allow a comparison of kinetic MHD with experiment.

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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 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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1994 International Sherwood Fusion Theory Conference
Dallas, Texas, March 14–16, 1994

A Numerical Study of the Neoclassical Bootstrap Current Using Adjoint Functions

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The adjoint function formalism familiar in the study of current drive with neutral beam and rf [1,2] is adapted to calculate the neoclassical bootstrap current. Transport coefficients for the electron contribution to the bootstrap current as well as the neoclassical resistivity are expressed as a flux-surface average of integrals of the adjoint function multiplied by appropriate source functions due to pressure, temperature gradients, and the ohmic electric field. The theoretical formalism is valid in all regimes of collisionality. Specializing to the banana regime, the bounce-averaged adjoint function for the full collision operator is obtained numerically using the ADJ code [3]. For arbitrary aspect ratio circular cross-section tokamak equilibria, the numerical results of the bootstrap current coefficients are compared with those obtained by the Hirshman-Sigmar moment method [4]. Excellent agreement between the numerical and analytic results is obtained for the pressure gradient coefficient L_{31} and the ohmic coefficient L_{33} for all ionic charge Z_i. Some discrepancies are observed for the temperature gradient coefficient L_{32}. The theoretical formalism and numerical calculations are being extended to consider the ion contribution to the bootstrap current.

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Progress on the Simulation of Toroidal ITG Turbulence

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The gyro-Landau fluid (GLF) model equations for toroidal geometry described in Waltz, Dominguez, and Hammett [Phys. Fluids B 4 (1992) 3138] have been applied to the study of ion temperature gradient (ITG) mode turbulence using a novel 3D nonlinear ballooning mode representation. Numerous case studies with adiabatic electrons have been done. Nonlinearly generated $n = 0$ "radial modes" are found to be particularly important. While the radial modes give no transport directly, they provide small scale $E \times B$ sheared rotations which have a stabilizing effect on the finite-n modes and reduce the overall transport ten-fold. The turbulence and particularly the transport is highly ballooning and the toroidal transport levels are more than ten-fold larger than slab transport levels. The scaling of diffusion with shear $\hat{s}$, safety factor q, and temperature gradient is found to be similar to the scaling of linear mixing length models at least near the threshold for strong to moderate shear. No evidence of subcritical diffusion has been found. Diffusion increases with q and decreases with $\hat{s}$ but remains finite for vanishing shear $\hat{s} < 1$. The equilibrium scale $E \times B$ sheared rotation causes the transport to vanish when the shear rate exceeds the maximum linear driving rate: $\gamma_{\mathrm{E}} = r\, d(V_{\mathrm{E}}/r)/dr - V_{\parallel}/L_{\mathrm{s}} \approx \gamma_{\mathrm{max}}$ (including the Kelvin-Helmholtz drive from parallel shear $\gamma_{\mathrm{P}} = dV_{\parallel}/dr$). A recent advance, using an implicit Green's function method suggested by M. Kotchenruther [Bull. Am. Phys. Soc. **37** (1991) 1432], allows the passing electrons to be treated non-adiabatically with a GLF model. This allows comparison of plasma and electron heat flow with ion heat flow.

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Chaotic transport analysis in hamiltonian systems

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Abstract

A new statistical diagnostic tool for chaotic transport in hamiltonian systems is proposed. The method, based on the concept of escape times, has an advantage over the calculation of diffusion coefficients in that it remains valid for non-diffusive transport processes. This method is tested on the Chirikov-Taylor standard map: one finds that it is more robust than usual diffusion coefficient D and conveys the same information as D when the latter is meaningful, for all values of the nonlinearity parameter K. We also extensively studied an asymetric standard map and found interesting behaviours of deviations to the quasilinear transport.

3C40

Bootstrap Current in Non-Axisymmetric Tori

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ABSTRACT

for 1994 International Sherwood Fusion Theory Conference

A specific group of particles exists in 3-D confinement systems, which make transitions back and forth between the toroidally and locally trapped states. The low-collisional distribution function of such particles is found with the appropriate boundary condition on the separatrix derived. This solution is then used to evaluate the bootstrap current. The physical origin of the current is the dependance of the distribution function of transition particles on the radial location of the transition point. Since the transition particles in the toroidally trapped states moving in the parallel and anti-parallel directions undergo the transition on different magnetic surfaces (separated by the distance of the order of the banana width), the number of particles moving in the parallel and anti-parallel directions in any particular point is also different, which gives rise to the additional longitudinal current. This current is found significant for the stellarator configuration.

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ABSTRACT
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Alpha Current and Radial Transport Driven by ICRH in a DT Tokamak Reactor *

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Use of Ion Cylotron Resonance Heating (ICRH) to drive toroidal current and radial transport of DT-fusion born alpha particles is studied in a tokamak reactor plasma condition. We find that a preferential heating of alpha particles traveling in one toroidal direction leads to toroidal current and radial transport. Theoretical estimates show that ICRH power of practical level (< 50 MW) can drive toroidal current and radial transport rate high enough to make a significant contribution to the current profile control and radial alpha flow control for a steady state burn of ITER-like reactor plasmas. Possible experimental studies in the present day tokamaks (TFTR, DIII-D, JET, and TEXTOR) will also be discussed.

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FEEDBACK CONTROL OF TOKAMAK INSTABILITIES

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An experimental demonstration of a multimode feedback stabilization with a single sensor-suppressor pair is presented. Two modes were simultaneously stabilized with a simple state feedback type method where more "state" information was generated from a single sensor Langmuir probe by appropriate signal processing. A single feedback modulated ion beam served as the remote suppressor. A simple theory shows good agreement with experiment. This experiment may be considered as a paradigm for controlling certain classes of important instabilities in tokamaks. First, we propose to control major disruptions in tokamaks via suppression of kink and/or tearing modes. This may be accomplished by using a modulated neutral beam suppressor in a feedback loop, which will supply a momentum input of appropriate phase and amplitude. Simple theoretical models predict modest levels of beam energy, current and power. Secondly, we propose suppression of electrostatic instabilities like the trapped particle and ITG modes via appropriate particle (ion) input from the modulated neutral beam. Again, feedback power levels are seen to be modest. Feedback control of these fluctuations will lead to significant reduction in anomalous transport.

A Set of Tokamak Edge Plasma Fluid Equations from First Principles*

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A common approach to obtaining the equations which describe fluid transport in the edge plasma of a tokamak is to describe the transport along either field lines or poloidal flux surfaces using the Braginskii equations, and add *ad-hoc* "anomalous" diffusive radial terms of particles, momentum, and energy. Accurate determination of background flow fields is important because they may have an influence on the impurity transport in the scrape-off layer and divertor regions. Consequently, it may be useful to compare the solutions obtained from these semi-quantitative equations with the full two-fluid Braginskii equations. Under the assumption of toroidal symmetry, we obtain balance relations for densities, temperatures, velocities, and electric potential in a suitable 3-D coordinate system. Under this formulation, the fluid drifts appear in a natural and rigorous manner. Rather than solving the electron momentum balance directly, we obtain a Generalized Ohm's Law. The resulting equation for the potential, φ, has the interesting property that in the limit of zero Larmor radius for the ions but including ion inertia and viscosity, only potential gradients parallel to the magnetic field remain:

$$\nabla_{\|}\left(\frac{\sigma_{\|}}{B}\nabla_{\|}\varphi\right)=\frac{c}{B}\nabla\cdot\left\{\frac{1}{B^2}\left[\mathbf{B}\times\nabla p+\mathbf{B}\times\left(\nabla\cdot\Pi_i\right)+m_i\,n\,\mathbf{B}\times\left(\mathbf{v}_i\cdot\nabla\mathbf{v}_i\right)\right]\right\}+\nabla_{\|}\left[\frac{\sigma_{\|}}{enB}\left(\nabla_{\|}p_e+0.71\,n\,\nabla_{\|}T_e\right)\right]$$

where **B** is the magnetic field, $\sigma_{\|}$ is the parallel electrical conductivity, p and p_e are the total and electron pressure respectively, n and T_e are the density and electron temperature respectively, Π_i is the ion viscosity tensor, $\mathbf{v}_i$ is the ion velocity, e is the magnitude of the elemental charge, c is the speed of light, and m_i is the ion mass. More detail will be presented at the meeting covering the specific form of the equations in a representative coordinate system, discussion of boundary conditions, and considerations for numerical solution.

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Nonlocal theory of excitation of Trivelpiece-Gould(TG) mode in a plasma filled wavbeguide by plasma return current

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Abstract

Propagation of high current relativistic electron beams to long distances is accomplished by passing them through a plasma. The plasma provides partial current and charge neutralization to the beam. The plasma current carried by the plasma electrons, i.e. plasma return current, can drive Trivelpiece - Gould (TG) mode unstable. We have developed nonlocal theory of TG mode excitation taking realistic radial profiles of beam current and plasma current distribution. Numerical calculations have been carried out for the parameters of the University of Maryland backward wave oscillator (BWO) where introduction of plasma in the device dramatically improves the efficiency of 8.6 GHz radiation generation from 5% to 40%.

Consider the propagation of relativistic electron beam (REB) through a cylindrical plasma column immersed in a strong magnetic field . Following Miller the current density profiles at the beam and plasma return current as a function of r, can be written as :

$$J_{bz} = -e n v_b \, J_0\left(\frac{\lambda_1 r}{R}\right) g(u),$$

$$J_{pz} = -J_{bz}\left[\exp\left(-\frac{\lambda_1 r}{R}\right)\frac{c}{4\pi\sigma^2}\left(t-\frac{z}{v_b}\right) - \exp\left\{-4\pi\sigma\left(t-\frac{z}{v_b}\right)\right\}\right]$$

where V_b is the beam velocity r is the radial distance from the z-axis. R is the waveguide radius, n is the density of electrons, and $u=\gamma(v_b t - z)$, γ being the relativistic gamma factor, and $g(u) = \begin{cases}1, & u>0\\ 0, & u<0\end{cases}$, λ_1's are zeros of (Bessel functions), is the conductivity of plasma (assumed to be scalar).

We perturb the equilibrium by an electrostatic perturbation, Viz., a TG mode $\phi = \phi(r)\, e^{i(\omega t - kz)}$

Seeing the response of beam electrons and ions (the ion response is taken to be unmagnetized) to this potential and using Poisson's equations $\nabla^2\phi = 4\pi(n - n_i)e$, where n_i being the ion
and e is the electronic charge.
density, we get

$$\frac{\partial^2\phi}{\partial r^2} + \frac{1}{r}\frac{\partial\phi}{\partial r} - k^2\phi = 4\pi\,(n - n_i)e$$

We have solved the above equation numerically for the plasma current profile given above. The modes turn out to be localized around the current maxima. We would estimate the level of saturation of these modes.

WE are also generalizing the analysis to incorporate across the field dynamics of electrons.

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Neoclassical ∇p-Driven MHD Instability in TFTR Supershots*

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ABSTRACT

Understanding the physics of the low (m,n) tearing-type MHD activities which are often observed in TFTR supershots (both in DD and DT discharges) is important. Development of these modes (typically with m/n=3/2 and 4/3) often correlates with a plasma performance deterioration[1].

Among several candidates for explaining the observed MHD, neoclassical ∇p-driven tearing mode theory[2,3] seems to have many features consistent with the observations. According to this theory, the evolution of a magnetic island is primarily determined by $dw/dt=D_m[\Delta'(w)+w_c/w]$, where w is the island width, $D_m=\eta/\mu_0$ is the magnetic field resistive diffusion coefficient, Δ' is the usual $\tilde{B}_r$–discontinuity parameter which determines the classical current-driven tearing mode instability, $w_c = \sqrt{\varepsilon}\beta_p L_q/L_p$ is the neoclassical island threshold width. First of all, when the plasma is stable to the classical current-driven tearing mode, i.e., $\Delta' < 0$, the plasma can still be unstable to the neoclassical ∇p-driven tearing mode. In this case, the island will grow with $w \propto \sqrt{t}$ (or $\tilde{B}_r \propto t$). Secondly, the saturated island width ($\propto w_c$) is proportional to β_p. These two features are found to agree with the TFTR supershot MHD database. In addition, the saturated neoclassical island width ($w_s = w_c\, r_s/2m$, assuming $\Delta' = -2m/r_s$) calculated using the TRANSP or SNAP analysis agrees with the island width calculated using the edge $\tilde{B}_p$ measured from the Mirnov coils.

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A Generic Gyrokinetic PIC Simulation Code For Parallel Computers *

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Gyrokinetic particle–in–cell (PIC) simulation of tokamak core turbulence is a key part of the Numerical Tokamak Project, an HPCC Grand Challenge. We describe a new three–dimensional simulation code developed to make use of high–performance parallel computers. This code uses the generic approach of domain–decomposition and message–passing to implement the algorithm on multiple processors. This approach has a successful history for PIC simulation[1] and results in a program which is portable to a wide range of MIMD computer architectures

We slice the simulation domain in all three directions into subdomains. Processors work only on the particle and grid data within their subdomain; required data from neighbor subdomains is gathered and passed explicitly as messages. For example, particles that move across subdomain boundaries are passed to the appropriate neighbor processor, which then takes up the processing chores for those particles.

We compare this approach to alternate parallel programming paradigms such as control parallelism (loop–level) and data parallelism (High Performance Fortran, CM Fortran). Its disadvantages are in the pain and suffering of explicit programmer choreography of data placement and communication. Its advantages are in portability and efficiency.

To demonstrate the efficiency of this approach, we present scaling studies with variation of processor count and problem size. We comment on the range of appropriate application using state–of–the–art parallel machines like the Thinking Machines CM5, and where that range lies outside the limits of current state–of–the–art vector supercomputers such as the Cray C90. We outline the new physics territory this can lead us into. We discuss our plans for high–resolution simulation of turbulent microinstabilities, and progress toward implementation of quasiballooning coordinates[2] in the parallel code to achieve true toroidicity and steady–state turbulence.

We implement parallelism in all phases of the simulation, including initialization and data output. For a given physical configuration (described by system size, grid resolution, and particle count), the loading of particle positions and velocities is identical for any number of processors or choice of subdomain geometries. Likewise, the output files are structured as if written by a single processor working with monolithic grid and particle data arrays. This allows restarts using different processor counts or subdomain geometries.

Furthermore, the output is in a machine-independent format which allows postprocessing on any platform having the (public–domain) NetCDF I/O library. We describe examples of using generic data analysis tools, such as using the commercial AVS system to read and visualize field data from the simulation output.

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CORSICA: A Comprehensive Tokamak Simulation Code *

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A comprehensive, long-time-scale simulation of a tokamak requires that many physical processes (turbulent fluctuations, core transport, edge transport, MHD equilibrium, various sources, etc.) be modeled and consistently coupled together. These processes vary in length- and time-scale, and in dimensionality. We are developing algorithms for coupling such processes in a manner that allows each to be advanced on a the relevant time-scale. In particular, the goal is to advance the transport equations with a time-step on the order of the energy confinement time. Our methods are being tested by developing a prototype simulation code, CORSICA. This code is being constructed by taking existing codes and coupling them together as modules in a single code. The three main focuses of the project are: (1) coupling a 1-D core transport code to an axisymmetric free-boundary MHD equilibrium code (LLNL's TEQ) and to circuit equations for the poloidal field coils and passive structure (the resulting 1-1/2 D transport code is known as CORSICA 1.0); (2) coupling the core transport code to a 2-D edge transport code (UEDGE); and (3) coupling the transport codes to turbulence simulation codes. Progress in all three of these areas will be discussed, including: Early results from CORSICA 1.0; An algorithm for coupling turbulence simulation fluxes into a transport code; Results from coupling local and nonlocal Hasegawa-Wakatani turbulence simulation codes to a 1-D slab transport code, including discussion of local versus nonlocal transport; And time-dependent results from coupling the UEDGE edge code to a 1-D slab ("core") transport code.

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Mode Structure in the Vicinity of an X-Point

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We undertake the solution of a 3-D mode equation in an axisymmetric magnetized plasma with an x-point. Our mode equation, containing the essential ingredients of both MHD and drift type fluctuations, is taken to be of the form

$$\left[\nabla_{\parallel}^2 - \epsilon^2 \nabla_{\perp}^2\right] \tilde{\phi} = 0, \tag{1}$$

where $\epsilon \ll 1$ and $\mathbf{B}_0 = I(\psi)\nabla\varphi + \nabla \times (\psi \nabla \varphi)$. Here, an x-point is defined as a point where the poloidal flux function, ψ, has a saddle point, as in diverted plasmas.

Standard analyses of normal modes in a magnetized plasma are inadequate for this problem, for at least two reasons. First, the usual flux coordinates, in which ψ or a related function is taken as a "radial" coordinate, are singular near an x-point, with a radial metric, h_ψ, that diverges at the x-point. Second, the usual ordering, in which a parallel time is much faster than a perpendicular time, breaks down near an x-point. Since this ordering underlies nearly all solutions to the above equation,[1,2] including flute modes and the ballooning formalism, a different approach to x-point mode structure is desirable.

In this work, we develop a new approach to the determining such mode strructure.

1. We first define a new type of flux coordinate, based on the poloidal flux function ψ but not singular near the x-point. One coordinate is the toroidal direction, and the remaining two coordinates resemble Cartesian coordinates in the poloidal plane, with each axis following one branch of the separatrix.
2. We write Eq. (1) in these coordinates, Fourier transforming in φ to obtain a 2D PDE.
3. We solve the 2D PDE in the neighborhood of the x-point; this turns out to be *separable* for high enough n and close enough to the separatrix.
4. The x-point solutions are asymptotically matched with the usual "flute-like" modes, thus forming solutions valid over the entire volume.

This solution sheds light on a recent work,[3] which showed that strict enforcement of the flute approximation through the x-point gives a mode with greatly increasing perpendicular wavenumber, $k_\perp$, implying that modes cannot carry a significant amplitude through an x-point. In contrast, our analysis shows a mode in which $k_\perp$ is largest near the x-point, and matches to flute-like modes where $k_\perp$ diminishes away from the x-point, thus allowing modes which continue through this region.

As an illustration of this modified structure and how it affects the dispersion relation, we consider the conducting-wall instability[4] for a model problem in which field lines are terminated at both ends by conducting plates close enough to the x point that B_p remains linear in distance from the x point. Compared to a conventional WKB analysis of the same field, our solution yields a considerably larger growth rate.

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Toroidal Simulations of Ion-Temperature-Gradient Turbulence.*

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We assess the implications of our gyrokinetic δf simulations of toroidal ion-temperature-gradient-driven (ITG) turbulence for transport in the tokamak core. Many simulation runs have been completed, so far mostly for parameters relevant to TFTR. The code is fully toroidal and uses quasiballooning coordinates for optimal spatial resolution. The physics model includes toroidal drives and coupling, trapped ions, and both externally driven and self-generated flow shear. We have generalized Kotschenreuther's offset-periodic radial boundary condition to allow for externally driven sheared flows. The toroidal compression of the poloidal $\boldsymbol{E} \times \boldsymbol{B}$ drift, which is important for the poloidal flow damping physics, has also been included.

Both with and without self-generated flows, gyroBohm thermal transport scaling is observed at rates sufficient to account for experimental observations. The self-generated flows reduce the transport roughly by half, in contrast to slab ITG turbulence for which the reduction is much larger. For strong magnetic shear ($L_s/L_T \simeq 20$) the transport rate increases roughly in proportion with the magnetic shear length. For $\eta_i \simeq 4$, the transport scaling with $\eta_i - \eta_{crit}$ is weaker than linear, possibly because closer to marginal stability, the modes are less strongly ballooning. Externally driven toroidal flow shear at the levels observed in the VH mode of DIII-D completely stabilizes the turbulence. For more moderate levels of toroidal flow shear, the destabilizing contribution of the parallel shear flow can be significant. The parameter scans will be extended in order to assess whether pure ITG turbulence can explain the minor-radius dependence of the thermal transport over any portion of the profile. Simulations for DIII-D parameters will be presented which include realistic poloidal-angle dependences of the magnetic field strength and local magnetic shear.

The code has undergone significant benchmarking and optimization. Tests of linear growth rates against theory and against the results of other codes give good agreement. Good code performance has been attained. With four-point averaging, average CPU times of less than 2.6 μsec. per particle per timestep have been obtained on the Cray C90 in the unitasking mode, and less than 0.32 μsec. per particle per timestep per processor, with a parallel overlap of 14.6, in the multitasking mode using 16 processors.

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TRANSITIONS IN ROTATING MAGNETOFLUIDS

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This paper is based on two assumptions: (1) that the tokamak "L to H transition," as shown by the experiments of R. J. Taylor and others, has something to do with plasma rotation; and (2) it is worthwhile to model the bulk dynamics of the transition within a purely MHD framework, even though it seems certain that other non-MHD effects are prominent in the transition. We extend the previous spectral-method, periodic-cylinder, MHD computations of Shan, *et al* [1] to the rotating case. A toroidal vorticity source term is added to the equation of motion and models the effect of departures from charge neutrality inside the plasma, of whatever origin. A wall friction term, important only near the boundary $r = a$, models the mechanical drag that the plasma must experience from whatever interaction with divertor or limiter may be present. It is shown computationally that by increasing the poloidal rotation rate, we may suppress the supercritical states (involving paired vortices and helical deformations) above the stability threshold. A rotating axisymmetric state results, with poloidal flow which may or may not be sheared in the interior, but which does involve a boundary layer near $r = a$ that contains a large velocity shear. This boundary layer is viewed as a consequence, rather than as a cause, of the rotationally-induced transition. From this perspective, poloidal rotation is seen as highly desirable for confinement. Designing reactors without having fully understood the role of plasma rotation can be argued to be premature.

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THREE KINDS OF MHD EQUILIBRIA

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The most common mathematical models for the configurations of magnetically-confined plasmas are steady-state solutions of the MHD equations. Some surprising uncertainty remains, however, as to just what constitutes a physically acceptable MHD equilibrium. There are at least three distinct candidates. The possibilities for ideal equilibria, with electrical conductivity assumed infinite, are essentially unlimited: an infinity of possible (Grad-Shafranov) solutions exists corresponding to a single set of boundary conditions. Slightly resistive equilibria, however, which enforce Ohm's law and Faraday's law from the beginning, appear to be unique for a given set of boundary conditions. The only non-uniqueness in those solutions seems to be associated with bifurcations at instability thresholds; there, the static axisymmetric equilibrium branch may be replaced by preferred branches with finite velocity fields and different (helical) symmetries. (And resistive toroidal equilibria, unlike ideal ones, differ greatly from those in periodic straight cylinders.) Finally, there is the possibility that current profiles may select themselves on statistical mechanical grounds as "most probable" states that maximize information-theoretic entropies, subject to constraints provided by exact or approximate conservation laws. First formulated as a way of discriminating among ideal equilibria, maximum-entropy methods have recently shown predictive power in dissipative computations of turbulent relaxation to quasi-steady states in Navier-Stokes fluids and/or guiding-center plasmas. The three methods are not the same and do lead to different answers. The intent of this paper is to bring into focus the differences between, and the possible connections among, these three differing ways of arriving at MHD equilibria.

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3C52

Gyrofluid Vortex Cell Structure and Evolution.*

G.D.KERBEL AND R.E.WALTZ, *NERSC and General Atomics*—The effects of $E \times B$ rotational shear stabilization and the self consistent development of *radial* modes on η_i turbulence levels have been discussed in recent studies.[1] The mechanisms involved here are distinct in character and can be identified by the distortion and convection of vortex cell structure caused by each.

We have developed high performance visualization tools for distributed and massively parallel computing and tuned them for the study of tokamak turbulence. These tools can be used to generate animations and composite images interactively even when working with very large data sets (10^9 gridpoints).

A visual study of the effects of rotational shear and radial mode stabilization on ITG turbulence levels showing some of the mechanisms involved will be presented.

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3C53

Semi-Lagrangian Advection in Tokamak Gyrofluid Turbulence Simulations

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The large E X B advection velocity present in our Numerical Tokamak Project simulations cause a stringent limitation on the time step. This Courant condition limitation becomes worse as the grid point spacing is reduced. In the current version of the TRB code the convection terms are computed by evaluation of convolutions using a pseudo-spectral method. This convolution, in addition to limiting the time step, is one of the most computationally costly parts of the simulation. We are in the process of developing an alternate to this convolution using a semi-Lagrangian advection method. This method computes the changes due to advection in real space. It computes the change in a quantity at a grid point by interpolating (bilinear) to the position of the point along a stream line at the previous time. Since this position will not necessarily be on a grid point, another interpolation method (4th order Lagrangian) is used to determine the function value (from the grid point values) at the previous time. This semi-Lagrangian method has been shown to operate stably at large Courant numbers, thus we anticipate being able to use a much larger time step. Since this advection algorithm computes in real space, it can be easily modified to aid in the visualization of the E X B flow field. This technique will be useful as a flow visualization diagnostic and will be integrated into the parallel visualization system designed for the TRB code.

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Parallel Fully Implicit Algorithms For ITG Gyro-Landau Fluid Tokamak Turbulence Simulations:*

J.L.Milovich, G.D.Kerbel and R.E.Waltz, *NERSC and General Atomics*—We have incorporated a fully implicit multi-tasked solver into TRB. The solver is based on a preconditioned Krylov iteration scheme.[1] This method can be used to solve either stiff or non-stiff problems. TRB has been succesfully used to study the Gyro-Landau fluid (GLF) model equations[2] with adiabatic electrons, a non-stiff system of equations. We have reported earlier on the efficiency of the method in this case.[3] When the adiabaticity condition for passing electrons is relaxed the model produces a stiff system of equations. Conventional methods require prohibitively small time-steps. The efficiency and performance of the method for the stiff system will be discussed.

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