

1996 International Sherwood Fusion Theory Conference

March 18-20, 1996 Philadelphia, Pennsylvania

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March 18–20, 1996
Philadelphia, Pennsylvania



"Proclaim Liberty throughout all the land unto all the inhabitants thereof"

HOSTED BY
Princeton Plasma Physics Laboratory

1996 International Sherwood Fusion Theory Conference

March 18–20, 1996
Doubletree Hotel,
Philadelphia, Pennsylvania

Hosted by

Princeton University
Plasma Physics Laboratory
Princeton, New Jersey

United States Department of Energy
Office of Fusion Research

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Michael Kotschenreuther, IFS
Henry Strauss, CIMS, NYU

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GENERAL INFORMATION

212 papers were submitted, 52 of these electronically. 13 were selected for oral presentation. In addition, there are 3 review papers. Several ancillary meetings are scheduled.

- The **review papers** will be presented in the Ormandy Ballroom (lobby level) at 8:30 a.m. Monday through Wednesday.
- The **oral papers** will be presented in the Ormandy Ballroom (lobby level) as follows: On Monday from 9:30 a.m. to 12:00 p.m. On Tuesday from 9:30 a.m. to 10:30 a.m. and from 7:30 p.m. to 9:30 p.m. And on Wednesday from 9:30 a.m. to 10:30 a.m.
- All **poster sessions** will be presented in two-hour sessions in the Symphony Ballroom (third floor), starting at 2:00 p.m. and 4:00 p.m. on Monday and at 10:30 a.m. on Tuesday and Wednesday.
- **Poster boards** will be available for the review and oral speakers in a designated poster session after their presentations.
- **Registration**, together with a light *hors d'oeuvres* welcoming reception, will begin in the Overture area (outside the Symphony Ballroom on the third floor) on Sunday evening from 6:00 p.m. to 9:00 p.m. The registration desk will be open in the Overture area during the poster sessions, and in the Preassembly area (outside the Ormandy Ballroom on the lobby level) during the review and oral paper sessions.
- A **Philadelphia Style Reception** will be held on Monday evening from 7:00 p.m. to 9:00 p.m. with no-host cocktails from 6:30 p.m. in the Ormandy Ballroom.
- A **Companions' breakfast** will be held Monday morning at 9:00 a.m. in the Café Academie.
- **Coffee** will be served in the Preassembly area (outside the Ormandy Ballroom) at 9:15 a.m. Monday through Wednesday.
- **Beverages** will be served in the Overture area (outside the Symphony Ballroom) on Monday afternoon at 3:30 p.m. and in the Preassembly area (outside the Ormandy Ballroom) at 8:00 p.m. on Tuesday.
- The **MHD working group** will meet on Sunday, March 17, from 2:00 p.m. to 6:00 p.m.
- The **Divertor Task Force/Plasma Edge Theory Working Group** will meet on Sunday, March 17, from 8:30 p.m. to 10:00 p.m.
- A special **ITER session** will be held on Tuesday afternoon, March 19, from 2:30 p.m. to 5:30 p.m. in the Ormandy Ballroom (lobby level).
- An open **Alternate Concepts Theory Community** meeting, will take place on Tuesday, March 19, from 5:00 p.m. to 6:00 p.m.
- Registration for the **Joint 5th Annual Numerical Tokamak Symposium and US-Japan Workshop** will begin at 2:00 p.m. on Monday, March 18. The joint symposium and workshop will be held Wednesday afternoon and evening, March 20 and all day Thursday, March 21.
- **Requests for satellite meetings and audio visual equipment** should be made at the Conference Registration desk.
- **Future Sherwood meetings:** *Sherwood 97*, hosted by The University of Wisconsin, will meet in Madison, Wisconsin. *Sherwood 98*, hosted by Auburn University, will meet in Atlanta, Georgia.

Doubletree Hotel
Philadelphia, Pennsylvania
March 18-20, 1996

Registration Schedule

The registration desk will be located by the active sessions

Sunday	6:00 p.m.-9:00 p.m.	Overture room: <i>outside the Symphony Ballroom (third floor)</i>
Monday	7:30 a.m.-12:00 noon	Preassembly area: <i>outside the Ormandy Ballroom (lobby level)</i>
	2:00 p.m.-5:00 p.m.	Overture room
Tuesday	8:00 a.m.-10:30 a.m.	Preassembly area
	10:30 a.m.-12:30 p.m.	Overture room
	7:00 p.m.-9:00 p.m.	Preassembly area
Wednesday	8:00 a.m.-10:30 a.m.	Preassembly area
	10:30 a.m.-12:30 p.m.	Overture room

Presentations Schedule

Review and Oral Presentations: Ormandy Ballroom (lobby level)
Poster Presentations: Symphony Ballroom (third floor)

Monday

8:20 a.m.-8:30 a.m.	Welcome	Morrell Chance, <i>Chairman</i>
8:30 a.m.-9:20 a.m.	1A	Review Paper <u>Perkins</u>
9:30 a.m.-12:00 noon	1B	Oral Session (5 30-minute talks)
		Lunch break
2:00 p.m.-4:00 p.m.	1C	Poster Session (50 poster papers)
4:00 p.m.-6:00 p.m.	1D	Poster Session (50 poster papers)

Tuesday

8:30 a.m.-9:20 a.m.	2A	Review Paper <u>Graves</u>
9:30 a.m.-10:30 a.m.	2B	Oral Session (2 30-minute talks)
10:30 a.m.-12:30 p.m.	2C	Poster Session (50 poster papers)
		Free afternoon
7:30 p.m.-9:30 p.m.	2D	Oral Session (4 30-minute talks)

Wednesday

8:30 a.m.-9:20 a.m.	3A	Review Paper <u>Prager</u>
9:30 a.m.-10:30 a.m.	3B	Oral Session (2 30-minute talks)
10:30 a.m.-12:30 p.m.	3C	Poster Session (47 poster papers)

Coffee: 9:15 a.m. Monday through Wednesday
Beverages: 3:30 p.m. Monday afternoon and 8:00 p.m. Tuesday evening

Oral Presentations

Monday Morning

- Review Paper** 1A Morrell Chance, Presiding
8:30 a.m. F. W. Perkins, *ITER physics: design and operations*
- Oral Session 1B Mike Kotschenreuther and Ernie Valeo, Presiding
9:30 a.m. J. A. Krommes, *Theoretical approaches to turbulent transport near marginal stability*
10:00 a.m. J. F. Drake, *Local reversed magnetic shear and the formation of a transport barrier*
10:30 a.m. G. M. Staebler, *Core transport barriers predicted by drift wave models with flow shear*
11:00 a.m. X. Q. Xu, *Theory and 3D fluid simulations of turbulences in detached SOL plasmas*
11:30 a.m. D. Uzdensky, *Theoretical analysis of the magnetic reconnection experiment, MRX*

Tuesday Morning

- Review Paper** 2A Fred Jaeger, Presiding
8:30 a.m. David Graves, *Modeling and simulation of plasma materials processing devices*
- Oral Session 2B John Johnson, Presiding
9:30 a.m. B. Coppi, *Feasibility of ignition experiments: major issues for debate*
10:00 a.m. W. Dorland, *Predictions of reactor performance using anomalous transport models*

Tuesday Evening

- Oral Session 2D Janardhan Manickam and Hank Strauss, Presiding
7:30 p.m. M. S. Chu, *Resistive instabilities in negative central shear tokamaks with peaked pressure profiles*
8:00 p.m. Z. Chang, *Neoclassical tearing modes in TFTR reversed shear experiments*
8:30 p.m. G. Y. Fu, *Recent progress in TAE stability analysis in tokamak plasmas*
9:00 p.m. H.A. Holties, *Profile dependent signature of the linear MHD spectrum*

Wednesday Morning

- Review Paper** 3A Rick Nebel, Presiding
8:30 a.m. Stewart Prager, *Alternative concepts: physics advances and prospects*
- Oral Session 3B Dan D'Ippolito, Presiding
9:30 a.m. J. Menard, *Ideal MHD stability limits of ultra-low aspect ratio tokamaks*
10:00 a.m. F. L. Waelbroeck, *Rotational stabilization of $q < 1$ modes*

Conference Presentations

Sherwood '96
Doubletree Hotel
Philadelphia, Pennsylvania
March 18-20

The registration desk will be located by the active sessions

Monday Morning

Welcome: 8:20 a.m. — Morrell Chance, *Local Chairman*

1A Review Talk Ormandy Ballroom — lobby level

Monday, 8:30 a.m.–9:20 a.m.

Morrell Chance, *presiding*

1A01. Rip Perkins, *ITER Physics: Design and Operations*

Coffee: 9:15 a.m. — Preassembly Area

1B Oral Presentations Ormandy Ballroom — lobby level

Monday, 9:30 a.m.–12 noon

Mike Kotschenreuther and Ernie Valeo, *presiding*

1B01. Theoretical approaches to turbulent transport near marginal stability

J. A. Krommes and S. Boldyrev

1B02. Local reversed magnetic shear and the formation of a transport barrier

J. F. Drake, Y.-T. Lau, P. N. Guzdar, A. B. Hassam, S. V. Novakovskii, and A. Zeiler

1B03. Core transport barriers predicted by drift wave models with flow shear

G. M. Staebler, R. E. Waltz, and J. C. Wiley

1B04. Theory and 3D fluid simulations of turbulences in detached SOL plasmas

X. Q. Xu and R. H. Cohen

1B05. Theoretical analysis of the magnetic reconnection experiment, MRX

D. Uzdensky, R. M. Kulsrud, and M. Yamada

Lunch Break: 12 noon–2:00 p.m.

Monday Afternoon

1C Poster Presentations Symphony Ballroom — third floor

Monday, 2:00 p.m.–4:00 p.m.

Beverages: 3:30 p.m. — Overture Room

1C01. Charge particle dynamics in the field of two monochromatic waves in a magnetized plasma

D. R. Shklyar, A. Sen, and S. Benkadda

- 1C02. Scoring in Degas 2
C. F. F. Karney, D. P. Stotler, and A. Yu. Pigarov
- 1C03. Plasma confinement with an RF trap
R. A. Nebel, J. M. Finn, and A. H. Glasser
- 1C04. MHD stability study for the ITER reference case
O. Sauter, D. Boucher, F. Porcelli, M. N. Rosenbluth, M. S. Chu, H. Lütjens, A. Bondeson, and A. D. Turnbull
- 1C05. Effect of 3D shear flow and 3D neutral turbulence on the propagation of a heat front towards the divertor plate in the gas blanket regime
G. Vahala, L. Vahala, J. Morrison, S. I. Krasheninnikov, and D. J. Sigmar
- 1C06. Exactly conservative integrators
B. A. Shadwick, J. C. Bowman, and P. J. Morrison
- 1C07. Isotopic mass dependence of the transport of hydrogenic species in TFTR discharges
R. V. Budny
- 1C08. Spectral theory for the inviscid vortex
N. J. Balmforth and P. J. Morrison
- 1C09. Pseudo-MHD ballooning modes in tokamak plasmas
J. D. Callen and C. C. Hegna
- 1C10. Recurrent and random explosive events: relevant theoretical models
A. C. Coppi and B. Coppi
- 1C11. Long wavelength ITG gyrofluid simulations
S. A. Smith and G. W. Hammett
- 1C12. Application of adaptive gridding to magnetohydrodynamic flows
D. D. Schnack, I. Lotatti, and P. Satyanarayana
- 1C13. Implementation of the Quiet Implicit PIC (QIP) moment equations in toroidal geometry
W. D. Nystrom, D. C. Barnes, and R. A. Nebel
- 1C14. Gyrokinetic simulations of the effect of negative magnetic shear on trapped particle drift instabilities
R. D. Sydora, S. E. Parker, and W. W. Lee
- 1C15. Finite orbit width and Larmor radius effects of fast particle drive on low- n TAE stability
N. N. Gorelenkov and C. Z. Cheng
- 1C16. Generalized ballooning and sheath instabilities in the divertor scrape-off layer
J. R. Myra, D. A. D'Ippolito, and J. P. Goedbloed
- 1C17. MHD stability of reversed shear configurations
J. Manickam
- 1C18. Comparison of two drift wave models in transport simulations
A. H. Kritz, A. J. Redd, J. E. Kinsey, and G. Bateman
- 1C19. Effect of a plasma turbulence on the properties of the sheath in a grazing magnetic field
R. H. Cohen and D. D. Ryutov
- 1C20. Catastrophe in the stochastic layer due to dipole perturbation for a single-null divertor tokamak
H. Ali, M. Watson, A. Punjabi, and A. H. Boozer
- 1C21. Parallel shear-driven instability for detached divertors
Yu. A. Tsidulko, H. L. Berk, R. H. Cohen, and X. Q. Xu

- 1C22. Renormalized theory of MHD turbulence with electron compressibility
P. W. Terry, E. Fernandez, and A. S. Ware
- 1C23. Coupling the UEDGE plasma model and EIRENE neutrals model
M. E. Rensink, T. D. Rognlien, and D. P. Coster
- 1C24. Full-wave modeling of high harmonic heating and current drive in NSTX
E. F. Jaeger, D. B. Batchelor, and R. Majeski
- 1C25. The influence of collisional and anomalous radial diffusion on parallel ion transport in edge plasmas
P. Helander, R. D. Hazeltine, and P. J. Catto
- 1C26. Symbolic analysis of turbulent fluctuations
M. Lehrman, A. B. Rechester, and R. B. White
- 1C27. Full-wave and Fokker Planck analysis of ICRF heating experiments in the Alcator C-Mod tokamak
P. T. Bonoli, S. Golovato, M. Porkolab, and Y. Takase
- 1C28. Ballooning mode stabilization by moderate sheared rotation
E. Hameiri
- 1C29. Kinetic features of TdeV tokamak SOL plasmas
M. M. Shoucri, O. V. Batishchev, A. A. Batishcheva, S. I. Krasheninnikov, D. J. Sigmar, and I. P. Shkarofski
- 1C30. Simulation of lower hybrid current drive in enhanced reversed shear plasmas in the TFTR using the lower hybrid simulation code
R. Kaita, S. Bernabei, R. V. Budny, J. Hosea, D. Ignat, S. C. Jardin, F. Jobes, B. LeBlanc, F. Levinton, J. Manickam, D. McCune, K. M. McGuire, D. Mikkelsen, C. K. Phillips, E. J. Valeo, J. R. Wilson, and M. C. Zarnstorff
- 1C31. Simulations of enhanced reversed shear TFTR discharges with lower hybrid current drive
J. Kesner and G. Bateman
- 1C32. Interpretive 2-D treatment of scrape-off-layer plasmas
M. Umansky, A. Allen, W. Daughton, R. Nachtrieb, K. Shadman, J. P. Freidberg, J. Kesner, and B. LaBombard
- 1C33. Nonlinear evolution of magnetic islands in a two fluid torus
L. E. Sugiyama and W. Park
- 1C34. Stability of an antisymmetric discrete point vortex row in electron-magnetohydrodynamics
F. Pegoraro, S. V. Bulanov, T. J. Esirkepov, and M. Lontano
- 1C35. Modeling of finite aspect ratio effects on current drive
J. C. Wright and C. K. Phillips
- 1C36. MHD stability of plasmas with hollow current profiles
E. K. Maschke
- 1C37. On the evidence for breaking gyro-Bohm scaling in toroidal transport
W. Horton, T. Tajima, G. Furnish, Y. Kishimoto, and J.-Y. Kim
- 1C38. Notched velocity profiles, radial electric field shear and ion thermal confinement in TFTR supershots
D. R. Ernst and S. D. Scott

Posters: Monday, 2:00 p.m.–4:00 p.m.

- 1C39. Kinetic simulation of detachment in a scrape-off-layer plasma
O. V. Batishchev, J. A. Byers, R. H. Cohen, S. I. Krasheninnikov, T. D. Rognlien, D. J. Sigmar, and X. Q. Xu
- 1C40. Nonlinear particle-wave kinetics in weakly unstable plasmas
B. N. Breizman, H. L. Berk, M. S. Pekker, J. Fitzpatrick, H. V. Wong, and K. L. Wong
- 1C41. Linear and nonlinear studies of resistive-ballooning modes in a tokamak edge plasma with scrape-off layer
Y.-T. Lau, S. V. Novakovskii, J. F. Drake, P. N. Guzdar, A. B. Hassam, and C. S. Liu
- 1C42. A stellarator with the symmetry of a tokamak
P. R. Garabedian
- 1C43. A hybrid symplectic PIC/spectral scheme for one-dimensional electrostatic simulations
I. Doxas and J. R. Cary
- 1C44. Finite- β minimum energy states of a two-fluid flowing plasma
L. C. Steinhauer
- 1C45. Fluctuations in multicomponent plasmas: magnetic effects on the short-wave convective cells
P. P. Sosenko and M. O. Vakulenko
- 1C46. Ripple induced trapped particle loss in tokamaks
R. B. White
- 1C47. Improved core-edge tokamak transport simulations with the CORSICA 2 code
A. Tarditi, R. H. Cohen, J. A. Crotinger, N. N. Mattor, G. D. Porter, T. D. Rognlien, and G. R. Smith
- 1C48. On the dynamics of a radiatively cooling divertor plasma
B. Meerson and H. R. Strauss
- 1C49. The modeling of non-axisymmetric halo currents in tokamaks
J. McCarrick and J. P. Freidberg
- 1C50. Trapped particle stabilization of the resistive wall mode
R. Betti and J. P. Freidberg
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1D Poster Presentations Symphony Ballroom — third floor
Monday, 4:00 p.m.–6:00 p.m.

Beverages: 3:30 p.m. — Overture Room

- 1D01. Numerical studies of magnetic turbulence in the 3-field reduced MHD model
E. Fernandez and P. W. Terry
- 1D02. Theory-based transport modelling of tokamak temperature and density profiles
G. Bateman, J. E. Kinsey, A. H. Kritz, A. J. Redd, S. Kaye, J. Weiland, and B. Brown
- 1D03. Triggering internal disruptions in tokamaks at high β
L. Zakharov, R. V. Budny, Z. Chang, and B. Rogers
- 1D04. Progress on first-principles turbulence simulations for realistic tokamak parameters
A. M. Dimits and T. J. Williams

- 1D05. The breaking of up-down symmetry of trapped particle orbits by a toroidal electric field
P. Martin and M. G. Haines
- 1D06. Omnigenous transport barriers
L.-J. Zheng, M. Tessarotto, and J. L. Johnson
- 1D07. Omnigenous non-quasihelical systems
J. R. Cary and S. G. Shasharina
- 1D08. Transport matrix of orbit squeezing and finite orbit width effects on plasma transport
K. C. Shaing, C. T. Hsu, and M. C. Zarnstorff
- 1D09. Resistive toroidal MHD equilibria
D. Montgomery
- 1D10. Hybrid simulations of the interaction of hot gyrokinetic particles with MHD waves
E. V. Belova, R. E. Denton, M. K. Hudson, and A. A. Chan
- 1D11. Nonlinear saturation of the parallel velocity shear instability
S. Migliuolo, W. Daughton, and B. Coppi
- 1D12. Neoclassical transport theory in a tokamak plasma with large spatial gradients
C. S. Chang
- 1D13. Thermal transport from a phenomenological description of ion-temperature-gradient-driven turbulence
M. Ottaviani, W. Horton, and M. Erba
- 1D14. First principles analysis of advanced confinement regimes
M. Kotschenreuther and W. Dorland
- 1D15. Energy conserving truncations for convection with shear flow
J.-L. Thiffeault and W. Horton
- 1D16. Robust and accurate numerical methods applied to the edge plasma equations
D. A. Knoll and P. R. McHugh
- 1D17. Reduction of transport in stellarators by self-shielding
A. H. Boozer
- 1D18. The theory of the quasi-optical grill: a lower hybrid wave launcher in the 4–10 GHz range for high field tokamaks
J. Preinhaelter, L. Vahala, and G. Vahala
- 1D19. Definition of collisional radiative rate coefficients in plasma
B. J. Braams
- 1D20. A gyro-Landau-fluid transport model
R. E. Waltz, W. Dorland, G. W. Hammett, and M. Kotschenreuther
- 1D21. Symbolic analysis of spatio-temporal systems: the measurement problem
R. Brown, X. Tang, and E. R. Tracy
- 1D22. Quasi-spherical multipinch configuration
F. Winterberg
- 1D23. Low current approach to ignition
G. Cenacchi, L. E. Sugiyama, A. Airoidi, and B. Coppi
- 1D24. Neoclassical and anomalous transport in toroidal plasmas with drift-ordered turbulence
H. Sugama and W. Horton
- 1D25. Tests of the improved Weiland ion temperature gradient transport model
J. E. Kinsey, G. Bateman, J. Weiland, A. H. Kritz, and A. J. Redd

- 1D26. Non-linear interaction of Alfvén waves with fast particles
S. D. Pinches, J. Candy, S. E. Sharapov, L. C. Appel, B. N. Breizman, T. C. Hender, K. I. Hopcraft, G. T. A. Huysmans, and W. Kerner
- 1D27. Magnetic field reconnection in collisionless plasmas
D. Grasso, E. Cafaro, A. Saluzzi, F. Pegoraro, and F. Porcelli
- 1D28. The radiative condensation instability in non-coronal equilibrium
D. R. McCarthy and S. Krasheninnikov
- 1D29. Forced reconnection in a rotating plasma
C. Ren, J. D. Callen, and C. C. Hegna
- 1D30. Resistive MHD studies of reversed shear current profiles
M. H. Hughes and M. W. Phillips
- 1D31. Theory of probe measurements at the divertor plate
G. D. Porter and D. D. Ryutov
- 1D32. Relativistic gyrokinetic equation in the presence of strong drifts
M. Pozzo and M. Tessarotto
- 1D33. 2-D WKB-j ballooning numerical analysis of high- n TAE modes
C. T. Hsu, C. Z. Cheng, L. Chen, G. Y. Fu, G. Rewoldt, and W. M. Tang
- 1D34. Onset of the radial electric field oscillations in the neoclassical plasmas
C. S. Liu, S. V. Novakovskii, R. Z. Sagdeev, A. A. Galeev, V. B. Lebedev, P. N. Yushmanov, and P. H. Diamond
- 1D35. Double-cross instability in nonuniform plasma
A. J. Brizard, A. N. Kaufman, J. J. Morehead, and E. R. Tracy
- 1D36. Global stability and operational regimes of Ignitor, ITER, and Alcator C-Mod
P. Detragiache, F. Bombarda, B. Coppi, A. H. Glasser, and S. Migliuolo
- 1D37. Second stable regime of mixed slab-toroidal ITG mode with an isotropic η_i^*
H. Song and A. K. Sen
- 1D38. Stabilization of the resistive wall mode using a fake rotating shell
R. Fitzpatrick and T. H. Jensen
- 1D39. Effects of molecular hydrogen and plasma recombination on plasma flow in divertor
S. I. Krasheninnikov, A. Yu. Pigarov, D. J. Sigmar, and T. K. Soboleva
- 1D40. Nonlinear theory for fishbone modes
F. Porcelli, H. L. Berk, B. N. Breizman, and J. Candy
- 1D41. A transport bifurcation model for L to reverse shear mode transition
K. Avinash, P. Kaw, and R. Singh
- 1D42. Effects of beam-driven poloidal rotation on the neoclassical bootstrap current
Y. R. Lin-Liu and F. L. Hinton
- 1D43. E_r shear suppression of turbulence in enhanced reversed shear mode plasmas
T. S. Hahm
- 1D44. Nonlinear saturation of high mode number toroidal Alfvén eigenmodes
L. Chen and T. S. Hahm
- 1D45. Computation of resistive instabilities with DCON and MATCH
A. H. Glasser
- 1D46. Bifurcation analysis and nonlinear self-sustainment of drift turbulence
S. Boldyrev and J. A. Krommes

Posters: Monday, 4:00 p.m.–6:00 p.m.

- 1D47. Scaling of magnetic turbulence with Lundquist number in relaxed state devices
N. N. Mattor
- 1D48. Modeling SOL evolution during disruptions
T. D. Rognlien, R. H. Cohen, J. A. Crotinger, L. D. Pearlstein, G. D. Porter, and G. R. Smith
- 1D49. Combined JET and DIII-D temperature and density profile parameterization and ITER prediction
K. Imre, K. S. Riedel, D. P. Schissel, and B. Schunke
- 1D50. A thermal transport coefficient for ohmic and ICRF plasmas in Alcator C-Mod
W. Daughton, B. Coppi, F. Bombarda, L. E. Sugiyama, and M. Greenwald
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Monday Evening

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“Philadelphia Style” Reception

Ormandy Ballroom — lobby level

7:00 p.m.–9:00 p.m.

No-host cocktails from 6:30 p.m.

★ ★ ★★ ★ ★★ ★ ★★ ★ ★ ★

Tuesday Morning

2A Review Talk Ormandy Ballroom — lobby level

Tuesday, 8:30–9:20 a.m.

Fred Jaeger, *presiding*

2A01. David Graves, *Modeling and Simulation of Plasma Materials Processing Devices*

Coffee: 9:15 a.m. — Preassembly Area

2B Oral Presentations Ormandy Ballroom — lobby level

Tuesday, 9:30 a.m.–10:30 a.m.

John Johnson, *presiding*

2B01. Feasibility of ignition experiments: major issues for debate

B. Coppi

2B02. Predictions of reactor performance using anomalous transport models

W. Dorland and M. Kotschenreuther

2C Poster Presentations Symphony Ballroom — third floor

Tuesday, 10:30 a.m.–12:30 p.m.

2C01. Destabilization of contained interacting modes by fusion products

G. Penn, C. Riconda, and B. Coppi

2C02. Two-dimensional modeling of plasma diagnostic reflectometry

T. B. Kaiser and B. I. Cohen

2C03. Slow temporal evolution of long mean free path Laminar tokamaks

H. Weitzner

2C04. Growth rate for core-localized toroidal Alfvén eigenmodes

J. W. Van Dam, B. N. Breizman, J. Candy, and S. E. Sharapov

2C05. Physics of advanced, high magnetic field experiments

A. Airoidi, G. Cenacchi, and B. Coppi

2C06. Neoclassical transport in ERS regime

Z. Lin, W. M. Tang, and W. W. Lee

2C07. Mercier criterion modified by kinetic effects

M. N. Rosenbluth and F. Porcelli

2C08. Determination of eddy transport coefficients in thermo-lattice Boltzmann modeling of two-dimensional turbulence

L. Vahala, G. Vahala, P. Pavlo, and M. Soe

2C09. Stability of high bootstrap fraction low aspect ratio tokamaks

V. S. Chan, Y. R. Lin-Liu, R. L. Miller, and A. D. Turnbull

2C10. Fast wave current drive in low aspect ratio tokamaks

S. C. Chiu, V. S. Chan, T. K. Mau, Y. R. Lin-Liu, R. L. Miller, and A. D. Turnbull

- 2C11. Application of multi-species, collisional radiative model to the recombining divertor plasma
A. Yu. Pigarov and S. I. Krasheninnikov
- 2C12. Self-generated magnetic chains in plasma flow
J. Vranješ and D. Jovanović
- 2C13. The spectral problem of global microinstabilities in tokamak-like plasmas using a gyrokinetic model
S. Brunner, J. Václavík, M. Fivaz, and K. Appert
- 2C14. Predictive transport simulations of tokamak discharges
R. Gatto and T. K. Fowler
- 2C15. Linear and nonlinear dynamics of Alfvén modes driven by energetic particles
G. Vlad, S. Briguglio, F. Romanelli, and F. Zonca
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A. Jaun, T. Hellsten, K. Appert, A. Fasoli, J. Lister, J. Václavík, L. Villard, W. W. Heidbrink, and E. Carolipio
- 2C18. Strong drifts effects on neoclassical transport
M. Tessarotto, D. Gregoratto, R. B. White, and L.-J. Zheng
- 2C19. A self-organized criticality model for plasma transport
B. A. Carreras, D. E. Newman, and V. E. Lynch
- 2C20. 1-D kinetic divertor gas-box simulations and development of a 2-D code
J. A. Byers, O. V. Batishchev, R. H. Cohen, S. I. Krasheninnikov, T. D. Rognlien, D. J. Sigmar, and X. Q. Xu
- 2C21. Realistic magnetic equilibria in global nonlinear gyrokinetic simulations
T. M. Tran, M. Fivaz, G. DeRidder, K. Appert, O. Sauter, S. E. Parker, and V. K. Decyk
- 2C22. Ballooning modes in Heliotron/Torsatrons
N. Nakajima
- 2C23. Particle motion in a sheath in a strongly tilted magnetic field
D. D. Ryutov and R. H. Cohen
- 2C24. Radial structure of toroidal drift modes in tokamaks
H. E. Mynick and S. E. Parker
- 2C25. Explanation of $L \rightarrow H$ mode transition based on gradient stabilization of edge thermal fluctuations
W. M. Stacey
- 2C26. A toroidal boundary-value problem in resistive MHD
J. W. Bates and H. R. Lewis
- 2C27. Implementation of bootstrap current effects in the PIES code
D. A. Monticello and A. H. Reiman
- 2C28. What's fair is fair
R. Nachtrieb and J. P. Freidberg

- 2C29. Orbit squeezing in a magnetic well
E. R. Solano, K. C. Shaing, M. C. Zarnstorff, and C. T. Hsu
- 2C30. Simple map for single-null divertor map
A. Verma, A. Punjabi, and A. H. Boozer
- 2C31. Neoclassical rotation velocities in multispecies plasmas
W. A. Houlberg, S. P. Hirshman, and K. C. Shaing
- 2C32. Nonlinear stability studies of coupled tearing modes in toroidal finite- β plasmas using PEST-3
A. Pletzer
- 2C33. Magnetic error field effects on magnetic island formation in a tokamak plasma
T. A. Gianakon, J. D. Callen, and C. C. Hegna
- 2C34. Topology, finite time Lyapunov exponents, and barriers for diffusive transport in advection-diffusion problems
X. Tang and A. H. Boozer
- 2C35. Three-dimensional calculations using the quiet implicit PIC method
D. C. Barnes, R. A. Nebel, C. R. Sovinec, and W. D. Nystrom
- 2C36. Curvature and temperature gradient driven instabilities in tokamak edge plasmas with SOL
S. V. Novakovskii, P. N. Guzdar, J. F. Drake, and C. S. Liu
- 2C37. Spectral reduction for two-dimensional turbulence
J. C. Bowman, B. A. Shadwick, and P. J. Morrison
- 2C38. Hamiltonian description of toroidal magnetic fields in vacuum
H. R. Lewis and J. W. Bates
- 2C39. Importance of radial localization on the interaction of fusion products with high-frequency modes
C. Riconda, G. Penn, and B. Coppi
- 2C40. Detonation and ballooning modes
S. Cowley, B. Fong, and O. Hurricane
- 2C41. Multi-dimensional conversion to the ion-hybrid mode
E. R. Tracy, A. N. Kaufman, A. J. Brizard, and J. J. Morehead
- 2C42. Simulation studies of high- β disruptions and alpha particle loss in reversed shear plasmas
W. Park, E. D. Fredrickson, and L. E. Sugiyama
- 2C43. Observations on resistive wall modes
R. A. Gerwin and J. M. Finn
- 2C44. Nonlinear simulation study of the toroidal Alfvén eigenmode
Y. Todo and T. Sato
- 2C45. MHD and current profile control studies of reversed shear tokamak configurations
J. J. Ramos, P. T. Bonoli, and M. Porkolab
- 2C46. Relaxation of poloidal rotation in tokamak plasmas in the plateau regime
V. B. Lebedev, P. N. Yushmanov, P. H. Diamond, S. V. Novakovskii, and A. I. Smolyakov
- 2C47. Disruptions in DIII-D
A. H. Reiman, P. Taylor, A. Kellman, and R. LaHaye

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

- 2C48. Interactive Exploration of tokamak turbulence simulations in virtual reality
G. D. Kerbel, T. Pierce, J. L. Milovich, D. E. Shumaker, A. Verlo, R. E. Waltz, G. W. Hammett, M. A. Beer, and W. Dorland
- 2C49. Numerical Lundquist number scaling of magnetohydrodynamic turbulence in reversed-field pinches
C. R. Sovinec and S. C. Prager
- 2C50. Perturbations to SOC models as a mechanism for transport control
H. Chen, D. E. Newman, and B. A. Carreras
-

Tuesday Afternoon

Free afternoon: no formal conference agenda

ITER session

Ormandy Ballroom — lobby level

2:30 p.m.–5:30 p.m.

Several invited talks on scientific areas of interest to ITER, and also a panel session from members of the community.

Tuesday Evening

Beverages: 8:00 p.m. — Preassembly Area

- 2D Oral Presentations Ormandy Ballroom — lobby level
Tuesday, 7:30 p.m.–9:30 p.m.
Janardhan Manickam and Hank Strauss, *presiding*
- 2D01. Resistive instabilities in negative central shear tokamaks with peaked pressure profiles
M. S. Chu, J. M. Greene, L. L. Lao, R. L. Miller, A. Bondeson, A. Pletzer, O. Sauter, B. W. Rice, E. J. Strait, T. S. Taylor, and A. D. Turnbull
- 2D02. Neoclassical tearing modes in TFTR reversed shear experiments
Z. Chang, E. D. Fredrickson, S. Batha, M. Bell, R. Bell, R. V. Budny, C. Bush, A. Janos, F. Levinton, K. M. McGuire, G. Schmidt, E. Synakowski, G. Taylor, and M. C. Zarnstorff
- 2D03. Recent progress in TAE stability analysis in tokamak plasmas
G. Y. Fu, C. Z. Cheng, R. V. Budny, Z. Chang, D. S. Darrow, E. D. Fredrickson, E. Mazzucato, R. Nazikian, K. L. Wong, S. Zweben, H. Kimura, T. Ozeki, M. Saigusa, M. S. Chu, W. W. Heidbrink, and E. J. Strait
- 2D04. Profile dependent signature of the linear MHD spectrum
H. A. Holties, J. P. Goedbloed, G. T. A. Huysmans, W. Kerner, and A. Fasoli

Wednesday Morning

3A Review Talk Ormandy Ballroom — lobby level

Wednesday, 8:30 a.m.–9:20 a.m.

Rick Nebel, *presiding*

3A01. Stewart Prager, *Alternative Concepts: Physics Advances and Prospects*

Coffee: 9:15 a.m. — Preassembly Area

3B Oral Presentations Ormandy Ballroom — lobby level

Wednesday 9:30 a.m.–10:30 a.m.

Dan D'Ippolito, *presiding*

3B01. Ideal MHD stability limits of ultra-low aspect ratio tokamaks

J. Menard, S. C. Jardin, S. Kaye, C. Kessel, J. Manickam, and M. Ono

3B02. Rotational stabilization of $q < 1$ modes

F. L. Waelbroeck and A. Y. Aydemir

3C Poster Presentations Symphony Ballroom — third floor

Wednesday, 10:30 a.m.–12:30 p.m.

3C01. Influence of beam orbit loss on radial electric field in NBI heated Heliotron/Torsatrons

S. Murakami, N. Nakajima, and M. Okamoto

3C02. Dynamo beyond the regime of MHD theory

I. Raskolnikov and N. N. Mattor

3C03. MHD simulations on an unstructured mesh

H. R. Strauss and W. Park

3C04. Simulation of current generation in a 3-D plasma model

F. S. Tsung and J. M. Dawson

3C05. Two-dimensional divertor simulation scaling laws

P. J. Catto, D. A. Knoll, and S. I. Krashennnikov

3C06. Runaway electron distributions obtained with the CQL3D Fokker-Planck code under tokamak disruption conditions

R. W. Harvey and V. S. Chan

3C07. Monte Carlo simulation of superthermal alpha particles in rippled field of tokamak

A. Punjabi, M. Lam, and A. H. Boozer

3C08. Microinstability properties of negative magnetic shear discharges in TFTR and DIII-D

G. Rewoldt, W. M. Tang, M. Artun, and L. L. Lao

3C09. Cross correlations in the general theory of electromagnetic plasma fluctuations

M. O. Vakulenko

3C10. Self-organization and transport in electrostatic turbulence of tokamak scrape-off-layer

S. Benkadda, P. Gabbai, and A. D. Verga

- 3C11. Alfvén stability properties of reversed shear regimes in DT tokamaks
D. A. Spong
- 3C12. Non-modal analysis in plasmas
S. M. Mahajan, A. D. Rogava, and V. Berezhiani
- 3C13. Toroidicity stabilization of low- n ion temperature gradient-driven modes
M. Fivaz, R. D. Sydora, K. Appert, J. Václavík, and V. K. Decyk
- 3C14. Stability studies of tokamak discharges with negative central shear
J.-N. Leboeuf, V. E. Lynch, and B. A. Carreras
- 3C15. Semiconductor plasmas
V. Berezhiani and S. M. Mahajan
- 3C16. Atomic and surface physics data in DEGAS 2
D. P. Stotler, C. F. F. Karney, A. Yu. Pigarov, and R. J. Kanzleiter
- 3C17. Development of parallel Fokker-Planck code ALLAp
A. A. Batishcheva, O. V. Batishchev, S. I. Krashenninnikov, A. E. Koniges, G. G. Craddock, D. J. Sigmar, and M. M. Shoucri
- 3C18. The dynamics of internal transport barrier formation in reverse shear and weak shear discharges
D. E. Newman, B. A. Carreras, P. H. Diamond, and V. B. Lebedev
- 3C19. MHD waves, reconnection, and plasma transport at the dayside magnetopause
J. R. Johnson and C. Z. Cheng
- 3C20. Self-consistent 2D model for L – H transitions in tokamaks
P. N. Guzdar and A. B. Hassam
- 3C21. Magnetic field generation and “Weibel Resonance” in inhomogeneous plasmas
S. V. Bulanov, F. Califano, and F. Pegoraro
- 3C22. The PIES code and its applications
J. L. Johnson, D. A. Monticello, and A. H. Reiman
- 3C23. Particle orbits in an RF combined trap
J. M. Finn, R. A. Nebel, A. H. Glasser, and H. R. Lewis
- 3C24. Nonlinear gyrofluid simulations of improved confinement with reversed magnetic shear
M. A. Beer
- 3C25. Stationary shear flows in CGL anisotropic toroidal plasmas
V. P. Pastukhov and V. I. Ilgisonis
- 3C26. Non-standard stellarator configurations
P. Moroz
- 3C27. An investigation of thermal transport during tokamak sawtooth events
Y. Nishimura, J. D. Callen, and C. C. Hegna
- 3C28. Implicit low-noise particle simulation methods
B. I. Cohen and A. M. Dimits
- 3C29. Gyrokinetic-magnetohydrodynamic simulation of MHD instabilities in tokamak plasmas with reversed shear
R. A. Santoro and L. Chen
- 3C30. Synergism between profile and cross section shape optimization for negative central shear advanced tokamaks
A. D. Turnbull, T. S. Taylor, B. J. Lee, L. L. Lao, M. S. Chu, and R. L. Miller

- 3C31. Finite element modelling of transport and drift effects in tokamak divertor and SOL
M. Simard, R. Marchand, C. Boucher, J. P. Gunn, J. Mailloux, and B. L. Stansfield
- 3C32. Ideal stability limits of reverse shear equilibria
M. W. Phillips and M. H. Hughes
- 3C33. Progress on CORSICA 3: coupling 3D turbulence to 1D transport in tokamaks
L. L. LoDestro, R. H. Cohen, J. A. Crotinger, A. M. Dimits, G. R. Smith, and X.Q. Xu
- 3C34. Nonlinear theory of ballooning modes with electron compressibility
A. S. Ware, J. D. Callen, C. C. Hegna, and P. W. Terry
- 3C35. Enhancement of particle-wave energy exchange by resonance sweeping
H. L. Berk, B. N. Breizman, and M. S. Pekker
- 3C36. Kinetic modeling of electron transport in C-Mod and DIII-D tokamaks
D. J. Sigmar, A. A. Batishcheva, O. V. Batishchev, S. I. Krasheninnikov, B. LaBombard, B. Lipschultz, and G. D. Porter
- 3C37. Nonlinear TAE instability driven by trapped particles
H. V. Wong, H. L. Berk, and B. N. Breizman
- 3C38. Geometrical approach to Hamiltonian fluids
B. N. Kuvshinov and T. J. Schep
- 3C39. Fractional kinetics and accelerator modes
G. M. Zaslavsky and B. A. Niyazov
- 3C40. Stability of the $n = 1$ internal kink mode in equilibria with flows
A. Y. Aydemir and F. L. Waelbroeck
- 3C41. Classical convective energy transport in large gradient regions
F. L. Hinton
- 3C42. Simulation of the xerographic recharge process
C. Feng, S. E. Parker, and M. H. Lean
- 3C43. Relabeling symmetries in MHD
N. S. Padhye and P. J. Morrison
- 3C44. Deducing noninductive current profile from surface voltage evolution
C. Litwin, S. Wukitch, and N. Hershkowitz
- 3C45. Explanation for MARFE formation and subsequent evolution into a detached symmetric plasma edge
W. M. Stacey
- 3C46. Magnetic reconnection in collisionless regimes with reversed shear
B. Coppi and L. E. Sugiyama
- 3C47. Reversed shear operation for high field ignition
L. E. Sugiyama
-



Abstracts

Arranged in presentation order

*1996 International Sherwood Fusion Theory Conference***ITER Physics: Design and Operations**

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Physics considerations are central to the ITER Engineering Design Activity and impact it in several ways. First, the ITER size, shape, and magnetic field strength are chosen via a judicious balance of cost, technological constraints, and extrapolation of confinement data from present tokamak experiments by a process mostly empirical in nature but constrained to obey fundamental principles of plasma physics. Present experiments indicate that resistive modes and collisionality govern the beta-limit for discharges of the ITER shape and collisionality. The resulting machine parameters yield a design that, by intent, has modest margins with respect to obtaining the desired goal of steady, controllable thermonuclear burn. Operational responses, especially driven-burn operations, exist that will likely enable ITER to fulfill its mission of 1-1.5 GW of sustained fusion power if shortfalls in projected performance occur. Second, the scale of ITER presents especially difficult challenges in the areas of divertor and disruption effects, which are generic to tokamak fusion reactors. It is the role of ITER to meet these challenges and demonstrate reliable, continuing operations of a tokamak at the reactor scale. Third, the ITER design strives to accommodate a variety of advanced tokamak operations. Plasma shaping capabilities are comparable to those of ASDEX-U, the principal constraint being that of a single-null divertor. A segmented central solenoid is under consideration as a potential design improvement that could augment plasma shaping capabilities and reduce cost. Site power requirements are set by a criterion that calls for the ability to apply almost the full auxiliary heating power (70 MW out of 100 MW) while ramping up the plasma current. NBI is planned to provide plasma rotation appreciably in excess of the natural diamagnetic rotation velocity. In addition to its ability to increase the threshold for the enigmatic error field instability, plasma rotation is associated with internal transport barriers, and needed to stabilize low- n modes in advanced scenarios.

Acknowledgement The ITER Joint Central Team acknowledges the work of the Four Parties' Voluntary Physics R&D programs in providing the physics basis upon which the EDA design rests. In particular, the efforts of the members of ITER Physics Expert Groups are recognized.

Theoretical approaches to turbulent transport near marginal stability*

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The presence of large microturbulent transport, such as caused by ion-temperature-gradient-driven (ITG) fluctuations, tends to drive temperature profiles toward marginal (linear) stability over much of the minor cross-section. The possibility that some profiles may be *submarginal* (linearly stable) yet carry substantial turbulent flux is of particular interest: it affects the interpretation of experimental data, and may imply that linear analysis is inadequate for the accurate determination of stable (e.g., enhanced-reversed-shear) operating regimes. Submarginal profiles are intimately related to nonlinear instability mechanisms for the self-sustainment of turbulence even in the presence of eigenmodes that are linearly stable. Such self-sustainment has been observed in a variety of computer simulations [1, 2].

In the present work, the following approaches to the analysis of submarginal transport and nonlinear self-sustainment are conceptually linked and exploited: exactly solvable statistical model problems; discrete “sand-pile” dynamics and self-organized criticality (SOC); bifurcation theory; and “nonlinear instability” mechanisms. A nontrivial yet solvable statistical advection model is constructed that emphasizes the importance of subcritical bifurcations to submarginal turbulent profiles. The SOC of discrete lattice automata is interpreted as a consequence of a kind of subcritical bifurcation, and the submarginal profiles of certain SOC models are related to the subcritical dynamics of the solvable model. Drake’s recent reduced model [2] for the nonlinear instability of collisional drift waves is shown to exhibit a subcritical Hopf bifurcation, lending support to the interpretation of the mechanism as a driver for self-sustained turbulence. An analogous bifurcation is sought for a simple model of ITG turbulence, and the universality of the nonlinear instability is addressed.

Although the possibility of subcritical bifurcations calls into question the relevance of the linear growth rate γ and estimates such as $D \sim \gamma/k_{\perp}^2$ for turbulent transport, it does not entirely vitiate them. It is premature to conclude that all plasma microturbulence is driven by nonlinear subcritical instabilities, whose overall importance remains to be clarified. One’s understanding of the nonlinear driving and saturation mechanisms of plasma microturbulence is still remarkably primitive. An enormous number of unresolved questions, both conceptual and practical, remain to be answered; a sampling of those is presented.

* This work was supported by U.S. Dept. of Energy Contract No. DE-AC02-76-CHO-3073.

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- [2] J. F. Drake, A. Zeiler, and D. Biskamp. Nonlinear self-sustained drift-wave turbulence. *Phys. Rev. Lett.*, 75:4222, 1995.

Local reversed magnetic shear and the formation of a transport barrier*

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We derive a set of 3-D nonlinear equations describing drift-resistive ballooning modes in a torus including the self-consistent modification of the local magnetic shear due to the shift of the flux surfaces in a plasma torus. 3-D simulations using these equations reveal that a bifurcation of the transport occurs when the local magnetic shear on the outside midplane reverses sign. Resistive ballooning modes in the edge of tokamak plasmas are unstable at low values of the poloidal β . As the local edge gradients increase, compression of the poloidal magnetic flux on the outside of the torus causes the local magnetic shear to reverse, which stabilizes resistive ballooning modes [1]. The same mechanism stabilizes ideal modes at higher values of poloidal β . The bifurcation results when a local increase in the pressure gradient causes the negative shear stabilization of the edge turbulence to beat out the increase in transport resulting from the larger gradient. The complete structure of the bifurcation diagram, anomalous transport rate D versus the control parameter β_p , has been mapped out by completing a series of 3-D simulations. This fully self-consistent bifurcation diagram reveals significant hysteresis, *i.e.*, the transport barrier is maintained at lower values of β_p than is required for the formation of the barrier, as expected from the experimental observations. The approach taken in these calculations to map the structure of the transport bifurcation can be used as a template for transport calculations being carried out on internal transport barriers [2]. The formation of local regions of negative shear have been measured in both H and VH mode on the outside midplane of the edge of DIII-D [3], consistent with the present theory.

References

- [1] T. M. Antonsen *et al.*, to be published
- [2] M. A. Beer *et al.*, to be published
- [3] B. W. Rice, q-Profile Measurements with Motional Stark Effect in DIII-D, to be published

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Core Transport Barriers Predicted by Drift Wave Models with Flow Shear

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A transport model which includes the suppression of turbulence by sheared $E \times B$ rotation has been successful in reproducing much of the phenomenology of the L/H transition [1]. The VH-mode naturally follows from the model at high power. Other enhanced confinement modes with core transport barriers have also been predicted by the model. If the power deposition is strongly peaked at the center and the recycling is low at the edge, a transport barrier can form in the core and not at the edge. These predicted model discharges are similar to the recently discovered enhanced core confinement regimes with weak or negative central magnetic shear. The previous model has been extended to include much more of the physics of drift wave energy, particle, and momentum transport. A rather comprehensive local quasilinear dispersion theoretic model fitted to gyrofluid nonlinear simulations [2] as well as a simpler formula based model are used to treat all transport channels. These models are applied to DIII-D negative central shear discharges. The predicted power threshold for the bifurcation to an interior transport barrier is lower if the density profile is more peaked which is suggestive of the pellet enhanced (PEP) confinement modes. Toroidal momentum injection counter to the current is predicted to be more favorable than co-injection. Negative central magnetic shear and finite Shafranov shift is found to lower the power threshold, but is not essential to the bifurcation caused by $E \times B$ rotational shear stabilization. Negative magnetic shear is essential to avoid MHD instabilities which would otherwise limit the pressure gradient in the transport barrier. The predicted scaling of the power threshold for core transport barriers to reactor scale devices like ITER at smaller relative gyroradius depends crucially on whether the $E \times B$ rotational shear is induced diamagnetically or by toroidal momentum input.

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*FRC, The University of Texas at Austin.

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Theory and 3D Fluid Simulations of Turbulences in Detached SOL Plasmas

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In this paper, we present theory and 3D simulations of scrape-off-layer (SOL) turbulences in detached plasmas. The detached plasmas are characterized as rapid variation of the equilibrium plasma profiles along the magnetic field line between the x-point and the divertor. Our analysis shows that the steep parallel gradients near the x-point might play the same role as surface impedance in the plasma sheath and thus drive conducting-wall-like mode[1, 2] or axial shear mode[3]. The 3D Fluid Simulations of edge turbulence in the electrostatic limit is described by a four-field model of the reduced Braginskii equations in a model x-point geometry, including drives for (1) conducting-wall mode, (2) Kelvin-Holmhotz mode, (3) curvature-driven mode, (4) $\nabla_x v_{||}$, and (5) dissipative axial shear mode. For uniform axial equilibrium profiles, we have obtained a flute mode structure along the field line. Fluctuating amplitudes for $e\tilde{\phi}/T_e \geq \tilde{n}/n_0 \geq \tilde{T}_e/T_e \sim 0.2$, and diffusivities $\chi_e \sim D_e \sim 2 \text{ m}^2/\text{s}$, are comparable to 2D results. We also find $\tilde{V}_i/C_s \sim \tilde{T}_e/T_e$ and the momentum diffusivity $\chi_m \simeq D_e/2$; both are peaked at the sheath entrances. In a detached plasma with $T_{e0}/T_{ed} = 50$ and $N_{e0}/N_{ed} = 0.2$, and without magnetic shear, we find that either a conducting-wall-like mode or dissipative axial shear mode is the dominant drive even if turbulence drive from the sheath is small. The axial fluctuation profiles between x-points are approximately flute. The relative fluctuating amplitudes are comparable to the case for uniform axial equilibrium profiles. But diffusivities are much higher. The magnetic shear effect and transport scaling for detached regimes are discussed.

References

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Theoretical Analysis of the Magnetic Reconnection Experiment, MRX *

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In the MRX experiment[1] two identical spheromaks with a common major axis are driven together. Their poloidal fields are oriented so that at the point of contact reconnection occurs. Their toroidal fields are oriented either parallel (the cohelicity case) or antiparallel (the counterhelicity case). The general theoretical picture of the physics of the experiment is discussed. It is believed that an axisymmetric current layer forms between the two spheromaks in which the reconnection occurs. In this layer the electron temperature is high due to ohmic heating, and there is considerable magnetic tension due to the merging poloidal field. In addition, in the counterhelicity case, there is magnetic tension in the toroidal direction. As a result of these forces large velocities develop in the layer. These velocities take the plasma out of the reconnection region, and into a thin separatrix region that lies between the regions of unreconnected flux and common flux. In this separatrix region the motion quickly develops into heat.

We first describe the experiment from a global point of view[2]. At any time the plasma is in magnetostatic equilibrium everywhere except in the reconnection and separatrix regions. Across these regions the sum of magnetic pressure and the gas pressure is continuous. The high pressure in the region of common flux results from the dissipation of kinetic energy, and can be found by energy conservation since it really comes from dissipation of poloidal and, in the counterhelicity case, toroidal field energy. Thus, from the global point of view a unique sequence of equilibria is given. Once the global situation is determined the proper boundary conditions and geometry are available to treat the local behavior in the reconnection region by asymptotic analysis. The rate of reconnection determines the rate of passage through the sequence of equilibria.

We attempt to carry out the inner analysis for a variety of reconnection rates ranging from the Sweet-Parker rate to the Petschek maximum reconnection rate. It appears that the solution can be followed from the center of the reconnection region outward towards the downstream region. We attempt to show that the matching of this solution to the dynamics of the flow in the separatrix region is only possible for one reconnection rate. If this is the case, then the entire time dependent solution, both global and local can be uniquely determined.

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CHARGE PARTICLE DYNAMICS IN THE FIELD OF TWO MONOCHROMATIC WAVES IN A MAGNETIZED PLASMA

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ABSTRACT

We study the dynamics of charged particles in the presence of two electrostatic waves propagating obliquely to an ambient magnetic field. The presence of a second wave makes the problem a two dimensional and time dependent one with a complicated phase space behaviour. We derive a set of difference equations (maps) for the nonrelativistic particle motion limit and numerically study them to elucidate the various aspects of the phase space dynamics. For the general case of oblique propagation, we observe synergistic effects leading to the lowering of the stochasticity threshold and the concomitant reduction in electric field amplitudes for particle heating applications. These results can be understood in terms of the resonance structures associated with the two waves and we obtain approximate analytic expressions for the thresholds. For the degenerate case of $\omega_1 = n\Omega$, $\omega_2 = m\Omega$ (where ω_1, ω_2 are the frequencies of the two waves, Ω is the cyclotron frequency and n, m are integers) and strictly perpendicular propagation, the problem simplifies to a one and half dimensional one. We observe the presence of stochastic webs in this situation.

Scoring in Degas 2*

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Degas 2 is Monte Carlo code to compute neutral gas transport with a primary application to the understanding of tokamak divertors. In this paper, we describe the procedure for computing Monte Carlo scores which are a statistical measure of quantities that the code attempts to measure. There are two issues to consider: (a) How to compute these score with minimum variance. Degas 2 addresses this by using a track length estimator which it is able to do efficiently because of the way the geometry is handled. (b) How to let the user specify which scores need to be computed. Degas 2 lets the user specify quantities that are scored either when a test flight traverses a volume or intersects a surface. This lets users specify the usual quantities of interest for coupling to a plasma code (e.g., momentum transfer) and for simulating a diagnostic (e.g., an H_α detector).

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Plasma Confinement with an RF Trap*

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A fusion device based on an RF trap is described. An RF trap combines the axial field of a Penning Trap with the pondermotive confinement of a Paul Trap. The pondermotive confinement is provided by standing electromagnetic waves in a resonant cavity, although driven electrostatic fields may also be employed if one wishes to operate at lower frequencies. The major advantage of this device is that the electrostatic breakdown problem for high energy Penning traps can be alleviated allowing one to utilize larger sizes and potentially higher fusion power densities than a standard Penning Trap. Also, multiple species can be confined and focused in this device permitting the utilization of advanced fuels in pure ion plasmas. The major disadvantage is that the device requires large standing wave energies which may lead to unacceptable wall dissipation. The equations describing the trap, spatial and temporal focusing criteria, and reactor embodiments of the device will be presented.

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MHD STABILITY STUDY FOR THE ITER REFERENCE CASE

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The ITER reference case presented in the interim design report (IDR) is obtained using the transport code PRETOR¹. The code has been modified to more correctly take into account the bootstrap current profile. We have coupled the code to the equilibrium code CHEASE², which computes also the Mercier and Ballooning criteria and is interfaced to the ideal MHD code ERATO³ and the resistive code MARS⁴. We find that the reference case, having $\beta_N=2.5$, is stable to all these criteria, ideal and resistive. The results obtained by modifying the profiles and the stability margins will also be shown.

We have also investigated the stability of internal kink modes in ITER. A sawtooth trigger prescription that accounts for resistive, kinetic and fast particles effects has been implemented in PRETOR. Sawtooth periods of typically 100s are found. The ERATO code has been used to more accurately determine the MHD δW contribution to the $m=1$ stability threshold.

¹D. Boucher et al, in Proc. IAEA Tech. com. on *Advances in Simulation and modell. of Thermonuclear plasmas*, June 15-18 1992, Montreal (1993) 142.

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EFFECT OF 3D SHEAR FLOW AND 3D NEUTRAL TURBULENCE ON THE PROPAGATION OF A HEAT FRONT TOWARDS THE DIVERTOR PLATE IN THE GAS BLANKET REGIME

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Abstract

It is well known that laminar heat conduction leads to a totally inadequate gas blanket detachment region. Restricting ourselves to 2D mean toroidal flow over toroidal cavities and utilizing the K- ϵ compressible turbulence code *ISAAC* we have shown^{1,2} how 3D neutral turbulence can lead to a significantly larger detachment region due to an order of magnitude increase in the heat conduction to the toroidal sidewalls.

We now extend these results by incorporating the full 3D divertor geometry and consider 3D mean shear flows: Mach 1.2 toroidal flow over the cavities as well as Mach 0.2 poloidal flow towards the divertor plate. The propagation of the heat front towards the divertor plate is considered as an initial value problem. Heat loads to the toroidal sidewalls, divertor walls as well as the divertor plate will be calculated. The turbulence is (and must) be treated 3D.

¹ G. Vahala, L. Vahala, J. Morrison, S. Krasheninnikov and D. Sigmar, Phys. Lett. **A205**, 266 (1995)

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* work supported by DoE

Exactly Conservative Integrators*

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Typically when numerically integrating a system of differential equations, nonlinear constants of motion possessed by the system are not conserved by the numerical method. We present a nontraditional algorithm that exactly conserves a systems' constants of motion to all orders.¹ In contrast to traditional numerical methods, the time advance algorithm described here is not a polynomial function of the time step. We show that this is a generic requirement of an exactly conservative integrator. We apply our method to turbulent fluids simulations as well as to the motion of a point particle in an external electromagnetic field. We discuss further applications and extensions of this method.

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Abstract for the International Sherwood Theory Conference
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Isotopic Mass Dependence of the Transport of Hydrogenic Species in TFTR Discharges*

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Abstract

In plasmas with deuterium-only neutral beam injection, the presence of tritium recycled from the walls, or puffed in as a gas can be detected by measuring the deuterium-tritium neutron emission profiles. The TRANSP plasma analysis code [1] can be used to simulate these profiles. A single prescription for the tritium transport and recycling has been used to model deuterium-only neutral beam injection TFTR supershots, reversed shear (RS) and enhanced reversed shear (ERS) discharges, H-mode discharges, and L-mode discharges. Good agreements are achieved between simulated and measured quantities.

TRANSP calculates the particle balance from measured quantities. The radial flux profile for the hydrogenic species j can be modeled with explicit diffusivity and pinch profiles as

$$\Gamma_j(R,t) = -D_j \text{grad}(n_j) + V_j n_j$$

The best agreement with neutron emission measurements is achieved with the following mass dependencies: $\{D \sim A^0 \text{ and } V \sim A^{-1}\}$. Alternative prescriptions have been tested. For instance, $\{D \sim A^0 \text{ and } V \sim A^0\}$ or $\{D \sim A^0 \text{ and } V \sim A^{-0.5}\}$ or $\{D \sim A^{-1} \text{ and } V \sim A^0\}$ are incompatible with neutron emission measurements. The effects of brief tritium gas puffs into discharges with deuterium-only neutral beam injection can also be modeled using the same prescription by changing the boundary conditions. The tritium ionization rate in the edge is increased during the puff.

The results for D_j and V_j will be compared with measurements of He transport during He gas puffs, of tritium transport derived directly from the neutron emission during tritium gas puffs, and of deuterium transport in discharges with tritium-only neutral beam injection.

*Work supported by the U. S. Dept. of Energy Contract No. DE-ACO2-76-CHO-3073.

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Spectral theory for the inviscid vortex*

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We consider the linear eigenvalue problem for perturbations about two-dimensional ideal vortices. For differentially rotating vortices, the spectrum generally contains a continuous component. This introduces the well-known singularity into the equation at the *critical radii*. We construct the singular eigenfunctions of the continuous spectrum and address questions regarding their completeness. For incompressible vortices we can prove completeness provided there are no discrete, complex mode pairs representing unstable/decaying mode pairs. For incompressible vortices within an ambient vorticity field and for vortices in shallow water, there are other modes in the spectrum that need to be taken into account. We also consider the properties of the singular eigenfunctions and connect them with the Hamiltonian structure of the problem. The techniques employed are of very general utility and can be applied to essentially all ideal fluid and plasma linear problems.

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Pseudo-MHD Ballooning Modes in Tokamak Plasmas*

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Abstract

The magnetohydrodynamic (MHD) description of a plasma is extended to allow electrons to have both fluid-like ($\omega/k_{\parallel} > v_{Te}$) and adiabatic regime ($\omega/k_{\parallel} < v_{Te}$) responses within an instability eigenmode. In the resultant "pseudo-MHD" model, magnetic field line bending can be significantly reduced in the adiabatic electron regime. This makes possible an important new class of ballooning-type, long parallel extent, geodesic-curvature-driven, robust MHD-like instabilities in tokamak plasmas for $-d\sqrt{\beta}/d\tau > (2^{1/6}/3)(s/R_0q)$ where $\beta \equiv 2\mu_0 P/B^2$, $s \equiv (\tau/q)(dq/dr)$. The marginally stable pressure profile is similar to that observed in ohmically heated tokamak plasmas.

Recurrent and Random Explosive Events: Relevant Theoretical Models

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There are events of relatively brief duration (involving for instance accelerated or heated particles, excitation of fluctuations, radiation emission) that can be related to the onset of different kinds [1,2] of explosive instabilities and that can recur at regular intervals or randomly. An analytical model [3] is introduced, to represent these events, consisting of a set of non-linear differential equations which involve a characteristic singularity. This corresponds to an explosive or quasi-explosive event for a "primary" factor (e.g. the population of heated or accelerated particles) or for the relevant plasma fluctuations that are excited when the primary factor exceeds an appropriate threshold value.

In the case where quasi-explosive events are periodically recurring a non-canonical Hamiltonian is derived from which the equations for both the primary factor and the excited fluctuation amplitude can be derived. Significant examples of the numerical solution of these equations are given. A comparison is made with the well known Volterra-Lotka equations and with previously considered equations producing sawtooth oscillations of the primary factor [4, 5, 6] all of which do not involve singularities and do not describe explosive events.

The random occurrence of this kind of events, involving the primary factor and the fluctuation level, is found by introducing a relatively small time dependent component of the source of the driving factor or of the instability threshold for the fluctuation level, with a period that is not related to that of the original non-linear equation. This case is also illustrated by representative numerical solutions.

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Long Wavelength ITG Gyrofluid Simulations*

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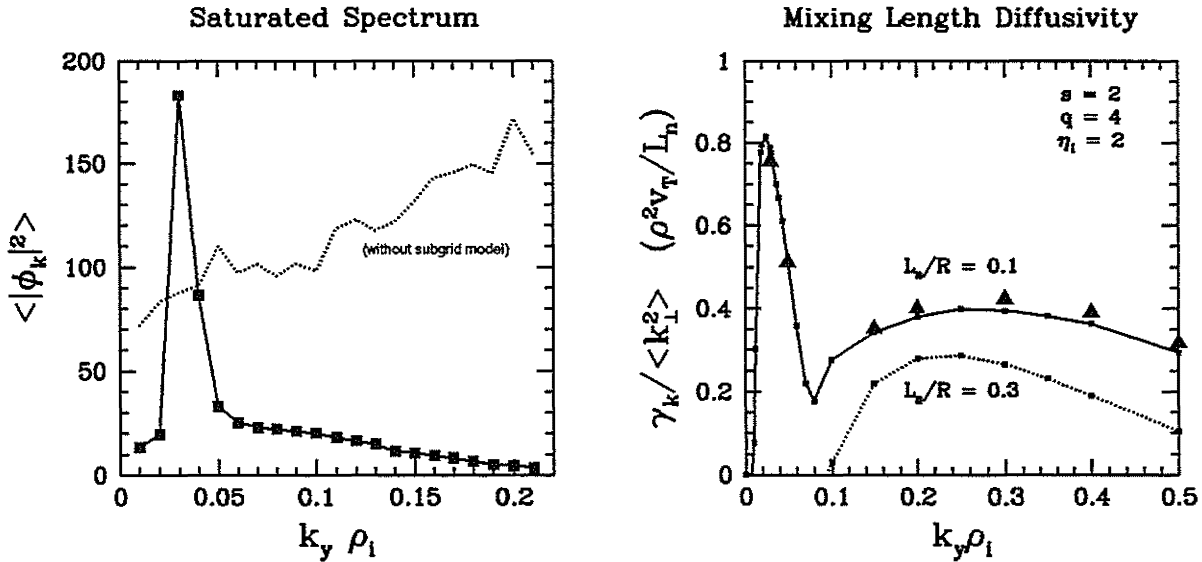
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Significant progress has been made recently[†] in explaining the anomalous ion heat diffusivity, χ_i , in the core of tokamaks. Extending these results to edge-like parameters can be computationally expensive as one needs to simultaneously resolve very long wavelength instabilities that drive the turbulence as well as the dissipation scales on the order of the ion gyroradius. We have developed a novel 3D extension of a nonlinear hyperviscosity-type subgrid turbulence models based on our previous extensive tests of 2D models,[‡] and implemented it in a toroidal gyrofluid turbulence code. The extension to 3D correctly accounts for the anisotropic transfer of fluctuation energy to high $|k_{\parallel}|$ and to high $|k_{\perp}|$ by $\mathbf{E} \times \mathbf{B}$ velocity shear.

Nonlinear simulations are presented for a high gradient regime ($L_n \sim 0.1$ m, $L_t \sim 0.05$ m) where very long wavelengths ($k_{\perp} \sim 0.03$) are linearly unstable and dominate the spectrum. The regime considered here may be relevant to the transition to longer wavelength turbulence observed in the edge of tokamaks[§] Since the spectrum peaks at a significantly longer wavelength than is typical, these simulations are also useful for testing the hypothesis that the peak $\gamma/k_{\perp}^2$ sets the location of the spectral peak and estimates the turbulent diffusivity.



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Application of Adaptive Gridding to Magnetohydrodynamic Flows*

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

Recently we have concentrated on the details of the mesh adaption algorithm used in TRIM. We present several two-dimensional results relating to the use of grid adaptivity to track the evolution of hydrodynamic and MHD structures. Examples of plasma guns, opening switches, and supersonic flow over a magnetized sphere are presented. Issues relating to mesh adaption criteria are discussed.

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Implementation of the Quiet Implicit PIC (QIP) Moment Equations in Toroidal Geometry*

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The Quiet Implicit PIC (QIP) method separates the distribution function into a bulk distribution f_0 , describing the fluid-like behavior, and a remaining part δf , describing the intrinsically kinetic behavior. For fusion plasmas, f_0 is chosen as a local Maxwellian distribution. The evolution of f_0 is governed by Maxwell's equations and a set of moment equations which include closure terms depending on δf . The evolution of δf is represented by marker particles which follow the characteristics of the kinetic equation in the PIC (Particle In Cell) technique. The attractiveness of the QIP equations is the potential to efficiently and accurately model the fluid-like behavior of low-collisionality plasmas while retaining kinetic effects through δf . Shot noise is sufficiently low that physically important fluctuations are resolved. The numerical closure of the moment equations provided by QIP also provides more insight into analytical closure schemes.

The implementation of QIP divides into two parts. First, the moment equations coupled to Maxwell's equations are solved on a computational grid. Second, particle equations of motion determine δf which is then used to close the moment equations. Disparate time scales of the plasma require implicit time differencing for the moment equation solution. This leads to a large, stiff linear system, whose solution presents the major numerical challenge.

Implementation of the first part of the QIP algorithm has recently been completed in the TPCN code by the addition of the pressure evolution equation. Additionally, TPCN now solves the implicitly time-differenced moment-Maxwell equations in a numerically generated orthogonal equilibrium flux coordinate system using the orthogonal trajectory method.[1] This greatly facilitates separating the disparate scales associated with modes parallel and perpendicular to the equilibrium magnetic field. Calculations of global toroidal modes have been accomplished efficiently with the full two-fluid algorithm with realistic electron to ion mass ratio. Results will be presented on the performance of this algorithm and its application to a study of the internal $m=1$ kink mode.

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Gyrokinetic Simulations of the Effect of Negative Magnetic Shear on Trapped Particle Drift Instabilities*

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Recent experimental results have shown that significant improvements in tokamak plasma confinement are achievable in plasma configurations with negative magnetic shear^{1,2}. Here, we investigate the effects of local negative shear on anomalous thermal and particle diffusivities using a fully nonlinear gyrokinetic particle model in field-line-following coordinates³ including the effects of self-generated shear flows and proper toroidal periodicity. This model includes the nonadiabatic electron density response due to trapped electron dynamics.⁴ Trapped electrons use full dynamics and require only a factor of five reduction in timestep with $T_i = T_e$. We use parameters from Enhanced Reverse Shear (ERS) discharges in TFTR and initialize the simulations with the local parameters before, during and after the transition from "RS" (regular transport) to "ERS" (improved confinement).⁵ The trapped electron gradient-driven drift instability is most strongly affected by negative shear and we present results of the saturation dynamics, quasi-steady state thermal and particle diffusivities and radial correlation lengths from the nonlinear simulations.

Results from an alternative approach for modeling the electron response in toroidal geometry, based on the cut-off scheme⁶, will be compared with those from the model presented above (where trapped particles use full dynamics and passing particles are adiabatic). This method treats particles with a fast parallel velocity, $v_{||} > v_c$, as adiabatic, while slower particles use full dynamics.

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Abstract Submitted for the
 INTERNATIONAL SHERWOOD THEORY CONFERENCE
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**Finite Orbit Width and Larmor Radius Effects of Fast Particle
 Drive on Low- n TAE Stability.**

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The effects of finite drift orbit radial width and Larmor radius of fast particles on the stability of low- n TAE are studied. The formulation is based on the solution of gyro-kinetic equation. A quadratic form has been derived in terms of invariant variables: energy $\mathcal{E}$, magnetic momentum μ , and toroidal momentum P_φ . The growth rate is computed perturbatively. Numerical calculation is based on averaging over the fast particle drift orbit. The TAE structure is calculated using the NOVA code [C. Z. Cheng, Phys. Reports **211** (1992) 1]. The results are compared with previous calculations [G. Y. Fu and C. Z. Cheng, Phys. Fluids, **4** (1992) 3722] based on small radial width approximation.

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Generalized Ballooning and Sheath Instabilities in the Divertor Scrape-off Layer*

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The stability of the scrape-off-layer (SOL) in divertor tokamaks is important both because of the desire to stabilize edge localized modes (ELM's) and to ensure a sufficient broad (i.e. turbulent) SOL so as to spread the heat load on the divertor plates. One aspect of this problem, treated in the present paper, is the SOL stability to high toroidal mode number (n) ballooning-type instabilities. Our equilibrium includes a simple model of the X-point geometry, and parallel (as well as cross-field) equilibrium variations of temperature, density and potential. The latter are computed numerically from the Braginskii form for Ohm's law. The high- n stability analysis includes the effects of curvature drive, parallel variation of the $E \times B$ drift frequency,^{1,2} and sheath boundary conditions² at the divertor plate. Importantly, the equilibrium model assures consistency among the possible instability drives; i.e. the pressure weighting of the curvature, the plasma potential ($E \times B$ drift) and the conditions at the divertor plate are coupled by the equilibrium model. By using energy-principle-like integrals of the ballooning equation, the relative importance of the various destabilizing drives can be extracted and compared for different divertor equilibria. Sample numerical solutions will be presented.

* Work supported by USDOE Grant No. DE-FG02-88ER53263.

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MHD stability of reversed shear configurations

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We present a review of MHD stability issues in reversed shear configurations. This work will focus on identifying issues relevant to existing and proposed devices. The aim is to provide a framework for assessing the value of different designs. We will use available experimental data to support our conclusions where it is possible. This work was supported in part by DoE Contract No. DE-AC02-76-CHO-3073.

Comparison of Two Drift Wave Models in Transport Simulations*

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Predictive transport simulations of the temperature and density profiles have been carried out using a combination of theoretically derived models, with the intent of discovering the best available model for drift wave contribution to the transport in tokamak plasmas. These self-consistent time-dependent simulations are performed using the BALDUR 1-1/2 D transport code. The theoretically-derived multi-mode transport model used in this study includes contributions from either the Weiland theory of trapped electron and ion temperature gradient modes[1, 2] or the Dominguez-Waltz drift-wave model[3]. These theoretically derived models are utilized without any introduction of adjustable parameters in our studies. Simulation results are presented for L-mode scans in plasma current, density, and neutral beam power for the Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET). The Dominguez-Waltz model has been reasonably successful in previous studies. However, the Weiland model predicts transport separately for four different transport channels (electrons, ions, hydrogenic particles and impurities) and accounts for physical effects not included in Dominguez-Waltz theory, such as non-diffusive terms, unequal electron and ion temperatures, and finite Larmor radius. It has been found in these simulations that the Weiland model predicts electron density profiles that more closely fit experimental data than does the Dominguez-Waltz model. The particle pinch included in the Weiland model often results in more peaked density profiles in agreement with experimental data. The differences between temperature profiles predicted by the Weiland and Dominguez-Waltz drift wave models are relatively small for many cases.

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Effect of a Plasma Turbulence on the Properties of the Sheath in a Grazing Magnetic Field*

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The object of this study is the effect of plasma turbulence on the properties of the Debye sheath in the case where the magnetic field intersects the wall at a very shallow angle, $\alpha \ll 1$. This situation is important for the divertor regions of tokamaks, as well as for some plasma processing and space applications. By the sheath we mean a region which includes both a quasineutral layer with a thickness of order of the ion gyro-radius where most of the density drop occurs, and a much thinner non-quasineutral layer immediately adjacent to the wall. Classical theory of the sheath in an oblique magnetic field is well developed (see, e.g., the most recent survey [1] and references therein) but relatively little is known about possible effects of plasma turbulence (though the problem has been already identified as an important one, see, e.g., [2]).

We analyse two types of the turbulent effects: i) effects associated with the turbulence in the bulk of the plasma and, ii) excitation of microturbulence in the sheath itself.

When considering the effect of the “bulk” plasma turbulence, one should note that the wave structure of turbulent fluctuations is strongly modified in the vicinity of the wall; hence, one can not use the bulk plasma diffusion coefficient to describe the ion transport through the sheath.

The “average” ion traverses the sheath during many ($\sim 1/\alpha$) gyroperiods. This sets a time-scale for the fluctuations which could cause an enhanced transport through the sheath: their frequency should exceed $\alpha\omega_{ci}$. Slower fluctuations affect the ions only adiabatically, and cannot have a strong influence on the sheath structure (unless their amplitude is unreasonably high). We analyse the role of faster oscillations and find conditions under which they cause broadening of the sheath.

The other group of turbulent effects is that caused by instabilities in the sheath itself. The source of the free energy for these instabilities is a strong deviation of the ion distribution function from Maxwellian. To facilitate the identification of the potentially unstable modes, we consider two special classes of the distribution function of impinging ions: i) a majority of “warm” ions with a small admixture of “cold” ions and, ii) a majority of “cold” ions and a small admixture of “warm” ions. We find that the both distributions are unstable with respect to a kind of a two-stream mode. A purely Maxwellian distribution of impinging ions tends to be more stable. The instabilities considered are important because of their influence on the sheath current-voltage characteristics and the ion distribution function at the wall.

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Catastrophe in the Stochastic Layer
due to Dipole Perturbation
for a Single-null Divertor Tokamak

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We use the method of maps developed by Punjabi and Boozer to investigate the motion of magnetic field lines in stochastic scrape-off layer in the presence of dipole perturbation of a single-null divertor Tokamak. This method is based on the idea that the magnetic field line trajectories in a divertor tokamak are mathematically equivalent to a single degree of freedom, time dependent Hamiltonian System, and that the basic features of motion near a separatrix broadened by asymmetric perturbations are generic for such Hamiltonian and near-Hamiltonian systems. The magnetic topology of a single-null divertor tokamak with the effects on dipole perturbations is represented by the Symmetric Simple Map followed by Dipole Map. We have found that as the amplitude of the dipole perturbation increases, the width of the stochastic layer also increases. At some critical value of the amplitude is reached, there is a catastrophic increase in the width of stochastic layer. This may have significant implications for tokamak divertor physics. This work is supported by US DOE. The computational resources for this work are provided on CRAY EL 92 computer by HU Computer Science department.

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Parallel Shear-Driven Instability for Detached Divertors*

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It was previously noted¹ that variation along the magnetic field of the $\mathbf{E} \times \mathbf{B}$ rotation velocity can give rise to an instability in an open-ended magnetic configuration such as a tokamak scrape-off layer. The previous analysis assumed that the plasma was in the low-beta electromagnetic regime. We extend this analysis to the case of interest for detached and partly detached plasmas, where, because of the large drop in electron temperature, the axial shear region is collisional and the instability near the plates is in the electrostatic regime. As in the pure electromagnetic regime, we find instability for a field line even if it is terminated only at one end (in contrast to the conducting-wall mode², which requires two conducting walls), or if there are two end walls which are either conducting or insulating. In the interesting case where the bulk of the field line is weakly collisional relative to the wave frequency, or in the electromagnetic regime, the cold end wall is accompanied by modified conducting wall and shear-driven modes with phase shifts induced by electron collisions. The solution for the case where the parallel wavelength is small compared to the shear gradient length in the axial shear region in x-point geometry is under investigation. These results might account for observations in various tokamaks, as well as in simulations³, that the fluctuation level is comparable under attached and detached conditions, although details of the turbulence may change.

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* Work performed for the U.S. Department of Energy at LLNL under contract W7405-ENG-48.

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Renormalized Theory of MHD Turbulence with Electron Compressibility

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Measurements of the power density spectrum for high frequency fluctuations in MST yield a spectrum decaying as $k^{-5/2}$ instead of the $k^{-3/2}$ spectrum long predicted to result from the high frequency Alfvénic excitations of MHD.¹ It has been hypothesized that this behavior is due to diamagnetic effects introduced through electron density evolution.² While MHD models with density evolution have a diamagnetic branch, it has not been clear what mechanism allows the small diamagnetic frequency to dominate the much larger Alfvén frequency in the spectrum balances, as required for agreement with experiment.

We detail here a closure calculation for the reduced three-field MHD model³ that verifies prior hypotheses and predicts spectra consistent with those of experiment. In the closure, the nonlinear response function must be solved as an eigenmode problem in which the driven fluctuations of all three fields are retained. There are three eigenfrequencies, two of which are an Alfvénic conjugate pair corresponding to Alfvén waves propagating in either direction along the magnetic field, and one of which is a diamagnetic frequency. To lowest order in the ratio of diamagnetic frequency to Alfvén frequency, this third branch is purely diamagnetic. The frequency spectrum is dominated by the nonlocal Alfvénic interaction between high frequency fluctuations and the long wavelength magnetic field fluctuation. However, the triplet interactions that govern spectral transfer project onto both Alfvénic and diamagnetic branches. A portion of each triplet correlation therefore decays at the slower diamagnetic time scale and survives longer than the Alfvénic components of each triplet correlation. The diamagnetic frequency thus dominates the spectrum balances.

The spectrum balance equations are analyzed to show that in a weak to moderate turbulence regime, where the diamagnetic frequency exceeds the fluid straining rate (eddy turnover rate), the magnetic fluctuation spectrum decays as $\tilde{B}_k^2 = \varepsilon_M^{1/2} V_D^{1/2} k^{-3/2} (1 + k^2 \rho_s^2)^{-1/2}$, where ε_M is the rate of magnetic energy injected into the spectrum at low wavenumber, V_D is the diamagnetic velocity, and ρ_s is the ion gyroradius evaluated at the electron temperature. In a strong turbulence regime where the diamagnetic frequency is less than the fluid straining rate, all three fields decay as $k^{-5/3}$, consistent with the observation of the power density spectrum for density fluctuations in the interstellar medium.

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Coupling the UEDGE Plasma Model and EIRENE Neutrals Model*

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For simulation of tokamak divertors, a fluid neutrals model may be appropriate in highly collisional regimes, whereas a kinetic model may be appropriate in collisionless regimes. In this report we investigate techniques for supplementing the fluid neutrals model in UEDGE with the EIRENE Monte Carlo neutrals model. We examine both steady-state and time-dependent coupling methods in which the EIRENE code calculates the plasma source terms for particles, parallel momentum, and electron and ion energy arising from interaction with neutral gas. For steady state modeling, the finite radius of convergence of the Newton-like method for the plasma update dictates that the plasma not be too far from the final solution. It may be possible to partially relax this constraint by incorporating a Jacobian derived from a fully implicit fluid model for both plasma and neutrals, while using the source terms from the Monte Carlo code to define residuals. For time-dependent simulations, the explicit nature of the plasma-neutral coupling limits the size of the time step for which the iteration will converge. This constraint might also be relaxed somewhat by using a Jacobian for the plasma update that is based on a fully implicit fluid model. Some degree of implicitness can also be introduced by scaling the plasma source terms from EIRENE during a plasma update, e.g., with the ion current to the divertor plates. Results from a simulation with simple cartesian geometry will be presented.

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Full-wave Modeling of High Harmonic Heating and Current Drive in NSTX*

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The proposed low aspect ratio tokamak experiment, NSTX, provides a totally new and unique environment for ion cyclotron range of frequencies heating and current drive experiments. At the proposed frequency of 41 MHz and magnetic field of 0.3 T, electron beta is high and Landau damping is very strong [1]. Wave energy is rapidly and totally damped between the antenna and plasma center, and the result is a current driven well off axis. High cyclotron harmonic ion resonances also occur in the machine with a ratio of rf frequency to ion cyclotron frequency of 6.0 and above for majority deuterium and 3.0 and above for minority hydrogen. Near the plasma center, the product of perpendicular wave number and ion gyroradius is about 6 for deuterium so that the small Larmor radius expansion clearly breaks down. To calculate ion absorption, it is therefore necessary to use the full modified Bessel functions which are valid for all Larmor radii. We have extended the PICES global wave code [2] to use the modified Bessel functions in evaluating power absorption at the high harmonic ion cyclotron resonances. Results show an ion power fraction of about 0.35 percent at 41 MHz and 3.5 percent at 21 MHz. The question remains as to the validity of the second order Larmor radius expansion for the plasma current in the wave equation. At low ion temperature, the expansion is valid. Since the overall wave propagation and absorption is relatively insensitive to ion temperature, it might be argued that the expansion has little effect on the result. However, this conclusion must await more detailed calculations which do not rely on the expansion.

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THE INFLUENCE OF COLLISIONAL AND ANOMALOUS RADIAL DIFFUSION ON PARALLEL ION TRANSPORT IN EDGE PLASMAS

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The orderings in the kinetic equations commonly used to study the plasma core of a tokamak do not allow a balance between parallel ion streaming and radial diffusion, and are, therefore, inappropriate in the plasma edge. Different orderings are required in the edge region where radial transport across the steep gradients associated with the scrape-off layer is large enough to balance the rapid parallel flow caused by conditions close to collecting surfaces (such as the Bohm sheath condition) [1]. In the present work, we derive and solve novel kinetic equations, allowing for such a balance, and construct distinctive transport laws for impure, collisional, edge plasmas in which the perpendicular transport is (i) due to Coulomb collisions of ions with heavy impurities, or (ii) governed by anomalous diffusion driven by electrostatic turbulence. In both the collisional and anomalous radial transport cases, we find that one single diffusion coefficient determines the radial transport of particles, momentum and heat. The parallel transport laws and parallel thermal force in the scrape-off layer assume an unconventional form, in which the relative ion-impurity flow is driven by a combination of the conventional parallel gradients, and new (i) collisional or (ii) anomalous terms involving products of radial derivatives of the temperature and density with the radial shear of the parallel velocity. **Thus, in the presence of anomalous radial diffusion, the parallel ion transport cannot be entirely classical, as usually assumed in numerical edge computations.** The underlying physical reason is the appearance of a novel type of parallel thermal force resulting from the combined action of anomalous diffusion and radial temperature and velocity gradients. In highly sheared flows the new terms can modify impurity penetration into the core plasma.

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SYMBOLIC ANALYSIS OF TURBULENT FLUCTUATIONS*

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A new method for identification of turbulent fluctuations governed by the same dynamics is introduced. The method of correlation functions or Fourier transfer that are often used for the analysis of fluctuations in fluids, plasmas, etc. do not allow one to do that. In order to demonstrate how our method works we present an explicit example. The application of this method for the study of turbulent plasma fluctuations could give us new physics insights into the dynamical processes which govern these fluctuations.

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Full-Wave and Fokker Planck Analysis of ICRF Heating Experiments in the Alcator C-Mod Tokamak*

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The Alcator C-Mod device is a high field, high density, shaped tokamak with parameters $a = 0.22$ m, $R_o = 0.67$ m, $B_o \leq 9.0$ T, $\kappa \leq 1.8$, $\delta \leq 0.8$, and $1.0 \times 10^{20} \text{ m}^{-3} n_e(0) \leq 1.0 \times 10^{21} \text{ m}^{-3}$. Four megawatt of ICRF power is available at 80 MHz. The wide operating range in magnetic field makes several heating schemes possible: (i) Second harmonic heating of hydrogen ($f_o = 2f_{CH}$) at 2.6 T in (D-H); (ii) Fundamental heating of (H) ($f_o = f_{CH}$) at 5.3T in a D-(H) plasma; and (iii) Fundamental heating of (^3He) ($f_o = f_{C^3\text{He}}$) at 7.9 T in a D-(^3He) plasma. The most successful heating regime to date has been (H)-minority heating at 5.3 T. Pellet enhanced performance (PEP) modes have also been achieved in C-Mod in D-(H) at 5.3 T and in D-(^3He) at 7.9 T, with a combination of intense ICRF heating and Li-pellet injection.

A variety of numerical models are used to analyze these heating schemes. A 1-D full-wave code (FELICE) is used to study "single pass" damping of the ICRF wavefront and damping of mode-converted ion Bernstein waves. A toroidal full-wave code (FISIC) is used to study interference and focussing effects of the ICRF waves as well as damping of the ICRF power upon multiple passes of the ICRF wavefront. A combined bounce averaged Fokker Planck and toroidal full-wave code (FPPRF) is used to study the ion tail formation, orbit losses, and the power partition of the ICRF tail to the background electrons and ions.

Full-wave and Fokker Planck analyses confirm the strong single pass absorption of the ICRF power in D-(H) at 5.3 T. Analysis of PEP-mode plasmas in D-(^3He) indicates improved wave focussing and ^3He - cyclotron absorption of the ICRF waves relative to L-mode. A dramatic increase in the transfer of ^3He tail power to the background deuterium is also found for PEP-mode plasmas. A transition to off-axis electron Landau damping of mode converted ion Bernstein waves (IBW) at $n_{^3\text{He}}/n_e \geq 20\%$ is predicted for these experiments by 1-D analysis. However, this electron damping of mode- converted waves is not predicted by the toroidal full-wave models (FISIC and FPPRF). Reasons for this disagreement will be discussed. Second harmonic heating of (H) at 2.6 T has been studied in detail using FPPRF. The sensitivity of tail orbit losses to plasma current, electron density, and (H)-concentration will be shown.

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Ballooning Mode Stabilization by Moderate Sheared Rotation

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Sheared toroidal plasma rotation has been known for some time to have a stabilizing effect on the ballooning modes.¹ A recent calculation² showed that a large flow shear, with $d\Omega/dq$ of the order of the Alfvén toroidal frequency, can stabilize the ballooning modes. This latest result is, in fact, not so optimistic. For observed flows with Mach number of order unity one gets $d\Omega/dq$ smaller by a factor $O(\sqrt{\beta})$ from the required level (if the flow shear length is of the same order as the magnetic shear length). Moreover, the calculation does not take into account a possibly large transient growth of the mode amplitude due to its Floquet structure.¹

We show here that, in fact, there is a general tendency of the ballooning mode to stabilize as soon as the flow shear $d\Omega/dq$ exceeds the ($O(\sqrt{\beta})$ smaller) “slow” magnetosonic wave frequency. Our analysis is perturbative, where the small parameter is related to the small coupling between the slow and Alfvén waves—as is the case in a high aspect-ratio tokamak. (In the perturbation it is important to take the Hamiltonian nature of the governing equations into account.) Moreover, our results apply to the relevant transient growth of the mode amplitude.

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Kinetic Features of TdeV Tokamak SOL Plasmas*

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We apply our 1D2V adaptive Fokker-Planck code ALLA¹ to model detached plasma flow in the scrape-off-layer of Tokamak-de-Varrenes (TdeV). Our previous simulations of the electron transport in the last two meters of open magnetic lines in TdeV showed the importance of kinetic effects.² In this investigation we use an improved model of the TdeV SOL plasma which permits us to simulate the whole magnetic line and impose the proper boundary conditions at the target. Also our model uses actual experimental data for detached plasma³ given by divertor and fast-scanning probes. We begin by using a heat conduction model to reconstruct the plasma temperature and density in the midplane-plate region. We obtain an electron distribution function and calculate the deviation of reaction rates and transport coefficients from their equilibrium values. We also estimate how non-Maxwellian electrons distribution features affect divertor and reciprocating probe measurements. Next we study the sensitivity of the parallel electron transport on plasma profile variations. For comparison we present results for attached TdeV SOL plasma flow modelling, again using recent experimental data.

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Simulation of Lower Hybrid Current Drive in Enhanced Reversed Shear Plasmas in the Tokamak Fusion Test Reactor Using the Lower Hybrid Simulation Code*

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The Enhanced Reversed Shear (ERS) mode has already shown great potential for improving the performance of the Tokamak Fusion Test Reactor (TFTR) and other devices. Sustaining the ERS, however, remains an outstanding problem. Lower hybrid (LH) current drive is a possible method for modifying the current profile and controlling its time evolution. To predict its effectiveness in TFTR, the Lower Hybrid Simulation Code (LSC)[1] model is being used in the TRANSP code and the Tokamak Simulation Code (TSC).[2] Among the results from the simulations are the following.

- Single-pass absorption is expected in TFTR ERS plasmas. The simulations show that the LH current follows isotherms of the electron temperature. The ability to control the location of the minimum in the q profile ($q_{\min}$) has been demonstrated by varying the phase velocity of the launched LH waves and observing the change in the damping location.
- LH current drive can be used to sustain the $q_{\min}$ location. The tendency of $q_{\min}$ to drift inward, as the inductive current diffuses during the formation phase of the reversed shear discharge, is prevented by the LH current driven at a fixed radial location. If this results in an expanded plasma volume with improved confinement as high power neutral beam injection is applied, the high bootstrap currents induced during this phase can then maintain the larger $q_{\min}$ radius.
- There should be no LH wave damping on energetic beam particles. The values of perpendicular index of refraction in the calculations never exceed about 20, while ions at TFTR injection energies are resonant with waves having values closer to 100.

Other issues being addressed in the study include the LH current drive efficiency in the presence of high bootstrap currents, and the effect of fast electron diffusion on LH current localization.

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Simulations of Enhanced Reversed Shear TFTR Discharges with Lower Hybrid Current Drive *

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The BALDUR [1] based BBK code [2] permits predictive simulations of time-dependent tokamak discharges and has the capability to include neutral beam heating, pellet injection, bootstrap currents and lower hybrid current drive. BALDUR contains a theory based multi-regime transport model and previous work has shown excellent agreement with both L-mode and supershot TFTR discharges [1]. These simulations reveal that core transport is dominated by η_i and trapped electron modes and the outer region by resistive ballooning. We simulate enhanced reverse shear discharges by beginning with a supershot simulation with a reversed shear profile. Similarly to the TFTR experiments the reversed shear profile is obtained through the programming of the current during startup and the freezing in of these profiles by subsequent heating. At the time of transition into the enhanced confinement regime we turn off the η_i and trapped-electron mode transport. We examine the further modification of the plasma current profile that can be obtained with the application of lower hybrid current drive. The results of these simulations will be discussed.

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Interpretive 2-D Treatment of Scrape-off-Layer Plasmas*

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The width of the scrape-off-layer in a tokamak is determined by cross field transport. In Alcator C-mod the plasma parameters in the scrape-off-layer are measured at upstream and divertor plate locations [1]. We solve a 2-D scrape-off-layer heat conduction equation in the flux geometry (as determined by EFIT) of the C-mod experiment. Bolometric measurements are utilized for the radiative loss term. We use the end wall probe measurements of electron temperature as a boundary condition and the fast scanning probe measurements of upstream temperature are treated as constraints to determine the cross field transport and thermal conductivity. Results are compared with 1-D onion-skin-model predictions [2].

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Nonlinear Evolution of Magnetic Islands in a Two Fluid Torus*

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A numerical model MH3D-T for the two fluid description of macroscopic evolution in a full three dimensional torus has been developed [1]. Based on the perturbative drift ordering, generalized to arbitrary perturbation size, the model follows the full temperature evolution, including the thermal equilibration along the magnetic field. It contains the diamagnetic drifts, ion gyroviscous stress tensor, and the Hall term in Ohm's law. Electron inertia is neglected. The numerical model solves the same equations in a torus and in several simplified configurations. It has been benchmarked against the diamagnetic ω_{*i} stabilization of the resistive $m = 1, n = 1$ reconnecting mode in a cylinder. The nonlinear evolution of resistive magnetic islands with $m, n \neq 1, 1$ in a cylinder is found to agree with previous analytic and reduced-torus results, which show that the diamagnetic rotation vanishes early in the island evolution and the saturated island size is determined by the same external driving factor Δ' as in MHD. The two fluid evolution in a full torus, however, differs from that in a cylinder and from the resistive MHD evolution. The poloidal rotation velocity undergoes a degree of poloidal momentum damping in the torus, even without neoclassical effects. The two fluid magnetic island grows faster, nonlinearly, than the resistive MHD island, and also couples different toroidal harmonics more effectively. Plasma compressibility and processes operating along the magnetic field play a much more important role than in MHD or in simple geometry. The two fluid model contains all the important neoclassical fluid effects except for the $\hat{\mathbf{b}} \cdot \nabla \cdot \Pi_{\parallel j}$ parallel viscous force terms. The addition of these terms is in progress.

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STABILITY OF AN ANTISYMMETRIC DISCRETE POINT VORTEX ROW IN ELECTRON-MAGNETOHYDRODYNAMICS

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The two-dimensional electron dynamics in a collisionless plasma, on fast time scales such that the ions can be considered at rest, can be described in terms of the "Electron-magnetohydrodynamic" (EMHD) equation

$$(\partial/\partial t + \hat{z} \times \nabla B \cdot \nabla)(B - \Delta B) = 0. \quad (1)$$

This equation expresses the "freezing" of the z -component of the generalized vorticity $B - \Delta B$, i.e. of the rotation of the generalized momentum $\nabla \times [\mathbf{p} - (e/c)\mathbf{A}]$, into the electron fluid moving with velocity $\mathbf{v} = -\nabla \times (\hat{z}B)$. Here, dimensionless units are used with lengths normalized on the electron skin depth and times on the inverse of the electron cyclotron frequency, $\mathbf{p}$ is the electron momentum and $\mathbf{A}$ is the vector potential of the magnetic field along the z -direction created by the electron vortices. The second term in the expression of the generalized vorticity arises from the effect of electron inertia.

We consider two configurations: a) a single vorticity layer and b) two (propagating) parallel layers of opposite vorticity, and study their stability by adopting two different approaches.

- First we exploit the fact that Eq.(1) admits discrete vortex solutions and represent the single vorticity layer as a vortex chain made by equally spaced discrete vortices of equal strength. The double vorticity layer, instead, is represented by two parallel vortex chains of opposite polarity made of equally spaced discrete vortices of equal absolute strength these vortices are placed either symmetrically (a positive vortex opposite to a negative one) or antisymmetrically (vortices of opposite polarities are shifted along the chain by half the inter-vortex distance s inside the chains).
- We find that the single chain and the symmetric double chain are unstable to a bending instability, while the antisymmetric chain is stable when $s \gg 1$ and $3s^2/4 > q^2 > s/2$, where q is the distance between the parallel chains.
- Second, we simulate the nonlinear development of this bending instability by integrating Eq.(1) numerically for the case of smooth initial distributions. The iso-magnetic and the iso-vorticity curves, that show the nonlinear evolution of configurations a) and b), are presented.

Modeling of Finite Aspect Ratio Effects on Current Drive

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Most 2D RF modeling codes use a parameterization¹ of current drive efficiencies to calculate fast wave driven currents. This parameterization assumes a uniform diffusion coefficient and requires *a priori* knowledge of the wave polarizations. These difficulties may be avoided by a direct calculation of the quasilinear diffusion coefficient from the Kennel-Englemann form with the field polarizations calculated by a full wave code. This eliminates the need to use the approximation inherent in the parameterization. Current profiles are then calculated using the adjoint formulation². This approach has been implemented in the FISIC code³. The accuracy of the parameterization of the current drive efficiency, η , is judged by a comparison with a direct calculation:

$$\eta = \frac{\int d^3v \vec{\Gamma} \cdot \vec{\partial}_v \chi}{\int d^3v \vec{\Gamma} \cdot \vec{\partial}_v \varepsilon}$$

where χ is the adjoint function, ε is the kinetic energy, and $\vec{\Gamma}$ is the quasilinear flux. It is shown that for large aspect ratio devices ($\epsilon \rightarrow 0$), the parameterization is nearly identical to the direct calculation. As the aspect ratio approaches unity, visible differences between the two calculations appear.

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MHD STABILITY OF PLASMAS WITH HOLLOW CURRENT PROFILES

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In recent tokamak experiments with current drive by Lower-Hybrid waves, hollow current profiles are naturally obtained due to the properties of the wave absorption and of the bootstrap current. Different profiles of this type, obtained in the experiments, have been found to have widely different MHD stability properties. Therefore, we have started a systematic investigation of the MHD stability of equilibria with hollow current profiles, and of the nonlinear evolution of such instabilities. Numerical calculations are carried out using a recently developed modular MHD code, which is based on a scalar representation of MHD. Our first results concern low-beta plasmas as they are presently obtained in the Tore Supra tokamak, and are mainly restricted to tearing and double-tearing instabilities, for which particular examples will be presented. In addition, the possible role of plasma rotation will be discussed.

On the Evidence for Breaking Gyro-Bohm Scaling in Toroidal Transport*

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Abstract. The scaling of drift wave turbulence and the anomalous fluxes with $\rho^* = \rho_s / a$ has been an important issue in both theory and fusion reactor scale-up projections for a number of years. In the early 3D sheared slab study, the ρ^* - scaling was explicitly investigated for eta-i modes for the perturbed density the $\tilde{n} / \bar{n}$. Simulations showed gyro-Bohm scaling for the sheared slab. Subsequent theoretical studies in toroidal geometry gave global radial mode widths of order $a(\rho^*)^{1/2}$, re-opening the issue of the amplitude and radial correlation of the toroidal drift wave turbulence. Here we report the results for new ρ^* - scaling studies with a global toroidal particle code that has gyrokinetic ions. The radial correlation lengths of the electrostatic potential as well as the particle radial step sizes are investigated for a series of simulations with $a/\rho_s = 70, 90, 180, 270, 360$, and 540. While states driven sufficiently far away from the critical gradient give rise to secondary instabilities that destroy the large radially extended mode structure and thus lead to gyro-Bohm scaling, the relaxed near-critical turbulent states may well have large-scale coherent structures with a strong enough dependence on size (minor radius a) that the Bohm scaling prevails.

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Notched Velocity Profiles, Radial Electric Field Shear, and Ion Thermal Confinement in TFTR Supershots*

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Sharply non-monotonic features are frequently present in the toroidal ion velocity profiles observed by Doppler shift spectroscopy of carbon impurity spectral lines during high temperature experiments on TFTR. These features take the shape of a counter-directed “notch” in V_ϕ^C centered roughly where the ion temperature gradient is a maximum. Assuming, as has been accepted practice, that this measured profile represents the toroidal velocities of all ion species present, a question arises as to how the centrally deposited angular momentum can be transported across this “notched region”, against the gradient of the angular velocity.

In this work, we resolve this longstanding question with an analytical model that quantitatively reproduces the measured (corrected) *non-monotonic* carbon toroidal velocity profile while resulting in inferred hydrogenic toroidal velocity profiles that are essentially *monotonically decreasing* toward the plasma edge. In particular, we find[4, 2]

$$V_\phi^{HDT} = V_\phi^C + \frac{3}{2} \frac{\alpha_2^{(B)}(\alpha, A_i) f_t/f_c}{\left(\frac{15}{16} \frac{1}{\sqrt{2}} + \frac{5}{4} \alpha\right) [1 + A_2 \nu_{*i}] [1 + B_2 \varepsilon^{3/2} \nu_{*i}]} \frac{1}{B_\theta} \frac{dT_i}{dr}.$$

is robustly well-behaved, where $\alpha_2^{(B)}$, A_2 , and B_2 are bilinear in the impurity strength parameter α the average hydrogenic mass A_i .

The success of the above model when applied to a wide range of TFTR supershot experiments leads us to a reasonable expression for the radial electric field E_r , based on the same underlying physics, that can be applied without a measurement of the poloidal velocity. A favorable correlation between ion thermal confinement in TFTR supershots and the core radial electric field shear is then demonstrated, for the first time, with a TRANSP analysis of a well-controlled torque scan of lithium-conditioned TFTR supershots [2, 4]. We investigate the potential role of radial electric field shear in “exceptional supershots” as well as the strong isotope effect observed[5] in DT plasmas.

As a part of this investigation, we make use of an expression[1] for the “shearing rate” $\omega_\theta = \hat{s}^{-1} \varepsilon q^{-1} dV_\phi/dr$ of collective modes that are described by the ballooning representation. This expression, found independently, is equivalent (apart from the factor $\hat{s}$), to Hahm’s expression [3], when the dominant contribution to changes in E_r is due to changes in V_ϕ . We have previously presented [1] an analysis correlating γ_V/ω_θ with improved ion thermal confinement in supershots, where γ_V is the enhancement in the linear ITG growth rate due to toroidal velocity shear. We refine this with better data for V_ϕ^C , including the energy dependence of the CHERS cross-section, and use the TRANSP transport code to infer χ_i .

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Kinetic Simulation of Detachment in a Scrape-off-Layer Plasma*

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We present results from a 1D2V kinetic simulation of the transition from attached to detached flow in a tokamak scrape-off-layer (SOL) plasma. To model this we use our collisional hybrid PIC code W1.¹ It is known that SOL plasma detachment can be initiated by either dropping the heat flux into the scrape-off-layer or by increasing radiative impurity concentration. Both mechanisms are studied in this work.

In the first part of our work we show results from the kinetic modelling of a SOL plasma with Knudsen neutrals for a range of midplane energy fluxes that can produce both detached and attached solutions. The important new feature added to the present model not contained in the previous one² is the use of the actual real electron/ion mass ratio. To make this improvement possible a significant modifications of the W1 code was carried out. This code modifications will also be discussed in the work.

In the second part of our work we give results from a kinetic simulation of impurity radiation induced SOL plasma detachment. We study this phenomena in more detail and use a more advanced experiment-related model than was implemented in our preceding investigation.³

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Nonlinear Particle-Wave Kinetics in Weakly Unstable Plasmas*

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With the motivation to address the behavior of the fusion produced alpha particles in a thermonuclear reactor, a theory is developed for predicting the wave saturation levels and particle transport in weakly unstable systems with a discrete number of modes in the presence of energetic particle sources and sinks. Conditions are established for either steady state or bursting nonlinear scenarios when several modes are excited for cases where there is and there is not resonance overlap. Depending on parameters, the particles can undergo benign relaxation, with only a small fraction of the available free energy released to waves and with no global transport, or the particles can experience rapid global transport caused by a substantial conversion of their free energy into wave energy. When the resonance condition of the particle-wave interaction is varied adiabatically, the particles trapped in a wave are found to form phase space holes or clumps that enhance the particle-wave energy exchange. This mechanism, which has been experimentally observed when there is frequency chirping, causes increased saturation levels of instabilities. If resonance sweeping is imposed externally, the particle free energy can even be tapped in stable systems where background dissipation suppresses linear instability. Externally applied resonance sweeping can be important for alpha particle energy channeling, as well as for understanding fishbone and some Alfvén wave instability experiments. Near instability threshold, that is when the destabilizing drive just exceeds the background dissipation, a more sophisticated analysis is developed to predict the correct saturation. To leading order, this problem reduces to an integral equation for the wave amplitude with a temporally non-local cubic term. This equation has a self-similar solution that blows-up in a finite time. When the blow-up occurs, higher order nonlinearities become important and the mode saturates due to a plateau forming in the distribution function of resonant particles arising from particle trapping in the wave. Otherwise, the simplified equation gives a solution that saturates at a level reflecting closeness to the instability threshold. The developed theory is being used to interpret the experimental results on the excitation of the Toroidal Alfvén Eigenmodes and fishbone oscillations.

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Linear and Nonlinear Studies of Resistive-Ballooning Modes in a Tokamak Edge Plasma with Scrape-off Layer*

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We will present 2D linear and 3D nonlinear studies of resistive-ballooning modes in tokamak edge plasmas which include a closed flux region, as well as a limiter scrape-off layer (SOL) region. These studies therefore go beyond most earlier work, where the stability of the edge in the closed flux region and in the SOL have been considered separately. A 2D linear code, 2D-BALLOON, examines the stability of these curvature driven modes and provides the complete 2D eigenfunction spanning the closed flux surface region as well the open field line region. The sheath boundary condition in the SOL introduces an important new parameter $\lambda = (m_e/m_i)^{1/2} \nu_{ei} q R / v_{Te}$. This parameter plays a significant role in determining the stability of these modes in both the closed flux and SOL regions because of the radial coupling across the last closed flux surface (LCFS). For small λ the spectrum of unstable modes is broad and extends into the low toroidal mode number! regime where the spatial structure is flute-like. The amplitude for these modes is larger in the SOL compared to the closed flux region. However when λ is increased, the low mode numbers are strongly stabilized and the high mode numbers which are strongly ballooning are the dominant modes. In this regime the radial modes straddle the LCFS. In both these cases, the variation in the plasma density is necessary for the radial localization. In the three-dimensional nonlinear simulations, we have solved a set of fluid equations in a toroidal geometry with both the closed flux region and the SOL. The introduction of the SOL to the twisted tube for the closed flux region, has been a major addition to our 3D code. We find that the turbulent transport in the SOL drops significantly as λ is increased, which is consistent with our expectations from the 2D linear code results. However the transport levels inside the closed flux surface region is not that significantly altered. This is because the! radial correlation length in the nonlinear case are smaller than that in the linear case. As a consequence the coupling between the closed flux region and the SOL is weakened in the nonlinear case compared to the linear case.

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A Stellarator with the Symmetry of a Tokamak

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To meet the requirements of the U.S. Stellarator Power Plant Study, a Modular Helias-like Heliac (MHH) configuration was developed that has features in common with the quasi-helically symmetric HSX experiment being constructed at the University of Wisconsin. Improvements have been made in the design of the MHH that raise the β limit, increase the confinement time, and simplify the geometry of the coils. In particular, specifications have been found for a stellarator with just two field periods that has a magnetic field spectrum B_{mn} close to axial symmetry. The aspect ratio of the plasma is only 4.5, the magnetic axis is nearly planar, and there is little twist in the coils. The toroidal coefficients B_{m0} are smaller than those of a comparable tokamak, and the fully three-dimensional terms B_{mn} with $n \neq 0$ remain below a few percent of the toroidal field strength. This configuration has physical properties that make it an interesting candidate for a follow-on experiment to assess the equilibrium, stability and transport of advanced stellarators.

A HYBRID SYMPLECTIC PIC/SPECTRAL SCHEME FOR ONE-DIMENSIONAL ELECTROSTATIC SIMULATIONS

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Abstract

We develop a hybrid PIC/spectral integration scheme based on the explicit symplectic integrator of reference [1]. We find that for low-accuracy short-term integration (5% accuracy over $\omega_p t = 500$) the second-order symplectic method is most efficient, outperforming the fourth-order method by 65% and non-symplectic methods such as Runge-Kutta, Bulirsch-Stoer and ‘naive’ leap-frog by a factor of 3–10. For high-accuracy short-term integration (10^{-4} over $\omega_p t = 500$) the second-order symplectic method is 20% more efficient than both the fourth-order method and Bulirsch-Stoer, and a factor of 8–20 more efficient than Runge-Kutta and ‘naive’ leap-frog. For long-term integration ($\omega_p t = 10^5$) the second order symplectic method outperforms all non-symplectic methods by a factor of 8–20. We also show that the symplectic method is more robust to roundoff error than all other methods we tested, and that for simulations with a small number of particles per wavelength (usuall in plasma simulations) cubic spline interpolation is more efficient that linear interpolation.

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FINITE- β MINIMUM ENERGY STATES OF A TWO-FLUID FLOWING PLASMA*

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The minimum energy theory of an ideal one-fluid plasma with invariant magnetic helicity, $K_B = \int d\tau \mathbf{A} \cdot \nabla \times \mathbf{A}$, leads to the familiar Taylor states. A more general plasma model is an ideal two-fluid flowing system of ions and electrons. A reasonable extension of K_B in such a medium is to replace $\mathbf{A}$ by the canonical momenta (using the specie flow velocity). The generalized helicities, one for each specie, are invariant in an ideal two-fluid plasma. If one postulates that both helicities are also invariant in a turbulent relaxation, then a pragmatic theory of minimum energy states can be developed, *i.e.* one that is verified *a posteriori* by comparison with laboratory plasmas. Essential features of these equilibria are sheared flows and finite β , both of which are absent in Taylor states. Adopting simplified geometries a range of equilibria are computed. These reproduce striking qualitative features observed in laboratory plasmas: FRC-like states exhibit hollow current profile, and a sharp density gradient at the edge; and tokamak-like states exhibit reversed magnetic shear, hollow current profile, and sheared toroidal flows.

*This work has been performed in collaboration with A. Ishida, Niigata University

FLUCTUATIONS IN MULTICOMPONENT PLASMAS: MAGNETIC EFFECTS ON THE SHORT-WAVE CON- VECTIVE CELLS

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As the philosophy of [1] stands, the convective cells concept can be applied to study of the multicomponent plasma with hot component (the subject of [2] is, in fact, electron-electron plasma with adiabatic hot ions), that has much practical interest. The hot component which may arise, in particular, due to the injection of the energetic particles in the plasma or RF heating, is displayed mainly in the plasma periphery ([1]). The presence of the hot component may result in the transition from strong to weak turbulence.

We apply the general theory of the low-frequency electromagnetic fluctuations in the multicomponent plasma to the study of short-wave potential (density) and magnetic perturbations in a finite-temperature ($\beta_e \cong \beta_i \cong 1$) plasma, and obtain stationary spectra corresponding to zero fluxes of integrals of motion, and electron heat conductivity coefficient. We show that the nonlinear broadening of the convective spectrum is dominated by the magnetic component. In a strongly nonlinear regime, the relevant renormalized width has cubic k -dependence with no $\log$ corrections and exceeds much the value obtained within the electrostatic approximation [2]. The anomalous electron heat conductivity is reduced, whereas its coefficient has no Bohm-like behaviour.

The renormgroup approach to the problem [3] indicates existence of the same cubic corrections.

Also, it is tempting to take into account non-zero correlations between potential and magnetic component (being related to the cross-helicity invariant) that, as emphasized in [4-6], may arise from nonlinear mode interaction and could influence the nonlinear transfer processes and spectra formation.

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Ripple Induced Trapped Particle Loss in Tokamaks

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The threshold for stochastic transport of high energy trapped particles in a tokamak due to toroidal field ripple is examined by explicit construction of resonances, including locations and widths. The expressions are given in magnetic coordinates and make no assumptions regarding shape or up-down symmetry. Approach to stochastic threshold is not simply given by the Chirikov criterion, but governed also by nonlinear separatrix broadening.

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Improved Core-Edge Tokamak Transport Simulations with the *CORSICA 2* Code

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The *CORSICA 2* code models the nonlinear transport between the core and the edge of a tokamak plasma. The code couples a 2D axisymmetric edge/SOL model (*UEDGE*) to a 1D model for the radial core transport in toroidal flux coordinates (the transport module from the *CORSICA 1* code). The core density and temperature profiles are joined to the flux-surface average profiles from the 2D code sufficiently inside the magnetic separatrix, at a flux surface on which the edge profiles are approximately constant.

In the present version of the code, the deuterium density and electron and ion temperatures are coupled. The electron density is determined by imposing quasi-neutrality, both in the core and in the edge. The model allows the core-edge coupling of multiple ion densities while retaining a single temperature (corresponding to the equilibration value) for the all ion species.

Applications of *CORSICA 2* to modeling the DIII-D tokamak are discussed. This work will focus on the simulation of the L-H transition, coupling a single ion species (deuterium) and the two (electron and ion) temperatures. These simulations will employ a new self-consistent model for the L-H transition that is being implemented in the *UEDGE* code.

Applications to the modeling of ITER ignition scenarios are also discussed. This will involve coupling a second density species (the thermal alphas), bringing the total number of coupled variables up to four.

Finally, the progress in evolving the magnetic geometry is discussed. Currently, this geometry is calculated by *CORSICA*'s MHD equilibrium module (TEQ) at the beginning of the run and fixed thereafter. However, *CORSICA 1* can evolve this geometry quasistatically, and this quasistatic treatment is being extended to include the edge/SOL geometry. Recent improvements for code speed-up are also presented.

ON THE DYNAMICS OF A RADIATIVELY COOLING DIVERTOR PLASMA

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We employ a simplified two-dimensional nonlinear one-fluid model to study the dynamics of a radiatively cooling optically thin plasma in a divertor geometry. We assume that the plasma motions proceed along the magnetic field lines while the heat conduction is two-dimensional and anisotropic. We choose a simple model form of the radiative loss function. A scaled form of the governing equations is obtained using the characteristic conductive, $\lambda_{\parallel}$ and $\lambda_{\perp}$, and acoustic, λ_s , field lengths of the system [1,2]. When $\lambda_s \gg \lambda_{\parallel}$, we can neglect the flow inertia and regard the pressure uniform along the field. Then, going over to a mixed Eulerian-Lagrangian description, we reduce the problem to a reaction-diffusion-type equation with nonlocality which is quite convenient for numerical simulations [3]. We report on a series of preliminary simulations when we fixed the (scaled) “core” plasma temperature and geometric factors and varied the heat flux at the divertor plate. We observed that if thermal condensation occurs, the plasma near the divertor plate always approaches one of the two following final states. The first represents plasma detachment, and it requires a large divertor heat flux, while the second looks like a marfe and occurs for small heat fluxes. A marfe cannot persist near the divertor plate if the plasma is detached. Presently we are studying the effects of the “core” plasma temperature and geometric factors on the divertor plasma dynamics.

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The Modeling of Non-Axisymmetric Halo Currents in Tokamaks

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Abstract

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

Trapped Particle Stabilization of the Resistive Wall Mode

1996 International Sherwood Fusion Theory Conference

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The resistive wall mode is a pressure/current-driven external kink destabilized by the finite resistivity of the surrounding shell. Although the wall mode growth rate is small ($\gamma \sim 1/\tau_w$ where τ_w is the resistive wall diffusion time), its stability is an important requirement for the design of steady-state tokamaks operating at high- β ($\beta_N \sim 4 - 5$). According to the ideal MHD model [1], the wall mode growth rate satisfies the following energy relation

$$\gamma\tau_w = -\frac{\delta W_f + \delta W_{v\infty}}{\delta W_f + \delta W_{vb}} \quad (1)$$

where δW_f is the well-known MHD fluid potential energy, and δW_{vb} , $\delta W_{v\infty}$ are the vacuum energies with and without the wall. Equation (1) shows that the wall mode is unstable for $0 < -\delta W_f < \delta W_{vb}$ and $-\delta W_f > \delta W_{v\infty}$. The purpose of this paper is to investigate the stabilizing effect of thermal trapped particles. Since the wall mode frequency is typically smaller than the trapped particle precession drift frequency, the trapped particle compressibility is stabilizing. Using the gyro-kinetic equation, a kinetic energy principle for the wall mode is derived;

$$\gamma\tau_w = -\frac{\delta W_f + \delta W_{kin} + \delta W_{v\infty}}{\delta W_f + \delta W_{kin} + \delta W_{vb}} \quad (2)$$

where δW_{kin} represents the trapped particle contribution. It is shown that, in the absence of an equilibrium radial electric field, δW_{kin} is positive, and therefore stabilizing. In addition, δW_{kin} is maximum at zero frequency [$\delta W_{kin}(\omega = 0) \sim \delta W_{kin}(|\omega| \rightarrow \infty)/\epsilon$, where $\epsilon = a/R_0 < 1$ is the inverse aspect ratio] and its contribution to the wall mode stability is significant. By minimizing the kinetic energy principle, a new stability condition on the plasma beta is derived and compared with the ideal MHD beta limits. The effects of a finite equilibrium radial electric field and plasma rotation on the wall mode stability are also discussed.

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Numerical Studies of Magnetic Turbulence in the 3-field Reduced MHD Model

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Numerical studies of spectral transfer, saturation balances and frequency spectrum characteristics are made in the 3-field RMHD model to determine the roles played by the Alfvén, diamagnetic and fluid straining times in saturation. Specifically, we seek to verify theoretical predictions from closure theory which indicate that the fluid straining and diamagnetic frequencies set the spectrum balances even though they are smaller than the Alfvén frequency.

Frequency spectra for a fixed k are obtained for inertial range modes from steady state turbulent states. From the spectra, one calculates the average mode frequency and the spectrum width and compares it with the mode frequency predicted from theory. Comparison with theory is also obtained by examining spectrum balances at saturation. Energy input rates and saturation levels in the simulation yield a characteristic transfer time, which can then be compared with the theoretical estimate. Finally, transfer diagnostics have been developed to measure the transfer of energy, flux, enstrophy and cross helicity from each nonlinearity in the model. The theoretical calculation of the k spectra assume some terms dominate in the energy balance equations. The importance of the different terms (nonlinearities) can be checked numerically via the transfer diagnostics.

Preliminary results indicate that while the Alfvén frequency dominates the frequency spectrum width, it is the slower time scales - either fluid straining or diamagnetic - which dictate the energy transfer, in agreement with theory. These results will be discussed in connection with measurements of the electron density fluctuations spectrum in the interstellar medium, and the magnetic fluctuation spectrum in the Madison Symmetric Torus.

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Theory-Based Transport Modelling of Tokamak Temperature and Density Profiles*

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We use a combination of theoretically derived transport models in transport simulation codes to predict the temperature and density profiles in tokamaks[1]–[4]. The simulated profiles match experimental data well for more than 50 discharges from at least 7 different tokamaks including L-mode scans in current, heating power, density, normalized gyro-radius (ρ_*), collisionality (ν_*) and β , as well as TFTR supershot current scans and a variety of discharges from the ITER Profile Database. The transport model in these simulations combines the Weiland Ion Temperature Gradient and Trapped Electron Mode model[3] together with the Guzdar-Drake resistive ballooning mode model[2] as well as smaller contributions from kinetic ballooning modes and neoclassical transport. For resistive ballooning modes, we found that the nominal Guzdar-Drake model matches current scan data better than the nominal Carreras-Diamond model (*i.e.*, with coefficient 1.0).[2]

The simulations of the ρ_* scans from DIII-D, TFTR and JET are particularly interesting because we find that our fundamentally gyro-Bohm transport models produce the observed non gyro-Bohm behavior of the experimental data[1]. Since edge neutrals penetrate less far into the higher density (lower ρ_*) plasmas, they change the shape of the density and collisionality profiles near the plasma edge which, in turn, changes the scaling of the transport. This effect cascades into the core of the plasma, where small changes in profile shape have a relatively large effect on the transport. Supershot simulations are also strongly affected by the influx of edge neutrals. Our predictive simulations of experimentally measured data using theoretically derived transport models have lead to some surprising new insights.

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Triggering Internal Disruptions in Tokamaks at High- β ¹

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At high- β , both minor or major tokamak disruptions can arise abruptly without (or at best with a very short) precursor. This fact is difficult to explain based on the picture of crossing some stability limit. Our analysis of TFTR supershots shows that highly peaked pressure profiles in tokamaks may create conditions for coupling between the internal reconnection mode and the ballooning modes.

In standard supershot regimes, the q_0 value at the plasma center sits below 1. Although the ideal MHD theory predicts the $m = 1$ instability in these regimes, the sawtooth oscillations are stabilized by FLR effects. This stabilization is proportional to the pressure gradient at the $q = 1$ surface. When the pressure gradient approaches the ballooning stability limit near the $q = 1$ surface, the excitation of ballooning modes suppresses FLR stabilization of the reconnection $m = 1$ mode. In turn, the growing reconnection mode significantly enhances the local pressure gradient $p' = p'_0(1 + \xi' \cos(\theta - \phi))$ at the $q = 1$ surface where $\xi' \simeq 1$ and, thus, amplifies the ballooning modes. This mechanism reveals the positive feedback between the reconnection mode and ballooning modes and explains the abrupt onset of internal disruptions at high- β . Because of the positive feedback, the disruptions can start either with or without the $m = 1$ or ballooning precursors present as it is observed in experiment.

The criterion for sawtooth stabilization has been validated earlier for all of TFTR regimes. The same two-fluid model, now applied to ballooning modes, shows good correlation with experimental data. In particular, it predicts that the central β_N , calculated within $\sim 1/3$ of the minor radius, rather than the global β_N is responsible for the onset of internal disruptions. This explains the fact that depending on the peakedness of the pressure profile, disruptions may occur at unexpectedly low levels of the total β . Also, without involving interaction with the resonant particles, the model explains the appearance of so-called kinetic ballooning modes, their localization, mode frequency and the range of wave numbers. These predictions are supported by an extensive comparison with the experimental data on TFTR for more than 70 high performance DD and DT shots and can constitute a basis for a real time disruption avoidance scheme.

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Progress on First-Principles Turbulence Simulations for Realistic Tokamak Parameters.¹

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We previously reported the results of the most complete three-dimensional non-linear gyrokinetic- δf -ion, adiabatic-electron simulations of ITG turbulence in TFTR to date.² While the transport rates were consistent with experiment for the inner portion of the profile, it was found that for some TFTR L-mode discharges a significant portion of the ion-temperature profile ($r/a > 0.6$) could not be accounted for by the simulated transport rates. Here, we report three new developments that represent greater realism in the physics than previous kinetic models. (A) The simulation model has been extended to general axisymmetric geometry and interfaced to use reconstructed experimental equilibria from DIII-D. Comparisons will be made between the simulation results and experiment will be presented for DIII-D reversed-magnetic-shear discharges of current interest. (B) We have developed a new bounce-averaged drift-kinetic nonlinear- δf electron model. We will investigate whether this addition results in improved agreement with in the simulated ion-thermal transport rates with TFTR L-mode data. (C) A new massively parallel version of our code enables us to access sufficient computational resources to address for the first time with a first-principles simulation whether toroidal ITG turbulent transport has Bohm or gyroBohm scaling for realistic tokamak parameters. The results of this investigation will be presented.

¹This work was performed for USDoE, by LLNL under contract W-7405-ENG-48, and by LANL under contract W-7405-ENG-36.

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The breaking of up-down symmetry of trapped particle orbits by a toroidal electric field.‡

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A breaking of the up-down symmetry due to the inductive electric field E_ϕ is analyzed in detail for particles describing quasi-banana orbits in the large aspect ratio approximation. Time independent and time dependent electric fields are considered. In the first case it is proved that the classical ∇B drift and the breaking of up-down symmetry due to E_ϕ lead to a net inward radial drift, which agrees with the well known Ware pinch formula. The weak points of previous treatments of the Ware pinch, e.g. taking only leading terms in the Taylor expansion of A_ϕ , are discussed. Yet the results obtained here lead to the same pinch formula, even for banana orbits with large amplitude of poloidal angle and for more general conditions than previously considered. A more general formula for a time dependent E_ϕ has also been found. Our results show from a very general basis that the corresponding polarization drift does not play any role in the inward pinch; however the second time derivative of the inductive electric field E_ϕ could increase or decrease significantly the usual Ware pinch.

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Omnigenous transport barriers*

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An outstanding issue in magnetic confinement is the establishment of effective *local transport barriers* for which collisional (and anomalous) transport can be locally suppressed or at least substantially reduced with respect to the standard transport models. The establishment of such barriers would be useful in connection with quasi-stationary magnetic confinement (*i.e.*, MHD equilibria). In fact, they could effectively reduce loss cones due to trapping of energetic particles in magnetic and/or electrostatic potential wells which may be introduced by both error fields and intrinsic field asymmetries. Even if it might be difficult to be establish such transport barriers, it would still be important to optimize transport by suitable control of the shaping of the equilibrium profiles. Indeed, recent observations^{1,2} of enhanced confinement in tokamak discharges with reversed magnetic shear in the presence of balanced co-and counter tangential neutral beam heating seem to suggest that local transport barriers might actually be produced and maintained over a significant period of the discharge.³ Here we point out that transport barriers can in principle be achieved both in tokamaks and stellarators by establishing *local omnigenous equilibria*^{4,5} which are *quasi-helical*⁶⁻⁹ or, in the case of stellarators, can be represented as suitable superpositions of *quasi-helical harmonics*. However, elementary arguments indicate that this is not the correct physical explanation of the recently observed enhanced reverse shear discharges.^{1,2} We first investigate quasi-helical MHD equilibria.⁶ We find that they can admit one (or more) locally omnigenous magnetic surfaces, located in the plasma core (but not necessarily close to the magnetic axis), subject to the existence of suitable conditions on the local toroidal and poloidal electric currents. We next consider the case of non-symmetric, stellarator-type equilibria to point out that the condition of local omnigenicity implies a mild restriction on the general form of the equilibrium magnetic field. In particular, we find that its magnitude can be locally expressed in terms of a superposition of quasi-helical components. Finally, we point out possible applications of this concept to tokamak and stellarator confinement.

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Omnigenous non-quasihelical systems

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Quasihelical magnetic equilibria, which have the property that the magnetic field is a function of only the flux variable ψ and one linear combination ($\ell\theta - m\phi$) of the Boozer angles, have no superbananas or transitioning particles and, hence, have neoclassical transport with the same scaling as occurs in axisymmetric systems. However, quasihelical equilibria exist only for large aspect ratio. Omnigenous equilibria, for which the bounce averaged drift is in the surface, should have the same neoclassical transport. Our preliminary results indicate that the set of omnigenous equilibria is larger than the set of quasihelical equilibria. Hence, there remains the possibility of finding small-aspect-ratio three dimensional equilibria with these good transport properties.

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Transport Matrix of Orbit Squeezing and Finite Orbit Width Effects on Plasma Transport

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In advanced tokamak operations such as H-mode and ERS-mode, ion orbit subjects to strong squeezing due to the large gradient of the electric field. A complete transport matrix is derived to including the effects of orbit squeezing. It is Onsager symmetric. The term of the order of $(M_e/M_i)^{1/2} S^{3/2}$ is kept. Here, S is the orbit squeezing factor. Thus, bootstrap current, ion heat flux and electron particle flux will all be affected by the orbit squeezing.

When the radial scale length of plasma density and temperature is of the order of the ion orbit size. It is necessary to investigate the effects of finite ion orbit width on the standard plasma transport theory. A partial differential equation is derived to determined the equilibrium distribution function in the collisionless regime including the effects of orbit squeezing. In the small, but finite, orbit width limit, the equilibrium distribution function is modified by its curvature. In the constant temperature (in radius) case, a general solution for the arbitrary orbit width is obtained. It exhibits the radially non-local nature as expected. In the limit where the size of the orbit is larger than the scale length of plasma density and temperature, the general solution of the distribution function can have a radial dependence that is either linear in radius or constant in radius. Transport fluxes are calculated from the equilibrium distribution function.

RESISTIVE TOROIDAL MHD EQUILIBRIA

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In an earlier publication, it was shown that toroidal resistive MHD equilibria, for spatially uniform resistivity and under a standard set of assumed symmetries, do not exist¹. The difficulties are associated with the non-vanishing nature of $\text{curl}(\mathbf{j} \times \mathbf{B})$, and disappear in the "straight cylinder" limit. Here, we inquire into whether there exist spatial dependences for the (scalar) electrical resistivity which permit axisymmetric, toroidal, zero-flow resistive steady states to exist. The question is answered in the affirmative. A differential equation derived from Ohm's law replaces the Grad-Shafranov description, and the pressure is derived from the Laplace equation obtained from taking the divergence of the equation of motion. There are some novel features to the states that result. For example, the resistivity required is not a "flux function" -- i.e., it is not constant on a magnetic surface, thus suggesting that the temperature will not be either.

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Hybrid Simulations of the Interaction of Hot Gyrokinetic Particles with MHD Waves

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A self-consistent study of the interaction of energetic ions with low-frequency MHD waves is performed using hybrid MHD-gyrokinetic particle simulations. In particular, the excitation of magnetospheric hydromagnetic waves by magnetic drift-bounce resonance with energetic ring current ions is investigated. In the model, energetic ions are treated as gyrokinetic particles using fully electromagnetic gyro-center equations[1], while the cold background plasma is treated as a fluid. The particles are coupled to the fluid equations through their density and current, which appear in the bulk plasma momentum equation[2]:

$$\rho_b \frac{d\mathbf{v}_b}{dt} = -\nabla p_b + (\mathbf{j} - \mathbf{j}_h) \times \mathbf{B}/c - en_h \mathbf{E},$$

where ρ_b , $\mathbf{v}_b$ and p_b are bulk plasma density, velocity and pressure, n_h and $\mathbf{j}_h$ are hot ion density and current density.

Other equations for the bulk plasma are that of the MHD equations including $\mathbf{E} = -\mathbf{v}_b \times \mathbf{B}/c$. It is assumed that $n_h \ll n_b$.

Spatial gyroaveraging in the gyro-center equations of motion as well as transformation to physical space are performed by using four or eight point gyroangle distribution, in order to include the finite Larmor radius effects. In test runs, good conservation of the total energy was obtained and the finite Larmor radius effects were well reproduced for $k_\perp \rho_h \sim 1$.

Since magnetic drift-bounce resonant instability is driven by radial pressure gradients and requires resonance between azimuthal ion drift motion and bounce motion along magnetic field line, 3-D simulations are necessary for its investigation. The use of a multiple spatial scale expansion method enables to separate the equilibrium spatial scale lengths from those of the perturbations. In this case the zero-order ion pressure and magnetic field gradients become input parameters for the 2-D simulation (azimuthal and parallel directions). The 2-D numerical model with fixed background inhomogeneity was developed and it is used to study the drift-bounce resonant instability in 2-D box geometry. Numerical results are compared with linear theory.

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Nonlinear Saturation of the Parallel Velocity Shear Instability*

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Plasma flows in the direction parallel to the ambient magnetic field are nearly ubiquitous. They occur naturally in linear plasma columns (e.g., Q-machines) or in toroidal experiments under a variety of conditions. These flows are also observed in the near-Earth environment as the solar wind is deflected by the bow shock and flows past the flanks of the magnetosphere. A shear in the flow (i.e., $\mathbf{B} \times \nabla V_{\parallel} \neq 0$) can lead to instabilities and spontaneous break-up of the flow. In driven systems, saturation by quasilinear processes such as relaxation of the velocity gradient is not realistic, thus one is led to consider other processes such as the coupling to a damped mode.

Linear stability analysis predicts two very distinct limits for the velocity shear problem. With relatively large values of the velocity gradient ($dV_{\parallel}/dx \sim V_{thi}/L_n$) a mode first found by D'Angelo[1] can occur. This mode is characterized by ($\gamma \gg \omega_r$) but is easily stabilized in the presence of significant density gradients. A new dissipative instability can occur for relatively low values of the velocity gradient as first suggested by Coppi[2]. The relevant dissipation can enter through a parallel ion viscosity or ion-neutral collisions. This mode is characterized by ($\omega_r \approx \omega_{*e} \gg \gamma$) and is not stabilized by the presence of density gradients.

In our nonlinear analysis, we consider both the strongly growing D'Angelo mode and Coppi's weakly growing dissipative mode. A plane geometry including both density and velocity gradients is analyzed with two fluid equations. The linear stability of these modes is such that if a mode with wave number $\vec{k}$ is unstable then so are all of its harmonics ($2\vec{k}, 3\vec{k}, \dots$). The inclusion of FLR corrections in the fluid equations introduces a stability boundary in k-space so that we may consider a single linearly unstable eigenmode coupled to a linearly damped harmonic. For Coppi's weakly growing dissipative mode this scheme results in saturation of the instability at weak to moderate levels, while in the strongly growing D'Angelo limit the scheme breaks down and does not saturate. Both analytical and numerical methods have been used.

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Neoclassical Transport Theory in a Tokamak Plasma with Large Spatial Gradients*

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Usual neoclassical theories assumed that the spatical inhomogeneity of the plasma was weak. Specifically, this included the following two strong assumptions: banana width was negligible compared to the radial gradient scale length and variation of any physical quantity along the field line was small. This led to the simplification that the spatial inhomogeneity itself did not affect the fundamental transport processes.

However, there have been many experimental suggestions that the spatial inhomogeneity may not be small. Firstly, both H-mode and ERS mode experiments have indicated that the finite banana width effect may be important to understand the plasma transport processes. Secondly, the RF and auxiliary heating processes may be sufficiently localized in space so that we may need to consider a strongly inhomogeneous heating effect along the field lines.

In the present work we develop a modified neoclassical theory, in parallel with the old theories, which can include the finite banana width effect and the inhomogeneous heating effect. Several new and significant transport terms have been identified, which can play important roles in the understanding of the fundamental transport processes in a tokamak plasma.

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Thermal transport from a phenomenological description of Ion-Temperature-Gradient-Driven Turbulence

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In this work, a phenomenological model of the thermal transport caused by ion-temperature-gradient-driven (ITG) turbulence is introduced. By combining the semi-quantitative knowledge of ITG turbulence provided by the general theory and by the numerical simulations with working hypothesis suggested by the experimental data, new formulas for the turbulence correlation length and for the ion and electron heat conductivities are proposed.

A remarkable property of this model (unlike previous microturbulence-based models) is that the correlation length and the conductivities increase with minor radius, as observed in the experiments. A wide class of models possessing this property is indeed consistent with dimensional analysis of the general ITG equations.

Transport simulations with the JETTO code [1] based on the new model are then carried out, after calibration of two multiplicative constants on a particular JET shot. The results are compared with L-mode experimental profiles of a number of machines drawn from the ITER data base and with the prediction of more conventional Bohm and gyro-Bohm models.

The overall performance of the model in the outer half radius is good. Qualitatively, it predicts overall gyro-Bohm scaling for the energy confinement time, but, as a consequence of the radial behavior of the transport coefficients, the profiles turn out similar to those predicted by Bohm models.

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First Principles Analysis of Advanced Confinement Regimes

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Here, profiles of improved confinement regimes are examined to verify that they can be understood from first principles calculations. A comprehensive gyrokinetic stability code which fully includes Shafranov shifts, gradients of Z effective and both trapped electron mode and ITG modes is used. Experimental profiles from TFTR, DIII-D and JET are examined in regimes including supershots, reversed shear modes, and ERS and NCS modes. Supershots are found to be close to marginal stability in the temperature gradient (and often the density gradient) once trapped electron modes, velocity shear stabilization and Z effective gradients are taken into account. (Quantitative disagreements with previous simple parameterized formulas are shown to be due to the neglect of effects in the parameterization, not puzzling physics.) NCS modes on DIII-D can similarly be understood, due to a weakening of the ITG mode from Ti/Te and Z_{eff} effects, combined with large rotation shear. Enhanced Reverse Shear regimes on TFTR can also be understood, building on the analysis of Beer and Hammett (APS, 1995). The validity of recent first principles transport calculations is thus extended and strengthened. Reversed shear shots on JET will also be examined. In addition, quantitative analysis of the H-mode pedestal will be considered, using gyrokinetic calculations in the full near-separatrix geometry and including estimates of velocity shear effects. In view of the agreement between first principles calculations and experiment, factors needed for advanced confinement operation can be identified to assess reactor extrapolations of the regimes. It is found that several crucial criteria for improved confinement are much more difficult to satisfy in large reactors than in existing experiments. We would like to acknowledge support from DoE contract #DE-FG03-96ER-54346.

Energy Conserving Truncations for Convection with Shear Flow*

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A method is presented for making finite Fourier mode truncations of the Rayleigh–Bénard convection system that preserve invariants of the full partial differential equations in the dissipationless limit.¹ This system is analogous to the flute-reduced MHD equations for large aspect-ratio axisymmetric toroidal systems. These truncations are shown to have no unbounded solutions and provide a description of the thermal flux that has the correct limiting behaviour in a steady-state. A particular low-order truncation (containing 7 modes) is selected and compared with the 6 mode truncation of Howard and Krishnamurti, which does not conserve the total energy in the dissipationless limit. A numerical example is presented to compare the two truncations and study the effect of shear flow on thermal transport.

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Robust and Accurate Numerical Methods Applied to the Edge Plasma Equations*

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We present results from advanced numerical methods development in support of dissipative divertor research. Results are presented from simulations using a combined edge plasma / Navier-Stokes neutral transport model. The tokamak edge plasma fluid equations are known to contain a wide disparity in time scales and space scales. They also contain extreme nonlinearities in transport coefficients and reaction rates. Obtaining steady-state solutions is often the motivation of the simulation rather than following a time accurate transient. The multiple time scales and the strong nonlinearities have motivated research into the use of Newton-Krylov algorithms, which form the basis of the UEDGE code. Improvements are presented which increase the radius of convergence of Newton's method, enhance the parallel nature of the algorithm, and increase the accuracy of the discretization. The performance of a pseudo-transient technique, which adaptively transitions to a steady-state solution is studied. In a Newton-Krylov algorithm, formation and application of the preconditioning matrix is usually the bottleneck to parallelization. We present results employing domain decomposition preconditioning (additive Schwarz) to the edge plasma equations and discuss the parallel performance of this Newton-Krylov-Schwarz algorithm. Traditionally, edge plasma fluid codes have used first-order accurate methods for discretizing the convective derivatives. We study the effects of using a higher-order, monotone, discretization on both solution accuracy and algorithm performance. Additionally, we present the latest advancements in our combined edge plasma / Navier-Stokes neutral transport model.

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Reduction of Transport in Stellarators by Self-Shielding

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The enhancement of neoclassical over Pfirsch-Schlüter transport at low collisionality is the effect of the parallel viscosity. The parallel viscosity allows the external coils to produce forces within the magnetic surfaces. These forces are balanced along the magnetic field by a poloidal and toroidal variation of the plasma pressure orthogonal to the field, $p_{\perp}$. The oscillatory part of $p_{\perp}$ gives a radial force that is balanced by shielding currents. If the Fourier components of the perpendicular pressure and the field strength are p_{MN} and $\epsilon_{MN}B_0$, then a Fourier component of the field is shielded when the parameter $\Delta = (\mu_0/B_0^2)(p_{MN}/\epsilon_{MN})$ becomes larger than unity. Each Fourier component in the perpendicular pressure also produces an in-surface force, which is balanced by a radial current. This non-ambipolar transport is characterized by a diffusion coefficient $D_{MN} = (M/2) D_B (p_{MN}/p) \epsilon_{MN}$ with M the poloidal mode number and the Bohm-like diffusion coefficient $D_B = (T/eB)/\{-d\ln(n)/d\ln(r)\}$. In the absence of external forces, such as neutral beams, quasineutrality implies the overall viscosity induced transport must be ambipolar, and $\sum p_{MN}\epsilon_{MN} = 0$. That is, the parallel flow and radial electric field will adjust themselves to insure ambipolarity and $\sum p_{MN}\epsilon_{MN} = 0$. Nevertheless, the individual Fourier terms, the $p_{MN}\epsilon_{MN}$, need not vanish, and a non-zero p_{MN} generates shielding currents. The heat transport of a species is approximately given by the p_{MN} of that species. Even if a p_{MN} vanishes, the individual contributions of the electrons and ions to the p_{MN} need not vanish. An estimate of the importance of shielding can be made by noting that $n\tau T \approx (\beta n B a^2)/(4 M \Delta \epsilon_{MN}^2) \approx 2 \times 10^{24} \text{m}^{-3} \text{eVs}$ in a power plant with $\beta=5\%$, $n=2 \times 10^{20} \text{m}^{-3}$, $B=6\text{T}$, and $a=2\text{m}$. This implies ripples ϵ_{MN} smaller than a few tenths of a percent cannot cause prohibitive transport since they would be shielded. The p_{MN} terms can be easily calculated using a δf Monte Carlo code to obtain an accurate estimate of the shielding in a given stellarator configuration. This work was supported by the U.S. Department of Energy grant DE-FG02-95ER54333.

THE THEORY OF THE QUASI-OPTICAL GRILL: A LOWER HYBRID WAVE LAUNCHER IN THE 4 - 10 GHz RANGE FOR HIGH FIELD TOKAMAKS

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Abstract

Lower hybrid (LH) waves have been utilized for plasma heating and current drive in tokamaks. LH current drive has good efficiency in low to moderate plasma temperatures and is an excellent tool for attaining the reversed shear regions of much interest in advanced steady state tokamak scenarios.

For high field tokamaks, the waveguides of the standard multijunction grills would become very narrow and the walls separating the waveguides would need to be very thin. As a result, the cooling of such structures becomes very difficult. Moreover, there are concerns that the classical grill launcher could not withstand the conditions at the reactor first wall.

The Quasi-Optical Grill (QOG) was first proposed by Petelin & Suvorov¹ to overcome some of these difficulties. QOG attempts to couple the RF power to the plasma slow wave by means of the diffraction of the incident wave on an array of rods. However, these original calculations^{1,2} are based on certain idealized assumptions and lead to poor coupling to the plasma.

Preinhaelter³ has suggested a new QOG in which the rods are placed in one oversized waveguide ("hyperguide") and irradiated obliquely by the wave emerging as a higher order mode from an auxiliary oversized waveguide. The confining walls are now an intrinsic part of the structure and thus one avoids the need for mirrors and the introduction of 'point-like' structures. This new QOG is compact - with several orders of magnitude less construction elements than the classical LH launcher - and the problem of wave diffraction can be readily solved using the full wave method.

Here we consider the optimization of a large scale QOG at a given frequency. The irradiation of either a single row or double set of rows of rods are considered as well as their optimal separation. One can achieve transmissivity and directivity comparable to those of the multijunction grill. Design of a QOG for TORE-SUPRA will also be discussed.

This work was supported by the Czech Academy of Sciences, DoE and a U.S-Czech Science and Technology Joint Fund.

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Definition of Collisional-Radiative Rate Coefficients in Plasma*

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The *Collisional-Radiative* (CR) model for atomic rate coefficients was introduced in Ref. [1] in connection with hydrogen and hydrogenic ions, and has been employed since by many authors to define effective rate coefficients for ionization and recombination in cases where collisional processes on excited states are important. In such cases a fine-level description of the plasma would use as unknowns the densities in each possible excited state of any charge state of any plasma constituent, and would explicitly consider all possible transitions between such excited states; all this coupled to spatial transport and boundary conditions. In practice the transport description of plasma has to be done on a coarser level in which the unknowns represent just densities in each charge state, while the population in excited states is assumed to be in some sense in an equilibrium defined by the charge state densities.

The traditional CR model uses as the unknowns in the reduced description the densities in the ground state associated with any charge state. It is assumed that the transition matrix in the fine description has a particular block structure, in which excited states of charge state i , say, are coupled only to other excited states of that same charge state, to the ground state of charge state i , and to the ground state of charge state $i + 1$. In this case, under the assumption that transport processes and source processes are slow compared to the transitions among excited states, the excited state population at charge state i is expressed in terms of the population densities of the ground states of levels i and $i + 1$, and this assumption allows to define effective ionization and recombination coefficients for transitions between ground states, thus eliminating the excited states from the description.

Here we propose a different definition of effective CR rate coefficients, which applies also when excited states of one charge state couple directly to excited states of a neighbouring charge state, and which uses as the unknowns the total densities per charge state rather than the ground-state densities – making particle conservation a trivial property of the transport laws even when a large fraction of the population is in excited states. Viewing the coarse description (excited states lumped together for each charge state) as a mathematical projection of the fine description, our CR rate coefficients are defined by three properties: (1) particle conservation; (2) correct equilibrium, i.e. the equilibrium solution of the coarse description must be the projection of the equilibrium solution of the fine description; (3) correct slow dynamics, i.e. the eigenvector belonging to the smallest nonzero eigenvalue of the transition matrix in the coarse description must be the projection of the corresponding eigenvector in the fine description. Some computational issues will be discussed in the poster.

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A Gyro-Landau-Fluid Transport Model

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A comprehensive but practical dispersion theoretic transport code model has been developed which can be tuned to reproduce the linear growth rates of a 3D ballooning mode gyrokinetic stability (GKS) code and the transport coefficients of 3D nonlinear gyro-Landau-fluid (GLF) simulations. An eight-fold set of 2D GLF equations of motion is solved for all linear growth rates and quasilinear energy, particle, and momentum flows. The toroidal ion temperature gradient (ITG) mode, the collisionless to dissipative trapped electron drift modes, and the ideal MHD ballooning modes, as well as the edge resistive modes, are included. The dependence on magnetic shear and toroidicity is retained by evaluations with a fixed trial wave function in the extended ballooning angle. The leading ballooning modes at $k_y \propto 1/(q\rho_s)$ are used to evaluate a mixing length rule given by $\tilde{v}_{E \times B} \cdot k_\perp \approx (\gamma\gamma^-)^{1/2}$ where γ is the growth rate of the leading ballooning mode and γ^- is the damping rate of a radial mode ($k_y = 0$, $k_z \neq 0$). The ion heat diffusion $\chi \approx \gamma^- k_\perp^2 \cdot \gamma^2 / (\gamma^2 + \omega^2)$ shows the dependence on radial modes and saturation with temperature gradient seen in recent simulations. Rotational shear stabilization is included by setting $\gamma = \gamma_0 - \gamma_E - \gamma_*$ where γ_E is the Doppler rotational ($E \times B$) shear rate and γ_* is a general diamagnetic rotational shear rate. Unlike the shearless ballooning mode growth rate γ_0 which is independent of ρ^* , γ_* and (diamagnetically induced) γ_E increase with ρ^* breaking the otherwise gyroBohm scaling of the transport coefficients. Transport coefficients decrease going to small ρ^* or decrease to the point of stability at large ρ^* where $\gamma_0 = \gamma_E + \gamma_*$: $\chi \propto \chi_{\text{Bohm}} \cdot \rho^* \cdot (1 - \alpha\rho^*)$. The model has been tested against the ITER transport database, and DIII-D ρ^* scaling and negative central shear (NCS) shots. Although negative central shear and large Shafranov shift parameter in the NCS discharges allows high β MHD stability, they may only be a trigger for improved core confinement which results from $E \times B$ rotational shear stabilization.

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Symbolic analysis of spatio-temporal systems: the measurement problem

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We consider the problem of measuring physical quantities using time-series observations. The approach taken is to validate theoretical models which are derived heuristically or from first principles. The fitting of parameters (*e.g.* a transport coefficient) in such models constitutes the measurement. This is a basic problem in measurement science and a wide array of tools are available. However, an important gap in the present toolkit exists when the system of interest, and hence the models used, exhibit chaotic or turbulent behavior. The development of reliable schemes for analyzing such signals is necessary before one can claim to have a quantitative understanding of the underlying physics.

In experimental situations, the number of independently measured time-series is limited (in our numerical studies, we have restricted ourselves to simulated data taken from a *single* ‘probe’), but the number of dynamical degrees of freedom can be *large*. In addition, the signals of interest will typically be embedded in a noisy background.

In the *symbol statistics* approach, the time-series is coarse-grained and converted into a long symbol stream. The probability of occurrence of various symbol sequences of fixed length constitutes the symbol statistics. These statistics contain a wealth of information about the underlying dynamics and, as we shall discuss, can be used to validate models.

Previously, we have applied this symbolic approach to low dimensional systems with great success [1]. The symbol statistics are robust up to noise/signal $\approx 20\%$. At higher noise levels the symbol statistics are biased, but in a relatively simple manner. By including the noise characteristics into the model, we were able to use the symbol statistics to measure parameters even when signal/noise is $\approx O(1)$.

More recently, we have extended the symbolic approach to spatio-temporal systems. We have considered both coupled-map lattices (which are discrete in both space and time) and the complex Ginzburg-Landau equation (which is continuous). This equation arises generically near the onset of instabilities. Our numerical investigations have demonstrated that the symbol statistics can measure system parameters for “turbulent” spatio-temporal systems using single-site time-series.

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Quasi-Spherical Multipinch Configuration

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If a large number of pinch discharges, produced by laser-, particle-beam channeling, or along gas jets, with alternating directions of the currents flowing in adjacent discharge channels, intersect in one point, a quasispherical plasma configuration is obtained with a $1/r^2$ pressure profile [1]. Therefore, if the plasma pressure at the periphery of a 25 cm plasma sphere is ~ 100 atm, corresponding to a confining magnetic field of $\sim 5 \times 10^4$ G, the pressure would rise to about $\sim 10^6$ atm at the center of the sphere where all the discharge channels meet. Because of this high pressure the particle number density at thermonuclear temperatures can there become as high as $\sim 10^{19} \text{ cm}^{-3}$. The release of thermonuclear energy by this configuration then only depends on its stability and the radial heat conduction losses. Because of its spherical arrangement such a multipinch-configuration should have a much better degree of stability, with the heat conduction losses greatly reduced by the presence of a strong transverse magnetic field. Estimates show that the amount of thermonuclear energy released into charged fusion products exceeds the heat conduction losses, a necessary condition for thermonuclear burn. Because of the high plasma density the device would have to operate with short-pulsed cycles, each cycle lasting for example $\sim 10^{-4}$ sec, whereby plasma stability would have to be ascertained only for this rather short time.

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Low Current Approach to Ignition *

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The “standard” path to achieve ignition conditions so far has been that of producing plasmas with the maximum current and poloidal field that are compatible with the applied toroidal field and the geometry of the adopted configuration (the low q_a approach.) The other approach is that motivated by recent experiments with reversed shear configurations, with relatively low currents and high fields corresponding to high values of q_a (e.g., $q_a \simeq 6$). While the first approach can be pursued with ohmic heating alone, the second one necessarily involves an auxiliary heating system. One of the advantages of this approach is that the onset of large scale internal modes can be avoided as $q(\psi)$ is kept above 1 over the entire plasma column. Since quite peaked density profiles are produced in the regimes where enhanced confinement is observed, the α -particle power levels for which ignition can be reached and therefore the thermal wall loading on the first wall, can be reduced [1] relatively to the standard, low q_a , approach. The possibility is considered that ignition is reached in the reversed shear, high q_a , regime and that this is followed by a transition to non-reversed profiles, or even the low q_a regime, assuming that the excitation of modes involving magnetic reconnection will not undermine the needed degree of confinement. These results have been demonstrated by numerical transport simulation for the Ignitor-Ult machine [1], but are applicable to all high field ignition experiments.

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Neoclassical and Anomalous Transport in Toroidal Plasmas with Drift-Ordered Turbulence*

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Neoclassical and anomalous transport fluxes are determined for axisymmetric toroidal plasmas with weak electromagnetic drift wave fluctuations. The neoclassical and anomalous fluxes are defined based on the ensemble-averaged kinetic equation with the statistically averaged nonlinear wave-particle interactions. The anomalous forces derived from that quasilinear term induce the anomalous particle and heat fluxes. For the microscale fluctuations $k_{\perp} \rho_i \sim 1$ the parallel neoclassical fluxes remain invariant. For mesoscale fluctuations the mixing length fluctuation level with broken symmetry from (weak) shear flows the neoclassical banana-plateau fluxes are affected by the fluctuations through the parallel anomalous forces and the modified parallel viscosities. The entropy production rate due to the anomalous transport processes is formulated and used to identify conjugate pairs of the anomalous fluxes and forces, which are connected by the matrix with the Onsager symmetry. The proof of the Onsager symmetry is carried out by splitting the response function up into the even and odd parts under the $(t, \mathbf{B}) \rightarrow (-t, -\mathbf{B})$ transformation and using the self-adjointness of the linearized Landau collision operator and the quasilinear formalism. An explicit calculation of the symmetric transport coefficients is possible when the Krook collision model replaces the Landau collision operator. The importance of low aspect ratio tokamaks and helical systems for experimental investigations of the Onsager symmetries is emphasized.

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Tests of the Improved Weiland Ion Temperature Gradient Transport Model*

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The Weiland theoretically derived transport model for ion temperature gradient and trapped electron modes has been improved to include the effects of parallel ion motion, finite beta, and collisionality[1]. The model also includes the effects of impurities, fast ions, unequal ion and electron temperatures, and finite Larmor radius. This new model has been implemented in our time-dependent transport code and is used in conjunction with pressure-driven modes and neoclassical theory to predict the radial particle and thermal transport in tokamak plasmas. Simulations of TFTR, DIII-D, and JET L-mode plasmas have been conducted to test how the new effects change the predicted density and temperature profiles. Comparisons are made with results obtained using the previous version of the model which was successful in reproducing experimental data from a wide variety of tokamak plasmas. Specifically, the older model has been benchmarked against over 50 discharges from at least 7 different tokamaks including L-mode scans in current, heating power, density,[2] and dimensionless scans in normalized gyro-radius,[3] collisionality, and beta. We have also investigated the non-diffusive elements included in the Weiland model, particularly the particle pinch in order to characterize its behavior. This is partly motivated by recent simulations of ITER. In those simulations, the older Weiland model predicted a particle pinch and ignition was more easily obtained.

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Non-Linear Interaction of Alfvén Waves With Fast Particles*

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Concern surrounds instabilities driven by fast particles in large tokamaks and their possible consequences for particle transport. This has motivated the development of HAGIS which is a numerical code capable of calculating the power transfer from a hot-particle source to a spectrum of Alfvén waves, and the ensuing non-linear wave evolution, up to and following saturation.

Fast particle motion is treated using a guiding centre Hamiltonian description, whilst the wave evolution uses a Lagrangian formulation for shear Alfvén waves. The system utilizes straight field line coordinates with the Jacobian chosen to simplify the equations of motion. The magnetic field is modelled as the superposition of an axisymmetric toroidal field and a set of time dependent electromagnetic perturbations, with the perturbed fields accorded two degrees of freedom corresponding to their amplitudes and phase shifts. The model accounts for non-linear wave-particle interactions, which is dominant for weakly-driven systems, but ignores MHD wave-wave nonlinearities. Hence the linear mode structure can be taken directly from linear calculations with the CASTOR normal mode code.

Numerical noise in the system is reduced by only considering those ‘particles’ present in the system which constitute the change in the fast particle distribution function, this being the so-called δf technique. As the physical system evolves the fast particle distribution ‘flattens’ through a transfer of free energy to the unstable wave spectrum. The growth in wave amplitude eventually leads to a modification of particle orbits and ultimately to the wave itself saturating.

With the HAGIS code the linear wave growth rates and self-consistent saturation amplitudes can be determined for arbitrary geometry and for realistic trapped and passing particle distributions.

Results from HAGIS will identify regions of enhanced diffusion in the presence of fixed [1] and varying amplitude TAEs, and indicate possible loss mechanisms.

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MAGNETIC FIELD RECONNECTION IN COLLISIONLESS PLASMAS

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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 laboratory plasmas produced by tokamaks such as JET. At the high plasma temperatures of these experiments, internal plasma relaxations can occur on a time scale shorter than the electron-ion collision time. Recently, the linear theory of the $m = 1$ kink-tearing modes has been extended to experimentally relevant regimes, leading to the conclusion that these modes can remain virulent at low collisionality with an initial growth rate that compares favorably with that observed in the experiments¹⁻⁴. The nonlinear evolution of this process can be analysed on the basis of a two-dimensional incompressible fluid model. A numerical and analytical solution of this model that neglects ion Larmor radius and electron pressure effects has been presented⁵. The reconnection process is accompanied by the formation of a current density sublayer narrower than the skin depth and that keeps shrinking with time. This numerical solution was obtained with a pseudospectral code that can no longer resolve the sublayer after the early nonlinear phase is entered. With the aim of resolving this sublayer we adopted a different approach based on a finite-difference method.

- Under the same initial and boundary conditions, we can reproduce the results obtained with the pseudospectral code. In particular we find the same quasi-explosive behavior of the reconnection process in the early non linear phase.
- The code is implemented with a non-uniform grid and this increases our ability to follow the evolution of the microscale inside the current-sheet.
- Now, we can extend this model and generalize its equations so as to include the effect of the thermal ion Larmor radius⁶ which is of the order of, or larger than, the electron skin depth in the regimes of interest.

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The radiative condensation instability in non-coronal equilibrium*

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Linear and nonlinear investigations of the radiative condensation instability in non-coronal equilibrium are presented. Typically, it is assumed that radiating impurities return to their equilibrium charge state on a very fast time scale compared to the radiation rate, however, for a tokamak edge plasma, the opposite is true. To account for this, we allow the radiation to depend upon both the charge state as well as the temperature, and evolve the charge state self-consistently. A linear analysis of this system shows that there is a dramatic reduction in the growth rate of the mode when the charge state is allowed to evolve. Fully nonlinear fluid simulations are presented which substantiate the predictions of the linear theory. A preliminary nonlinear theory is also presented which shows that a linear stable system can be driven unstable by a large enough perturbation, and driven to large amplitude by the nonlinear terms.

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Forced Reconnection In A Rotating Plasma*

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The dynamics of forced reconnection in a sheared slab geometry confined between two perfectly conducting walls is studied. This model, which was first proposed by Taylor, has been studied previously for the case of a static plasma subject to a stationary boundary deformation.^{1,2} In the present study, we extend these calculations by introducing an equilibrium plasma flow. Implications for the problem of field error penetration in rotating toroidal plasmas will be discussed.

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Resistive MHD Studies of Reversed Shear Current Profiles*

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Abstract

Experiments at TFTR, DIII-D and elsewhere, in which current density distributions possessing an off-axis maximum are generated and sustained on a resistive diffusion timescale, continue to be of interest. Here, attention is concentrated on the possible role of resistive instabilities in such plasmas. Using experimental profile information from TFTR as initial data the parameters of interest are varied systematically to study the excitation of resistive instabilities over a range of β from zero to the limits determined by ideal MHD. Computationally, there is a wealth of resistive modes predicted to occur. Thus, it is found that when the minimum value of the safety factor, $q_{\min}$, exceeds 2 the configuration is either stable or, in some circumstances, the resistive interchange mode can be excited. When $q_{\min} \leq 2$ localized tearing or double tearing modes are excited at low pressures becoming more global in character as the pressure nears the ideal MHD limit.

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Theory of Probe Measurements at the Divertor Plate*

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Probe measurements represent a technically simple and inexpensive approach to the characterization of plasma parameters in the divertor region. On the other hand, the interpretation of the probe signals is sometimes not straightforward, with discrepancies between the results of probe measurements and Thomson scattering measurements often arising.

The difficulty of interpretation of probe measurements stems predominantly from the unknown influence of a strong magnetic field on the probe current-voltage characteristics (CVC). There have been many studies of this issue, among the most recent ones papers [1], [2].

In our paper, we present analysis of the physics issues which determine the performance of so called "flush mounted probes" (see, e.g., [3]). We note that, in case of an infinitely strong magnetic field, the flux-tube whose footprint coincides with the probe surface, is completely isolated from the rest of the plasma, and the probe CVC becomes more similar to the CVC of a double probe. As a next step in the analysis, we consider classical cross-field transport processes and conclude that, for the flux tubes with dimensions of a few ion gyroradii (as is the case for the probes of the type used in DIII-D, Ref.[3]) the cross-field currents are dominated by the ion viscosity. We derive the probe CVC for this case and find that it has a remarkable similarity with the aforementioned characteristics of the double probe.

We consider possible effects of plasma turbulence on the cross field transport through a thin flux tube leaning on the probe. We conclude that the character of this effect strongly depends on the spatial and temporal scale of the plasma fluctuations: the influence of fast (frequency higher than a fraction of the gyrofrequency) short-wavelength (shorter than a couple of the ion gyroradii) fluctuations *can* be described in terms of enhanced diffusion across the flux tube, while the influence of the slow ones *can not*. As the SOL turbulence is usually slow (in the aforementioned sense), we consider in more detail the effect of slow fluctuations. We find that they produce a "surface erosion" of the fluxtube which intersects the probe, without causing any enhanced transport inside the tube. We present a quantitative picture of this process and relate erosion rate to experimentally measured anomalous diffusion across the SOL. Based on our analysis, we find a simple fitting equation for the probe CVC which is formally similar to the CVC of a double probe.

To provide an independent check of the assumptions made in the proposed version of the CVC, we suggest using of a new variant of the flush-mounted probe - that of the probe surrounded by the grounded flush-mounted ring, isolated from the probe and the rest of the divertor plate. The current to this ring is a direct measure of the cross-field transport and the analysis of the current variation vs. the probe potential can be used to eliminate an ambiguity of the probe measurements.

All in all, the presented comprehensive analysis should considerably improve the reliability of the probe measurements in the divertor region.

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Relativistic gyrokinetic equation in the presence of strong drifts*

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Toroidal differential rotation (shear flow) produced by $E \times B$ drift in tokamak plasmas [1],[2],[4],[5] is currently regarded important for its role in plasma equilibrium, stability and transport [2],[3],[4],[5],[6],[7],[8]. Experimental observations of enhanced confinement and transport regimes in Tokamaks, especially during H-modes and reverse magnetic shear configurations [9],[10] demonstrate, however, evidence of the existence of strong drifts, corresponding not only to the $E \times B$ drift, but also produced by steep radial profiles of density $[N_s]$, temperature $[T_s]$ and mass flow $[V = \omega R e_\varphi]$, with e_φ the toroidal unit vector, R the distance for the symmetry axis of the torus and ω being the toroidal angular rotation velocity]. Thus, a fundamental problem appears the formulation of the gyrokinetic equation in the presence of strong drifts, based on a consistent formulation of guiding-center mechanics. A further potentially important feature which seems desirable to address in this connection is the treatment of weakly relativistic corrections to the electron dynamics in such a general case, extending recent work on the weakly relativistic kinetic theory [11]. Such aspects are well known in the limit of weak drift, for which both the non-relativistic and relativistic gyrokinetic equations in the presence of electromagnetic perturbations have been extensively investigated by several authors (see, respectively, for example Antonsen and Lane [12] and Littlejohn [13]). This includes also the treatment of the special case of strong $E \times B$ drift considered by Artun and Tang [8]. This paper is motivated, in part, by recent work in which a [non-relativistic] Lagrangian approach to guiding-center mechanics in the presence of strong drifts has been proposed [14], which has proven useful for constructing accurate guiding-center variables and invariants. The purpose of this investigation involves, preliminarily, the formulation of relativistic guiding-center mechanics in the presence of strong drifts in terms of a perturbative theory, extending the nonrelativistic Lagrangian approach to guiding-center mechanics recently developed by Tessarotto *et al.* [14],[15]. For this purpose, use is made of the hybrid form of Hamilton variational principle [16] to formulate a new direct construction method of the guiding-center variables in the presence of electromagnetic perturbations. The approach represents a convenient alternative to iterative schemes or to Lie transform approaches [17]. Thus, this permits to construct in a convenient way, in terms of a perturbative approach, the relativistic gyrokinetic equation describing the plasma response to linear ballooning perturbations in the presence of strong [equilibrium] drifts. For this purpose the ballooning representation recently obtained by Tessarotto *et al.* [18] is here adopted. Consequences and applications of the present theory to linear stability analyses will be discussed.

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2-D WKBJ-Ballooning Numerical Analysis of High- n TAE modes

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Recently, a two-scale numerical framework (HINT) based upon the WKBJ-Ballooning formalism has been developed [1] owing to the urgent ITER research need for a detailed 2-D analysis of high- n TAE modes. The WKBJ-Ballooning formalism reduces the 2-D toroidal eigen-equation into a 1-D ballooning equation on the fast scale and a WKBJ description of the radial envelope function. The advantage of this formalism is the capability of non-perturbatively retaining the effects of general geometry, self-consistent equilibrium, and non-ideal physics, by solving the non-ideal 1-D ballooning equation, local and global eigen-frequencies in the complex plane. Hence, non-ideal physics such as full FLR-effects, collisional effects, deeply trapped energetic particle drive, finite beta effects has been included non-perturbatively in Ref. [1,2]. It has been found that (i) Non-perturbative inclusion of non-ideal effects strongly change the TAE spectrum, (ii) Resonant TAE modes (RTAE) has been found with strong resonant interaction of energetic particles with TAE modes, (iii) full FLR effects induces upper KTAE modes, but no lower KATE exists, (iv) the global eigen solution is very sensitive to the detailed calculations in local ballooning space. With ITER parameters and circular geometry, $n = 10$ RTAE modes[2], has been found unstable near $r/a/simeq 0.4$. In the present work, importance non-ideal effects such as background Landau damping, more realistic and complete contribution of energetic particle drive including energetic particle FLR effects, passing particle contribution, finite drift orbit width (FDW) effects, realistic tokamak geometry, will be further included in the well established HINT framework. TAE stabilities will then be recalculated for ITER parameters.

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Onset of the radial electric field oscillations in the neoclassical plasmas*

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It is shown that the relaxation of the radial electric field in the tokamak plasmas towards its neoclassical value is accompanied by the fast oscillations of the order of the ion transient frequency V_T/qR . This happens during the transition from the Pfirsch-Schluter collisional regime to the plateau regime at $\nu_c qR/V_T \leq \hat{\nu}_{cr} \leq 1$. The investigation has been performed with the help of the specially developed numerical code for solution of the nonsteady-state drift kinetic equation with the exact collisional term in the Hirshman-Sigmar-Clarke form¹. Comparison with the analytical results, corresponding to the regime of the very low collisions² as well as with previous approximate models³⁻⁵ for the plateau regime will also be reported.

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Double-cross Instability in Nonuniform Plasma*

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One fascinating characteristic associated with the presence of an energetic minority-ion population in a background magnetized plasma is that, if the population is inverted, it can support *negative-energy* waves (e.g., negative-energy energetic-minority-ion Bernstein waves supported by an inverted alpha-population in tokamak plasmas [1]). In our continuing study of negative-energy waves in nonuniform magnetized plasmas [2], we investigate a new type of linear *absolute* instability associated with the resonant interaction between a negative-energy wave and a positive-energy wave in a nonuniform plasma.

According to the standard scenario for a linear *convective* instability associated with the resonant interaction between a negative-energy wave and a positive-energy wave in a one-dimensional background plasma, a negative-energy ray crosses *transversely* the dispersion surface of a positive-energy wave and resonantly transfers some of its action to create a positive-energy ray. Because of background plasma nonuniformity, however, the two waves interact resonantly only during a finite time interval and, consequently, this linear instability is convective.

In this work, we investigate a new scenario for a linear absolute instability in which the negative-energy ray crosses the dispersion surface of the positive-energy wave twice. The new ray topology allows repeated resonant interactions between the two waves if they experience constructive interference at each crossing. This *double-cross* absolute instability is shown to have a threshold which depends on the area enclosed between the two dispersion curves and the strength of the wave coupling. Numerical and analytical descriptions of this new absolute instability will be presented as well as a discussion of its possible significance in magnetic fusion research.

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Global Stability and Operational Regimes of Ignitor, ITER, and Alcator C-Mod*

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One of the primary requirements for an experiment capable of approaching ignition conditions is the macroscopic stability of the plasma column. For two proposed ignition experiments (Ignitor and ITER) we analyze numerically (using both the PEST and DCON codes, involving the ideal MHD linearized approximation) the stability of their confinement configuration for different plasma pressure and current profiles. Since in both cases the aspect ratio is tight (2.8 and 2.9, respectively), when the unwinding parameter $q(\psi) < 1$ for $r \lesssim a/2$, $n = 1$ modes, for which the $m = 1$ and $m = 2$ poloidal harmonics prevail, involve a major part of the plasma column ($q(\psi) = 2$ for $r_s \approx 3a/4$).

For profiles that are nearly flat up to the $q(r_s) = 1$ surface and are represented by $p = p_0(1 - \psi^2)^{3/2}$, where ψ is the (normalized) poloidal flux variable, pressure driven modes, dominated by the $m = 2$ harmonic, may be found, depending on the value of $\beta_p = 2 \mu_0 \langle p \rangle / B_p^2$. These modes are unstable for the reference parameters of operation of ITER ($B_T \approx 5.7$ T, $n_0 \approx 1.5 \times 10^{20} \text{ m}^{-3}$, $T_0 \approx 20$ keV), but are stable in the case of Ignitor ($B_T \approx 13$ T, $n_0^{\text{equiv}} \approx 0.8 \times 10^{21} \text{ m}^{-3}$, $T_0 \approx 12$ keV).

For relatively peaked profiles represented [1] by $p = p_0(1 - \psi^2)^{3/2}$, the numerical analysis produces a stability threshold corresponding to extremely low values of β_p , but the validity of the linearized approximation ($|d\hat{p}/dr| < |dp/dr|$, $\hat{p}$ = perturbed plasma pressure) breaks down for very small values of $|d\hat{p}/dr|$ well before threshold. We consider the predicted instability meaningful when, for instance, $|\hat{p}|_{\text{BD}} \geq 5 \times 10^2 |p|$, $|\hat{p}|_{\text{BD}}$ = value of $|\hat{p}|$ for breakdown. The value of β_p for the ITER reference discharge leads to values of $|\hat{p}|_{\text{BD}}$ exceeding this threshold while those for Ignitor are well below it.

We have also considered operating conditions corresponding to the reversed shear configuration, with reduced plasma currents ($q_s \approx 6$). In this case, stability against ballooning modes become a concern in view of the low values of $\bar{B}_p$ that can be produced (e.g. $\bar{B}_p \approx 0.5$ T in the case of ITER).

In order to assess the possibility of the onset of large scale sawtooth oscillations of the plasma column, the excitation of collisional $n = 1$ modes involving magnetic reconnection is also considered. Thus we have analyzed 12 discharges obtained by Alcator C-Mod [2] with and without RF heating, all exhibiting sawtooth oscillations while ideal MHD stability is verified. Resistive $n = 1$, $m = 1$ modes are found to remain unstable according to the theory given in [3] (i.e. the relevant plasma parameters fall in the regions III-IV of the $\lambda_H - \omega$ parameter space).

The Alcator C-Mod Group is gratefully acknowledged for providing the experimental data.

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SECOND STABLE REGIME OF MIXED SLAB-TOROIDAL ITG MODE WITH ANISOTROPIC η_i *

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The mixed slab-toroidal ITG instability with anisotropic η_i is investigated with both analytical and numerical approaches. Local analysis clearly indicates a second stable regime at high $\eta_{i\perp}$. Non-local effects of magnetic shear and magnetic drifts in a toroidal system are considered via a perturbation technique. It is seen that the second stability regime is expanded due to these non-local effects.

In addition to the perturbation method described above, a comprehensive numerical code, for high- n linear eigenmodes using the ballooning representation, is used to investigate the possible second stability regime for a set of parameters in TFTR.¹ Although the code is designed to include some complex effects that cannot be accurately handled with the simple theoretical model discussed above, its result reveals the same important physics result that there is restabilization of the mode at high $\eta_{i\perp}$, indicative of a second stable regime. From a strictly theoretical point of view, this result provides a possible stabilization scheme for the ITG instability.

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Stabilization of the Resistive Wall Mode using a Fake Rotating Shell

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The goal of an advanced tokamak design is to *simultaneously* maximize the fusion reactivity (*i.e.*, the plasma β), the plasma energy confinement, and the non-inductive bootstrap current [1]. The eventual aim is, of course, to achieve a steady-state fusion reactor in which all of the toroidal current is maintained in the plasma by non-inductive means. The β limits in advanced tokamak designs are invariably set by low mode-number external-kink modes. The full potential of such designs is only realized when the stabilizing effect of a close-fitting conducting shell is incorporated into the MHD stability calculations [2]. This is only reasonable provided that the so-called “resistive wall mode” is stabilized. Stabilization of this mode has been achieved in present-day tokamaks by spinning the plasma rapidly [3]. Unfortunately, such a scheme is not reactor relevant. A more promising approach is to apply external feedback in order to make a resistive shell placed around the plasma act like a perfect conductor. A scheme is outlined by which a network of feedback controlled conductors surrounding the plasma can be made to act like a *rotating* shell, as far as its interaction with the plasma is concerned. This “fake” rotating shell, when combined with a stationary conventional shell (*e.g.*, the vacuum vessel), can *completely* stabilize the resistive wall mode. The gain, bandwidth, current, and power requirements of the feedback amplifiers are extremely modest. A previously proposed stabilization scheme [4] (the intelligent shell) is also investigated, and is compared with the fake rotating shell concept. The main disadvantage of the former scheme is that it requires extremely high gain amplification.

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Effects of Molecular Hydrogen and Plasma Recombination on Plasma Flow in Divertor

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We investigate the effects of hydrogen molecules and plasma recombination on plasma-neutral gas interactions in the recycling region of a tokamak divertor. We treat plasma-neutral interaction in a fluid approximation retaining the effects of plasma recombination and employing a neutral viscosity term to describe neutral interaction with the divertor plate. We consider both conventional three body recombination and recombination induced by the molecules through the formation of negative ions, H^- , and molecular ions, such as H_2^+ , in combination with the ensuing neutralization, $H^- + H^+ \rightarrow 2H$ and $H_2^+ + e \rightarrow 2H$.

We show that even in current tokamaks, the plasma recombination processes could be the dominant mechanism responsible for the decrease of plasma flux onto the target in detached regimes. Implementation of the recombination induced by the molecular effects significantly expand to much higher temperatures the range in which plasma recombination must be retained.

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Nonlinear Theory for Fishbone Modes*

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We present a nonlinear theory for fishbone activity, on the basis of a recently developed weak turbulence model of beam driven plasma waves with a discrete spectrum^[1] near the instability threshold. Fishbone oscillations are triggered by an internal kink mode driven unstable by the resonant interaction with trapped fast ions^[2,3]. We focus on the regime where the mode frequency is close to the thermal ion diamagnetic frequency^[3]. In this regime, a (stable) internal kink mode exists in the absence of the fast ions, which can therefore be treated perturbatively. A Lagrangian formalism for the nonlinear wave-particle interaction is used^[4]. The oscillatory behavior of the resonant ions trapped in a finite amplitude toroidal wave is discussed on the basis of a nonlinear pendulum model. Numerical estimates of saturation levels and resonant fishbone losses for present Tokamak experiments are obtained.

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A Transport Bifurcation Model For L to Reverse Shear Mode Transition

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ABSTRACT

Recently Theoretical and experimental observations have shown that tokamak equilibria with bootstrap driven negative magnetic shear have significantly enhanced particle confinement. The particle diffusivity in these equilibria which are characterised by peaked pressure profiles is reported to have been reduced by nearly 50 times in the region of the negative shear while the thermal diffusivity improves by 2 to 3 times. Such confinement regimes may prove crucial for ultimate economic viability and steady state performance of Tokamak reactors. In this paper we present a transport bifurcation model for L to Reverse Shear mode (R/S) or super H-mode transition. Model equations for fluctuation level and density gradient which is proportional to the bootstrap current are obtained. Two equilibria, one with high fluctuation level and low bootstrap current (L-mode) and another with zero fluctuation level and large bootstrap current (R/S mode) are obtained. For positive shear, L-mode equilibrium is stable and R/S mode is unstable while for negative shear R/S mode is shown to be stable.

Effects of Beam-Driven Poloidal Rotation on the Neoclassical Bootstrap Current

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Unbalanced neutral beam injection drives toroidal and poloidal rotations in a tokamak plasma. The beam toroidal momentum input drives the toroidal rotation, and the parallel friction between the thermal ions and fast ions induces the poloidal rotation. A theory of the beam-driven poloidal rotation and its effects on energy transport was given recently by Hinton and Kim [1]. In this work, we extend their considerations to the effects on the neoclassical bootstrap current. For parameters of interest in present neutral beam heated tokamaks, the magnitude of the beam-driven poloidal rotation can be significantly larger than that of the standard neoclassical value due to the ion temperature gradient. The presence of this driven poloidal rotation will manifest itself in modification of the neoclassical bootstrap current. In the case of coinjection, the driven poloidal rotation is in the opposite direction to the rotation driven by the temperature gradient, therefore it enhances the bootstrap current. In comparison with the standard theoretical predictions of the neutral beam-driven current, that enhancement in the bootstrap current varies with the beam and plasma parameters. A calculation of the parallel transport coefficients associated with the driven poloidal flow in finite-aspect ratio tokamaks will be presented. Experimental conditions for observing the enhancement in bootstrap current will be discussed.

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E_r Shear Suppression of Turbulence in Enhanced Reversed Shear Mode Plasmas ¹

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Abstract

Confinement enhancement of the reversed magnetic shear plasmas in TFTR and DIII-D is discussed in the context of the hypothesis of $\mathbf{E} \times \mathbf{B}$ flow shear suppression of turbulence. Recent nonlinear theory on flow shear induced fluctuation suppression in an arbitrary shape finite aspect ratio tokamak plasmas² indicates that the relevant $\mathbf{E} \times \mathbf{B}$ shearing rate in toroidal geometry is proportional to the radial shear of $E_r^{(0)}/RB_\theta$. This result has compared well with magnetic braking experiments on VH-mode in DIII-D.³ Recent data from both TFTR⁴ and DIII-D⁵ also indicate the essential role of the shear in $E_r^{(0)}/RB_\theta$ in the fluctuation suppression and the formation of transport barrier. According to a recent phase-transition theory for confinement enhancement in reversed shear configuration,⁶ the bifurcation occurs when fluctuation is suppressed due to E_r shear. Transition to ERS-mode in TFTR is predicted to be easier for higher T_i/T_e and lower electron density. Extension to general geometry including Shafranov shift indicates a favorable role of high β_p through high q_{min} and central deposition.

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Nonlinear Saturation of High Mode Number Toroidal Alfvén Eigenmodes¹

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Abstract

Many theoretical works and simulations² have confirmed that the single wave trapping is the dominant nonlinear saturation mechanism of low mode number TAE's. On the other hand, for high mode number TAE's which are of major concern in ITER, nonlinear mode coupling effect associated with the bulk ion Compton scattering can be important.³ In this work, other possibilities of high mode number TAE saturation are discussed in the context of the energetic particle-wave resonance detuning rate and the hot particle radial profile evolution. The predicted fluctuation amplitude at nonlinear saturation scales like the weak turbulence theory result³ and is higher near the lowest order rational surface where the Chirikov criterion for the hot particle radial excursion is easily satisfied.

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Computation of Resistive Instabilities with DCON and MATCH*

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DCON [1] was originally developed to determine the ideal MHD stability of an axisymmetric toroidal plasma by the generalized Direct Criterion of Newcomb. Its key numerical procedure is the numerical solution of a $2M$ th-order system of ordinary differential equations, where M is the number of poloidal Fourier harmonics retained. These are the Euler-Lagrange equations for making the perturbed potential energy δW stationary, or equivalently the zero-frequency ideal equations of motion. They are also the equations governing the ideal outer region of resistive instabilities, treated by the method of matched asymptotic expansions. DCON has been extended to compute the outer region matching data and write it to a file. The matching data are based on the vectors $\mathbf{c}_A$ of asymptotic coefficients of the large resonant, nonresonant, and small resonant solutions, computed by evaluating a fundamental matrix of power series solutions $\mathbf{U}_A$ and solving $\mathbf{U}_A \mathbf{c}_A = \mathbf{u}$, for each independent, numerically integrated solution vectors $\mathbf{u}$. A new code called MATCH has been written to read this information; combine it with corresponding data describing the dynamics inside the resonant layers; and set up, study, and solve a dispersion relation obtained by matching across all of the resonant layers. Most of the computational effort goes into determining the ideal region matching data for a given equilibrium. By extracting this information into a file and writing a separate code for setting up and studying the dispersion relation, great flexibility is allowed for exploring different models of the resonant layers, including different linear and nonlinear physics and varying detailed parameters. Preliminary results will be presented for the layer model of Glasser, Greene, and Johnson. [2]

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Bifurcation analysis and nonlinear self-sustainment of drift turbulence*

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Several conceptual and technical issues in the theory of nonlinear self-sustainment of turbulent transport [1] are discussed. As discussed in Ref. 1, the possibility that linearly stable macroscopic profiles can nevertheless sustain turbulence and carry a significant turbulent flux is linked to the existence of subcritical bifurcations of the nonlinear dynamics. This issue is explored in the context of simple models. An introduction to bifurcation theory is presented. Then, as an example, the details of the bifurcation analysis of Drake's recent reduced model of nonlinear instability [2] are described. Attention is paid to the role of dissipation in the model. A variety of "unfoldings" of the bifurcation in terms of dissipation parameters are classified, and their relationship to the behavior near the point of bifurcation is explained. The relevance of the results to the behavior and interpretation of computer simulations and experimental data is discussed.

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Scaling of Magnetic Turbulence with Lundquist Number in Relaxed State Devices

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The scaling of magnetic turbulence with Lundquist number, $\tilde{B}(S)$, as generated by the dynamo in reversed field pinches and spheromaks, is addressed. A theoretical framework is described, showing how the fluctuations arise from the dynamo and what dynamics determine the $\tilde{B}(S)$ scaling. There are two limits of the dynamo. For a discrete (sawtooth) dynamo, the time average of the magnetic fluctuations is given by $\tilde{B} \propto S^0$, but it is argued that the averaged flux surface destroying magnetic field fluctuations scale as $\tilde{B}_{br} \propto S^{-1/2}$. For a continuous dynamo, with a steady state saturated turbulent spectrum, the magnetic field perturbations scale as $\tilde{B} \propto S^{-1/4}$. Previous theories of S scaling¹⁻⁶ are reviewed.

This work was performed at LLNL under Department of Energy contract No. W7405-ENG-48.

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Modeling SOL Evolution during Disruptions*

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We present the status of our models and transport simulations of the 2-D evolution of the scrape-off layer(SOL) during tokamak disruptions. This evolution is important for several reasons: It determines how the power from the core plasma is distributed on material surfaces, how impurities from those surfaces or from gas injection migrate back to the core region, and what are the properties of the SOL for carrying halo currents. We simulate this plasma in a time-dependent fashion using the SOL transport code UEDGE. This code models the SOL plasma using fluid equations of plasma density, parallel momentum (along the magnetic field), electron energy, ion energy, and neutral gas density. A multispecies model is used to follow the density of different charge-states of impurities. The parallel transport is classical but with kinetic modifications; these are presently treated by flux limits, but we have initiated more sophisticated models giving the correct long-mean-free path limit. The cross-field transport is anomalous, and one of the results of this work is to determine reasonable values to characterize disruptions. Our primary focus is on the initial thermal quench phase when most of the core energy is lost, but the total current is maintained. The impact of edge currents on the MHD equilibrium will be discussed.

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Combined JET and DIII-D Temperature and Density Profile Parameterization and ITER Prediction

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We analyze a profile database of a 142 steady state Elmy H-mode electron profiles from DIII-D and JET. Using smoothing splines and model selection criteria, we fit the normalized profiles to the models:

$$\frac{n_e(\rho)}{\bar{n}} = \mu_n(\rho) q_{95}^{f_q(\rho)} (\bar{n})^{f_n(\rho)} \quad \text{and} \quad \frac{T_e(\rho)}{\bar{T}_e} = \mu_T(\rho) q_{95}^{g_q(\rho)} P_L^{g_p(\rho)} R^{g_R(\rho)},$$

where ρ is the normalized toroidal flux radius. In DIII-D, the electron temperature goes rapidly to zero in the range $.85 \leq \rho \leq 1.0$, while the measured JET temperature does not decrease significantly near the edge. As a result, we have difficulty fitting the edge temperature. We examine temperature fits which exclude the edge region data. To model the empirical observation that larger tokamaks have broader profiles, we also examine models with a size dependent ρ scaling:

$$\frac{T_e(\rho)}{\bar{T}_e} = \mu_T(\rho') q_{95}^{g_q(\rho')} P_L^{g_p(\rho')},$$

where $\rho' = \rho(\frac{R}{R_{D3D}})^\gamma$ with $\gamma \approx -0.3$. Using the R dependent flux, ρ' , significantly improves the overall fit. With the stretched variable, $\rho = 1$ at JET corresponds to $\rho \approx .85$ and DIII-D. Our rescaling of flux models this observation. Note no size dependence is necessary to model the density shape. The mean fit error is 7-8%. We regress the line average electron temperature and density versus the control variables:

$$\bar{T}_e = 1.02 I_p^{.37 \pm .03} B_t^{.39 \pm .06} P^{.36 \pm .03} \bar{n}_e^{-.31 \pm .03}, \quad \text{and} \quad \bar{n}_e = 9.12 I_p^{.71 \pm .13} B_t^{-.66 \pm .15} P_L^{.20 \pm .06} R^{-1.07 \pm .18}.$$

Our $\bar{T}_e$ and $\bar{n}_e$ regressions predict a larger temperature (17.1 KeV) and smaller density (7.2×10^{19}) for ITER than the design values. (Our ITER temperature is based on $P = 150$ MW, $I_p = 21$ MA, $B_t = 5.8$ T and $\bar{n} = 13 \times 10^{19}$.)

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A Thermal Transport Coefficient for Ohmic and ICRF Plasmas in Alcator C-Mod*

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The energy confinement in plasmas produced by Alcator C-Mod machine is markedly different from that observed by previous high field compact machines such as Alcator A and C, FT, and more recently FTU[1]. For ohmic plasmas at low and moderate densities, the confinement times routinely exceed those expected from the so-called “neo-Alcator” scaling by a factor as high as three[2]. For both ohmic and ICRF heated plasmas, the energy confinement time increases with the current and is approximately independent of the density[2]. The similarity in the confinement between the ohmic and ICRF regimes opens the possibility that the thermal transport in Alcator C-Mod may be described by one transport coefficient for both regimes. We introduce a modified form of a transport coefficient previously used to describe ohmic plasmas in Alcator C-Mod[3]. The coefficient is inspired by the properties of the so-called “ubiquitous” mode that can be excited in the presence of a significant fraction of trapped electrons and also includes the constraint of profile consistency. A detailed series of transport simulations are used to show that the proposed coefficient can reproduce the observed temperature profiles, loop voltage and energy confinement time for both ohmic and ICRF discharges. A total of nearly two dozen ohmic and ICRF Alcator C-Mod discharges have been fit over the range of parameter space available using this transport coefficient.

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Modeling and Simulation of Plasma Materials Processing Devices

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Plasma processing has emerged as a central technology in the manufacture of integrated circuits (ICs) and related industries. These plasmas are weakly to partially ionized gases, typically operated at a few to several hundred *mTorr* gas pressure, with neutral temperatures ranging from room temperature to 500°K . Electron mean energies are typically a few *eV* and ion energies in the bulk plasma are about $0.05\text{--}0.5\text{ eV}$. Positive ions are accelerated in the sheaths to impact surfaces with energies ranging from about 10 eV to hundreds of *eV*. These energetic ions profoundly affect rates of surface chemical reactions.

One of the consequences of the recent rapid growth in the IC industry has been a greater focus on manufacturing productivity. The capital costs of equipment that is used in manufacturing IC's has become a large fraction of the $\sim \$1$ billion cost of building a wafer fab. There is now a strong economic incentive to develop workstation-based simulations of plasma chemical reactors in order to design, optimize and control plasma reactors.

I will summarize efforts to develop such models, including electromagnetic coupling, and transport and kinetics of charged and neutral species. Length and time scale disparities in the plasma tool challenge current simulation approaches, and I will address strategies to attack aspects of this problem. In addition, I will present some of our recent efforts to exploit molecular dynamics simulations employing empirical potentials to get hints about qualitative mechanisms and ideas on how to formulate rate expressions for plasma-surface chemical processes. Video illustrations of selected sets of ion trajectories impacting near-surface regions of the substrate will be presented.

Feasibility of Ignition Experiments: Major Issues for Debate

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The demonstration of ignition has been repeatedly recognized as the most important objective of fusion research, stressing the principle that "the initial model (experiment) need not resemble the one that is later commercialized" [1]. For ignition, there are difficult conditions to be met that include the macroscopic stability of the plasma column, the rate of thermal energy transport, the degree of plasma purity, the thermal loading on the first wall, the ability to survive major disruption events, etc. At typical DT ignition parameters, the electron collision frequency exceeds the ω_* -frequencies related to the pressure gradients so that the modes producing magnetic reconnection are not of the (relatively benign) collisionless type. For reasons of confinement, the plasma current must be the maximum compatible with the applied toroidal field, corresponding to low values of the safety factor, (e.g., $q_a \simeq 3$), for monotonic shear profiles, or be relatively low (e.g., $q_a \simeq 6$) for a reversed shear configuration. In the case of low q_a , the ideal MHD stability against $m^0 = 1$ and coupled $m^0 = 2$ modes requires that β -poloidal be sufficiently low, such as $\beta_p \lesssim 0.3$. Since the central plasma pressure is prescribed within a rather well defined range at ignition, relatively high poloidal fields, B_p , are required. In the case of high q_a , the toroidal field B_T should be sufficiently high, since there is a limitation on plasma size and on the minimum value of B_p that is acceptable for stability against ballooning modes. In all cases, the fields required are well above those permitted by present superconducting magnet technology.

Thus the objective of ignition sustained over several (> 10) energy replacement times should be pursued by high field normal conducting magnets, and at first by compact experiments igniting at peak densities $n_{eo} \simeq 10^{21} \text{m}^{-3}$ and relatively low temperatures ($T_o \simeq 12 \text{ keV}$). Considering the collisional current equilibration time $\tau_I \propto a^2 T^{3/2}$ as another reference for the duration of the ignited state (a is the plasma minor radius), it is clear that relatively small dimensions and low ignition temperatures are compatible with relatively short current pulses. The same argument applies for the density limit, which is commonly related to the average plasma current density and is higher at high fields and compact dimensions.

In the range of high field machines that have been studied, from Ignitor ($R_0 \simeq 1.32 \text{m}$) to Candor ($R_0 \simeq 2.5 \text{m}$), the two sets of parameters chosen for construction are based on issues of cost versus benefits. Ignitor is suitable for D-T ignition while Candor is, in principle, capable of reaching D- ^3He burn conditions. The superconducting ITER device, as presently conceived, and assuming that a field of 13 T can be achieved at the coils, does not satisfy macroscopic MHD stability conditions for internal modes, even with flattened pressure profiles when its reference plasma parameters are considered. The smaller "PCAST-machine" that employs normal-conducting magnets (at a cost $\sim 6 \text{G}\$$) has a similar stability problem when its reference plasma parameters are analyzed.

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

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Predictions of Reactor Performance Using Anomalous Transport Models

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There is a critical need for scientifically credible predictions of the confinement performance of proposed reactor-scale devices. Experimental tests and detailed simulations of tokamak turbulence and stability boundaries indicate that most candidate theoretical explanations for anomalous core transport in present-day experiments are grossly at variance with experimental data from standard reactor-relevant discharges (equilibrated L- or H-modes) and/or with comprehensive solutions of the toroidal gyrokinetic equation. Here, we examine the current diffusive ballooning mode, resistive ballooning modes, the RLW critical electron temperature gradient model, empirical expressions of varying degrees of complexity, and various descriptions of trapped electron modes, ion temperature gradient modes, and trapped ion modes. Straightforward theoretical treatments indicate that most of these instabilities are neither unstable nor close to marginal stability for standard reactor-relevant experimental parameters; in fact, the ITG mode is the only unstable mode away from the edge. Moreover, the profiles are found to be close to marginally stable to the ITG mode in the core of L-modes and from the core to the top of the pedestal in H-modes. Widely reported JET results that show an extremely fast response of the central temperature when the edge temperature is perturbed rule out most candidate theories, yet are quite consistent with models which predict strong transport from the ITG instability, as long as the critical gradient is calculated in sufficient detail. In conjunction with the success of our simulations of steady state profiles in a wide variety of operating regimes and tokamaks, this is strong evidence that ITG modes are responsible for transport and therefore that projections of confinement for L- or H-mode operation of reactor-scale devices based on the ITG mode are scientifically credible. We would like to acknowledge support from DoE contract #DE-FG03-96ER-54346.

Destabilization of Contained Interacting Modes by Fusion Products*

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The instability related to the interaction between high-frequency “contained modes” and the fusion products population in a toroidal configuration is studied.^{1,2} Emphasis is placed on the dependence of the growth rate on finite Larmor radius effects of the fusion products,^{3,4} the characteristics of the particle distribution function,⁵ and factors, such as the magnetic drift velocity and bounce-averaging,^{4,6} related to the inhomogeneity of the magnetic field in a toroidal configuration. In particular, a sufficient degree of anisotropy in the energetic particle distribution is required in order to have a positive growth rate for realistic parameters.

Only a small region of phase space is involved in the resonant interactions associated with the considered modes. We consider first the limit where the growth rate is larger than the bounce frequency (local approximation), that is the simplest case by which it is possible to identify the regions of phase space that are involved in the instability. Another evaluation of the growth rate γ is given in the case, that we consider realistic, where γ is comparable to the average bounce frequency of the interacting particles. We solve for γ by integrating the linearized Vlasov equation over the unperturbed particle orbits, and by reducing the integrals through saddle-point approximations.

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Two-Dimensional Modeling of Plasma Diagnostic Reflectometry*

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Microwave reflectometry has become an important diagnostic in the measurement of both plasma density profiles¹ and density fluctuation spatial correlations.² Ultra-short-pulse reflectometry³ is a recent innovation that has important technical advantages: a compact broadband source and the ability to track the temporal evolution of density profiles and fluctuations. We have extended our earlier numerical modeling of reflectometry⁴ to two-dimensional full-wave computations of both ordinary and extraordinary mode pulsed reflectometry in a cold plasma. We have demonstrated the robustness of ultra-short-pulse, O-mode density-profile reconstructions in the presence of either radial or poloidal stationary density perturbations of significant amplitude. We are also modeling the use of X-mode reflectometry for density-fluctuation correlation measurements in two dimensions. Our reflectometry computations have proved to be very flexible and easy to use, and have become an important tool for concept evaluation in support of the UC Davis Plasma Diagnostics Group's reflectometry experiments.

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Slow Temporal Evolution of Long Mean Free Path Laminar Tokamaks*

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The condition that a tokamak in the long mean free path regime evolves slowly in time, but remains in a laminar flow-like state is examined. The plasma is described by separate, coupled, Fokker-Planck equations for ions and for electrons, with Ampère's law, the Faraday law, and charge neutrality. For simplicity only an Ohmic drive is assumed. First, one examines the particle orbits in the case of slowly varying electric and magnetic fields. The fields must satisfy severe constraints to insure that the orbits allow distribution functions which are smooth and not chaotic in phase space. Two distinct classes of fields appear. The first is of limited interest in that all quantities just grow by a similarity transformation in time. The second class of fields does not satisfy the constraints exactly, but only to some moderate order in an aspect ratio expansion. The result implies that time-varying moderate aspect ratio tokamaks must be turbulent.

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Growth Rate for Core-Localized Toroidal Alfvén Eigenmodes

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Unstable core-localized modes^{1,2} may occur in the central region of an ignited plasma since the alpha particles are most plentiful here. Evidence of core-localized modes has apparently been found in a D-D plasma in TFTR, with fast ions produced by ion-cyclotron heating.³

In the reversed-shear mode of operation, these modes could become prevalent. NOVA-K simulations by G. Y. Fu, reported at the 1995 DPP/APS Meeting,⁴ find such instability, but only when the shear is rather weakly reversed, in order for the radiative and continuum damping to be minimized.

Recent work⁵ has, in fact, demonstrated the existence of an enlarged spectrum of ideal toroidal Alfvén eigenmodes within a toroidicity-induced Alfvén gap when the inverse aspect ratio is comparable to or larger than the value of the magnetic shear, which limit is appropriate for the low-shear region in most tokamaks, especially those with low aspect ratio ("spherical tokamaks"). This feature might facilitate the consideration of low-shear modes for the purpose of investigating Alfvén-type instability properties in present-day deuterium/tritium experiments and future such devices (e.g., ITER). Non-ignition experiments that can use external antennae to excite and study Alfvén eigenmodes may be able to observe this multiplicity of core-localized modes. Two-dimensional codes for TAE stability analysis of fusion plasmas should also confirm this result. Due to their broadened width, the new modes may be destabilized by alpha particles more easily than the standard toroidal Alfvén eigenmodes.

Here we calculate the growth rate for these modes. The stability threshold can then be examined by a comparison of the growth rate with estimates for various appropriate damping rates.

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Physics of advanced, high magnetic field experiments*

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In identifying the optimal performance of an advanced experiment such as Ignitor [1], presently known constraints on the plasma parameters that can be achieved are taken into account. These constraints are mutually linked. In particular, Ignitor can operate well within the known limitations for the particle density and the plasma pressure (beta limit). Detailed simulations of the plasma current ramp up and of plasma heating to ignition have been carried out. These are consistent with the engineering constraints of the machine design. A special updated version of the free boundary, $1 + 1/2D$ JETTO transport code has been employed.

The plasma shape and position are controlled to achieve consistency with the reference magnetic confinement configurations, introducing also the first wall contour as a bound. The avoidance of the disruption boundaries in the (l_i, q_ψ) diagram is assured while taking the technical constraints on the poloidal coils (e.g. mechanical and thermal stresses) into account. Transport diffusion coefficients which lead to energy confinement times close to those predicted by "L-mode" scalings have been chosen.

Special attention is being given to the influence of the parameters of the outermost region of the plasma column on the evolution of the current density.

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

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Neoclassical Transport in ERS Regime *

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The core ion thermal conductivity has been observed to fall below the standard neoclassical level in recent TFTR reversed magnetic shear discharges [1]. Due to the combination of high central q and small local inverse aspect ratio, the ion poloidal gyroradius can be larger than the minor radius and comparable to the pressure gradient scale length in this ERS regime. It is then expected that finite orbit width effects play a key role in modifying the standard picture of neoclassical transport. Specifically, both the trapped particle fraction and the banana orbit width are reduced by the finite minor radius and possibly by the pressure-gradient-driven radial electric field. In addition, the steep pressure gradient can generate neoclassical poloidal flows which, in turn, could reduce the particle and heat transports. Results from analytic estimates as well as those from full toroidal gyrokinetic neoclassical simulations [2] will be presented.

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MERCIER CRITERION MODIFIED BY KINETIC EFFECTS

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The ideal MHD Mercier criterion for the stability of localized interchange modes is easily violated by modest pressure gradients in the central region of a Tokamak plasma where the magnetic winding index q drops below unity. However, kinetic effects can substantially modify this criterion, allowing for stable peaked pressure profiles. In this paper, we discuss the modifications to the Mercier criterion brought about by the fusion alpha particles and by the thermal trapped ions in the collisionless Kruskal-Oberman limit.

DETERMINATION OF EDDY TRANSPORT COEFFICIENTS IN THERMO-LATTICE BOLTZMANN MODELING OF TWO-DIMENSIONAL TURBULENCE

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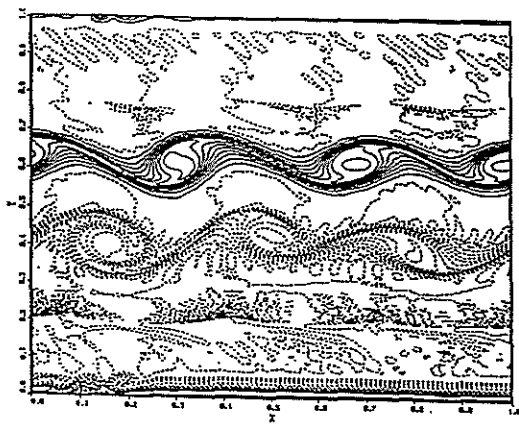
Min Soe, William & Mary

Abstract

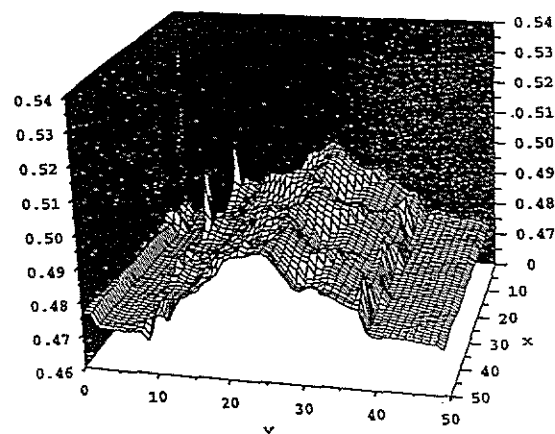
Thermal Lattice Boltzmann (TLBE) techniques are used to consider the time evolution of free-decaying two dimensional (2D) turbulence induced by a double velocity shear layer. In particular, we consider the effect of this turbulence at a Reynolds number of 2555 on a strong temperature gradient. Since all structures are resolved on the 1024 x 1024 grid, the Smagorinsky model is employed to compute directly the eddy viscosity and eddy diffusivity. These transport coefficients play an integral part in large eddy simulations at very high Reynolds numbers where a direct simulation, like TLBE cannot resolve all the excited scales.

TLBE codes have the virtue of being readily extended to 3D, can readily handle non-periodic geometries, and are ideally suited for multi-parallel computer architectures.

vorticity contours



temperature profile



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Stability of High Bootstrap Fraction Low Aspect Ratio Tokamaks

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Low aspect ratio equilibria require maximum use of bootstrap current drive due to the combination of large total current and no Ohmic coils. The ballooning mode stability limits the amount of bootstrap current and the achievable β with well-aligned bootstrap current profile. We have adopted a unique approach to computing fully bootstrap aligned equilibria which are marginally stable to ballooning modes. With an initial equilibrium, we determine the $s - \alpha$ ballooning mode stability boundaries on each flux surface using a Greene-Chance analysis. Since p' and the current are related through the bootstrap condition, s and α are linearly related as well. The $s - \alpha$ boundary and this linear relation allow us to predict a marginally stable p' on each flux surface of the equilibrium. This process is iterated until the desired marginally stable profile is achieved. The resulting equilibria are also tested for stability for low- n kink modes. We consider both $p' = 0$ and $\neq 0$ at the edge, and the achievable β values are calculated.

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Fast Wave Current Drive in Low Aspect Ratio Tokamaks

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Low aspect ratio tokamaks (LAT) have appeal as reactors because of favorable MHD stability and confinement scalings. However, because the magnetic field is non-monotonic as a function of major radius, the accessibility of rf waves in the plasma becomes more stringent, making the problem of rf heating and current drive (CD) very challenging. Recently [1,2], two frequency ranges were identified as plausible in terms of accessibility. One is fast magnetosonic waves (FW) below the ion cyclotron frequencies, and the other is fast waves in the high ion cyclotron harmonics range. While there have been considerable works in the past on FWCD, they implicitly assume large aspect ratios and applicability of these works to LAT is questionable. Here, FWCD is calculated in a ray tracing code CURRAY using the adjoint technique and numerical equilibria, without the assumption of large aspect ratio. The ADJ [3] code is interfaced with CURRAY to provide the Spitzer function for calculating the CD efficiency. FWCD efficiencies are calculated and compared for the above mentioned two frequency ranges. The effects of electron trapping and the presence of energetic alpha particles shall be evaluated. Projections to LAT reactors shall be discussed.

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Application of multi-species, collisional radiative model to the recombining divertor plasma*

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Recombination of hydrogen plasma in the divertor volume can be considered as a simple explanation of divertor plasma detachment phenomena experimentally observed on many tokamaks. As will be shown in this report, the presence of co-vibrationally excited molecules significantly enhances the conventional three-body recombination of plasma and expands the plasma temperature and density range responsible for plasma recombination to much higher temperatures and/or lower densities.

Elementary atomic and molecular processes relevant for a divertor plasma will be reviewed. The following reaction chains are found to be predominant in the multi-species plasma recombination:

- A) multi-step recombination of a ion and an electron;
- B) dissociative attachment of an electron to a molecule with a consequent reaction of mutual neutralization of the negative ion and a proton;
- C) atomic to molecular ion conversion with a consequent dissociative recombination of the molecular ion.

The chains B and C are incomplete as only the excited atoms are produced and collisional-radiative (CR) analysis of $H(n > 1)$ relaxation to the ground state atom must be employed.

The set of coupled collisional-radiative models (CRAMD code) was used to study the kinetics of destruction and production of following particles: H_2 , H_2^+ , H , H^- ; taking into account the excitation and CR transitions within the electronic quantum structure of particles. As the molecular reaction rates depend strongly on the vibrational quantum number, v , of the ground state of H_2 and H_2^+ , appropriate CR models include the calculation of the cascade of vibrational excitation via $e-v$, $v-T$, and $E-v$ processes.

We will present the effective rate coefficients for plasma recombination due to the processes involving H^- and H_2^+ ions, calculated as a function of plasma density and temperature. A comparison of these coefficients with the three-body ion-electron recombination rate coefficient will be given. The influence of enhanced plasma recombination upon the plasma state in the divertor will be discussed.

We will also describe the way of incorporation in the CR model of plasma electric micro-fields effects on an atomic particle. The impact on the reaction rates of including motional and fluctuating ionic micro-fields will be discussed.

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SELF-GENERATED MAGNETIC CHAINS IN PLASMA FLOW

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A set of nonlinear equations for the magnetic field and temperature are derived, describing the electron magnetic modes in an unmagnetized plasma with flow:

$$\begin{aligned} \frac{\partial}{\partial t} \left(\frac{1}{\mu_0 e n_0} \nabla^2 - \frac{e}{m} \right) B - \frac{n'_0}{m n_0} \frac{\partial T_1}{\partial y} - v_0 \frac{e}{m} \frac{\partial B}{\partial y} + \frac{1}{(\mu_0 e n_0)^2} \{B, \nabla^2 B\} \\ - \frac{1}{\mu_0 e n_0} \left[v_0'' - \frac{n'_0 v'_0}{n_0} \right] \frac{\partial B}{\partial y} - \frac{v_0}{\mu_0 e n_0^2} \left\{ n_0, \frac{\partial B}{\partial x} \right\} + \frac{v_0}{\mu_0 e n_0} \nabla^2 \frac{\partial B}{\partial y} = 0, \\ \frac{\partial T_1}{\partial t} + \frac{1}{\mu_0 e n_0} \{B, T_0 + T_1\} + v_0(x) \frac{\partial T_1}{\partial y} + \frac{(\gamma - 1) T_0}{\mu_0 e n_0^2} \{n_0, B\} = 0. \end{aligned}$$

where v_0 is an arbitrary function of x describing the plasma velocity profile. For a homogeneous plasma, in the linear limit, the above equations can be decoupled, and solutions for the self-generated magnetic field are in the form of associated Legendre functions. As a consequence, for the plasma flow proportional to $\tanh(\kappa x)$, for any given characteristic length κ of the shear flow, there is only one value of the wavenumber k_y for which the magnetic field perturbation is spatially localized.

However, in the strongly nonlinear case, $\partial/\partial t = -u\partial/\partial y$ where u is the phase velocity, the corresponding equation for the magnetic field can be integrated once to give:

$$(\nabla^2 - 1)B - F(x)(e^{-B} - 1) = 0, \quad F'(x) = \frac{8\kappa^2}{e^{2\kappa x} + e^{-2\kappa x} + 2}.$$

Two different numerical solutions of the above equation, whose wavenumber k_y has values which are forbidden for the linear mode, are given in Fig. 1 (single chain), and Fig. 2 (double chain). It should be expected that in the presence of finite dissipation the former structure would last much shorter than the latter. In both cases the self-generated magnetic field yields a significant steepening of the electron flow profile (Fig. 3).

FIG. 1

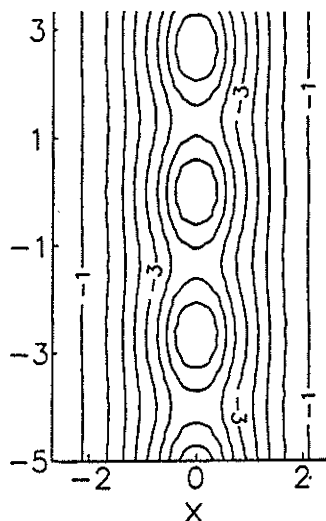


FIG. 2

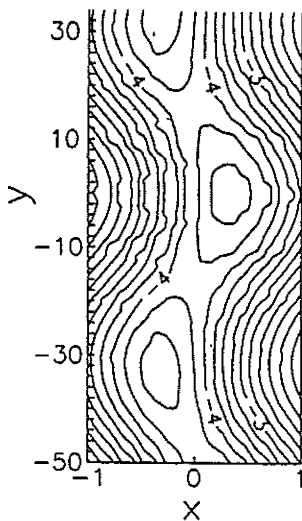
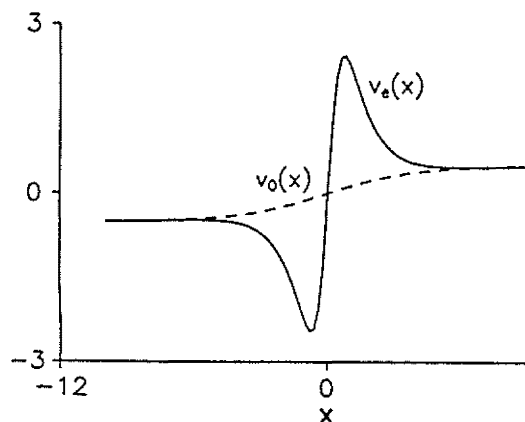


FIG. 3



The Spectral Problem of Global Microinstabilities in Tokamak-like Plasmas using a Gyrokinetic Model*

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Tokamak-like plasmas are modeled by a periodic cylindrical system with magnetic shear and realistic density and temperature profiles. Linear electrostatic microinstabilities in such plasmas are studied by solving the eigenvalue problem starting from gyrokinetic theory. The actual eigenvalue equation is then of integral type. With this approach, finite Larmor radius (FLR) effects to all orders are taken into account. FLR effects provide for the only radial coupling in a cylinder and to lowest order correspond to polarization drift.

This effectively one-dimensional problem helped us to gain useful knowledge for solving gyrokinetic equations in a curved system. When searching for the eigenfrequencies of the global modes, two different methods have been tested and compared. Either the true eigenvalue problem is solved by finding the zeroes of the characteristic equation, or one considers a system driven by an antenna and looks for resonances in the power response of the plasma. In addition, mode structures were computed as well in direct as in Fourier space. The advantages and disadvantages of these various approaches are discussed.

Ion temperature gradient (ITG) instabilities are studied over a wide range of parameters and for wavelengths perpendicular to the magnetic field down to the scale of ion Larmor radii. Flute instabilities driven by magnetic curvature drifts are also considered. Some of these results are compared with a time evolution PIC code[†]. Such comparisons are valuable as the convergence of PIC results is often questioned. Work considering true toroidal geometry is in progress.

*Work in part supported by Cray Research-EPFL Parallel Application Technology Program and the Swiss National Science Foundation.

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Predictive Transport Simulations of Tokamak Discharges*

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We present the results of the numerical simulations of selected TFTR and DIII-D discharges. These studies aim to explore the predictive capabilities of a transport model derived by applying the generalized Balescu-Lenard theory [1] to the case of magnetic turbulence induced transport in tokamaks [2]. The level of turbulence is obtained self-consistently via a tearing mode linear stability analysis [3]. The ability of the model to predict heat pinches, the consistency property of the profiles and the features of the induced current density transport, caused by the coupling of various thermodynamic forces, is emphasized. The results are compared with a previous series of simulations [4] based on a recently proposed model of coupled transport [5].

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Linear and Nonlinear dynamics of Alfvén modes driven by energetic particles

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The understanding of the stability of global Alfvén eigenmodes in the presence of energetic particles has been recognized to be very important in evaluating the success of the next step generation of thermonuclear fusion devices. The mode stability depends strongly on the spatial localization of the mode, being typically damped in the internal part of the discharge by Ion Landau Damping and being driven unstable if the mode is localized around the maximum value of the pressure gradient of the energetic particles. Thus, the fully 2-D structure of the eigenmode is required in order to properly assess the issue of global Alfvén modes stability, as, e.g., the Toroidal Alfvén Eigenmodes (TAE). Furthermore, for realistic parameters, the effect of the drive and damping terms, as well as finite orbit widths of energetic particles and bulk-ions finite Larmor radius effects, cannot be treated perturbatively but should be considered at the same order as that at which toroidicity enters.

The linear stability of TAE, Kinetic TAE (KTAE), and Energetic Particle continuum Mode (EPM) is studied using a code which solves the two-dimensional mode structure and global stability, in the limit of high toroidal mode number n , using a two spatial-scale WKBJ formalism treating drive and damping terms non-perturbatively.

The nonlinear dynamics of these modes is studied by means a hybrid MHD-gyrokinetic particle simulation code. The code is able to treat low and moderately low toroidal mode number n . Nonperturbative treatment of the finite drift-orbit effects has been found to be crucial. It has been found that for typical parameters, the KTAE is indeed more unstable than the TAE. In particular, in the nonlinear phase, the EPM is found to be particularly dangerous, leading to the expulsion of the energetic particles from the plasma column.

Theory of Discrete Dynamo Activity in Laboratory Plasmas: RFP Sawteeth*

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Reversed field pinch experiments (RFP) exhibit relaxation phenomena which sustain the magnetic configuration longer than electrical resistivity should allow. This effect is due to the MHD dynamo. An interesting feature of the dynamo is that the relaxations often occur in a discrete and nearly periodic sawtooth fashion. Unlike the tokamak sawtooth where a single Fourier harmonic is believed to play a central role in the sawtooth dynamics, RFP sawteeth are characterized by a set of tearing instabilities which play the essential role in the MHD dynamo.

A theoretical explanation of the discrete dynamo is presented which is based upon a description of the RFP dynamics as a low order dynamical system. The calculation accounts for the evolution of the equilibrium that is affected by applied electrical fields, diffusion processes and the MHD dynamo, as well as a dynamical description of the MHD dynamo which is determined from the behavior of the tearing instabilities and the properties of the equilibrium. The system can be reduced to two ordinary differential equations for the averaged current gradient, which measures the degree of plasma relaxation, and the dynamo amplitude. The dynamical system exhibit a predator-prey type periodic limit cycle, which is characterized by a slow current peaking phase followed by a rapid crash. The sawtooth amplitude and period are predicted to increase with Lundquist number and plasma current, features which are in qualitative agreement with experimental observations.

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Kinetic Alfvén Eigenmodes in JET and DIII-D

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Kinetic effects are studied for global Alfvén eigenmodes in realistic tokamak equilibria with finite aspect ratio and plasma β , comparing calculations from the full wave code PENN [1] with experimental measurements. The kinetic plasma model is based on a Larmor radius expansion in toroidal geometry and takes into account the gradients in the equilibrium density and temperatures [2]. It allows for a consistent description of the mode conversion to the kinetic Alfvén wave (KAW) and the effect of diamagnetic drifts on electromagnetic waves.

Comparisons are first carried out for a JET discharge, showing that multiple peaks measured in the low frequency Alfvén spectrum [3] are the signature of kinetic Alfvén eigenmodes (KAE) induced through coupling between a global ellipticity Alfvén eigenmode (EAE) and the KAW. In general, series of modes appear in the proximity of global fluid modes, some with a regular spacing in frequency and a very weak Landau damping of $|\gamma/\omega| \simeq 0.0007$.

A kinetic analysis of a DIII-D discharge [4] shows that TAE mode wavefields reach the plasma core through electromagnetic drift waves which propagate because of finite temperature gradients in the regions of small $k_{\parallel}$. They can lead to particle diffusion and may explain the large losses of beam ions observed during the TAE instabilities. Comparisons of frequency and eigenmode structure are carried out for resistive and kinetic models, between the theoretical calculations using the PENN code and the experimental measurements from magnetic probes.

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Strong drifts effects on neoclassical transport*

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It is well known that strong drifts play an important role in plasma equilibrium, stability and confinement. A significant example concerns, in particular for tokamak plasmas, the case of strong toroidal differential rotation (shear flow) produced by $E \times B$ drift [1],[2],[3],[4], which is currently regarded as potentially important for its influence in equilibrium, stability and transport. In fact, theoretically, it has been found that shear flow can substantially affect the stability of microinstabilities [5],[6] as well modify substantially transport [2],[7],[3],[4].

Recent experimental observations of enhanced confinement and transport regimes in Tokamaks, show, however, evidence of the existence of strong drifts in the plasma core [8],[9],[10]. These are produced not only by the radial electric field [which gives rise to the $E \times B$ drift], but also by density $[\bar{N}_s]$, temperature $[T_s]$ and mass flow $[V = \omega R e_\varphi]$, with e_φ the toroidal unit vector, R the distance for the symmetry axis of the torus and ω being the toroidal angular rotation velocity] profiles which are suitably steep. This implies that, in a significant part of the plasma core, the relevant scale lengths of the gradients [of $\bar{N}_s, T_s, \omega$], *i.e.*, respectively L_N, L_T and L_ω can be as large as the radial scale length characterizing the banana orbits, L_b . Interestingly enough, the transport estimates obtained [8] appear close or even lower than the predictions based on the simplest neoclassical model, *i.e.*, those obtained using the conventional theory of Hirshman and Sigmar [11]. However, as is well known, the latter applies, in a strict sense only in the case of weak drifts and also ignoring even the contribution of shear flow related to strong $E \times B$ drift.

Thus a fundamental problem appears the extension of neoclassical transport theory to include the effect of strong drifts in Tokamak confinement systems.

The goal of this investigation is to develop a general formulation of neoclassical transport embodying such important feature. For this purpose, the role of strong drifts in the particle and transport dynamics is investigated. This is achieved making use of a Lagrangian approach to guiding-center mechanics in the presence of strong drifts and the general solution method for the drift-kinetic equation recently developed by Tessarotto *et al.* [12],[13],[14]. As a consequence, self-consistent kinetic equilibria are explicitly constructed and a general formulation of collisional transport theory applying to multi-species magnetoplasmas in the presence of strong drifts is obtained.

In this investigation basic consequences and applications of the present theory are discussed.

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A Self-Organized Criticality Model for Plasma Transport*

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Many models of natural phenomena manifest the basic hypothesis of self-organized criticality (SOC) [1]. The SOC concept brings together the self-similarity on space and time scales that is common to many of these phenomena. The application of the SOC modelling concept to the plasma dynamics near marginal stability [2] opens new possibilities of understanding issues such as Bohm scaling, profile consistency, broad band fluctuation spectra with universal characteristics and fast time scales. A model realization of self-organized criticality for plasma transport in a magnetic confinement device is presented. The model is based on subcritical resistive pressure-gradient-driven turbulence. Three-dimensional nonlinear calculations based on this model show the existence of transport under subcritical conditions. This model that includes fluctuation dynamics leads to results very similar to the running sandpile paradigm.

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1-D Kinetic Divertor Gas-Box Simulations and Development of a 2-D Code*

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We report on 1-D kinetic simulations of a gas-box divertor using the W1 collisional PIC code to compare with previous slot-divertor calculations.¹ Two gas-box models are used: one with a uniform gas density and another where the gas is allowed to be attenuated by the plasma. We discuss initial comparisons of the kinetic W1 results with 1-D fluid theory to assess changes needed in SOL transport codes.

We also present progress on the extension of W1 to two spatial dimensions. The simplest model couples adjacent magnetic field lines by an anomalous cross-field diffusion operator, but the potential is determined by 1-D ambipolar flow.² We compare this model with a 2-D potential equation obtained by solving the current continuity equation, $\nabla \cdot \mathbf{J} = 0$. Here the cross-field current can be described by conductivity from ion-neutral collisions, anomalous toroidal momentum transport, or polarization current. Such calculations require a high level of parallel computations to be practical, and we will report on experience with the T3D computer in this regard.

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Realistic Magnetic Equilibria in Global Nonlinear Gyrokinetic Simulations*

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Magnetic equilibrium effects such as finite-beta, triangularity and elongation have been shown in some cases to have a significant effect on drift-wave type microinstabilities.^{1,2} Here, we study these effects on ion-temperature-gradient driven turbulence using a fully nonlinear and global gyrokinetic simulation with realistic tokamak magnetic equilibria (in contrast to past studies using unshifted circles). Progress has been made integrating numerically calculated magnetic equilibria³ into a global nonlinear electrostatic gyrokinetic δf simulation.⁴ The gyrokinetic code evolves the equations of motion and solves for the electrostatic field in cylindrical (R, Z, ϕ) coordinates. The poloidal magnetic flux function ψ , its gradients, the toroidal magnetic field and the plasma pressure have been mapped onto the same (R, Z) coordinates yielding all the necessary equilibrium quantities. The gyrokinetic simulation runs on the Cray T3D massively parallel supercomputer using a domain decomposition in the toroidal direction with PVM. The code scales very well with a speed of approximately 14 Mflops per processor. We plan to investigate the differences between circular and shaped plasmas for low to intermediate values of n , studying the linear eigenmodes, as well as, the nonlinear saturated turbulent fluctuations and associated heat transport. Simulation results using an equilibrium from the TFTR ERS mode,^{5,6} where there is a strong shift in the magnetic axis may also be reported.

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Ballooning Modes in Heliotron/Torsatrons

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Abstract

The characteristics of the high- n ballooning modes and the relation between high- n and low- n modes are examined in an $L = 2/M = 10$ heliotron/torsatron where L and M are the polarity of helical coils and the toroidal pitch number, respectively. The eigenvalue ω^2 is the function with respect to ψ , θ_k , and α : $\omega^2 = \omega^2(\psi, \theta_k, \alpha)$ where ψ and α are the label of the flux surfaces and the magnetic field lines, respectively, and θ_k is the radial wave number. In tokamak cases, $\omega^2 = \omega^2(\psi, \theta_k)$.

The local magnetic shear $\hat{s}$ is characterized by the Shafranov shift and it is shown that $\hat{s}$ may disappear even in the stellarator-like global magnetic shear region. The reason results from the fact that the local compression of the poloidal magnetic field outside of the torus to keep the toroidal force balance is suppressed in the stellarator-like global magnetic shear region due to the radially increasing global rotational transform ι up to over unity. It is the vacuum rotational transform that makes the base of such a ι profile, so that the dependence of $\hat{s}$ on α is weak. The influence of the pressure profile on $\hat{s}$ is weak compared with one due to ι .

The local magnetic curvature consists of one due to toroidicity and one due to the helicity of the helical coils. The former basically has no α -dependence. The latter stems from the strength of B in the vacuum configuration, so that it has strong α -dependence. The influence of the pressure profile on the local magnetic curvature is not so significant.

The influences of the pressure profile most significantly appear in the Mercier criterion because the averaged magnetic hill region always exists in the plasma periphery. The peaked pressure profiles such as CHS experimental results give slightly Mercier unstable or Mercier stable equilibria since the pressure gradient is weak in the magnetic hill region. In contrast with it, the broad pressure profiles give Mercier unstable equilibria because the pressure gradient is strong in the magnetic hill region.

The high- n ballooning modes in stellarator-like global shear region for the Mercier unstable equilibria weakly depend on α . Thus, the contours of $\omega^2(< 0)$ in (ψ, θ_k, α) space are topologically cylindrical as well as ones in tokamaks. These modes can be expected to lead to the low- n ballooning modes.

In contrast to it, the high- n ballooning modes for the slightly Mercier unstable or the Mercier stable equilibria has a strong α -dependence that the contours of $\omega^2(< 0)$ become topologically spheroids. This situation is inherent in heliotron/torsatrons, so that such modes are considered not to lead to the low- n ballooning modes and the Finite Larmor Radius effects (FLR) may suppress them.

Particle Motion in a Sheath in a Strongly Tilted Magnetic Field*

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The ions approaching the wall along the strongly tilted magnetic field, get gradually "scraped-off" by the wall, so that the ion density begins to drop at a distance of the order of the ion gyro-radius, ρ_i , from the wall [1,2]. The quasineutrality constraint then leads to formation of the ambipolar potential that repels electrons and attracts the ions. This quasineutral region that can be called the "ion sub-sheath" is followed by a thin non-quasineutral layer (with a thickness of the order of Debye radius) adjacent to the wall which we call the "electron sub-sheath". Particle motion in the ion sub-sheath has been studied in some detail both numerically and analytically [1-4].

In our paper we point out that, if the angle α between the magnetic field and the wall is small, the ion motion in the ion sub-sheath can be described in terms of an adiabatic invariant, despite the fact that electrostatic potential varies at a scale $\sim \rho_i$. The presence of an adiabatic invariant makes it possible to carry out a general classification of the ion trajectories. We find that ions with high energies approach the electron sub-sheath at shallow angles, less than $\alpha^{1/2}$, while ions with low energies "dive" towards the wall from the middle of the ion sub-sheath. We present simple expressions for the ion distribution function at the wall for high and low electron temperatures. We consider the motion of heavy impurity ions in different charge states and present the classification of the ion trajectories for different values of the parameters α and Z/M . Our assessment of the ion motion provides a basis for evaluating the sputtering rate and for analyzing the sheath stability.

Electron motion in the *ion sub-sheath* is governed by the ordinary drift approximation and has been considered in some detail in paper [5]. In our present paper, we consider electron motion within the *electron sub-sheath* under conditions where the electron Debye radius is much greater than electron gyroradius (the opposite limiting case has been studied in paper [6]). We present a general expression for the distribution function of electrons hitting the wall. Its most salient feature is that electrons intersect the wall at shallow angles, typically less than $\alpha^{1/2}$. Our expression for the electron distribution function can be used, in particular, for evaluating the secondary electron emission from the wall.

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Radial Structure of Toroidal Drift Modes in Tokamaks

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We test and extend the developing analytic picture for the radial structure of toroidal drift-type modes in tokamaks,¹⁻⁵ by concentrating on understanding the dominant ion temperature gradient-driven eigenmodes seen in full-volume gyrokinetic (GK) toroidal simulations,⁶ with and without toroidal flow, and with standard and reversed magnetic shear. While in Ref.[5] it is pointed out that in the large- n limit the ballooning formalism of [1-4] cannot be used with flow shear, for moderate values of n the ballooning method can be directly extended to flow shear provided $(r/sv_{ti})\partial_r v_\phi \ll 1$, which includes typical experimental cases. Refs. [1,2] expect that Weber-like solutions of the radial problem, which exist only around extrema in the radial potential $Q(r)$ are exceptional, and that most modes will be Airy-like solutions, localized about any radius r_0 where $\partial_r Q$ is not too small. Instead, we find that $Q(r)$ instead typically has at least one extremum, with well depths large enough to localize one to a few radially broad modes, and that Airy-like solutions are generally too broad for the first-order expansion of $Q(r)$ their validity requires to hold. The resultant expectation of a discrete spectrum of broad modes localized about extrema in $Q(r)$ is consistent with what is observed in the simulations.

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EXPLANATION OF L→H MODE TRANSITION BASED ON GRADIENT STABILIZATION OF EDGE THERMAL FLUCTUATIONS

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A linear analysis of thermal fluctuations, using a fluid model which treats the large radial gradient related phenomena in the plasma edge, leads to a constraint on the temperature and density gradients for stabilization of edge temperature fluctuations. A temperature gradient, or conductive edge heat flux, threshold is identified. It is proposed that the L→H transition takes place when the conductive heat flux to the edge produces a sufficiently large edge temperature gradient to stabilize the edge thermal fluctuations. The consequences following from this mechanism for the L→H transition are in accord with observed phenomena associated with the L→H transition and with the observed parameter dependences of the power threshold.

First, a constraint is established on the edge temperature and density gradients that are sufficient for the stability of edge temperature fluctuations. A slab approximation for the thin plasma edge and a fluid model corrected to account for the large radial gradients present in the plasma edge are used. Equilibrium solutions are characterized by the value of the density and of its gradient $L_n^{-1} \equiv -n^{-1} dn/dr$, etc. Temperature fluctuations expanded about the equilibrium value are then used in the energy balance equation summed over plasma ions, electrons and impurities to obtain, after linearization, an expression for the growth rate ω of edge localized thermal fluctuations. Thermal stability of the equilibrium solution requires $\omega \leq 0$, which establishes a constraint that must be satisfied by L_n^{-1} and L_T^{-1} . The limiting value of the constraint ($\omega = 0$) leads to an expression for the minimum value of $(L_n^{-1})_{\min}$ that is sufficient for thermal stability, for a given value of L_T^{-1} . It is found that there is a minimum value of the temperature gradient, $(L_T^{-1})_{\min}$, that is necessary for a stable solution to exist for any value of L_n^{-1} . Thus, $L_T^{-1} \geq (L_T^{-1})_{\min}$ is a necessary condition for thermal stability, and $L_n^{-1} \geq (L_n^{-1})_{\min}$ is a sufficient condition for thermal stability of modes with inverse wavelength k , in the edge. There is also an upper limit on L_n^{-1} for which the condition $\omega \leq 0$ is satisfied, $L_n^{-1} \leq (L_n^{-1})_{\max}$.

The explanation for the L→H transition is as follows. At low values of the conductive power flux $q'' = n\chi_L T L_T^{-1}$ to the edge, $L_T^{-1} < (L_T^{-1})_{\min}$ and the edge is thermally unstable to short wavelength thermal instabilities. As the conductive power flux to the edge increases, the edge temperature gradient increases and eventually $L_T^{-1} = (L_T^{-1})_{\min}$; as the conductive heat flux is further increased, $(L_n^{-1})_{\min}$ is decreased until it is less than the actual density gradient, at which point the thermal fluctuations are stabilized. The value of the conductive heat flux at which the thermal fluctuations are stabilized is the conductive power threshold for the L→H transition, corresponding to the temperature gradient threshold $(L_T^{-1})_{\text{thresh}}$. When the edge thermal fluctuations are stabilized, the edge χ_L and D_L are reduced, and the edge temperature and density gradients must increase proportionately in order to maintain the heat and particle fluxes flowing through the edge. Thus, large sudden increases in both L_T^{-1} and L_n^{-1} would follow an L→H transition, as observed. The increase in edge density and temperature gradients would produce an increase in edge density and temperature on the slower transport time scale, as observed.

An increase in the temperature and density gradients would produce a positive acceleration of the perpendicular velocity, $v_\perp$, through the gyroviscous force in the perpendicular momentum balance, as observed. The sharp increase in the (positive) perpendicular rotation would immediately produce through radial momentum balance, $E_r \approx -v_\perp B$, a more negative radial electric field, as observed. The increase in edge density would reduce the penetration of neutrals, hence reduce the D_α signal, as observed.

The reduction of power threshold with wall conditioning is explained by the increase in $(L_T^{-1})_{\text{thresh}}$ by atomic physics effects increase. The reduced reverse H→L threshold is explained by the reduction in $(L_T^{-1})_{\text{thresh}}$ by reduced neutral penetration and reduced thermal conductivity in the H-mode.

A Toroidal Boundary-Value Problem in Resistive MHD

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Recently,¹ Montgomery and Shan considered the implications of finite resistivity for static magnetohydrodynamic equilibria in axisymmetric toroidal geometry. The present work is meant to address a boundary-value problem which arose in that discussion: the solution for the magnetic stream function given a resistivity that is spatially uniform, or which is inversely proportional to the square of the distance from the toroidal axis. Assuming that the magnetofluid is surrounded by a perfectly-conducting toroidal shell with a circular cross section, this problem can be solved exactly in both cases. Using toroidal coordinates, we derive closed-form analytic expressions for the stream function.

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Implementation of bootstrap current effects in the PIES Code^a

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The PIES code[1] (Princeton Iterative Equilibrium Solver) has been modified to take into account the effects of bootstrap current. A simple bootstrap current model, applicable to tokamaks, is presently being employed. Pressure flattening, caused by the evolution of islands, has an important effect on the bootstrap current, which in turn has an important large effect on the island width. Analytic models[2] have shown that the overall result of this interaction is, for negative shear, a destabilization of the islands. Recently, Chang et al. [3], has shown that good agreement exists between the analytic expression proposed by reference[2] and experiments on TFTR. Approximations used in this analytic expression, such as the expressions for $\Delta'(w)$, are avoided in the calculations done with the PIES code. A comparison of the two results will be presented.

^aWork supported by U.S. Department of Energy Contract No. DE-AC02-76-CH03073.

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What's Fair is Fair

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The newly elucidated strategy for the magnetic fusion program set forth by the Department of Energy calls for increased emphasis on alternate concepts. This strategy is motivated by the recognition that in spite of its many attractive features, a tokamak tends to be a low power density device, ultimately translating into large and correspondingly expensive reactor. ITER, as it is currently envisaged, is a good example of a large, expensive, plain vanilla tokamak. In its defense, ITER rightly claims that its base design is very conservative in order to minimize the risk of failure.

In order to increase power density and reduce cost there are two qualitatively different approaches that one can follow: discover advanced modes of tokamak operation (e.g. TPX, spherical tokamak) or develop new alternate concepts (e.g. RFP, FRC, stellarator). To decide which path to follow is a difficult task because of the uncertainties involved in making accurate comparisons between different concepts at different stages of development.

One area, however, that most would agree is meaningful is ideal MHD stability. For any given concept to be credible as a reactor, it must at least be stable against macroscopic ideal MHD modes. The TPX design, for instance, goes to considerable trouble to obtain stability against external kinks: a close fitting metallic cage, rotation to stabilize the resistive wall version of the external kink, and, if all else fails, feedback. For credibility any other advanced tokamak or alternate concept should be held to the same standards of ideal MHD stability. After all, "what's fair is fair".

As a first step in addressing this requirement we have investigated the stability of the RFP since it can be simply and accurately modeled as a straight cylinder. The RFP is well known to have good stability at high β against internal modes but is very unstable to external modes. We have developed a linear stability code which treats the plasma as an ideal compressible fluid, and includes longitudinal flow and a resistive wall. The goal is to determine the requirements on the flow velocity to permit operation in the resistive wall stability window first pointed out by Bondeson and Ward.

The parameter space of interest is quite large: β , m , k , b/a , τ_{wall} , ω , V_{flow} , profile parameters. Results will be presented for a high β case, ($\beta = .15$), which is stable to all internal modes as well as all external modes with a perfectly conducting wall. The wall is then made resistive and plasma flow is introduced. In this way the stability window can be determined and a comparison made between the RFP and advanced tokamak operation.

Orbit Squeezing in a Magnetic Well

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It is shown that the size of a charged particle's drift orbit is squeezed, i.e., reduced, in a magnetic well in tokamak plasmas. The squeezing factor depends on the energy of the particle. The higher the energy a particle has, the larger the squeezing factor is. Therefore, for high energy particles, the size of the drift orbit depends only on the magnetic geometry. The implications on the core confinement improvement physics and the confinement of the advanced fuel are discussed.

1996 INTERNATIONAL SHERWOOD FUSION THEORY CONFERENCE**Simple Map for Single-null Divertor Map**

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ABSTRACT

The parameter k in the simple map [1, 2] for a single-null divertor tokamak represents the level of toroidal asymmetries. We investigate the effects resulting from change in this parameter on width of the stochastic layer, footprint of the field lines on the divertor plate, area of the footprint, edge safety factor q_{edge} , Liapunov exponents, fraction of toroidal flux from stochastic layer diverted onto the plate, the average and median values of toroidal and the poloidal angle and length of field lines before they strike the divertor plate. These results have significant implications for the tokamak divertor physics. This work is supported by US DoE. The computer time provided by NERSC and by the Department of Computer Science, Hampton University on Cray EL92 is gratefully acknowledged.

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Neoclassical Rotation Velocities in Multispecies Plasmas*

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We examine the relationships between the poloidal, toroidal and parallel rotation velocities for typical plasma conditions in existing tokamak experiments. The radial force balance, neoclassical solution to the poloidal flow from the parallel force balance, and anomalous toroidal rotation are included. A full multispecies formulation of the neoclassical transport theory[1] is implemented in the NCLASS code (which includes arbitrary axisymmetric geometries and plasma collisionalities) to determine the poloidal rotation velocities. Comparisons are made with analytic relationships derived from a single impurity formulation of the problem[2]. The roles of the radial electric field and species density and pressure gradients are evaluated. The determination of the radial electric field using the NCLASS solution for poloidal rotation and a local measurement of the toroidal rotation in conjunction with measured plasma profiles is discussed; it has been used in analysis of TFTR enhanced reverse shear plasmas[3].

The ordering of banana orbit size small relative to local minor radius and gradients (as incorporated into initial versions of NCLASS) are examined for typical negative shear plasmas. We show the degree to which these constraints are violated and demonstrate that finite orbit corrections are required for better determination of the bootstrap current, particle fluxes and ion heat fluxes, i.e., the conditions $r \ll \Delta_b \ll r_n, r_T, r_E$ are significantly violated. Progress in relaxing these constraints is discussed.

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Nonlinear stability studies of coupled tearing modes in toroidal finite- β plasmas using PEST-3 *

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Linear solutions of the toroidal Newcomb equation are matched to inner layer solutions satisfying the nonlinear resistive finite- β Kotschenreuther, Hazeltine and Morrison equation [1], which has been extended to account for current gradient effects [2]. The evolution of the normalized tearing mode width $2w$ is shown to be governed by $dw/dt \propto \Delta' + k_2 D/w + k_1 \kappa^2 w \ln w$ where k_1 and k_2 are positive constants, $D \approx D_R$ is the resistive Mercier index, $-\kappa \sim$ current gradient and $\Delta' = (\Psi'_+ - \Psi'_-)/\Psi$ is the well known outer region matching index. This form is essentially in agreement with Thyagaraja's bifurcation model [3] in the $\beta \rightarrow 0$ limit.

It is shown by means of a simplified analytic model of Newcomb's outer region equation, that $\Delta' > 0$ for the generic ($m = 2, n = 1$) mode with $D < 0$, allowing for the existence of a succession of stable and unstable fixed points $0 < w_1 < w_2 < w_3$, respectively. This has been confirmed numerically by computing the ($m = 2, n = 1$) Δ' using PEST-3 [4] in toroidal equilibria with ellipticity $1 \leq E \leq 2.4$ and triangularity $0 \leq T \leq 0.5$.

The nonlinear stability criterion is generalized to the multirational surface case and shown to derive from a variational principle, which is applied to treat the problem of the double tearing mode in a plasma with nonmonotonic q profile.

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Magnetic Error Field Effects on Magnetic Island Formation in a Tokamak Plasma*

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Helically resonant magnetic error fields are expected to generate magnetic islands in plasmas— islands which at a minimum can reduce plasma confinement or can ultimately lead to plasma disruptions. To simulate the effect of error fields on the dynamics of resistive MHD tearing modes, a static magnetic field perturbation has been added to the boundary conditions of a toroidal, neoclassical reduced MHD model/simulation code. The static field perturbation is also used to assess the threshold destabilization of neoclassical MHD tearing modes¹.

The model consists of a set of incompressible, reduced-MHD equations for the poloidal flux ψ , the velocity stream function ϕ , and the plasma pressure p , which have been implemented in a reduced version of the fully three dimensional, toroidal, initial value FAR² code. The model includes neoclassical viscous-stress effects ($\nabla \cdot \vec{\pi}$) based on analytical kinetic closures³ and an anisotropic pressure diffusivity.

Simulation results with this static perturbation result are compared with analytic predictions based on resistive tearing stable profiles in slab geometry of 5 dynamical growth phases⁴ that describe the mode dynamics from the current sheet formation to the Rutherford island growth regime. However in beam-driven plasmas, strong plasma rotation is expected to provide a viscous damping which can partially shield the effect of the error field. To simulate such an effect, a rotating magnetic field perturbation has also been added to the model. Results based on this dynamic field perturbation will be presented.

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Topology, finite time Lyapunov exponents, and barriers for diffusive transport in advection-diffusion problems

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A wide range of transport problems are of advection-diffusion type. Typical fluid problems of this type are the relaxation of temperature differences in a room or the spread of a contaminant in a river. Important examples in plasma include the relaxation of electrons in a region of stochastic magnetic field lines and the evolution of the magnetic field embedded in a conducting fluid. The archetypal model equation is the advection-diffusion equation,

$$\partial\phi/\partial t + \mathbf{v} \cdot \nabla\phi = -(\nabla \cdot \Gamma_d)/\rho. \quad (1)$$

The quantity being transported is ϕ . The flow velocity of the medium, $\mathbf{v}(\mathbf{x}, t)$, is assumed given and independent of ϕ . The diffusive flux is $\Gamma_d = -D\nabla\phi$. If the flow is chaotic, the properties of the transport are determined by the spatial and time dependence of the finite time Lyapunov exponent $\lambda(\xi, t)$. The rapid diffusive transport occurs only along the field line ($\hat{s}$ line) of the vector $\hat{s}_\infty$, which defines the stable direction in which neighboring points asymptotically converge.

The topology of the $\hat{s}$ lines (stable foliation) affects the diffusive transport through the finite time Lyapunov exponent. We discover that the spatial variation of the finite time Lyapunov exponent along the $\hat{s}$ lines is smooth and determined by the topology of the $\hat{s}$ lines [1]. For example, the finite time Lyapunov exponent reaches local minima if the $\hat{s}$ line makes a sharp bend. These topological bends hinder the diffusive transport and act as a barrier for diffusive relaxation. Such barriers for diffusion reside inside the chaotic region and they persist even the flow is highly chaotic.

In the case of the electron relaxation in a region of stochastic field lines, there is a rapid diffusive relaxation of the spatial inhomogeneity in the electron distribution function which is typical of the chaotic transport of a passive scalar. But the diffusive relaxation of the pitch angle distribution is much slower. However, there is strong intermittence for the diffusive relaxation of the spatial dependence due to the prevalence of transport barriers for diffusion associated with the topological bends of the $\hat{s}$ lines.

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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 to large sparse linear systems. These methods suffer 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 has been constructed, using a pseudospectral Fourier treatment of the poloidal and toroidal directions, and a finite difference treatment of the radial direction. The radially-dependent, poloidal and toroidal averaged operator is used as a preconditioner. Convergence is rapid, with a typical iteration count of 10 for 10^{-5} convergence. New results of the two-fluid form of this code to an internal $m = 1$ internal kink mode will be presented.

The algorithm's ability to reproduce kinetic properties of plasmas is being tested with a one-dimensional code, which has recently been modified to permit periodic boundary conditions. When a nonuniform temperature distribution is imposed as an initial condition, the gradients are reduced by long mean-free-path particles that stream parallel to the magnetic field. Tests of collisionless wave damping have also been conducted for the ion-cyclotron range of frequencies, and results are compared with analytic predictions.

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Curvature and temperature gradient driven instabilities in tokamak edge plasmas with SOL*

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Curvature driven resistive ballooning modes^{1,2} (RBM) as well as the electron temperature gradient (ETG)^{3,4} modes have been investigated in the tokamak edge region and the SOL, with the help of the numerical code "2D-BALLOON"⁵. This is an initial value code, which determines the stability properties and estimates the quasi-linear transport for given density, temperature, the magnetic and electric field profiles, taking into account the SOL geometry as well as a closed flux region. The results related to the following issues will be presented:

1. Comparative analysis of the ETG and the RBM instabilities in the SOL and their influence on the transport in the edge region (inside the Last Closed Magnetic Surface).
2. The influence of the effective Debye sheath current.
3. Different poloidal positions of the toroidal limiter and their effect on the instabilities.

Other aspects of the edge plasma turbulence, such as finite β effects, flow-shear of the poloidal rotation etc. will also be discussed.

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Spectral Reduction for Two-Dimensional Turbulence*

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A new method for predicting the statistical properties of fluid turbulence, called Spectral Reduction, is described. Collections of Fourier wavenumbers are represented by certain nonuniformly spaced sample modes that interact *via* enhanced coupling coefficients. The approximation reduces to the exact Navier–Stokes equation as a control parameter, the number of fundamental wavenumbers associated with each sample mode, tends to unity. Even at large values of this parameter, the time-averaged predictions of the theory can be shown to recover the statistics of the exact dynamics to high accuracy. Preliminary results from the numerical implementation of Spectral Reduction for two-dimensional homogeneous turbulence are very encouraging; for example, the method is used to illustrate a recent modification to Kraichnan’s logarithmically corrected two-dimensional enstrophy cascade. Higher-order statistics, such as the kurtosis, are also examined: for weak forcing, it is found that the probability distribution function is highly non-Gaussian.

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Hamiltonian Description of Toroidal Magnetic Fields in Vacuum

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An investigation of vacuum magnetic fields in toroidal geometry has been initiated. Previously,¹ the general form of the magnetic scalar potential for fields regular at the poloidal axis was given. Here, these results have been expanded to obtain the magnetic scalar potential in a vacuum region that may surround a toroidal current distribution. Using this generalized magnetic scalar potential in conjunction with Boozer's canonical representation of a magnetic field,² a field-line Hamiltonian for nonaxisymmetric vacuum fields has been derived. These fields are being examined using a novel, "time-dependent" perturbation theory, which permits the iterative construction of invariants associated with magnetic field-line Hamiltonians that consist of an axisymmetric zeroth-order term, plus a nonaxisymmetric perturbation. By choosing appropriate independent variables, an explicit constructive procedure is developed which involves only a single canonical transformation. Such invariants are of interest because they provide a means of investigating the topology of magnetic field lines. Our objective is to elucidate the existence of magnetic surfaces for nonaxisymmetric vacuum configurations, as well as to provide an approach for studying the onset of stochastic behavior.

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Importance of Radial Localization on the Interaction of Fusion Products with High-Frequency Modes*

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We investigate modes that can interact with high energy reaction products in fusion burning plasmas giving rise to instability for frequencies that correspond to harmonics of the energetic particles' cyclotron frequency. The corresponding modes in a homogeneous plasma would be classified as Magnetosonic-Whistler modes. It is known that in a configuration with inhomogeneous magnetic field, density, and temperature, it is possible to find radially localized solutions,¹ that we call "contained modes," for the perturbed field.

We study new localized solutions for the perturbed fields by solving the equations obtained by linearizing the extended MHD equations, including the Hall term. The main effects associated with this term are to break the symmetry in $\pm k_{\perp}$, and to include a (Whistler type) term in the dispersion equation related to propagation in the direction of the equilibrium magnetic field. We point out how the existence of this solution is essential to make it possible that the resonant interaction of the considered modes with relatively few fusion products will yield a positive growth rate.²

In fact, travelling modes in the radial direction would convect away the energy gained from the (few) resonating particles in too short a time to allow an increase of their amplitude.

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Detonation and Ballooning Modes*

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Ballooning modes are shown to have explosive growth near the instability threshold. This behavior is entirely analagous to the behavior of gravitationally driven modes.[1] Typically the system crosses the linear stability boundary in a narrow region. The nonlinearity is destabilizing and broadening causing the instability to develop fingers and broaden into the linearly stable region. The linearly stable region is in fact meta-stable. The energy in the fingers is large enough to destabilize the meta-stable region – a process we call detonation. A simple nonlinear equation which is valid near marginal stability is derived. Analysis of this equation shows that the displacement becomes singular like $(t_0 - t)^{-2.1}$, the energy like $(t_0 - t)^{-6.4}$ and the destabilized width like $(t_0 - t)^{-0.4}$. The relevance of this mechanism for high beta disruptions will be discussed.

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Multi-dimensional conversion to the ion-hybrid mode

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We first demonstrate that the dispersion matrix for linear conversion of a magnetosonic wave to an ion-hybrid wave [1] (as in a D-T plasma) can be congruently transformed to Friedland's normal form [2]. As a result, this conversion can be represented as a two-step process [3] of successive linear conversions in phase space. We then proceed to study the multi-dimensional case of tokamak geometry. After fourier transforming the toroidal dependence, we deal with the two-dimensional poloidal xy -plane and the two-dimensional $k_x k_y$ -plane, forming a four-dimensional phase space. The dispersion manifolds for the magnetosonic wave [$D_M(\mathbf{x}, \mathbf{k}) = 0$] and the ion-hybrid wave [$D_H(\mathbf{x}, \mathbf{k}) = 0$] are each three-dimensional. (Their intersection, on which mode conversion occurs [4], is two-dimensional.) The incident magnetosonic wave (radiated by an antenna) is a two-dimensional set of rays (a lagrangian manifold): $\mathbf{k}(\mathbf{x}) = \nabla\theta(\mathbf{x})$, with $\theta(\mathbf{x})$ the phase of the magnetosonic wave. When these rays pierce the ion-hybrid dispersion manifold, they convert to a set of ion-hybrid rays. Then, when those rays intersect the magnetosonic dispersion manifold, they convert to a set of "reflected" magnetosonic rays. This set of rays is *distinct* from the set of incident rays that have been reflected by the inner surface of the tokamak plasma. As a result, the total destructive interference that can occur in the one-dimensional case [1] may become only partial. We explore the implications of this startling phenomenon both analytically and geometrically.

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Simulation Studies of High- β Disruptions and Alpha particle loss in Reversed Shear Plasmas*

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The 3D nonlinear MH3D code is used to study high- β disruptions and alpha particle loss during the disruption in reversed shear(RS) plasmas.

In normal shear plasmas, it had been found that toroidally localized high- n ballooning modes can be driven unstable by the local pressure steepening at the bad curvature region which arises from the evolution of low- n modes.¹ Nonlinearly, the high- n mode becomes even more localized and produces a strong local pressure bulge which destroys the flux surfaces resulting in a thermal quench.

A similar behavior is also seen in simulations of RS plasmas. However, in RS, disruptions can also be caused by low- n modes alone without a toroidally localized high- n ballooning mode. Brief descriptions of the simulation results of the two types of disruption in RS plasmas, one with high- n ballooning modes and the other without, follow.

The initial equilibrium of the first case is unstable to the $n=1$ ballooning mode with an $m=2$ dominance. The nonlinear evolution of this mode results in a 3D equilibrium with two local pressure steepenings, one inside the RS core region and the other outside. A toroidally localized high- n ballooning mode grows out of the local steep pressure region outside the RS core, and eventually destroys the flux surfaces resulting in a thermal quench. The toroidally localized steep pressure gradient inside the RS core, although much stronger than the one outside, remains stable, showing that the advantage of RS configuration regarding pressure driven modes extends far into the 3D configuration.

The second example has a similar initial linear behavior, except that the saturation amplitude is smaller than in the first case. Therefore, the resulting local pressure gradient is smaller, and is not enough to drive a toroidally localized high- n ballooning mode. The low- n modes however, undergo a very large $m=2$ distortion and the tip of this deformation pushes out toward the plasma surface. This causes the x-points to line up along this line of force, and drives magnetic reconnection that proceeds until island overlap, stochasticity, and thermal quench occur.

Alpha particle loss during disruptions has also been studied using the particle/fluid hybrid MH3D-K version. The main particle loss mechanism is the crossing of the passing-trapped boundary due to the large magnetic perturbation.

The above results agree with experimental data.

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Observations on Resistive Wall Modes*

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Several results on resistive wall modes and their application to tokamaks are presented. First, it is observed that in the presence of collisional parallel dynamics (parallel thermal conduction, parallel viscosity, and sound wave propagation) there is an exact cancellation to lowest order of the dissipative and sound wave effects for an ideal Ohm's law. This is easily traced to the fact that the parallel dynamics occurs along the *perturbed* magnetic field lines for such electromagnetic modes. Such a cancellation does not occur in the resistive layer of a tearing-like mode. The relevance to models for resistive wall modes using an electrostatic Hammett-Perkins [1] type operator to model Landau damping will be discussed.

Second, we observe that with an ideal Ohm's law, resistive wall modes can be destabilized by rotation in that part of parameter space in which the ideal MHD modes are stable with the wall at infinity. This effect can easily be explained by interpreting the resistive wall instability in terms of mode coupling between the backward stable MHD mode and a stable mode locked into the wall. Such an effect can occur for very small rotation for tearing-resistive wall modes in which inertia dominates viscosity in the layer, but the mode is stabilized by further rotation (of order the nominal tearing mode growth rate). For modes for which viscosity dominates in the layer, rotation is purely stabilizing. For both tearing models, a somewhat higher rotation frequency gives stability essentially whenever the tearing mode is stable with a perfectly conducting wall. These tearing/resistive wall results are also simply explained in terms of mode coupling. It has been shown that resonant external *ideal* modes can be stabilized in the presence of resistive wall and resistive plasma with rotation of order the nominal tearing mode growth rate [2]. We show that these modes behave as resistive wall tearing modes in the sense above. This strengthens the suggestion [2] that rotational stabilization of the external kink with a resistive wall [3] is due to the presence of resistive layers, even for ideal modes.

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Nonlinear Simulation Study of the Toroidal Alfvén Eigenmode

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Nonlinear evolution of the toroidal Alfvén eigenmode destabilized by energetic alpha particles is investigated using a particle simulation method coupled with MHD equations. In this method, alpha particles are represented by drift kinetic super particles while the bulk plasma is described by the full-MHD model. The contribution of the alpha particle current is extracted from the total current in the MHD momentum equation to take into account the effects of alpha particles on the bulk plasma in a self-consistent way.

$$\rho \frac{\partial}{\partial t} \mathbf{v} + \rho \mathbf{v} \cdot \nabla \mathbf{v} = \left(\frac{1}{\mu_0} \nabla \times \mathbf{B} - \mathbf{j}_\alpha \right) \times \mathbf{B} - \nabla p. \quad (1)$$

The δf method [1] is employed in order to reduce the numerical noise. We consider the alpha particle current as the sum of the parallel current, the magnetic drift current, and the magnetization current which are calculated through the particle weight w .

$$\begin{aligned} \mathbf{j}_\alpha &= \mathbf{j}_\parallel + \mathbf{j}_d + \mathbf{j}_{mag} \\ &= \mathbf{j}_{\alpha 0} + \sum_i w v_\parallel S(\mathbf{x} - \mathbf{X}_i) + \sum_i w \mathbf{v}_d S(\mathbf{x} - \mathbf{X}_i) + \nabla \times \mathbf{M}_1, \end{aligned} \quad (2)$$

$$\mathbf{M}_1 = - \sum_i w \mu \mathbf{b} S(\mathbf{x} - \mathbf{X}_i). \quad (3)$$

Time evolution of the particle weight is given by

$$\frac{d}{dt} w = -(1 - w) \frac{1}{f_0} (\mathbf{v}_1 \cdot \nabla f_0 + \frac{d\epsilon}{dt} \frac{\partial}{\partial \epsilon} f_0). \quad (4)$$

This particle-MHD simulation method enables us to set the initial slowing down distribution of the alpha particles to be isotropic in the velocity space. Saturation of the instability is caused by the wave-particle trapping, which is consistent with our previous Vlasov-MHD simulation study [2]. Saturation level is in proportion to the square of linear growth rate. Nonlinear oscillation in the toroidal momentum of resonant particles is observed.

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MHD AND CURRENT PROFILE CONTROL STUDIES OF REVERSED SHEAR TOKAMAK CONFIGURATIONS*

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Given the observed enhancement of energy and particle confinement, and the possibility of achieving high betas and high bootstrap current fractions, reversed magnetic shear equilibria have become the leading concept in advanced tokamak scenarios. The performance limits for these configurations are most likely to be set by MHD stability constraints. The other essential issue for this advanced tokamak concept is the non-inductive, steady state sustainment of the current profile. These two topics are covered in the present work. We concentrate on equilibria with minimum value of q greater than 2 so as to avoid double-tearing mode problems and to have global access to the $n=\infty$ ballooning second stability region. Then the MHD limit is set by the $n=1$ (pressure-current driven) external mode. The critical parameters for the onset of the $n=1$ instability in terms of the plasma beta and current are obtained for several classes of equilibria, allowing for a systematic study of geometrical shaping and profile effects. It is shown that triangular shapes and broad profiles yield optimal results. The realistic sustainment of the reversed shear current profiles is investigated by generating equilibria with the ACCOME code [1]. This simulation model combines a free boundary solution of the Grad-Shafranov equation with the calculation of driven currents due to neutral beam injection, lower hybrid waves, ICRF fast waves and bootstrap effects. Such equilibrium code is coupled to the JSOLVER [2] and PEST-II [3] codes in order to perform the stability analysis. Specific simulations for the ALCATOR C-mod and ITER tokamaks are provided. Optimal parameters for completely stable equilibria without conducting walls thus obtained reach $\beta_N=3.7$, $\beta=3.7\%$, $\beta_*=5.0\%$ and bootstrap fraction in excess of 75%.

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Relaxation of poloidal rotation in tokamak plasmas in the plateau regime*

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The equation describing the relaxation of the radial electric field in the neoclassical plateau¹⁻³ regime has been derived. The neoclassical viscosity of plasmas has been obtained in the presence of fluctuations as well as external forces. The regime of very low collisions, such that $\nu_c qR/V_T \ll 1$ but $\nu_c qR/V_T \gg \epsilon^{3/2}$, has been considered analytically. This corresponds to almost collisionless plasmas but in the absence of banana particles. It has been shown that the electric field relaxation occurs in the form of the damped oscillations with the time scale proportional to the ion transient time.

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Disruptions in DIII-D*

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We report on the results of a statistical analysis of the DIII-D disruption data base, and on an examination of a selected subset of the shots to determine the likely causes of disruptions. The statistical analysis focuses on the dependence of the disruption rate on key dimensionless parameters.

We find that the disruption frequency is high at modest values of the parameters, and that it can be relatively low at operational limits. For example, the disruption frequency in an ITER relevant regime ($\beta_N/l_i \approx 2$, $3 < q < 4$, $n/n_G > 0.6$, where n_G is the Greenwald limit) is approximately 23%. For this range of q , the disruption frequency rises only modestly to about 35% at the β limit, consistent with previous observations of a soft β limit for this q regime. For the range $6 < q < 7$, the disruption frequency is only about 6% at the highest achievable values of β . At low q , where the disruption rate does get high at the operational limits, there is no sharp threshold in the disruption frequency, with the high disruption rate decreasing only gradually as we move away from the density and beta limits.

We find a disruption-free regime at high q and high density ($6 < q_{95} < 10$, $.811 < n/n_G < .894$). We calculate an upper bound on the disruption frequency in this regime of 2%. In general, disruptivity as a function of density has a minimum at relatively high density ($.6 < n/n_G < .9$) in all q regimes we have studied. The location of the minimum moves to higher density with increasing q .

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Interactive Exploration of Tokamak Turbulence Simulations in Virtual Reality *

Sherwood '96

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We have developed an immersive visualization system designed for interactive data exploration as an integral part of our computing environment for studying tokamak turbulence[†]. This system of codes can reproduce the results of simulations visually for scrutiny in real time, interactively and with more realism than ever before. At peak performance, the VR system can present for view some 400 coordinated images per second.

The long term vision this approach targets is a 'holodeck-like' virtual reality environment in which one can explore gyrofluid or gyrokinetic plasma simulations interactively and in real time, visually, with concurrent simulations of experimental diagnostic devices.

In principle, such a 'virtual tokamak' computed environment could be as all encompassing or as focussed as one likes, in terms of the physics involved. The computing framework is one within which a group of researchers can work together to produce a real and identifiable product with easy access to all contributions. This could be our version of NASA's next generation Numerical Wind Tunnel.

The principal purpose of this VR capability for Numerical Tokamak simulation is to provide interactive visual experience to help create new ways of understanding aspects of the convective transport processes operating in tokamak fusion experiments.

The effectiveness of the visualization method is strongly dependent on the *density of frame-to-frame correlation*. Below a threshold of this quantity, short term visual memory does not bridge the gap between frames well enough for there to exist a strong visual connection. Above the threshold, evolving structures appear clearly.

The visualizations show the 3D structure of vortex evolution and the gyrofluid motion associated with it. We discovered that it was very helpful for visualizing the cross field flows to *compress* the virtual world in the toroidal angle. This masked the parallel motion and enhanced the convective motion, thus making the vortex structure more apparent.

Given these conditions, the disassembly of large scale structured initializations in gyrofluid micro-turbulence is particularly beautiful to watch.

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Numerical Lundquist Number Scaling of Magnetohydrodynamic Turbulence in Reversed-field Pinches*

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Three-dimensional, nonlinear magnetohydrodynamic (MHD) simulations with Lundquist number (S) ranging from 2.5×10^3 to 4×10^4 produce a weak fluctuation scaling of $\text{rms}(b) \sim S^{-0.18}$ for reversed-field pinch (RFP) plasmas, where $\text{rms}(b)$ is the root-mean-square of the magnetic field fluctuations. The weak nature of the scaling is consistent with earlier results of $\text{rms}(b) \sim S^{-0.22}$ calculated with a spectral code. [1] The new results have been obtained with a pseudo-spectral algorithm, and hyper-dissipation terms have been added to the pressureless MHD equations to suppress numerical aliasing. [2] The scaling is significantly influenced by $m=0$ modes, whose fluctuation level increases with S in this range. This behavior is attributed in part to enhanced nonlinear coupling as dissipation is reduced and in part to changes in the parallel current profile. The parallel current gradient at the $m=0$ resonance surface increases with S due to an increasingly more effective MHD dynamo. We expect this effect will eventually saturate, leading to a decreasing $m=0$ fluctuation level and a stronger overall scaling.

The temporal behavior of the simulations also changes as S is increased. Oscillations in the reversal parameter become more regular, acquiring a sawtooth character at the largest values of S in this study. Similar but less dramatic observations have been reported earlier. [3] Here, the nonlinear coupling between internally resonant $m=1$ modes and $m=0$ modes plays an important role. The events leading to a sawtooth crash are consistent with Ho's description of quasiperiodic oscillations at modest S . [4] His three phases of MHD dynamo (1. interior $m=1$ modes gain energy, 2. nonlinear transfer of energy to $m=1$ modes that are resonant near the reversal surface, and 3. mean poloidal current drive) produce enhanced current inside the reversal surface. However, at large S , there is an added phase of mean current redistribution from $m=0$ modes, which subsequently suppresses these modes. When they are small, the second phase of the dynamo is impeded until the $m=1$ modes are large enough to nonlinearly drive the $m=0$ modes back to a significant level.

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Perturbations to SOC Models as a Mechanism for Transport Control*

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Recently the concept of Self-Organized Criticality (SOC) was advanced as a paradigm for turbulent transport in magnetically confined plasmas.^{1,2} The type of model has the advantage of predicting general features of the transport dynamics and profiles independent of the local instability driving the fluctuations. Such a model predicts profile resiliency, sub-marginal profiles maintaining active transport, intermittency in flux and transport events which have large correlation lengths while the underlying fluctuations have short correlation lengths. Given that many of these features have been observed in experiments, an investigation is made of the dynamics of a perturbed SOC system as a mechanism for the control of transport. One of the problems faced by magnetic confinement devices is the control of the heat and particle fluxes. If the fluxes are very "bursty" then even if the walls and divertor can safely absorb the average flux the instantaneous flux could damage or destroy these surfaces. Additionally, in enhanced confinement regimes (H-mode, VH-mode, Enhanced Reversed Shear modes and such) the limiting factor is often the buildup of a super-critical gradient which gives rise to a sudden large transport event. Computational experiments with a sandpile model of SOC dynamics suggests that some modification of the transport dynamics may be possible with periodic perturbations of the internal sources.

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Resistive Instabilities in Negative Central Shear Tokamaks with Peaked Pressure Profiles

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The resistive ($n = 1$) instabilities in negative central shear (NCS) advanced tokamaks with peaked pressure profiles are investigated systematically by using the MARS resistive MHD code [1,2]. Two characteristically different types of resistive modes are found. One localized to the inner of the two mode rational surfaces and the other more global. The localized mode is destabilized by shear reversal and plasma pressure peaking. The mode structure has an interchange parity and corresponds to the predicted localized resistive interchange mode [3] when the resistive interchange stability criterion is violated locally ($D_R > 0$). In a rotating plasma, this mode rotates with the inner rational surface. The global mode has structure corresponding to the coupling of a double pitched mode with an external kink. This mode usually rotates with the outer portion of the plasma. It is destabilized by plasma beta and stabilized by wall and rotation shear.

Experimentally, MHD bursts localized on the inside rational q surfaces in NCS discharges were detected prior to disruption in DIII-D [4,5]. The β_N value at disruption has been found to be independent of $q_{\min}$ and also decreases with $p(0)/\langle p \rangle$ in quantitative agreement with the predictions of resistive MHD theory; this constitutes the first positive identification of the resistive interchange mode in the tokamak plasma. The resistive β limit is typically 20% smaller than the ideal limit. The relationship of the observed disruption precursor with the computed global mode will also be discussed. Stability of the plasma is enhanced by reduced shear reversal and pressure peakedness, indicating possible avenues for the optimization of NCS operations.

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Neoclassical Tearing Modes in TFTR Reversed Shear Experiments*

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Abstract

Coherent MHD modes are often observed in reversed magnetic shear experiments in TFTR. The majority of the modes have toroidal mode number $n = 2$ and poloidal mode number $m = 5$. They appear in the high power heating phase on both the reversed shear (RS) and enhanced reversed shear (ERS) plasmas. Tearing parity is observed from the local ECE fluctuation measurement. Namely, the δT_e changes phase across the mode rational surface. The measured q profile from MSE polarimetry shows that the mode is located $\sim 10 - 15$ cm outside the minimum q (or q_{min}). The radial width of the mode is about 25 cm, which extends to or beyond q_{min} . Due to the high m number, the magnetic island size calculated using the q profile and edge magnetic coil measurements is small, *i.e.*, $w < 5 - 6$ cm, or $w/a < 5 - 6\%$.

The stability of the classical current-driven tearing mode is estimated using the analytic formula[1]:

$$\Delta' = -\pi \frac{m}{r} \frac{\sigma}{\tan(\pi\sigma/2)}, \quad \sigma \equiv -\frac{1}{m} \frac{q^2}{q'} \frac{d}{dr} \left[\frac{1}{r} \frac{d}{dr} \left(\frac{r^2}{q} \right) \right]. \quad (1)$$

It is found that for typical TFTR RS/ERS plasmas, Δ' is negative (stable) to $m/n = 5/2$ modes in both the negative and positive shear regions. On the other hand, neoclassical ∇p -driven tearing theory[2], which has been proved to provide a very good description of the observed island evolution in TFTR supershot[3], gives a consistent physical picture in agreement with the observation. According to the theory,

$$\frac{dw}{dt} = 1.22 \frac{\eta_{mc}}{\mu_0} \left(\Delta' + k_2 \sqrt{\epsilon} \beta_p \frac{L_q}{L_p} \frac{1}{w} \right), \quad (2)$$

where $L_q = (q'/q)^{-1}$, $L_p = -(p'/p)^{-1}$, $\epsilon = r/R$, β_p is the poloidal β and k_2 is a constant of order unity. In the reversed shear region, $L_q < 0$, so the neoclassical term is strongly stabilizing. For example, for a 1 cm 5/2 island to grow in the reversed shear region of an ERS plasma, it requires $r_s \Delta' > 200$. The most unstable region should be the positive shear region. Using measured plasma profiles, we found that the single helicity island evolution of Eq. (2) agrees with experiments reasonable well. This result indicates that the observed island evolution is mainly determined by the local plasma pressure gradient with positive shear. Detailed experimental data and simulation will be presented. Discussion on some theoretically related issues (*e.g.*, mode frequency, rotation, critical island width, etc.) will also be addressed.

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Recent Progress in TAE Stability Analysis in Tokamak Plasmas*

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A critical issue for tokamak reactors is whether the fusion alpha particles can excite MHD instabilities, such as the Toroidal Alfvén Eigenmodes (TAE). Substantial progress has been made recently in understanding the stability of TAE driven by energetic particles in tokamak plasmas. In this work, we present results of stability calculations using the kinetic-MHD NOVA-K code for several tokamak experiments, including TFTR DT experiments, JT-60 ICRF experiments, and DIII-D NBI experiments. Work is in progress to assess the damping mechanisms in JET antenna-driven TAE experiments. Our physics model includes the finite orbit width effects of energetic particles, the electron and ion Landau damping, the collisional damping, and the radiative damping. The main results are: (a) In TFTR DT experiments, TAE modes are calculated to be stable, consistent with the experimental observations [1]. The main damping mechanisms are the beam ion Landau damping and the radiative damping. The core localized TAE modes [2] are predicted to be driven unstable by alpha particles for weakly reversed shear profiles; (b) In JT-60U ICRF experiments, TAE modes are destabilized by fast minority ions powered by the ICRF heating. The stability of TAE modes are strongly dependent on the mode location [3]. This results in sequential excitation of high- n TAE modes as the central q drops in time. The effects of finite banana width of fast ions are essential. The radiative damping is found to be the dominating stabilizing mechanism. The calculated threshold is somewhat lower than the estimated experimental value. This indicates that the continuum damping might play a role. (c) In DIII-D NBI experiments, TAE modes are destabilized by energetic beam ions. The main damping mechanism comes from the radiative damping. The calculated stability threshold agrees reasonably well with the experimental observations. The implications of these results for ITER will be discussed.

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Profile dependent signature of the linear MHD spectrum.

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We have been studying in detail the spectrum of linear MHD waves in tokamak plasmas using the CASTOR code. This spectrum consists of global modes like Toroidicity induced Alfvén Eigenmodes (TAE's) that show up as resonances in active excitation experiments, and continua of modes that are localised on flux surfaces, in particular the Alfvén continuum. From our numerical studies we have found that several aspects of the spectrum can be directly related to properties of the plasma equilibrium. From a single measurement it is possible to relate the continuum response to the plasma safety factor and density profiles near the edge. The dependence of TAE frequencies and damping rates on equilibrium profiles is more difficult to understand, however the dynamical behaviour of the TAE's can reveal changes in the safety factor profile in the centre and at the edge of the plasma. For some parameter regimes the signature of the Alfvén spectrum changes dramatically. We find that for an equilibrium with a non-monotonic safety factor profile a series of global Alfvén modes appears. These modes are localised in the plasma centre and have an increasing number of radial nodes with decreasing frequency. If there is sufficient information on the mode structure of the excited waves this can give additional information on equilibrium parameters. This work, that has been given the name MHD-spectroscopy, demonstrates the possible use of Alfvén waves, that can be excited in a straightforward way by a set of external coils in tokamak experiments and measured by using, for example, the magnetic pick-up coils. Such measurements can be used for diagnostic purposes to give information on the same parameters that are of essential importance to global (MHD) stability of these plasmas. The TAE measurements done in the JET tokamak using the saddle coils to excite Alfvén waves at small amplitudes are especially suited for comparison with linearised MHD calculations. In this paper we will compare the results of our numerical calculations with active Alfvén measurements performed at JET.

ALTERNATIVE CONCEPTS : PHYSICS ADVANCES AND PROSPECTS

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Research in a diverse range of confinement concepts permits study of fusion plasma physics in ways not possible in only one concept; ultimately, a fusion reactor will likely draw on attributes from many configurations (to which we presently apply distinct labels which understate their physics connections). For example, the field reversed configuration, reversed field pinch, spherical tokamak, spheromak, stellarator, dense z-pinch and electrostatic Penning trap combine to offer a range of concepts with varying magnetic shear, curvature, fluctuation levels and spectra, plasma flow, density and temperature gradients, plasma currents and boundary conditions. Resulting from this diversity, a wide range of new phenomena and ideas has been uncovered in recent years involving confinement with safety factor $q < 1$, currentless two dimensional systems, dynamo phenomena, large orbit effects on stability, magnetic fluctuation driven transport, physics at extreme toroidicity, plasma relaxation, helicity injection, plasma flow and mode locking, and particle focusing, to name a few.

In addition, many of these alternative concepts (by which we mean anything other than the medium-aspect-ratio advanced tokamak) arguably have potential advantages as a fusion reactor. Many are aimed at a smaller, simpler, higher beta reactor with lower magnetic field.

This talk will focus on selected recent physics advances (experimental and theoretical) arising within alternative concepts research. We will also discuss the reactor potential of the concepts, particularly key physics obstacles (or challenges).

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Ideal MHD Stability Limits of Ultra-Low Aspect Ratio Tokamaks *

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Recently, there has been interest in exploring the reactor potential of the low aspect ratio tokamak. The distinguishing features of the low aspect ratio tokamak are the non-superconducting toroidal field (TF) coils made of copper or copper alloy and the lack of both ohmic heating and inboard poloidal field coils. These two features allow a compact design with little or no shielding on the inboard side of the tokamak and very low aspect ratio. While a compact design is desirable, such a design is viable only if sufficiently high fusion power density $\sim \beta^2 B_T^4$ can be obtained. For reactor optimizations at standard aspect ratios ($A=2.5-4$) it has been found that the necessity of inboard shielding and a limit on the maximum toroidal field strength at the superconducting TF coils causes the toroidal field at the plasma center to vary as $\sqrt{A}$. These considerations imply that for fixed β_N and q_* the fusion power density is effectively independent of A . At very low A this degeneracy is broken due to the normal conducting TF and minimal TF shielding - leading to a net win in fusion power density. However, the economic requirement that most of the toroidal plasma current be provided by the bootstrap effect is at apparent odds with this conclusion, since conventional (large A) scalings show that the bootstrap fraction $f_{BS} \sim \sqrt{\epsilon} \beta_P \sim \sqrt{A} \beta_N q_*$. Thus for fixed β_N and q_* it would appear that larger A is advantageous.

During the last 2 years we have investigated the ideal MHD stability and bootstrap current properties of ultra-low aspect ratio ($A \geq 1.25$) tokamaks. Initial studies found that very high stable β 's were achievable. Subsequent studies found that stable equilibria with moderately high β and $f_{BS} \sim 1$ exist, due to the large increase in the maximum stable β_N at low A , even with elevated q_0 . Thus, high β can be achieved simultaneously with high f_{BS} . By performing systematic scans and optimizations in which we have varied the aspect ratio, pressure and density profiles, the current profile, and elongation and triangularity, stable equilibria with with $\beta \approx 45\%$ and pressure gradient driven current fractions $> 80\%$ have been found. Further, regimes which require only small amounts of core current drive have been found with $\beta > 20\%$. Cases have also been found with stable β as large as 80% , but these cases have unacceptably small bootstrap fractions. Numerical simulation results will be presented showing that the stability of these low A equilibria is strongly influenced by the pressure profile, the plasma elongation, triangularity, and the presence of a nearby conducting wall. Data will also be presented showing that the natural elongation and triangularity are strong increasing functions of decreasing aspect ratio and internal inductance. These results have influenced the design of the proposed National Spherical Tokamak Experiment (NSTX), a device with $A \geq 1.25$, $\kappa \leq 2.2$, and close fitting passive stabilizers, all of which will allow the MHD stability of these very high β regimes to be tested experimentally.

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Rotational Stabilization of $q < 1$ modes*

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Analyses of high performance discharges with central safety factor below unity have shown that the ideal Magnetohydrodynamic stability threshold for the $n=1$ kink mode is often violated with impunity. For TFTR (Tokamak Fusion Test Reactor) supershots, the experimental observations can be explained by diamagnetic stabilization of the reconnecting mode¹ provided that the fluid free energy is suitably reduced by trapped particle effects. For the broader profiles typical of other high confinement regimes, however, diamagnetic effects cannot account for the experimental results. Furthermore, there is evidence that the Mercier stability condition can also be violated in some cases.

Here, we show that toroidal rotation of the plasma can stabilize the kink mode even in the presence of resistivity in configurations that would otherwise be ideally unstable. Two effects can be distinguished. The first effect consists in a reduction of the ideal driving energy. This can be understood in view of the fact that, to a good approximation, the internal kink is a rigid body displacement combining a tilt of the plasma inside the $q = 1$ surface with a translation along the tilt axis. In the presence of rotation, this displacement must be accompanied by a precessional motion so as to conserve angular momentum. The kinetic energy of the precessional motion must be extracted from the energy driving the displacement. The second effect of rotation is to resolve the Alfvén singularity. This is a consequence of the pressure perturbation caused by the equilibrium variation of the entropy within the flux surfaces. It results in the stabilization of resistive as well as weak ideal instabilities, including Mercier modes. For rotationally stabilized equilibria, it also implies the presence of a neutrally stable mode with frequency of the order of the growth rate of the internal kink. The analytic results are in good agreement with numerical simulations using the compressible toroidal code CTD, and are in qualitative agreement with the experimental observations on DIII-D after allowing for the stabilizing effect of thermal trapped particles.²

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Influence of Beam Orbit Loss on Radial Electric Field in NBI Heated Heliotron/Torsatrons

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Experiments with tangential NBI heating in the CHS ($l = 2$, $m = 8$ heliotron device, NIFS) have shown the strong negative radial electric field and significant reduction of thermal diffusivity in the plasma periphery[1]. In non-axisymmetric configurations the radial electric field could be determined by the ambipolarity condition and the large positive ion radial flux or negative electron flux is considered to enhance the observed negative radial electric field. Recently, we have shown the large drift orbit deviation of tangentially injected NBI particle from the original magnetic surface to occur the prompt orbit loss in the CHS[2]. This loss flux would enhance the negative radial electric field. In this paper we study the beam orbit loss effects on the radial electric field in heliotron/torsatrons numerically solving the time development of radial electric field with the neoclassical radial particle fluxes[3] and the beam orbit loss flux calculated by the Monte-Carlo simulation code. We find an enhancement of the strong negative radial electric field at the periphery due to the radial flux of escaping beam ions in the weak magnetic field. Thus we have shown that the large negative electric field observed in the CHS would be enhanced by loss of beam ions.

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Dynamo beyond the regime of MHD theory

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Conservation of magnetic helicity $K = \int dV \mathbf{A} \cdot \mathbf{B}$, requires Ohm's law to be valid, which can be rather restrictive. More generally, in fluid theory each charged species has its own helicity,

$$K_\alpha = \int dV \left(\frac{q_\alpha}{c} \mathbf{A} - m_\alpha \mathbf{v}_\alpha \right) \cdot \nabla \times \left(\frac{q_\alpha}{c} \mathbf{A} - m_\alpha \mathbf{v}_\alpha \right),$$

where q_α , m_α , and $\mathbf{v}_\alpha$ are the charge, mass and velocity of species α . The K_α are conserved¹ in the limit where $\nabla n_\alpha \times \nabla T_\alpha = 0$; if this term does not vanish, then K_α can be generated. For a neutral two-species plasma with low electron mass and $a\Omega_i \gg v_i$ (where a is a characteristic lengthscale of the magnetic field), it can be shown that K_e conservation reduces to the usual MHD conservation of K , and the difference $K_i - K_e$ reduces to the usual conservation of cross helicity, $\int dV \mathbf{v}_i \cdot \mathbf{B}$.

This suggests that MHD dynamo theory² can be generalized to any regime where fluid theory is valid. With $K_e \simeq K$ for small m_e , then the presence of $\nabla n_e \times \nabla T_e \neq 0$ can generate K , which can then generate large scale magnetic fields, as in the usual dynamo theory.³ Cross helicity can also be generated if $\nabla n_e \times \nabla T_e \neq 0$, which also affects the cascade dynamics.³

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MHD Simulations on an Unstructured Mesh

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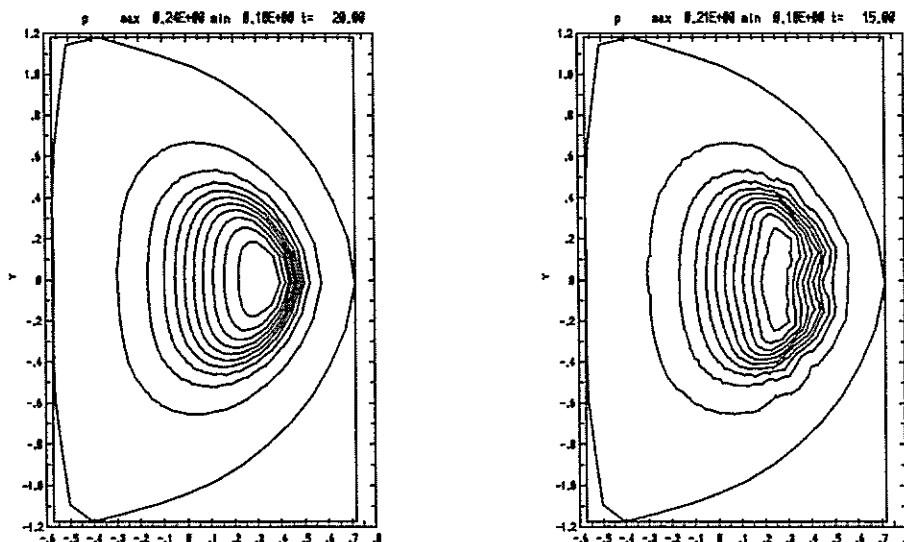
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We describe work on a full MHD code using an unstructured mesh.

MH3D++ is an extension of the PPPL MH3D resistive full MHD code. MH3D++ replaces the structured mesh and finite difference / fourier discretization of MH3D with an unstructured mesh and finite element / fourier discretization. Low level routines which perform differential operations, solution of PDEs such as Poisson's equation, and graphics, are encapsulated in C++ objects to isolate the finite element operations from the higher level code. The high level code is the same, whether it is run in structured or unstructured mesh versions. This allows the unstructured mesh version to be benchmarked against the structured mesh version.

As a preliminary example, disruptions in DIII-D reverse shear equilibria are studied numerically with the MH3D++ code. Numerical equilibria were first produced starting with an EQDSK file containing equilibrium data of a DIII-D L-mode negative central shear discharge. Using these equilibria, the linearized equations are time advanced to get the toroidal mode number $n = 1$ linear growth rate and eigenmode, which is resistively unstable. The equilibrium and linear mode are used to initialize 3D nonlinear runs. An example shows poloidal slices of 3D pressure surfaces: initially, on the left, and at an intermediate time, on the right.



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Simulation of Current Generation in a 3-D Plasma Model*

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Two wires carrying current in the same direction will attract each other, and two wires carrying current in the opposite direction will repel each other. Now, consider a test charge in a plasma. If the test charge carries current parallel to the plasma, then it will be pulled toward the plasma core, and if the test charge carries current anti-parallel to the plasma, then it will be pushed to the edge. The electromagnetic coupling between the plasma and a test charge (i.e., the $A_{\parallel} \cdot v_{\parallel}$ term in the test charge's Hamiltonian) breaks the symmetry in the parallel direction, and gives rise to a diffusion coefficient which is dependent on the particle's parallel velocity. This is the basis for the "preferential loss" mechanism described in the work by Nunan et al[1]

In our previous 2+1/2D work, in both cylindrical and toroidal geometries, showed that if the plasma column is centrally fueled, then an initial current increases steadily. The results in straight, cylindrical plasmas showed that self generated parallel current arises without trapped particle or neoclassical diffusion, as assumed by the bootstrap theory. Ref [1] suggests that the fundamental mechanism seems to be the conservation of particles' canonical momenta in the direction of the ignorable coordinate.

We have extended the simulation to 3D to verify the model put forth in Ref [1]. A scalable 3D EM-PIC code, with a localized field-solver, has been implemented to run on a large class of parallel computers. On the 512-node SP2 at Cornell Theory Center, we have benchmarked the 2+1/2D calculations using 32 grids in the previously ignored direction, and a 100-fold increase in the number of particles. Our preliminary results show good agreements between the 2+1/2D and the 3D calculations. We will present our 3D results at the meeting.

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TWO-DIMENSIONAL DIVERTOR SIMULATION SCALING LAWS

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Divertor scaling laws need to be developed in order to extrapolate present experimental dissipative divertor results to ITER operating conditions. Scaling law information can be obtained from numerical simulations to aid in the design of a dissipative divertor for ITER. However, two-dimensional numerical models of divertors contain large numbers of dimensionless parameters that must be varied to investigate all operating regimes of interest. To simplify the task and gain insight into steady state divertor operation, similarity techniques can be employed to investigate whether a fluid plasma and fluid neutral (including perpendicular transport due to the neutrals) system of equations plus boundary conditions admits scaling transformations that lead to useful divertor similarity scaling laws [1]. A fully recycling simulation of the divertor region between the x-point and target is considered to illustrate how similarity results can be used to benchmark large computer simulations of divertors and obtain useful scaling laws. A modified rectangular version of UEDGE with thermally equilibrated neutrals and plasma which retains anomalous transport but ignores recombination is used to illustrate that doubling the geometry (SOL and divertor widths and the divertor depth), halving the upstream pressure and parallel heat fluxes, and doubling the anomalous transport coefficients leaves the solution unchanged in agreement with the scalings. Collisionality imposes a severe constraint on the similarity of present tokamaks to ITER. Its large size also makes it difficult to model using enough grid points to resolve important physical effects. Our results show that it might be possible to use smaller geometries in divertor codes to model ITER relevant collisionalities up to the onset of detachment.

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Runaway Electron Distributions Obtained with the CQL3D Fokker-Planck Code under Tokamak Disruption Conditions

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Runaway of electrons to high energy during plasma disruptions occurs due to large induced toroidal electric fields which tend to maintain the toroidal plasma current, in accord with Lenz' law. This has been observed in many tokamaks. Within the closed flux surfaces, the bounce-averaged CQL3D Fokker-Planck code is well suited to obtain the resulting electron distributions, nonthermal contributions to electrical conductivity, and runaway rates. The time-dependent 2D in momentum-space ($p_{\parallel}$ and $p_{\perp}$) distributions are calculated on a radial array of noncircular flux surfaces, including bounce-averaging of the Fokker-Planck equation to account for toroidal trapping effects. In the steady state, the resulting distributions represent a balance between applied toroidal electric field, relativistic Coulomb collisions, and synchrotron radiation. The code can be run in a mode where the electrons are sourced at low velocity and run off the high velocity edge of the computational mesh, giving runaway rates at steady state. At small minor radius, the results closely match previous results reported by Kulsrud *et al.* [1]. It is found that the runaway rate has a strong dependence on inverse aspect ratio ϵ , decreasing by a factor ≈ 5 as ϵ increases from 0.0 to 0.3. The code can also be run with a radial diffusion and pinching term, simulating radial transport with plasma pinching to maintain a given density profile. Results show a transport reduction of runaways in the plasma center, and an enhancement towards the edge due to the electrons from the plasma center. Avalanching of runaways due to a knock-on electron source [2,3] is being included.

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1996 International Sherwood Fusion Theory Conference**Monte Carlo Simulation of Superthermal
Alpha Particles in Rippled Field of Tokamak****Punjabi A, Lam M, and Boozer A*****Center for Fusion Research and Training
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We study the transport of superthermal alpha particles in the rippled field of TFTR using the Monte Carlo method for the transport of plasma particles due to MHD modes in toroidal plasmas developed by Punjabi and Boozer, and Rapid Guiding Center Calculations Code SHAF developed by White and Boozer. We use drift Hamiltonian equation of motion in non-canonical, rectangular coordinates. The effects of pitch angle and energy scattering with electrons, deuterons, tritons and Carbon-12 impurity are included. The deposition of alpha energy into electrons, ions and Carbon as a function of radial coordinate is also calculated. The initial results of this study will be presented. The assistance provided by Professors R. B. White and S. Zweben of PPPL is gratefully acknowledged. HU Computer Science department provided computing time on the CRAY EL 92 Supercomputer for this work. This is gratefully acknowledged. This work is supported by the US DOE.

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Microinstability Properties of Negative Magnetic Shear Discharges in TFTR and DIII-D*

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The microinstability properties of discharges with negative (reversed) magnetic shear in the TFTR and DIII-D experiments with and without confinement transitions are investigated. A comprehensive kinetic linear eigenmode calculation[1,2] employing the ballooning representation is employed with experimentally measured profile data, and using the corresponding numerically computed MHD equilibria. The instabilities considered are the toroidal drift mode (trapped-electron- η_i mode) and the kinetically-calculated MHD ballooning mode. In particular, different negative magnetic shear discharges at different times in the discharge for TFTR and DIII-D are analyzed. The effects of sheared toroidal rotation, either from direct spectroscopic measurements for carbon or from E_r/RB_θ measurements[3], are analyzed in comparison with results from a two-dimensional calculation[4]. The relative importance of changes in different profiles (density, temperature, q , rotation, *etc.*) on the linear growth rates is considered.

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CROSS CORRELATIONS IN THE GENERAL THEORY OF ELECTROMAGNETIC PLASMA FLUCTUATIONS

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The correlated plasma states has been the subject of intensive theoretical and numerical treatment (see the refs. in [1]).

It was established in [2] that the finite cross-correlations give rise to extra negative terms in the denominators of the expressions for equilibrium electrostatic, cross and magnetic fluctuation spectra that indicate increase in the mean values of the nonlinear interaction invariants (energy, cross-helicity and anisotropy). Also, the cascade rates inhibition takes place, as it will take a longer time for a system to approach an equilibrium state.

As shown in [1,3-5], the cross correlations (arising, for example, due to external current) may dismantle or distort the linear solutions to the fluctuation spectra and may "generate" new solutions. Influencing the renormalized spectra widths, that will lead to change in anomalous transport rate.

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SELF-ORGANIZATION AND TRANSPORT IN ELECTROSTATIC TURBULENCE OF TOKAMAK SCRAPE-OFF-LAYER

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A model of turbulence driven by resistive interchange instability in the tokamak scrape-off-layer is proposed and investigated numerically. Large scale coherent structures are observed in the saturated regime of turbulence. The use of the proper orthogonal decomposition method and conditional sampling [1, 2] allows us to extract and identify the coherent structures. It also clarifies the role played by these structures in the radial transport. These results issued from a simplified model of turbulence are compared to experimental data.

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Alfvén Stability Properties of Reversed Shear Regimes in DT Tokamaks*

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The formation of transport barriers with reduced neoclassical transport and centrally reversed shear q -profiles can potentially lead to high fusion reactivities near the magnetic axis. The concomitantly high alpha production in this region can be a drive for Alfvén instabilities. We have analyzed the stability thresholds of such modes and find that reversed shear can result in significant differences from the more normal tokamak q -profiles which have been analyzed previously. The larger values of $q(0)$ and $q_{\min}$ (i.e., 2 - 4) which characterize the reversed shear profiles will lower the shear Alfvén frequency gap. In principle, this should have no effect on the resonance velocity ($v_{\text{res}} = \omega/k_{\parallel}$) in the center of the gap since $k_{\parallel}$ decreases by a similar amount as ω with increasing q . However, due to the fact that the mode structure has a finite radial width and poloidal couplings, it always will sample a range of $k_{\parallel}$'s. As a result, we find TAE destabilization in reversed shear profiles predominately occurs at sub-Alfvénic velocities ($v_{\text{res}}/v_{\text{Alfvén}} \sim 0.3$ to 0.4). TAE thresholds for energies characteristic of the neutral beam species then can become quite low even for full field tokamaks. This can have consequences for the understanding and maintenance of the sheared flow (which is thought to cause the transport barriers) since sheared flows have also been shown to be a nonlinear consequence of unstable toroidal Alfvén modes¹. Recent cases from DIII-D and TFTR will be analyzed.

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NON-MODAL ANALYSIS IN PLASMAS*S.M. MAHAJAN, A.D. ROGAVA[†] and V. BEREZHIANI[†]*Institute for Fusion Studies, The University of Texas at Austin
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The techniques of non-modal analysis are applied to investigate the time evolution of a variety of plasma flows with velocity shear. It is shown that large transient amplifications may result for appropriate initial perturbations. The role of this amplification in determining the nonlinear dynamics of these systems (when all the normal modes are stable) is discussed. Examples are taken from Laboratory, astrophysical and cosmic plasmas.

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Toroidicity Stabilization of Low- n Ion Temperature Gradient-Driven Modes*

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We present here a study of the low toroidal mode number (n) spectra of the toroidal ion temperature gradient-driven (ITG) instability using both a linear¹ and a nonlinear² global gyrokinetic particle-in-cell code. Both of these initial value codes are running on massively parallel computing environments (Cray T3D and IBM SP2) and allow us to do detailed convergence studies of our results. The effect of toroidicity on the low- n ITG spectrum is systematically investigated by varying the aspect ratio and analyzing the effects of each independent toroidal term in the gyrokinetic equation.

We have found that an important contribution to the linear eigenmode stability for low- n modes is the effect of wave curvature drive, i.e. the absorption of energy by the gyrocenter undergoing a magnetic drift in the perpendicular electric field of the wave. This curvature drive is found to have a strongly stabilizing effect at realistic tokamak aspect ratios and therefore should not be neglected. We investigate the nonlinear consequences of this effect using the nonlinear code. In particular, the saturation levels of the fluctuations and the ion thermal flux in the saturated state is analyzed with and without the wave curvature drive effect.

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Stability Studies of Tokamak Discharges with Negative Central Shear*

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The stability properties of tokamak discharges with reversed or negative central shear are being investigated using the linear and nonlinear, ideal and resistive, magnetohydrodynamic (MHD) stability code FAR.¹ The FAR code solves either the reduced or the full set of MHD equations in toroidal geometry, including shaping, compressibility, and finite beta effects. Linear ideal calculations indicate that such discharges (e.g. DIII-D shot #87009 at 1675 msec),² exhibit robust stability to current-driven and pressure-driven modes. Preliminary linear resistive calculations with the full set of compressible MHD equations point to the existence of a weak pressure-driven instability in the region of negative central shear. More systematic studies are currently under way in preparation for nonlinear calculations and their results will also be presented.

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Semiconductor Plasmas*V. BEREZHIANI[†] and S.M. MAHAJAN*Institute for Fusion Studies, The University of Texas at Austin
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With the advent of femtosecond lasers with pulse width ΔT smaller than the collision times, it becomes theoretically possible to see the manifestations of collective phenomena in semiconductor plasmas. It is shown that very sizable Wakefields can be created in semiconductors like InSb and GaAs. The structure of the Wakefield could be used as an important diagnostic to determine the nature of the conduction band electrons in these doped semiconductors. For narrow band semiconductors, 'relativistic' effects can be simulated in a simple, cheap, tabletop experiment.

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Atomic and Surface Physics Data in DEGAS 2*

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As recent simulations of Balmer- α emissions in TFTR have demonstrated[1], a Monte Carlo neutral transport code requires accurate atomic and surface physics data in order to match experimental results. In fact, it is work of this sort which drives the acquisition and incorporation of new data into codes such as DEGAS. For this reason, the mechanisms for handling atomic and surface physics data in DEGAS 2 have been designed to allow the greatest possible flexibility in data formats. As one example we will discuss the treatment of elastic scattering reactions and the way in which the requisite data are represented in DEGAS 2. In the future, even more complicated data formats will be needed[2].

Fortunately in the case of surface physics data a particularly general format and related sampling technique already exists[3]. This five dimensional differential scattering distribution describes the dependence of each surface interaction process (e.g., reflection or sputtering) on incident energy and angle, as well as on the two exiting angles and energy. Details about the surface physics data currently incorporated into DEGAS 2 and the user input required to control them will also be presented.

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Development of Parallel Fokker-Planck Code ALLAp*

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We report on our ongoing development of the 3D Fokker-Planck code ALLA¹ for a highly collisional scrape-off-layer (SOL) plasma. A SOL with strong gradients of density and temperature in the spatial dimension is modeled. Our method is based on a 3-D adaptive grid (in space, magnitude of the velocity, and cosine of the pitch angle) and a second order conservative scheme. Note that the grid size is typically 100x257x65 nodes. It was shown in our previous work² that only these capabilities make it possible to benchmark a 3D code against a spatially-dependent self-similar solution of a kinetic equation with the Landau collision term.³ In the present work we show results of a more precise benchmarking against the exact solutions of the kinetic equation using a new parallel code ALLAp with an improved method of parallelization and a modified boundary condition at the plasma edge. We also report first results from the code parallelization using Message Passing Interface for a Massively Parallel CRI T3D platform. We evaluate the ALLAp code performance versus the number of T3D processors used and compare its efficiency against a Work/Data Sharing parallelization scheme and a workstation version.

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The Dynamics of Internal Transport Barrier Formation in Reverse Shear and Weak Shear Discharges*

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The experimental regime with reversed central magnetic shear and a coincident enhanced confinement region has opened an operating window which provides the confinement benefits of VH-mode discharges without the difficulties of coupling to the edge physics. A theoretical challenge is to model the dynamics of the transition to the enhanced confinement regime. This requires incorporating the linear effects of the reversed shear profiles in a nonlinear model to capture the bifurcation dynamics.

A simple first principles model incorporating the nonlinear coupling between the turbulent fluctuations and the sheared radial electric field is used to investigate the dynamics of the transition to an enhanced confinement mode in the reversed shear/weak shear discharges. From this simple version of the model it is found that by incorporating both growth rate profiles and particle/power deposition profiles a rich variety of transition dynamics exist. The power threshold for the transition is found to depend on the local growth rate (which depends on the magnetic shear) and the local gradient in the deposition profile. The size of the enhanced confinement region is predicted to depend on the growth rate profile and the total deposition inside the reversal region. The transition itself can take the form of a propagating front like transition. After the transition the transport in the enhanced regime is neoclassical (or modified neoclassical) with the performance limits determined by MHD stability which is not included in the model presented. The simple model can predict the evolution of the transition, scaling of the threshold levels and the optimal deposition profiles. It also predicts a wide region of suppression of the turbulent fluctuations and the end point of the enhanced confinement region.

In order to allow an increasingly reasonable investigation of power thresholds and hysteresis effects a more complete transport model is needed. This transport model is coupled to the simple dynamical model allowing the transition dynamics to be self-consistently evolved. With simple further extensions to include the toroidal flow profile evolution, more complete threshold effects can be investigated which are thought to be important in devices such as DIII-D and JT-60U. Understanding the transition dynamics can aid in the control of the transport in this regime, allowing extended operation and preventing MHD unstable gradients from developing.

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MHD Waves, Reconnection, and Plasma Transport at the Dayside Magnetopause*

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The magnetic field of the Earth creates a huge cavity in the solar wind known as the magnetosphere. The transition region between the solar wind plasma and magnetosphere plasma is of substantial interest because many magnetospheric processes are governed by the transport of particles, momentum and energy across that boundary. At this boundary, the magnetopause, there is an abrupt decrease in plasma bulk flow, density and pressure, and large increase in temperature and magnetic field. Throughout this region the plasma- β is large (≥ 1). Large amplitude compressional waves are nearly always found in the region just outside of the magnetopause. These waves are either intrinsic solar wind fluctuations or they may be global mirror modes which are generated in a localized region of large pressure anisotropy just outside the magnetopause. The substantial background gradients observed at the magnetopause strongly couple the compressional waves with kinetic Alfvén waves near the Alfvén resonance location ($\omega = k_{\parallel} v_A$) [1], leading to substantial particle transport. Moreover, for a sheared background magnetic field, as is found at times of southward interplanetary magnetic field, the mode converted kinetic Alfvén waves can propagate to the location where $k_{\parallel} = 0$ and generate islands in phase space. We present a solution of the kinetic-MHD wave equations for the magnetic field structure based on a realistic steady state profile which includes: a sheared magnetic field; magnetic curvature; and gradients in the background density, pressure and magnetic field. We incorporate wave-particle resonance interactions for electrons and ions to obtain the dissipation. The background magnetic field curvature and gradient give rise to drifts which alter the resonance condition for the various particle species ($\omega - \mathbf{k} \cdot \mathbf{v}_d - k_{\parallel} v_{\parallel}$) and reduces the Landau damping of the kinetic Alfvén wave, allowing it to propagate to the $k_{\parallel} = 0$ location. Our analysis differs from earlier studies, *e.g.* [1], in that we consider a high β plasma including the important kinetic effects introduced by the curvature and ∇B drifts. Using the solutions near the $k_{\parallel} = 0$ location we investigate the formation of magnetic islands and the consequences for particle transport.

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Self-consistent 2D model for L-H transitions in tokamaks*

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A two-dimensional self-consistent model for L-H transitions in tokamaks has been developed. A set of 'fast' equations for the density and vorticity of resistive ballooning modes, and 'slow' equations for the equilibrium density, vorticity and the parallel momentum have been derived for a toroidal plasma, and have been solved numerically. The L-mode phase consists of strong poloidally asymmetric particle transport driven by resistive ballooning modes with a single toroidal mode number with larger flux on the outboard side compared to the inboard side. As a consequence the density is more flattened on the outside of the tokamak compared to the inside and is no longer constant on a flux surface. With the onset of shear flow driven by a combination of toroidal drive mechanisms as well as the Reynold's Stress, the fluctuations associated with the resistive ballooning modes are attenuated which leads to a strong reduction in the particle transport. The drop in the particle transport results in steepening of the density profile. The time development of the fluctuations shows that the fluctuations on the outside are the first to be reduced in amplitude during the build-up of the shear flow. The fluctuations on the inside first increase in amplitude during the transition, followed by a reduction. The fluctuations in the H-mode phase are poloidally localised at the top/bottom. The strong radial localization of these secondary modes does not degrade the particle transport and the H-mode is sustained in the late phase by the toroidal drive.

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MAGNETIC FIELD GENERATION AND “WEIBEL RESONANCE” IN INHOMOGENEOUS PLASMAS

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The Weibel instability is an effective general mechanism of magnetic field generation in anisotropic plasmas. Recently, it has been invoked¹ in order to explain the magnetic field wake observed in PIC simulations of the interaction of ultrashort ultra-intense laser pulses with an underdense plasma. In this case the Weibel instability is thought to arise because of the formation in the plasma of two opposite streams of electrons^{1,2}. When the electric currents carried by these streams are displaced one respect to the other by a transversal disturbance, a magnetic field is produced that grows because the repulsion of the oppositely directed currents reinforces the initial displacement. The evolution of this instability can be described, before wavebreaking takes place, within the framework of the (relativistic) EMHD equations where the ions are considered to be at rest and the electrons are described as a (relativistic) fluid.

- If the plasma is inhomogeneous and/or if the two electron streams are spatially localized, the EMHD equations show the presence of a singularity which is reminiscent of the Alfvén resonance, found for Shear-Alfvén waves.
- In the simple case of two symmetric streams, this “Weibel resonance” occurs where $\gamma^2 = 2v^2$ where γ is the normalized growth rate and v the local value of the normalized electron velocity. As a result, a resonant mode localized around the singularity develops from an initial perturbation at a rate which depends on the characteristic gradient of the electron velocities.
- The growth rate of this mode is nearly independent of the initial wavelength of the perturbation and is comparable to the growth rate that would be obtained with homogeneous electron velocities equal to their maximum value in the inhomogeneous case.

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The PIES code and its applications*

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The 3-D MHD equilibrium code PIES¹ can calculate stellarator and tokamak equilibria with magnetic islands. It appears to be the only one in existence that has the possibility of determining free-boundary configurations with magnetic islands near the plasma edge in which the proper boundary condition of specifying the currents in the coils is satisfied.^{2,3} As part of an effort to decrease the computational time needed to determine equilibria, we have implemented⁴ a new algorithm that allows us to start with a finite- β equilibrium as calculated by the VMEC code.⁵ This has eliminated a major problem in treating systems where the rotational transform changes as β is increased and passes through a region with a rational transform at the magnetic axis. We present some calculations for a Modular Helias-like Heliac configuration⁶ to illustrate the improvements that this change has made and discuss future work.

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Particle Orbits in an RF Combined Trap*

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An RF combined trap is designed to confine a nonneutral plasma by a combination of RF fields and a uniform magnetic field. We take the RF fields to be given by the TM01 (axisymmetric) mode in a cylinder. For sufficiently high frequency the particle motion is described in terms of an effective potential consisting of the ponderomotive potential $V_{pon}(r, z)$ plus a radial potential $m\Omega_c r^2/8$ due to the magnetic field B_z plus a centrifugal potential $p_\theta^2/(2mr^2)$. Near the origin $r = 0$, $z = 0$ and for $p_\theta = 0$, the equations reduce to a pair of Mathieu equations for the r and z motions, with parameters $a_r \sim \Omega_c$, $q_r = k_z a_j$, $a_z = 0$, $q_z = 2q_r$, where the jitter amplitude $a_j = eE_{z0}/m\omega^2$ and ω is the RF frequency. For $a_r = 3q_r^2/2$ the effective potential is spherically symmetric near the origin. This system has a Brillouin limit for the spherical case above equal to the usual cylindrical Brillouin limit.

We have integrated the exact differential equations and the ponderomotive equations numerically for parameters near those giving spherical symmetry near the origin. The ponderomotive equations are a two degree of freedom autonomous system, and therefore can be analyzed with a conventional surface of section, either $r - p_r$ or $z - p_z$. There is a $\Omega_r/\Omega_z = 1$ resonance near the origin, giving $m = 2$, $n = 2$ islands in each surface of section. For particles with large effective energy E_{pon} in the ponderomotive well, there can be chaos, depending on the elongation of the RF cavity. The $m = 2$, $n = 2$ islands limit the size of a focus at the origin, even for $p_\theta = 0$. These islands appear, and have a similar effect of the focus, even for E_{pon} small. However, in this limit, a small detuning of the spherical parameters δa proportional to E_{pon} gets rid of the islands. The overall effects regarding the limits on a spherical focus and the relation with a conventional combined trap ($\omega \ll \omega_{RF}$) will be discussed.

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Nonlinear Gyrofluid Simulations of Improved Confinement with Reversed Magnetic Shear*

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Nonlinear gyrofluid simulations using a bounce averaged trapped electron fluid model[1] are used to investigate particle transport and electron and ion heat transport arising from ITG and trapped electron modes (TEM). This fluid model has been validated by detailed linear comparisons with the most comprehensive kinetic calculations[2]. The speed of the fluid calculations makes possible the investigation of a wide range of experimental data, and, in addition, provides fully nonlinear capability. Specific attention is focused on comparisons with TFTR discharges with reversed magnetic shear[3] which have highly peaked density profiles and improved confinement. For typical core parameters of reversed magnetic shear operation in TFTR, the dominant instability is the TEM, thus an accurate trapped electron model is required. In the ERS mode, transport is greatly reduced by the stabilization of the long wavelength trapped electron modes. While negative magnetic shear plays a stabilizing influence through trapped electron toroidal drift reversal, a more pronounced effect is stabilization via Shafranov shift drift reversal, as the core of these plasmas is well into the ballooning second stable regime. Across the transition from a non-enhanced Reversed Shear (RS) mode to the Enhanced Reversed Shear (ERS) mode, the long wavelength trapped electron modes are stabilized, and although a shorter wavelength TEM is still unstable after the transition, nonlinear simulations find that the transport after the transition is reduced by a factor of 40, in rough agreement with experiment. The bifurcation into this enhanced confinement regime requires a positive feedback mechanism[4]. The stabilization from the Shafranov shift is a possible trigger mechanism for the transition to this enhanced confinement regime, since steeper pressure gradients lead to larger shifts, more drift reversal, less transport, and in turn, to even steeper pressure gradients. Another potentially important mechanism is stabilization via radially sheared electric fields[5]. Detailed comparisons with TFTR ERS discharges will be used to elucidate the relative importance of the various mechanisms which could be responsible for the improved confinement.

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Stationary Shear Flows in CGL Anisotropic Toroidal Plasmas*

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Recently [1] a general structure of stationary shear flows in toroidal plasmas was obtained in the frame of ideal isotropic-pressure MHD model. The structure of the stationary plasma flows was shown to be determined by a hidden symmetry of MHD equations inherent in the toroidal systems with nested magnetic surfaces. However, the characteristic frequencies of the stationary plasma motion can considerably exceed the collisional frequencies in real plasma experiments. In this case the CGL collisionless MHD model seems to be more adequate than the simplified isotropic-pressure MHD model to describe the stationary plasma flows.

In this paper we have generalized our approach [1] to analyze the stationary plasma flows in the frame of the collisionless CGL model. We have found again that the hidden symmetry inherent in the toroidal topology results in two integral invariants which depend on two independent surface functions. The structure of stationary flows for CGL model is still the same as for isotropic MHD, however, the pressure tensor components satisfy a condition that two CGL adiabatic functions have to be surface functions. This circumstance appreciably modifies the steady state force-balance equation. These results are applied to analyze the generalized equilibrium in axisymmetric (tokamak-like) magnetic confinement systems.

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The 1996 International Sherwood Fusion Theory Conference
NON-STANDARD STELLARATOR CONFIGURATIONS*

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A discussion of a number of novel and non-standard stellarator configurations will be presented. Some of them are based on the recently considered configurations of a tokamak with inclined coils [1] and the stellamak concept [2-4], and a few other promising configurations feature an ultra-low aspect ratio, which is very unusual for stellarators. A stellamak represents a type of a stellarator configuration, or a stellarator-tokamak hybrid configuration, which improves its properties when the tokamak features, such as plasma current, are added to the system. This is opposite to the standard stellarator configuration, where addition of the ohmic plasma current or even a small bootstrap current degrades the system, and special efforts are needed to find the configuration with the smallest bootstrap current possible. A tokamak with inclined coils gives an example of a system where the plasma current, in the direction such that current rotational transform and the vacuum rotational transform add constructively, improves the system. Another interesting configuration can be obtained by combining the standard toroidal field coils of a tokamak with an additional system of vertically inclined planar coils. Such a hybrid allows two different modes of operation, the pure stellarator and the pure tokamak modes, and successive switching between them without significant plasma loss. By keeping the plasma current in the stellarator or hybrid system we obtained a set of configurations that have a potential of combining the best properties of both, tokamaks and stellarators, to make an ohmically heated and continuously operated device. The numerical examples of the coil systems and main properties of the confining magnetic fields and plasma equilibria for each of the novel configurations considered will be presented in detail. The magnetic field tracing code, UBFIELD, the 3D MHD equilibrium code, VMEC [5], in its free-boundary mode, and some other standard codes are used in our calculations, and the results will be presented to demonstrate the above mentioned advantages of the novel stellarator configurations.

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An Investigation of Thermal Transport During Tokamak Sawtooth Events*

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A numerical investigation of the $m = 1, n = 1$ ideal/resistive kink mode is undertaken with an emphasis on understanding the important mechanisms that control the temperature dynamics during a sawtooth event. Recently, the magnetic field line structure and the temperature profile have been measured simultaneously during a sawtooth crash phase^{1,2}. A possible interpretation of the experiments could be that a stochastization of the magnetic field lines in the vicinity of the $q = 1$ surface occurs and because of this, fast electron thermal energy transport ensues. To explore the details of this energy transport, and also the time scale of the final stage of the crash, non-linear MHD simulations of the $m = 1, n = 1$ mode are being conducted with the FAR code³. The calculations include a pressure evolution equation which account for thermal transport self-consistently and are based on an incompressibility assumption and large aspect ratio expansion. A curvature effect term has been implemented to study the finite pressure effects and toroidal effects on the mode. The formation and the evolution of the $m = 1, n = 1$ magnetic island and the pressure evolution will also be presented.

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Implicit Low-Noise Particle Simulation Methods *

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Particle simulation of kinetic plasma phenomena is an important tool in numerous application areas: magnetic and inertial fusion, space and astrophysical plasmas, high power microwave devices, and plasma processing. Recent innovations in implicit techniques, e.g., quiet implicit PIC¹ and implicit δf ,² involving the use of both fluid and particle equations to achieve greater efficiency in the control of unwanted high frequency modes and particle noise, are being exploited in two distinct examples reported here.

We are extending an implicit gyrokinetic δf model to accommodate drift-kinetic electrons and electromagnetic effects for application to drift-wave turbulent transport simulation. Implicit equations for both the scalar electric potential and the parallel vector potential are coupled iteratively. We report our progress in implementing this new algorithm in a two-dimensional slab testbed code suitable for studies of ion-temperature-gradient and collisionless drift instabilities with electromagnetic modification.

We have also developed a one-dimensional general-hybrid "quiet- δf " code. The distribution function is split into a local Maxwellian and a kinetic remainder. At each timestep, the resulting fluid-equation components of the system are evolved with a standard fluid push, while the kinetic δf remainder is evolved via a direct nonlinear δf -particle push. The code correctly reproduces the frequencies and growth and damping rates of plasma oscillations and beam-plasma instabilities. The code is useful, both for one-dimensional applications and as a test-bed code for multiple-timescale schemes that are expected to be useful in magnetic-fusion-plasma edge-transport and core-turbulence simulations, as well as in space-plasma and ICF simulation. The results of the above test cases and from comparisons of the quiet- δf algorithm with a "standard" nonlinear- δf algorithm³ and with standard PIC will be shown.

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Gyrokinetic-Magnetohydrodynamic Simulation of MHD Instabilities in Tokamak Plasmas with Reversed Shear *

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Recent experiments on TFTR and DIII-D have shown greatly improved particle and ion thermal confinement in the central region of plasmas with a reversed magnetic shear configuration. In the current study we focus on these types of plasmas in order to study their stability to MHD modes in the presence of a significant energetic particle population. Special attention is paid to the high- β regime which will be relevant for future fusion reactors. We use a nonperturbative treatment of the energetic particle dynamics for Alfvén instabilities excited by energetic particles [1, 2] to study modes over the full range of frequencies ranging from low frequency kinetic ballooning modes (KBM) to high frequency toroidal Alfvén eigenmodes (TAE). This type of treatment is required for present-day high-power heating experiments (and future reactors) where the energetic particles typically constitute a significant fraction of the total plasma energy and, thus, may not be simply considered as perturbations to the nominally existing MHD modes. In particular, treating the energetic particle dynamics on the same status as that of the core plasma (i.e., nonperturbatively) has the important consequence of introducing new unstable modes and significantly modifying the existing modes. These energetic-particle modes (EPM) have frequencies in the range of the characteristic energetic-particle frequencies such as transit, bounce, and precession frequencies. In addition, since the kinetic instability drive of the energetic particles is mainly due to the pressure gradient, it can be expected that the instability growth rate tends to scale with ω_{*pE} and therefore with the toroidal mode number n . Thus, instabilities favor high- n modes, and for this reason we adopt a ballooning formulation for our current study. On the other hand, the finite orbits of the energetic particles tend to limit the maximal n , and the maximum growth rate of the mode tends to occur for $k_\theta \rho_E \sim \mathcal{O}(1)$ where k_θ is the poloidal wave number and ρ_E is the energetic particle gyroradius. Furthermore, since the mode frequency is much lower than the energetic particle gyrofrequency we use a gyrokinetic formulation for the energetic particle dynamics. An initial value problem formulation is developed for easy extension to the nonlinear regime. A solution to the initial value problem is obtained through the application of a hybrid numerical scheme in which a set of MHD fluid equations are solved along with a gyrokinetic vlasov equation for the energetic particles.

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Synergism Between Profile and Cross Section Shape Optimization for Negative Central Shear Advanced Tokamaks

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The Advanced Tokamak (AT) concept is aimed at achieving high beta, high confinement, and a well aligned high bootstrap current fraction in a tokamak configuration consistent with steady state operation. The required improvements over the simple 0-D scaling laws, normally used to predict standard, pulsed tokamak performance, are obtained by taking into account the dependence of the stability and confinement on the 2-D equilibrium; the planned TPX experiment was designed to take full advantage of both advanced profiles and advanced cross-section shaping.

Systematic stability studies of the promising Negative Central Shear (NCS) configuration have been performed for a wide variety of cross-section shapes and profile variations. The ideal MHD beta limit is found to be strongly dependent on both and, in fact, there is a clear synergistic relationship between the gains in beta from optimizing the profiles and optimizing the shape. Specifically, for a circular cross-section with highly peaked profiles, β is limited to normalized β values of $\beta_N = \beta/(I/aB) \sim 2\%$ (mT/MA). A small gain in beta can be achieved by broadening the pressure; however, the root-mean-square beta (β^*) is slightly reduced. With peaked pressure profiles, a small increase in β_N over that in a circular cross-section is also obtained by strong shaping. At fixed q , this translates to a much larger gain in β and β^* . With both optimal profiles and strong shaping, however, the gain in all the relevant fusion performance parameters is dramatic; β and β^* can be increased a factor 5 for example. Moreover, the bootstrap alignment is improved. For an optimized strongly shaped configuration, confinement, beta values, and bootstrap alignment adequate for a practical AT power plant appear to be realizable. Data from DIII-D supports these predictions and analysis of the DIII-D data will be presented.

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Finite Element Modelling of Transport and Drift Effects in Tokamak Divertor and SOL*

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A finite element code is used to simulate transport of a single-species plasma in the edge and divertor of a tokamak. The physical model is based on Braginskii's fluid equations for the conservation of particles, parallel momentum, ion and electron energy. In modelling recycling, transport of neutral density and energy is treated in the diffusion approximation. The electrostatic potential is obtained from the generalized Ohm's law. It is used to compute the electric field and the associated $\mathbf{E} \times \mathbf{B}$ drift. In a first approximation, transport is assumed to be ambipolar. The system of equations is discretized on an unstructured triangular mesh, thus permitting good spatial resolution near the X-point and an accurate description of divertor plates of arbitrary shape. Special care must be taken to prevent numerical corruption of the highly anisotropic thermal diffusion. Comparisons will be made between simulations and experimental results from TdeV. This will focus, in particular, on density and temperature profiles at the divertor plates, and on the plasma parallel velocity in the SOL. The asymmetry in the power deposited to the inner and outer divertors and the effect of magnetic field reversal will be considered. Comparisons with B2-Eirene simulation results will also be presented.

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Ideal Stability Limits of Reverse Shear Equilibria*

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The dependence on various plasma parameters of the ideal stability limit of reverse shear current profiles in TFTR and other tokamaks has been thoroughly explored. Profiles with reverse shear allow core access to the second ballooning stability region. In addition, for sufficient shear reversal, modes with $n = 2$ and greater are also stabilized. The $n = 1$ stability threshold is only slightly affected by reverse shear and becomes the limiting instability. The mode is predominately an infernal mode with a significant external contribution. Particular emphasis will be on analysis of recent experimental results of enhanced reverse shear (ERS) profiles in TFTR and a study of those profile characteristics which optimize TFTR performance.

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Progress on CORSICA 3: Coupling 3D Turbulence to 1D Transport in Tokamaks*

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Self-consistent quantitative modelling of surface-averaged radial profiles, which both drive and evolve under the influence of small-amplitude turbulence, is essential both for understanding transport in present tokamaks and for predicting the performance of future large machines. However, the large separation of transport and turbulence timescales makes straightforward running of 3D turbulence codes on the long, transport timescale prohibitively expensive. An efficient method for numerical solution of the scale-separated equations has been previously reported using the 2D Hasegawa-Wakatani equations as the turbulence model.¹ Both local and global versions have been implemented; the latter correctly accounts for all nonlocal effects and achieves a significant CPU-savings. Algorithms have been successfully devised to treat problematic cases, e.g., $\Gamma \frac{\partial n}{\partial x} > 0$.

CORSICA 3 represents the first self-consistent inclusion of turbulent transport into the CORSICA code, LLNL's global tokamak numerical simulation project. A multi-field extension of the above algorithm has been used to couple the 3D toroidal radially local gyrofluid turbulence code GRYFFIN to the 1D core-transport module of CORSICA. Preliminary results were reported in Ref. 2. In this paper we present our recent progress. Whole-cross-section steady-state coupled simulations will be presented, with most CORSICA and GRYFFIN fields treated self-consistently. The status of our PVM implementation on various platforms (CORSICA on workstations coupled to GRYFFINs on T3D, c.f. all on C90) will be discussed.

In addition, an application to GRYFFIN of a recently developed "quasiradial" Fourier transform will be reported. The pseudospectral calculation in ballooning coordinates of the derivative $(\partial/\partial r)$ in the *physically radial* direction is made much more accurate if the alias of the radial wavenumber in the lowest Brillouin zone [i.e., $k_x \bmod(N_x)$] is used.³ The resulting numerical representation is essentially equivalent to the quasiballooning representation and provides a very easy way to realize large performance gains in existing ballooning-coordinate pseudospectral codes.

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Nonlinear Theory of Ballooning Modes with Electron Compressibility[†]

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Bispectral analysis of BES (Beam Emission Spectroscopy) data from high temperature TFTR tokamak plasmas indicates the presence of growing modes at long poloidal wavelengths ($m \approx 10 \sim 15$).¹ Motivated by these results, a theory of ballooning modes with parallel electron compressibility and diamagnetic effects has been developed.² It was shown that electron compressibility acts similarly to resistivity in reducing the stabilizing effect of field line bending and a fast growing mode at low poloidal wavenumbers was found. These modes, however, persist even in the high temperature limit where the effects of resistivity are negligible. The growth rate associated with these modes, $\gamma_P = c_s[(1 + T_i/T_e)^2 |k_\theta \rho_s| / R^2 L_n]^{1/3}$, is very fast.

In this work we present the nonlinear theory of ballooning modes with electron compressibility. The range of unstable poloidal mode numbers is narrow ($m \approx 10 \sim 20$). These modes saturate through coupling to a broad band of weakly dissipative modes ($m > 20$). Statistical closure theory is used to calculate the nonlinear diffusivity acting on the growing modes.³ The linear modes and the nonlinear saturation are dominantly electrostatic. Estimates of the fluctuation levels and nonlinear mode width will be presented.

[†]Research supported by U.S. DoE grant DE-FG02-86ER53218.

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Enhancement of Particle-Wave Energy Exchange by Resonance Sweeping*

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When the resonance condition of the particle-wave interaction is varied adiabatically, the particles trapped in a wave are found to form phase space holes or clumps that enhance the particle-wave energy exchange. This mechanism can cause increased saturation levels of instabilities and even allow the free energy associated with instability to be tapped in a system in which background dissipation suppresses linear instability.

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Kinetic Modeling of Electron Transport in C-Mod and DIII-D Tokamaks*

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We present results from a kinetic simulation of parallel electron transport in the scrape-off-layer of C-Mod and DIII-D tokamaks. Modelling is carried out using the 1D2V Fokker-Planck code ALLA.¹ In our model electrons can evolve in the Braginskii electric field and collide with Maxwellian background plasma which is taken to match available experimental measurements and assumed to be frozen. We start with C-Mod detached and attached profiles, obtained from reconstructions of the experimental data² using a heat conduction model. We use different plasma profiles and have improved the numerical model used in our previous work.³ Next we use DIII-D profiles taken from an advanced two-dimensional simulation performed with the fluid code UEDGE.⁴ We find significant deviations of the electron distribution function from Maxwellian for both cases. This results in a substantial modification of the heat conduction coefficient and effective plasma and neutrals reaction rates with respect to the equilibrium quantities. We also evaluate how the non-Maxwellian tail of the electron distribution function affects the divertor and reciprocating probe measurements. Finally we present a comparison of non-local features of parallel electron transport in the C-Mod and DIII-D tokamaks.

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Nonlinear TAE Instability Driven by Trapped Particles*

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TAE (toroidal Alfvén eigenmode) instabilities excited by ICRF heating are due to the resonant coupling of energetic “trapped” particles. A single unstable mode nonlinearly saturates when there is ‘flattening in phase space’ of the particle distribution function in the neighborhood of the resonant particles or the perturbed particle excursion becomes comparable to the ‘internal’ radial mode width. We derive a ‘pendulum’ equation to describe the resonant particle motion and we obtain estimates of the single mode saturation amplitude using either energy conservation requirements or calculation of the radial particle excursions. We compare these estimates with computer simulations in which the TAE eigenfunction is modeled by simplified ‘test’ functions. We explore scenarios in which overlap of ‘resonant surfaces’ may occur for a spectrum of unstable modes with these estimated mode amplitudes and thereby result in global phase space diffusion and the enhanced loss of energetic particles. We compare the magnitude of the associated perturbed magnetic fields with the results of experiments in which losses of energetic particles have been observed when TAE modes are driven unstable by ICRF heating.

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GEOMETRICAL APPROACH TO HAMILTONIAN FLUIDS

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Differential geometry based on the Cartan calculus of differential forms is applied to investigate invariant properties of equations that describe the motion of continuous media. The advantage of geometrical methods is that they provide an universal approach to the problem of invariance in hydrodynamics and magnetohydrodynamics.

The main feature of the approach is that the hydrodynamic quantities are considered as geometrical objects and that the notion of invariance is formulated in terms of Lie derivatives. The solutions of the equations for invariant fields can be written in terms of Lagrange variables. This gives a generalized Cauchy formulation. A procedure for the construction of invariant fields using operations of differential geometry is presented.

The formalism for finite-dimensional, canonical systems is extended to the case of continuous media. Similar to finite-dimensional systems, Hamiltonian fluids are defined as those that conserve some exact two-form. It is shown that the equations of motion of charged barotropic fluids and of ideal plasmas belong to this class of equations. New type of scalar invariants for Hamiltonian fluids are constructed.

It is the opinion of the authors that the application of these methods will be very fruitfull for the future development of the theory of fluid and plasma dynamics.

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Fractional Kinetics and Accelerator Modes

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Abstract

Kinetic properties of chaotic dynamics are studied for the web-map. It is shown that depending on the values of the perturbation parameter K , there are alternative possibilities: kinetics, of the quasilinear (normal, i.e. Gaussian) type or kinetics of the anomalous (Lévy) type. If K is close to the values $K = \ell\pi$ when the accelerator modes occur, then there is superdiffusion with anomalous values of the transport exponent. We consider self-similar properties of trajectories near the islands in the phase space. Fractional kinetic equation is proposed and fractal exponents are obtained. Local properties of trajectories (exit time) and nonlocal ones (Poincaré cycles) are studied and compared for the normal and anomalous kinetics. It is shown that the power-like law of the trapping distribution function imposes the same kind of asymptotics for the Poincaré cycles distribution.

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Stability of the $n = 1$ Internal Kink Mode in Equilibria with Flows*

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Stabilizing influence of mass flows, either directly or through their “shearing” action, on various modes is now generally recognized. Here we examine linear and nonlinear stability of the $n = 1$ internal kink mode in equilibria with toroidal rotation, using our nonlinear, initial-value MHD code CTD, which can be used to generate self-consistent equilibria with flows in arbitrary geometries.

It is well known[†] that equilibrium mass flows introduce complications in determination of MHD equilibria and their stability properties, such as the loss of self-adjointness and an increase in the number of conditions required to uniquely determine the equilibria. Thus, even with purely toroidal flows, an implicit statement about the equation of state is needed, in addition to a knowledge of the magnetic field and velocity profiles; rotation in an adiabatic plasma leads to a different equilibrium than, for example, in an isothermal one, with possibly quite different stability properties.

We find that the expected stabilizing influence of toroidal rotation on $n = 1^{\ddagger}$ is generally absent in adiabatically generated equilibria in which, of all the relevant thermodynamic variables, only the specific entropy is a flux function, $s = s(\psi)$. Fortunately, physically more relevant isothermal case where the temperature is constant on flux surfaces, $T = T(\psi)$, has more favorable stability characteristics. On the other hand, an inconsistent but common practice of ignoring density perturbations, a benign omission for static equilibria, leads to overly optimistic results when equilibrium flows are present, predicting stability when there may not be any. The crucial role played by the equation of state in determining equilibrium raises questions regarding the role of parallel transport in stability calculations; this and other nonideal effects, along with the role of plasma β vs. the rotational β , and nonlinear stability when the mode is pushed beyond marginality, will be discussed.

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Classical Convective Energy Transport in Large Gradient Regions

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Large gradients in density and temperature occur near the edge in H-mode plasmas and in the core of tokamak plasmas with negative central shear. Transport in these regions may be comparable to neoclassical. Standard neoclassical theory does not apply when the gradient lengths are comparable to an ion orbit excursion, or banana width. A basic question for neoclassical transport in large gradient regions is: do ion-ion collisions drive particle transport? Near the plasma edge in H-mode, where ion orbit loss requires that the ion energy transport be convective, neoclassical particle transport due to ion-ion collisions may play an important role. In negative central shear plasmas, where transport is inferred to be near neoclassical, it is important to have accurate predictions for the neoclassical rate of energy and particle transport.

A simple 2-D slab model has been used, with a momentum-conserving collision operator, to show that ion-ion collisions do drive particle transport. When the gradients are large, the "field particle" contribution to the particle flux is non-local, and does not cancel the "test particle" contribution, which is local. Solutions of the kinetic equation are found which show that the steepness of the density profile, for increasing particle flux, is limited by orbit averaging. The gradient length is limited by the thermal gyroradius, and the convective energy flux is independent of ion temperature. This will allow an ion thermal runaway to occur, if there are no other ion energy loss mechanisms.

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Simulation of the Xerographic Recharge Process

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Laser xerography (e.g. laser printing, photo-copying, etc.) involves the sequential steps: uniform charging of the photoconductor surface, discharging spots with a laser beam, developing the latent image on the photoconductor surface by the attachment of charged toner particles, and finally transferring the image to paper through mechanical and electrostatic forces. Simulations have been developed that model these process from first-principles[1].

Color reproduction involves multiple passes through these steps; once for each color separation (e.g. multiple toner layers on the photoconductor). Here we study the charging of the photoconductor surface, in situations of high mass-coverage with a 2D fluid model, and low mass coverage with a 3D particle model. Charge is sprayed using a corona type discharge called a scorotron.

We are developing a 2D fluid model of the recharge process based on extending existing models[1,2]. We use empirical I-V data for the scorotron. A Boundary Integral Equation Method (BIEM) is used to solve for the field, and method of characteristics (MOC) to solve the charge continuity equation. Also developed, is a 3D particle model, where the field is solved using 3D BIEM and ionized air molecules are treated as point charges which follow their average drift motion. Diffusion can be neglected because of the high voltage bias. Toner particles are treated as finite size spherical dielectrics with nonuniform attached surface charge.

We will show initial numerical results for both models. The purpose of this work is to develop a better understanding of how charge is transported through the toner layers in subsequent recharging during color laser xerography.

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Relabeling Symmetries in MHD*

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Lagrangian symmetries associated with the relabeling of fluid elements are found for hydrodynamics and magnetohydrodynamics (MHD). In hydrodynamics this results in Ertel's theorem of conservation of potential vorticity, while in MHD it yields the conservation of cross helicity and a new invariant which is a generalization of magnetic helicity. We also show that the reduction from Lagrangian to Eulerian variables for a fluid has the same symmetry and use it to construct the Casimir invariants of the Hamiltonian formalism.

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Deducing Noninductive Current Profile From Surface Voltage Evolution

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Solving the resistive diffusion equation in the presence of a noninductive current source determines the time-evolution of the surface voltage. By inverting the problem the current drive profile can be determined from the surface voltage evolution. We show that under wide range of conditions the deduced profile is unique. If the conductivity profile is known, this method can be employed to infer the noninductive current profile, and, ipso facto, the profile of the total current. We discuss the application of this method to analyse the Alfvén wave current drive experiments in Phaedrus-T.

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**EXPLANATION FOR MARFE FORMATION
AND SUBSEQUENT EVOLUTION INTO A
DETACHED SYMMETRIC PLASMA EDGE**
Sherwood 1996

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A linear thermal stability analysis leads to expressions for the maximum impurity densities for which edge plasma modes with different poloidal mode number, m , are stable against thermal, edge localized instabilities. The density limits are higher for the $m > 0$ modes than for the $m = 0$ mode because of the stabilizing effect of parallel thermal conduction on the former, and the density limits are successively higher for the successive m -modes because of the higher associated parallel temperature gradients. When atomic physics effects are taken into account, it is found that the strong positive temperature dependence of the ionization cross section in the temperature range around 10 eV provides a strong stabilization mechanism which acts to reduce the impurity density limits for all modes.

These results provide an explanation for the experimentally observed tokamak phenomenon of a symmetric radiating edge evolving with increasing density into a MARFE and then cooling into a detached plasma with a symmetric edge that radiatively exhausts essentially all the heating power. As the edge impurity density increases, first the $m = 0$ mode density limit is exceeded, causing the edge plasma to evolve into a mixture of $m > 0$ modes which becomes more highly asymmetric as the density increases further and exceeds the density limits of successively higher modes, forcing the plasma into the remaining stable higher- m modes--the stable MARFE. If the radiative cooling of the edge is sufficient to reduce the temperature to $T_e \approx 10$ eV, the various thermal modes are stabilized by the strong positive temperature dependence of the ionization cooling in the presence of neutral atoms, the impurity density limits are thereby reduced, and the plasma edge evolves back into a stable $m = 0$ mode. On the other hand, if the plasma becomes highly enough asymmetric before sufficient cooling takes place, nonlinear effects drive a disruptive collapse of the radial temperature distribution. From this comes a suggestion for MARFE avoidance; increase the impurity density in the cooling plasma edge so as to remain below the increasing (with decreasing temperature) impurity density limit for the $m = 0$ mode.

This explanation is in semi-quantitative agreement with observations in TEXTOR and TFTR neon injection experiments which evolve into detached plasmas. With the further assumption that the plasma in front of the divertor plate is strongly connected to the edge plasma by rapid thermal transport, this explanation also agrees qualitatively with observations in diverted plasmas in ASDEX-U and DIII-D, although the observation of MARFEs in the divertor in DIII-D indicates that the divertor needs to be included in the edge stability analysis for diverted plasmas.

The $m = 0$ impurity density limit is in good quantitative agreement with limiting densities found in 1.5D transport simulations of the ITER plasma edge for the injection of iron and krypton, implying that impurity density limits identified in 1.5D simulations are actually MARFE density limits, not disruption density limits. Since simulations already indicate that $\approx 2/3$ of the heating power can be radiated to the first wall in ITER, the possibility of developing radiative power exhaust solutions in which essentially all the heating power is radiated to the first wall is encouraged by this finding.

Magnetic Reconnection in Collisionless Regimes with Reversed Shear*

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The observed persistence of plasma regimes with reversed, or nonmonotonic, q and current density profiles and the improved confinement associated with some of them suggest the conclusion that magnetic reconnection processes in collisionless plasmas are rarely strong enough to destroy these plasma configurations. We propose that this weakness should be consistent with the process that has been hypothesized to allow for the occurrence of magnetic reconnection in similar, non-reversed conditions where the resulting modes and magnetic islands are observed, that is, an underlying state of microturbulence. In those cases, the laminar collisionless driving process, the electron inertia, was far too weak to permit the formation of significant islands. Microturbulence, however, has been shown [1,2] to be capable of allowing the development of a consistent instability. In the case of reversed shear configurations, a process that reduces the microturbulence, that should also be associated with the improved plasma confinement within the reversed shear region, may be responsible for the observed stability to macroscopic magnetic reconnection as well.

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Reversed Shear Operation for High Field Ignition*

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The improvement of plasma confinement that has been observed during the operation of neutral beam heated tokamaks with nonmonotonic current and q profiles ("reversed shear") introduces the possibility of a new regime of D-T ignition at low density and very low fusion power in high field, magnetically confined plasmas. Reversed shear current profiles should be attainable with modest amounts of auxiliary heating, for discharges running at parameters that are well below the maximum design values that are intended to support full field ohmic or low-auxiliary-power ignition in such machines. In the reversed shear ignition scenario, the current ramp plays an important part in efficient plasma heating to ignition, as well as in establishing the current profile. Reversed shear conditions can be established part way into the initial current ramp-up phase of a discharge. Enhancement of the energy confinement during this part of the ramp provides the optimal heating path to ignition and minimizes the external heating requirement and the fusion power at ignition. The degree of shear reversal decreases with time after the end of the current ramp, and particularly with the time spent at sub-ignition temperatures. The minimum q falls below two, but can easily be kept well above unity. Machines that can achieve high magnetic fields are likely to gain the greatest benefit from reversed shear ignition. Detailed examples of reversed shear scenarios are shown for the Ignitor-Ult [1].

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

[1] B. Coppi, M. Nassi, L.E. Sugiyama, *Phys. Scripta* 45 112 (1992).

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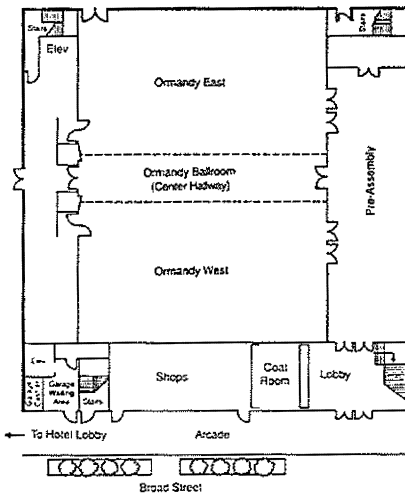
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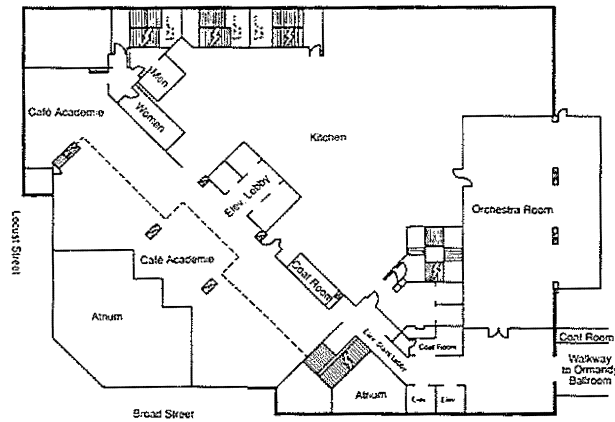
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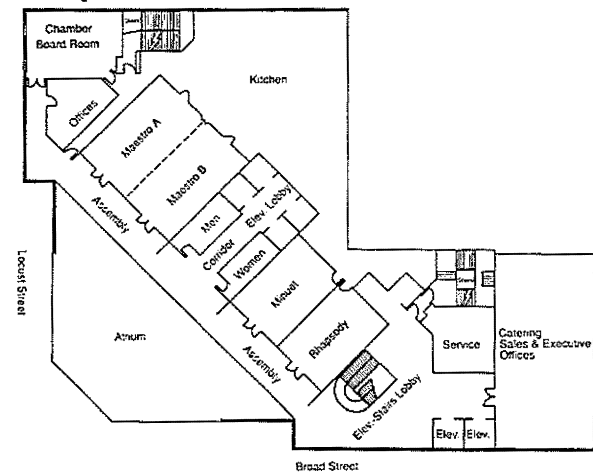
The Ormandy Ballroom Lobby Level



Restaurant Level Second Floor



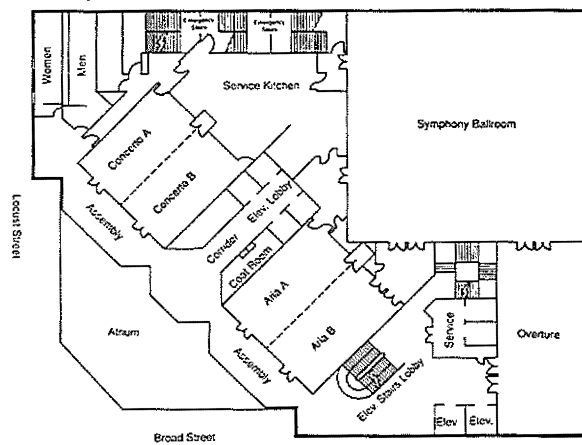
Meeting Level Fourth Floor



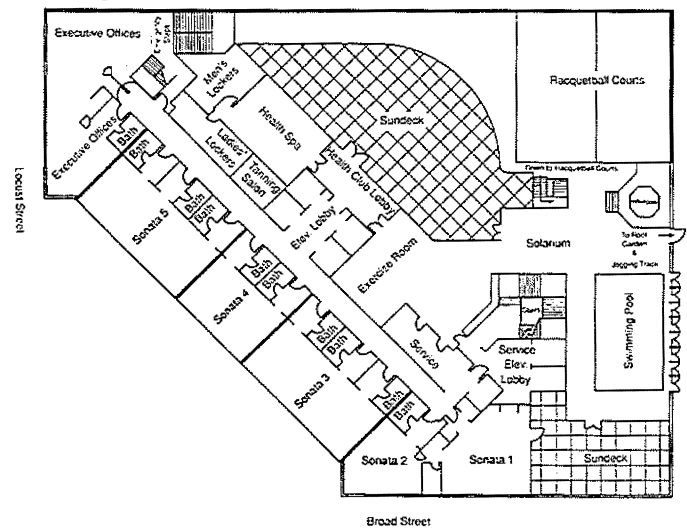
Floor Plan

Doubletree Hotel
Philadelphia, Pennsylvania

Meeting Level Third Floor



Meeting/Recreation Level Fifth Floor



Review and Oral Presentations: Ormandy Ballroom (lobby level)
Poster Presentations: Symphony Ballroom (third floor)