IAEA Technical Committee Meeting on First Principle-Based Transport Theory

June 21-23, 1999
Kloster Seeon, Germany

Abstracts

IPP 5/87

June 1999

IAEA Technical Committee Meeting on First Principle -Based Transport Theory

June 21-23, 1999

Kloster Seeon, Germany

Hosted by

Max-Planck-Institut für Plasmaphysik, Garching

International Programme Committee
D. Biskamp
J. Connor
C. W. Horton
K. Itoh
K. H. Spatschek
W. M. Tang
J. Vaclavik

Local Organizing Committee
D. Biskamp
K. H. Spatschek
A. Zeiler

IAEA Scientific Sectretary
T. Dolan

Conference Secretary
Mrs. Ch. Stahlberg

Conference programme

Monday morning *(chairman: R. Waltz)*

8:15-8:30	opening
8:30-9:30	**Z. Lin** (review): *Turbulent transport in the tokamak core plasma*
9:30-10:00	--- coffee break ---
10:00-12:00	**W. Dorland, M. Kotschenreuther**: *ETG turbulence*
	W. Horton, P. Zhu, T. Tajima, P.J. Morrison, Y. Kishimoto, J.-M. Kwon, D.-I. Choi: *Transport Barriers in optimized shear toroidal confinement*
	F. Jenko: *(3+2)D Vlasov simulations of drift wave turbulence*
	D.R. Mikkelsen, G. Taylor, W. Dorland, M. Greenwald, A. Hubbard, J. Irby, E. Marmar, D. Mossessian, J. Rice, S. Wolfe: *Temperature gradient scale lengths in C-mod, theory and experiment*

Monday afternoon *(chairman: A. Thyagaraja)*

14:00-15:00	**P.H. Diamond** (review): *Turbulence suppression, shear amplification and transport bifurcation dynamics*
15:00-15:30	**V. Naulin, J. Juul Rasmussen**: *Cross field plasma transport and poloidal flows*
15:30-16:00	--- coffee break ---
16:00-18:00	Poster session

Tuesday morning *(chairman: G. Hammett)*

8:30-9:30	**B.N. Rogers** (review): *Turbulent transport in the tokamak edge plasma*
9:30-10:00	--- coffee break ---
10:00-12:30	**J. Connor, P. Helander, H.R. Wilson**: *Transport at the plasma edge*
	K. Hallatschek, A. Zeiler, D. Biskamp: *Nonlocal simulation of the transition from ballooning to ITG mode turbulence in the tokamak edge*
	Sanae-I. Itoh, K. Itoh: *Statistical theory of subcritically-excited strong turbulence in inhomogeneous plasmas*
	X.Q. Xu, R.H. Cohen, G.D. Porter, T.D. Rognlien, J.R. Myra, D.A. D'Ippolito, R. Moyer: *BOUT model of boundary turbulence in divertor geometry*
	M. Yagi: *Transport simulation based on MHD transport model*

Tuesday afternoon: excursion

Wednesday morning *(chairman: H. Wobig)*

8:30-9:30	**X. Garbet** (review): *Global aspects of turbulent transport in tokamak plasmas*
9:30-10:00	--- coffee break ---
10:00-12:00	**R. Grauer**: *Singular structures in fast reconnection*
	M. Ottaviani, G. Manfredi: *Global fluid simulations of ITG turbulence*
	B. Scott: *ExB shear flows and electromagnetic gyro-fluid turbulence in realistic tokamak geometry*
	A. Thyagaraja: *A computational approach to mesoscale plasma dynamics in tokamaks*

Wednesday afternoon *(chairwoman: S. Itoh)*

13:30-14:30	**J. Nührenberg** (review): *Neoclassical transport in stellarators*
14:30-16:30	**P. Helander, Tünde Fülöp**: *Nonlinear neoclassical transport theory for the tokamak edge*
	A.L. Rogister: *Determination of H mode profiles from revisited neoclassical theory and the concept of turbulence quench by rotation shear*
	D.J. Sigmar, P. Helander: *Neoclassical transport at low aspect ratio*
	H. Wobig: *Destruction of drift surfaces in toroidal systems*

Poster session

(Monday afternoon 16:00-18:00)

p01	**C. Angioni, O. Sauter**	*Computation of neoclassical transport coefficients in general axisymmetric equilibria and arbitrary collisional regime*
p02	**M.A. Beer, G.W. Hammett**	*Turbulence-driven zonal flows in gyrofluid simulations*
p03	**C.D. Beidler, H. Maaßberg**	*Ripple-averaged kinetic theory for stellarators*
p04	**J.C. Bowman, A. Zeiler, D. Biskamp**	*A multigrid algorithm for nonlocal collisional electrostatic drift-wave turbulence*
p05	**G.L. Falchetto, J. Vaclavik, M. Maccio, S. Brunner, L. Villard**	*Application of the ballooning transform to trapped ion modes*
p06	**G.W. Hammett, M.A. Beer, W. Dorland, M. Kotschenreuther, P.B.Snyder**	*Issues in gyrofluid turbulence simulations and in theory-based transport models*
p07	**R. Hatzky**	*Simulation of ion-temperature-gradient-driven (ITG) modes: on the way to W7-X*
p08	**Yu. Igitkhanov, O. Pogutse**	*Physics of LH transition and type III ELMs: scaling properties and dimensional analysis*
p09	**G. Jost, T.M. Tran, K. Appert, W.A. Cooper, L. Villard**	*First global linear gyrokinetic simulations in 3D magnetic configurations*
p10	**Y. Kishimoto, J.Y. Kim, W. Horton, J.N. Leboeuf, T. Matsumoto, Y. Ishii, J.Q. Li, S. Dettrick, T. Tajima, H. Shirai**	*Turbulent structure and flow generation from toroidal ITG mode in weak/reversed magnetic shear plasma*
p11	**R. Kleiber**	*Resistive drift instability for a sequence of l=2 stellarators*
p12	**S.B. Korsholm, P.K. Michelsen, V. Naulin, J.Juul Rasmussen**	*Poloidal flows and transport in non-periodic 3D simulations of the Hasegawa-Wakatani model*
p13	**D. Li**	*Coulomb collision and classical transport in plasma*
p14	**M. Maccio, J. Vaclavik**	*Effect of strong electric fields on ITG modes linear stability using a global gyrokinetic model*
p15	**V.S. Mikhailenko, V.V. Mikhailenko, K.N. Stepanov**	*Initial value problem solutions for Hasegawa-Wakatani equations for plasma with radial electric field shear*
p16	**W.C. Müller, D. Biskamp**	*Macroscopic and statistical properties of three-dimensional magnetohydrodynamic turbulence*
p17	**A.G. Peeters, R. Dux**	*Neoclassical transport calculations in the ASDEX Upgrade geometry*

p18	**S. Puri**	*Anomalously enhanced transport via Kirchhoff radiation*
p19	**X.M. Qiu**	*Pinches-induced transport reduction in reversed shear/optimized shear tokamak plasmas*
p20	**A.L. Rogister, J. Weiland, J. Ongena, M.-Z. Tokar**	*Numerical simulation of rotation and confinement in TEXTOR high density discharges*
p21	**M. Romanelli, M. Ottaviani**	*Ion transport in rotating tokamak plasmas in the presence of heavy impurities*
p22	**K.H. Spatschek, S. Abdullaev, D. Lesnik**	*On the construction, statistical analysis, and control of maps for magnetic field line transport in an ergodic divertor*
p23	**T.M. Tran, J. Vaclavik, K. Appert**	*Global gyrokinetic simulation of electromagnetic instabilities using particles*
p24	**V.S. Tsypin, I.C. Nascimento, R.M.O. Galvao, A.G. Elfimov, M. Tendler, G.S. Amarante Segundo**	*Suppression of anomalous and neoclassical transport in tokamaks by Alfven waves*
p25	**R.E. Waltz, J. Candy, F. Hinton, M.N. Rosenbluth**	*Full radius electromagnetic gyrokinetic turbulence code*
p26	**A. Zeiler, J.F. Drake, B.N. Rogers**	*Electromagnetic ITG mode turbulence at the plasma edge*

Turbulent transport in the tokamak core plasma

Z. Lin

Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA

Significant progress has been made in understanding tokamak core turbulent transport, which is generally believed to arise from low frequency electrostatic pressure-gradient driven instabilities. In particular, considerable insight has been obtained in the scaling of ion thermal transport and the mechanism of turbulence suppression by shear flows. The lack of a generally accepted fundamental theory of plasma turbulence motivates the development of direct numerical simulation methods. The interaction between experiment, theory, and computation propels rapid progress toward a quantitative interpretation of the dynamical processes underlying the turbulent transport. Most of the recent computational work focuses on the ion temperature gradient (ITG) instability. As a result, fundamental understanding of the ITG turbulence is emerging. Recent gyrokinetic and computational advances in this area will be highlighted.

In collaboration with T. S. Hahm, W. W. Lee and W. M. Tang

ETG Turbulence

W. Dorland, M. Kotschenreuther*
Institute for Plasma Research, Univ. of Maryland
*Institute for Fusion Studies, Univ. of Texas

At wavelengths characterized by $k_\perp \rho_e \sim 1$, a drift-type instability (the "ETG" mode) is linearly unstable when $R/L_{Te} > R/L_{Tc}$. Because of the short wavelength of the instability, the ion response is adiabatic. The linear dynamics are very similar to the ITG mode, except that the roles of ions and electrons are reversed. Thus, the length and time scales of the ETG instability are characterized by ρ_e and v_{te}/L_{Te}. At these scales, a simple mixing length estimate of the thermal transport from the ETG instability predicts feeble transport. Thus, with a few exceptions, the ETG mode has not generally been considered to be an important player in anomalous tokamak transport. Here, we present the first three-dimensional, toroidal simulations of the ETG instability. Somewhat surprisingly, and unlike the analogous case of ITG turbulence, we find that the mixing length estimate of thermal losses driven by the ETG mode significantly underpredicts the simulation results. The simulations predict that the electron thermal transport from ETG turbulence is strong enough to force $R/L_{Te} \sim R/L_{Tc}$ for typical experimental conditions. The reason for the large electron thermal transport observed in the nonlinear simulations has been elucidated, and will be described. Experimental implications of these results will also be presented.

Transport Barriers in Optimized Shear Toroidal Confinement

W. Horton[1], P. Zhu[1], T. Tajima[1], P.J. Morrison[1], Y. Kishimoto[2], J.–M. Kwon[3], D.–I. Choi[3]

[1] *Institute for Fusion Studies, University of Texas, Austin, TX 78712*

[2] *Naka Fusion Research Establishment, JAERI, Naka, Ibaraki 310–0195 Japan*

[3] *Department of Physics, KAIST 373–1, Kusung–dong, Yusung–ku, Taejon 305–701, KOREA*

The turbulent transport properties in low magnetic shear toroidal confinement systems are reported and compared with those in reversed magnetic shear (RS). The basic properties of RS systems reported earlier are (1) the breaking of the ballooning mode symmetry with a new local mirror symmetry in its place and (2) the introduction of shearless invariant curves in the guiding center phase space.[1] For toroidal mode number n the radial gap of width $\Delta r_{\rm RS} = (1/nq''_{\rm min})^{1/2}$ at $q_{\rm min}$ separates the drift waves on each side producing the discontinuity model verified with PIC simulations for the 2D mode toroidal convective structures.[2] The result of these processes is to produce an internal transport barrier (ITB). For low shear the density of the drift wave mode rational surfaces is sufficiently low to reduce the toroidal coupling leaving the cylindrical drift wave turbulence. We show that the optimized shear (OS) confinement barriers are explained by the Hamaguchi–Horton E_r–shearing parameter $\Upsilon_s = L_s v'_E/c_s \rightarrow (qR/c_s)d(E_r/RB_p)/dq$ rather than the Hahm–Burrell parameter. For the two JET internal transport barrier discharges we compare the r,t–development of the two E_r–shearing parameters with the onset and radial expansion of the ITB. The change from L–mode confinement to the ITB confinement appears strongly correlated with $\Upsilon_s(r,t)$ parameter measuring the ratio of E_r–shear to magnetic shear. The shredding of the correlated radial mesoscale convective structures responsible for Bohm transport is clearly shown in the particle and fluid simulations.

1. W. Horton, H.–B. Park, J.–M. Kwon, *et al.*, Phys. Plasmas **5**, 3910 (1998).

2. Y. Kishimoto, J.–Y. Kim, W. Horton, *et al.*, 17th IAEA Fusion Energy Conference, CN–69/TH1/2, Yokohama, Japan, 1998.

(3+2)D Vlasov simulation of drift wave turbulence

Frank Jenko

MPI für Plasmaphysik, EURATOM Association, D-85748 Garching, Germany

There are two main reasons for this kind of research: (1) In recent years there has been much progress in the field of turbulence simulation using gyrokinetic ions and adiabatic electrons. It is widely recognized, however, that the next step towards more comprehensive and realistic models involves the inclusion of nonadiabatic electrons which we focus on. (2) Drift wave turbulence is one of the main causes for anomalous transport in the edge of tokamaks. A careful investigation of the relevant plasma parameter regime shows that generally the parallel electron motion is at most weakly collisional. Thus edge turbulence cannot be treated by conventional fluid models which fail to capture important kinetic effects like electron Landau damping. Therefore we use an electromagnetic (finite beta) hybrid model of drift-kinetic electrons and cold ions to examine the basic properties of nonlinear electron dynamics in the collisionless regime. The basic equations are solved numerically on a massively parallel computer using explicit finite-difference methods on a (3+2)D phase space grid.

It is shown that the nonlinear drift instability discovered in collisional fluid models also exists in the collisionless limit. Here electron Landau damping replaces resistivity as the main energy sink of the turbulence. A very important result concerns the trapping of electrons in fluctuations of the electrostatic potential. This nonlinear kinetic effect is observed to diminish the turbulent transport significantly in certain parameter regimes. Because it cannot be modeled by fluid equations, it has been mostly neglected in previous work. It is an interesting feature of the present nonlinear model that it resolves fundamental contradictions between experimental results and (quasi-)linear theory, namely the dependence of turbulent transport on radial position and ion mass. In both cases the dependence on plasma parameters like the density profile scale length $L_n = |\nabla \ln n|^{-1}$ and magnetic shear $\hat{s} = (dq/dr)/(q/r)$ was strong enough to reverse the trends one derives from the gyro-Bohm scaling. Furthermore the system exhibits a particle pinch, i.e., the turbulent particle flux is directed up-gradient for sufficiently high values of η_e. Preliminary comparisons with a companion Landau-fluid model are quite successful in that the observed transport levels are always within 50% of each other in the parameter regime under consideration. More detailed comparisons in wider ranges of parameter space are underway. It is also planned to incorporate gyrokinetic ions in the near future.

Temperature Gradient Scale Lengths in C-mod: Theory and Experiment

D. R. Mikkelsen, G. Taylor
Princeton Plasma Physics Laboratory

W. Dorland
University of Maryland

M. Greenwald, A. Hubbard, J. Irby, E. Marmar,
D. Mossessian, J. Rice, S. Wolfe
Plasma Science Fusion Center, MIT

IAEA Technical Committee Meeting on
First Priciples Based Transport Theory
Kloster Seeon, 21-23 June, 1999

Theoretical estimates of the ITG critical gradient scale lengths from several codes are in agreement, and can be directly tested in C-mod discharges. The IFS-PPPL model predicts that the conducted power rises very rapidly as the temperature gradient scale length, L_{Ti}, decreases below the critical value. The conducted power quickly grows to levels far greater than the available power, so C-mod is expected to be close to marginal stability. This expectation holds even if the gyrofluid calculations of the thermal diffusivities are overestimates by 100-200%. Thus, it should be possible to test the stability 'half' of the transport picture, with minimal dependence on the more controversial estimates of the actual thermal diffusivities. Precise experimental measurements of L_{Te} are possible because it is insensitive to the absolute magnitude of the T_e diagnostic calibration, and the *relative* calibration of the Michelson interferometer at different frequencies (->spatial positions) has very low uncertainty. In C-mod T_e and T_i are tightly coupled so they should have very similar gradient scale lengths. In a number of C-mod discharges the measured L_{Te} are significantly shorter than the IFS-PPPL model's formula for the theoretical critical L_{Ti}. The propagation of experimental uncertainties in L_{ne}, q, Z_{eff}, etc., create uncertainty in the theoretical estimates for the critical L_{Ti} which will be discussed. In addition, the GS2 code will be used to calculate the critical L_{Ti} for ITG mode linear stability for C-mod discharges, and the code results will be compared to experiment and the IFS-PPPL analytic formula.

Turbulence Suppression, Shear Amplification and Transport Bifurcation Dynamics

P.H. Diamond
University of California at San Diego, La Jolla, CA 92093-0319, USA

The basic physics of transport bifurcations due to turbulence suppression is reviewed. Special emphasis is devoted to mechanisms of flow shear amplification by turbulence.

Turbulence may be suppressed, stabilized or quenched by deterministic shearing (due to mean E-fields) or random shearing (due to zonal flows). The physical process at work in all cases is eddy spiral wind-up, which may be either ballistic or diffusive. The detailed impact of eddy wind-up on dynamics varies from case to case, however. Eddy wind-up can affect both fluctuation levels and fluctuation cross phase, in both cases leading to flux reduction. While shear suppression is a popular, frequently invoked mechanism, certain exceptions to the general trend have been identified and will be discussed.

Energy conservation dictates that flow shear amplification by Reynolds work must accompany shear suppression of turbulence. Also, stabilization of fluctuations invariably leads to amplification of the diamagnetic electric field shear. These two mechanisms are the underpinning of all self-consistent shear amplification models, and will be discussed in detail. In general, the combined effects of the Reynolds work and amplification of diamagnetic electric field shear which must accompany turbulence suppression admit the possibility of several routes to transport bifurcation.

The coupled evolution of turbulence, transport and sheared flow is highly nonlinear, so that spatiotemporally propagating bifurcation are possible. We will discuss the bifurcation dynamics in terms of its constituent elements and in terms of the front propagation dynamics which occurs as a consequence. The factors influencing barrier width, speed and location are identified for various models. Special attention is given to the predictions of a simple bifurcation model for the parameter scalings of the width of the H-mode pedestal.

Throughout, an effort is made to relate shearing and transition dynamics infusion plasmas to related phenomena in other areas of physics.

Cross field plasma transport and poloidal flows

V. Naulin and J. Juul Rasmussen

Optics and Fluid Dynamics Department
Association EURATOM-Risø National Laboratory
Risø, DK-4000 Roskilde, Denmark

Using two-dimensional drift-wave simulations the connection between particle transport and the establishment of poloidal (zonal) flows is investigated.
It is shown that the non-linear ion-polarization drift gives rise to a finite particle flux, which persists even in the absence of a phase shift between density and potential fluctuations [1]. The connected transport can be linked to the motion of (monopolar) vortical structures.
Along with the polarization drift induced flux goes a transport of charge, necessary for the buildup of long-range electric fields in the plasma. The averaged polarization-drift transport is equivalent to the well known Reynolds stress, which is observed to be connected to the buildup of radial electric fields in plasmas.
The resulting potential profiles are discussed in connection with the turbulent equipartition [2] of vorticity.

[1] Volker Naulin. Turbulent transport by higher order particle drifts. *Europhys. Lett.* **43**, 533 – 538, 1998.
[2] Volker Naulin, J. Nycander, and J. Juul Rasmussen. Equipartition and transport in two-dimensional electrostatic turbulence. *Phys. Rev. Lett.* **81**, 4148 – 4151, 1998.

Turbulent Transport in the Tokamak Edge Plasma

B. N. Rogers

Institute for Plasma Research, University of Maryland, College Park, MD 20742, USA

Turbulent transport in the tokamak edge region is strikingly different from the conventional η_i-mode driven turbulence predominating in the core plasma due largely to the small values of $L_n/R \sim 10^{-2}$ in the edge. Recent efforts to model this edge transport, based mainly on three dimensional simulations of the Braginskii equations, indicate the edge turbulence arises from relatively long-wavelength ($k_\perp \rho_i \ll 1$) instabilities that are destabilized by a combination of resistivity and electron inertia. These modes fall into one of two classes depending on the parameter regime, in particular on the strength of diamagnetic effects: resistive ballooning modes (weak diamagnetic regime) or drift waves (strong diamagnetic regime). In the strong diamagnetic regime, by definition, diamagnetic effects are sufficient to effectively stabilize resistive ballooning modes, thereby allowing the (weaker) drift wave instability to emerge as predominant. The edge parameters of H-mode discharges appear to fall exclusively in this strong diamagnetic limit, while L-mode discharge parameters represent a mixture of the two regimes. Electromagnetic effects, the strength of which are controlled by the normalized edge pressure gradient $\alpha \sim -q^2 R\beta'$, have a dramatic and opposite impact on the turbulent transport in the two cases. In the weak diamagnetic limit, increasing α leads to a strong enhancement of transport well below the threshold for ideal ballooning instability. Some experimental evidence suggests this effect may be correlated with density limit disruptions. In the strong diamagnetic limit, on the other hand, increasing α leads to a strong suppression of turbulence. Comparisons to experiment as well as numerical simulations suggest this suppression may be associated with the L-H transition. Some simulations of this transition have been carried out by introducing a fueling source into the Braginskii model. These simulations show the edge pedestal pressure gradient following the transition may steepen well beyond the first ideal ballooning stability limit due to a combination of stabilizing factors, including ion diamagnetic effects, $\vec{E} \times \vec{B}$ shear, and the finite radial localization of the pedestal pressure gradient.

Transport at the Plasma Edge

J W Connor, P Helander and H R Wilson
EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK

Abstract

Core transport models can display considerable sensitivity to the edge pedestal temperature, T_{ped}, so an understanding of the height of the H-mode transport barrier is important. This in turn depends on the width of the barrier, Δ, and the pressure gradient that it can sustain. A common view is that the transport barrier arises from the suppression of turbulent transport by a sheared radial electric field, E_r; this electric field can result from poloidal flows, V_θ, or the ion pressure gradient, dp_i/dr. In the former case the Reynolds stress arising from the radial structure of ballooning drift waves at the plasma edge suggests a width $\Delta \propto \rho_i^{2/3} a^{1/3}$, where ρ_i is an ion Larmor radius; a calculation of the limiting pressure gradient from MHD ballooning modes at the plasma edge then provides a scaling for T_{ped}. In the latter case a self-consistent treatment of profile curvature in calculating dE_r/dr is found to prevent the simple bifurcation to, say, neoclassical transport, obtained with simplified 'local' models where only profile gradient terms are retained. However, the transport fluxes resulting from this self-consistent theory are sensitive to boundary condition, such as those associated with the scrape-off layer (SOL), and these might lead to transitions in confinement. These considerations rely on simple fluid plasma models: when gradient lengths are comparable with the poloidal ion Larmor radius, a kinetic model is needed to calculate the transport properties and profiles at the plasma edge. If turbulent transport in the edge barrier is suppressed, then the profiles will be controlled by collisional transport. To provide understanding of the relevant neoclassical calculation, we develop a kinetic model for classical collisional transport at the plasma edge, where scale-lengths are comparable with ρ_i and loss processes due to finite ion orbits and parallel streaming in the SOL compete. This model provides boundary conditions for core transport and determines the poloidal flows which can suppress turbulence.

Acknowledgements

This work is jointly funded by UK DTI and EURATOM.

Nonlocal simulation of the transition from ballooning to η_i mode turbulence in the tokamak edge

K. Hallatschek, A. Zeiler, D. Biskamp
Max-Planck-Institut für Plasmaphysik,
D-85748 Garching, Germany

The transition from resistive ballooning to η_i mode turbulence due to the collisionality and gradient variation in the tokamak edge has been simulated in three dimensions using the electrostatic reduced Braginskii equations with ion temperature dynamics. Most previous simulations of plasma edge turbulence assume that the mean gradient scale lengths are large compared with the turbulence scale length, such that the mean density and temperature and their gradients can be taken constant across the computational domain (local approximation). In this study we have retained the nonlinear dependence of the coefficients in the fluid equations on the fluctuating fields allowing for the large realistic gradients of the mean plasma parameters. Simulations have been performed in a simple scenario with linear density profile and constant $\eta_i = L_n/L_{Ti}$ and a more realistic case with tanh-type profiles for temperature and density and spatially varying η_i. The profiles have been made stationary by adding suitable radially varying source terms for the temperature and density. The parameter profiles were chosen to include the resistive ballooning dominated regime in the very edge as well as the η_i regime at the outside of the plasma core. The linear growth rates and characteristics of resistive ballooning and η_i modes in the nonlocal scenario have been compared with the local approximation for different locality parameters $\lambda_n = L_n/L_\perp$, where $L_\perp$ is the turbulence scale length. For large values of λ_n we have found good agreement between nonlocal and local results. Nonlinearly, the local characteristics of the ballooning and η_i turbulence survive in the general nonlocal case at least to $\lambda_n \sim 30$. Furthermore, the transfer of various quantities, e.g., the kinetic energy or the density fluctuation amplitude, between the different mode regimes has been studied.

Statistical Theory of Subcritically-Excited Strong Turbulence in Inhomogeneous Plasmas

Sanae-I. Itoh[1] and Kimitaka Itoh[2]

[1]*Research Institute for Applied Mechanics, Kyushu University, Kasuga 816-8580, Japan*
[2]*National Institute for Fusion Science, Toki, 509-5292, Japan*

A statistical mechanics description is extended for a self-sustained inhomogeneous turbulence, including the effects of thermal fluctuations. Interchange mode in the presence of inhomogeneous magnetic field, which reveals a subcritically-excited strong turbulence, is considered as a collective mode. A Langevin equation is formulated for a test mode, in which the coherent interactions with thermal fluctuations are kept as a collisional drag and the incoherent ones are considered to be thermal noise: The coherent nonlinear interactions are kept as a renormalized turbulent drag, and the incoherent ones are considered to be a random self-noise. Both thermal and turbulent excitations are thus included. The solutions of stationary turbulent state are obtained, provided that both noises are statistically independent (Ansatz of large number of positive Lyapunov numbers). The analysis for the fluctuation level, decorrelation rate, and the correlation functions clearly shows the connection between a mode which is excited by thermal fluctuations and the one being subcritically self-excited. The level is expressed as nonlinear functions (with hysteresis) of nonequilibrium parameter (gradient). A phase diagram is obtained in the gradient-temperature space. An application of the extended fluctuation-dissipation theorem for far non-equilibrium system is explicitly made and new statistical relations are presented.

Through these considerations, we intend to illustrate the nature of high temperature plasma as a far-nonequilibrium system.

This work is partly supported by the Grant-in-Aid for Scientific Research of Ministry of Education, Science, Sports and Culture of Japan. Authors acknowledge the hospitality of Max-Planck-Institut für Plasmaphysik and Alexander von Humboldt-Stiftung.

BOUT model of Boundary Turbulence in Divertor Geometry*

X. Q. Xu, R. H. Cohen, G. D. Porter, and T.D. Rognlien,
Lawrence Livermore National Laboratory
University of California, Livermore, California 94550
J. R. Myra and D. A. D'Ippolito
Lodestar Research Corporation, Boulder, CO 80301 USA
R. Moyer
University of California, San Diego , La Jolla, CA 92093 USA

Recent results are presented from the 3D nonlocal electromagnetic turbulence code BOUT[1] for studies of turbulence in tokamak boundary plasmas and its relationship to the L-H transition, in a realistic divertor geometry. BOUT models the boundary plasma using fluid equations for plasma vorticity, density, electron and ion temperature and parallel momentum.

For fixed plasma profiles, the dominant pressure-gradient-driven resistive X-point turbulence is peaked near the X-point, due to the competition between electromagnetic perturbations at the mid-plane and electrostatic dissipation near the X-point[2, 3]. The classical resistive ballooning modes coexist with the resistive X-point mode and are sub-dominant modes in the X-point divertor geometry[4]. On DIII-D larger electron pressure, T_e and n_i are observed near the X-point than on the same magnetic surface upstream[5]. The impact of stochastic heating due to the turbulence near the X-point will be discussed. Based on simulation results in L-mode discharges, the scaling scans of the transport show the sensitivities of turbulent flux on plasma parameters[3]. Results show that the transport increases as the electron-ion collisonality increases, and the transport decreases as plasma beta increases. The dynamic evolution of the L-H transition has achieved from L-mode phase which incorporates simple sources and sinks in BOUT. The simulation results show that the H-mode-like pedestal is formed during core-edge heating and the large negative radial electric field Er are established near the magnetic separatrix due to the turbulence-generated plasma rotation. The pedestal width and height, and Er well are qualitatively consistent with experimental measurements. The large edge pedestal pressure due to the increase of the heating power and its relationship to ELMs will be discussed. The progress of the coupling between transport code the UEDGE and BOUT will be presented.

REFERENCES

[1] Xu, X. Q., and Cohen, R. H., Contrib. Plasma Phys., Vol.38, 158 (1998).

[2] X.Q. Xu, R.H. Cohen, and G.D. Porter J.R. Myra and D.A. D'Ippolito, R. Moyer, Jrl. of Nuclear Materials, Vol.266-269, 993-996 (1999)..

[3] X.Q. Xu, R.H. Cohen, and G.D. Porter, et al., submitted to Nuclear Fusion

[4] J.R. Myra, Invited talk, PET Workshop, Oct. 1999, Toki, Japan

[5] M. J. Schaffer et al., Bull. APS 43, 1889 (1998), paper R8P5.

*Work performed under USDOE contract W-7405-ENG-48 at LLNL, grants DE-FG03-97ER54392 at Lodestar Research and DE-FG03-95ER54294 at UCSD

Transport Simulation Based on MHD Transport Model*

M. Yagi

Research Institute for Applied Mechanics, Kyushu University, Kasuga 816-8580, Japan

Much work has been done in the research of inhomogeneous plasma turbulence and associated transport. Recent research shows, however, nonlinear instabilities play an important role in the transport driven by the inhomogeneous plasma turbulence rather than linear instabilities[1]. The analysis of subcritical turbulence indicates that the strong turbulence is sustained by the inhomogeneities and that the conventional method which is based on elaborate evaluation of the linear growth rate is insufficient.

On the other hand, 1D or 1.5D transport models which take account of turbulence effects via diffusivities are used to analyze the evolution of temperature and density. However, recent experiments show that toroidal symmetry is easily broken down by the generation of poloidal flow or magnetic island formation. Therefore the framework is needed which could describe the dynamics of self-organization of temperature or density in the system with toroidal asymmetry. Here we propose MHD transport model which is relevant to describe the dynamics of temperature and density in such a system. 1D or 1.5D transport model is coupled with low m mode fluctuations via quasi-linear term and with high m mode via an eddy-viscosity model or an anomalous diffusivity model. The source terms and sink terms are elaborately handled which has not been so much cared in turbulence simulations. The transient response of transport is considered as an application of this model.

We also propose the methodology of turbulence analysis. In the study of turbulence, a system with high Reynolds number is important. In order to understand the relation between the correlation time of turbulence and the irreversibility due to global transport, we consider a hierarchy of the models, i.e., (1) a model with many degrees of freedom like direct simulation [1], (2) a model with intermediate degrees of freedom such as a shell model[2], (3) a model with a few degrees of freedom such as the Lorenz model[3]. Results obtained from models of different levels are compared and characteristics of the interchange mode turbulence such as chaotic nature, cascade and intermittency are discussed.

Reference

[1] M. Yagi et al., Phys. Plasmas **2**, 4140(1995).
[2] M. Yagi et al., submitted to CHAOS.
[3] T. Aoyagi et al., J. Phys. Soc. Jpn. **66**, 2689(1997).

* In collaboration with S.-I. Itoh, K. Itoh, A. Fukuyama

Global Aspects of Turbulent Transport in Tokamak Plasmas

X. Garbet
Association Euratom-CEA sur la Fusion Contrôlée,
CEA Cadarache, France

The traditional picture of turbulent transport in fusion plasmas relies on a locality assumption. Indeed the usual procedure consists in calculating the turbulence within a plasma layer (or flux tube), where the gradient is fixed. Once fluctuations are known, turbulent diffusion coefficients are determined, after space and time averages. This procedure results in a predictive expression of the turbulent flux as a function of the gradient. This expression can be compared to experimental values or can be used to design a new device. This scheme is based on scale separability: the characteristic time and length of the fluctuations are assumed to be smaller than those of the equilibrium. This assumption is generally justified a posteriori. However, a tokamak plasma turbulence may exhibit a global behavior for several reasons. One reason comes from the structure of the linear eigenmodes, called global modes. Indeed their radial width and frequency depend on the gradient length. It turns out that a turbulence at fixed gradient may keep some memory of these eigenmodes near the stability threshold. However, when the gradient is pushed well above the critical value, these global modes are decorrelated by the non linear mode coupling, and the dynamics becomes local. Another reason for a global behavior comes from the fluctuations of the equilibrium profile. This occurs when the system is controlled by a flux and the gradient is allowed to fluctuate. In this case, propagating fronts are sometimes observed in simulations. The propagation range of these transport events can reach the plasma size, and the propagation time is in between a diamagnetic and a confinement time. Therefore this type of dynamics does not satisfy the scale separability assumption. It presents some similarities with avalanches in sandpile automatons. The mechanisms at work will be described. Also, the impact on transport modelling will be discussed.

Singular structures and fast reconnection

Rainer Grauer
Institut für Theor. Physik I
Heinrich-Heine-Universität Düsseldorf
40225 Düsseldorf, Germany

Explaining temporal and spatial scales in reconnection problems like sawtooth oscillations is a fascinating problem and still a controversial issue.
Most attempts concentrate on the inclusion of electron inertia into the MHD equations or the treatment of small scales and high frequencies such that an electron magnetohydrodynamic approach is appropriate. Another process for fast reconnection is the appearance of localized three dimensional instabilities in non perfect helical symmetry. Nevertheless, common to all scenarios is the importance of the singular structures for the reconnection process and the generated small scale turbulence: current sheets in two dimensional MHD which will become tearing unstable and current and vortex sheets in two dimensional electron MHD, getting destroyed by the Kelvin-Helmholtz instability. For the three dimensional MHD equation the situation is not so clear. In order to investigate the most singular structures which will develop, we simulate the ideal three dimensional MHD equations numerically. Using the technique of adaptive mesh refinement, we were able to achieve an effective resolution of 4096^3 grid points. We report on results for three different initial conditions showing similar behavior: in the early stage of the evolution a fast increase in vorticity and current density is observed. Thereafter the evolution towards nearly two-dimensional current sheets results in a depletion of nonlinearity such that a blow up of vorticity or current density in finite time is not likely to happen.
In addition, we report on simulations both for the dissipative and ideal electron MHD equations. In the dissipative simulations producing a turbulent regime, we consider the question whether differences between longitudinal and transversal structure functions exist. Our simulations suggest, that for the case of electron MHD this is a finite size effect. In addition, the scaling of the current density fluctuations could be described using a scale invariant approach based on the assumption of log-Poisson statistics, where the geometry of the most singular structures is an important ingredient. For the ideal equations the question is addressed, in how far the electron skin depth influences the evolution of vorticity from exponential growth to a possible finite time blow up.

Global fluid simulations of ITG Turbulence

M. Ottaviani
DRFC/SCCP CEA Cadarache,
13108 St. Paul lez Durance, France
and
G. Manfredi
LPMI, Université Henri Poincaré, Nancy-1,
BP 239 F-54506 Vandoeuvre-les-Nancy cedex, France

A three-dimensional fluid code is employed to study various aspects of ion thermal transport caused by Ion-Temperature-Gradient-Driven (ITG) turbulence in a tokamak, and in particular the scaling of the effective ion thermal conductivity χ_i on the reduced gyroradius $\rho* \equiv \rho_s/a$, where ρ_s is the ion sound Larmor radius and a the machine minor radius. The code includes toroidal effects and is capable of simulating the whole torus.

It is found that both close to the ITG threshold and well above threshold, the thermal transport exhibits the gyro-Bohm scaling $\chi_i/\chi_B \sim \rho*$, where χ_B is the Bohm diffusivity, at least for plasmas with moderate poloidal flow. This result is confirmed by the analysis of some quantities that characterize the turbulent fluctuations (correlation lengths and time and the fluctuation level), which also exhibit gyro-Bohm scaling.

In addition, results from a parametric study of the dependence of the conductivity on the plasma current, and the analysis of the mechanisms driving the poloidal flow are discussed. Finally, the first results of the simulations with strong rotation, aimed at the investigation of the possible deviations from the gyro-Bohm scaling, will also be presented.

ExB Shear Flows and Electromagnetic Gyrofluid Turbulence in Realistic Tokamak Geometry

B. Scott

Max-Planck-Institut für Plasmaphysik
EURATOM Association, D-85748 Garching

IAEA TCM Jun 1999

A finite difference model of the gyrofluid equations has been extended to include the effects of self-consistent, electromagnetic electron dynamics parallel to the magnetic field. The resulting dynamical system represents fluidlike ExB turbulence with arbitrary ion gyroradius exciting pressure disturbances in planes perpendicular to the magnetic field, with the planes tied together by dissipative parallel Alfvén dynamics — an extension of drift Alfvén turbulence to the collisionless, hot-ion regime. The turbulence is computed in globally consistent flux tube geometry, with the magnetic flux surface form resulting from a computed equilibrium closely modelling the ASDEX Upgrade tokamak. Magnetic flux surface geometry has a decisive effect on edge turbulence, even its parameter dependence, so that efforts to explain confinement transition and pedestal dynamics from first principles must rely on as realistic computations as possible. ExB shear is not strongly generated by the turbulence, but it arises through the neoclassical equilibrium and therefore can play a role in state transitions. Computations setting the ExB shear strength to the local drift parameter ("diamagnetic shear") while ramping the temperature provides a sharp transition to a regime dominated by ExB shear decorrelation which may correspond to the L-to-H transition observed in tokamaks. An additional result is that passing electrons play their role in the Alfvén dynamics even deep in the plasma core in modern tokamaks, due to the finite beta regime (of order 10^{-2}) which allows resonance between Alfvén and drift waves. The character of edge turbulence is relatively unchanged by the extra finite ion gyroradius effects, due to its relatively large scale (of order 10 gyroradii). There is no change in basic character of tokamak turbulence moving from edge to core, due to the Alfvén dynamics; inferred turbulent diffusivities rise towards the edge solely due to the increasing parallel/perpendicular scale ratio.

A Computational Approach to Mesoscale Plasma Dynamics in Tokamaks

A. Thyagaraja

EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK.

Plasma turbulence is believed to be responsible for anomalous transport in tokamaks. The dynamics of this turbulence and the consequences thereof for tokamak confinement are investigated using the CUTIE code which is global, nonlinear, and incorporates electromagnetic effects in three spatial dimensions using the two-fluid drift approximated equations of motion. The model is based on the experimentally supported observation that the length and time-scales relevant to tokamak turbulence primarily involve the so-called 'mesoscale', spatially intermediate between the system size and the ion Larmor radius and temporally intermediate between the confinement time and the shear Alfvén frequency. It has been used to investigate scalings of global particle and energy confinement in systematic scans of ρ_*, β, ν_* and isotope mass at constant q and geometry. In addition, studies have been made of auxiliary heated discharges for typical COMPASS-D conditions under different scenarios relating the magnetic and radial electric field shear. An important qualitative result of significance is that instantaneous temperature, density and current profiles have a relatively rapidly varying (in both space and time) component superposed on the long-time averaged profiles. The effect of these 'corrugations' (reported recently on several tokamaks: eg. RTP, TEXT-U, and JET) is to produce rather strong spatio-temporal variations in the radial electric field and the bootstrap current. The feed-back implied by these corrugated profiles on the turbulence and the associated fluxes makes the resulting dynamics (and energetics) rather complicated and not readily amenable to traditional linear stability analyses which rely on perturbations about *smooth* profiles. A computational approach to the problem has been developed. It enables a rather complete diagnostic analysis of the fluctuation dynamics to be carried out, including production of movies showing the development in space and time of crucial plasma variables such as the fluctuation current density, vorticity, density, temperature and field fluctuations. Spectrograms of these variables have also been obtained and show unsuspected regularities and structures. The latest results obtained using this approach relating to internal transport barriers and flow rotation/shear effects will be presented.

Acknowledgements: This work was jointly funded by the UK Dept. of Trade and Industry and EURATOM.

NEOCLASSICAL TRANSPORT IN STELLARATORS

J. Nührenberg, U. Schwenn, E. Strumberger

Max-Planck-Institut für Plasmaphysik,

IPP-Euratom Association

Structural features, physical properties and computational methods of neoclassical transport in stellarators will be reviewed. Among these are the dependence of guiding centre motion on the structure of the magnetic field (and in this context quasi-symmetries) and the electric field, local vs. global transport, the dependence of transport coefficients on mean free path, the bootstrap current, high-energy particle confinement, continuous vs. Monte Carlo methods. Some of these points will be illustrated by computer animations.

Nonlinear neoclassical transport theory for the tokamak edge

Per Helander[1] and Tünde Fülöp[2]

[1] *EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, U.K.*
[2] *Department of Electromagnetics, Chalmers University of Technology, SE-412 96 Göteborg, Sweden*

It is widely recognized that the conventional theory of neoclassical transport in tokamaks is not applicable to regions where the pressure and temperature profiles are very steep, such as the pedestal at the plasma edge. In this work, the theory of neoclassical ion transport in an impure, toroidally rotating plasma is extended to allow for steeper gradients than are usually considered. Contrary to conventional theory, these gradients are allowed to be so large that the friction force between the bulk ions and heavy impurities is comparable to the parallel impurity pressure gradient.

When this is the case, the impurity ions are found to undergo a spontaneous rearrangement on each flux surface, which reduces their parallel friction with the bulk ions. This is the driving force for the neoclassical ion flux, which therefore *decreases* if the gradients become sufficiently steep. The neoclassical flux is thus a *non-monotonic* function of the gradients for plasma parameters typical of the tokamak edge, and the neoclassical ion particle and energy confinement is improved in regions with large gradients, such as the edge pedestal.

If the plasma rotates toroidally so that the impurity Mach number is of order unity, the centrifugal force pushes the impurities to the outboard side of each flux surface, as observed in many tokamaks. When the gradients are weak, this is found to substantially increase the neoclassical transport, which can then well exceed the conventional Pfirsch-Schlüter value. On the other hand, when the gradients are steep and the plasma rotates toroidally, the neoclassical transport acquires a number of unusual features. The particle flux can have either sign and is typically *inward* if the ion magnetic drift is toward the X-point in a single-null magnetic configuration. The impurities, whose flux is in the opposite direction, are then screened from the plasma core. These fluxes change sign if the toroidal field is reversed.

This work was funded jointly by the UK Department of Trade and Industry and Euratom, and by the European Community under an association contract between Euratom and Sweden.

Determination of H mode profiles from revisited neoclassical theory and the concept of turbulence quench by rotation shear

André L. Rogister

Institut für Plasmaphysik, Forschungszentrum Jülich GmbH,
EURATOM Association, Trilateral Euregio Cluster, D-52425 Jülich, Germany

The revisited neoclassical theory extends the conventional neoclassical description by taking finite Larmor radius and inertia into account[1]. Ion and electron radial transport are decoupled as a result, leading to a nondegenerate ambipolarity constraint; the latter allows, together with the radial momentum balance and the (revisited) parallel momentum equations, to determine the poloidal and toroidal velocities $U_{\theta,i}$ and $U_{\varphi,i}$ and the radial electric field E_r if the temperature and density profiles are known. Application of the theory to the problematic of the L to H transition yields quantitative agreement[2] with observation on the following issues: i) jump of E_r; ii) width of the E_r shear layer; iii) position of the shear layer, always near the last closed magnetic surface; iv) local threshold criterion, including the role of neutrals and of the isotope mass. The $\vec{E}_r \times \vec{B}$ shear stabilization rate[3] calculated for experimental profiles turns out to be one order of magnitude larger than the growth rate of the dissipative trapped electron mode, suggesting that another concept is required. On physical grounds, a simple, more pertinent shear stability condition will be proposed which, combined with the equations of the revisited neoclassical theory, yields E_r and T profiles in agreement with those measured if an adiabatic law $T \propto N^{\eta}$ is postulated. The novel stability condition would lead to inadequate T profiles, increasing outwards, if applied to the ion temperature gradient driven mode.

1. Rogister A 1994 Phys.. Plasmas **1** 619
2. Rogister A 1998 Phys. Rev. Lett. **81** 3663;
   Rogister A 1999 Phys. Plasmas **6** 200
3. Hahm T S and Burrell K H 1995 Phys. Plasmas **2** 1648

Neoclassical Transport at Low Aspect Ratio

D.J. Sigmar (MIT)

The pioneering works of the first decade of neoclassical transport theory completely evaluated the large aspect ratio ($a/R << 1$) limit [Hinton and Hazeltine, 1976, Hirshman and Sigmar, 1981] in terms of the general equilibrium quantities, such as $<B^2>$, and the circulating particle fraction f_c. Subsequent work presented a number of useful approximate fits to f_c for finite aspect ratio equilibria [Kim et al., 1991; Hsu et al., 1992; Houlberg, et al., 1997], which give the underlying equilibrium description for finite aspect ratio. This does not fully address the increasingly strong effect of very low aspect ratio on pitch angle scattering of trapped and circulating particles at $R/a = 1$, where the role of the circulating particles is shut off altogether ($f_c = 0$, trapped fraction $f_t = 1$), leaving only Pfirsch-Schlüter transport. The $R/a = 1$ asymptotic limit was considered by Shaing et al. [1995] to evaluate the ion thermal conductivity and the bootstrap current. For realistic "fat tokamak" experiments, not even the outer most flux surface can reach $R/a = 1$ and since accurate values for the bootstrap current, the ion thermal conductivity, the poloidal flow (and its shear) are of interest, we extend the banana regime theory for both electrons and ions into the regime $f_c/f_t << 1$ so as to cover all values of f_c/f_t between zero and infinity. Moreover, this must be done using the exact Fokker-Planck collision operator for all aspect ratios, i.e., by dealing with strong trapping effects on the operator when solving the banana regime drift kinetic equation. While this presents no difficulty for the pitch angle scattering operator, the like-like collision operator gives rise to a new type of problem in the momentum restoring term. Previously, this was handled by a momentum conserving approximation which could be justified a posteriori [Rosenbluth et al., 1972, Connor et al., 1973]. This approximation works well for $f_t << 1$ but fails to connect smoothly to Shaing et al. [1995] in the asymptotic limit $f_c = 1$ because it neglects the coupling of different Legendre Polynomials in pitch angle space caused by low aspect ratio toroidal geometry.

We have developed an analytic and simple numerical method to fill this gap by extending the earlier collision operator theory of Hirshman and Sigmar [1976] and its further adaptation by Taguchi [1988] to include strong trapping effects. For arbitrary f_c/f_t, the ensuing exact operator retains the full differential pitch angle operator, but expands the momentum restoring piece in a new set of trapped particle pitch angle eigenfunctions for odd (in parallel velocity) driving terms needed for the response to density and temperature gradients (i.e. ion thermal conductivity and bootstrap current). This expansion can be justified since the momentum restoring piece of the collision operator contains only velocity space integrals which smooth the increasingly strong pitch angle scattering structure as $f_t \rightarrow 1$.

Destruction of Drift Surfaces in Toroidal Systems

Horst Wobig

Max-Planck-Institute für Plasmaphysik, D-85748, Garching, Germany, EURATOM-Ass.

Abstract:

In non-axisymmetric stellarator configurations particle orbits can develop islands and stochastic regions as it it well known for magnetic field lines. In general, circulating particles exhibit only small deviations from magnetic surfaces and their contribution to neoclassical transport is very small. Under the effect of symmetry breaking perturbations, however, drift surfaces of these particles can break up, and if the perturbation is large enough, transition to global stochasticity occurs. In that case anomalous loss of circulating particles results.

Starting from the Hamiltonian formulation of particle orbits in stellarators a map has can derived, which generates the Poincaré plot in the surface of section for circulating particles. In the case of time-independent electromagnetic perturbations this is an area-preserving map in a 2D phase space, which allows one to study the transition to stochasticity by iterating the map. This transition to stochasticity and enhanced radial diffusion depends on the Fourier spectrum of the perturbations and on the profile of the rotational transform. Low shear and a particular choice of the rotational transform inhibits the onset of global stochasticity, since by these methods the overlap of islands can be avoided.

In order to distinguish unperturbed KAM-drift surfaces from perturbed ones, the fractal dimension of the surfaces has been calculated numerically, showing those regions of the iota-profile, which are the most robust ones against perturbations. In particular, these are regions close to low order rational magnetic surfaces. The results are compared with the experimental results in Wendelstein 7-A, Wendelstein 7-AS and the expected plasma behaviour in Wendelstein 7-X.

In case of time-dependendent electromagnetic perturbations, which are associated with plasma turbulence, the Hamiltonian equations of circulating particles can be converted into a map in a four-dimensional phase space. Numerical results of this map are compared with those of the time-idependent case.

COMPUTATION OF NEOCLASSICAL TRANSPORT COEFFICIENTS IN GENERAL AXISYMMETRIC EQUILIBRIA AND ARBITRARY COLLISIONAL REGIME

C. Angioni, O. Sauter

Centre de Recherches en Physique des Plasmas
Association EURATOM - Confédération Suisse,
EPFL - CH - 1015 LAUSANNE

We have computed all the bootstrap current coefficients and the neoclassical conductivity, using the adjoint function formalism which gives simple equations [1] to be solved in numerical codes. We have generalized this approach, following the standard scheme of neoclassical transport theory [2], to obtain a simple and complete formulation for all the neoclassical transport coefficients, with only one ionic species, which allows to easily compute the complete transport matrix in general axisymmetric equilibria and arbitrary collisional regime. In this context we will also show that the adjoint formalism is however not necessary, using the linear dependence of the first order perturbation of the distribution function on the thermodynamic forces, and the same final analytical expressions for the transport coefficients can be obtained as with the adjoint function. These expressions will be shown to easily satisfy the Onsager relations of symmetry. Numerical computations in general axisymmetric equilibria and arbitrary collisional regime are performed with the 3-D code CQLP [3]: this code solves the drift-kinetic Fokker-Planck equation along the magnetic field line on a given flux surface taking into account the complete collision operator. The code CQL3D has also be modified to solve the bounce-averaged equations in order to obtain the coefficients in the banana limit. Some results will be shown: in particular a set of formulae which fit the code results and which allow to compute easily the bootstrap current coefficients and the neoclassical conductivity in general axisymmetric equilibria, for arbitrary collisionality and effective charge will be presented. The electron and ion heat conductivities will be discussed.

[1] Y.R. Lin-Liu et al, International Sherwood Theory Conference, Dallas, Texas (1994) paper 3C37.

[2] F.L. Hinton and R.D. Hazeltine, Rev. Mod. Phys. **48** (1976) 239.

[3] O. Sauter et al, in Proc. of the Theory of Fusion Plasmas workshop, Varenna 1994, Editrice Compositori E. Sindoni, Bologna, (1994) p. 337.

Turbulence-Driven Zonal Flows in Gyrofluid Simulations

M. A. Beer and G. W. Hammett

Princeton Plasma Physics Laboratory
Princeton, NJ 08543

We investigate the dynamics of small-scale turbulence-driven sheared $\mathbf{E} \times \mathbf{B}$ flows in nonlinear gyrofluid simulations. The importance of these zonal flows in the regulation of the turbulence was shown in our early simulations[1] and has been widely confirmed. Most of these flows experience fast collisionless linear damping, but there is a residual non-Maxwellian component[2] of the flow which was not included in our previous gyrofluid model. Here, we modify our treatment of the zonal flows with new fluid closures to include this linearly undamped component, and test its effect on the turbulent dynamics. Our preliminary results indicate that the undamped component does reduce the heat flux somewhat, and improvements to our treatment of the residual component may reduce it further. In most cases the residual component does not grow secularly, indicating that turbulent viscosity is saturating the flow, but near marginal stability we see the flows rise to large levels and shut off the turbulence, recovering the result of Dimits.[3] In this regime the simulations may be very sensitive to collisions and initial conditions. Experimental signatures of these fluctuating zonal flows will be presented.

[1]Hammett, Beer, Dorland, et al., Plasma Phys. Contr. Fusion 35, 973 (1993); Beer, Ph.D. Thesis, Princeton Univ. (1995).
[2]Rosenbluth and Hinton, Phys. Rev. Lett. 80, 724 (1998).
[3]Dimits, et al., Sherwood Fusion Theory Conference (1998).

Ripple-Averaged Kinetic Theory for Stellarators

C.D. Beidler, H. Maaßberg
Max-Planck-Institut für Plasmaphysik
IPP-EURATOM Association
85748 Garching bei München
GERMANY

Theoretical efforts to describe neoclassical particle and heat transport in toroidal stellarators have often taken the *bounce-averaged* drift kinetic equation as their point of departure. The name is indicative of the time average employed in the equation's derivation, performed over the "bounce" motion of particles trapped within a single local ripple of the stellarator's magnetic field. Such localized particles are expected to dominate the radial transport processes in the fusion-relevant long-mean-free-path regime. A considerable body of literature is devoted to solutions of the bounce-averaged kinetic equation and the determination of the resulting transport coefficients. The validity of the results is often limited to the qualitative, however, by a number of simplifying assumptions which are made (typically concerning the role of non-localized particles, the "smallness" of certain terms and the model for the magnetic field strength). Quantitative accuracy, on the other hand, is considered to be the domain of numerical approaches such as the Drift Kinetic Equation Solver (DKES) or those based on the Monte Carlo approach.

By extending the definition of the time average to also account for non-localized particles it is possible to remove one of the principal shortcomings of the bounce-averaged theory; here it is more appropriate to speak of a *ripple average* as the extent of the local ripple sets bounds on the average regardless of whether particles are reflected or not. An appropriate change of coordinate system and local model for the magnetic field strength also makes further assumptions of the conventional theory unnecessary. This formulation of the ripple-averaged kinetic theory is too complex to allow an analytical treatment but a (relatively simple) numerical implementation is capable of providing accurate estimates for the radial transport coefficients in a tiny fraction of the computational time required by DKES or Monte Carlo codes. This should ultimately make it possible to determine fully self-consistent solutions of the kinetic equation, i.e. those which satisfy simultaneously the constraints of ambipolarity and quasi-neutrality.

A Multigrid Algorithm for Nonlocal Collisional Electrostatic Drift-Wave Turbulence

John C. Bowman[a)]

partment of Mathematical Sciences, University of Alberta, Edmonton, Alberta, Canada T6G 2G1

and

A. Zeiler and D. Biskamp

Max-Planck-Institut für Plasmaphysik, EURATOM Association,D 85748 Garching, Germany

We have developed a three-dimensional anisotropic multigrid solver for simulating nonlocal collisional electrostatic drift-wave turbulence in the tokamak edge region. The use of a field-aligned coordinate system allows one to exploit the extremely long scale lengths in the direction of the magnetic field. The anisotropy and the sheared magnetic field introduce further complications, all of which may be handled in a natural way with a multigrid solver.

The solver is demonstrated by applying it to obtain entire flux surface solutions of the nonlocal Hasegawa–Wakatani equations in the absence of curvature effects. The implicit treatment of the parallel-gradient terms permits the use of a relatively large time step. Considerable effort was made in the design of the implicit solver to ensure that the presence of anisotropy does not lead to a significant degradation in performance. Our multigrid algorithm has several advantages over a pseudospectral Poisson solver; most importantly, all nonlinear terms, including those in the Ohm's law, can be retained in a straightforward manner. In addition, a multigrid solver parallelizes much more effectively over a distributed memory architecture. Although in this work the solver is illustrated using straightened tokamak geometry, the object-oriented construction of the code will facilitate the eventual inclusion of curvature terms and the complete nonlinear reduced Braginskii equations, including ion thermal dynamics. We comment also on the feasibility of generalizing the solver to handle electromagnetic effects.

[a)] bowman@math.ualberta.ca

APPLICABILITY OF THE BALLOONING TRANSFORM TO TRAPPED ION MODES

G.L. Falchetto, J. Vaclavik, M. Maccio, S. Brunner[(a)], L. Villard

Centre de Recherches en Physique des Plasmas, Association Euratom - Confédération Suisse, Ecole Polytechnique Fédérale de Lausanne, PPB, CH-1015 Lausanne, Switzerland

[(a)] *Princeton Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ 08543-0451, USA*

In the scope of the study of low-frequency microinstabilities of tokamak plasmas, attention has been focused on the effect of trapped ions.
In the frame of gyrokinetic theory, the ballooning transform has been applied to the gyrokinetic equation, for the case of a large aspect ratio plasma, with circular magnetic surfaces. A new eigenvalue code has been developed to solve the resulting equation, for the case of adiabatic electrons and full ion dynamics, thus taking into account both circulating and trapped ions.
The goal has been to assess the validity of the ballooning transform for Trapped Ion Modes (TIM) by comparing the results of this code with the ones obtained using a global gyrokinetic code (S.Brunner et al., Physics of Plasmas 5, 3929, 1998).

Issues in gyrofluid turbulence simulations and in theory-based transport models *

G.W. Hammett, M.A. Beer, W. Dorland[1], M. Kotschenreuther[2], P.B. Snyder

Plasma Physics Laboratory, Princeton University, Princeton NJ 08543 USA.
[1] *Institute for Plasma Research, University of Maryland, College Park, MD, USA*
[2] *Institute for Fusion Studies, University of Texas at Austin, Texas, USA*

This paper has two main parts. The first part looks at the sensitivity to various assumptions of the predictions of a transport model based on ITG simulations. This helps identify which key physics improvements to focus on in near-term turbulence simulations for improved comparisons with experiments. The second part is a status report on recent extensions of gyrofluid ITG turbulence simulations to include magnetic fluctuations.

In the sensitivity analysis, among other sources of variability, the effect of modifying the IFS-PPPL model (originally based on gyrofluid simulations) to roughly fit the lower turbulence levels of gyrokinetic simulations[1] is shown. There is still a fairly strong dependence on the assumed H-mode pedestal temperature. Various models for the scaling of the pedestal temperature are considered[2], but they all share some common features that suggest that performance might be improved significantly for compact, higher field tokamak designs with stronger plasma shaping[3] and modest density peaking, such as in ARIES-RS or similar designs. However, more work is needed to be confident of these scalings.

An electromagnetic gyrofluid model has recently been developed to study turbulent processes in tokamak plasmas. This work extends earlier electrostatic gyrofluid simulations to include magnetic fluctuations and non-adiabatic passing electron dynamics. An asymptotic expansion in m_e/m_i is used to remove the fast electron thermal timescale from the system, while retaining the slower drift and shear Alfvén dynamics ($\beta \gg m_e/m_i$ is assumed). Next order corrections are included with a model of electron Landau damping, which is usually dominant over collisions for typical core tokamak plasmas. This model is used to study the growth and saturation of turbulence driven by both ITG and kinetic Alfvén ballooning instabilities. At low values of plasma β, transport is reduced, due to the finite-β stabilization of the ITG mode. However, as β approaches the ideal-MHD stability threshold, transport can dramatically increase. Although electron Landau damping and electron-ion collisions cause the linear growth rate to decline, they cause the nonlinear flux in this kinetic Alfvén regime to increase. In addition, Alfvénic turbulence is found to be important at characteristic edge parameters, and may explain the increased heat conductivity observed near the plasma edge.

*Supported by US DOE Contract DE-AC02-76-CH0-3073.

[1] A. Dimits, et.al., IAEA 1998

[2] M. Kotschenreuther, W. Dorland, et.al., Proc. 16th Int. Conf. Plasma Physics and Control. Nucl. Fusion Res. (IAEA 1996); F.W. Perkins et.al. ibid; T. Hatae et.al., Plasma Phys. Control. Fusion 40 1073 (1998).

[3] Y. Kamada et.al. Plasma Phys. Control. Fusion 38, 1387 (1996).

Simulation of Ion-Temperature-Gradient-Driven (ITG) Modes: on the way to W7-X

R. Hatzky

Max-Planck-Institut für Plasmaphysik, Teilinstitut Greifswald, IPP-EURATOM-Assoziation, Walther-Rathenau-Str. 49a, D-17489 Greifswald, Germany

ITG-instabilities are now commonly held responsible for turbulence giving rise to anomalous ion heat transport in the core of tokamaks. It is very likely that ITG-turbulence could become the dominant transport mechanism as collisional transport has been optimized in modern stellarators such as W7-X. Therefore a linear gyrokinetic simulation code for W7-X is envisaged to be developed.

An intermediate step to reach this ambitious goal is to approximate the W7-X equilibrium by a straight so-called bumpy θ-pinch configuration, i.e. an axisymmetric plasma in which the axis of symmetry and the magnetic axis coincide. In this preliminary 2D approximation the effects of particles trapped in a field period due to the fivefold periodicity of W7-X, a radial magnetic well and a rotational transform are included. It does not take into consideration the helical and toroidal curvatures of which the latter is low, i.e. similar to that of a tokamak of aspect ratio 20. The plasma is modeled with gyrokinetic ions and adiabatic electrons; the code simulates the time-evolution of quasi-neutral electrostatic perturbations by using a global PIC approach [1] over the whole plasma volume. If the configuration is unstable the frequency ω, growth rate γ and spatial structure of the most unstable mode are derived by analyzing the electrostatic potential $\delta\tilde{\phi}$.

Our calculations have shown that the variation of the magnetic field along the magnetic axis of 10 % per field period (bumpiness) has only a minor influence on the growth rates. The magnetic well of 10 % has a stabilizing effect and reduces the growth rates for $\eta_{\rm i} = L_{\rm n}/L_{\rm T_i} \approx 2.5$ by a factor of ≈ 2. This is expected because the induced ∇B drift is in opposite direction to the diamagnetic drift and has a stabilizing effect on the slab ITG modes.

The effect of the rotational transform on the growth rates depends on the relative position of the mode ($\iota = n/m$ value) to the resonant surface. Since slab ITG's are stable at the resonant surface the mode tries to avoid radially the area where the resonant surface is localized. Hence it is radially pushed inside respectively outside and the growth rates can be damped respectively amplified by ≈ 10 %.

A marginal point study for the most unstable mode gives a value of $\eta_{\rm i} \approx 1.6$ and is influenced only little by the effects of bumpiness and magnetic well.

[1] Fivaz, M., Brunner, S., De Ridder, G., Sauter, O., Tran, T. M., Vaclavik, J., Villard, L., and Appert, K., *Comp. Phys. Comm.*, **111**, 27 (1998)

Physics of LH transition and Type III ELMs : Scaling Properties and Dimensional Analysis

Yu. Igitkhanov, O. Pogutse*

ITER Joint Central Team, Joint Work-Site, D-85748 Garching, Germany

JET, Abington, UK

Abstract

The Alfven drift turbulence suppression at the plasma edge is suggested as a triggering mechanism for the L to H transition. The instability is characterised by two significant parameters, i.e. the normalised plasma beta, β_n, and the normalised collision frequency, ν_n. The turbulent transport is suppressed when the normalised beta is greater than a critical value, i.e. $\beta_n > 1 + \nu_n^{2/3}$, which depends on collisionality, ν_n. The transport coefficients change strongly their dependence on plasma parameters at this threshold. Such a change causes the formation of the transport barrier and defines the onset condition for the LH transition. The model predicts the experimental scaling of threshold temperature dependence on magnetic field and plasma density. After the LH transition, when the Alfven drift turbulence becomes low the interchange resistive instability (RI) accompanied by magnetic perturbation (flutter) emerges as the dominant phenomena in form of Type III ELMs. In this case the magnetic perturbation starts to contribute to the electron transport at the very edge of the plasma and leads to a non-ambipolar motion of the electrons and ions in radial direction. This causes a strong negative electrical field to develop just inside the separatrix which increases with increasing β. If this electrical field becomes sufficiently strong it can stabilise the RI modes. This condition gives the upper boundary for the Type III ELMs in the n_e -Te diagram plane. After stabilisation of the Type III ELMs the gradients near the edge increase further and the plasma then evolves until the ideal ballooning boundary (Type I ELMs) is reached. The proposed theory allows to derive a scaling for the different plasma parameters, the frequency of the Type III ELMs, the dependencies of the lower and upper boundary for Type III ELMs in the Te-ne plane as well as the scaling for the amplitude of the Type III ELMs oscillation.. Comparison with existing experiments shows a good correlation with the theoretical predictions.

FIRST GLOBAL LINEAR GYROKINETIC SIMULATIONS IN 3D MAGNETIC CONFIGURATIONS

G. Jost, T.M. Tran, K. Appert, W.A. Cooper, L.Villard

Centre de Recherches en Physique des Plasmas
Association Euratom - Confédération Suisse
Ecole Polytechnique Fédérale de Lausanne

The full 3D global linear gyrokinetic Particle-In-Cell (PIC) code developed in [1] has been successfully validated in helical configurations. Comparisons were performed with the 2D helical code GYGLES [2, 3]. This code we describe here employs a 3D finite element method in a straight field line magnetic system of coordinates and includes a fast parallel iterative solver [4] of the gyrokinetic Poisson equation. The MHD equilibrium code VMEC [5] is used to generate 3D configurations with nested magnetic flux surfaces. On the other hand, the GYGLES code solves the problem in a 2D helical system of coordinates and the magnetic configurations are given by analytical vacuum solutions.

An important improvement in the formulation has been the analytical extraction of the fast spatial phase variation. This makes the study of high mode numbers possible.

First results of Ion-Temperature-Gradient (ITG) modes in 3-D configurations will be presented.

References

[1] G. Jost *et al.*, in Theory of Fusion Plasmas, Proc. Int. Workshop Varenna, 1998.

[2] L. Villard *et al.*, in Theory of Fusion Plasmas, Proc. Int. Workshop Varenna, 1998.

[3] M. Fivaz *et al*, Comp. Phys. Comm. **111** (1998) 27.

[4] S. Balay, W. D. Gropp, L. C. McInnes and B. F. Smith, Portable Extensible Toolkit for Scientific Computation 2.0 User's Manual, ANL-95/11 - Revision 2.0.22, (Argonne National Laboratory, IL. 1998).

[5] S. P. Hirshman and D. K. Lee, Comp. Phys. Comm. **39** (1986) 161.

Turbulent Structure and Flow Generation from Toroidal ITG Mode in Weak / Reversed Magnetic Shear Plasma

Y. Kishimoto, J.Y. Kim+, W. Horton++, J.N.Leboeuf+++, T. Matsumoto, Y.Ishii, J.Q.Li, S. Dettrick, T. Tajima++, and H. Shirai

Naka Fusion Research Establishment,
Japan Atomic Energy Research Institute, Naka, Ibaraki, 311-01 Japan
+ Korea Basic Science Institute, 52 Yeoeundong, Yusung Korea
++ Institute for Fusion Studies, University of Texas, Austin, Texas 78712 USA
+++ University of Calofornia, Loa Angeles USA

The turbulent structure of drift waves in toroidal geometry is becoming clearer due to recently developed theory in which the profile effect to zeroth order ballooning theory is taken into account [1], and according to the analyses, the linear drift waves form a radially extended non-local structure whose radial width is given by $\Delta r \sim (\rho_i L/s)^{1/2}$ (ρ_i : ion Larmor radius, $L \sim |\, d\ln T_i/dr|^{-1}$). Although such a mode structure is deformed in nonlinear stage as observed in nonlinear simulations, the result suggests that "non-local effect" and/or "finite size effects" of the plasma are important to understand various transport properties including improved modes. Among them, internal transport barrier (ITB) formation observed during weak and reversed magnetic shear discharges shows remarkable features and has been widely interested[2]. In such circumstances, since the toroidal coupling due to the magnetic shear is weakened and is sometimes disappeared, the usual ballooning representation breaks up and a careful treatment is necessary for the transport study.

Based on an idea that the ITB formation results from a local break-up of the toroidal drift modes due to the weak/zero magnetic shear and plasma shear rotation around q (safety factor) minimum surface, we presented a "discontinuity model", in which the phase relation of the toroidal modes excited inside and outside the q-min surface is disconnected and then the transport is greatly reduced around the q-min surface [3,4]. Although the model was confirmed vir a toroidal particle simulation, it is also found whether such a discontinuity is established depends sensitively on the details of the plasma condition around the q-min surface, such as position of the q-min surface relative to the maximum pressure gradient surface, curvature of the q-profile around q-min surface, strength and direction of diamagnetic and also self-generated flow shear etc. Namely, in some cases, we observed different types of eigenmodes which are excited across the q-min surface. Once such modes are excited, the discontinuity is deteriorated and the heat flux is ejected from the inside region to the outside.

In the paper, we investigate the detail of the drift wave structure in weak/reversed magnetic shear configuration by using toroidal particle code and toroidal gyro-fluid code in which the effect of initial equilibrium profile change is taken into account. Specifically, we study in more details the mode which deteriorate the discontinuity near q-min in some special case. Candidates for these modes are a trapped ion mode which is insensitive to the local magnetic shear and localized at a larger pressure gradient region and also slab-like modes. We also investigate the structure of a self-generated electric field and the related plasma flow (zonal flow) in weak/reversed magnetic shear configuration, which is important in determining the steady state fluctuation level.

Another observation of the ITB is that the ITB is localized in a narrow radial region so that the typical pressure scale length becomes comparable to the ion poloidal Larmore radius ($\rho_p \cong L$). This suggests that not only the turbulent or pressure driven radial electric field, but also neo-classically driven electric field due to fast ion loss in high-q negative shear region can be important in understanding such a barrier formation. We investigate neo-classically driven radial electric field vir a toroidal particle simulation in which the collision effects are taken into account.

REFERENCES

[1] J.Y. Kim, et. al. Phys. Plasma 3, 1-7 (1996), J.W.Conner et.al. Phys. Rev. Lett, 70,1803 (1993).
[2] T.Fujita et.al. Phys.Rev.Lett. 78, 2377 (1997), S.Ishida, Phys. Rev. Lett. 79, 3917 (1997).
[3] Y. Kishimoto, J-Y. Kim, et.al. Proceedings of the 16th international conference on fusion energy, (IAEA, Vienna, 1997), Vol.2, 581-591, 1997,
[4] Y. Kishimoto J.Y. Kim et.al. Plasma Phys. Control Fusion 40, A663 (1998).

Resistive Drift Instability for a Sequence of ℓ=2 Stellarators

Ralf Kleiber
Max-Planck-Institut für Plasmaphysik, Teilinstitut Greifswald,
IPP-EURATOM-Association, Walther-Rathenau-Str.49a, 17489 Greifswald

In order to gain insight into the anomalous transport in the boundary region of stellarators a code allowing the calculation of global linear resistive drift waves in general geometry has been developed. It is based on a two-fluid-description of the plasma and the assumptions of electrostatic perturbations and cold ions.
After employing a Fourier decomposition with phase factor transformation (in order to allow the calculation of high wavenumber modes) in the angle like variables and a finite-difference-discretization in the flux label the resulting generalized complex eigenvalue problem is solved by an Arnoldi Method.
To investigate the influence of the toroidal curvature on the growth rate a sequence of ℓ=2-stellarator equilibria with $P = 5$ field periods, aspect ratio per period $A/P = 2$, bell shaped density profile and fixed ι-profile was calculated. Starting with a straight stellarator this sequence consists of equilibria with increasing toroidal curvature (characterized by the major radius R). A small density scale length and physical parameters characteristic for a boundary region where used in the calculation of the eigenmodes.

Unstable modes with poloidal wave number M_P between 20 and 2200 were calculated in the straight stellarator. The highest growthrate was obtained for $M_P \approx 800$. A rapid variation of the complex frequency as a function of M_P is observed. Radially the modes are located near the outer boundary in a region about ten inertia length wide.
In the straight stellarator relatively few Fourier coefficients for the perturbation have to be taken into account while addition of a small toroidal coupling ($R = 20$) raises its number considerably. Increasing the toroidal curvature leads to a decrease in the growthrate (for $R = 20$ it is diminished by approximately 20%).
The influence of the equilibrium quantities on the mode structure (especially the location of the maximum of the mode modulus) is investigated.

Poloidal flows and transport in non-periodic 3D simulations of the Hasegawa-Wakatani model

S. B. Korsholm, P. K. Michelsen, V. Naulin, and J. Juul Rasmussen

Optics and Fluid Dynamics Department
Association EURATOM-Risø National Laboratory
Risø, DK-4000 Roskilde, Denmark

Three dimensional simulations of drift-wave turbulence using the Hasegawa-Wakatani equations

$$\begin{aligned} \partial_t n + \partial_y \phi + \{\phi, n\} &= \partial_{zz}(n - \phi) \\ \partial_t \nabla^2 \phi + \left\{\phi, \nabla^2 \phi\right\} &= \partial_{zz}(n - \phi) \end{aligned}$$

for fluctuations in density n and potential ϕ are performed.
Previous investigations of this model considered a triply periodic domain only [1]. The behaviour of the system changes drastically if non-permeable walls in the direction of the background density gradient (i.e. radially) are assumed. The evolution of a global poloidal flow pattern, which reduces the fluctuation levels, is a characteristic feature of this system. Its influence on the transport is investigated.
Since the effect of the constant background density gradient is significantly reduced by the transport of density a flux-driven system was also considered. The model was extended to include a source and a sink region, close to the left and right radial boundary of the box, respectively. Questions of profile evolution and statistics of the transport events are considered.

References

[1] D. Biskamp and A. Zeiler, *Nonlinear Instability Mechanism in 3D Collisional Drift-Wave Turbulence*, Phys. Rev. Lett. **74** (1995) 706–709.

Coulomb Collision and Classical Transport in Plasma

D. Li

Department of Modern Physics, University of Science and Technology of China, P.O. Box 4, Hefei 230027, China

Recently, it was demonstrated that the customary approach to Fokker-Planck coefficients for inverse-square force has three defects. First, small scattering angle cannot guarantee small Taylor expansion argument. Secondly, a cutoff on scattering angle did not fulfill Debye shielding theory because it cannot exclude distant (weak) collisions with small relative velocity meanwhile cannot include close (effective) collisions with large relative velocity. Third, a singularity attributed to zero relative velocity had been overlooked. The reason is the scattering angle cannot replace the momentum transfer to describe the Coulomb collision in plasma [Chang and Li, Phys. Rev. E **53**, 3999, 1996].

In the present work, it is found that the Coulomb logarithm $\ln \Lambda$ should be replaced by $\ln\sqrt{\Lambda}$ if the cutoff at the small-momentum transfer is introduced according to the effective condition for the Coulomb collisions. It is easier to show that such cutoff can guarantee the convergence of the Taylor expansion for the Fokker-Planck integral and fulfills the Debye shielding theory. Consequently, the relaxation times are enhanced by a factor 2 so that the classical transports are enhanced or reduced by a factor 2 comparing with the results of classical transport theories. For example, the diffusion and electrical conductivity are reduced by a factor 2. The parallel thermal conductivity and viscosity are enhanced by a factor 2. The transverse thermal conductivity and viscosity are reduced by a factor 2. These results may partially explain the phenomenon that the measured diffusion and transverse thermal conductivity are below the levels of conventional neoclassical transport theory in the core of reversed magnetic shear plasma in tokamaks.

The probability function for a type of non-Maxwellian scatters is derived by the normal original Fokker-Planck approach. All the Fokker-Planck coefficients can be obtained by the normal original Fokker-Planck approach with help of the probability function. The completed Fokker-Planck coefficients are generated as a uniform expression. The transport coefficients are derived for the non-Maxwellian scatters.

EFFECT OF STRONG ELECTRIC FIELDS ON ITG MODES LINEAR STABILITY USING A GLOBAL GYROKINETIC MODEL.

M. Maccio, J. Vaclavik

Centre de Recherches en Physique des Plasmas
Association Euratom - Confédération Suisse
Ecole Polytechnique Fédérale de Lausanne
PPB-Ecublens - CH-1015 Lausanne/Switzerland

Strong electric fields generate sheared $E \times B$ rotation of the equilibrium plasma. Experiments have shown that this effect could lower the anomalous transport in tokamaks [1]. We have therefore undertaken the study of the effect of strong electric fields on the linear stability of micro-instabilities. Lie transforms formalism is used to include equilibrium electric fields in the gyrokinetic equation [2]. We then solve this new gyrokinetic equation globally in the Fourier space [3]. It is important that the resolution is done globally, as it has been shown that ballooning representation breaks down for strong electric fields [4]. Systematic study of the effect of magnitude and shape of the $E \times B$ rotation, combined with positive and negative magnetic shear, will be presented.

References

[1] K.H. Burrell, Physics of Plasmas **4**, 1499, (1997)

[2] T.S. Hahm, Physics of Plasmas **3**(12), 4658, (1996)

[3] S.Brunner, M. Fivaz, T.M. Tran and J. Vaclavik, Physics of Plasmas **5**(11), 3929, (1998)

[4] J.B. Taylor, H.R. Wilson, Plasma Phys. Control. Fusion **38**, 1999, (1996)

Initial—value problem solutions for Hasegawa-Wakatani equations for plasma with radial electric field shear.

*Mikhailenko V.S**)*., Mikhailenko V.V.**)*, Stepanov K.N.*
NSC "Kharkiv Institute of Physics and Technology
*)*Kharkiv State University ,*
310108, Kharkiv -108 , Ukraine

The linear properties of the Hasegawa-Wakatani (H-W) model equations for resistive drift fluctuations for poloidal plasma flow with uniform shear of the radial electric field are investigated on the basis of a nonmodal method.

The initial value problem for the linearized H-W slab model is solved for two limits of the parameter $C = T_e k_{\|}^2 / n_0 e^2 \eta_{\|} v'_E \rho_s^2 l^2$ values. Here l and $k_{\|}$ are poloidal and toroidal wave numbers respectively , $v'_E = const$ is the velocity shear, $\eta_{\|}$ is the parallel resistivity, ρ_s is the ion Larmor radius at electron temperature, T_e and n_0 are temperature and density of the electrons respectively. In the case $C \to \infty(\eta_{\|} = 0)$, i.e. for the Hasegawa-Mima equation, solution of the initial value problem is obtained which is uniformly valid for all time moments. Wave-packet solution for this case reveals that the group velocity vanishes with time as t^{-3} and wave-packets stagnates in the radial direction due to the flow shear. Solution obtained has a modal form as $exp(-i\omega t)$ only for short time. At a large time drift-wave solution of nonmodal form transforms into the convective cell-type solution in the convected frame.

We also obtain the solutions of the initial value problem in which finite resistivity (terms with $C >> 1$) is included also. We find that under the condition $S^2 > C > 1$ (where $S = v_* / v'_E \rho_S$, v_* is the velocity of the diamagnetic drift) the linear initial value solution preserves a modal form during a long time $t > \gamma^{-1}$, where γ is the linear growth rate of the resistive drift instability. For the condition $C >> S^2 >> 1$ the nonmodal effects become essential at the time considerably less than γ^{-1}. It may be anticipated that the stationary state in this case would be set in due to the developing nonmodal rather than nonlinear effects.

For the strong resistivity ($C << 1$) the modal type solution does not arise at any time. Instead the solution possesses a form of convective-cell.-

Macroscopic and statistical properties of three-dimensional magnetohydrodynamic turbulence

Wolf-Christian Müller and Dieter Biskamp
Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany

Energy decay laws and scaling behavior of statistical moments for three-dimensional incompressible magnetohydrodynamic turbulence are obtained from high-resolution numerical simulations using up to 512^3 modes. For the typical case of finite magnetic helicity H the energy decay is found to be governed by the conservation of H and the decay of the energy ratio $\Gamma = E^V/E^M$. One finds the relation $(E^{5/2}/\epsilon H)\Gamma^{1/2}/(1+\Gamma)^{3/2} = const$, $\epsilon = -dE/dt$. Use of the observation that $\Gamma(t) \propto E(t)$ results in the asymptotic law $E \sim t^{-0.5}$ in good agreement with the numerical behavior. For the special case $H = 0$ the energy decreases more rapidly $E \sim t^{-1}$, where the transition to the finite-H behavior occurs at relatively small values.

The scaling of the total energy spectrum is shown not to conform with the Iroshnikov-Kraichnan phenomenology. Instead it is found to be described by an extended Kolmogorov law which contains a second integral length scale related to the magnetic helicity. Using hyperdiffusion, the structure functions of the Elsässer fields $\mathbf{z}^{\pm} = \mathbf{v} \pm \mathbf{B}$ display a clear scaling range. From this absolute scaling exponents are retrieved, in particular $\zeta_3 \approx 1$, being consistent with the observed Kolmogorov-like scaling behavior of the energy spectrum and recent theoretical results.Using extended self-similarity of the $|\mathbf{z}^{\pm}|$ structure functions, the scaling exponents ζ_p are calculated for up to $p = 8$. They fit well to a modified She-Lévêque intermittency model, $\zeta_p = p/9 + 1 - (1/3)^{p/3}$, assuming Kolmogorov phenomenology together with the MHD-typical sheet-like dominant dissipative structures.

Neoclassical transport calculations in the ASDEX Upgrade geometry

A.G. Peeters, R. Dux

A neoclassical transport code NEOART has been developed. It calculates the fluxes in all collisional regimes in arbitrary toroidally symmetric geometry. The banana plateau contribution of this code is calculated in the same way as the NEOClASS code of Houlberg [W.A. Houlberg et al., Phys Plasmas 4, 3230 (1997)]. The calculation of the Pfrisch Schlüter fluxes, however, are extended to also cover the collisional regime. The code uses a reduced charge state formalism for both contributions which makes it well suited for impurity transport studies. An interface with the ASDEX Upgrade experiment exists which calculates the geometry dependent parameters from the reconstruction of the magnetic equilibrium.

The code is used to study several phenomena:

The ion heat flux in ITB discharges. Compared are 2 and 3 Laguerre polynomial results, the influence of the carbon impurities is investigated in detail.

The screening of Wolfram by Carbon impurities. It is suggested in the literature that light impurities can lead to screening of more heavy impurities. It is investigated if this effect can explain the occurrence of Wolfram screening in ASDEX Upgrade.

The total energy flux in the H-mode edge. Is the transport in the H-mode barrier down to neoclassical or are anomalous effects still present?

Anomalously enhanced transport via Kirchhoff radiation

Satish Puri
Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany

The principal toroidal transport anomalies, namely (i) enhanced particle and thermal diffusivities, including anomalous electron thermal conduction, (ii) magnetic-field dependence, (iii) isotope-mass dependence, (iv) temperature dependence, (v) density dependence, (vi) power degradation in auxiliary heated plasmas, (vii) anomalous radially inward particle convection, and (viii) impurity transport behavior, are all traced to momentum-exchange collisions induced via Kirchhoff thermal radiation.

Radiation is a ubiquitous plasma phenomenon. Random thermal fluctuations excite plasma waves spanning the entire frequency spectrum at wavenumbers compatible with the dispersion relation $D(\omega, \mathbf{k}) = 0$ and with a cutoff at the Debye wavenumber. If the plasma is in local thermodynamic equilibrium, and if the absorption distance for the waves is small compared to gradient lengths and plasma dimensions, the number density of waves corresponds to the black-body spectrum. Kirchhoff law states that thermal equilibrium for such a plasma is characterized by an exact balance between wave absorption and emission. Since a plasmon of energy $\hbar\omega$ carries a parallel (to the ambient magnetic field B_0) momentum $\hbar k_\parallel$, the radiation and absorption of thermally excited waves in a plasma is inevitably accompanied by momentum exchange collisions between the plasma particles, which is additional to the two-particle collisions included in the standard Fokker-Planck description. The radiation-induced collision frequency is given by[1,2]

$$\nu_{\sigma\xi}^{rad} = \frac{T}{\pi^2 n_\sigma} \sum_j \sum_{\tilde{l}_j} \int_0^{k_D} \int_0^{k_D} \sum_{l_\sigma} \left| \frac{k_\parallel^2 k_\perp}{m_\sigma(\omega - l_\sigma \omega_{c\sigma})} \frac{\Im\left[\omega^\sigma\right]_{l_\sigma} \Im\left[\omega^\xi\right]}{\Re\left[\omega\right] \Im\left[\omega\right]} \right| dk_\parallel dk_\perp, \qquad (1)$$

where T is the temperature in energy units, $\omega = \Re[\omega] + i\Im[\omega]$, $\Im[\omega^\sigma]$ is the absorption contributed by species σ, $\Im[\omega^\sigma]_{l_\sigma}$ is the absorption occurring at the l_σ harmonic of the cyclotron frequency $\omega_{c\sigma}$, and n_σ is the density. The summations extend over all non-degenerate cyclotron harmonics $\tilde{l}_j$ of all particle species j.

Small wavelength, large $|k|$, electrostatic-cyclotron-harmonic Bernstein[3] waves are the prime contributors to radiative collisionality. In particular, the electron-electron collisions are enhanced by a factor of up to and over one hundred compared to the neo-classical values, thereby resolving the most persistent plasma transport anomaly of enhanced electron thermal conductivity. The close parallelism of the transport scaling derived using Eq.(1) with the experimental observations carries the clear implication that Kirchhoff radiation is indeed the dominant transport mechanism in toroidally-confined thermonuclear fusion plasmas.

[1]S. Puri, Phys. Plasmas **5**, 2932 (1998).
[2]S. Puri, in Proceedings of the 25th EPS, Prague (1998).
[3]I. B. Bernstein, Phys. Rev. **109**, 10 (1958).

Pinches-Induced Transport Reduction in Reversed Shear/Optimized Shear Tokamak Plasmas

X. M. Qiu*

Southwestern Institute of Physics, P.O.Box 432, Chengdu 610041, China

Recently, the tokamak discharges with the reversed magnetic shear[1] in TFTR, DIII-D, Tore Supra and JT-60U as well as optimized magnetic shear[2] in JET have been realized and internal transport barriers have been observed, leading to a new regime of remarkably enhanced core confinement. The leading features of this regime are the significant reduction of the effective particle and ion thermal diffusivity, *i.e.*, D_e^{eff} and χ_i^{eff} in the core region fall below the standard neoclassical values. According to widely accepted transport theories, however, the transport in tokamak plasmas can only reach the neoclassical level but cannot be smaller than it. Therefore, to explore the physical mechanism causing these experimental results has been attracting extensive theoretical interest. We propose here another route to the problem. In this talk, a simple model, based on "hybrid trapped electron ion temperature gradient mode"[3] responsible for the turbulence giving rise to anomalous particle and ion thermal transport (D_e^t and χ_i^t) in the core of tokamaks, is presented to explain in a unified formulation these experiments in the reversed shear/optimized shear tokamak plasmas. It is found that the combination of the (reversed/optimized) magnetic shear L_B and the $\mathbf{E}\times\mathbf{B}$ sheared velocity $\mathbf{V}_E$ (here $\mathbf{E}$ is from the gradient of ion pressure P_i) and the three ways of coupling between them, $L_B^{-1}(dV_E/dr)$, $L_B^{-1}V_E$ and $\mathbf{k}\cdot\mathbf{V}_E$ (here $\mathbf{k}$ is the L_B-dependent wavevector), can produce turbulent particle- and heat- pinch, *i.e.*, $D_e^t<0$ and $\chi_i^t<0$ in the core region, and hence make D_e^{eff} and χ_i^{eff} reduce significantly in that region. In addition, it is found that in the five factors, $L_B(r)$, $\mathbf{V}_E(r)$, $L_B^{-1}(dV_E/dr)$, $L_B^{-1}V_E$ and $\mathbf{k}\cdot\mathbf{V}_E$, the last, representing the one of the coupling effects between the magnetic shear and the sheared velocity itself, plays an important role in the turbulent pinches and hence the significant reduction of D_e^{eff} and χ_i^{eff}, because it appears in the formulas for D_e^t and χ_i^t in the form of "quasi-resonance". The numerical results for D_e^{eff} and χ_i^{eff} are in good agreement with experimental trends. Finally, we emphasize to point out that because all the five factors depend on q-or/and P_i-profile, controlling the two profiles can make some or all of the five factors play more efficient part in the turbulent pinches and hence the substantial reduction of transport. Currently, the reversed and optimized shear are the two excellent scenarios of the controlling; There may be more excellent one to be tried to find out.

[1] C.Kessel *et al.*, Phys.Rev.Lett. **72** (1994) 1212.

[2] F.Soldner and JET team, Plsama Phys. and Contr. Fus. **39** (1997) B353.

[3] L.Bai, X.M.Qiu, L.Huang and X.M.Song, Phys.Plasmas **3** (1996) 3004.

---

* E-mail: xmqiu@swip.edu.cn

Numerical simulation of rotation and confinement in TEXTOR high density discharges

A.L. Rogister[1)], J. Weiland[2)], J. Ongena[3)], M-Z. Tokar[1)]

[1)]Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, EURATOM Association, D-52425 Jülich, Germany*
[2)]Department of Electromagnetics, EURATOM/NFR Association, Chalmers University of Technology, Göteborg, Sweden
[3)]Laboratoire de Physique des Plasmas/Laboratorium voor Plasmafysica, ERM/KMS, EURATOM Association, B-1000 Brussels, Belgium*

By including finite Larmor radius and inertia, the recently developed revisited neoclassical theory[1] provides (unlike the conventional theory) equations for *both* the toroidal and the poloidal rotation velocities; the radial electric field can then be calculated from the radial momentum balance equation. The results obtained in Ref. [1] for the high collisionality regime have been both simplified and somewhat heuristically generalized to all collisionality regimes. Inserted in a numerical transport code[2], they allow to predict self- consistently the $\vec{E}_r \times \vec{B}$ rotation and rotation shear rate throughout the discharge. Application to TEXTOR-94 high density plasmas with and without edge radiating impurities will be discussed with emphasis on the mechanism of radiation induced shear stabilization of the prevailing instabilities.

1 Rogister A 1994 Phys. Plasmas **1** 619
2 Strand P, Nordman H, Weiland J and Christiansen J.P. 1998 Nucl. Fusion **38** 545

1st IAEA Technical Committee Meeting on First Principle-Based Transport Theory

---

* Partner in the Trilateral Euregio Cluster (TEC)

Ion Transport in Rotating Tokamak Plasmas in the Presence of Heavy Impurities

M. Romanelli[1] M. Ottaviani[2]

[1]JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, UK

[2]CEA Cadarache, 13108 Saint-Paul les Durence, France

The effects of plasma rotation on transport coefficients have been investigated in early theoretical works [1],[2] in regimes in which the induced poloidal perturbation on the ion densities is small. We present a study of ion collisional transport in the presence of strongly poloidal asymmetric impurity-density induced by momentum injection via neutral beam injection. It is found that the poloidal asymmetry of the impurity-density, which occurs because of the rotation, brings about a large enhancement of the diffusivity and indeed of the pinch velocity above the conventional Pfirsh-Schlüter values. A two-scale ordering of the particle flux in powers of the inverse parallel diffusion coefficient and the inverse aspect ratio has been adopted. For fast plasma rotation the Mach number of heavy ions is greater than unity and the poloidal density-perturbation becomes of the same order as the unperturbed density, the fast rotation permits strong asymmetries on the magnetic surface to survive. As a consequence the ion diffusion coefficient is enhanced up to one order of magnitude above the conventional value. Since the density poloidal-asymmetry dominates over the temperature poloidal-asymmetry a strong inward pinch is found. We consider this result a noteworthy conceptual advance. Indeed finding an enhancement of the pinch velocity over the standard neoclassical level is required to explain the experiment (typically a factor of 10), which had previously eluded theoretical efforts; unlike the enhancement of the diffusivity which could be obtained with a modest amount of electrostatic turbulence.

[1] S. K. Wong (1987) Phys. Fluids **30** (3), pp. 818

[2] C. T. Hsu and D. J. Sigmar (1990), PPCF, **32** (7), pp. 499

[3] M. Romanelli and M. Ottaviani (1998), PPCF, **40**, pp. 1767

On the Construction, Statistical Analysis, and Control of Maps for Magnetic Field Line Transport in an Ergodic Divertor

Karl H. Spatschek, Sadrilla Abdullaev, and Dmitri Lesnik
Institut für Theoretische Physik
Heinrich-Heine-Universität Düsseldorf, D 40225 Düsseldorf, Germany

Motivated by the proposed experiment of a Dynamic Ergodic Divertor at the Jülich tokamak TEXTOR, theoretical investigations on the field line transport in partially chaotic systems have been performed. Due to the development of a systematic procedure for constructing a symplectic twist map from the original continuous Hamiltonian system, extensive statistical evaluations were possible. In several tests, the results from the mapping turned out to be as good as the very time consuming predictions from field line tracing codes, or from symplectic integrators. The global analysis showed that three regions of field line transport occur: (i) diffusive, (ii) sub-diffusive, (iii) and ballistic areas. The diffusive behavior is compared with quasi-linear predictions, whereas the ballistic behavior is understood from model calculations in finite systems. The traces of the incomplete chaos become evident in the sub-diffusive transport. Due to the stickiness at reminiscents of islands, the wandering of the field lines is hindered. To understand the latter process in more detail, a local analysis is performed. From generalized separatrix maps, the transition probabilities and mean waiting times are determined. Numerical results are compared with analytical predictions from continuous time random walk models. Furthermore, several control methods for area preserving maps are applied in order to find out the possibilities to change the transport scaling, and to estimate the influences on the cycle expansion formulas.

The present investigation can be understood as the starting point for more relevant particle transport calculations in stochastic magnetic fields. The generalization of the above methods to the drift orbits of particles is obvious. Some ideas to include collisions are also presented.

Global Gyrokinetic Simulation of Electromagnetic Instabilities using Particles

T. M. Tran, J. Vaclavik and K. Appert
Centre de Recherches en Physique des Plasmas, Association Euratom-Confédération Suisse, Ecole Polytechnique Fédérale de Lausanne, PPB, 1015 Lausanne, Switzerland

The physical model is based on the *linearized* gyrokinetic equations for both the ions and the electrons, the quasi-neutrality condition and the parallel magnetic potential approximation. The δf method, which has been utilized successfully for the electrostatic ion-temperature-driven (ITG) instabilities[1,2], is used for the discretization of the ion and electron gyrocentre distribution functions. The spline finite elements are chosen to represent the two potentials ϕ and A as well as the *macro-particle* shapes in the magnetic coordinates (s, θ, φ). In order to simulate the time evolution of the instabilities in *realistic axisymmetric magnetic configurations*, numerically computed equilibria from the Grad-Shafranov solver `CHEASE[3]` are considered. The first results of the code together with the physical model and the numerical implementation will be described in detail.

[1] M. Fivaz et al., *Comp. Phys, Comm.*, **111**, 27 (1998)
[2] T.M. Tran et al., *Joint Varenna-Lausanne Int. Workshop on "Theory of Fusion Plasmas"*, Varenna, Italy, (1998)
[3] H. Lutjens et al., *Comp. Phys. Comm.*, **69**, 287(1992)

Suppression of anomalous and neoclassical transport in tokamaks by Alfvén waves.

V.S.Tsypin[1)], I.C.Nascimento[1)], R.M.O. Galvão[1)], A.G. Elfimov[1)], M. Tendler[2)], G.S.Amarante Segundo[1)]

[1)] *Physics Institute, University of São Paulo, Cidade Universitaria 05508-400, Brazil.*
[2)] *The Alfvén Laboratory, EURATOM - NFR, 10044 Stockholm, Sweden*

The suppression of the anomalous and neoclassical transport in tokamaks by the sheared electric field[1,2], induced by kinetic Alfvén waves, considered in the paper. In previous papers, these problems were investigated by the present authors in the framework of the approximate estimates[3,4]. In these approaches, differential equations, governing spatial dependences of normalized ion viscosity coefficients $\mu^*_{\theta i}$ and $\mu^{*p}_{\theta i}$ in the banana and potato tokamak regions, respectively, were replaced by algebraic equations. Such a kind of dependences on the radial coordinate appears as a result of ion banana squeezing in tokamaks in the presence of kinetic Alfvén waves. Previous investigations showed that the appropriate absorbed power, which is necessary to suppress anomalous and neoclassical transport in tokamaks, is generally speaking higher than was employed in past experiments with Alfvén waves.

In the present paper, the more explicit consideration of these problems is fulfilled. The spatial differential equations for the ion viscosity coefficients, which were obtained previously by the present authors for banana and potato regions of the tokamak plasma, are solved in the paper. Their solutions are shown in plots. The radial distribution of the absorbed power, which was used in these calculations, is a result of the solution the rf wave conversion, into kinetic Alfvén waves, problem. The spatial behavior of the ion viscosity in the vicinity of the conversion point depends on the sign of the normalized absorbed power P^*_w. In other words, it depends on the sign of the poloidal wave number m. If P^*_w is positive, $\mu^*_{\theta i}$ is decreased in the vicinity of the conversion point r_0, at $r < r_0$, and increased at $r > r_0$. If the sign of P^*_w is changed, i.e., the sign of the poloidal wave number m is changed, the Fig.1 will be the same, but it is necessary to transform $x \to -x$.

Such the shear of $\mu^*_{\theta i}$ and the sharp radial dependence of the absorbed power give rise to the strongly sheared radial electric field and the resulting suppression of the neoclassical and anomalous transport in tokamaks by kinetic Alfvén waves. Analyses of differential solutions and of resulting plots showed that the necessary absorbed power of KAW for the twofold suppression of the neoclassical transport in tokamaks is about $1W/cm^3$. Approximately the same value of the absorbed power P^{av}_w is necessary to suppress the anomalous transport in the banana and plateau regions of tokamaks. These values of the absorbed power P^{av}_w are higher or on the level of those to be used in existing experiments, and substantially less of those which were obtained in previous considerations of the problem.

[1]K.H. Burrell. Phys. Plasmas 4, 1499 (1997)

[2]K.C. Shaing, R.D. Hazeltine. Phys. Fluids B, 4, 2547 (1997).

[3]V.S. Tsypin, A.G. Elfimov, M. Tendler, A.S. de Assis, and C.A. de Azevedo. Phys. Plasmas. **5**, 7 (1998)

[4]V.S. Tsypin, R.M.O. Galvão, I.C. Nascimento, A.G. Elfimov, M. Tendler, C.A. de Azevedo, and A.S. de Assis. Phys. Rev. Lett. **81**, 3403 (1998)

Progress on a full radius electromagnetic gyrokinetic turbulence code[1] R. E. Waltz, J. Candy, M. N. Rosenbluth, and F. Hinton, *General Atomics* _Work is in progress to formulate a real geometry full radius nonlinear electromagnetic gyrokinetic code to simulated high-n turbulence and transport in tokamaks. The nonlinear electromagnetic gyrokinetic equations reduce to those of Frieman and Chen[2] (or Antonsen and Lane[3] linearly) in the ballooning mode or "flux tube" cyclic boundary condition limit. Our code goes beyond the flux tube to a full radius or "wedge tube" which will allow simulations at finite ρ* including profile shear stabilization effects. It has a mode of reduced operation in the flux tube limit and is expected to recover the (ρ*->0) gyroBohm scaled results from a similar gyrokinetic code being developed by Dorland and Kotschenreuter. The code is formulated with real geometry using Miller's generalized s^-α local MHD equilibrium model[4]. Lagrangian continuum (fluid-like) numerical methods are used with a 5 dimensional grid (n,r,θ,ε^,λ^) where n is the toroidal mode number from a Fourier transform in the field line angle, $\alpha=\phi-\int_0^\theta \hat{q}d\theta$, r is the midplane minor radius flux surface label, θ the poloidal angle (-π,π), ε^ the temperature normalized energy ε/T, and λ^=(μ/ε)B(r,θ=0) with μ the magnetic moment. Linear implicit numerical techniques from Kotschenreuther's linear ballooning mode gyrokinetic code[5] allow the fast transition motion of the current carrying passing electrons to be passed over, thus permitting finite beta simulations up to the MHD critical beta. The code is programmed with the expensive Green's functions, and gyro-averaging matrices and inverted response matrices computed once and stored. The code is laid out for fast parallel processing with one radial grid per processor. A grid suitable for present day moderate ρ* tokamaks fits on the T3E computer. Future terascale (100x faster) computers should allow high-n simulations at ITER ρ* values or permit full torus simulations (n=0,10,20...100)->(n=1,2,3....100) to study interaction of small scale turbulence with low-n MHD modes.

----

[1] Supported by U.S. DOE Grant DE-FG03-95ER54309

[2] E.A. Frieman and Liu Chen, Phys. Fluids 25 (1982) 502

[3] T.M. Antonsen and B. Lane, Phys. Fluids 23 (1980) 1205

[4] R.L Miller et al Phys. Plasmas 2 (1998) 973

[5] M. Kotschenreuther, G. Rewoldt, and W.M. Tang, Comp. Phys. Comm. 88, (1995) 128 .

Electromagnetic η_i mode turbulence at the plasma edge

A. Zeiler,
Max-Planck-Institut für Plasmaphysik,
EURATOM Association, 85748 Garching, Germany

J. F. Drake and B. N. Rogers,
Institute for Plasma Research, University of Maryland,
College Park, MD 20742, USA

Electromagnetic toroidal η_i mode turbulence is investigated linearly and nonlinearly for parameters typical for the plasma edge. Linearly the η_i mode is shifted to long wavelength due to electromagnetic effects while the growth rate remains unchanged. Thus, the usual linear estimate $D \propto \gamma/k_\perp^2$ would predict an increase of the transport rates at the plasma edge. Nonlinear simulations, however, exhibit a strong drop of the transport rates, when electromagnetic effects are included. This reduction of the transport rates is associated with a fundamental change of the overall character of the underlying turbulence. Highly localized eddies are observed, which result from magnetic reconnection events and lead to strong spikes of the transport. Specific investigations of the secondary instabilities, which limit the growth of the linear η_i mode, suggest, that the tearing mode becomes the dominant saturation mechanism, taking the role of the Kelvin-Helmholtz, drift-type instabilities, which are characteristic for the electrostatic regime. Thus, the main electromagnetic modifications occur in the nonlinear regime. Consequently magnetic fluctuations should generally be included in simulations of η_i mode turbulence, at least at the plasma edge.