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# Second IAEA Technical Meeting on the Theory of Plasma Instabilities: Transport, Stability and their Interaction

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# *OVERVIEW AND INVITED TALKS ABSTRACTS*

## What We Know About Magnetohydrodynamic Turbulence

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Understanding turbulence in magnetized fluids is a critical first step in understanding turbulence in realistic systems. In fact, in many astrophysical systems collisionless effects are negligible and magnetohydrodynamic turbulence is a realistic model. In contrast, in laboratory systems and space plasmas MHD turbulence is only a crude approximation. Despite its comparatively simple nature, progress in our understanding of MHD turbulence has been slow and important fundamental issues remain in dispute. Here I will describe the evolution of this field, from the purely hydrodynamic model developed by Kolmogorov to the most recent computer simulations of fully developed magnetized turbulence. Despite important physical differences between magnetized and unmagnetized systems many aspects of MHD turbulence turn out to be similar to hydrodynamic turbulence.

Note to the committee: I've asked for some financial support. This meeting is sufficiently distant from my own academic field (astrophysics) that I have some difficulty justifying spending grant money on travel to it. I have a small slush fund due to my work for the Astrophysical Journal, and my university has agreed to pay about $500 towards my plane ticket, but I would appreciate some help meeting local expenses.

# Comparative studies of nonlinear ITG and ETG dynamics

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The present work demonstrates that the crucial difference in nonlinear dynamic behaviors of ion temperature gradient (ITG) instabilities with respect those of electron temperature gradient (ETG) modes, stands in the particle response to zonal flows (ZF). On the one hand, for ITG, massless electron response imposes that the lowest order zonal density fluctuation vanishes; on the other hand, for ETG, the ion response is adiabatic, due to $k_\perp \rho_i \gg 1$, even for $n = m = 0$. The main consequence of these different behaviors is that the specular symmetry between ITG and ETG, which holds linearly, is nonlinearly broken. This results into two main facts, *i.e.*, that the ZF polarizability is much lower for ITG [1] than for ETG [2, 3] and that the dominant Drift Wave - Zonal Flow (DW-ZF) interaction is due to E $\times$ B nonlinearity for ITG, while ETG are characterized by the usual Hasegawa-Mima nonlinear coupling [4].

Based on these facts, the paradigm model for ITG, presented here, assumes that different DW interactions on the shortest non-linear time scale are mediated by ZF, which is spontaneously generated by ITG via modulational instability [5]. The resulting coherent model demonstrates turbulence spreading [6] to be the cause of transport scaling with system size [6, 7, 8]. The non-linear saturated state can be either coherent, with limit cycles, or chaotic, depending on proximity to marginal stability [9]. Meanwhile, ZF spontaneous generation is the weakest nonlinear dynamics for ETG, which saturate via nonlinear toroidal couplings that transfer energy successively from unstable modes to damped modes preferably with longer poloidal wavelengths [2, 3]. The ETG turbulence is dominated by nonlinearly generated radial streamers, but both fluctuation intensity and transport level are independent of the streamer size [2, 3]. Nonlinear Gyrokinetic particle simulations indicate that typical ETG transports are smaller than those of experimental relevance [2, 3].

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# Profile-turbulence interactions, MHD relaxations and transport in tokamaks

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In this paper we present recent results of extensive computational studies using the CUTIE Ref[1], global, electromagnetic, two-fluid turbulence code applied to the elucidation of the evolution of tokamak mesoscale structures on long (ie., resistive) time-scales. Attention is focussed on examples relating to typical data drawn from the Rijnhuizen Tokamak Project (RTP), and the JET experiments. These studies reveal the key roles played by the synergetic effects, due on the one hand to spontaneously generated or externally driven flows, and, on the other hand to current redistribution caused by bootstrap and dynamo effects in the electron channel. Central to the model is the idea of profile-turbulence interactions. The examples will include, on and off-axis sawteeth in Ohmic and ECH heated conditions, outward heat pinches, edge relaxations, transport barrier dynamics during shallow and deep pellet injections. These simulations show that the low mode number part of the turbulent fluctuation spectrum is excited (and maintained) by an inverse cascade[2], even if one starts with high mode numbers. These relatively long wavelength modes are associated with low order rational values of $q$, and play a key role in the tendency of the system to 'self-organize'. Firstly, they generate fine-scale, intermittent turbulence through nonlinear and toroidal mode couplings and give rise to secondary instabilities (direct cascade). Secondly, they imply corrugated fluxes due to fast radial variation in amplitude, and nonlinear, dissipative, cross-phase relations. These fluxes react on profiles and determine the local gradients of both magnetic and electric fields, which in turn, control the turbulence in a relaxation process. The paper will review the basic features of the model and the assumptions used in the simulations. It will also seek to clarify the nature of the MHD relaxations found and how they appear to organize the radial electric field and the safety factor profiles. Where appropriate, comparisons are made with experimental data. An outline is given of recent developments to the model attempting to incorporate advanced features like tight-aspect ratio, high betas and rapid rotation in the next generation code CENTORI which takes CUTIE as its point of departure but allows very high speed parallel supercomputers to be used.

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# The case of the trapped singularities

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In this work two different views of the physics behind plasma confinement transitions are smoothly reconciled in a unified model for the coupled dynamics of potential energy, turbulent kinetic energy, and shear flow kinetic energy subsystems.

Magnetized fusion plasmas are strongly driven nonequilibrium systems in which the kinetic energy of small-scale turbulence can drive the formation of large-scale coherent structures such as shear and zonal flows. This inherent tendency to self-organise is a striking characteristic of flows where Lagrangean fluid elements see a strongly two-dimensional velocity field, and is a consequence of the inverse energy cascade [1]. The distinctive properties of quasi 2-d fluid motion are the basis of natural phenomena such as zonal structuring of planetary flows, but are generally under-exploited in technology.

In plasmas the most potentially useful effect of 2-d fluid motion is suppression of high wavenumber turbulence that degrades confinement, which can manifest as a dramatic enhancement of sheared poloidal or zonal flows and reduction in cross-field turbulent transport. These low- to high-confinement (L–H) transitions have been the subject of intensive experimental, *in numero,* and theoretical investigations since the 1980s. Two major strands in the literature emerged early and have persisted: (1) They are an internal phenomenon that occurs spontaneously when the rate of upscale kinetic energy transfer exceeds the nonlinear dissipation rate; (2) They are due to ion orbit losses near the plasma edge or induced biasing, the resulting electric field providing a torque which drives shear flows nonlinearly.

These two different views of the physics of confinement transitions are assimilated in this work in a dynamical model developed by a systematic iterative method: 1. Interrogate degenerate singularities in the simplest model; 2. Unfold the singularities in physically meaningful ways, 3. Interrogate any new singularities that appear in enhanced model; 4. Repeat steps 2 and 3 until the model is free of pathological or persistent degenerate singularities, is self-consistent, reflects observations in experiments, and is therefore predictive.

The work is presented as a case study in bifurcation and stability analysis. A systematic methodology for characterizing the equilibria of dynamical systems involves finding and classifying high-order singularities then perturbing around them to explore and map the bifurcation landscape [2]. In a broad sense, this paper is about applying singularity theory as a diagnostic tool while an impasto picture of confinement transition dynamics is compounded [3, 4, 5].

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# On Control of Tokamak Plasma Transport

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Plasma transport in tokamaks is anomalous . The magnitude of transport is determined by the level of superthermal fluctuations driven by various microinstabilities and by the radial correlation length of the turbulence. Some degree of control may be exercised by influencing either a) the level of fluctuations or b) by influencing the radial correlation length. Both techniques have been successfully used in tokamaks . In negative central shear advanced tokamak discharges , the ITG instabilities are stabilized to the extent that the ion thermal transport drops down to sub-neoclassical values and an ion transport barrier results . This is a control of type a) where the level of fluctuations drops because the relevant modes are strongly stabilized . In the L to H transitions observed in tokamaks, the improvement in transport results because the self-consistently generated mean flows significantly reduce the radial correlation length of the turbulence . This is a control of the type b).

Yet another form of transport control is possible in tokamaks but has not been seriously attempted experimentally . If we carefully examine the basic drive of all transport related microinstabilties in a tokamak( viz. ITG , ETG ,DRBM , SOL turbulence etc ) we see that a dominant role is played by the bad curvature of the field lines on the outside of the torus. In principle, it should be possible to compensate for this bad curvature by RF induced ponderomotive forces opposing the gravity. Such a scenario for ideal ballooning mode stabilization was examined in a paper presented at the Kyoto IAEA conference (Sen and Kaw 1986 ). It should be possible to examine similar ideas for tokamak micro-instability control .

Recent work by Ciraolo et al (2004) suggests a novel scheme for transport control , based on feedback methods using chaos control theory. This scheme has been applied to test particle guiding centre diffusion in the field of a bunch of randomly phased low frequency electrostatic waves. It is shown that by the addition of a control electrostatic perturbations, the diffusion coefficient of guiding centres can be significantly reduced. To implement this scheme one has to learn how to apply the control electrostatic perturbations with specified parameters throughout the bulk of the turbulent plasma say in the core, edge or SOL region). The key questions will be how to ensure that, after self consistent shielding effects due to plasma are included, one still has the correct form of the control perturbations and whether test particle transport is really representative of the actual self consistent transport observed in the devices.

# Two-dimensional structure and particle pinch in a tokamak H-mode

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Steep gradient of the radial electric field is found to suppress turbulence transport, so the structural formation mechanism in toroidal plasmas is crucial to understand improved confinement. Much of researches were devoted to the study of the steep radial electric field structure in the L-H transition physics [1], but poloidal shock has been predicted theoretically when a large poloidal flow exists [2]. In a tokamak H-mode, a large poloidal flow exists in an edge transport barrier, and electrostatic potential and density profiles can be steep both in the radial and poloidal direction. Two-dimensional structures of the potential, density and flow velocity near the edge of tokamak plasma are investigated in the case that the strong radial electric field exists. The analysis is carried out with the momentum conservation law with the shock ordering. A set of equations is derived by considering the nonlinearity in bulk-ion viscosity and turbulence-driven shear viscosity [3]. The two-dimensional structure of the electric field in a transport barrier is obtained, giving a poloidal shock with the solitary radial electric field profile. The poloidal electric field induces convective transport in the radial direction, and poloidal asymmetry generates inward pinch of particles, which has pinch velocity of order of 1[m/s]. Large poloidal flow with radial shear enhances the inward pinch velocity. The jump of this inward flux at the onset of transition explains a rapid establishment of the density pedestal at the L-to-H-mode transition.

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# Neoclassical momentum transport and radial electric field in tokamak transport barriers

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The radial electric field is widely believed to be responsible for establishing transport barriers in tokamak plasmas, leading to regimes of improved confinement. This field is controlled by the cross-field transport of toroidal angular momentum, which can be due to either turbulence or Coulomb collisions. Since turbulence is suppressed in transport barriers and ion thermal transport in such regions is observed to be comparable to the neoclassical prediction, the radial electric field inboard of the barrier foot is likely to be governed by neoclassical momentum transport. We calculate the transport matrix, including the classical contribution, for the case of a low-collisionality (banana-regime) plasma with collisional impurity ions. The toroidal rotation velocity is taken to be larger than the diamagnetic speed and so large that the heavy impurity ions undergo poloidal redistribution under the action of the centrifugal force, however the bulk plasma remains subsonic. Previously only rotation shear was considered to drive the radial angular momentum transport, with an associated momentum diffusivity typical of the Pfirsch-Schlüter regime (which is much smaller than the heat diffusivity in the banana regime). The presence of impurities is seen to give rise to off-diagonal terms in the transport matrix, causing the plasma to rotate spontaneously, even in the absence of momentum sources in the core, with the rotation direction determined by the edge boundary condition. This result may shed light on recent experiments showing substantial plasma rotation in the absence of neutral-beam injection. The poloidal redistribution of impurities has previously been shown to have a dramatic effect on their transport, increasing it by a factor comparable to the aspect ratio, and a similar effect has now been shown to occur in the angular momentum transport. At conventional aspect ratio the flux is increased by a factor up to $\varepsilon^{-3/2}$ compared to the usual prediction, making it comparable to banana regime heat transport. Radial pressure and temperature gradients are the primary driving forces of the flux whilst the effect of rotation shear is enhanced only mildly over previous results. The classical transport is also seen to be enhanced by the impurity redistribution.

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**I1-S3**

# Theory of the Anomalous Transport Reduction

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There has been mounting evidence from laboratory and computer experiments that the reduction in turbulent transport by shearing by mean flows and zonal flows is critical to the formation of transport barrier (e.g. the L-H transition and the formation of internal transport barrier). In particular, the recent theoretical study [1] has indicated that zonal flows play an important role in regulating turbulence before the L-H transition until the shearing by mean flows becomes dominant due to the steepening of the mean pressure gradient near the transition, keeping the plasmas in the H-mode after the transition. Therefore, the medelling of the formation of transport barrier requires a quantitative prediction as to how much flux is reduced by both mean and zonal flows. Here, we consider a few simple turbulence models to study the scaling of the transport with (mean or RMS) shearing rate and then to examine the model dependence of such scalings.

First, we examine how the mean shearing (with shearing rate $\Omega$) affects the turbulent transport. In the passive scalar field model where random turbulence is arbitrarily specified, the transport is weakly reduced as while cross-phase is very weakly suppressed as [2]. In simple interchange and ion-temperature gradient turbulence models where turbulent flow is allowed to evolve dynamically, the transport of particle and heat is more strongly reduced with shearing rate $\Omega$ as [3], compared to the passive scalar transport [2]. This stronger reduction in the transport results from a severe reduction in the amplitude of turbulent velocity in both models. However, the cross-phase is only modestly reduced, as in the scalar field case [1]. These results are in qualitative agreement with the results from both gyrokinetic and gyrofluid simulations of toroidal ion-temperature gradient turbulence [4], but contradict recent claims in some literature. These results highlight the importance of the detailed properties of the flow in determining the overall transport level. We further discuss the effect of mean shearing on the reduction in the intermittent transport due to coherent structures.

Second, we assess the efficiency of random shearing by zonal flows in transport reduction in a scalar field model [5]. A random zonal flow with a finite correlation time renders decorrelation of two nearby fluid elements less efficient, leading to larger amplitude with a slightly different scaling compared to the coherent shearing. In the strong shear limit, the flux is found to have a scaling with the RMS shear as . Thus, the effectiveness of zonal shear decorrelation depends on both the strength of the shear and its auto-correlation time.

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# Global structure of ITG turbulence-zonal mode system in tokamak plasmas

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Using a global Landau fluid code in toroidal geometry, an electromagnetic ion temperature gradient (ITG) driven turbulence-zonal mode system in tokamak plasmas is investigated. Two different types of zonal flows, i.e. stationary zonal flows in a low q (safety factor) region and oscillatory ones in a high q region which are called geodesic acoustic modes (GAM) [1], are found to be simultaneously excited in a torus. The stationary flows efficiently suppress turbulent transport, while the oscillatory ones weakly affect the turbulence due to their time varying nature [2]. As a result of the different behaviour of the zonal flows, the tokamak plasma divides into the zonal flow dominant region and the turbulent region [3].

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# Non-linear fluid simulations of the effect of rotation on heat turbulent transport, in tokamak plasmas

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An out-standing issue in the study of turbulent transport is the generation of plasma rotation and its interplay with the transport properties. In particular, zonal flows (self-generated large-scale poloidal ExB flows) are known to efficiently regulate the turbulence level [1]. Evidence of anomalous toroidal momentum has also been reported in the plasma core of several tokamaks, without any external momentum sources. The origin of such a toroidal rotation is yet not well understood, though recent theoretical and experimental works show that turbulence can generate a flow through non-zero Reynolds stress [2-5].

These topics have been addressed by means of numerical simulations with a 3D fluid global model describing flux-driven plasma turbulence, in the core of a toroidal plasma [6]. The equation system includes an evolution equation for parallel velocity and models parallel Landau damping and collisional damping of zonal flows. Simulations of electrostatic toroidal Ion Temperature Gradient (ITG) driven turbulence have first allowed one to investigate the role of large-scale poloidal flows, such as the zonal flows on turbulent transport. It is found that both an increased driving heat flux and a reduced collisionality, $\nu^*$ raise the zonal flow shear. Also, the effective critical temperature gradient for the onset of ITG turbulence increases with zonal flow shear, as obtained in the simulations. Thus, the net result of a decrease of the collisionality is a larger temperature gradient, for a given flux at lower $\nu^*$ [7]. This is a favorable trend for reactor working conditions.

The effectiveness of the mechanism of toroidal momentum generation by the parallel component of the Reynolds stress is being studied. Preliminary results will be presented.

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# Theory, Simulation, and Experimental Test of Turbulence Spreading

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## Abstract

We study turbulence spreading corresponding to the spatio-temporal propagation of a patch of turbulence from a region where it is locally excited to a region of weaker excitation, or even local damping. A single model equation for the local turbulence intensity $I(x,t)$ includes the effects of local linear growth and damping, spatially local nonlinear coupling to dissipation and spatial scattering of turbulence energy induced by nonlinear coupling. In the absence of dissipation, the front propagation through the linearly unstable zone is ballistic with a charateristic speed given by a geometric mean of the linear growth rate and turbulent diffusion at nonlinear local saturation. The turbulence radial spreading into the linearly stable zone reduces the turbulent intensity in the linearly unstable zone, and introduces an additional dependence on the $\rho^* \equiv \rho_i/a$ to the turbulent intensity and the transport scaling. These are in broad, semi-quantitative agreements with a series of global gyrokinetic simulation results from GTC (gyrokinetic toroidal code). The front propagation stops when the radial flux of fluctuation energy from the linearly unstable region is balanced by local dissipation in the linearly stable region. The implications of these results on the inward spreading of edge turbulence toward the core and possible experimetal measurements are explored. It is found that transport in the edge-core transition region is significantly affected by the turbulence which is originated near the outer edge.

# Instabilities and Confinement of Energetic Ions on JET

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In preparation for burning plasma such as ITER, studies of instabilities and confinement of energetic ions were performed on JET with innovative diagnostic techniques, in conventional and shear-reversed plasmas, exploring a wide range of effects. In a surprising development, the use of internal density fluctuation diagnostics [1, 2] in shear-reversed plasmas has revealed many more Alfvén cascade eigenmodes [1-4] excited by energetic ions than has been detected with magnetic probes. Corollary discoveries are the detection of modes excited by sub-Alfvénic NBI-produced ions [2] and the observation of a depleted density of rational magnetic surfaces just before the times when $q_{\min}$ passes integer values [1, 5]. The new findings are used for MHD spectroscopy based on measurements of TAEs and Alfvén Cascades, which became on JET a routine technique for developing Internal Transport Barriers [5]. Alpha tail production using ICRF-acceleration of $^4$He NBI-produced ions from 100 keV to the MeV energy range have been employed for dedicated studies of the MeV range trapped $^4$He ions and their effect on plasma stability in the neutron-free environment [6]. Temporal evolution of ICRF- accelerated ions of $^4$He, $^3$He, D and H was assessed with and without energetic ion driven instabilities by measuring profiles and energy spectra of these energetic ions with the gamma-ray diagnostics [7]. Coupling between modes of different types and the energetic ions was investigated based on the measured profiles.

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# Energetic Particle Physics in Tokamak Burning Plasmas*

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Energetic particle confinement is a critical physics issue in tokamak burning plasmas because energetic particles provide the dominant plasma heating power in fusion reactors and their loss can cause harmful effect on the wall. In particular, Alfven type modes such as toroidicity-induced Alfven eigenmodes (TAEs), reversed shear Alfven eigenmodes (RSAEs), fishbones and other resoanating energetic particle modes have been shown both theoretically and experimentally to cause serious energetic particle loss or redistribution in the radial profile. In this talk we will review theories of TAE type modes, RSAEs and fishbones, and present the experimental results of these modes and associated energetic transport. We will then discuss the implication of these modes in ITER plasmas.

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# Damping of Alfvén Eigenmodes

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The ability to predict the stability of fast-particle-driven Alfvén eigenmodes in burning fusion plasmas requires a detailed understanding of the dissipative mechanisms that damp these modes. Although previous gyro-kinetic calculations [1] for the $n = 1$ TAE modes at JET agreed with experimental damping measurements [2] there is still no agreement on the dominant physical damping process [3]. A detailed investigation into this open question has been made using two different approaches: the linear, drift-kinetic perturbative-MHD code CAS3D-K [4] and the linear, gyro-kinetic, non-perturbative MHD code LIGKA [5]. The former of these two codes has also been applied to obtain theoretical stability boundaries for a TAE mode in a realistic 3-D W7-AS stellarator configuration. For the particular shot considered, the fast particle pressure is low and the ions contribute primarily to the damping via the stellarator-specific helical resonance.

Additionally, if the level of damping almost balances the fast particle drive such that the mode is only marginally unstable then the character of the nonlinear mode evolution may be modified [6]. Simple mode saturation is replaced with a frequency sweeping phenomenology that arises due to the formation of structures in the fast particle phase-space as shown by simulations with the nonlinear drift-kinetic HAGIS code [7].

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# Extension of GAM theory to Helical Systems

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Abstract

GAM oscillations, whose existence have been reported first as early as in 1986, is now gathering attention. Electrostatic fluctuations are divided into those in high and low frequency ranges. Drift waves belong to the former and the GAM oscillations belongs to the latter with other residual zonal flows. The interaction of the fluctuations in these two frequency ranges is broadly accepted as key mechanisms to determine the turbulence and governs the transports. The existence of Zonal flows including GAM have been recently evidenced in tokamak experiments in DIII-D and JIPP-TII U by using developed fine diagnostics BES and HIBP, respectively. Similar oscillations were found also in a helical device CHS by use of a dual HIBP. The most significantly, these papers indicate that the associated flows have rather narrow radial structure with the shearing rates attaining the decorrelation times. The present paper addresses a problem, if a GAM oscillation can be found in theory as it is extended to cover helical systems, which so far has been applied to tokamaks. By using drift kinetic equations for three-dimensional equilibriums, a generalized dispersion relation is obtained including Landau damping. It is found that the GAM frequency in a helical system is typically higher than that of tokamaks. An analytic form of the damping rate of GAM is obtained by solving the dispersion relation perturbatively. It is found that the damping is stronger in helical systems than in tokamaks due to the shorter connection length associated with the larger toroidal mode number. The connection length, however, becomes exceptionally large in the radial domain satisfying m-nq=0 and suggests presence of a singular layer of weaker damping. For instance, (m,n)=(2,6) for CHS giving the helical pitch of the device and the singularity occurs just a little out side the last closed flux surface.
The same formula is applied to tokamaks of noncircular cross-section regarding it as a class of multi-helicity problem. The obtained formula suggests an additive in the oscillation frequency proportional to the degree of ellipticity and singularity. It also suggests an enhancement of the damping rate due to the presence of the harmonics with their shorter connection length. Common through all the cases, it is shown that the damping rate is small for large values of Te/Ti and it is the case for JIPP T-IIU and CHS. Comparison of the experimental transport coefficients with the damping rate of the GAM in their radial structure and dependence on Te/Ti will give some clues to an assessment of the role of GAM in regulating turbulences via associated shearing rate.

# On the Excitation of Zonal Flows by Wave Particle Resonances

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Abstract

Excitation of zonal flows by ion temperature gradient driven modes has been studied using both fluid and kinetic models. Previous fluid derivations have shown that a strong excitation of zonal flows occurs through the nonlinearity in the energy equation and is enhanced by the fluid magnetic drift resonance. Thus a new derivation has been made by nonlinear kinetic theory, confirming that a strong excitation occurs through the kinetic magnetic drift resonance. Fluid and kinetic results are compared.

# Basic Turbulence Studies on TORPEX and Challenges in the Theory-Experiment Comparison

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The TORPEX experiment is dedicated to the study of instabilities, turbulence and transport. Plasmas are produced by waves in the electron cyclotron frequency range and are confined by a toroidal magnetic field of about 0.1 T, to which a small vertical component, $B_z$, is added. $B_z$ produces cylindrical concentric flux surfaces, whose topology does not match that of the toroidal vacuum vessel, a situation comparable to tokamak Scrape Off Layers (SOLs). Basic phenomena relevant to magnetic fusion can thus be studied in TORPEX, with the advantage of great diagnostic accessibility and independent variability of key parameters such as connection length, field line pitch with respect to the vacuum vessel, density and temperature gradients.

A quasi-static confinement model has been developed and verified experimentally, highlighting the crucial role of parallel flows in short circuiting charge separation produced by grad B drifts [S.H.Müller et al., PRL **93**, 165003]. The confinement time related to this basic mechanism and the fluctuation properties are observed to depend upon $B_z$ in a similar way, suggesting a common physical basis and opening the question of the role of $B_z$ on turbulence and related transport, either via local effects at the plasma-wall transition or via a global parameter such as the connection length.

More generally, in the comparison between theory and experiment two approaches are possible. The output of theoretical models can be interpreted as realizations of random processes and compared to the data in terms of statistical quantities, e.g. probability distributions, but the inherently necessary long time series still pose problems for numerical simulations, in particular for the advanced (gyro)kinetic models. The second method is to compare the spatio-temporal properties of the turbulence and related structures, a difficult task for experiments, particularly in the fusion domain. TORPEX offers both approaches for comparison. Data obtained simultaneously from more than 180 electrostatic probes covering the whole plasma cross-section and from fast optical diagnostics provides not only a complete statistical characterization, but also a space and time resolved reconstruction of the plasma fluctuations. Using the capability of TORPEX to induce a plasma current, the transition between core-like and SOL-like turbulence can be studied by progressively increasing the fraction of closed flux surfaces.

# Role of thermal instabilities and anomalous transport in the density limit

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The density limit is one of the most fundamental operational boundaries for fusion devices. A number of explanations have been proposed, which consider the density limit as a result of thermal instabilities at the plasma edge, which can be triggered by the specific dependence on the plasma parameters of the energy losses with impurity radiation, plasma recycling on divertor plates or inner wall. Other approaches stress the fact that the density limit is often preceded by a significant reduction of the particle confinement and by an increase in the cross-field convective power losses at the plasma edge. This evolution is accompanied by a fundamental change in the edge micro-turbulence, and, in particular, the amplitude of low-frequency perturbations attributed to drift resistive ballooning instability increases drastically.

A model for the plasma edge in limiter tokamaks is elaborated, which combines self-consistently the effects from impurity radiation, particle recycling and edge turbulence in order to investigate the synergy of these phenomena in the density limit. The model includes a description of the anomalous transport generated by the most important for the edge conditions micro-instabilities: drift-Alfven, drift resistive and drift resistive ballooning modes. Computations show that the scenario of the density limit is essentially determined by the poloidal inhomogeneities introduced from the Shafranov shift of magnetic surfaces and the ballooning character of the edge turbulence. In the case when the effect from the Shafranov shift dominates, Multi-Facetted Asymmetric Radiation From the Edge (MARFE) develops at the high field side when the density limit is exceeded. For a small shift, the transition in edge turbulence takes place when the limit is approached, after which the transport is governed by drift resistive ballooning modes and plasma detachment is initiated at the low field side.

The effect on the density limit from Dynamic Ergodic Divertor (DED), installed on tokamak TEXTOR in order to control the edge transport by artificial perturbations of the magnetic field, is analyzed. In agreement with experiments it is demonstrated that by changing the pattern of plasma-wall contact, DED can significantly modify the density limit scenario.

# Aspects of Mean Field Dynamo Theory

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One of the great breakthroughs in the modelling of natural dynamos – astrophysical or geophysical – was the formulation of mean field electrodynamics, in which one solves for the mean, or large-scale, magnetic field, with the behaviour of the small scale field and flow captured in various transport coefficients. The most important of these leads to what is known as the $\alpha$-effect, which provides a means of regenerating magnetic field.

Obtaining closed form expressions for $\alpha$ (and also the other transport coefficients) is possible only under certain restrictions; in particular when either the magnetic Reynolds number ($Rm = UL/\eta$) is small, or when the correlation time for the turbulence is very short. Much of our intuition about the nature of the $\alpha$-effect comes from results obtained in these two cases. Astrophysical plasmas however typically have huge values of Rm and O(1) correlation times. With modern computational resources it has become possible to begin to explore MHD turbulence at moderately high values of Rm (though a long way from astrophysical values) and O(1) correlation times, and to see whether our earlier ideas carry through to this regime.

I shall consider two models aimed at addressing mean field dynamo theory – and particularly the nature of the $\alpha$-effect – in turbulent plasmas with reasonably high values of Rm. The first is forced helical turbulence, for which I shall present results showing the dependence of $\alpha$ on both Rm and on the correlation time. The second considers the nature of dynamo action driven by rotating thermal convection. I shall show that whereas small-scale dynamo action (magnetic field on the scale of the driving turbulence) is extremely healthy, there are considerable obstacles to the generation of strong large-scale fields.

# Kinetic and fluid descriptions of interchange turbulence

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The fluid description of turbulent transport in magnetised plasmas requires less numerical resources, both in CPU-time and memory, than the kinetic approach. However, fundamental aspects of plasma physics, namely resonant wave-particle interactions, cannot be properly accounted for by fluid theories. Also, collisional closures of the fluid hierarchy lead to an over damping of zonal flows, which are known to govern the turbulent transport magnitude. As a result, fluid models overestimate both the linear instability threshold and the effective transport coefficients [1].

The present paper addresses these issues in a simple electrostatic model for interchange turbulence. With the flute assumption, the system is 2D in space, the radial and azimuthal directions in a cylinder. In the limit $k_\perp\rho_i \ll 1$, the drift-kinetic model is reduced to 1D-in-energy, by only considering $v_\perp$. Fluid and kinetic simulations are performed with the same semi-Lagrangian code, ruling out any discrepancy due to the numerics [2]. The collisional closure first considered governs the linear threshold of the 2-field fluid system involving vorticity and pressure. Two cases built to exhibit the same linear properties, namely the same threshold and unstable *k*-spectrum, are compared in the non-linear regime. The heat flux in the fluid simulation is larger by at least one order of magnitude, even when zonal flows are artificially suppressed. Consequently, the discrepancy is not only generated by the zonal flow dynamics. Furthermore, the projection coefficients of the distribution function onto the Laguerre function basis exhibit a slow convergence towards zero. This suggests that *f* cannot be properly described by only two moments in the fluid description.

An alternative closure is considered, such that the quasi-linear entropy production rates have a similar structure in the frequency space in the fluid and kinetic approaches. Such a matching requires the presence of the operator $|k_{//}|$ in Fourier space, analogous to the standard Landau fluid damping. Encouraging results are obtained linearly. Indeed, linear thresholds and unstable spectra can be fitted, and the fluid system exhibits damping of small scales in the absence of collisional diffusion.

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# Turbulence and intermittent transport in the edge/SOL of a toroidal plasma

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Recent experimental observations have revealed that the transport in the edge and scrape-off-layer (SOL) of toroidal plasmas involves large outbreaks of hot plasma. These bursts have a significant effect on the profiles of density and temperature. We have modelled these effects by deriving a consistent set of equations for the low frequency 2-D evolution in a slab geometry describing the outboard mid-plane of a toroidal device. The model governs the two-dimensional dynamics of interchange convection modes and includes the self-consistent evolution of the full pressure as well as potential profiles [1].

The model equations are solved numerically on a two-dimensional domain bounded in the radial direction and periodic in the poloidal direction. The numerical solutions comprise the different time scales of the problem from the fast growth time of the interchange instability to the slow viscous timescale. The fluctuations are driven by a source of particles and heat located at the inner wall. In the outer part of the domain the SOL is simulated by including local damping terms modelling the losses of density, heat and charge to the limiter/divertor plates.

The transport in the SOL is strongly intermittent and dominated by large events in the form of concentrated blobs of density and heat. In the quite periods between the transport events the dynamics is governed by a large scale poloidal flows generated self-consistently by tilted convective structures. The importance of conservative energy transfer from fluctuating to mean flows is demonstrated. These flows manage to sustain the strong pressure gradient during a viscous timescale. The blobs may propagate through the entire extent of the SOL. The statistical properties of these events and their influence on the averaged profiles are investigated and found to compare very well with experimental observations

Based on this work it is evident that a self-consistent description of plasma edge turbulence must account for the full profile evolution. The self-regulating mechanism mediated by energy transfer from fluctuating to mean flows should play an essential role also in connection with the dynamics of edge localized modes.

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# Gyrokinetic Edge Turbulence and the Edge/Core Transition

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The gyrokinetic model for low frequency turbulence in magnetized plasmas is applied to the tokamak edge. This steep-gradient region is sufficiently nonlinear that the turbulence has its own properties distinct from linear instabilities, which are found by computational diagnosis of the fully developed turbulence. The computational model is a 5-D phase-space grid representation of the gyrokinetic distribution function of each species, with field equations for the electrostatic and magnetic potentials arising from the field Lagrangian. Full energetic self consistency is assured. The transition from the edge region into the core shows clear effect of the changing collisionality and perpendicular/parallel scale length ratios, not least in the distribution of contributions to the turbulent flux in velocity space. The onset of effect due to trapped electrons following the decrease of collisionality is properly captured by the model and leads to a gradual change from fluidlike to a more kinetic "weak turbulence." Energetic pathways from gradient to thermal disturbances to E-cross-B eddies to parallel currents and to dissipation reveal the corresponding change in mode structure and dynamical character. Progress in modelling of experimentally measured tokamak edge phenomena, including the existence of pedestal structures in the temperature and density profiles, will be reported at the conference.

# Recent Progress in Gyrokinetic Particle Simulations of Turbulent Plasmas*

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Work is in progress for the Gyrokinetic Toroidal Code (GTC) on several fronts. GTC is a global, nonlinear, particle-in-cell (PIC) simulation code that is designed to run on massively parallel platforms. (1) We report on recent investigations involving the inclusion of a velocity-space (parallel) nonlinearity term in GTC. Initial results with adiabatic electrons show that this term can enhance the zonal flow and thus reduce the thermal flux, in the nonlinearly saturated state. Enhanced fluctuations of the m/n=1/0 mode are also observed.[W.W. Lee, Bull. Am. Phys. Soc. **49**, 135 (2004)] (2) Recent interest in electron temperature gradient (ETG) turbulence to explain electron thermal transport in tokamaks comes from numerical simulations in flux-tube geometry. Here, GTC is used to simulate ETG turbulence in an annulus of a DIII-D-size tokamak, showing that ETG modes saturate by nonlinear toroidal mode coupling. The ETG turbulence is dominated by nonlinearly-excited low-n streamers, but with a transport level well below that previously found in flux–tube simulations.[Z. Lin, *et al.*, IAEA 2004, Vilamoura, Portugal, paper CN-116/TH8-4 & Bull. Am. Phys. Soc. **49**, 247 (2004)] (3) The split-weight scheme for PIC simulations, following only the nonadiabatic part of the electron response, requires the global solution of Poisson-like equations. The efficiency of the global Poisson solver, using finite-element methods, is addressed. Results for modes including complete electron response in the electrostatic and electromagnetic regimes will be discussed. (4) A general geometry capability has been developed for GTC with generalized and extended features. Application of nonlinear electrostatic simulation to shaped plasmas will be presented. (5) The related code GTC-Neo, for the calculation of neoclassical fluxes of particles and energy, and of the equilibrium radial electric field, is now being used to obtain initial results for realistic tokamak cases, and these will be presented and discussed.
*Work supported by U.S. Department of Energy SciDAC Program, and contracts DE-AC02-76-CHO-3073 with Princeton University and DE-FC02-03ER54695 with University of California, Irvine.

## Linear stability analysis of the ITG/TEM system

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This paper deals with linear stability analysis and quasi-linear estimates of the ITG/TEM system. It is not intended to accurately predict the transport fluxes, but rather the emphasis is on how different physics effects could qualitatively influence them. The following effects will be discussed:

• The effect of collisions on the trapped particle response. This strongly affects the particle flux which decreases with collisionality resulting in a low $D/\chi$ ratio for high collisionalities $\nu/\epsilon\omega_D$. Collisionality however also affects the ratio of the diagonal (diffusion) to off diagonal (pinch) terms leading to a flattening of the density profile at higher collisionality.

• An outward particle flux driven by the temperature gradient could explain the observed density pump-out. It is shown that the direction of such a flux depends on the direction of the mode rotation, i.e. pump-out is expected when the dominant mode is a trapped electron mode, but not if it is an ITG.

• The influence of zero shear and rational surface on the electrostatic ITG. This influence is shown to be negligible. This result is essentially a linear result. Poloidal mode coupling is in general much more strong that the damping due to the non-rational nature of the flux surface.

• The influence of a uniform electric field. A uniform electric field can rotate a toroidal ITG in the poloidal direction into the region in which it is stable, therefore, stabilising the mode. It is shown, however, that one should not only consider the electric field and the Maxwell background. Parallel flows can significantly change the result. In essence the background distribution needs to be a solution of the gyro-kinetic equation and the stabilising effect disappears if the plasma rotates toroidally.

• Electron heat transport: It is shown that the electron heat flux is linear in the gradient of the electron temperature, and that under normal conditions in the experiments the gradient length can be twice the threshold, i.e. the electron temperature profile is only moderately stiff.

# Recent developments in the theory of neoclassical magnetic islands

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We will review recent developments in the theory of neoclassical magnetic islands. Emphasis will be made on the effects of neoclassical damping of the polodal rotation, its effects on the polarization current, and on the ion sound effects

# Synthesis of full MHD simulation results of neoclassical tearing modes in ITER geometry

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The dynamics of neoclassical tearing instabilities in ITER geometry is studied with our nonlinear full magneto-hydrodynamic (MHD) code XTOR. The extended MHD model in XTOR includes thermal diffusion and some neoclassical effects. In this work, both the issue of nonlinear onset and saturation are addressed [1-3]. The simulation results are compared with the predictions of the general Rutherford equation

$$\frac{\tau_r}{1.22}\frac{dw}{dt} = \Delta'(w) + 6.35\frac{D_R}{\sqrt{w^2 + 0.65W_c^2}} + 6.35\frac{R_o q}{B_o s_s} f_{bs} J_{boot,0}\frac{w}{w^2 + (1.8W_c)^2} \tag{1}$$

which describes the nonlinear evolution of the island size of Neoclassical Tearing Modes (NTM's). $W_c = 2\sqrt{2}(\chi_\perp/\chi_{//})^{1/4}\sqrt{r_s R/n s_s}$ is a diffusion length scale, $D_R$ is the resistive interchange parameter and $s_s$ the magnetic shear at the resonant surface.

It is shown that in the small to moderate island size regime, i.e. typically the nonlinear onset regime of NTM's, the numerical results and the theoretical predictions agree reasonably. In particular, the nonlinear threshold due to the Glasser term (=curvature term) is confirmed numerically with XTOR in the small island size limit. However, in the moderate to large island size regime, i.e. typically in the saturation regime of NTM's, theoretical predictions and full scale simulation results differ significantly. The reasons for this divergence are discussed and solutions for its reduction are presented.

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# Kinetic simulations of the NTM polarisation current

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The analytic theory of the Neoclassical Tearing Mode is usually developed assuming that the neoclassical ordering holds, i.e., the scale lengths associated with the orbit of the particles must be small compared to the scales associated with the plasma profiles. However, this is not the case under experimental conditions, since many plasma parameters (density, temerature, electric potential) vary on the scale of the island width, which is comparable to the ion banana width, at least in the early phase of the mode. In this paper the focus is on the neoclassical ion polarisation current due to the motion of the island with respect to the surrounding plasma, which is studied by means of Monte Carlo $\delta f$ simulations. The parallel closure of the polarisation current is predicted to play a role in the evolution of the NTM and has been invoked as a possible explanation for both the observed threshold for the minimum island size that can grow unstable and the scaling of the plasma $\beta$ at the mode onset with $\rho_*$. In order to obtain a tractable set of equations within the analytic theory, limitations of the variability range of the island size, and also of island rotation frequency and collision frequency are necessary. The numerical solution of the drift kinetic equation presented here does not require assumptions of this kind. These quantities are chosen as input parameters of the simulations. The motion of the ions is calculated in full toroidal geometry in the presence of a helical perturbation. In the case of an island width comparable to the ion banana width it turns out that the polarisation current decays linearly with decreasing island width. Moreover, the sign of the polarisation current can flip for rotation frequencies close to the diamagnetic frequency even in the absence of any pressure gradient. Finally, it is found that the so-called "high-collisionality" regime of the polarisation current can hardly be reached when the plasma is in the banana regime.

# Internal Kink Stabilisation and the Properties of Auxiliary Heated Ions and Alpha Particles

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It is well known that the stabilising effect of alpha particles is expected to extend the sawtooth period of ITER up to the order of the resistive diffusion time [1]. A pertinent question to ask is to what extent the stabilising effects of auxiliary heated minority ions of existing tokamaks can represent the role of alpha particles. Addressing this problem requires evaluation of the stability of the internal kink mode taking into account toroidal plasma rotation [2], anisotropy [3] and energetic ion velocity asymmetry [4]. Such effects are relevant to auxiliary heated ion stabilisation, but are not fundamentally important to alpha particle stabilisation. Finite orbit effects [5] however significantly modify the response of both auxiliary heated ions and alpha particles. This paper will address these issues upon consideration of the adiabatic and non-adiabatic fast ion response to the internal kink mode with the relevant effects included.

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# *POSTERS ABSTRACTS*

*(in alphabetical order)*

# Flux driven two-dimensional fluid turbulence simulation in the edge and scrape-off layer tokamak plasma

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## Abstract

A novel two-dimensional (2D) fluid model is proposed for investigating flux driven plasma turbulence in the tokamak edge and scrape-off layer (SOL). Unlike most previous turbulence simulations of this region, our model treats the two regions in a consolidated manner with a smooth transition region in between. Our unified 2D model is simpler and less computer intensive than three-dimensional (3D) models, but captures most features of 3D edge and 2D SOL turbulence. It also illustrates the influence of tokamak edge turbulence on the SOL transport, something not captured by the earlier 2D SOL simulations. Existence of an equilibrium radial electric field in the edge and SOL regions is confirmed, this electric field is found to change sign in the edge-to-SOL transition region. Turbulence in the edge is characterized by radially elongated streamers and zonal flows. The streamer structures occasionally break to form blobs. We obtain a phenomenological condition for the breaking of streamers. Formations of density blob and its dynamics in the edge and SOL regions have been studied. It is found that blobs are created in the edge region where the radial electric field changes sign. All the blobs, which form in this region are not ejected deep into the SOL. Only few of them are ejected. The ejection condition has been discussed. In the SOL region, the effective diffusion co-efficient has been calculated from the simulation results and is found to be consistent with most tokamak experimental values. Statistical properties of the particle transport obtained from this simulation are compared with the earlier flux driven 2D SOL turbulence simulation results and also with Aditya tokamak results.

# P-2

# Alfvénic Instabilities Driven by Alpha Particles in ITER Scenarios

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We examine the stability of proposed ITER scenarios with respect to Alfvénic instabilities driven by fusion-produced alpha particles by particle-in-cell simulations. Three scenarios are considered: SC2, characterized by a monotonic profile of the safety factor $q$, the reversed-shear SC4 scenario and a flat-$q$-profile "hybrid" scenario, SCH. We find that the reversed-shear scenario is the most unstable one, though the growth rates of the modes are quite small. In this case, the modes are localized close to the minimum-$q$ surface at mid radius. Also for the other two scenarios the most relevant modes are destabilized where the $q$ profile is rather flat; in these case, however, this condition occurs in an inner region. For SC2, it is the same region where the drive is maximum. For SCH, this is not the case (the maximum drive is localized around an outer flux surface), and the growth rate of the modes is very low. An interesting features of all these modes is that they smoothly connect, in the limit of zero drive, to MHD quasi-marginally-stable modes.

If the drive is artificially increased above that of the reference scenario (preserving its radial profile), apart from the obvious increase of the growth rates of these MHD-like modes, we find that destabilization of fast-growing Energetic Particle Modes (EPMs) can occur in the SCH case, if the energetic-particle drive exceeds a certain threshold. In the SCH case, such threshold corresponds to an alpha-particle energy content a factor 1.6 greater than the reference value. This does not seem too unrealistic, if the strong dependence of the fusion-produced alpha-particle density on the electron and bulk-ion temperatures, and the uncertainties intrinsic to the transport models are considered.

Concerning nonlinear dynamics of the system, the effects on the alpha-particle containment at the reference drive values are very small for the SC2 and the SCH cases. For the SC4 scenario, some broadening of the alpha-particle pressure profile is observed, indicating a certain level of inconsistency of the scenario itself. Simulations performed with increasing drive intensity show that a strong flattening of the alpha-particle pressure profile can occur in the inner plasma region for the SC2 case, while the global confinement of such particles is not significantly affected. The SC4 and SCH cases present the opposite situation, the effects being more pronounced in the outer portion of the discharge, where the modes are localized, with less impact on the on-axis pressure value. For the latter scenario, such effects are observed only above the threshold for EPM destabilization.

# Neoclassical tearing Modes in the presence of sheared flows

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The influence of equilibrium shear flows on the evolution of neoclassical tearing modes is an important issue for future long pulse experiments on tokamaks and for reactor grade machines like ITER. Sheared flows can be generated in a tokamak plasma due to a variety of reasons, such as due to neutral beam injection, ion cyclotron heating and self-consistent drift turbulence. A number of past studies have examined the effect of flows on classical tearing modes, particularly in the linear regime and for simplified geometries. There have also been a few nonlinear studies of the classical tearing mode but the problem is quite complex, particularly in realistic toroidal geometries, and is an important area of present and future study for major numerical initiatives such as NIMROD. A detailed understanding of the evolution of NTMs in the presence of flows is still lacking. In this paper we study certain aspects of this problem through numerical solutions of a set of generalized reduced MHD equations that includes viscous force effects based on neoclassical closures. Our principal findings are that in general differential flow has a strong stabilizing influence leading to lower saturated island widths for the classical tearing mode and reduced growth rates for the neoclassical modes. Velocity shear on the other hand is seen to make a destabilizing contribution. We delineate the contributions of various linear and nonlinear terms in the model equations towards this evolution process and also compare our results with some of the present experimental findings

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# Effect of sheared equilibrium plasma rotation on the stability of tearing modes

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Abstract

Plasma confinement in tokamak plasma discharges is known to be degraded by the onset and growth of tearing modes. Robust high plasma performance operation of present and future magnetic confinement devices requires a thorough understanding of the possible driving mechanisms for the destabilisation of such modes (e.g. local bootstrap and polarisation currents for neoclassical tearing modes-NTMs) as well as finding strategies for avoiding or controlling the amplitude of such modes (including complete suppression). In this work, the effect of sheared equilibrium toroidal plasma rotation on the stability of tearing modes in an ohmic (low ) regime is investigated. It is found that plasma rotation can be both destabilising and stabilising (i.e. increasing or decreasing the growth rate). Anomalous perpendicular plasma viscosity plays a key role on the effect of shear flow since for Prandtl numbers (ratio of the resistive to viscous diffusion time scales) above 1-5 and parabolic-like plasma rotation profiles with above ~10kHz on axis, the mode is stable.

# Nonlinear saturation of magnetic curvature driven Rayleigh Taylor instability in three dimensions

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The nonlinear regime of the magnetic curvature driven Rayleigh Taylor (MCDRT) instability is a suitable description of plasma behaviour in currentless toroidal devices. However, even in tokamaks where the equilibrium magnetic field lines are both curved as well as sheared the MCDRT mode can be viewed as a simplified representation of the balooning mode which manifests in the bad curvature region of the tokamak. Keeping this similarity in view we have in the past numerically simulated in two dimensions the nonlinear regime of MCDRT [1, 2]. Studies in two dimensions have shown evolution towards two distinct shear flow symmetry patterns viz. transport enhancing radially elongated streamers and transport inhibiting poloidally symmteric zonal flows for low and high dissipation parameters respectively. These flow patterns are observed in tokamaks and play a crucial role in regulating tokamak transport. This indicates that the simplified MCDRT model captures the crucial transport features of tokamaks even though it is devoid of complications associated with the magnetic shear effects. We have now generalized the MCDRT model in three dimensions and have also incorporated effects due to electromagnetic perturbations. A detailed description of the MCDRT instability in three dimensions in the presence of electromagnetic effects will be provided. The results obtained from extensive three dimensional simulations will also be presented which show evolution towards a variety of nonlinear states depending on the parametric regime of dissipation, the plasma $\beta$ etc.

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# Crystal – like structure in two dimensional dusty plasmas

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The massive, negatively charged dust grains are considered as discrete particles, while the electrons and ions assume to be distributed by Boltzmannean with the same temperatures, $T_e = T_i = T$. Assuming the grains to be conductors and charge of grain depend on the surface potential of the grain. The Poisson equation for small potentials takes then the form of the Schrodinger equation. The spatial distribution of the potential in the lattice includes the effect of whole system of dust particles. Such a self consistent description gives the dispersion relation for the dust lattice waves. It is shown that for the existence of ideal lattice the dusty plasma parameters must satisfy the definite relation. The calculation are carried out for two dimensional lattice putting the cyclic boundary condition on dust grains.

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# Relativistic current driven nonlinear Langmuir structure in plasmas

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The nonlinear stationary states of a relativistic electron beam moving in a homogeneous positive background are calculated for the full range of amplitudes of a longitudinal self-induced electric field in the collision less limit. The parameter that controls the system is the ratio of the electrostatic energy of the fluctuations over the kinetic energy of the beam ($\kappa$). In the collision less limit it might be that the number density of electrons and velocity of the beam in the stationary case are constant. If $\kappa > 2$ it is shown that no wave breaking occurs. Instead, the electric field becomes discontinuous at certain points and the electrons delay there forming periodic electrostatic (Langmuir) structures centered around negatively charged planes. The size and charge of the above structures as well as their wavelength, which now depends on the ratio of the electrostatic energy of the fluctuations over the kinetic energy of the beam, are derived.

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# Self-field in free-electron laser with planar wiggler and ion-channel guiding

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A self- consistent method for the analysis of self electric and self magnetic field for a free-electron laser with a one-dimensional planar wiggler and ion-channel guiding is presented. The equilibrium orbits and their stability, under the influence of self-electric and self-magnetic fields are analyzed. New unstable orbits, in the first part of the group I orbits and in the resonance region of the group II orbits, are found. It is shown that an increase in the defocusing effect of self-field will widen the unstable orbits. An anomalous self-field regime is found where an increase in the defocusing effect of self-field can have stabilizing effect on the resonance region. The application of an ion-channel as an electron beam-guiding medium not only eliminates the use of solenoid or quadruple magnets , but also allows for beam currents higher than the vacuum limit .

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# Interplay between density profile and zonal flows in drift-kinetic simulations of slab ITG turbulence

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Understanding turbulent transport in magnetically confined fusion plasmas remains a key issue for present and future devices. The instabilities driven by ion temperature gradients (ITG) are mainly responsible for ion anomalous transport. This work addresses non-linear global drift-kinetic simulations of slab ITG turbulence in an inhomogeneous collisionless plasma confined by a strong uniform magnetic field [1]. One considers the limit $k_\perp \rho_i \ll 1$, so that finite Larmor radius effects are only taken into account in the quasi-neutrality equation. In such a limit the ion distribution function is 3D in space and 1D in the velocity, namely $v_\parallel$. The $\mathbf{E} \times \mathbf{B}$ drift governs the transverse dynamics, while the parallel motion is governed by $\mathbf{E}_\parallel$. The electron response is assumed adiabatic hence impeding particle transport. The Vlasov-Poisson like system is solved on a fixed grid with a Semi-Lagrangian scheme [2] for the entire distribution function. The energy conservation, which is recognized as a key test of validity, is achieved with an accuracy better than 2.5%. The profiles of density, electron and ion temperatures are initialized as hyperbolic tangents. In the non-linear regime, the system is found to relax preferentially either via heat transport or via mean sheared flows, depending on the density profile. A strong density gradient appears to be stabilizing both linearly, by increasing the instability threshold, and non-linearly, by activating sheared flows. A quasi-linear analysis in the fluid limit suggests that the latter mechanism is due to the dependence of the Reynolds stress on the gradients of the density profile.

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# The influence of edge viscosity on plasma instabilities

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The interface between the plasma edge and its surroundings affect both the structure of plasma instabilities and the quality of confinement. According to well established procedures in MHD theory, the boundary conditions for the analysis of free-boundary instabilities is set by the flow of energy, mass, or flux across the boundary. However, ideal MHD disregards the role of viscosity in fluid motion. Even considering that viscosity effects are negligible for large scale instabilities in the core of high temperature plasmas, the effect of viscosity in the boundary is similar to surface tension, having a strong influence on high order modes of oscillation near the plasma edge. In water the balance between the forces of gravity and surface tension marks the transition from gravity waves to capillary waves [1].

This paper reports two instances where edge viscosity may be important in the behavior of natural as well as laboratory plasmas. In the first example the turbulence associated with the Rayleigh-Taylor instability, which is driven during the contracting stage of the decaying return stroke of a lightning discharge, creates anomalous viscosity that defines the spatial structure of bead lightning [2,3]. In the second example the kink modes in circular cylindrical plasmas are examined by taking into account the effect of viscosity in the boundary. It is shown that the $m=1$ kink mode is barely changed, but the higher order $m\geq 2$ modes are significantly damped if the collisionality is high. This has interesting implications for magnetic fusion, since the ballooning modes, which set a limit to the maximum pressure that can be confined in a tokamak, could be strongly affected. One may conjecture that anomalous ion viscosity associated with drift wave turbulence increases the surface tension thus leading to improved confinement. Since the anomalous viscous stress has a non-Newtonian character, one would have eventually a situation of bifurcation, allowing for drastic changes in the equilibrium. These topics are presently under investigation. One should point out that improved confinement by surface effects is the standard operational scenario envisioned for ITER, in conditions that have not been fully explained to date.

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# Dusty plasma as a Left-handed Medium

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In 1968, Veselago [1] studied theoretically the electrodynamics properties of a medium having both negative dielectric permittivity _(_) and magnetic permeability _(_) simultaneously and concluded such media must have surprising propagation characteristics in comparison with the conventional ones. These media were called the "left-handed materials" (LHM). In particular, they posses the reversal effects of the Doppler shift and the Cherenkov radiation. Such a medium was manufactured in form of a long line of the three-dimensional array of intersecting thin straight wires. The propagating modes of this line have the dispersion relation analogous to the usual plasma [2]. The anomalous optical properties of the LHM were discussed in [3].

In this communication we report the results of our study of the dispersion properties of the dusty plasma with ferromagnetic grains in the strong magnetic field $H_0$ when following inequality holds true $d_M H_0/T_0 >> 1$ ($d_M$ is the magnetic dipole moment of a grain, $T_0$ is the grain system temperature). We also suppose that $H_0 >> 4\pi N_g d_M$ ($N_g$ is the grain density number) that allows us ignore the influence of the magnetic field created by the magnetised grains. This system has the additional typical frequency _$_0$ = $(d_M H_0/J)^{1/2}$ associated with the small vibrations of the magnetic moments of grains around the direction of the magnetic field ( J is the inertia moment of a grain).

The linearly polarised electromagnetic wave propagating along y-axis in our medium transversally to the constant magnetic field (z-axis). We have shown that this media have simultaneously negative _ and _ in the following range of frequencies: _$_0$ < _ < _$_e$ , _$_e$ = $(4\pi N_e e^2/m_e)^{1/2}$ is the electron plasma frequency.

The left-hand side of this inequality depends on the magnetic parameters of grain and external constant magnetic field and its right hand side depends only on the electron density number. This allows us to make a statement that above-described system may be considered as a good candidate of the LHM with controlled parameters.

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# CONDITION OF DAMPING OF ANOMALOUS RADIAL TRANSPORT, DETERMINED BY ORDERED CONVECTIVE ELECTRON DYNAMICS

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Anomalous plasma particle transport due to low-frequency perturbations in the cross-field edge region of the toroidal devices is investigated now intensively. In turbulence of small amplitudes the electron trajectories are stochastic. At achievement of the large amplitudes when frequency, , of the electron oscullations in the convective cell of the perturbation exceeds the growth rate of its excitation, (t)>, the cell changes in its vicinity the electron density gradient $n_e$, which strengthens the next cells. Thus on the cell bounderies the jumps of $n_e(r)$ arise. On these jumps the growth rates of the next cell excitation are much more than the growth rate, determined by not perturbed $n_e$. It provides faster electron transport. In other words, the selfconsistent excitation of the low-frequency convective cells in the nonequilibrium plasma, drifting in crossed electric and magnetic fields in stelarator, by a radial gradient of density is unstable concerning occurrence of correlations. Thus convective-diffusion radial electron transport and partly ordered lattice of convective cells in space (r, z) arise. The perturbations of lattice-electron bunches reflect resonant electrons. The perturbations of lattice-electron holes trap resonant electrons. The convective-diffusion equation, describing these convective-diffusion radial dynamics of the electrons has been derived. It has been shown, that in the plasma, drifting in crossed electric and magnetic fields in stelarator, two kinds of perturbations, strongly distinguished on properties, are excited: not moving and quickly moving convective cells. The spatial structures of these not moving and quickly moving convective cells have been constructed. It has been shown, that the radial dimensions of these convective cells depend on their amplitudes and essentially depend on a radial gradient of density. It has been shown, that the observed fingers of density in peripheral area may be explained by the formation of these convective cells. The dispersion equation, describing the excitation of the perturbations in collisional plasma of stelarator, drifting in the crossed electric and magnetic fields, has been derived. It has been shown, that there is the universal parameter, controling the excitation of these perturbations. It has been obtained, that

# EVOLUTION EQUATION OF INTERMITTENCY OF LOW FREQUENCY VORTICES NEAR WALL IN NUCLEAR FUSION DEVICES

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The crossed structure of electric and magnetic fields near the wall in nuclear fusion devices is very important. The crossed electric and magnetic fields near the wall in nuclear fusion devices can lead to excitation of low frequency perturbations by radial gradients of the plasma parameters. These perturbations can be a vortical turbulence. It is investigated theoretically in this paper in the cylindrical approximation the excitation of the vortical perturbations. It is shown that the process of vortices excitation is unstable with respect to arising of correlation between an electric field and radial electrons' movement, when the vortex-electron interaction time becomes smaller than the inverse growth rate of vortex amplitude. In this case a convective radial movement of electrons and chain along stellarator surface in the case of intermittency of vortices in space (r, z) are appeared. Vortices of the chain reflect and trap the resonant electrons. In this case the fingers of electron density near wall in stellarator are formed.

The spatial structure of the electron trajectories in the fields of these vortical perturbations are constructed. The expression for the frequency of the electron oscillations in the field of the vortex is derived. The convective-diffusion equation is derived. At instability development of vortical turbulence excitation the intermediate regime of radial particle transport (convective-diffusion) is realized.

At instability development of vortical turbulence excitation the vortices not only result to convective-diffusion radial dynamics of electrons, but also can move collisionlessly in the radial direction, similar to observation.

In this paper it is also shown that taking into account of longitudinal electron dynamics can lead to damp of turbulence excitation in the following case. Namely, the lattice of vortices is not formed if period of electron movement along stellarator surface is shorter than time of instability development.

The radial transport equation of intermittency has been derived.

# EFFECTIVE SEPARATOR FOR EXTRACTION OF HEAVY DROPS FROM PLASMA FLOW

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The separation of heavy drops from plasma flow for the film coating is very important. The optimized parameters of such separator is researched in this paper. This separator has cylindrically symmetrical cusp kind of the magnetic field geometry. Plasma flows propagate along separator axis towards each other. Plasma electrons are magnetized. According to condition of plasma charge neutralization the light particles of plasma flows propagate along magnetic field lines to cylindrical wall. Due to particle collisions, small magnetic field or oscillation excitation the electron dynamics is not controlled effectively by magnetic field. It is shown in this paper that for any plasma flow density there is optimal value of the magnetic field for the best separation. For the smaller and larger magnetic field value the separation is essentially worse. For the small magnetic field the electrons are not magnetized. In this case radial velocity of electrons is large due to collisions. For the larger magnetic field the oscillated fields are excited and lead to anomalous transversal electron transport. The expressions for the optimal magnetic field value and optimal plasma flow density are derived. For optimal parameters the plasma electrons are magnetized, but oscillated fields are not excited. The mechanisms of suppression of oscillated field excitation are also considered.

# EFFECTIVE ELECTROSTATIC PLASMA LENS FOR FOCUSSING OF HIGH-CURRENT ION BEAMS

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Optimum plasma lens realized in experiments [1] at weak magnetic fields, when the Larmor radius of electrons is comparable with radius of the lens, has been theoretically researched. The optimum lens is lens, in which the vortical perturbations are not excited and particle density in which is uniform in space. Three possible reasons not excitation of vortices in near axis area of the high-current plasma lens have been researched: namely, finite time of ion movement through the plasma lens, finite time of electron renovating in it, proximity of the plasma lens parameters to optimum ones. It has been shown, that the vortical perturbations are not excited in the plasma lens, if the overbalance of ions by electrons is close to limiting one, determined from a condition of balance upset of radial forces retaining rotated electrons in the region of finite radius: magnetic retaining, centrifugal and electrical scattering forces. At an overbalance of ions by electrons, close to limiting one, the vortical perturbations are not excited in the plasma lens. Also it has been shown that the spatial uniformity of electron density is easier supported in the optimum plasma lens.

The possibility of supression of instability development of collective field excitation in near wall area of the plasma lens due to electron density increase on radius in this area has been considered. The influence of such electron distribution in the plasma lens on focussing of ion beam has been estimated and simulated numerically. It has been shown, that the aberrations, called by such electron density distribution on radius, are small.

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# THERMAL BARRIER FORMATION FOR PLASMA ELECTRONS AND IONS IN KIND OF CONNECTED DIP AND HUMP OF ELECTRIC POTENTIAL NEAR ECR POINTS IN CYLINDRICAL TRAP

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In [1] the thermal barrier formation for plasma particles near point of local electron cyclotron resonance (ECR) in monotonically inhomogeneous magnetic field along system axis for plasma flow has been observed experimentally. In this paper the mechanism of this large amplitude barrier formation for plasma electrons and ions has been proposed and investigated theoretically.

In a neighbourhood of ECR point transversal electron velocity increases strongly. At motion of electrons along an inhomogeneous magnetic field transversal electron velocity decreases and longitudinal electron velocity increases. The increase of longitudinal velocity results that electrons in the area, where they penetrate, will derivate negative volume charge. This charge is a dip of an electric potential, from which the electrons are reflected. The increase of longitudinal velocity in a neighbourhood of ECR point results also that a nonequilibrium state occurs. In other words, electron current velocity concerning to ions appears. The reflection of electrons from dip of an electric potential results in growth of its amplitude. The dip is excited on a slow ion modes with very small velocity.

Quasistationary properties of a dip are described in neglect by a non-equilibrium. Taking into account the non-equilibrium state results in excitation of the dip, in other words to growth of its amplitude.

As the large part of electrons of plasma flow is reflected from the electrical potential dip, and the ions pass through dip freely, a volume charge of ions there is formed, in which field ions are reflected. This volume charge forms large amplitude hump of the electrical potential. The flow of ions excites this hump of an electrical potential. The hump of the electrical potential is almost nonmobile in the space.

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# POSSIBLE WAY OF REDUCING HEAT AND PARTICLE LOADS ON DIVERTOR PLATES

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**Abstract:**

The heat and the particle loads on divertor plates of plasma from the scrape-off layer are studied in conditions of edge localized modes. Computer experiments with self-consistent simulation of neutral particles are performed varying the contribution of energetic particles from the burning plasma, the regime of neutral gas puffing and the size of edge localized mode. The results for optimization of the heat and particle loads on the targets will be discussed in aspect of ITER conditions with ELM discharges.

# Study of nonlinear phenomena in a tokamak plasma using a novel Hilbert Transform technique

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Tokamak plasma is rich in non-linearities of various kinds. The interacting low frequency long wavelength coherent modes are dominant in the core and the confinement regions whereas modes in a broad range of frequencies and wavelengths typically characterize the edge plasma. These interactions have been studied conventionally using a varieties of techniques including Fourier and wavelet transforms.

Recently a new technique as empirical mode decomposition (EMD) has been introduced which allows extraction of a finite number of intrinsic modes from the data. The Hilbert transform of such modes help to determine instantaneous frequencies and sharp changes in the instantaneous frequencies are identified as a signature of nonlinear phenomena in the data. This method is suitable for studying non-linearity present in the transient events.

The plasma transients during start-up and current termination phases in ADITYA tokamak have been studied using this technique. The analysis of signals from an array of Mirnov coils shows that nonlinear interaction among low frequency long wavelength modes plays an important role in current penetration during the start-up phase. On the other hand, interaction among low m modes lead to disruption during current termination phase.

Langmuir probe data from the turbulent edge plasma have also been analyzed using this technique. The data show signatures of intermittency in the form of sporadic bursts of mode energy. The Hilbert spectrum also allows evaluation of the degree of non-stationarity. It is observed that only high frequency signals (exceeding 20 kHz) are non-stationary.

# Dissipative Instability of Overlimiting Electron Beam In No Uniform Cross-Section System

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Streaming instabilities are the most frequently encountered plasma instabilities e.g. well known beam-plasma instability. Their physics is elaborated and it may seem that one fail to encounter a variety of that with new physics. This investigation presents new type of beam-plasma instability. It realizes under high beam current and in presence of high level of dissipation in no uniform cross-section system. Mechanisms of beam-plasma instability under very high beam current are of special interest. Traditional concepts of physical nature of beam-plasma instability are not applicable to such systems [1]. In this case beam inner degrees of freedom and its space charge play an important role. The instability is due not to induced radiation of the system proper waves, but either to aperiodic modulation of the beam density in system with negative dielectric constant or to excitation of beam space charge wave with negative energy. The last variety of beam instability realizes in system, which are no uniform in cross-section. The threshold current is limiting vacuum current for given system.

Apart from increasing of beam current, another physical phenomenon also leads to excitation of the beam wave with negative energy. Dissipation of high-level leads not to suppression of the beam instability, but transforms it to that of dissipative type. Dissipation serves as a channel of energy withdrawal and leads to excitation of beam wave with negative energy.

Present investigation considers superposition of the two processes that lead to excitation of the beam wave with negative energy. It causes instability of new type – dissipative instability of overlimiting electron beam. As expected, it has more critical (as compared with dissipative instability of underlimiting electron beam), inverse proportional dependence of the growth rate on dissipation. The influence of dissipation on excitation of the beam wave with negative energy and transition of instability to that of dissipative type as the level of dissipation increases are elaborated in detail. An approach is developed that enables to investigate space-time evolution of large variety electron beam instabilities. For underlimiting beams analogous approach was also developed [2], available for systems of arbitrary geometry. Influence of dissipation on other type of overlimiting electron beam instability is investigated in [3].

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# Large Scale Flows and Coherent Structure Phenomena in Flute Turbulence

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The properties of zonal and streamer flows in the flute mode turbulence are analytically investigated. The stability criteria and the characteristic oscillation frequency of these large-scale anisotropic flows are determined in terms of the spectra of the turbulent fluctuations. It is also shown that the non—linear growth of these flows can lead to the formation of long--lived coherent structures which can be characterized as regions with a reduced level of anomalous transport.

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## Generation and Saturation of Large Scale Flows in ITG turbulence

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The excitation and suppression of large-scale anisotropic flows during the temporal evolution of the toroidal ITG electrostatic instability is investigated. The non—linear formation of streamer and zonal flows is attributed to the inverse energy cascade towards large scales, as a result of the non--linear coupling with linearly unstable ITG modes. The growth, the saturation and the interplay between these large-scale structures are numerically investigated, and their dependence on diamagnetic and finite ion Larmor effects is depicted. The diffusion (spatial and energy) properties of test particles in the saturated fields is discussed.

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# EFFECT OF A PULSE MAGNETIC FIELD ON A HIGH PRESSURE PLASMA

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## ABSTRACT

An r.f.. induction plasma torch is a convenient source for the production of high temperature, and steady dence plasma to study the ionic process in this plasma. The temperature of this torch, supplied with organ, remains arround 10,000 K for a wide range of gass flow rate and r.f. power, although the size of the plasma varies with gass flow rate and r.f. power. The application of a pulse magnetis field, however, has shown to increase the plasma temperature by several thousand K

The application of the pulse field has been found to produce oscillation on the surface of the plasma. Because of the increased temperature and conductivity the skin depth of the pulse applied field is found less than 1.4 cm, which is the radius of the plasma.

# Nonlinear interaction of magnetized electrons with EC waves: Anomalous particle transport and self-consistent wave evolution

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The nonlinear interaction of relativistic electrons with electron-cyclotron waves in a constant magnetic field is studied. The interaction is analyzed over and near the local threshold to stochasticity. We analyze the electron diffusion across the magnetic field in real and energy space for various values of the wave amplitude and angle of propagation. The diffusion is found to obey simple power law in time and the scaling exponents correspond to sub-diffusion. This is connected to the effect of the resonant phase-space islands in the particle motion. The statistical character of the forces that control the trajectories of the particles is also studied. The forcing term is highly inhomogeneous along the particle orbit and contains non-Gaussian characteristics. This reflects to the properties of the particle motion. For example, the orbit of the gyro-center under the drift force **ExB** consists of smooth jumps between locations where the particle remains trapped. Finally, a self-consistent model for the wave-particle interaction is considered. In this model, the current density coming from the electron orbits is taken into account in the description of the temporal evolution of the wave amplitude and frequency. In this manner, wave generation and absorption in the plasma can be studied consistently with the dynamical behaviour of the beam and plasma particles.