A tutorial survey on problems of electric field in the H-mode physics

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Three decades have passed after the discovery of the H-mode, but the physics of H-mode remains a challenge for researchers. The study of the H-mode physics has been a source of motive force in plasma physics. In this tutorial survey, we illustrate some of essential elements that could stimulate the future progress of research.

We first discuss the problem definition, i.e., what are the problems:

> transition, steep gradient at edge, conditions and hysteresis of onset of transitions (threshold power), rapid transmission of change of transport into the core, limit cycle oscillations, ELMs and others.

With this problem definition in mind, the roles of the electric field in the H-mode problems are explained. Some of specific issues include:

> Bifurcation that is caused by electric field, roles of neoclassical process and other sources, impact of electric field on turbulent transport (shear and curvature of electric field), threshold conditions, and others.

The progresses of diagnostics and data-analysis methods are also commented, in conjunction with the recent rapid development of the research.

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Radial electric field dynamics on ASDEX Upgrade and comparison with neoclassical theory

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The dynamic evolution of turbulence and transport is the key to understand the transition to the high confinement mode (H-mode) in toroidally confined plasmas. An H-mode occurs through the generation of an edge transport barrier in which plasma turbulence is reduced by the shear of the edge radial electric field (E_r). Neoclassical theory predicts E_r to be dominated by the diamagnetic velocity of the plasma ions ($\nabla p_i/en_iB$), as also suggested by experimental observations in H-mode [1] but not assessed yet in the transition from the low confinement regime (L-mode). Recent observations at ASDEX Upgrade have shown a correlation between the ion heat channel and the H-mode onset [2]. However, the triggering mechanism in the transition process is still unclear. A pulsating phase of the edge E_r and of the turbulence amplitude (sometimes called limit cycle oscillation or "I-phase" [4, 5]) is often observed close the L-H transition where the role of turbulence induced flow shear is still under investigation [5, 6].

A recent upgrade of the charge exchange recombination spectroscopy (CXRS) diagnostic in the ASDEX Upgrade tokamak provides simultaneous measurement of the impurity density, temperature and E_r profiles with a time resolution of 50 μs. This allows to address the evolution of these profiles during the L-H transition. The fast dynamics of E_r and the ion profiles during the L-H transition will be presented for discharges with different L-H power thresholds obtained via a B_t-scan as well as a change of plasma isotopes. A comparison of neoclassical and measured E_r profiles and the evolution of the turbulence fluctuations will be shown in the different phases of the L-H transition process.

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Influence of electric fields on zonal flows in stellarators

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The self regulation of turbulent transport by zonal flows (ZFs) in fusion plasmas is widely accepted nowadays and a paradigm of drift-wave-ZF interaction has emerged [1].

Simplified models can provide valuable, although partial, information about the non-linear problem of ZF evolution. A number of works have treated the linear evolution of ZFs in tokamaks, finding that, in general, a zonal potential perturbation linearly relaxes to a finite residual level after an oscillatory phase in which the characteristic geodesic acoustic mode (GAM) appears (see [2] and references therein). In stellarators a similar situation occurs but with some differences. The long-wavelength-limit residual is zero and a low frequency oscillation (LFO) of the ZF is found in addition to the GAM found in tokamaks. The ambipolar neoclassical electric field influences both the residual zonal flow level and the LFO oscillations [3, 4]. Non-linear gyrokinetic simulations have provided indications that both the residual level and oscillations obtained in linear simulations are related with the level of turbulent transport [5, 6].

In this contribution a summary of results of gyrokinetic simulations of ZF evolution in stellarators carried out with the global code EUTERPE is presented. The linear evolution of ZFs for different radial wavelength has been studied in different stellarator configurations. The influence of the long-wavelength background electric field on the ZF residual level and oscillations in stellarator geometry is studied. A comparison of simulation results with recent experimental measurements of long range correlations in the TJ-II stellarator is provided.

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Observation of the ion internal transport barrier on HL-2A

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The internal transport barriers (ITBs) of ion temperature have been observed during the discharges of neutral beam injection (NBI) using charge exchange recombination spectroscopy (CXRS) of high spatiotemporal resolution on the HL-2A tokamak[1, 2]. The ITBs are routinely accompanied with the energetic particle induced MHD modes, such as the long lived modes and the fishbone instabilities, and can be easily developed at the beginning of the NBI heating. The position of the ITB foot is located at the q=1 surface. The inverse ion temperature gradient length (R/L_{Ti}) of the shots with the long lived modes (shots 24885 and 24893) is higher than those with strong sawtooth oscillations (shots 22865 and 22870), as shown in figure 1. The formation of the ITBs is closely related to the current drive of the NBI. Compared with that before the NBI, the width of the q=1 surfaces becomes wider after the NBI.

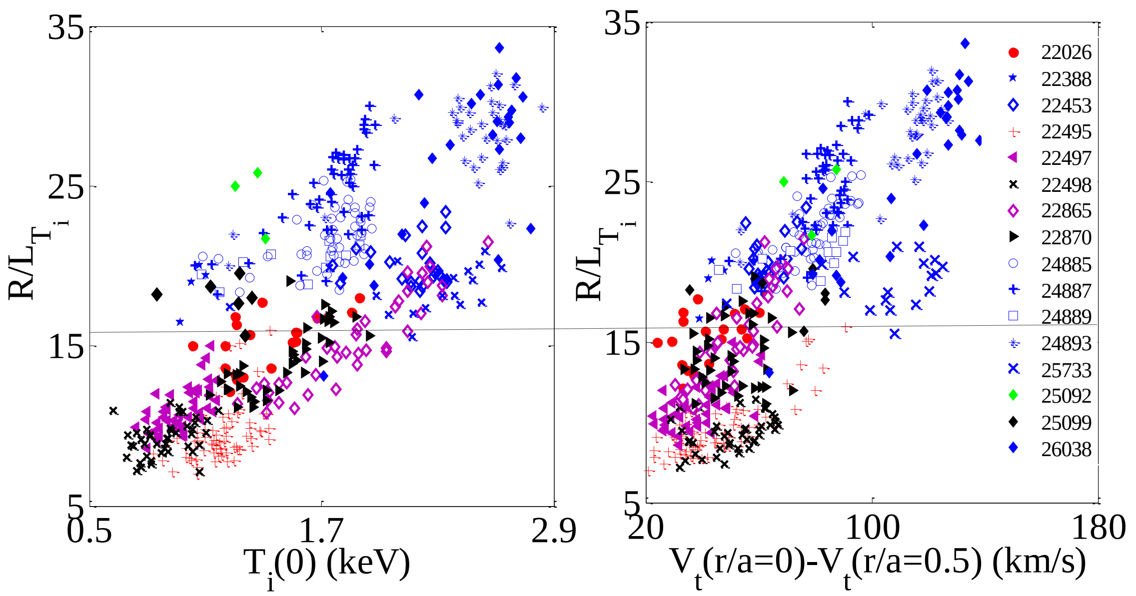

Fig. 1. R/L_{Ti} versus the ion temperature in the core (a) and the toroidal rotation (b).

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Experimental characterization of ExB staircases in Tore Supra plasmas

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A new kind of self-organized mesocale structures have been recently discovered in gyrokinetic simulations of turbulence in toroidal magnetized plasmas, using the GYSELA code [1]. These structures, referred to as the plasma ``**E**x**B** staircase", emerge spontaneously from the turbulent activity and endure on time scales much longer than those usually associated to turbulence. They consist in a set of quasi-regular localized shear flows and stress layers that form weak and spontaneous barriers to the propagation of long-scale transport events, thus regulating the transport of energy and particles.

Up to now, the **E**x**B** staircase has been mostly studied numerically as the direct measurement of flow shear in tokamaks is notoriously difficult [2]. However, the presence of the staircase structure can be indirectly detected through fast, radially-resolved measurements of turbulent fluctuations. A footprint of the quasi-regular pattern of shear flows indeed associated to the steps of the **ExB** staircase may be detected through a local reduction of the radial characteristic sizes of the turbulent fluctuations.

We report here experimental evidence of **E**x**B** staircases in Tore Supra whilst tracking local radial minima of the reflectometer coherence lengths [3], used as a proxy for the radial correlation length of the turbulent fluctuations. Quasi regularly spaced local reductions of the coherence lengths have been abundantly observed for a wide variety of experimental conditions. The possibility that the local reduction of the coherence lengths originate from MHD modes has been investigated and finally rejected as the positions of the coherence length minima do not depend of the local q value. About 180 occurrences of local minima have been observed so far, their radial extents were found to scale as 11 ρ_s, which agree well with the characteristics length of shear flows measured in GYSELA.

The above observations are consistent with the presence of staircases in Tore Supra plasmas [4]. We conclude the presentation by delineating the parameter space for which **E**x**B** staircases are observed.

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The Plasma Staircase:
Turbulence Self-Regulation through Spontaneous Flow Patterning

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A puzzling result in the recent years in plasma turbulence has arguably been the discovery of the quasi-regular pattern of ExB flows and interacting avalanches that we have come to call the "**E**x**B** staircase" [1]. This structure is a spontaneously formed, self-organising pattern of quasi-regular, long-lived and localised shear layers that organise the turbulent transport. Called "jets" in the context of planetary flows they are pervasive features of planetary atmospheres and critically influence the transport properties of heat, momentum, chemicals or even biota. An acute proximity exists between fusion plasmas and geophysical fluid dynamics. The plasma staircase is investigated through flux-driven gyrokinetic computations using the GYSELA code. Extensive parameter scans show that this flow pattern is a robust feature of plasma size, collisionality, turbulence drive, safety factor profile and poses new challenges in understanding profile stiffness, distance to criticality and nonlocal effects. The **E**x**B** staircase is intimately linked with heat and momentum avalanching, its step size is mesoscale, it modulates the outer scale of the avalanche distribution, is beneficial for confinement, displays a dynamics of its own and meanders, river-like. The overall transport is really that of a self-organised state in which the staircase is a key dynamical player. Observed and characterised theoretically, we now found it experimentally, using fast-sweeping reflectometry turbulence correlation measurements in ToreSupra. This is a rare instance of *prediction from a numerical model leading to discovery in observations* [2]. Many of its observed features agree remarkably well with the theoretical predictions. This observation may have far-reaching consequences for the understanding of turbulent organisation and for the validation of models of plasma turbulence.

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Abstract

This talk will look at both older published studies of the L-H transition and laboratory studies of turbulent driven shear flow generation as in the zonal flow. Then we examine more recent work in tokamak devices with a focus on the evolution of the edge ExB layer and turbulence during the approach to and transition into both the limit cycle regime (in which the plasma oscillates between low confinement and higher confinement regimes) and the final H-mode regime. We pay particular attention to experiments that provide a focused test the hypothesis that the edge turbulence itself acts to initiate the transition by driving a turbulent plasma flow which has an associated ExB component to it. Results from EAST, HL2A, DIIID, and ALCATOR C-Mod using probes, GPI and BES diagnostics are examined. All of these studies show evidence for the role of a turbulent-driven sheared ExB flow in initiating the transition via the strong nonlinear transfer of kinetic energy from the higher frequency fluctuations into the shear flow via the action of the turbulent Reynolds work. Recent work from ALCATOR CMod also shows clearly the development of a strong edge pressure gradient occurring *after* the transition ExB flow. Studies from HL2A and ALCATOR CMod also provide insights into the evolution of turbulence-shear flow coupling in the steady-state L-mode regime as the heating power is increased so as to approach the threshold for transitioning into H-mode. Both studies show the nonlinear energy transfer growing progressively stronger as heating power is increased. We also examine emerging turbulence simulations which show the same basic physical picture of the transition into high confinement. Together these multiple experimental and computational modeling results point to the critical role played by turbulent-driven zonal flows in mediating the transition into H-mode. However, all is not understood. Results from ALCATOR CMod also provide interesting insights into the origin of the I-mode. In that work, it is the finite-frequency sheared ExB flow associated with the GAM, and the associated nonlinear exchange of turbulent kinetic energy with the GAM, that appears to play a role in accessing the I-mode state. Further work is needed to fully understand the interplay of turbulence, zonal flows, and GAMs in accessing these confinement transitions, and in particular in defining the conditions needed to enter either I-mode or H-mode.

The I-phase and its relation to other phenomena at AUG

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The I-phase [1], sometimes referred to as limit-cycle oscillations [2] between perpendicular flow velocity and the turbulence amplitude, appears close to the L- to H-transition and shows pulsations with frequencies in the low kilohertz range. At ASDEX Upgrade, it is shown that the I-phase - typically measured with Doppler reflectometry - is accompanied by a magnetic response visible in pick up coils measuring $\dot{B}_\theta$. By means of these diagnostics, the properties and appearance of the I-phase can easily be studied in practically all discharge conditions due to the weak limitations of the magnetic measurement.

It is observed that the regular pulsation of the I-phase can smoothly transit into an intermittent phase during the density build-up from L- to H-mode. In this intermittent phase, the pulsation is accompanied by magnetic precursors visible in $\dot{B}_r$ probes being reminiscent of the dynamics of edge instabilities like type-III ELMs. This points to an electromagnetic component of the dynamics during the I-phase pulsations.

The findings raise the questions how the observation of precursors during the I-phase is related to the turbulence-flow interaction paradigm and whether further ingredients from magnetohydrodynamics should be included into the description of the phenomenon. These questions will be discussed based on examples of I-phases in different plasma scenarios from ASDEX Upgrade.

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Collisionality dependence of the energy transfer to zonal flows at the stellarator TJ-K

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Through the Reynolds stress, energy is transferred from the small-scale drift-wave structures to the zonal flow. Drift-wave eddies are tilted and drive the shear flow, which leads to a self-amplification of the zonal flow. The driving mechanism is equivalent to three-wave coupling and is reflected in the cross bispectrum.Thereby, the collisionality plays the key role for the interactions in the drift wave-zonal flow system. To study the drive of the zonal flow and its energy exchange channels, measurements with a poloidal Langmuir-probe array were carried out at the stellarator TJ-K. The array covers four neighbouring flux surfaces in the edge of the confinement region, whereby it is possible to investigate the energy transfer directly in wave-number space. Simultaneous measurements of density and potential fluctuations allow to address the nonlinear cross-coupling in drift-wave turbulence. Using the Kim method, which incorporates moments of fourth-order, it is then possible to estimate the spectral transfer of density fluctuation activity, which includes the nonlinearity of the $E \times B$-drift. A conditional averaging technique is used to calculate the temporal ensemble average. For the zonal flow as trigger event, an energy transfer from small-scale drift waves to the $k_\theta = 0$ mode is found, confirming the previously found non-local energy transfer [1]. Now the collisionality dependence of the process was studied in detail. By changing the ion mass and magnetic field strength, the collisionality is varied over a wide range. For low collisionality, the drift-wave damping is reduced and also the coupling between density and vorticity gets stronger, which makes the tilting mechanism more efficient. In the adiabatic case, the relative spectral zonal-flow power shows a strong increase. Furthermore, the energy transfer from drift waves to the $k_\theta = 0$ mode increases with decreasing collisionality.

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Zonal Flows in Fluid, Gyrokinetic and Planetary Turbulence Simualtions.

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Gyrokinetic simulations include the most accurate physics in current turbulence modelling in the low gradient, nearly collisionless region in the core of tokamak discharges. On the other hand, fluid turbulence simulations allow much higher spatial resolution, become more reliable at large collision frequency, and can be adapted to non-Boussinesq scenarios (at present the full nonlinearities of the edge cannot be implemented in a gyrokinetic framework), all relevant to the notoriously difficult edge region of tokamaks. The large ratios of domain size to vortex diameter accessible by fluid simulations are also relevant to the study of deterministic zonal flow (ZF) interactions.

Results on ZF [3] and geodesic acoustic modes (GAM) [4, 5, 6] obtained with the fluid code have been compared with the gyrokinetic code to isolate special kinetic effects from the presumably more robust fluid physics, and to allow a more reliable operation of both approaches in their respective fringe regions of validity, comparative studies using the GYRO [1] and the NLET [2] code have been performed. As a third tool a planetary simulation code (NAN) has been used to compare with the features of turbulence in a completely different turbulence system, to isolate features of the ZF independent of geometry and special conditions in magnetised plasmas.

Major differences can arise due to the neoclassical polarizability due to ion trapping, the relevant parameter of which are the aspect ratio and the ratio of turbulent diffusion versus the bounce frequency. Other deviations are from the non-adiabatic electron behavior due to trapping in the kinetic code. Overall, ZFs are generated similarly by a Reynolds stress based self amplification and interact with the turbulence modes through wave kinetic effects.

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GAM-ZF activity in I-mode transitions

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Turbulence and flow characteristics of the I-mode are studied on Alcator C-Mod with the specific focus of understanding the physics of access to the regime. The I-mode is a steady state confinement regime, characterized by a relaxed density profile while developing a strong temperature pedestal [1]. Discharges from a wide range of parameters (toroidal field, plasma current, density, and composition) are analyzed, and results point to a difference between the scaling behavior of the typical edge fluctuation, the Weakly Coherent Mode (WCM) and flows. Geodesic-acoustic modes (GAM) have been known to play a significant role in shaping the edge turbulence of the regime [2], while exhibiting drive–damping characteristics which scale similarly to the L-I threshold in macroscopic parameters. Nonlinear interactions between flows and turbulence in both L-mode and I-mode are estimated based on gas-puff-imaging using bispectral methods in steady state, with the L-to-I and I-to-H transitions analyzed in a time-resolved manner analogously to the L-H transition. Results clarify the role of GAM and zonal flows (ZF) in different types of transitions. Taken together, these results highlight that access to improved confinement regimes is profoundly affected by the nonlinear interaction between turbulence and ZF/GAM.

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Gyrokinetic investigation of isotope effect on flow oscillations in ohmic tokamak discharges

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Experimental studies show that increasing the isotope mass improves plasma confinement [1]. This improvement is known as the isotope effect. While turbulence is understood to reduce confinement, shearing of the turbulent structures induced by plasma flows has been identified as one possible cause for the improvement [2, 3]. The flows include the geodesic acoustic mode (GAM), a radial potential oscillation associated with a poloidal mode in density. Conway et al. have established interaction of GAMs, mean flow shear and turbulence in experiments. A correlation of GAM activity and increased confinement has been observed in hydrogen and deuterium FT-2 tokamak discharges, suggesting a connection between isotope effect and GAMs [4, 5].

We investigate the effect of isotope species on transport and flows in simulations of ohmic FT-2 tokamak discharges. The simulations are conducted using ELMFIRE, a full-f 5D particle-in-cell application of gyrokinetic theory. Experimental discharges with similar temperature, density, and current profiles but differing isotopes are adapted for the computations. Fluctuation levels, GAM amplitudes, fluxes, transport coefficients and correlation analysis of these quantities are presented.

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Investigation of transient nonlocal transport and its role in triggering neoclassical tearing modes at the HL-2A tokamak

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The mechanism governing the transient non-local heat transport has puzzled scientists for more than twenty years [1]. In the HL-2A tokamak, we have investigated the properties of self-organized criticality (SOC) dynamics in the non-local transport induced by supersonic molecular beam injection (SMBI). Experimental evidence shows that, along with reduction of flow shear at the plasma edge, the SOC or avalanche behaviors are strongly enhanced during the prompt non-local phase by increase in (i) radial correlation length of electron temperature fluctuations; (ii) Hurst parameters on self-similar character of turbulent events and (iii) inward avalanche propagation. These results unravel the importance of the SOC in governing the transient non-local transport.

In addition, during the non-local experiments at HL-2A an intimate interaction between the neoclassical tearing modes (NTMs) and the nonlocality has been observed for the first time [2]. Nearby the reversion surface of nonlocality, the increase of local temperature (or pressure) gradient results in onset of NTMs at q=2/1 or 3/2 surface. No seeding island was seen, implying that the local pressure gradient grows strong enough to linearly drive the NTMs. Because of the non-local effect, the NTM can be triggered at lower β_N. Meanwhile, it is found that with the presence of NTMs, the non-local phenomenon is weakened due to reduction of avalanche propagation, which might be associated with enhanced shear flows in the magnetic island of NTMs.

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Dynamics of Nonlinear Interactions between Electron Temperature Gradient Mode and Ion-scale Fluctuations in Linear Magnetized Plasmas

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Nowadays, anomalous electron heat transports induced by the electron temperature gradient (ETG) mode in magnetic plasma confinement devices are an important issue. We have investigated the physical mechanism of the ETG mode-induced anomalous transport through disparate scale nonlinear interactions in Linear Magnetized Plasmas [1]. In our previous work, we demonstrated that the ETG mode (~0.4 MHz) energy was transferred to the drift wave (DW) mode (~7 kHz) via multiscale nonlinear interactions between the ETG mode and the DW mode [2].

Recently, we have observed another low-frequency fluctuation with $f \simeq 3.6$ kHz, i.e., the flute mode when the inverse electron temperature gradient $\nabla T_e/T_e$ exceeded a certain threshold [3]. Figure 1 gives (a) the normalized amplitude $\tilde{I}_{es}/\bar{I}_{es}$ of fluctuations with the ETG and flute modes and (b) bicoherence between the ETG and flute modes as a function of $\nabla T_e/T_e$. The $\tilde{I}_{es}/\bar{I}_{es}$ of the ETG mode increased for $\nabla T_e/T_e \geq 0.2$ cm^{-1}, and the $\tilde{I}_{es}/\bar{I}_{es}$ of the flute mode increased for $\nabla T_e/T_e \geq 0.54$ cm^{-1}. In addition, the bicoherence between the ETG and flute modes increased for $\nabla T_e/T_e \geq 0.2$ cm^{-1}, namely, the flute-mode increase tendency did not correspond to the increase tendency of the nonlinear coupling between the ETG and flute modes.

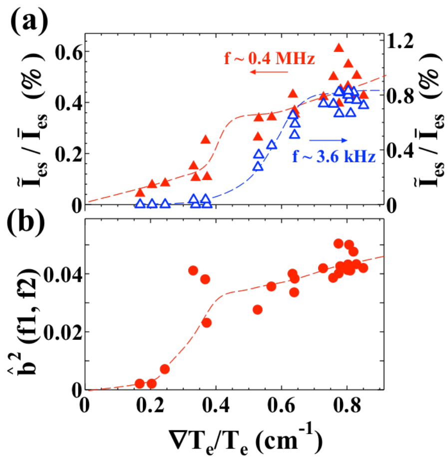

Fig. 1. (a) $\tilde{I}_{es}/\bar{I}_{es}$ of fluctuations with the ETG and flute modes and (b) bicoherence between the ETG and flute modes as a function of $\nabla T_e/T_e$.

Accordingly, we investigated the nonlinear coupling between the DW mode and the flute mode. Figure 2 shows (a) the $\tilde{I}_{es}/\bar{I}_{es}$ of fluctuations with the DW and flute modes and (b) bicoherence between the DW and flute modes as a function of $\nabla T_e/T_e$. The $\tilde{I}_{es}/\bar{I}_{es}$ of the DW mode was saturated when $\nabla T_e/T_e$ was higher than ~0.54 cm^{-1}. On the other hand, the $\tilde{I}_{es}/\bar{I}_{es}$ of the flute mode began to suddenly increase when the $\nabla T_e/T_e$ strength exceeded 0.54 cm^{-1}. Furthermore, the bicoherence between the DW mode and the flute mode steeply increased for $\nabla T_e/T_e \simeq 0.54$ cm^{-1}. Therefore, it is considered likely that the ETG mode energy was transferred to the DW mode [2] and then transferred to the flute mode [3] through the dominant nonlinear interaction between the DW and flute modes.

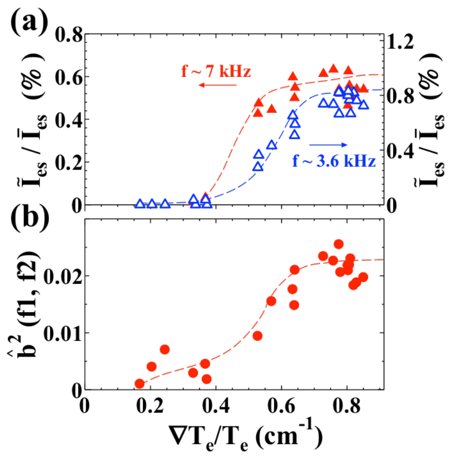

Fig. 2. (a) $\tilde{I}_{es}/\bar{I}_{es}$ of fluctuations with the DW and flute modes and (b) bicoherence between the DW and flute modes as a function of $\nabla T_e/T_e$.

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Investigation of plasma turbulence and geodesic acoustic modes using tangential phase-contrast imaging in the TCV tokamak

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The anomalous transport caused by the plasma turbulence is one of the outstanding physics issues in magnetic-confinement fusion research, due to the attendant degradation of energy confinement and ultimately fusion reactivity. Experimental measurements of plasma microturbulence, i.e., fine-scale, broadband fluctuations have thus become an essential need. A tangential phase-contrast imaging (TPCI) diagnostic [1] has been designed and installed on the Tokamak à Configuration Variable (TCV) to measure line-integrated density fluctuations with high sensitivity and temporal resolution; by employing a spatial filtering technique, radially localized measurements can also be performed with excellent spatial resolution from the core to the edge plasma, taking advantage of the flexibility of TCV regarding plasma shape and position. TPCI measurements have been performed to study the dependence of density fluctuations on plasma shape and radial position as well as collisionality. In particular, we sought to investigate the improvement in energy confinement at negative edge triangularity in the core region where *local* triangularity is vanishingly small. The measurements show a substantial reduction of the turbulence amplitude from positive to negative triangularity, consistent with the experimental observation of transport reduction in TCV [2] and with non-linear gyrokinetic simulations. In addition, the geodesic acoustic modes (GAM) have been characterized further on TCV [3] through parametric studies of the GAM frequency and amplitude. A transition between a frequency continuum and a single-frequency global eigenmode was observed for the first time in a single discharge by varying the edge safety factor.

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Structure and properties of geodesic acoustic mode oscillations in ASDEX Upgrade

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Three Doppler reflectometry systems are in operation on ASDEX Upgrade (AUG): two fixed antenna V-band systems (50 – 75 GHz, O- and X-mode) and one W-band system (75 – 108 GHz) with an adjustable tilt angle on the tokamak low-field-side. The sampling rate of 20 MHz allows the investigation of velocity fluctuations and radial electric field perturbations with high temporal and spatial resolution. Doppler reflectometry has previously been used on AUG to study the properties of zonal flows and geodesic acoustic modes (GAMs), in particular the GAM frequency scaling and the role of flow oscillations in confinement mode transitions.

By coupling both V-band reflectometers to a single X-mode antenna pair, a number of radial correlation measurements were made. These allowed investigation of the radial structure and localization of the GAM. The GAM was generally observed as a coherent structure with a radial width of 1–2 cm. Depending on the discharge conditions, evidence of radially inward GAM propagation could be found. The scaling behaviour of GAM frequency and amplitude has been compared to a number of theoretical and empirical models.

Furthermore, measurements from recent experiments have confirmed the presence of a magnetic GAM signature in ASDEX Upgrade. First results on the properties of the magnetic signature and its mode structure under various discharge conditions will be presented. Comparisons of the GAM spatio-temporal structure with the gyrokinetic code NEMORB and the gyrofluid code GEMR will be shown.

Experimental investigation of geodesic acoustic modes on JET using Doppler backscattering

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Geodesic acoustic modes (GAMs) are characterized by a symmetric potential structure in the poloidal and toroidal directions and a rapidly varying radial structure with finite wavelength. Because of their small radial structure, the E×B shearing rate due to GAMs can be important before and during the L-H transition when the mean shear flow is modest [1]. Recently, the influence of isotope mass on the GAM amplitude has been studied [2] showing a systematic increase in the GAM amplitude during the transition from H to D dominated plasmas. Consequently, understanding GAMs may yield important implications for the dynamics of the L-H transition.

This contribution focuses on the characterization of GAMs in the JET edge plasma using mainly Doppler backscattering (DBS). Experiments were performed in Ohmic and NBI heated vertically-shifted plasmas (where a correlation reflectometer works for DBS) for different values of plasma current ($1.5 < I_p < 2.75$ MA) and line-averaged density ($1.5 < n < 4 \times 10^{19}$ m^{-3}). GAMs are generally most intense in the edge density gradient region in a radial region of about 2 cm, coinciding with the location of the radial electric field well. The GAM has a constant frequency with radius, not varying with the local temperature. The GAM RMS E×B flow velocity is up to 1.5 km/s, corresponding to about 50% of the local mean value.

There are two factors that determine the magnitude of the GAM: its drive and damping. The GAM amplitude is observed to decrease with the edge safety factor, in contradiction with the expected reduction due to collisionless damping. GAMs on JET appear to be regulated by the turbulence drive – the density fluctuation level, as well as the density and temperature inverse scale lengths, increase with plasma current and line-averaged density, concurrent with the enhancement of the GAM amplitude.

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comparisons of GAM characteristics and dynamics between Tore Supra experiments and gyrokinetic simulations

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Geodesic acoustic modes (GAMs) have been studied in Tore Supra using a Doppler backscattering, in a series of experiments where the collisionality has been varied while keeping other dimensionless parameters constant. Observations are compared to the results of a simulation with the gyrokinetic code GYSELA using the experimental plasma parameters. The GAM frequency in experiments is found to be lower than predicted by simulation and theory. The disagreement is higher in the low collisionality scenario.

Bursts of non harmonic GAM oscillations have been characterized with filtering techniques, such as the Hilbert-Huang transform. When comparing this dynamical behaviour between experiments and simulation, the probability density function of GAM amplitude and the burst autocorrelation time are found to be remarkably similar. In the simulation, where the radial profile of GAM frequency is continuous, we observed a phenomenon of radial phase mixing of the GAM oscillations, which could influence the burst autocorrelation time.

Comparative study of multi-scale turbulence at FT-2 by Doppler backscattering and global gyrokinetic modeling

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Large-scale mean E×B flows, meso-scale zonal flows and fine-scale micro-turbulence excited in inhomogeneous tokamak plasmas and leading to anomalous transport have been for a long time in focus of parallel experimental and theoretical research in magnetically confined plasmas utilizing sophisticated diagnostic tools and massively parallelized particle-in-cell simulations of the electron and ion gyrokinetic (GK) particle distribution function and the electric field. In recent papers [1, 2] a comprehensive comparison of global GK simulations of the FT-2 tokamak ohmic discharge to the experimental data obtained by highly localized turbulence backscattering diagnostics, performed at the low magnetic field side of the torus, had been provided.

In this paper results of a more detailed comparative study of the mean and oscillating parts of the poloidal plasma rotation as well as poloidal and radial structure of the turbulence performed at FT-2 tokamak at different poloidal angles by Doppler backscattering (BS) (reflectometry and enhanced scattering in the UHR) [2, 3] and global gyrokinetic (GK) modeling [1] are presented. The Doppler reflectometer (DR) spectra, obtained at the high field side, as well as the signal dependence on the incidence angle are shown to be similar to those predicted by the synthetic diagnostic developed for the X-mode DR in the framework of the ELMFIRE global GK code. The radial and poloidal correlation length (CL) dependencies on the poloidal angle θ are investigated both by the DR radial correlation technique introduced and justified in [4, 5], accordingly, and by GK code. It is shown that in agreement with the GK modeling predictions the radial CL quickly decreases at $110^{\circ} < \theta < 210^{\circ}$ and then steadily grows in direction of plasma rotation at the low-field side [6]. It is shown that estimations of the poloidal CL are close to the corresponding radial CL values at low-field side and exceed them at high-field side. The correlative study of the medium-scale GAM turbulence by UHR BS and small-scale turbulence by reflectometry revealed the effect of the turbulence level modulation at the GAM frequency, supported by GK modeling demonstrating the modulation of density fluctuations as well as of the heat flux and diffusivity [7].

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Experimental Observation and Characterization of Microtearing Modes in a Toroidal Fusion Plasma

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The Reversed Field Pinch (RFP) device has nowadays achieved the Quasi Single Helicity (QSH) scenario as its standard way of operation. This magnetic configuration features a central plasma volume with good magnetic surfaces and appearance of transport barriers with reduced heat transport. In such plasmas microturbulence is invoked as responsible for a non-negligible level of transport beyond collisional limits, as for the other classes of toroidal fusion devices.

Recently, a theoretical stability analysis of microtearing modes in RFP, performed by means of the GS2 code, indeed revealed the QSH states to be prone to microtearing modes.

In striking contrast with the body of theoretical work on microturbulence in fusion plasmas, the number of experimental investigations is fairly limited; most proofs about the existence of the microturbulence are indeed deduced from measurements of largescale quantities (profiles, fluxes, flows, etc...), and a number of supplementary hypotheses to link the micro- and the macro-scales are needed.

We provide here the first direct observations in laboratory plasma of the presence of microtearing modes in the plasma core.

The measurements are carried out in the RFX-mod device by means of a system of in-vessel probes located at the wall, capable of detecting magnetic fluctuations with high time and space resolution. Small-scale electromagnetic modes are revealed during the helical states of the plasma; their amplitude is well correlated to the electron temperature gradient strength in the core. The identification of such instabilities in terms of microtearing modes derives from the comparison of experimental data with dedicated linear gyrokinetic simulations. The possible effect on heat transport in RFP plasma is discussed.

Nonlocal transport in the scrape-off layer

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The formation of plasma blobs is studied by analyzing their trajectories in a gyrofluid simulation in the vicinity of the separatrix at ASDEX L-mode parameters. Most blobs arise at the maximum radial electric field outside the separatrix. In general, blob generation is not bound to one particular radial position or instability. A turbulence spreading model has been developed which allows the estimation of the impact of turbulence spreading based on standard diagnostics of SOL plasmas. The simulations show that the blob dynamics can be represented by turbulence spreading, which constitutes a substantial energy drive for far scrape-off layer turbulence and is a more suitable quantity to study blob generation compared to the skewness. The impact of turbulence spreading is also estimated from experimental data from the International Stellarator-Heliotron Profile Database including data from TJ-K, WEGA and HSX.

Observation of Intermittent small scale turbulence during ELM mitigation on EAST

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Type-I ELMs, can eject a large quantity of particles and energy from the core plasma, causing significant erosion at the divertor target. How to reduce the transient peak divertor heat load induced by type-I ELMs is a critical issue in tokamaks. Mitigation of ELMs has been demonstrated in the EAST Tokamak in quasi-steady state by fueling with multi-pulses of supersonic molecular beam injection (SMBI). It has been shown that the ELM mitigation effect depends strongly on the SMBI pulse length i.e. fueling effect. These experiments have further revealed the underlying physics mechanism for ELM mitigation, demonstrating how small scale turbulence affects ELMs. This offers a relevant and profound insight on the interplay between fueling (SMBI), turbulence, transport and MHD instabilities in the pedestal.

The turbulence in the pedestal is measured by a Doppler reflectometry in X-mode. The small scale high frequency turbulence (f >300 kHz) is measured by the backscattering, with the turbulence poloidal wavenumber of $k_\theta \sim 7.3\mathrm{cm}^{-1}$, while the large scale low frequency turbulence (f <300 kHz) is measured by the forward scattering, with the turbulence poloidal wavenumber varying from 0 to 0.8 cm^{-1}. The small scale turbulence is intermittent and bursty with pulse length of about 10μs.

We find that the particle fluxes caused by ELMs are strongly correlated with large scale turbulence and anti-correlated with small scale turbulence. The large scale turbulence is directly generated by ELMs. The transition from large to small ELMs appears to be due to the enhancement of the particle transport in the pedestal and likely due to the extension of the Peeling Ballooning instability limit as well, with both being caused by small scale turbulence induced by SMBI or mitigated ELMs themselves. ELMs can be completely suppressed when the small scale turbulence becomes sufficiently strong.

Poloidal asymmetries in SOL transport on ASDEX Upgrade

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The edge region of the tokamak plasma plays a crucial role in the efficiency to produce fusion power and in defining the heat load to plasma facing components. Therefore, understanding of plasma turbulence and transport properties in edge and SOL plasma regions becomes of fundamental importance. Most edge measurements are made on the low-field side (LFS) because of easier diagnostics access but since SOL/edge properties are not poloidally symmetric therefore data from the high-field side (HFS) are essential.

At ASDEX Upgrade (AUG), the frequency modulated continuous wave (FMCW) reflectometry system has simultaneous measurements HFS/LFS. Operation in O mode provides measurements which are independent of the magnetic field, which is important in the studying different magnetic configurations. Radial profiles of the density fluctuation levels (δn/n) at the HFS and the LFS were obtained in L-mode in upper single null (USN), lower single null (LSN) and double null (DN) configurations.

The turbulence level is found to be much lower on the edge and SOL HFS in LSN and DN as expected from previous experimental results, with the lowest fluctuation levels observed in the DN configuration. The shapes of the turbulence frequency spectra display variations which are different in the high and low frequency parts of the spectrum. The strongest HFS/LFS asymmetry of fluctuations occurs outside of the separatrix in DN plasma shape that was also seen with three dimensional electromagnetic gyrofluid computations from the GEM code [1]. Inside the separatrix, poloidal asymmetries are less pronounced for all magnetic configurations. A $\delta n/n$ drop inside the separatrix is observed in the region of strong radial electric field E_r shear for all configurations. Surprisingly, in USN configurations inboard SOL turbulence increases above the LFS level. This is currently under investigation and as reported in [2] HFS/LFS asymmetries in the turbulence level may be induced by different electron temperature gradients at these locations that are configuration dependent.

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Influence of the I-Phase on blob properties in ASDEX Upgrade

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In many fusion experiments a regime is observed in a very narrow parameter range, where periodic variations of the turbulence level and radial electrical field in the edge plasma occur. At ASDEX Upgrage this regime is called the *I-phase* [1]. During the I-phase, also periodic changes in the kinetic profiles are observed. The typical oscillation frequencies of the fluctuating quantities are in the low kilohertz range ($< 5\,\mathrm{kHz}$). The I-phase is observed very close to the L-H transition and is sometimes regarded as an oscillatory state between L- and H-mode. It is not yet clear, however, if this interpretation is entirely correct. Nevertheless, these observations suggest that a closer insight in the L-H transition can be gained by studying the I-phase.

The most prominent fluctuations during the I-phase are observed in the edge plasma just inside the separatrix. However, recent experimental results from ASDEX Upgrade, which are presented in this contribution, show that significant changes extend to the far SOL. Gas-puff imaging data clearly shows a change in the emission characteristics of a neutral gas-cloud used to study filamentary transport in the SOL and even the properties of the filaments themselves are modified with the characteristic I-phase frequency. According to analytical blob models, the changes in the blob properties could be expected to mainly reflect changes in the electron temperature or magnetic configuration. The experimental database is not yet sufficient to discriminate between the two possibilities. It is clear, however, that they may provide further insight in the physics of the I-phase, the L-H transition, and also filamentary transport. This will be subject of dedicated experiments in the current experimental campaign of ASDEX Upgrade.

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Influence of magnetic configuration on edge turbulence and transport in the H1 Heliac

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Understanding the role of magnetic islands and ergodicity on confinement and turbulence is vitally important for understanding the suppression of edge localised modes via 3D fields in Tokamaks, and Stellarators alike. For example, resonant magnetic perturbation coils in Tokamaks are known to produce a density pump out and modify turbulence behaviour. The fixed, but finely tuneable magnetic configuration and relatively low beta of the H-1 Heliac Stellarator device is ideal for studying in detail the role of the magnetic configuration, including rational surfaces, magnetic shear, curvature and islands on turbulence and transport at the plasma boundary. For example, changing the current in the helical coil can produce changes in rotational transform continuously, with low shear profiles, from about 1 to 1.5. In particular, pervious results show that when the edge rotational transform is close to 7/5, a pronounced drop in the density can occur (globally), and is an ideal configuration for studying the effects of edge ergodicity on confinement. Recently, scans have been done in rotational transform on a shot-by-shot basis, as well as continuously during the discharge, and drops in density can be seen in both datasets. At particular values of rotational transform, the plasma density exhibits strong dithering type behaviour with a similar temporal pattern to that of ELMs. Some shots seem to suggest that the edge density decreases strongly, characteristic of flattening in the 7/5 island or ergodic region.

In H1, various coherent modes have been previously identified as shear and beta-induced Alfven eigenmodes, however there exists a broadband part of the spectrum which is thought to be due to drift waves or may be also due to resistive interchange modes driven by the magnetic hill arising from the current being outside the plasma volume. Langmuir probes based on tungsten /Al_2O_3 ceramic in various configurations including a ball-pen probe configuration have previously been used to characterize the plasma potential, electron temperature and density around island structures in low field Helicon wave heated Ar plasmas. However, recently, probes have been used in H/He minority RF heated discharges, where the smaller ion gyro-radius allows for interaction with smaller islands. These probes have been used to study parameter profiles, as well as turbulence and turbulent-driven flux. The total flux has also been measured based on H_α emission and S/XB (ionizations per photon) analysis, and the turbulent-driven component is seen to be of comparable to the total flux, and in particular, in some studied configurations, appears strongly dominated by certain low frequency coherent modes rather than the broad-band components characteristic of the ion gyro-scale. There is a also a significant bicoherence amongst these modes, suggestive of non-linear interaction from the driven source. Detailed changes in the turbulent-driven flux as a function of the edge rotational transform will be presented, to attempt to explain the loss of confinement at particular rotational transform values.

Finally, dual probes have been used and cross-correlations between these probes show the radial/poloidal structure of turbulence near the edge, exhibiting a slight eddy tilt (finite k_r) and a value of $k_\theta \rho$ of ~ 0.1 at around 100kHz for broadband modes (shown in figure, which is a fit to the experimental cross-coherence between two probes with one fixed and one movable in two dimensions).