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Numerical investigation of the turbulent perpendicular transport in the SOL of MAST

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17th Joint EU-US Transport Task Force Meeting
in combination with the
4th EFDA Transport Topical Group Meeting

Padova - September 3-6, 2012

Book of abstracts

		17th Joint EU-US TTF and 4th EFDA TTG Meeting	
		3-6 September 2012, Padua, Italy	
		Monday, September 3	
8:00		Registration	
9:00		Welcome by TTG Chars and LOC	
9:10	**Oral Session**	**SOL and edge turbulence and transport (Sala Rossini)** Chairs: V. Naulin and N. Vianello	
9:10	T. Eich	Power deposition and SOL transport in the edge of fusion plasmas	R1.1 35+15
10:00	M. Spolaore	Electromagnetic turbulent structures features in the edge region of toroidal plasma configurations	O1.1 15+5
10:20	F. Militello	Numerical investigation of the turbulent perpendicular transport in the SOL of MAST	O1.2 15+5
10:40		Coffee break	
11:10	L. Vermare (& A. Storelli)	Study of GAMs in TORE SUPRA with Doppler backscattering & the dependence of their properties on SOL and edge flows	LO1.3 20+10
11:40	F. D. Halpern	Global scrape-off layer electromagnetic fluid turbulence simulations	LO1.4 20+10
12:10	D. A. Schaffner	Modification of turbulent transport with continuous variation of flow shear in the Large Plasma Device	O1.5 15+5
12:30		Lunch at Caffe Pedrocchi	
13:50	I. Furno	Blob control and fast ion dynamics in the TORPEX device	O1.6 15+5
14:10	M. Agostini	Impact of the helical magnetic topology on the edge of RFX-mod	O1.7 15+5
14:30	G. Ciraolo	Evaluating barrier strength with turbulent bursts transmission	O1.8 15+5
14:50		Discussion	
15:30-18:00	**Poster Session**	**SOL-edge turbulence and transport and impurity transport (Sala Rinascimentale and Sala Egizia)**	
16:00		Coffee	
16:30	Poster Session	and Working Group meeting on impurity transport (Sala Egizia)	
18:00		Welcome Reception at Caffe Pedrocchi	
19:00		Piano Concert at Caffe Pedrocchi	

	17th Joint EU-US TTF and 4th EFDA TTG Meeting	
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	Posters on Monday September 3	
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R. Sanchez	On the relevance of uncorrelated sequencies of Lorenzian pulses for the interpretation of turbulent fluctuation data at the edge of magnetically confined toroidal plasmas	P1.12
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	Posters on Monday September 3	
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D. R. Mikkelsen	Density peaking in turbulence simulations of low-collisionality C-Mod plasmas	P1.18
A. Mollen	Effect of poloidal asymmetries on impurity peaking in tokamaks	P1.19
S. Moradi	Impurity transport due to electromagnetic drift wave turbulence	P1.20
M. L. Reinke	Impact of non-thermal particles on the poloidal variation of high-Z impurity density in tokamak plasmas	P1.21 (+ 03.2)
G. Szepesi	Turbulence driven particle transport analysis in FTU liquid lithium limiter experiments	P1.22
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		17th Joint EU-US TTF and 4th EFDA TTG Meeting	
		3-6 September 2012, Padua, Italy	
		Tuesday, September 4	
8:30	Oral Session	**Rotation and Momentum Transport (Sala Rossini)** Chairs: Y. Camenen, B.P. Duval and P. Mantica	
8:30	B. D. Scott	Energetic consistency and symmetry in gyrokinetic field theory	LO2.1 20+5
8:55	J. Abiteboul	Gyrokinetic simulations of intrinsic toroidal rotation and turbulent momentum transport	LO2.2 20+5
9:20	S. Jolliet	Influence of plasma size on heat and momentum transport in global steady-state ITG simulations	LO2.3 20+5
9:45	W. X. Wang	Interplay of turbulence and toroidal flow	O2.4 15+5
10:05		Discussion on theoretical aspects of simulations of momentum transport	
10:40		Coffee break	
11:10	W. M. Solomon	Overview of intrinsic rotation drive mechanisms in fusion plasmas	R2.1 35+15
12:00	R. M. McDermott	Connections between intrinsic toroidal rotation, density peaking, and plasma turbulence regimes in ASDEX Upgrade	LO2.5 20+10
12:30		Lunch at Caffe Pedrocchi	
13:50	H. Weisen	Momentum pinch and residual stress in the core of JET H-modes	O2.6 15+5
14:10	Y. Xu	Experimental measurements of residual stress and related parametric dependence for intrinsic toroidal rotation generation at the edge of TEXTOR tokamak	O2.7 15+5
14:30	L. Piron	Effects of 3D magnetic fields on plasma rotation in RFX-mod tokamak plasmas: experimental results and modelling	O2.8 15+5
14:50	D. L. Brower	Intrinsic flow from magnetic-fluctuation-driven kinetic stress	O2.9 15+5
15:10		Discussion	
15::45-18:30	**Poster Session**	**Rotation and momentum transport and impact of rotation on heat transport (Sala Rinascimentale and Sala Egizia)**	
16:00		Coffee	
16:30 - 18:30	Poster Session	and Working group meeting on impact of rotation and rotational shear on heat transport (Sala Egizia) +discussion on modulation experiments	

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F. Sattin	New technique for the accurate calculation of transport profiles in modulation experiments	P2.8
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G. Sonnino	Rotation in tokamak plasmas out of mechanical equilibria, in absence of external torques	P2.10
F. Spineanu	On the generation of convective cells of like-sign of vorticity in strong radial temperature gradients	P2.11
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A. R. Field	Characterisation of ion-scale turbulence in MAST	P2.14 (+LO3.1)
A. R. Field	Comparison of BES density turbulence measurements with synthetic data from global, non-linear gyro-kinetic simulations	P2.15
E. G. Highcock	Turbulence suppression, stiffness reduction and other effects of rotational shear	P2.16 (+LO3.1)
P. Mantica	Recent progress in understanding the effect of rotational shear on ion heat transport	P2.17
A. A. Schekochihin	Subcritical turbulence, critical balances and transport scalings	P2.18
G. M. Staebler	Verification of the spectral shift paradigm for ExB shear suppresion of transport	P2.19
G. Tardini	Status of the studies on the effect of plasma rotation on transport and MHD	P2.20

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		Wednesday, September 5	
8:30	Oral Session	Session on Rotation continues (Sala Rossini)	
8:30	A. R. Field / E. G. Highcock	Characterisation of ion-scale turbulence in MAST & Turbulence suppression, stiffness reduction and other effects of rotational shear	LO3.1 12+12+6
9:00	M. L. Reinke	Impact of non-thermal particles on the poloidal variation of high-Z impurity density in tokamak plasmas	O3.2 15+5
9:20	Oral Session	**L-H transition, H-mode pedestal physics (Sala Rossini)** Chairs: H. Meyer and M. N. A. Beurskens	
9:20	J. W. Connor	Recent progress in the theoretical modelling of the L-H transition	R3.1 30+10
10:00	G. D. Conway	Overview of recent progress in the experimental identification of the L-H trigger	R3.2 30+10
10:40		Coffee break	
11:10	K. Kamiya	Recent studies on the L-H transition in JT-60U: Turbulence, transport, and the origin of the radial electric field	LO3.3 20+10
11:40	T. Estrada	L-H transition experiments in TJ-II plasmas	O3.4 15+5
12:00	K. Miki	Spatio-temporal evolution of L-H transition	LO3.5 20+10
12:30		Lunch at Caffe Pedrocchi	
13:50	D. J. Battaglia	Investigation of the hidden variables of the P L-H using self-consistent full-f gyrokinetic simulations of the L-mode edge	O3.6 15+5
14:10	T. M. Bird	Nonaxisymmetric gyrokinetic turbulence simulations and the implications for RMP experiments	O3.7 15+5
14:30	M. Willensdorfer	Investigation of edge kinetic profiles throughout the L-H transition on ASDEX Upgrade	LO3.8 20+10
15:00	D. Dickinson	Kinetic instabilities that limit beta in the edge of a tokamak plasma: a picture of the H-mode pedestal	O3.9 15+5
15:20		Discussion	
16:00-18:30	**Poster Session**	**L-H transition and H-mode pedestal physics, and turbulence and transport in the region from core to edge (Sala Rinascimentale and Sala Egizia)**	
16:00		Coffee	
17:00-18:30	Poster Session	and Working Group meeting on eletctron heat transport and multi-scale physics (Sala Egizia)	
19:45		Conference Dinner at Caffe Pedrocchi	

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M. N. A. Beurskens	Core versus edge confinement in JET with the ILW compared to CFC first-wall	P3.2
H. Meyer	Dynamics of the L-H transitions at different density in MAST	P3.3
S. Moradi	Impact of sheared flow on non-Gaussian (Levy) plasma fluctuations	P3.4
P. Morel	Characterization of predator-prey dynamics in gyrokinetic turbulence using the evolution of free energy	P3.5
D. Told	Gyrokinetic studies of microturbulence in transport barriers	P3.6
	Transition region from Core to Edge (Sala Rinascimentale)	
J. A. Alcuson	Direct calculation of spatio-temporal transport kernels in simulations of near-marginal DTEM turbulence	P3.7
G. Dif-Pradalier	Locality, non-locality and the question of the forcing in turbulence modelling	P3.8
G. M. D. Hogeweij	Modelling of the non-local response of transport to peripheral perturbations	P3.9
H. Isliker	Test particle simulations in the transition region between the core and the edge	P3.10
F. Jenko	Gyrokinetic studies of the core-edge transition region in ASDEX Upgrade discharges: limits of quasi-linear theories and non-local effects	P3.11
S. M. Kaye	The continuous reduction of transport with increasing lithium in NSTX and the role of collisionality	P3.12
D. E. Newman	Electron and ion channel transport barriers: initiation and dynamical co-eolution and their implications for burning plasmas	P3.13
Y. Xiao	Experimental validation of turbulent transport with global gyrokinetic particle simulation	P3.14
F. Zonca	Nonlinear excitation of zonal structures by toroidal Alfven eigenmodes	P3.15
M. Zuin	Experimental investigation of microtearing modes in reversed field pinch plasmas	P3.16

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	Electron heat transport and multi-scale physics (Sala Egizia)	
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P. Hennequin	New regime of small scale density fluctuations in presence of electron heating in Tore Supra	P3.18
L. Porte	Recent results and prospects for core fluctuation measurements on TCV	P3.19
F. Sommer	H-mode characterization for dominant ECRH and comparison to dominant NBI heating - modelling results	P3.20
L. Vermare	Electron heat transport and multi-scale physics: experimental characterisation through fluctuation measurements and related theoretical modelling	P3.21
M. Vlad	Test particle study of multi-scale transport	P3.22

		17th Joint EU-US TTF and 4th EFDA TTG Meeting	
		3-6 September 2012, Padua, Italy	
		Thursday, September 6	
8:30	Oral Session	**Transition region from Core to Edge (Sala Rossini)** Chairs: C. Angioni and S. M. Kaye	
8:30	G. M. Staebler	Overview of turbulence and transport in the core-edge transition region	R4.1 30+10
9:10	C. Bourdelle	New glance at resistive ballooning modes at the edge of tokamaks	LO4.1 20+10
9:40	E. Fable	Experimental and theoretical study in the core-edge transition region at ASDEX Upgrade	LO4.2 20+10
10:10	O. Gurcan	Is "near edge" transport non-local ?	LO4.3 20+10
10:40		Coffee break	
11:10	Y. Ren	Response of Electron-scale Turbulence and Thermal Transport to Continuous ExB Shear Ramping-up in “No Man's Land” in NSTX	O4.4 15+5
11:30	K. Hallatschek	Time evolution of Zonal Flows and GAMs from core to edge	O4.5 15+5
11:50		Discussion	
12:30		Lunch at Caffe Pedrocchi, end of the meeting	

Gyrokinetic simulations of intrinsic toroidal rotation and turbulent momentum transport

J. Abiteboul, G. Dif-Pradalier, X. Garbet, Ph. Ghendrih
V. Grandgirard, G. Latu, Y. Sarazin, A. Strugarek

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TOPIC: D) Momentum and particle/impurity transport, and impact of rotation on transport

Toroidal flows are critical for the confinement of fusion plasmas as sheared flows contribute to the saturation of turbulent transport. In view of predicting toroidal rotation in next-step fusion devices such as ITER, where external momentum input will be small, understanding the physics of intrinsic rotation generation is crucial. Here, we investigate this issue by studying the dynamics of turbulent core momentum transport using global, full-f, gyrokinetic simulations.

We perform simulations of flux-driven ion temperature gradient (ITG) turbulence with the gyrokinetic code GYSELA, starting from a vanishing initial profile of toroidal rotation, in order to observe the generation of intrinsic rotation. As the gyrokinetic model accurately conserves toroidal angular momentum [1], the turbulent Reynolds stress initially drives a dipolar profile of toroidal rotation. After this initial phase, a non-vanishing momentum flux is observed at the edge of the simulation domain, due to "no-slip" boundary conditions (i.e., $V_{\|}=0$ at the radial boundary), leading to a *net* generation of toroidal rotation, with a dominant contribution in the co-current direction.

In order to understand the physics of intrinsic rotation, we statistically investigate the dynamics of toroidal momentum transport. First of all, it is found that turbulent heat and momentum transport are strongly correlated. More precisely, turbulent transport is dominated by large-scale avalanche-like events, which transport both heat and momentum. However, because these avalanches scale with the gyroradius rather than the tokamak size, gyro-Bohm scaling is found for both heat and momentum transport. To quantify the intermittency observed in the simulations, we compute the probability distribution functions (PDFs) of the heat and momentum fluxes. On the one hand, both PDFs exhibit heavy tails, as described by their fourth order moments (excess kurtoses of respectively 1.7 and 0.5), confirming the intermittent nature of heat and momentum transport. On the other hand, momentum transport in the steady-state regime is nearly symmetric, with a vanishing third order moment, while a significant asymmetry is measured for the distribution of heat transport (skewness~0.5). Comparisons with the XGC particle-in-cell gyrokinetic code show good statistical agreement between the results of both codes [2].

Finally, the open issue of the impact of scrape-off layer flows on core rotation is investigated by modifying the boundary conditions in GYSELA. For poloidally symmetric boundary conditions, a non-vanishing edge velocity propagates inward and is found to act as an offset rotation for the core plasma. The penetration of poloidally asymmetric boundary conditions, comparable to L-mode edge rotation profiles, also allows us to investigate the penetration of such flows, with or without net momentum input from the edge.

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[1] J. Abiteboul, V. Grandgirard, X. Garbet, et al. Conservation equations and calculation of mean flows in gyrokinetics. *Physics of Plasmas*, 18:082503, 2011.
[2] S. Ku, J. Abiteboul, P.H. Diamond, et al. Physics of intrinsic rotation in flux-driven ITG turbulence. Nuclear Fusion, 52:063013, 2012.

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Impact of the helical magnetic topology on the edge of RFX-mod

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TOPIC: Edge - SOL turbulence and transport

At high plasma current operations (Ip > 1 MA) RFX-mod reversed field pinch experiment shows a helical core surrounded by an almost quasi-symmetric boundary, due to the presence of a dominant m=1,n=-7 magnetic mode that resonates at the plasma core. Even if the edge ripple due to the helical shape of the plasma is small for affecting neoclassical transport significantly, it is strong enough to impact on parallel transport of electrons and ions, and plasma-wall interaction (PWI). The helical ripple can be described by the helical angle $u_{m,n} = m\theta - n\phi - \Phi_{m,n}$, where θ is a flux-surface poloidal angle and $\Phi_{m,n}$ is the appropriate mode phase (for RFX-mod $\Phi_{1,-7}$). This angle can be used to place in a helical frame of reference measurements coming from different diagnostics.
This 3-dimensional m/n = 1/-7 magnetic deformation affects in a significant way the pattern of the floating potential (V_f), perpendicular flow velocity (v_ϕ), plasma wall interaction, and electron density profile. Using a spatially distributed set of diagnostics for V_f, plasma influxes and electron density, we will show that the position $u_{m,n} = \pi/2$ (which corresponds to the O-point of the 1/-7 islands) is characterized by a more negative floating potential, larger v_ϕ, stronger plasma wall interaction (measured as an increase of the H_α influx), and higher electron density. This modulation of the kinetic properties causes also a modification in the edge turbulence: radial and toroidal correlation lengths of the edge fluctuations and the fluctuations amplitude show the same m/n=1/-7 spatial periodicity, with a decrease of the turbulence level at $u_{m,n} = \pi/2$.

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Direct calculation of spatio-temporal transport kernels in simulations of near-marginal DTEM turbulence

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In the modelling of radial transport in tokamaks and stellarators, it is usual to assume phenomenological relations between fluxes and gradients of the form $\Gamma_s(x,t) = -D\nabla s(x,t)$ for the various quantities of interest (pressure, density, etc.). This relation is known as Fick's law. Fick's law assumes an underlying local dependence, both in space and time, between the gradients of the quantity being transported and its flux. But it constitutes just an specific case of a more general relation between gradients and fluxes,

$$\Gamma_s(x,t) = \int_o^t dt' \int dx' K(x-x', t-t')\nabla s(x',t'), \tag{1}$$

where $K(\Delta x, \tau)$ is an spatio-temporal transport kernel that encapsulates the complexity of the microscopic transport processes. In the simplest case, $K = -D\delta(x-x')\delta(t-t')$ and the local Fick's law is recovered. But more complex forms of the kernel can be expected in situations in which non-locality or memory effects play a role in setting the transport dynamics. The ability to measure it can be used to detect them in cases of interest, as well as to help improve the modelling transport in those regimes. In this contribution we propose one method to compute the transport kernel K and validate it by applying it to one of these cases. Specifically, to near-marginal simulations of a magnetically confined plasma in which the radial turbulent transport is driven by the dissipative trapped electron mode (DTEM).

Gyrokinetic calculations of impurity transport including centrifugal effects

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TOPIC: D (Impact of rotation on impurity transport)

The impact of centrifugal effects on turbulent impurity transport is investigated by means of gyrokinetic calculations with the code GKW [1,2]. The gyrokinetic model is extended in order to include centrifugal effects due to the centrifugal trapping in the presence of a radial gradient of the background plasma rotation. A fluid model in simplified geometry is derived to clarify the separate roles of the centrifugal drift and the centrifugal trapping and a physical decomposition of the off-diagonal impurity transport contributions is presented. The main plasma parameters impacting the strength of centrifugal effects are identified. Centrifugal effects are shown to be significant in the turbulent transport of heavy impurities at typical plasma conditions obtained in present devices.

[1] A.G. Peeters, Y. Camenen, F.J. Casson, W.A. Hornsby, A.P. Snodin, D. Strintzi and G. Szepesi, Computer Physics Communications, 180, 2650 (2009)
[2] F. J. Casson, A. G. Peeters, C. Angioni, Y. Camenen, W. A. Hornsby, A. P. Snodin, and G. Szepesi, Phys. Plasmas **17**, 102305 (2010)

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Convective Transport Suppression in the Scrape-Off Layer Using Ion Cyclotron Resonance Heating

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Turbulence properties in the scrape off layer (SOL) of the ASDEX-Upgrade and the Tore Supra tokamaks in the presence of ion cyclotron frequency heating (ICRH) are compared to instance where it is absent. The discharges on ASDEX-Upgrade are in H-mode maintained by 5 MW of neutral beam injection. During ICRH, the SOL plasma density increases whereas turbulence large-scale and convective structures are shown to be suppressed. The probability distribution function is thus recorded to be closer to a Gaussian and a net decrease in the low-frequency density fluctuations is reflected in the power spectra. Consequently, the level of turbulent fluctuations decreases significantly. ELM-induced turbulence suppression is also reported. Similar results are obtained on the Tore Supra tokamak with L-mode plasmas [3]. Intermittent radial transport by avaloids is observed to be suppressed by ICRH in excellent agreement with the ASDEX-Upgrade results. This reflects that the effect is independent of the type of confinement and the magnetic configuration of the plasma. Turbulent fluctuations with field lines connected to the area close to the ICRH antenna were observed to be modified whereas no effect is detected when the probed region is far. The power threshold for this behavior is found to below 500 kW.

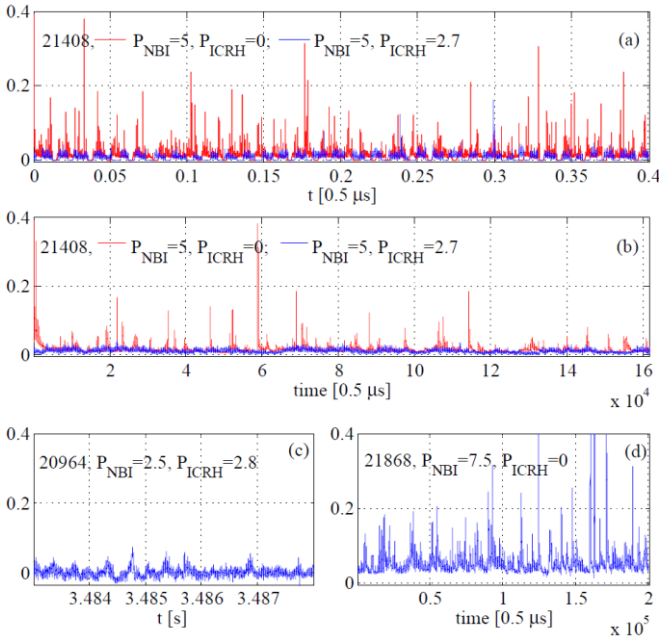

Fig: The ion saturation current in the SOL of the ASDEX-Upgrade tokamak with NBI and ICRH. Similar behaviour is recorded on Tore Supra.

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First fluctuations measurements in the new confined plasma configuration of the TORPEX device

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TOPIC: **Edge - SOL turbulence and transport**

The basic plasma physics device TORPEX features some of the main ingredients of the Scrape-Off Layer (SOL) of fusion devices, including gradients of density and magnetic field, as well as magnetic field curvature. A simple magnetized torus configuration (SMT) is produced using a small vertical magnetic field component superimposed to the main toroidal field, resulting in helical open magnetic field lines. A comprehensive study of electrostatic instabilities and turbulence in TORPEX plasmas has been performed in the last years.

A new experimental set-up has been recently implemented on the TORPEX device to produce a poloidal magnetic field and a rotational transform. This set-up is based on an in-vessel toroidal copper wire of 1 cm of radius, suspended in the middle of the vacuum vessel of TORPEX by several horizontal and vertical supports. These supports can also be used to position the current carrying wire at different vertical positions up to the top of the chamber to recover the original SMT configuration. The wire is powered by an external power supply providing a maximum current of 1 kA during a flat-top of about 0.5s. A 0.2s dynamics for the ramp-up and the ramp-down phases is given by the power supply temporal response. The current flowing in the toroidal wire generates a poloidal magnetic field that leads to a rotational transform. In the resulting magnetic field lines configuration the characterization of the plasma turbulence and instabilities can be performed on both the core region of closed flux-surfaces and the SOL region of open field lines. A proper value of the vertical magnetic field is used to precisely define the geometry of closed/open field lines, with the vessel walls acting as a limiter.

An overview of the new experimental set-up will be presented, together with the background plasma parameters and profile. We will discuss the first measurements of plasma fluctuations in the SOL and their spatio-temporal evolution. The more advanced magnetic configurations that are accessible with this new experimental set-up will also be presented.

This work was supported in part by the Swiss National Science Foundation.

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Coherent regions in the phase of k modes for 2D turbulence simulations

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TOPIC:

Interesting dynamics are found in the phase of Fourier modes in 2D turbulence simulations. The equations investigated can represent either 2D plasma drift wave turbulence or quasi-geostrophic turbulence. The interesting dynamics are found to be caused by the appearance of strong coupling in the phase of the Fourier modes. This happens in regions inside the high-k region of the spectrum where dissipation is dominant. In addition, a strong burst of energy transfer is associated with the phase-coupling event. Finally, these intermittent events can be shown to have strong connections with the saddle points of the velocity field. The mechanisms, importance and possible uses of these coherent events and their relation with the saddle points of the velocity field will be discussed.

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Investigation of the hidden variables of P_{LH} using self-consistent full-f gyrokinetic simulations of the L-mode edge

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TOPIC: L-H transition and physics of transport in the pedestal

The L-H power threshold (P_{LH}) is known to depend on a number of "hidden variables," including the grad-B drift direction, neutral fueling, impurity content, X-point location and X-point balance. It is important to develop quantitative models for the impact of these hidden variables on the P_{LH} for future devices, such as ITER, in order to optimize the design of heating systems and operational scenarios. The National Spherical Torus Experiment (NSTX) has recently conducted experiments to investigate the role of the triangularity (δ) and the neutral recycling rate on P_{LH}. NSTX achieves excellent flexibility of the plasma shape and divertor conditions due to a unique open divertor with recycling controlled via lithium coatings.

The experiments on NSTX found that P_{LH} increases with larger triangularity (i.e., smaller R_X) and neutral fueling rate. P_{LH} increased by about 30% as R_X decreased from 0.64 m to 0.47 m (triangularity of 0.36 to 0.64) and increased linearly with the normalized neutral density in the divertor. The electron temperature (T_e) and normalized density (n_e) profiles at the L-H transition are very similar for all discharges, despite a large range in heating and neutral recycling rates. The ion profiles suggest the edge T_i prior to the L-H transition is larger for the high-triangularity discharges, but the trend is sometimes within the large error bars. A ubiquitous increase in the currents between the divertor legs through the conducting wall leading up to the L-H transition was also observed.

The experimental results are interpreted using the self-consistent XGC0 pedestal-SOL simulation code, which is a 5D full-f gyrokinetic solver for ions, electrons and two impurity species, and includes 2D localized neutral fueling and recycling, and the SOL sheath. The simulations agree quantitatively with the experiment and indicate an ion-orbit loss hole and ion-neutral physics play significant roles in the $E \times B$ flow shear available for turbulence suppression. As the triangularity increases, the critical energy for ion-orbit loss increases, reducing its contribution to the negative E_r well near the separatrix. Consequently, the depth of the E_r well is only recovered in the high-δ shape with a larger edge T_i, which requires more heating power. Furthermore, the neutral penetration increases with δ, introducing larger energy losses to the ion channel that must be overcome with additional heating power. Overall, the simulations predict 30% more heating is needed in the high-δ shape compared to the low-δ shape on NSTX in order to achieve a similar level of $E_r \times B$ shearing rate, which is consistent with experiment. The XGC0 simulation also indicates that high-energy ion orbit loss to the divertor is amplified as E_r is evolving more negative, inducing a potential difference between the divertor legs and increasing the energy flux to one of the divertor legs (outboard leg in favorable grad-B drift). This is in agreement with the wall current and D_α measurements in the NSTX divertor 10 – 50 ms prior to the L-H transition.

This work will be extended to examine other known hidden variables of P_{LH}, including the ion grad-B drift direction, X-point height and X-point balance. The goal is to calculate the heating requirements needed to achieve the critical local parameters from different L-H trigger models to compare to established results from a wide variety of tokamak experiments.

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A simple transport model for the LH transition and the study of its internal turbulent entropy production

Topic: L-H transition and physics of transport in the pedestal

A simple 1D radial transport model, which includes turbulence spreading, is proposed. It is shown to describe the transition between two different profiles of density/pressure, corresponding to the Low and the High confinement modes. This model is based on the Hinton-Staebler model, but significant improvements have been made. First, a radial time evolution equation of turbulence is incorporated in the system. The level of turbulence that is computed is partly sensitive to its own characteristics such as turbulence spreading and non-linear damping. It is also constructed in such a way that it depends on density and pressure profiles through the growth rate and the shear flow frequency. The form of the shear flow frequency dependence is chosen in order to assure that at the fixed point of turbulence (without spreading) one simply recovers the ad-hoc expression for Hinton-Staebler shear suppression. The system is shown to display a critical value of heating power which determine the possibility of existence of the H mode. For heating power slightly higher than the critical value, it is observed that the profiles first reach a quasi steady-state (L-mode) before making the transition to a high density/temperature state after turbulence collapses at the edge. This behaviour, which is not possible with the standard Hinton-Staebler model or its variants is a direct result of the effect of turbulence evolution. Internal entropy production by turbulence throughout the transition is investigated and the role of each term responsible for turbulent entropy production is identified.

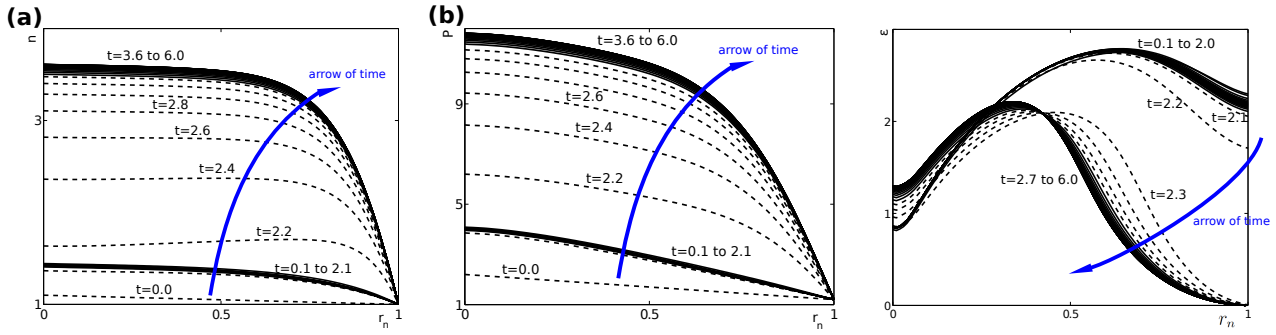

Figure 1: Time evolution of density (a) and pressure (b) profiles during the LH Transition : the profiles first reach a quasi-steady state before steepening rapidly until the H profile. (c) Evolution of turbulence profile during the LH transition : the level of turbulence starts from a high level near the edge before collapsing toward a low centered position.

Core versus edge confinement in JET with the ILW compared to the CFC first-wall.

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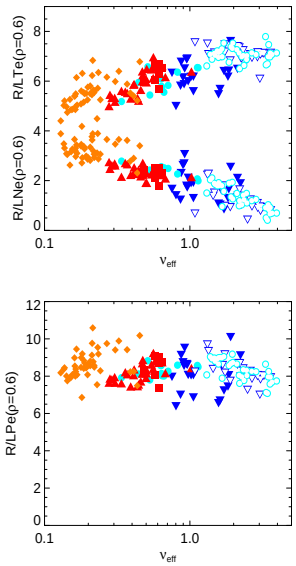
**See appendix of F. Romanelli et al., Fusion Energy, 2010 (23rd IAEA Intern. Conference, Daejeon, 2010).*

The baseline type I ELMy H-mode scenario has been re-established in JET with the new W MKII-HD divertor and Be-main wall (hereafter called ITER-like wall, ILW).

A steady state H-mode profile database has been constructed from high quality Kinetic diagnostics. It contains plasmas with low (δ~0.2-0.25) and high (δ~0.38-0.42) triangularity with both the CFC wall and the ILW. For the CFC wall, the database contains both baseline ELMy H-mode plasmas q_{95}=2.8-3.6 as well as Hybrid H-mode plasmas with q_{95}=3.5-4.2 and plasma current in the range 1-3MA [1]. For the ILW plasmas, the database only contains baseline ELMy H-mode plasmas at q_{95}=2.8-3.6 and Ip in the range 2.0-2.5MA. The applied heating systems are mainly NBI for all plasmas and some ICRH for the baseline plasmas (P_{ICRH}/P_{NBI} < 0- 10%).

During the steady state H-mode phase, the pedestal contribution to the total confinement is W_{ped}/W_{tot}~30±5% both in CFC wall and ILW. A strong coupling is found between the global normalised pressure β and the pedestal β in agreement with earlier CFC wall results [1,2].

The electron density, temperature and pressure profile (Ne, Te and Pe) are studied for a wide range of collisionality ($0.1 \leq \nu_{eff} \leq 4$). In the parameters range in which ILW and CFC plasmas have similar collisionality ($\nu_{eff} \approx 1$-2, see figure 1), the wall seems not to drastically affect the profile shape and the gradient length are relatively comparable ($R/L_{ne,\rho tor=0.6}$~1.5 and $R/L_{ne,\rho tor=0.6}$~7 for both ILW and CFC). On a wider ν_{eff} range, ILW plasmas have low Ne gradient length ($R/L_{ne,\rho tor=0.6}$~0-2), and high Te peaking ($R/L_{Te,\rho tor=0.6}$~7-8). Consequently, the Pe peaking remains constant, $R/L_{Pe,\rho tor=0.6}$~8-10 for both CFC and ILW plasma.



Temperature and density gradient length (upper frame) and pressure gradeint length (lower) for CFC wall (full symbols) and ILW shots (open symbols).

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Nonaxisymmetric gyrokinetic turbulence simulations and the implications for RMP experiments.

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Abstract

3-D magnetic perturbations can modify turbulent transport processes in Tokamak plasmas even when the resonant component of the radial field is perfectly shielded, preventing flux surface destruction. For experimentally relevant perturbation amplitudes, the local shear modulation has been found to impact the ideal MHD ballooning stability boundary which is sometimes used as a proxy for the onset of Kinetic Ballooning Modes (KBMs). 3-D perturbations of magnitude $\frac{\tilde{B}}{B_0} \sim 10^{-4}$, corresponding to millimeter deformations of the flux surface shape, can have a strong effect on the ideal MHD ballooning stability boundary through local shear modulation driven by near-resonant Pfirsch-Schlüter currents [1]. By triggering KBM turbulence at lower pressure gradients in the vicinity of low order rational surfaces, the resonant Pfirsch-Schlüter physics provides a possible explanation for RMP-induced changes in pedestal profiles which does not rely on stochasticization.

Local 3-D equilibrium theory is used to study local shear modulation resulting from small 3-D deformations of the shape of an otherwise axisymmetric flux surface. Ab initio gyrokinetic simulations are performed using a new version of the gyrokinetic turbulence code GENE which treats an entire flux surface of a nonaxisymmetric configuration. The code is local in the radial direction but global in the poloidal domain. Initial studies of ITG turbulence in Stellarator configurations have found several novel features of turbulence in nonaxisymmetry, in particular that the heat transport is non-stiff and the onset is below the linear critical gradient.

The nature of turbulent ITG-driven heat transport as axisymmetry is broken is studied by adding 3D perturbations with increasing magnitude to a Tokamak equilibrium. New features of turbulence in nonaxisymmetric configurations are examined, and the implications for modifying turbulent transport in Tokamaks with 3D fields is discussed. Ab initio simulation of KBMs will be attempted to study the effect of near-resonant Pfirsch-Schlüter currents and test ideal MHD calculations which predict destabilization of KBMs near rational surfaces in the presence of shielded RMPs.

[1] - T.M. Bird and C.C. Hegna, Submitted to Phys. Rev. Letters.

Neoclassical level poloidal rotation measured from the inboard-outboard asymmetry of toroidal rotation in TCV

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TOPIC: Momentum and particle/impurity transport, and impact of rotation on transport

Accurate measurement and prediction of poloidal rotation are needed in tokamaks for the implications of perpendicular flows on transport and MHD stability. The damping associated with toroidal geometry strongly constrains poloidal flows and it is not obvious whether flows much larger than the residual flow dictated by the neoclassical theory can be sustained or not. The latter is in general very small, of the order of few km/s in present-day tokamak devices. Such velocities are at the limit of the accuracy of the spectroscopic diagnostics, especially those based on charge exchange recombination, which inherently suffer from issues related to the parametric dependence of the rest wavelength, the energy dependence of cross sections and gyro-orbit effects. As a consequence, the neoclassical nature of poloidal rotation is still open.
In this work, we illustrate a different experimental approach, valid for weak plasma rotation (Mach number<<1). For the incompressibility of flows on a flux surface, the toroidal velocity results from the algebraic sum of a rigid body component and a component proportional to the poloidal rotation: $U_t = \omega(\psi)R + U_p B_t/B_p$. In turn, the poloidal rotation can be inferred from the difference between the toroidal rotation frequency $f_t=U_t/R$ measured at the inboard and outboard locations of the same flux surface. This type of measurement does not rely on the knowledge of the rest wavelength and benefits of generous 4q amplification of the measurable quantity (q is the local safety factor), as shown by the approximate expression $f_{t,in}-f_{t,out} \sim 4\ q\ U_{p,in}$.
We report the first indirect measurements of poloidal rotation, recently carried out in the TCV tokamak. Here, toroidal rotation is measured by a diagnostic neutral beam based charge exchange diagnostic, which provides full coverage of the mid-plane plasma diameter, with a radial resolution ~1 cm. In a variety of plasma conditions, including Ohmic and EC heated L-mode plasmas (n_{e0}=1.5-5x10^{19} m^{-3}, T_{e0}=0.8-2.5 keV, u_{t0}=-40-20 km/s), inboard/outboard differences in Carbon 6^+ toroidal velocity up to 10 km/s are ordinarily observed, from which a poloidal velocity in the range of 0.5-2.5 km/s is inferred.
A set of calculations performed with the NEOART code based on the experimental kinetic profiles indicate that the neoclassical prediction is in excellent agreement with the indirect measurement for all the considered cases, in the region of r/a<0.8, where the condition for the applicability of the method are met.

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New glance at Resistive Ballooning Modes at the edge of tokamaks

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TOPIC: Turbulence and Transport at the transition region between core and edge (recently dubbed no man's land)

To understand the L-H transition, one has to identify the modes to be stabilized at the edge of L mode plasmas. To address this issue, realistic edge tokamak parameters inspired by 3 different L modes, 1 from DIII-D and 2 from Tore Supra, have been investigated with a gyrokinetic code GENE [F. Jenko et al, Physics of Plasmas **7**, 1904 (2000)].

Former fluid theories of Resistive Ballooning Modes will be reviewed. Based on previous fluid findings [Drake and B.N Rogers, J.F. Drake and A. Zeiler, Phys. Rev. Lett. 81, 4396 (1998)], the parameters of the 3 studied L modes are predicted to be RBM unstable.

The linear gyrokinetic simulations demonstrate that RBM are indeed unstable in an even wider radial zone than predicted by the fluid models, at the edge of L mode tokamak plasmas. These modes are predominantly drifting in the electron diamagnetic direction and are destabilised by higher collisionality. They are further destabilized by higher normalised temperature gradient and higher q. The magnetic shear and the density gradient can either be stabilizing or destabilizing [C. Bourdelle et al, submitted to Plasma Physics and Control. Fusion].

The findings of this paper are then related to experimental observations corroborating the possible role of RBM at the transition region between core and edge (recently dubbed no man's land).

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Intrinsic Flow from Magnetic-Fluctuation-Driven Kinetic Stress

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Intrinsic flow has been observed in various toroidal magnetic confinement configurations. Self-generated flow is commonly believed to arise from MHD fluctuation-induced torques, such as the Reynolds and Maxwell stresses, and the finite pressure effects are often ignored. Flow generation is of great importance to fusion plasma research, especially low-torque devices like ITER, as it can act to improve performance. Here we present new experimental results from the MST reversed field pinch showing that the coherent interaction of magnetic and particle density fluctuations can produce a turbulent fluctuation-induced kinetic stress associated with finite pressure, $\nabla < \delta p_{//} \delta b_r > / B$, which acts to drive intrinsic plasma rotation. Measurements of the fluctuation-induced force are made in the high-temperature plasma core using a laser-based polarimetry-interferometry diagnostic. Key observations include; (1) the average kinetic force resulting from magnetic and density fluctuations, $\sim T_{//} \nabla < \delta b_r \delta n > / B \sim$ 0.5 N/m^3, is comparable to the intrinsic flow acceleration, $\rho \partial V_{//} / \partial t$, and (2) the spatial distribution of the kinetic force is directed to create a sheared parallel flow profile that is consistent with the measured flow profile in direction and amplitude. These observations indicate that effects beyond MHD may be responsible for intrinsic plasma rotation in these plasmas with β~6%.

Momentum pinch and residual stress in the core of JET H-modes

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TOPIC: Momentum and particle/impurity transport, and impact of rotation on transport
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A broad survey of the JET experimental database of beam heated baseline H-modes and hybrid scenarios has recently established the ubiquity of non-diffusive momentum transport in rotating tokamak plasmas [1]. Analyses based on a set of more than 1000 experimental profiles indicate that the non-diffusive transport contribution to the toroidal rotation gradient matches the diffusive one near the edge and progressively vanishes when moving towards the magnetic axis. The main parametric dependencies of the non-diffusive term, regressed in the form of a pinch, are R/L_n, q and $f_t=\varepsilon^{1/2}$, the trapped particle fraction. Remarkably, it corresponds to the three most relevant parameters of the theoretical scaling for the Coriolis pinch obtained from linear gyrokinetic simulations of about 400 representative samples selected from the experimental database. Based on the linear simulation results, a first order quantitative comparison between the experimental and theoretical transport coefficients indicates that the Coriolis pinch typically accounts for ~70% of the total non-diffusive momentum flux. From these results, the Coriolis pinch represents therefore the main non-diffusive momentum transport contribution, which is not totally unexpected in strongly rotating NBI-heated plasmas with Mach numbers in the range 0.05 to 0.35, but there is room for a non-negligible residual stress contribution. To refine the quantitative comparison and reach more definite conclusions about the respective contribution of pinch and residual stress, new simulations are being performed. First, the actual MHD equilibrium is now used instead of the circular flux surfaces approximation and the effects of collisions and electromagnetic fluctuations are included. Taking into account these physical ingredients typically changes the pinch coefficient by 10 to 30%. Neglecting these effects is therefore acceptable for a first order comparison but not to make an assessment about the magnitude of the residual stress contribution. Second, given the importance of the safety factor in the experimental and theoretical regressions an improved equilibrium reconstruction constrained with polarimetry measurements is used to compute the safety factor and magnetic shear. Third, the quasi-linear estimates are now backed up by a set of non-linear runs, that support the weighted average of momentum transport on the wave vector spectrum and assess the impact of ExB shearing. Finally, a finite radial wave vector is introduced in the linear simulations to quantify how large an additional symmetry breaking one would need to match the experimental momentum transport. This study is expected to allow quantifying the residual stress contributions, thereby also improving the assessment of the importance and of the parameter dependencies of the Coriolis pinch.

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[2] A.G. Peeters *et al.*, Nucl. Fusion **51**, 094027 (2011)

Overview of turbulence and transport studies on the Large Plasma Device

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TOPIC: **A) Edge - SOL turbulence and transport**

The LArge Plasma Device (LAPD) at UCLA is a 17~m long, 60~cm diameter magnetized plasma column with typical plasma parameters $n_e \sim 10^{12}$ cm^{-3}, $T_e \sim 10$eV, and B ~ 0.1T. I will provide an overview of studies of turbulence, transport and flows in LAPD. Broadband, fully-developed turbulence is observed in the edge of the LAPD plasma along with spontaneous azimuthal flows in the edge region. A spontaneous shear layer is observed in the edge region (near the edge of the plasma source region); the flow in this layer is in the ion diamagnetic direction (IDD). Recently, the capability to continuously vary the edge flow and flow shear has been developed in LAPD using biasing of an annular limiter. Biasing tends to drive flow in the opposite direction of the spontaneous flow, allowing a continuous variation of flow from the IDD to the electron diamagnetic direction, with a near-zero flow and flow shear state achieved along the way. Enhanced confinement and density profile steepening is observed with increasing shearing rate; degraded confinement is observed when spontaneous flow is nulled-out and near-zero shear is achieved. Strong changes in intermittency of LAPD edge turbulence is observed as the flow is varied. Skewness of the density fluctuation amplitude PDF is minimized at low flow and grows (more intermittency is observed) as the flow is increased in either direction. It is important to note that this trend is counter to changes in transport (minimum intermittency occurs when transport is near maximum) and that the skewness appears to scale with flow and not flow shear. The control over edge flows and flow shear and extensive measurement capability in LAPD provides an opportunity to validate edge turbulence models. LAPD turbulence has been modeled using the 3D Braginskii fluid turbulence code BOUT++. Good qualitative and semi-quantitative agreement is found between BOUT++ simulations and LAPD experimental measurements in low flow regimes.

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Modelling and measurement of impurities in ASDEX Upgrade

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TOPIC *D: Momentum and particle/impurity transport, and impact of rotation on transport*

Impurity transport in core plasmas is typically dominated by drift-wave turbulence which is best modelled with gyrokinetic simulations. The trace impurity limit permits a separation between the properties of the drift-waves which are completely determined by the bulk plasma conditions, and the impurity transport response, which is linear in the gradients of impurity density, temperature and rotation [1]. For a given impurity, these responses can be formulated as dimensionless ratios which are purely properties of the bulk plasma. A quasi-linear weighting of these coefficients over a prescribed turbulent spectrum can then be used to predict a steady-state impurity density gradient. Applying this approach to an experimental database of bulk plasma profiles and equilibria yields a prediction which can be compared to an independent direct measurement of the impurity density profile obtained with charge exchange recombination spectroscopy (CXRS). This approach has already obtained reasonable quantitative agreement for boron density profiles over a range of H-mode plasma conditions [2]. In the present work, we present an improved comparison between simulation and experiment over a range of radial locations, using density measurements from the recently upgraded CXRS system on ASDEX Upgrade [3]. These comparisons provide a subtle test of the turbulence models and build confidence in their predictive power for impurity transport.

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Evaluating barrier strength with turbulent bursts transmission

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TOPIC: **A) Edge - SOL turbulence and transport**

The H-mode pedestal plays a crucial role in setting the conditions that drive the plasma-wall interaction in ITER. Of particular importance is the particle and energy flux across the transport barrier. In a steady-state approach, the turbulent transport is considered to be quenched in a region of given extent. Transport through the barrier would then be dominated by collisions so that the energy flux would be predominantly in the ion channel with a vanishing particle flux. As reported theoretically, one can expect however that turbulence spreading occurs so that the largest turbulent transport burst can burn through the barrier and reach the Scrape-Off Layer. Such events can thus both change the transport properties of the barrier as well as modify the barrier properties themselves, such as the barrier width. The barrier thus plays a strong role in determining the turbulent transport fluctuations that feed in the SOL, and, consequently the numerous non-linear aspects of plasma wall interaction that will be most sensitive to large departure from the mean values.

In the present work we address the transport through the barrier in a dynamical framework. We thus consider a barrier with fluctuating radial extent interacting with a transport in bursts (the so called blobs) characterised by a distribution in magnitude and velocity. The approach is two-fold: on the one hand we reduce the model to coupled stochastic processes with interaction rules that allow one to classify the dynamics of the system, and, on the other hand we analyze barrier simulations on the basis of the key processes uncovered in the first analysis.

We present two models where stochastic processes are combined to recover the physics of this interaction. The three key stochastic variables are the barrier width, the spreading distance of the blobs within the barrier, and their level of correlation. We predict that for a class of Probability Distribution Function of these stochastic variables, the PDF of the escaping blobs will exhibit heavy tails, either exponential for a leaky barrier, or with power laws, for a tight barrier. Two-dimensional nonlinear fluid simulations of edge turbulence in tokamak plasmas are used and analyzed in terms of the properties of the stochastic models. The PDF of the blob penetration into the barrier is estimated as well as that of the barrier width for two different barriers generated in the plasma boundary layer. One can show that in the case of a barrier with large volumetric losses, as considered in our present simulations, the stochastic model predicts a leaky barrier with an exponential PDF of escaping blobs in agreement with the simulation data. This approach thus provides an effective tool to predict the statistics of the large deviation events that will dominate the non-linear response in the plasma-wall interaction.

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Comparison between ion temperature profile stiffness observations and non-linear gyrokinetic simulations

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TOPIC: Momentum and particle/impurity transport, and impact of rotation on transport

Recent experimental observations have shown a correlation between reduced ion temperature profile stiffness and concomitant low magnetic shear and high rotational shear in ITG turbulence regime JET plasmas at low normalized toroidal flux coordinates [1]. This has motivated a dedicated modelling effort with the GENE non-linear gyrokinetic code [2], aiming to uncover the physical mechanism leading to reduced stiffness. Detailed analysis is carried out at x=0.33, where the observed stiffness change is the most marked. We examine the effects of: rotation, magnetic shear, finite β (electromagnetic effects), $R/L_{n,}$ and real geometry including the effect of the rotation on the equilibrium. All simulations are local. According to the simulations, the experimentally observed level of rotation alone can decrease the profile stiffness in the vicinity of the linear threshold due to the competition between destabilizing parallel velocity gradient (PVG) modes and stabilizing perpendicular ExB shear. However, the degree of predicted stiffness reduction is significantly less than observed experimentally. Nevertheless, this observation indicates that careful scrutiny is needed when applying the 'Waltz-rule' for instability threshold shifts in regimes where q/ε is sufficiently high such that PVG modes are destabilizing, as also pointed out in [3]. The simulations show that reducing the magnetic shear within experimental uncertainties and incorporating electromagnetic effects can together further reduce the stiffness such that the ion heat flux at higher R/L_{Ti} is reduced to twice the experimental value. However, this still indicates stiffness significantly higher than the observed level. Regarding the physical mechanisms for the simulated stiffness reduction, it has been recently shown in gyrokinetic simulations that low magnetic shear (s<0.6) reinforces the coupling with stabilizing zonal flows [4]. In addition, a mechanism linking the onset of electromagnetic modes to increased mode-coupling with zonal flows has been recently suggested [5]. At higher radii (x=0.64), high stiffness and no discernible shift in R/L_{Ti} with rotation was experimentally observed. Simulations at x=0.64 show indeed that the transport is stiff, and the observed degree of rotation can produce an R/L_{Ti} shift of ~15%, not far beyond experimental uncertainties.

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Invited Talk Abstract for 17th Joint EU-US TTF, Padua

Recent Progress in the Theoretical Modelling of the L-H Transition

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Abstract

The physical mechanisms underlying the L-H transition remain an unsolved challenge for tokamak physics, of importance for ITER. Thus ascertaining the conditions under which the H-mode is accessed, such as the power threshold, tend to rely on the use of empirical scaling laws, whereas an understanding of the physics involved would greatly increase our confidence in such predictions. Since the L-H transition involves a transport barrier at the plasma edge, the situation is complicated by the edge conditions, possibly involving details of the magnetic geometry and atomic physics processes, but most theoretical models are based on purely plasma physics processes involving the dynamics of the radial electric field and its role in suppressing transport processes. In this review we will discuss recent progress in the development of theoretical models for the L-H transition and assess their ability to describe the associated experimental observations and phenomenology.

Overview of recent progress in the experimental identification of the L-H trigger

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TOPIC: (B) L-H transition and physics of transport in the pedestal

A review is presented of recent progress in the experimental identification of the trigger of the L to H-mode confinement transition. Facilitated by diagnostic developments providing high spatial and temporal resolution, particularly on edge plasma flows and turbulence, new insights are emerging on the potential candidates for triggering the confinement transition. In particular (but not only), much recent work has concentrated on the role of turbulence driven zonal flows and edge GAMs in promoting an enhanced (over neo-classical mean) $E \times B$ flow shear and turbulence moderation. Here, an overview is given of the main recent results on the dynamics of the flow - turbulence interaction in the build-up to the H-mode (through intermediate / Limit-Cycle-Oscillations and dithering phases) in both stellarators and tokamaks. These results are critically assessed with a view to the testing of various theories, such as the predator-prey model. Finally, some of the more prominent outstanding issues, together with an outlook on measurement requirements will be discussed.

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Kinetic instabilities that limit beta in the edge of a tokamak plasma: a picture of the H-mode pedestal

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TOPIC: Turbulence and Transport at the transition region between core and edge

High spatial and temporal resolution density and temperature profiles have been measured on the spherical tokamak MAST and used to reconstruct plasma equilibria with sufficient resolution to capture plasma evolution during the short period between type-I edge-localised-modes (ELMs) [1]. Immediately after the ELM, a steep gradient in density, n_e, forms close to the separatrix, and subsequently expands towards the core. Recent local linear gyrokinetic analysis [2] through the ELM cycle reveals the dominant microinstabilities in the shallow gradient region near the pedestal top (i.e. "no-mans land") to be microtearing modes whilst kinetic ballooning modes (KBMs) are found to become marginally unstable at the higher pressure gradients found in the pedestal. A study of the behaviour of these microinstabilities through the ELM cycle suggests a new physical picture for the formation and arrest of this pedestal: in the pedestal dP/dr is limited by kinetic ballooning modes (KBMs); in the core close to the pedestal, microtearing modes (MTMs) limit the electron temperature gradient; the pressure pedestal propagates into the core because increasing dn_e/dr stabilises the MTMs until they are supplanted by KBMs at higher dP/dr; deeper inside the core dP/dr is lower and MTMs become more virulent over the ELM cycle with rising local β; when the pedestal is almost fully developed, the pressure gradient transition region is close to an instability threshold where MTMs and KBMs become simultaneously unstable with large growth rates over a broad spectral range.

Microinstability driven turbulence, in combination with heat and particle sources, determines the profile evolution, which can vary between scenarios and tokamaks [3, 4]. To deepen our understanding of the possible microinstability mechanisms involved in the profile evolution we have studied a simple equilibrium with finite β to avoid the specific complications of strong shaping in MAST. By understanding this simple system we hope to gain generic insights into processes that determine profile evolution in more complex experimental plasmas.

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Locality, Non-Locality & the Question of the Forcing in Turbulence Modeling

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TOPIC: **(C) Turbulence and Transport at the transition region between core and edge**

Turbulent transport in fusion plasmas is critical for the Iter design and performance level. From a thermodynamics standpoint two distinct classes of forcing can maintain the system out of equilibrium. On the one hand a flux of particles and/or of heat can be imposed. The response of the plasma to this ``flux-drive'' is seen through the self-adjustment of the thermodynamic force –the mean plasma gradients– which can freely evolve and self-organise. On the other hand, the system can be forced to a greater level of homogeneity whilst keeping these mean gradients constant in time and throughout the modeled volume, regardless of the fact that this volume is the full plasma volume (`global' approach) or only a fraction of it (`local' approach). Though unrealistic from an experimental viewpoint, this ``local-like'' forcing is the common framework for most transport studies.

A such framework straightforwardly constrains the computed transport to be in close agreement with a Fick-like local and diffusive description, i.e. a description in which localised instabilities drive local mixing and diffusive transport and in which a linear relationship exists between local gradients and fluxes. This usual picture has been recently countered, theoretically and experimentally. Flux-driven systems on the other hand relax these Fick-like assumptions whilst displaying nonlocal dynamics, intermittency in the heat transport and the onset of large-scale, long-lived coherent structures that cannot be reconciled with usual local and diffusive pictures.

We discuss how this different framework, bearing close similarities with self-organised critical systems, impacts our current understanding of turbulence transport and flow organisation. Especially, we show that local and diffusive pictures can strongly underestimate the level of **E**x**B** shearing from the turbulence and lead, as compared to flux-driven systems, towards significantly different most probable states for the plasma, flow and stress patterns and levels, transport levels and mode stability. These results are based on various runs performed with the full-f, flux-driven GYSELA code. In particular, we show that when the forcing is varied, case (a): from a flux-driven volumic source, (c): to a fixed-like gradient forcing and (b): to a coupling to boundary thermal baths [intermediate to (a) and (c)] the PDFs of the heating power coupled to the plasma changes from being shapeless and localised [(c) and (b)] to a memoryless Poisson process (a). Also, the PDF of the heat flux changes from Gaussian (c) to Lévy-type [(a) and (b)]. We also show that within the flux-driven forcing (a) this Lévy-type PDF holds close to criticality and becomes more Gaussian far from instability threshold.

Further discussion includes the questions of profile stiffness (and criticality), of the understanding of the so-called ``Dimits upshift'' region and in explaining how this different framework may help to understand the now well documented discrepancy between experimental data and local-like modeling predictions in the far-core, near-edge so-called ``No Man's Land'' region. With a reduced 1D model which can be run in both flux-driven or gradient-driven conditions (local-like) we also show that a gradient-driven approach computed with the coarse-grained mean profile resulting from the same run but in a flux-driven regime always overestimates the turbulent heat flux. This discrepancy, though reduced when decreasing the system size endures.

This work is a first attempt to the larger goal of clearly isolating (i) what can and cannot be reconciled between these different approaches, of clearly quantifying (ii) the impact of the added physics contained in the flux-driven approach [nonlocality, the emergence of mesoscales and long-lived structures, the possiblity of self-organisation of the thermodynamics force, flows and stresses on larger scales and levels, different fluctuation levels] on the macroscopic and coarse-grained quantities usually debated. If significant, ask (iii) how to implement these pieces of physics in a simplified way and therefore complement existing coarse-grained local-like transport models which remain important for the future practical use of fusion.

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Intrinsic Rotation profile database for EFDA and beyond

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TOPIC: D) Momentum and particle/impurity transport, and impact of rotation on transport

Following the 1D study of toroidal scaling in H-mode[1] as a first attempt to predict possible rotation magnitudes for ITER and beyond, many more machines are now equipped to measure plasma rotation profiles. In order to facilitate an inter-machine comparison, a common data format in the form of a remotely accessible database has been created at the CRPP.
Initially, this database was envisaged to house intrinsic measurements of both toroidal and poloidal rotation. Since the database is also intended to provide enough experimental data to understand the underlying plasma/physics conditions for which the profiles are provided, a data model for each submitted database record was developed. The intention is to provide the raw experimental data together with the routines such that the calculation of the profiles is an explicit function of the recorded data and not simply fill the database with user-provided profiles.
Furthermore, to facilitate data provision from many experiments, plasma parameters, where possible, are expected in formats compatible with other international databases and a clear set of sign and unit conventions imposed.
In this initial incarnation, a large proportion of TCV's published rotation data has been uploaded to the database (>150 time slices) and graphical routines adapted to reproduce the graphs from those publications to demonstrate that the database is functional. Finally, the MdsPlus suite has been chosen for data storage and remote access as many Plasma Physics collaborators use this software that can be used to remotely access and upload data. By using a separate "tree" for each contributing laboratory, the result is a centralised rotation profile database which, when filled correctly will allow users to not only compare the final profiles but to analyse the plasma conditions and spectral analysis procedures that were used.

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L-H transition experiments in TJ-II plasmas

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The physical mechanisms behind the L-H transition have been experimentally studied in the TJ-II plasmas. To that end, plasma turbulence and flows are measured by means of Doppler reflectometry [1]. Close to the L-H transition threshold conditions, turbulence and flows display an oscillatory behaviour with a characteristic predator-prey relationship [2]. These results are consistent with models predicting L-H transition triggered by zonal flows [3]. This intermediate oscillatory transient stage has also been observed in other devices, but in general, only the temporal dynamics of the turbulence-flow interaction is described and no information is given on its spatial evolution. However, the spatial evolution should also be taken into account as a necessary step to go towards the L-H transition model. This fundamental issue has been addressed in TJ-II [4] and recently also in DIII-D [5]. In TJ-II plasmas, both, radial outward and inward propagation velocities of the turbulence-flow front are found. As the turbulence-flow front propagates outwards, the turbulence-flow events generate a dual shear layer and thus enhance the formation of the radial electric field well. A possible explanation for the spatiotemporal evolution of the oscillation-pattern could be linked to the radial spreading of the plasma turbulence from the plasma core to the edge barrier. As the turbulence propagates towards the barrier, the associated turbulence driven flow generates the inner shear layer which in turn regulates the turbulence level. The observations could be also figured out in terms of turbulent bursts propagating toward the plasma edge. These turbulent bursts could be generated in the plasma interior due to instabilities linked, for instance, to the magnetic topology. The results indicate that the edge shear flow linked to the L–H transition can behave either as a slowing-down, damping mechanism of outward propagating turbulent-flow oscillating structures, or as a source of inward propagating turbulence-flow events. Recent experiments devoted to study the L-H transition triggering mechanisms and the turbulence scales involved in the process will be also discussed.

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Experimental and theoretical study of transport in the core–edge transition region at ASDEX Upgrade

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A detailed analysis of electron and ion transport is carried out based on L–mode discharges performed on the ASDEX Upgrade tokamak. The observed increase of both electron and ion energy diffusivities towards the plasma edge is documented and its relationship with the plasma current established through a dedicated plasma current scan.

Quasi–linear modeling performed with TGLF [1], coupled to the ASTRA transport code [2], permits to discuss the validity of quasi–linear modeling in the studied regimes and clarify its limitations.

Understanding the correlation between the plasma current and the local transport properties in the outer plasma region is addressed by means of non–linear gyro–fluid simulations carried out with the GEM code [3]. The result of the non–linear simulations shed light on both the mechanism behind observed transport increase at the plasma edge, which is due to strong non–linear regime of drift–wave turbulence [4], and on specific characteristic of the turbulence spectrum when said drift–wave turbulence is of Alfvénic origin. Properties of the spectrum are compared to Doppler reflectometry measurements. Turbulence simulations are also compared with those performed in similar conditions in a parallel study [5], allowing for a comparative characterization of the turbulence properties obtained in simulations with different turbulence codes.

The computation of self–consistent profiles at prescribed input power allow to establish global scaling laws obtained from local transport. The estimated scalings are in close agreement with empirical scaling laws on both input power and plasma current.

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RF driven rotation in Tore Supra

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TOPIC : D
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Intrinsic plasma rotation can be understood as resulting from a competition between turbulent transport processes, MHD effects, fast particle effects and the ripple-induced toroidal friction. We focus here on RF heating and associated fast particle effects on plasma rotation in L-mode plasmas. Tore Supra is a large size tokamak (R_0 ~ 2.4m, a_0 ~ 0.7m) with negligible external momentum input (P_{DNBI} ~350kW), a strong magnetic field ripple (up to 7% at the plasma boundary) hence a rather large ripple-induced toroidal friction [1,2], and extensive RF heating capabilities (up to 8 MW of ICRH and 5 MW of LH). Here we show that,

- in LHCD plasmas, a clear toroidal velocity increment in the co-current direction is usually observed, which is consistent with JET [3] but opposite to C-Mod [4]. Plasma current (I_p= 0.6-1.4MA), density (n_{e0} = 3-6×10^{19} m^{-3}), and LH power (P_{LH} = 0.3-5MW) effects are discussed, together with the LH deposition profile characteristics.
- in ICRH plasmas with H-minority scheme, the toroidal velocity profile peaking is usually found to increase with the injected ICRF power in the counter-current direction, as observed in JET [3] and JT60U [5]. The fundamental H resonance layer position effect is investigated, as well as the relaxation of the profile inside the q=1 surface as the fast ion population is expelled during giant sawteeth cycles.

Overall, those observations seem consistent with ripple-induced fast particle loss effects, although other mechanisms can not be excluded, and experimental results are compared to neoclassical predictions including ripple [2].

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TOPIC: D) Momentum and particle/impurity transport, and impact of rotation on transport

Characterisation of ion-scale turbulence in MAST

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In current generation spherical tokamaks, the perpendicular (ExB) component of flow shear resulting from the strong toroidal rotation (toroidal Mach number $M_\phi = R\omega_\phi / v_{th} \sim 0.2$-$0.6$, where ω_ϕ is the toroidal rotation rate and v_{th} the ion thermal velocity) driven by the tangential NBI heating is thought to largely suppress anomalous transport due to ion-scale ($k_\perp \rho_i < 1$) turbulence. Recently, to verify this conjecture a Beam Emission Spectroscopy (BES) diagnostic has been implemented on MAST to image the ion-scale density turbulence at wave-numbers $k < 1.6$ cm^{-1} with sufficient signal-to-noise ratio ~ 300 to detect density fluctuations of amplitude $\delta n_e/n_e \geq 0.2\%$.

Correlation analysis of data from the 2D array (8 radial x 4 poloidal) detector is used to characterize the turbulence in terms of its relative amplitude $\delta n_e/n_e$, correlation time τ_c, perpendicular and radial correlation lengths L_y and L_x and poloidal drift velocity v_z. Typically, over most of the core plasma the fluctuation amplitude is observed to be small $\delta n_e/n_e < 1\%$, except at the periphery of L-mode plasmas where the ion thermal transport can exceed the neo-classical level by an order of magnitude or more and $\delta n_e/n_e$ approaches 10%.

In order to investigate the dependence of these turbulence characteristics on relevant mean quantities (e.g. q/ε (safety factor/inverse aspect ratio), normalised temperature gradients $R/L_{T_{i,e}}$, and toroidal flow shear $u' = dR\omega_\phi/dr/(v_{th,i}/R)$), a database has been constructed from L- and H-mode discharges comprising ~ 4000 data points from 8 radial locations at 5 ms intervals throughout beam heated phases. Mean values of R/L_{T_i} are found to increase with increasing u' and decreasing q/ε, while $\delta n_e/n_e$ exhibits the opposite scaling over most of the experimental parameter range. This behaviour is in good qualitative agreement with recent theories which predict that the maximum achievable temperature gradient may be limited by 'sub-critical' turbulence driven by the ion-temperature gradient or the parallel velocity gradient [1] with q/ε the essential parameter, the lowering of which leads to higher gradients.

The scaling of the correlation time τ_c with linear timescales has also been investigated [2]. Good correlation is found between τ_c and the inverse ion diamagnetic frequency $1/\omega_*^i$, indicating that the turbulence is driven at the outer scale by drift instabilities, although for small τ_c we find $\omega_*^e \sim \omega_*^i$ hence it cannot be concluded whether ion-temperature gradient (ITG) or electron drift modes provide the drive. Furthermore, in accordance with the principle of critical balance [3], it is found that τ_c is comparable to the particle streaming time $\tau_{st} \sim l_\parallel / v_{th,i}$, where $l_\parallel$ is defined by the shorter of $2\pi qR$ or v_{th}/γ_E, where $\gamma_E = (dR\omega_\phi/dr)/(q/\varepsilon)$ is the perpendicular shearing rate. This indicates that the parallel dynamics is crucial in determining the turbulence characteristics.

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Comparison of BES density turbulence measurements with synthetic data from global, non-linear gyro-kinetic simulations

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The availability of BES density turbulence measurements on MAST allows comparisons between observations and results of non-linear, gyro-kinetic calculations to be performed for the first time on a spherical tokamak [1]. The resolution of these measurements (~ 2 cm at 2 MHz) is sufficient to detect density fluctuations due to ion-scale micro-instabilities. In MAST plasmas, the NBI heating drives strong toroidal flow and the resulting $E \times B$ shearing rate can be sufficiently strong to exceed the growth rate of these instabilities. Discharges exhibiting internal transport barriers with a peripheral region unstable to ion-scale turbulence but with strong flow shear at mid-radius are ideal for performing such comparisons. Meaningful comparisons can only be performed by generating synthetic BES data from the simulated density turbulence, taking into account the response characteristics of the instrument. Non-linear, gyro-kinetic simulations are required to capture the dynamics of the saturated turbulence and these are performed using the global code NEMORB [2], which incorporates much of the physics required to reproduce the dynamics of the turbulence. Simulations have been performed with various levels of sophistication: adiabatic electrons; kinetic electrons (KE); KE with sheared toroidal rotation; and finally KE with collisions. The KE simulations with toroidal flow shear have fluctuation amplitude levels much higher than experiment (factor of 5 or 6), while the poloidal correlation lengths are longer by a factor of two and the correlation times by two or three orders of magnitude. Adding collisions lowers the fluctuation amplitudes to within a factor of two from experiment. While the correlation lengths now broadly agree, the correlation times are still much longer than measured by BES. Further simulations with KE, collisions and flow shear are planned.

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TOPIC: D) Momentum and particle/impurity transport, and impact of rotation on transport

Characterisation of ion-scale turbulence in MAST

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In current generation spherical tokamaks, the perpendicular (ExB) component of flow shear resulting from the strong toroidal rotation (toroidal Mach number $M_\phi = R\omega_\phi / v_{th} \sim 0.2$-$0.6$, where ω_ϕ is the toroidal rotation rate and v_{th} the ion thermal velocity) driven by the tangential NBI heating is thought to largely suppress anomalous transport due to ion-scale ($k_\perp \rho_i < 1$) turbulence. Recently, to verify this conjecture a Beam Emission Spectroscopy (BES) diagnostic has been implemented on MAST to image the ion-scale density turbulence at wave-numbers $k < 1.6$ cm^{-1} with sufficient signal-to-noise ratio ~ 300 to detect density fluctuations of amplitude $\delta n_e/n_e \geq 0.2\%$.

Correlation analysis of data from the 2D array (8 radial x 4 poloidal) detector is used to characterize the turbulence in terms of its relative amplitude $\delta n_e/n_e$, correlation time τ_c, perpendicular and radial correlation lengths L_y and L_x and poloidal drift velocity v_z. Typically, over most of the core plasma the fluctuation amplitude is observed to be small $\delta n_e/n_e < 1\%$, except at the periphery of L-mode plasmas where the ion thermal transport can exceed the neo-classical level by an order of magnitude or more and $\delta n_e/n_e$ approaches 10%.

In order to investigate the dependence of these turbulence characteristics on relevant mean quantities (e.g. q/ε (safety factor/inverse aspect ratio), normalised temperature gradients $R/L_{T_{i,e}}$, and toroidal flow shear $u' = dR\omega_\phi/dr/(v_{th,i}/R)$), a database has been constructed from L- and H-mode discharges comprising ~ 4000 data points from 8 radial locations at 5 ms intervals throughout beam heated phases. Mean values of R/L_{T_i} are found to increase with increasing u' and decreasing q/ε, while $\delta n_e/n_e$ exhibits the opposite scaling over most of the experimental parameter range. This behaviour is in good qualitative agreement with recent theories which predict that the maximum achievable temperature gradient may be limited by 'sub-critical' turbulence driven by the ion-temperature gradient or the parallel velocity gradient [1] with q/ε the essential parameter, the lowering of which leads to higher gradients.

The scaling of the correlation time τ_c with linear timescales has also been investigated [2]. Good correlation is found between τ_c and the inverse ion diamagnetic frequency $1/\omega_*^i$, indicating that the turbulence is driven at the outer scale by drift instabilities, although for small τ_c we find $\omega_*^e \sim \omega_*^i$ hence it cannot be concluded whether ion-temperature gradient (ITG) or electron drift modes provide the drive. Furthermore, in accordance with the principle of critical balance [3], it is found that τ_c is comparable to the particle streaming time $\tau_{st} \sim l_\parallel / v_{th,i}$, where $l_\parallel$ is defined by the shorter of $2\pi qR$ or v_{th}/γ_E, where $\gamma_E = (dR\omega_\phi/dr)/(q/\varepsilon)$ is the perpendicular shearing rate. This indicates that the parallel dynamics is crucial in determining the turbulence characteristics.

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Energy dynamics in a simulation of LAPD turbulence

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TOPIC: Edge - SOL turbulence and transport

It is often assumed that linear instabilities maintain turbulence in plasmas and some fluids, but this is not always the case. It is well known that many fluids undergo a bifucation to subcritical turbulence at a Reynolds number well below the threashold of linear instability. Certain plasma models such as drift waves in a sheared slab also exhibit subcritical turbulence [1]. In other instances such as drift-ballooning turbulence in tokamak edge plasmas, linear instabilities exist in a system, but they become subdominant to more robust nonlinear mechanisms that sustain a turbulent state [2, 3]. In our simulation of LAPD turbulence, which was previously analyzed in [4], we diagnose the results using an energy dynamics analysis [5]. This means that we derive the spectral energy evolution equations from our model equations and calculate the terms in the energy evolution equations. This allows us to track energy input into turbulent fluctuations and energy dissipation out of them. We also track conservative energy transfer between different energy types (e.g. from potential to kinetic energy) and between different Fourier waves of the system. The result is that a nonlinear instability drives and maintains the turbulence in the steady state saturated phase of the simulation. While a linear restistive drift wave instability resides in the system, the nonlinear drift wave instability dominates when the fluctuation amplitude becomes large enough. The nonlinear instability is identified by its energy growth rate spectrum, which varies significantly from the linear growth rate spectrum. The main differences are the presence of positive growth rates when $k_{\parallel} = 0$ and negative growth rates when $k_{\parallel} \neq 0$, which is opposite that of the linear growth rate spectrum.

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Electromagnetic simulations of plasma edge turbulence with experimental parameters

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1. Introduction

Experimental measurements of fluctuation levels on typical fusion devices reveal that magnetic perturbations are typically much smaller than electrostatic perturbations. However, as even small magnetic fluctuations (? 10?4) can locally modify the topology of the magnetic surfaces, they play an important role with respect to the transport properties of the plasma. Here, we show results from numerical simulations of resistive ballooning turbulence in toroidal geometry. These simulations have been performed with EMEDGE3D, a three dimensional global code which calculates the evolution of the pressure and the electrostatic potential at the plasma edge and also includes self-consistent electromagnetic fluctuations.

The simulations have been performed with parameters corresponding to experimental values obtained for Tore Supra tokamak. The goal is to determine in which cases the ballooning can be unstable compared to drift waves. These simulations let us verify the impact on instability threshold and the role of curvature and diamagnetic effects.

Blob control and fast ion dynamics in the TORPEX device

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TOPIC: **Edge - SOL turbulence and transport**

TORPEX is a device dedicated to basic plasma physics studies featuring a simple magnetized toroidal configuration with a dominant toroidal magnetic field and a small vertical field component. Recent developments include the possibility of generating closed field line configurations with rotational transform using an internal toroidal wire carrying a current. TORPEX is equipped with an extensive set of diagnostics and provides an ideal environment to study the effects of plasma turbulence and associated structures, such as blobs, on both thermal and suprathermal plasma components. We report, here, on progress in the fundamental understanding of blob physics, on advances in methods to control their dynamics, and on recent three-dimensional measurements of fast ions interacting with plasma turbulence.

Control of the blob dynamics by creating convective cells using biased electrodes is demonstrated in TORPEX. A two-dimensional array (2D) of electrodes is installed on a metal limiter to obtain different biasing patterns. Detailed 2D measurements across the magnetic field reveal the formation of a convective cell, which shows a high degree of uniformity along the magnetic field. Depending on the biasing scheme, radial and vertical blob velocities can be varied significantly. We present numerical simulations of the biased limiter configuration using a validated 2D drift-reduced Braginskii code.

Basic aspects of fast ion transport in turbulent plasmas are also investigated in TORPEX using a miniaturized source producing lithium 6+ ions with energies up to 1keV. Three-dimensional measurements of the fast ion beam are obtained using a toroidally movable source together with a double-gridded energy analyzer mounted on a two-dimensional movable system in the poloidal cross-section. The experiments are interpreted by following tracer fast ion trajectories in turbulent fields of TORPEX plasmas, which are obtained by numerical fluid simulations. These have revealed the presence of a ballistic phase followed by an interaction phase where the dispersion regime can be subdiffusive, diffusive or superdiffusive depending on the energy of the fast ions and on the amplitude of the turbulent fluctuations.

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Turbulence in the Helimak – A Model System for the Transition Region

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TOPIC: C) Turbulence and Transport at the transition region

The Helimak has the magnetic configuration of the cylindrical slab, a natural model of the SOL with dimensionless parameters similar to those of a large tokamak. The finite parallel connection length may be varied from the ~20m typical of the SOL to ~1 km, functionally indistinguishable from the confinement region for turbulence behavior. Based on fluid simulations, the turbulence is basically interchange-like in usual regimes.

For the typical L-mode profiles – a modest density gradient in unfavorable magnetic curvature, the turbulence levels and other characteristics are observed to vary only weakly with connection length, the difference between inside and outside the LCFS. Collisionality has more significant effects.

The largest effect on turbulence is caused by modification of the flows and radial electric fields and currents. Because the field lines are open, terminating on plates at the end of the machine, it is possible to bias one group of magnetic surfaces with respect to those at other radii without drawing any average parallel current. The bias alters the radial electric field and "poloidal" flow velocity and drives a weak radial cross-field current. Since the device is large in the sense of having a radial extent large compared with the turbulence radial correlation lengths, one can make local measurements of the turbulence, flow, and flow shear. Application of bias can induce a sharp transition to a state of reduced turbulence above a threshold, but with no hysteresis. The effect occurs for both signs of bias, although the threshold voltages and spatial distribution of effects differ. The experiments are done in a low-temperature argon plasma, which permits a direct measurement of flow velocity from the Doppler shift of an Ar^{+1} line. Turbulence levels, correlation lengths, and other characteristics together with flow velocities and flow shearing rates have been measured across the profile for a wide variety of conditions.

Considering the whole body of data, there is a general covariance of turbulence level (rms $\Delta n/n$) with radial correlation length, but with considerable scatter. Most surprising, there is no discernable relation between local turbulence level and local flow shear. Low and reduced turbulence levels have been found in regions of low flow shear, and high turbulence levels have been observed at locations of high flow shear, even though the shearing rate exceeded the measured turbulence decorrelation rate.

Results for a broad range of connection lengths and collisionalities will be shown. Similar results have been seen in a numerical simulation of the Helimak with bias.[1]

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Thermodynamical and microscopic properties of turbulent transport in the edge plasma

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TOPIC: A

Turbulent transport in plasmas appears to exhibit conflicting properties. On the one hand simulations of flux driven turbulence exhibit large fluctuations of the transport step size due to the interplay between avalanches and zonal flows, exceeding the correlation length and achieving values that are comparable to the e-folding length of the Scrape-Off Layer, namely the macroscale of the system. On the other hand, from the thermodynamical point of view, when the system is characterised by a very small set of independent parameters, one expects the turbulence flux to scale with the departure from equilibrium, hence typically proportional to the opposite to the gradient. While the latter property governs a Ficks law, compatible with diffusive transport, the former questions the validity of a transport described as a combination of diffusion and pinch velocities.

We investigate these issues with the TOKAM2D code, a minimum two field interchange turbulence code addressing edge density transport in 2D transverse to the magnetic field. The box size and simulation duration significantly exceed the correlation lengths and time. A key point when describing the thermodynamical properties is that of the necessary coarse graining that is required to step from the microscopic description, the scales governed by turbulent processes, up to the macroscopic scale range used to describe transport processes. Coarse graining can be considered along three directions, along time, in the radial direction from the particle source to the particle sink and in the poloidal direction. In the analysis we average all quantities along the latter direction. This reduces very significantly the fluctuation level. We then investigate the minimum coarse graining in the two remaining directions. One then finds that the thermodynamical transport properties are recovered when these scales reach macroscopic values, the SOL e-folding length radially and the particle confinement time along the field line. This indicates that the thermodynamical properties are recovered but are restricted to scales comparable to the size and lifetime of the system. The system obtained by the coarse graining procedure is therefore reduced to a few coupled reservoirs, with an evolution close to equilibrium. This result is not compatible with the description of transport based on the diffusion ansatz used for all scales in time and space.

When analysing the response of the system to low frequency modulation of the source one recovers a similar property, namely that the density response appears to be consistent with a diffusive process but only at the smallest wave vectors radially. Departure from standard diffusive response is also illustrated by large spikes of deviation from the diffusive response.

At the microscopic level, the self similarity of the autocorrelation functions in the radial direction and in time is achieved with a power 1.1 for the radial scale which is very close to a ballistic transport. Such a property agrees with the analysis of the mean density profile. Furthermore, it suggests that transport is governed by another departure from equilibrium than the density, namely the curvature g-term in the TOKAM-2D model.

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Is "near edge" transport non-local?

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Topic: *Turbulence and Transport at the transition region between core and edge*

The excess of fluctuations and transport near the edge region, which is reaccentuated by recent detailed code-experiment comparisons has been one of the outstanding challenges for understanding of turbulent transport in fusion devices. Two of the possible explanations of this discrepancy -namely the spreading of the edge turbulence (possibly in the form of resistive balooning modes) towards the core, or the core turbulence (possibly ITG) towards the edge (getting amplified due to "beach" effect)- involve spatial nonlocality. Nonlocal phenomena, which may simply mean a diffuse smooth profile of turbulent flux even when local gradients change sharply, may also appear in the form of avalanches and propagation of turbulent fronts. This dynamics can be described using a simple equation for the turbulence intensity. Mesoscale structures such as corrugations of potential vorticity, play an important role in this dynamics. In the spirit of animating discussion, recent fluctuation measurements from Tore Supra, via doppler backscattering technique, characterizing the turbulence in this region will be presented and the application of the hypothesis of nonlocal transport to these observations will be discussed. In addition, a dedicated effort in view of addressing this issue of non-local transport is presently undertaken with the global and flux-driven gyrokinetic code GYSELA.

EFDA task WP12-IPHA05-1-09/BS: "Investigation of multi-scale physics performing precise comparisons of micro-turbulence characteristics between measurements using Doppler backscattering system in Tore Supra and gyrokinetic simulations"

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Time Evolution of Zonal Flows and GAMs from Core to Edge

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TOPIC: C D A B in that order

The plasma turbulence controls the global flows through the transport of several quantities. The complex interplay of the various transport processes has been explored in detailed two-fluid and gyrokinetic simulations allowing clear predictions on the time evolution and structure of zonal flows (ZF) and GAMs in toroidal ballooning/ITG and sheared-slab drift-wave scenarios.
The turbulence controlled GAMs in the transition range between core and edge have been found to gain a strong dependence of the real frequency on their wavenumber, associated with a significant radial group velocity [1], i.e., a radial flux of fluctuation energy, in contrast to their linear dispersion relation, which also gives rise to rather extended global GAM eigenmodes. Curiously, for divertor geometries the direction of the propagation depends on the sign of the ion grad-B drift with respect to the X-point, reminiscent of a sensitive determinant of the H-mode threshold. In nonlocal turbulence computations a bursting behavior can result for the GAMs, similar to recent ASDEX Upgrade measurements [2].
These effects are also relevant for the analysis of the external electromagnetic excitation of GAMs, which results in localized GAM activity impacting the turbulence at a particular resonance surface [3].
The evolution of stationary ZFs in the core is governed by the radial transfer of perpendicular and parallel momentum by turbulent Reynolds stresses. For sufficiently large systems, the Reynolds stress becomes a deterministic functional of the flows, which can be determined using systematic measurements of the stress response in computational turbulence studies. The resulting functional details the mechanism establishing the empirically observed robust radial scale length of the ZFs in ITG turbulence. Differently, sheared-slab drift-wave turbulence most relevant to high gradient edges or transport barriers results in a stable shearing rate with a variable radial scale length depending on the past history [4].

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Global Scrape-Off Layer Electromagnetic Fluid Turbulence Simulations

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TOPIC: **Edge - SOL turbulence and transport**

Electromagnetic effects play a key role in tokamak edge turbulence. It has been suggested that the density limit and the L to H mode transition may both be due to an interplay between electromagnetic effects, diamagnetic flows and collisionality. (See, e.g., Ref [1].)

The present paper discusses the results of scrape-off layer (SOL) non-linear 3D fluid turbulence simulations including finite beta effects in the shear-less limit. These simulations were carried out using the GBS code [2], which evolves the drift-reduced Braginskii equations for a collisional plasma with cold ions in circular (s-α) geometry with a toroidal limiter in the high-field side midplane. The GBS code has been used to study turbulence in linear devices and in a simple magnetized torus configuration [2, 3]. We have recently adapted the code for tokamak edge geometry, and introduced s-α curvature operators as well as magnetic shear, finite aspect ratio, and finite beta effects.

The objective of our work is to describe the phase-space relevant to the tokamak SOL turbulence. In this paper, in particular, the role played by finite beta effects upon the characteristic lengths of the profile gradients, turbulence saturation levels, and other basic turbulence properties, is assessed in the context of fully global non-linear turbulence simulations. The non-linear steady-state turbulent plasma profiles are obtained as the result of a balance between plasma density and heat sources, turbulent fluctuations, and parallel losses at the limiter plates. The turbulence drive is *a priori* unknown and there is no separation between fluctuations and background profiles.

Linear analysis of the fluid equations has been carried out for SOL relevant parameters. In the presence of finite beta effects, we recover three instabilities: drift waves, resistive ballooning modes, and ideal ballooning modes. The onset of ideal ballooning modes is known to correspond to the instability threshold $\alpha_{MHD} = q^2 \beta R/L_p \sim 1$.

In the non-linear simulations, however, we observe the onset of catastrophic transport well below the ideal limit. The saturated states in this regime are characterized by large transport due to equilibrium $\mathbf{E}\times\mathbf{B}$ flows. The plasma density and temperature profiles are flat, and the turbulence is almost completely suppressed.

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Wavenumber-resolved turbulence investigations using Doppler reflectometry in the ASDEX Upgrade tokamak

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TOPIC: Turbulence and Transport at the transition region between core and edge (multi-scale turbulence measurements)

Turbulence is known to cause substantial particle and heat losses from magnetically confined fusion plasmas. In this context, different types of turbulence can (co-) exist, for example ion-temperature-gradient (ITG) and trapped electron mode (TEM) turbulence at large and intermediate scales and electron-temperature-gradient (ETG) turbulence at small scales. For the identification of the prevailing type of turbulence and its backreaction on external input parameters such as additional heating, scale-resolved measurements are necessary.

Doppler reflectometry has proven to be a powerful technique to measure the perpendicular velocity of density fluctuations $u_\perp$, the radial electric field E_r, and the perpendicular wave number spectrum $S(k_\perp)$ in magnetically confined fusion plasmas. In the ASDEX Upgrade tokamak, a new optimized bistatic Doppler reflectometer antenna front-end equipped with a linear in-vessel piezo motor steers the beam tilt angle θ_0 in a stepwise motion during the plasma discharge. This enables a full $k_\perp$-scan per discharge (between $k_\perp = 5 - 25$ cm^{-1}), allowing for the measurement of wavenumber spectra at several radial positions ($\rho_{\mathrm{pol}} \approx 0.50 - 1.00$, the normalized poloidal flux radius).

Discharges are investigated where the turbulence regime is expected to change due to different ECRH heating scenarios. In detail, the electron temperature gradient is modulated while the total deposited heating power is kept constant. Initial measurements of turbulence amplitudes at different perpendicular structure scales $k_\perp$ and radial positions ρ_{pol} and their reaction to the power modulation will be presented. Emphasis is placed on the identification of the underlying turbulence mechanisms through comparison with numerical simulations.

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New regime of small scale density fluctuations in presence of electron heating in Tore Supra

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Topic 3: Turbulence and Transport at the transition region between core and edge

Electron heat transport remains a subject of focus of the fusion plasma physics community, in particular because of the residual high level of electron transport through transport barriers while ion thermal and particle transport are quenched [1]. It is suspected that small scale fluctuations [2, 3, 4, 5], less sensitive to ExB shearing, can cause a substantial residual transport, due to the formation of large scale structures (streamers) [6].

In Tore Supra, in shots at reduced field with ICRH featuring dominant electron heating (2nd harmonic H heating and FWEH), a specific high frequency component of density fluctuations at relatively high k ($k\rho_s > 1.5$) has been observed , that could be related to electron modes. It appears as a separate small peak on the high frequency side of the broad frequency spectra measured via Doppler reflectometry [7] (X mode polarisation, $0.7 < r/a < 0.85$), and presents some similarity with high k UHR measurements [2, 8]. Moreover, we have found that the presence of this electron component at high k is accompanied by a change in turbulence dynamics: long lasting bursts of turbulence are observed, a feature which is not seen in usual conditions. The turbulence correlation time is much higher when the electron component is observed, and it increases with the wave-number, in contrast with the usual k dependence which is decreasing as $\tau_c \equiv k^{-1}$. The probability distribution function (of the fluctuation intensity) shows wide tails departing from standard PDF. These observations are to be compared to theoretical models and simulations. Linear stability analysis of these experiments indicates that Electron Temperature Gradient modes are unstable in the discharges in which the high frequency Doppler component has been observed, although at higher wavenumbers than experimentally measured.

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Turbulence Suppression, Stiffness Reduction and Other Effects of Rotational Shear

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TOPIC: Momentum and particle/impurity transport, and impact of rotation on transport

Recent numerical work has demonstrated the effects that toroidal rotational shear can have upon the turbulence generated by background gradients in a fusion plasma, including the reduction of transport stiffness, the total suppression of turbulence and bifurcations to reduced transport states. We use nonlinear gyrokinetic simulations to show that all of these effects are in turn profoundly affected by the ratio q/ε where q is the magnetic safety factor and ε the inverse aspect ratio, which is equal to the ratio of the parallel flow gradient to the perpendicular flow gradient. The lower the value of q/ε, the higher the temperature gradients that can be achieved without driving turbulence (see Figure 1). However, at lower values of this ratio, this optimum temperature gradient, and the low-stiffness regime occur at a higher value of the toroidal flow shear, and thus may not be accessible in experiments. At higher values of q/ε, by contrast, the improvement in confinement that can be achieved not quite so dramatic, but since they occur at lower values of the toroidal flow shear they are accessible in current experiments.

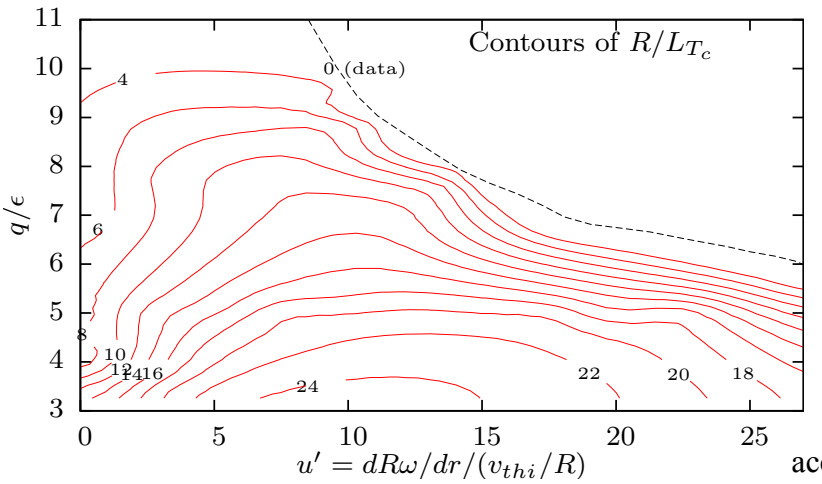

Figure 1: Contours of the nonlinear temperature gradient threshold for the onset of turbulence shown vs the ratio q/ε and the toroidal flow shear u'. At lower values of q/ε much higher temperature gradients can be reached without destabilising turbulence.

We present comparisons of these results with preliminary data obtained in the MAST experiment, using the new Beam Emission Spectroscopy (BES) diagnostic. We demonstrate good qualitative agreement in respect of the effects of the toroidal flow shear and q/ε between these experimental results and numerical results. We will also present similar comparisons with data obtained in the JET experiment. We present preliminary attempts to obtain quantitative agreement by simulating realistic experimental geometry.

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Modelling of the non-local response of transport to peripheral perturbations

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TOPIC: C) Turbulence and Transport at the transition region between core and edge

Non-locality phenomena in perturbative transport experiments have been reported from several experiments, e.g. RTP [1], LHD [2] and HL2A [3]. Here, non-locality means a rapid response in the core follows an edge perturbation on a time scale far shorter than any standard approximation to the global, diffusive model confinement time. E.g. in HL2A where sequential firing of supersonic molecular beam injection (SMBI) invoked an increase of core electron temperature (T_e) in response to the edge perturbation.

Recent theoretical work has linked turbulence spreading dynamics with these phenomena. In this theory the T evolution is governed by turbulent diffusion, given by $\chi_{\rm turb} = \chi_0 I/(1 + V_E'^2/\gamma_c'^2)$ where $V_E'^2/\gamma_c'^2$ is the electric field shear suppression factor and I is the turbulence intensity. The evolution of the latter is determined by a second diffusion equation governed by a local growth rate $\gamma \sim (R/L_T - R/L_T^{\rm crit})/(1+V_E'^2/\gamma_c'^2)\Theta(R/L_T - R/L_T^{\rm crit})$ where $\Theta(R/L_T - R/L_T^{\rm crit})$ is a Heaviside function. This theory provides a framework to explain the experimental observation without invoking non-local effects [4].

In this presentation results of numerical modelling of cold pulse experiments in HL2A and RTP will be given, based on the ideas of turbulence spreading.

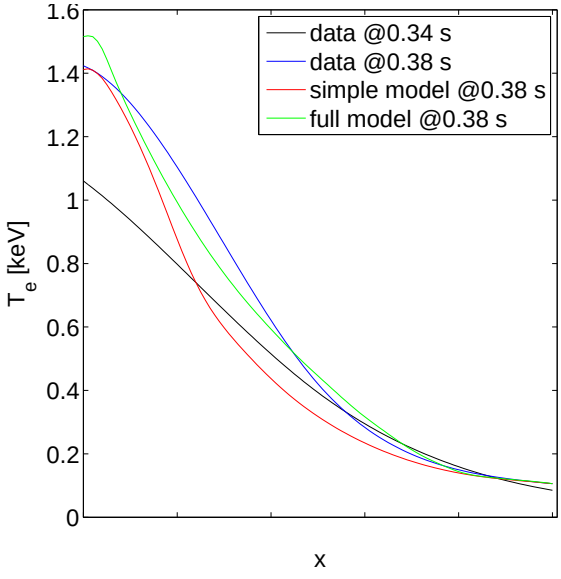

Figure 1: *Observed T_e profiles for HL2A discharge 16404 before and after SMBI (black and blue, respectively), and modelled T_e profiles at the same instance after SMBI, with two different formulas for χ_e(red and green).*

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Space-time characterization of the SOL turbulence in Tore Supra tokamak plasmas

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TOPIC: **A) Edge - SOL turbulence and transport**

The Scrape-Off-Layer (SOL) turbulence characterization is predominantly performed through Langmuir probes measurements, and more recently, with fast camera and gas puff imaging.
All these techniques are intrusive and the local perturbations induced by the measurements remain largely unexplored.

A sweeping reflectometer [1] operating on Tore Supra tokamak allows a continuous probing of the plasma density fluctuation profile from the edge to the core, thus covering both sides of the last close flux surface (LCFS), with a high radial resolution (mm range). By repeating sweeps, the evolution of electron density fluctuations is followed with 3 µs time resolution. The space-time resolution is thus comparable to that of Langmuir probes; moreover reflectometry is a non intrusive technique.
Thanks to the recent upgrade of the reflectometer, allowing for a sweeping time of the order of the turbulence correlation time, for the first time a strong intermittent behaviour could be observed in the SOL signals. Evidence of different turbulent regimes, namely depending on the plasma heating, is observed on the phase signals and it is even more pronounced on the amplitude signals. From the reconstructed instantaneous electron density profiles, the properties of turbulent fluctuations are then characterized statistically.
The spatial vicinity of the reflectometer and the reciprocating probes on Tore Supra allows for a pertinent comparison of the fluctuations signals measured by the two diagnostics. A set of well diagnosed Ohmic shots has been identified. Respectively, the reconstructed electron density and ion saturation current signals have been compared through four statistical quantities. The probability distribution functions (PDF) exhibit a significant deviation from normality and have similar shapes. The fluctuation levels, defined as the ratio of the standard deviation to the mean value, are of the order of few tens of percents as expected in the SOL plasma. The measured skewness is positive, depicting the preponderance of positive density fluctuations, and in agreement within a factor 2. The correlation time of fluctuations, defined as the full width half maximum (FWHM) of the autocorrelation function, is about 20 µs for the Langmuir probes whereas it is much smaller about 3 µs for the reflectometry signals. The observed discrepancy on the correlation time is due to the presence of a fast oscillating component on the reflectometer signal. The origin of this fast component is still under investigation.

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On Generation of Runaway Electrons in Fusion Plasmas

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TOPIC: A

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The generation of runaway electrons (RE) in the fusion reactor plasmas can cause strong erosion of plasma facing components. Mitigation of the RE can be achieved by injection of noble gases. Runaway electrons are able to penetrate the electron shells of partly ionized heavy ions during collisions, for which reason they may effectively be scattered by a greater positive charge than that of a shielded nucleus. This effect increases the Coulomb cross section and can be treated as an increase of the effective ion charge $Z_{eff}(\varepsilon)$ with increasing energy of the incident electrons ε .The increase of effective charge number with increasing electron energy in multi-component plasma brings qualitatively to the same result as for high Z_{eff} in Coulomb plasma. Since the generation of runaways depends exponentially on Z_{eff} , its production during the mitigation of disruption by massive gas injection could in some cases strongly decrease owing to heavy impurities concentration in the boundary region.

Test particle simulations in the transition region between the core and the edge

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TOPIC: **C) Turbulence and Transport at the transition region between core and edge (recently dubbed no man's land)**

The 3D, non-linear, dynamic MHD code MYDAS is used to model the transition region between the core and the edge, with the pedestal being modeled by applying reduced values of the particle and heat diffusivities. The electromagnetic fields of the MHD simulations are then used as background fields in which test-particle simulations are performed, and the particle and heat transport properties of electrons, ions, and impurities are determined. Also, a random walk view of transport is adopted, and the probability distribution functions in radial direction, as well as in energy, are determined as functions of time, with aim to identify possible anomalous, non-local transport phenomena. Furthermore, the effect of the transient phase is assessed, in order to validate the appropriateness of a Fokker-Planck type of modeling. In parallel, the transport properties in the transition region are determined with the gyro-kinetic code GENE, for the same particle species as mentioned.

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Gyrokinetic studies of the core-edge transition region in ASDEX Upgrade discharges: Limits of quasilinear theories and role of non-local effects

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TOPIC: C

To study the core-edge transition region in ASDEX Upgrade discharges, radially local and non-local gyrokinetic simulations with the GENE code [1] are carried out. Fully kinetic electrons, electromagnetic effects, inter- and intra-particle collisions, as well as fluctuations on (sub-)ion-gyroradius scales are taken into account; moreover, actual plasma profiles/parameters and MHD equilibria are used. It is investigated, in particular, to which degree quasilinear theories – widely used in transport modelling – are able to capture the turbulence physics under these conditions, and to which degree non-local effects play a role.

Over the last several years, careful and systematic comparisons between quasilinear and nonlinear gyrokinetic simulations for typical core conditions and relatively low beta values have been carried out (see, e.g., [2-5]). It was found that TEM and ITG turbulence usually retains many features of the underlying linear modes (like real frequencies, cross-phase relationships, parallel mode structures etc.) in the long-wavelength regime, justifying the use of the quasilinear approach and forming a sound theoretical basis for it. It can be expected, however, that this property breaks down somewhere in the core-edge transition region of L-mode discharges, given the highly nonlinear nature of edge turbulence [6].

Initial simulations for the outer core (at rho=0.85) of an ASDEX Upgrade L-mode discharge with 0.8 MA, covering the entire flux surface and reproducing the experimental fluxes reasonably well, indicate that the linear properties of the driving microinstabilities are still retained to a large degree. In this sense, there is no fundamental difference from typical core cases. Simulations extending further out in radius and documenting the changes in the turbulence properties will be presented, along with comparisons to results from other turbulence codes [7]. Meanwhile, for sufficiently high beta values, the turbulent transport tends to pick up a significant magnetic component which is due to linearly stable (but nonlinearly driven) or linearly unstable microtearing modes [8-10] – an effect which is not captured by conventional quasilinear theories. In addition, GENE simulations are used to assess the role of non-local effects in the core-edge transition region, building on the concept of an effective rho* parameter.

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Influence of plasma size on heat and momentum transport in global steady-state ITG simulations

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TOPIC: D) Momentum and particle/impurity transport, and impact of rotation on transport

The prediction of momentum and heat transport is one of the key issues for future fusion devices such as ITER, and is performed by means of gyrokinetic simulations. While the last decade has seen the emergence of global simulations, mostly focusing on heat transport, very little is known on global effects on momentum transport. So far, the theory has been developed in the local limit, identifying several mechanisms breaking the symmetry along the field line and producing momentum transport. On the other hand, ρ^*- effects potentially introduce additional mechanisms but are still relatively unkown. Recently, a study of profile-shearing effects on quasi-linear momentum transport [1] has shown that those effects could be important, but nonlinear results are still missing.

In this work, global steady-state gyrokinetic simulations of ion temperature gradient turbulence with the full-f Eulerian code GT5D [2] are presented. First, conservation properties associated with the Hamilonian formulation [3] will be shown, focusing in particular on the recent controversy [4] on the accuracy of momentum transport in gyrokinetic simulations. It is found that both energy and canonical momentum are conserved with very good accuracy. It will then be shown that canonical momentum conservation remains valid even when higher order drifts are included.

Second, a plasma size scaling has been performed [5]. For the first time, a worse-than-Bohm scaling has been obtained under experimentally realistic heating conditions. The study of turbulence characteristics indicates that the shearing rate plays a central role in dictating transport. In particular, it is shown that the usually assumed ρ^*-scaling of the shearing rate breaks down due to the build-up of a momentum profile. Such dependence can be inferred from the neoclassical force balance relation, which remains approximately valid in nonlinear simulations. By applying an adaptive momentum source to damp the momentum profile, the new size-scaling scan reveals that the ρ^* scaling of the shearing rate is recovered and that transport is globally higher: these simulations suggest that intrinsic momentum transport can reduce momentum heat transport.

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Recent studies on the L-H transition in JT-60U: Turbulence, transport, and the origin of the radial electric field

K. Kamiya[1], K. Ida[2], G. Matsunaga[1], and the JT-60 team[1]

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TOPIC: L-H transition and physics of transport in the pedestal

In recent experimental studies on JT-60U, we focus on the "intermediate" H-phase during the ELM-free H-mode [1-2]. It is well known that the normal L-H transition occurs on a faster time scale (e.g. within a few micro second) from L-phase to the "complete" H-phase, without showing their intermediate phase (but sometimes it falls into the dithering phase at around the threshold power). In many tokamaks, spontaneous generation of a well-shaped radial electric field, Er, structure is seen near the L-H transition in the localized region just inside the separatrix, and an ExB shear flow is created there. On the other hand, the intermediate H-phase seen in a higher toroidal magnetic filed discharges is characterized by a weak negative Er value at the Er well bottom with a well developed pedestal structure, and there is a complex multistage transitions in the edge Er values between weak negative and strong negative ones during ELM-free H-mode phase. Experimental observation suggests that the H-mode plasma has two qualitatively different phases: first, there is a long period of secular increase in both the rotation term and the diamagnetic term. This is followed by a violent phase, where the edge plasma bifurcates between a high-rotation and a low-rotation state of the carbon impurity ions, until it finally settles to the complete H-phase. An interesting feature is that the poloidal rotation velocity changes in the later H-phase without a comparable change in the main ion pressure gradient, indicating a change in the parallel momentum (and/or particle) balance channel. Characteristics of the turbulent density fluctuation, in addition to a toroidally axisymmetric MHD oscillation (i.e. toroidal mode number n=0), during both ELM-free and ELMing phases are also reported.

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The continuous reduction of transport with increasing lithium in NSTX and the role of collisionality

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TOPIC: C) Turbulence and Transport at the transition region between core and edge

Lithium wall coatings were found to have a profound effect on the profiles and performance of NSTX H-mode discharges[1, 2]. Experiments with increasing Li coating resulted in a continuous improvement in thermal energy confinement and confinement enhancement factor[3]. This improvement was due primarily to a progressive broadening of the T_e profile in the outer half of the plasma, and an associated reduction in electron collisionality ν_e^*, and increases in normalized gyroradius ρ^*, T_i and toroidal rotation and its shear. Further, the electron thermal diffusivity decreased by nearly two orders of magnitude both in absolute value and with respect to gyroBohm scaling. Results from these experiments and those with no lithium[4] show a strong increase of normalized confinement with decreasing ν_e^*, unifying these sets of data with a favorable scaling $B\tau_E \sim \nu_*^{-0.53}$. The ν_e^* scaling was found to be even more favorable when either a Bohm-like or gyroBohm-like ρ^* dependence was assumed. Turbulence measurements from microwave reflectometry near the edge and from high-k scattering measurements in the outer region of the plasma show reduced turbulence in and near the pedestal region. Reduced transport coefficients were found to be associated with this reduction in turbulence in the edge barrier region as well[5]. Linear gyrokinetic calculations have been performed, and these results indicate that both microtearing and Electron Temperature Gradient modes become more stable at lower ν_e^* for the lithiated discharges. For microtearing modes, this is primarily a consequence of increased collisionality, while for the ETG modes, this is partially due to changes in Z_{eff} and T_e/T_i, which influence the linear threshold.

1 Bell M. G., Kugel H. W., Kaita R., *et al.* 2009 *Plasma Phys. Control. Fusion* **51** 124054.
2 Ding S., S.M. Kaye, R.E. Bell, *et al.* 2010 *Plasma Phys. Control. Fusion* **52** 015001.
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5 Cank J.M., R. Maingi, S. Kubota *et al.* 2011 *Phys. Plasmas* **18** 056118.

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The continuous reduction of transport with increasing lithium in NSTX and the role of collisionality

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Lithium wall coatings were found to have a profound effect on the profiles and performance of NSTX H-mode discharges[1, 2]. Experiments with increasing Li coating resulted in a continuous improvement in thermal energy confinement and confinement enhancement factor[3]. This improvement was due primarily to a progressive broadening of the T_e profile in the outer half of the plasma, and an associated reduction in electron collisionality ν_e^*, and increases in normalized gyroradius ρ^*, T_i and toroidal rotation and its shear. Further, the electron thermal diffusivity decreased by nearly two orders of magnitude both in absolute value and with respect to gyroBohm scaling. Results from these experiments and those with no lithium[4] show a strong increase of normalized confinement with decreasing ν_e^*, unifying these sets of data with a favorable scaling $B\tau_{E-}\sim\nu_*^{-0.53}$. The ν_e^* scaling was found to be even more favorable when either a Bohm-like or gyroBohm-like ρ^* dependence was assumed. In this work, the profile variations are examined across the range of collisionality in order to assess the underlying cause of the anomalous electron transport and its variation. Linear gyrokinetic calculations have been performed, and these results indicate that both microtearing and Electron Temperature Gradient modes become more stable at lower ν_e^* for the lithiated discharges. For microtearing modes, this is primarily a consequence of increased collisionality, while for the ETG modes, this is partially due to changes in Z_{eff} and T_e/T_i, which influence the linear threshold.

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TOPIC: D) Momentum and particle/impurity transport, and impact of rotation on transport

Recent progress in understanding the effect of rotational shear on ion heat transport

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Recent work carried out both on the experimental and theoretical fronts on the effect of rotational shear in reducing ion heat transport and more specifically ion stiffness - first evidenced experimentally in JET [P.Mantica et al., Plasma Phys. Control. Fusion 53 (2011) 124033] - will be summarized.
On the experimental side, an empirical correction term ~ γ_E/s to the dimensionless stiffness coefficient in the Critical Gradient Model proposed in [X.Garbet et al., Plasma Phys. Control. Fusion 46 (2004) 1351] has been derived using the whole JET database on ion stiffness experiments. A confirmation of the JET experimental evidence has been sought in other devices. On TEXTOR, T_i profile analysis in discharges with different rotation profiles due to co- and counter NBI has indicated some impact of rotational shear on ion stiffness in regions of low magnetic shear. On DIII-D, ion heat flux scans at low and high torque have been performed using different combinations of co- and counter-NBI and keeping the pedestal temperature as constant as possible by a weak triangularity shape with poor edge peeling-ballooning stability and very rapid ELMs. Evidence is found that T_i profile peaking increases with power at high rotational shear whilst it is to good extent constant with power at low rotational shear. Electrons instead show significant stiffness in both cases. Detailed data analysis is ongoing. Simulations using TGLF [G.M.Staebler et al., Phys.Plasmas 14 (2007) 055909] provide a good match of the experimental observations. On MAST BES measurements of ion-scale turbulence ($k_\theta\rho_i < 1$) characteristics have been made as a function of equilibrium parameters, e.g. R/L_{Ti}, q/ε, γ_E, for a database of discharges with different flow levels. The results are broadly consistent with theoretical prediction of a threshold R/L_{Ti} for excitation of sub-critical turbulence [E.Highcock, subm. to PoP, arXiv.1203.6455.v1], within the experimental range the average observed R/L_{Ti} increasing with increasing γ_E and decreasing with increasing q/ε.
On the theory side, the idea proposed in [J.Weiland et al., EPS 2011] that an up-shift of the mode number of the fastest growing mode due to rotation is responsible for the stiffness variation has been further tested with full profile simulations in realistic geometry of two representative JET discharges at low and high rotational shear. Local simulations using the gyro-kinetic code GENE [http://gene.rzg.mpg.de] have been carried out with JET discharge parameters. The competition between (stabilizing) perpendicular and (destabilizing) parallel flow shear physics under realistic conditions leads to a reduction of stiffness rather than a threshold shift near the non-linear threshold. However the degree of predicted reduced stiffness is markedly less than experimentally observed. Significant dependence of stiffness on the magnetic shear itself and β is also predicted. The MAST BES measurements have been compared with synthetic data from non-linear ORB5 [S.Jolliet et al., Comput. Phys. Comm 177 (2007) 409] simulations both with and without sheared flow.

* *see Appendix of F. Romanelli et al., Fusion Energy 2010: Proc. 23rd Intern. Conf., Daejeon, 2010 [IAEA, Vienna,2010]*

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Connections Between Intrinsic Toroidal Rotation, Density Peaking, and Plasma Turbulence Regimes in ASDEX Upgrade

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TOPIC: D) Momentum and particle/impurity transport, and impact of rotation on transport

The combined measurements of intrinsic rotation from many tokamaks reveal a highly complex phenomenology that appears to defy simple characterization or theoretical explanation. However, the tokamak community has recently made significant progress in disentangling these observations and moving toward a single consistent framework within which much of the data can be understood. Recently, ASDEX Upgrade (AUG) has contributed to this research thanks to the upgrade of the core charge exchange recombination spectroscopy diagnostic, which now produces much higher quality ion temperature and toroidal rotation profiles. This upgrade enabled the development of an intrinsic rotation database with over 200 independent observations from Ohmic L-mode, and ion and electron cyclotron resonance heated (ICRH and ECRH) L- and H-mode plasmas [1]. This has allowed an unprecedented study of the dependencies of the intrinsic toroidal rotation profile on theoretically relevant plasma parameters to be performed [2].

Examination of the database reveals that the edge rotation is always co-current, while the core rotation can be either co- or counter-current directed. The latter results in a null point in the profile at finite rotation gradient, which is clear evidence of the presence of a localized residual stress momentum flux. In addition, the Mach number in the plasma core appears to be determined, in large part, by the normalized toroidal rotation gradient at mid-radius, u'. This correlation holds for all of the observations regardless of plasma confinement regime or type of auxiliary heating. Further examination shows that u' exhibits the strongest correlation with the local logarithmic electron density gradient, R/L_{ne} [2]. Hollow rotation profiles coincide with peaked n_e profiles, while peaked rotation corresponds to low values of R/L_{ne}. The known relationship between density peaking and plasma turbulence [3] suggests a connection between turbulence type and intrinsic rotation behavior as well. A study based on local linear gyro-kinetic calculations finds good quantitative agreement between the predicted and measured values of u' through the imposition of a finite constant tilting angle of -0.3 radians (TEM) on the turbulence mode structure [2]. The mechanism expected to produce such a tilting is a combination of **ExB** and profile shearing.

These database results demonstrate a very promising consistency with observations of residual stress in non intrinsic rotation scenarios. Flat to hollow rotation profiles are observed concomitant with peaked electron density profiles when sufficient ECRH is added to NBI heated H-modes causing the turbulence regime to transition from ITG to TEM. Momentum transport analyzes show clearly that these observations can only be explained by the presence of a core localized, counter-current directed, residual stress induced torque of the same order of magnitude as the applied NBI [1]. In addition, the developing picture points to the existence of a co-current intrinsic torque when the plasma is in the ITG regime, which has important implications for torque modulation experiments that assume the residual stress is negligibly small. Altogether these results provide a new framework within which experimental results from multiple devices can be analyzed to validate, or invalidate, the characterization of the intrinsic toroidal rotation described here.

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Dynamics of the L-H transitions at different density in MAST

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Topic: B) L-H transition and physics of transport in the pedestal

In recent years the increased importance of the fluctuating radial electric field compared to the mean radial electric field has become evident [1–3]. This is in qualitative agreement with predator-prey models for the L-H transition where the fluctuating E_r due to the turbulence driven zonal flows or geodesic acoustic mode preys on the turbulence itself. New measurements on MAST of toroidal and poloidal He^+ flows with $\Delta t \geq 20$ μs (50 kHz) at 9 spatial locations simultaneously through L-H transitions at three different densities in the range of $1.5 \cdot 10^{19}$ m$^{-3} \leq \bar{n}_e \leq 3.0 \cdot 10^{19}$ m^{-3} highlight the interplay between plasma flow and turbulence suppression. It is found that the evolution of the discharge into H-mode changes with the density before the L-H transition. In fact there are two types of transitions. On the one hand the transition from L-mode to a dithering H-mode state ($\tilde{\text{H}}$) similar to the I-phase observed on ASDEX Upgrade [1]. On the other hand the transition from $\tilde{\text{H}}$-mode into ELMy or ELM free H-mode. At the highest density point the transition is sharp with only a few dithers prior to the transition into ELMy H-mode and the power range over which the $\tilde{\text{H}}$ phase is observed is small. As the density is decreased the duration of the $\tilde{\text{H}}$ period prior to the transition into ELMy H-mode lengthens and the power range for the $\tilde{\text{H}}$-phase broadens. Below $\bar{n}_e < 2 \cdot 10^{19}$ m^{-3} only the $\tilde{\text{H}}$ phase is encountered with the available input power of $P_{\text{NBI}} \leq 3.4$ MW. The power required to access the L-$\tilde{\text{H}}$ transition as well as the access to the $\tilde{\text{H}}$-H transition above $\bar{n}_e > 2 \cdot 10^{19}$ m^{-3} increases with density. The $\tilde{\text{H}}$-phase is observed at densities as low as $\bar{n}_e \approx 0.9 \cdot 10^{19}$ m^{-3}, about 20% of the Greenwald density. A strong correlation of the reduced D_α emission with the spin-up of the perpendicular He^+ flow is observed (see Fig. 1). In the $\tilde{\text{H}}$ phase the flow change seems to precede the reduction of the D_α emission by 50 μs to 100 μs indicating a limit-cycle like dynamics. However, the increase in flow shear seems to be coincident with the turbulence suppression. On exiting the higher confinement phase large filaments are observed although strong flow shear is still present, which seems to contradict at least simple predator-prey models. In addition measurements of T_e and n_e profiles prior to the L-$\tilde{\text{H}}$-H transition as well as the He^+ flow behaviour during early ELMs are discussed. By averaging 8 profiles within 160 μs more accurate measurements of the T_e^{sep} and n_e^{sep} values close to the separatrix for comparison with theory are obtained.

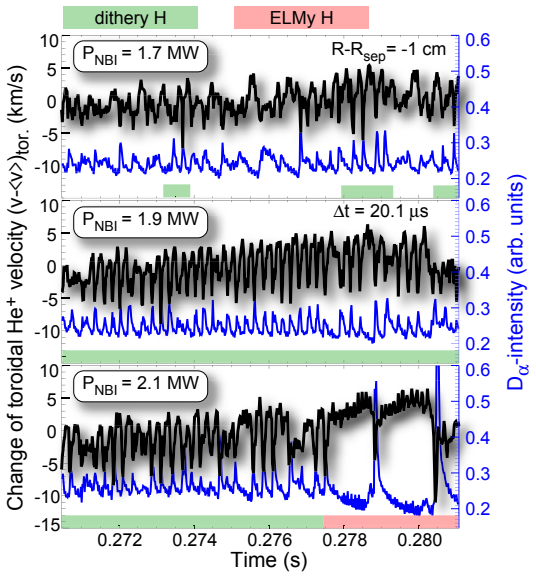

Figure 1: *Comparison of the toroidal He^+ flow dynamics with the D_α emission at different input power close to the L-H threshold.*

Work funded by RCUK Energy Programme and EURATOM

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Turbulence Suppression, Stiffness Reduction and Other Effects of Rotational Shear

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TOPIC: Momentum and particle/impurity transport, and impact of rotation on transport

Recent numerical work has demonstrated the effects that toroidal rotational shear can have upon the turbulence generated by background gradients in a fusion plasma, including the reduction of transport stiffness, the total suppression of turbulence and bifurcations to reduced transport states. We use nonlinear gyrokinetic simulations to show that all of these effects are in turn profoundly affected by the ratio q/ε where q is the magnetic safety factor and ε the inverse aspect ratio, which is equal to the ratio of the parallel flow gradient to the perpendicular flow gradient. The lower the value of q/ε, the higher the temperature gradients that can be achieved without driving turbulence (see Figure 1). However, at lower values of this ratio, this optimum temperature gradient, and the low-stiffness regime occur at a higher value of the toroidal flow shear, and thus may not be accessible in experiments. At higher values of q/ε, by contrast, the improvement in confinement that can be achieved not quite so dramatic, but since they occur at lower values of the toroidal flow shear they are accessible in current experiments.

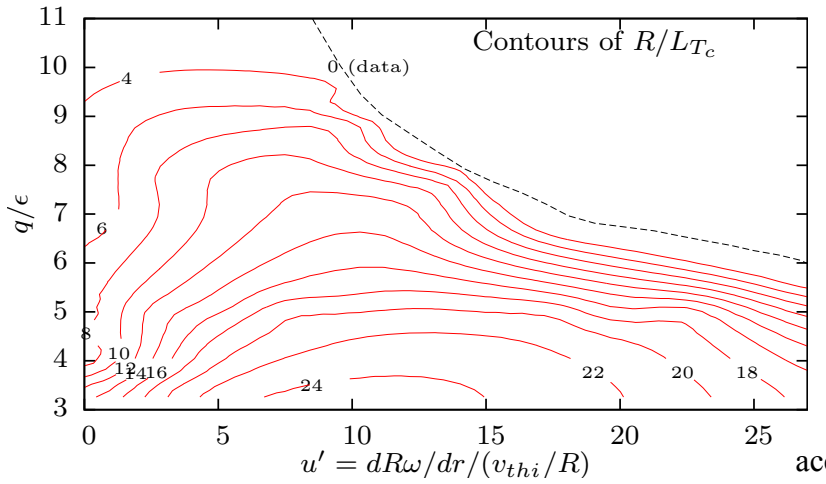

Figure 1: Contours of the nonlinear temperature gradient threshold for the onset of turbulence shown vs the ratio q/ε and the toroidal flow shear u'. At lower values of q/ε much higher temperature gradients can be reached without destabilising turbulence.

We present comparisons of these results with preliminary data obtained in the MAST experiment, using the new Beam Emission Spectroscopy (BES) diagnostic. We demonstrate good qualitative agreement in respect of the effects of the toroidal flow shear and q/ε between these experimental results and numerical results. We will also present similar comparisons with data obtained in the JET experiment. We present preliminary attempts to obtain quantitative agreement by simulating realistic experimental geometry.

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Spatio-Temporal Evolution of L→ H transition

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TOPIC: B) L-H transition and physics of transport in the pedestal

As recent experiments reveal that spatio-temporal structure of the interaction between turbulence and flows at L→H transition [1], we investigate the transition dynamics, using a one-dimensional predator-prey model which self-consistently describes time evolution of zonal flows (ZFs), mean flows (MFs), poloidal spin-up, and density and pressure profiles [2]. The model represents the physics of ZF and MF competition, turbulence suppression via E x B shearing, and poloidal flows driven by turbulence. Numerical solutions of the model show two kinds of the transition are possible. With slow power ramp up, the L→H transition occurs via I-phase that involves quasi-periodic oscillation. The I-phase appears as a nonlinear transition wave originating at the edge boundary, propagating inward. Locally, it exhibits the characteristics of a limit-cycle oscillation (LCO). On the other hand, with fast power ramp up, the I-phase is compressed into a single burst of ZF, leading to the transition without I-phase. Both EAST investigation [3] and the numerical model analyses consistently indicate the key role of ZF triggering L→H transition. As the rate of energy transfer from the turbulence into the shear flow becomes comparable to the energy input rate into the turbulence, the transition occurs. Poloidal flow appears predominantly neoclassical, except for thin layer, within pedestal, boundary.

The study of H→L back transition indicates that zonal flow excitation always occurs in the course of back transition. For slow power ramp-down, the discharge revisits an I-phase state during back transition. This suggests that so-called Type III ELMs observed during back transitions may, in fact, be the counterpart of the pre-transition LCO. For fast power ramp-down, a burst of ZF is observed. Hysteresis is observed, and the strength of the hysteresis in mean pressure gradient approximately linearly with Nusselt number for heat diffusivity, $Nu_p = \chi_{pre\text{-}tran}/\chi_{neo}$.

Recent studies on the EAST tokamak show that the edge zonal flows in a marginally subcritical plasma undergo both low frequency (sawtooth related) and high frequency modulation [4]. Model studies of the I-phase confirm the sawtooth-induced modulation of the coupled flow and turbulence system. Based on the hypothesis that the high frequency modulation originates from the arrival of core transport avalanches at the edge, we have explored the effect of white and colored noise (i.e. 1/f, as typical of avalanches) in the model heat source. Both types of noise can trigger transitions in case with constant, subcritical mean heat flux. Interestingly 1/f noise appears more effective for inducing transitions, on account of its higher temporal coherency. These results can explain observed instances of spontaneous sudden transitions, which occur in otherwise stationary I-phases.

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Density Peaking in Turbulence Simulations of Low-Collisionality C-Mod Plasmas

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TOPIC: D) Momentum and particle/impurity transport, and impact of rotation on transport

Experimental results from Alcator C-Mod have confirmed earlier AUG and JET findings that spontaneous peaking of the density profile in H-mode plasmas depends on collisionality. Previously reported nonlinear, 'full-radius' GYRO simulations [1] of low-collisionality, peaked-density H-mode plasmas in C-Mod generated a particle pinch that was produced exclusively by higher-k modes. Nonlinear simulations of AUG low-collisionality, peaked-density H-mode plasmas have a similar character [2], and detailed linear analyses [2,3] suggest that density peaking may be common in low collisionality plasmas. Here we increase the number of ion species in the simulations to determine whether the degree of hydrogenic density peaking has an isotope dependence or is influenced by the presence of impurity ions, and whether impurity density peaking depends on the species. The simulations include experimentally relevant levels of boron, and a 50/50 H/D mix. We find that the predicted deuterium density profile is slightly more peaked than hydrogen, the overall density peaking is very similar to pure deuterium simulations, and the boron impurity has no effect on hydrogenic density peaking. Low Z impurities (He & B) are predicted to have densities roughly as peaked as the electrons and hydrogen, while higher Z impurities (Ne, Ar, Fe, Mo) are increasingly more peaked. The ion temperature profile is varied in an attempt to align the predicted turbulent heat flux to the experimental transport analysis, and we find that the predicted density peaking is very weakly dependent on the turbulent power flow. The novel simulation procedure is very successful in producing robust predictions that are remarkably insensitive to temporal variations in the turbulent heat and particle fluxes. Each hydrogenic species is represented by two ions in each simulation (e.g. two D *and* two H); they differ only by having different density gradients, these offset each other so the total density for each species has the same shape as the electron density. Linear interpolation between the calculated particle fluxes (with R/L_{ni} as the independent variable) is used to estimate the density gradient that would produce no particle flux for each hydrogenic species (as required in steady state C-Mod plasmas), and the resulting R/L_{ni} is integrated to find the predicted density peaking.

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The dynamical coupling between gradients and transport

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TOPIC: A) Edge - SOL turbulence and transport

Using conditional probability techniques, the dynamic relation between the instantaneous density gradient and particle flux was studied using Langmuir probe data in tokamaks (JET, ISTTOK) and a stellarator (TJ-II). It was found that the size of turbulent flux events is minimized near the most probable density gradient [1]. These findings suggest that self-regulation is an important concept for the understanding of turbulent transport.

In the present work, we enhance this study further by analysing the full (instantaneous) two-dimensional probability function *p(flux,gradient)*, as well as its dynamic structure; here and in the following, the term "gradient" refers to the deviation from the most probable gradient. It is found that the parametric curves *(flux(t),gradient(t))* trace out "orbits" in *flux-gradient* phase space with a characteristic shape (lemniscate), as confirmed by a Hilbert analysis of the instantaneous phase. This characteristic behaviour may at least partly be explained using an eddy model for the edge fluctuations.

Selecting extreme events from the two-dimensional probability function *p(flux,gradient)*, and using radially distributed probe pins, it is observed that the large flux/gradient events are predominantly associated with *outward* propagating events (in the floating potential), regardless of the sign of the flux/gradient excursions. At JET, it was observed that such extreme events also have a temporal sequence (increasing gradient precedes flux burst; or flux burst precedes gradient reduction), which can be understood from the concept of profile self-regulation linking various radial positions.

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Numerical investigation of the turbulent perpendicular transport in the SOL of MAST

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TOPIC: A oral

The L-mode interchange turbulence in the Scrape Off Layer of the tight aspect ratio tokamak MAST is investigated numerically. The dynamics of the boundary plasma is studied using the 2D drift-fluid code ESEL, which has previously shown good agreement with large aspect ratio machines. After a successful validation of the code on a specific MAST shot, scans of various edge parameters, such as density, temperature and current, are numerically performed. These led to a detailed characterisation of the profiles, fluctuation level and statistics of the SOL density and temperature in MAST relevant operating regimes. In addition, we also discuss how the system changes when the length of the divertor leg is modified. This allows to identify the regime of operation of the Super-X divertor which will be implemented on MAST-Upgrade. The results obtained provide an insight that goes beyond the specificity of MAST and qualitatively agree with a number of experimental observations. In particular, a universal behaviour of the fluctuation statistics is found for disparate edge conditions. Furthermore, the density and temperature decay lengths are inversely proportional to the plasma current and the edge temperature, while they are rather insensitive to the edge density (not to be confused with the line averaged density).

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Effect of poloidal asymmetries on impurity peaking in tokamaks

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TOPIC: D) Momentum and particle/impurity transport, and impact of rotation on transport

Accumulation of impurities in the core of a fusion plasma has debilitating effect on fusion reactivity due to an increase in radiation losses and plasma dilution. Consequently significant effort has been put to find conditions in which accumulation in the plasma core can be avoided. Recent work noted that the impurity cross-field transport driven by electrostatic turbulence depends on the poloidal asymmetry of the impurities [1]. Poloidal impurity asymmetries are frequently observed in tokamaks arising due to various reasons, e.g. difference in impurity source location, toroidal plasma rotation, neoclassical effects or radio frequency (RF) heating.

In the present work we include the effect of the $\mathbf{E} \times \mathbf{B}$ drift of impurities on the turbulent transport, in the presence of poloidal asymmetries. In particular inboard impurity accumulation, induced by RF heating in the plasma core, is studied. The impurity transport is shown to be sensitive to the magnetic shear and changes sign for $s \gtrsim 0.5$ in the presence of inboard accumulation. The zero-flux impurity density gradient (peaking factor) turns out to be rather insensitive to collisions in both ion temperature gradient (ITG) and trapped electron mode (TEM) driven cases. The results suggest that the asymmetry (both the location of its maximum and its strength) and the magnetic shear are the two most important parameters which affect the impurity peaking [2].

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Impact of sheared flow on non-Gaussian (Lévy) plasma fluctuations

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Topic: A

There is a wealth of experimental evidence of the non-Gaussianity and long-range correlations of plasma fluctuations which suggests that fusion plasmas exhibit non-diffusive (scale invariant) transport. In particular, experimental observations of the edge turbulence in fusion devices show that in the Scrape of Layer (SOL) the nature of the cross-field transport is dominated by turbulence with a significant ballistic or non-local component where a diffusive description is improper. By comparing plasma edge density fluctuation PDFs from different types of fusion devices such as the linear device, spherical Tokamak, reversed field pinch, stellarator and several tokamaks similar observations were reported. All these PDFs have similar properties and exhibit a clearly skewed, non-Gaussian shape. It has also been observed that the statistical properties of the fluctuations show a near Gaussian character close to a velocity shear layer and many reports have shown that in the enhanced confinement modes (H mode), where a sheared flow is present the plasma turbulent fluctuations are significantly reduced and therefore the transport driven by turbulent fluctuations is decreased to a very low level where the so called transport barrier region is formed.

In this work we aim to elucidate on the effects of a sheared flow on the non-Gaussian (Lévy) plasma fluctuations. We have developed a simple model following an ensemble of charged particles in a shear-less slab geometry and in the presence of an external constant magnetic field where their equation of motion is described by a stochastic Langevin equation. The particles undergo a stochastic acceleration which represents the effect of plasma fluctuations. The statistical properties of the stochastic acceleration is chosen to be either of Gaussian or Lévy type. The impact of a sheared flow is introduced by the addition of a constant term to the velocities of the particles within a chosen boundary. This simple model allows for understanding the impact of a sheared flow on the plasma fluctuations satisfying different statistical properties. The results of our analysis for various conditions are presented.

Impurity transport due to electromagnetic drift wave turbulence

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Topic: D

In the view of an increasing interest in high β operation scenarios, such as hybrid scenarios for ITER the question of finite β effects on the impurity transport is a critical issue due to possible fuel dilution and radiative cooling in the core. Here, electromagnetic effects at finite β on impurity transport are studied through local linear gyro-kinetic simulations with GYRO [J. Candy and E. Belli, General Atomics Report GA-A26818 (2011)]; in particular we investigate the parametric dependences of the impurity peaking factor (zero-flux density gradient) and the onset of the kinetic ballooning modes (KBM) and micro-tearing modes (MTM) in spherical (NSTX) and standard tokamaks (AUG and JET).

Our results show that for the considered plasma parameters in JET Tokamak two possible modes can be unstable depending on the normalized electron pressure; ion temperature gradient (ITG) modes dominate in the region $\beta_e \leq 0.015$, while KBM dominate for $\beta_e \geq 0.015$. The KBM instability threshold depends on the plasma parameters, particularly strongly on plasma shape. The β_e scaling of the impurity peaking factor shows two branches in connection with the two branches of the unstable modes present. We find that electromagnetic effects even at low β can have significant impact on the impurity transport. In the ITG branch the peaking factor increases with β_e with strong charge dependence. This charge dependence increases as β_e increases, however, for heavy impurities with lower charge to mass ratio such as partially ionized tungsten, lower peaking factors with very little β_e dependence is observed. In the β range where the KBM is the dominant instability the impurity peaking factor is strongly reduced, with very little dependence on β and the impurity charge.

Also, in a comparative study we examined the parametric dependences of the impurity peaking factor between spherical and standard Tokamaks where the considered plasma parameters are taken from Refs. [1,2], respectively. In these references the MTM's are reported to be the dominant instability. The results of our analysis for two radial positions corresponding to $\rho_{tor} = 0.6$ and 0.8 are presented.

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A simple mechanism for rotation reversal in ohmic L modes

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TOPIC: C) **Momentum and particle/impurity transport, and impact of rotation on transport**

Rotation of L-mode plasmas is a complex issue, with many different effects having been observed. In general the L-mode rotation behaviour, unless there is a strong external source of momentum, is far less well understood than the rotation of H-mode discharges. H-mode rotation seems to be more robust, either because the H-mode is usually achieved at high heating power including external momentum input by beams or due to high rotation at the pedestal, which allows for a robust boundary condition for the rotation.
For plasmas with no obvious external momentum source spontaneous spin up poses a problem to transport theory as without initial rotation velocity or seed flow the momentum flux is zero everywhere and so no build-up of rotation, neither of net plasma rotation or of differential plasma rotation can take place.
While the most prominent source of plasma toroidal momentum is the tangential injection of neutral beams, there are several effects which allow for momentum input from the edge. None of these mechanism can so far explain the observed rapid transition from co to counter-rotation observed in Alcator C Mod and other devices when the edge density is increased in ohmic L-mode plasmas.

It has been suggested that turbulent momentum transport can lead to differential transport of positive and negative momentum fluctuations, thus leading to a differential rotation source, which can lead to spin up. This local momentum flux, which is generated in the plasma itself, cannot be expressed in terms of a transport term as it is neither proportional to the gradient of the velocity profile, e.g. to be expressed as a diffusion like term, nor to the velocity itself, e.g. a convective or pinch velocity like term. Its appearance in a transport equation is like a localised source.
Several experiments have tried to measure this effect, but it is notoriously difficult to separate from other sources of momentum and moreover only during spin up and spin down of the plasma it leads to measurable momentum fluxes out of the plasma. This Residual Stress exerts a zero net torque on the plasma but can create nonzero momentum fluxes. It is usually not captured by transport models. We here demonstrate in a simple transport model how RS can lead to rotation reversal.

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JET Intrinsic Rotation Studies

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In JET, intrinsic rotation has been studied in plasmas with Ohmic heating, ion-cyclotron radio-frequency (ICRF) heating and, lower hybrid current drive (LHCD). ICRF rotation measurements were done in two scenarios: minority heating [1] and mode conversion [2-3]. Recently, we focused on observations in ICRF heated ELMy H-mode plasmas with high normalised-beta [1]. Levels of intrinsic rotation measured in JET plasmas were found to be generally lower than expected from scaling laws that predict that rotation increases with normalised beta [4]. Experimentally several factors have been found to influence intrinsic rotation, such as fast ion losses and toroidal field ripple, suggesting that different physics mechanisms are at play to drive intrinsic rotation and that these should be taken into consideration when extrapolating to future devices. Toroidal field (TF) ripple, in particular, was found to have a significant effect on the intrinsic rotation of plasmas without momentum input [5]. JET results suggest that ITER intrinsic rotation, may be substantially less than what was previously predicted by the multi-machine rotation scaling of ref. [1] which was derived for co-current rotating plasmas.

In either L-mode or in H-mode, core counter-rotation is a common observation in JET plasmas. Intrinsic rotation profiles are often observed to change sign from co-rotation in the edge to counter-rotation in the core. The possible reasons for core-counter rotation were investigated. Some factors clearly influencing the direction of rotation are heating details, such as ICRF resonance position, plasma current and MHD activity. In view of models of turbulent momentum transport that predict that changes in rotation might be correlated to gradients of bulk plasma parameters, the possible correlation of JET core rotation with electron and ion temperatures and plasma density has been investigated. For ICRF and for Ohmic heated cases, the velocity in the counter-current direction generated in the core was found to be proportional to the ion temperature difference in the core divided by the plasma current, with a constant of proportionality, of the order of 10 km s^{-1} MA keV^{-1} [6].

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Electron and Ion Channel Transport Barriers: Initiation and Dynamical Co-evolution and their implications for burning plasmas

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TOPIC: Turbulence and Transport at the transition region between core and edge (poster)

Simple dynamical models have been able to capture much of the dynamics of the transport barriers found in many devices, however an open question has been the often disconnected nature of the electron thermal transport channel sometimes observed in the presence of a standard ("ion channel") barrier. By adding to a simple barrier model an evolution equation for electron fluctuations we can investigate the interaction between the formation of the standard ion channel barrier and the somewhat less common electron channel barrier. Barrier formation in the electron channel is even more sensitive to the alignment of the various gradients making up the sheared radial electric field then the ion barrier is. Electron channel heat transport is found to significantly increase after the formation of the ion channel barrier but before the electron channel barrier is formed. This increased transport is important in the barrier evolution. Parameters relevant to ITER like devices will be investigated.

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Effects of 3D magnetic fields on plasma rotation in RFX-mod tokamak plasmas: experimental results and modelling

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TOPIC: (d) Momentum and particle/impurity transport, and impact of rotation on transport

Understanding the influence of 3D magnetic fields on plasma rotation is an important challenge for fusion plasma science. 3D magnetic fields are always present in fusion machines as intrinsic magnetic field errors, due for example to coil misalignments or other machine imperfections. Or they can be intentionally applied through non-axisymmetric coils, for example in tokamaks to suppress MHD instabilities such as resistive-wall modes (RWM) and to mitigate edge-localized modes, by creating a stochastic field layer at the plasma edge. One important effect of 3D magnetic fields is their modification of B along a magnetic field line. Toroidal forces arising from such symmetry breaking generate a toroidal viscous torque that can affect significantly the toroidal plasma rotation. Sufficiently high toroidal plasma rotation has been shown to be beneficial for a number of reasons, such as the improvement of energy confinement through turbulence suppression [1], tearing mode [2] and RWM stabilization [3], and the screening of resonant magnetic perturbations [4].

In the last years, the RFX-mod reversed-field pinch experiment has been run also in tokamak configuration. Plasmas with q at the edge below 2 have been sustained thanks to the active feedback control of the m=2, n=1 RWM, using the system of 192 active coils available in this machine [5,6]. In such experiments a clear effect of non-resonant 3D magnetic fields on the flow behaviour has been observed. Both the toroidal and poloidal components of the plasma flow have been measured in these plasmas with a multi-chord passive Doppler spectroscopy diagnostic, while an accurate detection of MHD activity has been provided by a large set of radial, toroidal, and poloidal field sensors. It has been observed that, as the 2/1 RWM grows in amplitude, the toroidal flow at first decelerates and then inverts its sign from counter to co-I_P direction. The 2/1 mode amplitude and phase has been also feedback controlled at fixed values and the effect on rotation has been studied systematically. In this work, we model the physical mechanisms which can play a role on momentum transport in these plasmas, such as the neoclassical toroidal viscosity force, the radial electric field due to stochasticity induced at the plasma edge, and the friction force due to neutrals coming from the wall. All these mechanisms play an important role in the various situations mentioned above also in larger tokamaks. Note that the RFX-mod experiment has a simple geometry - circular cross section - and a wide m/n spectrum of 3D magnetic fields can be applied through magnetic feedback. For these reasons, it can give precious contributions to the detailed comprehension of the basic physics mechanisms responsible for the transport of momentum and other quantities in tokamaks.

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Recent Results and Prospects for Core Fluctuation Measurements on TCV

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Cross magnetic field transport of energy and particles in tokamak plasmas is larger than expected from theoretical considerations. It is believed that this is due to the presence of micro-instabilities and turbulence. Diagnostic techniques capable of making measurements of core turbulence are necessary for the advancement of magnetic fusion. Correlation Electron Cyclotron Emission (CECE) measurements and Phase Contrast Imaging (PCI) measurements can elucidate the statistical properties of core electron temperature fluctuations and electron density fluctuations, respectively, in hot, dense magnetised plasma. Both CECE and PCI have been used successfully in magnetic fusion experiments.

CECE measurements provide measurements of the statistical properties of the poloidal component of the turbulent wave vector (k_θ) and its radial correlation length. If the CECE radiometer is absolutely calibrated then an absolute measurement of the amplitude of the electron temperature fluctuations can be obtained.

A PCI diagnostic is a laser based system that generates an image of line-integrated density fluctuations on a plane perpendicular to the beam. Plasma waves scatter the beam inducing phase variations which are transformed into amplitude variations by means of a phase-contrast filter. On TCV a novel application of this technique is being developed, in which the beam is launched tangentially, i.e., nearly parallel to the magnetic field. The tangential geometry in combination with spatial filtering makes it possible to select a specific fluctuation wave-vector direction and to localize the measurement to a small fraction of the plasma minor radius. By varying the orientation of the filter, different regions from the core to the edge can be imaged, each with a specific fluctuation wave-vector orientation ranging from purely radial to purely poloidal.

A two channel CECE radiometer has been installed on TCV. This radiometer has a line of sight perpendicular to the magnetic field. The antenna pattern of this radiometer limits resolution to $k_\theta < 112$ m^{-1} or $k_\theta\rho_s < 0.3$ at 500 kHz. In this configuration a series of measurements has been made of the k_θ spectrum as a function of the poloidal angle as well as of plasma density, the measurements being made always on the same flux surface. The results and analysis from this set of measurements will be presented.

A 30 channel tangential PCI (TPCI) system based on a CO_2 laser has been installed on TCV and preliminary data has been obtained. The spatial bandwidth of the system in its preliminary configuration lies in the range $260 < k < 675$ m^{-1}. Measurements of fluctuation spectra at different plasma triangularities and at different values of ν_{eff} have been obtained. Initial analysis of these measurements will be presented.

Experimental runs to obtain measurements of the radial correlation length of the turbulence spectra are extremely time consuming with the two-channel CECE radiometer. Four additional channels have recently been acquired and are being installed on TCV at this time. This upgrade should reduce the required number of shots for a radial scan by a factor four. It is also planned to move the radiometer to a high resolution antenna that can be scanned both in the poloidal plane and in the toroidal plane [3]. The higher gain of this antenna should allow access to $k_\theta < 174 m^{-1}$ or $k_\theta\rho_s < 0.5$ at 500 kHz. It is expected to have a dedicated RF section for the upgraded CECE radiometer, separate from that of the main radiometer used for bulk temperature profile measurements. In addition the signal conditioning electronics and the data acquisition will be optimised in an effort to improve diagnostic performance. The proposed upgrades will be described in detail.

The TPCI diagnostic will be fully commissioned by improvements to its collection optics, extending the spatial bandwidth to the design range $75<k<6000$ m^{-1}. Upgrades to the laser power and to the detector array will optimize the system's sensitivity and wave-number coverage. The projected upgrades to the TPCI system will be described in detail.

Impact of non-thermal particles on the poloidal variation of high-Z impurity density in tokamak plasmas

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TOPIC: D) Momentum and particle/impurity transport, and impact of rotation on transport (poster)

In the Alcator C-Mod tokamak, strong, steady-state variations of molybdenum density within a flux surface are routinely observed in plasmas using hydrogen minority ion cyclotron resonant heating. Parallel impurity transport theory is extended to account for effects due to fast ions and shown to agree quantitatively with measured impurity density asymmetries [1]. Impurity accumulation on the low-field side (LFS) of a flux surface can be explained by the centrifugal force [2], and C-Mod results show the first observation of intrinsic rotation generating a substantial, $n_{z,cos}/\langle n_z \rangle \sim 0.3$, in/out asymmetry. The accumulation of impurity density on the high-field side (HFS) of a flux surface is shown to be driven by a poloidal potential variation sustained by magnetically trapped non-thermal, cyclotron heated minority ions [3], with $n_{cos}/\langle n \rangle \sim -0.2$ having been observed. Results from Alcator C-Mod H-mode and I-mode plasmas demonstrate that HFS accumulation occurs near the minority resonance layer when heating is on axis or on the LFS. When ICRH is deposited on the HFS, magnetic trapping of minority ions is reduced and LFS accumulation due to the centrifugal force dominates. The presence of background impurities are also shown to play an important role, leading to dependence of $n_{z,cos}/\langle n_z \rangle$ on Z_{eff}. Sensitivity of parallel transport of high-Z impurities to small, $e\phi/T_e < 1\%$, poloidal variations in the electrostatic potential due to non-thermal ions is demonstrated, an effect which may also be important in plasmas using strong neutral beam heating. Prior asymmetry studies in beam-heated plasmas on JET [4] and ASDEX-U [5] are discussed in context of the extended parallel transport theory that includes non-thermal ions. Initial investigations into the impact of poloidal asymmetries on anomalous radial impurity transport is also discussed.

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Response of Electron-scale Turbulence and Thermal Transport to Continuous ExB Shear Ramping-up in "No Man's Land" in NSTX

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TOPIC: **Turbulence and Transport at the transition region between core and edge**

Microturbulence is considered to be a major candidate in driving anomalous transport in fusion plasmas, and the equilibrium ExB shear generated by externally driven flow can be a powerful tool to control microturbulence in future fusion devices such as FNSF and ITER [1]. Here we present the first observation of the change in electron-scale turbulence wavenumber spectrum (measured by a high-k scattering system [2]) and thermal transport responding to continuous ExB shear ramping-up in "No Man's Land" in NSTX NBI-heated L-mode plasmas (r/a ~ 0.67-0.73). This ramping-up of ExB shear results from a plasma spinning-up due to a two-phased NB injection. It is found that while linear stability analysis using the GS2 gyrokinetic code [3] shows that the maximum linear growth rate ($\gamma_{\max}$) for ETG modes far exceeds the observed ExB shearing rate (ω_{ExB}) in the measurement region of the high-k scattering system, the unstable ITG modes can be susceptible to ExB shear stabilization ($\omega_{ExB}/\gamma_{\max} < 1$ where ω_{ExB} uses the Waltz-Miller definition for ExB shearing rate [4]). We observed that as the ExB shearing rate is continuously ramped up in the high-k measurement region, the ratio between the ExB shearing rate and the maximum ITG mode growth rate continuously increases and the maximum power of the measured electron-scale turbulence wavenumber spectra decreases. Meanwhile, both the electron and ion thermal transports are also reduced as long as MHD activities are not important. These observations are consistent with that some of the observed electron-scale turbulence is nonlinearly driven by the ion-scale turbulence and its power decreases as the ion-scale turbulence is progressively suppressed by the ExB shear. Local nonlinear gyrokinetic ITG simulations shows that ExB shear indeed reduces both electron and ion thermal transports. However, with experimental level of ExB shear the predicted electron and ion heat fluxes are larger than those from transport analysis, which is in contrast to conventional tokamaks where heat flux is consistently under-predicted by gyrokinetic simulations in the transition region between core and edge [5].

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Non-Diffusive Heat Transport, Rotation Reversals and Energy Confinement Saturation in Alcator C-Mod Ohmic Plasmas

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TOPIC: D) Momentum and particle/impurity transport, and impact of rotation on transport (oral)

Recently, the connection among rotation reversals, energy confinement saturation (the transition between the linear Ohmic confinement, LOC and saturated Ohmic confinement, SOC, regimes) and changes in underlying turbulence has been demonstrated. Examination of the rotation reversal results and a large body of confinement saturation observations suggests that there is a critical value of the collisionality where these effects transpire. Also occurring with the rotation reversals and the LOC/SOC transition is a saturation of the electron density profile peaking. There are two other phenomena which appear to be related and occur at the LOC/SOC transition: a transformation from non-diffusive, non-local to diffusive heat transport and a change from symmetric up/down edge impurity density profiles to up/down asymmetric. Heat transport was investigated by means of rapid edge cooling from impurity injection by laser blow-off, and following the electron temperature profile evolution from electron cyclotron emission. In the high density SOC regime, there is 'normal' diffusive heat transport, with a drop in the core temperature lagging the edge cooling by about an energy confinement time. Also with SOC, the core rotation is counter-current, and there is a significant up/down edge impurity density asymmetry. At low density in the LOC regime, the core electron temperature *increases* (on a faster time scale) following the edge cooling, indicating the workings of a convective heat pinch or transient ITB. The core rotation with LOC is co-current and the edge impurity density profile is up/down symmetric. Rotation reversal, the transformation from non-diffusive to diffusive heat transport, the switch of edge impurity density profiles from up/down symmetric to asymmetric and changes in turbulence have all been observed dynamically during a single discharge with a density ramp to change the collisionality. These empirical results unify a large body of previously seemingly unrelated phenomena. These results may be unified with the following *ansatz*: at low collisionality in the LOC regime, the underlying turbulence is dominated by trapped electron modes, the heat transport in non-diffusive and the core rotation is directed co-current; at high collisionality in the SOC regime, ion temperature gradient modes prevail, heat transport is diffusive, the rotation is counter-current and the density profile peaking saturates.

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Torque sources in Tore Supra Ohmic plasmas due to toroidal field ripple

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TOPIC: Momentum and particle/impurity transport, and impact of rotation on transport (3D effects)
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The torque sources generated by the toroidal field ripple, $\delta=(B_{max}-B_{min})/(B_{max}+B_{min})$, and their effect on plasma rotation are studied on the Tore Supra tokamak using an orbit following Monte Carlo code ASCOT. A set of five discharges from a ripple scan are analysed for the thermal ion ripple torque. In these experiments the direction of the toroidal rotation was observed to change from co-current to counter current with increasing ripple indicating the presence of a large ripple induced counter current torque [1]. The ripple scan covers the ripple magnitudes from about δ=0.5% to δ=5.5% and it was performed by adjusting the plasma volume while keeping q_{95} constant.

Thermal ion trajectories are significantly modified by the presence of the radial electric field which is this modelling work is taken from the Doppler reflectometry measurements. The sensitivity of the thermal ion ripple torque estimates to the radial electric field are studied and used to get error estimates for the calculated torque sources. Furthermore, the relatively small torque contribution from the diagnostics neutral beam (~400 kW), that is used for measuring the toroidal rotation is also evaluated and its effect on the rotation measurement is estimated. The figure 1 shows the total ASCOT calculated torque separated in the neutral beam (NB) contribution and thermal ion ripple contribution for a discharge where the edge rotation is slightly in counter current direction [1]. It is shown that the calculated torque sources are in good qualitative agreement with the experimental data.

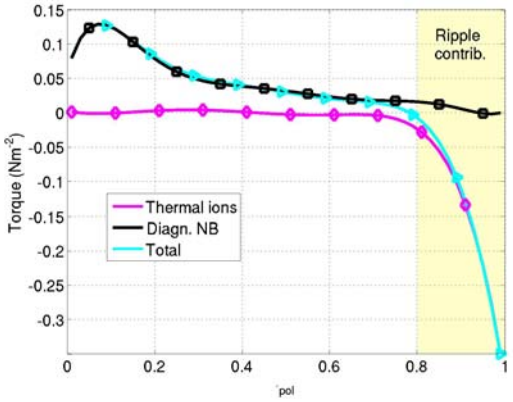

Figure 1 ASCOT calculated thermal ion ripple torque and diagnostics NB torque profiles for #43318 (δ=1.5%). NB torque is roughly 0.4 Nm (co-current) whereas the thermal ion ripple torque is about -2 Nm (counter-current).

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On the relevance of uncorrelated sequencies of Lorenzian pulses for the interpretation of turbulent fluctuation data at the edge of magnetically confined toroidal plasmas

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Recently, it has been proposed that the turbulent fluctuations measured in a linear plasma device could be described as a superposition of uncorrelated Lorentzian pulses with a narrow distribution of durations, which would provide an explanation for the reported quasi-exponential power spectra. Here, we study the applicability of this proposal to edge fluctuations in toroidal magnetic confinement fusion plasmas. For the purpose of this analysis, we introduce a novel wavelet-based pulse detection technique that offers important advantages over existing techniques. It allows extracting the properties of individual pulses from the experimental time series, and quantifying the distribution of pulse duration and energy, as well as temporal correlations. We apply the wavelet technique to edge turbulent fluctuation data from the W7-AS stellarator and the JET tokamak, and find that the pulses detected in the data do not have a narrow distribution of durations and are not uncorrelated. Instead, the distributions are of the power law type, exhibiting temporal correlations over scales much longer than the typical pulse duration. These results cast doubt on the proposed ubiquity of exponential power spectra in this context.

Modification of turbulent transport with continuous variation of flow shear in the Large Plasma Device

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External continuous control over azimuthal flow and flow shear has been achieved in a linear plasma device for the first time allowing for a careful study of the effect of flow shear on pressure-gradient-driven turbulence and transport in in the edge of the Large Plasma Device (LAPD). The flow is controlled using biasable iris-like limiters situated axially between the cathode source and main plasma chamber. LAPD rotates spontaneously in the ion diamagnetic direction (IDD); positive limiter bias first reduces, then minimizes (producing a near-zero shear state), and finally reverses the flow into the electron diamagnetic direction (EDD). Degradation of particle confinement is observed in the minimum shearing state and reduction in turbulent particle flux is observed with increasing shearing in both flow directions. Near-complete suppression of turbulent particle flux is observed for shearing rates comparable to the turbulent autocorrelation rate measured in the minimum shear state. Turbulent flux suppression is dominated by amplitude reduction in low-frequency (> 10kHz) density fluctuations and a reduction in the radial correlation length. An increase in fluctuations for the highest shearing states is observed with the emergence of a coherent mode which does not lead to net particle transport. Magnetic field is varied in order to explore whether and how field effects transport modification. Calculations of transport equations are used to predict density profiles given source and temperature profiles and can show the level of transport predicted to be necessary in order to produce the experimental density profiles observed. Finally, the variations of density fluctuations and radial correlation length are fit well with power-laws and compare favorably to simple models of shear suppression of transport.

Topic: A) Edge - SOL turbulence and transport
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Subcritical turbulence, critical balances and transport scalings

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TOPIC: Momentum and particle/impurity transport, and impact of rotation on transport

Differential rotation is known to suppress linear instabilities in fusion plasmas. However, even in the absence of growing eigenmodes, subcritical fluctuations that grow transiently can lead to sustained turbulence. Here transient growth of electrostatic fluctuations driven by the parallel velocity gradient (PVG) and the ion temperature gradient (ITG) in the presence of a perpendicular ExB velocity shear is considered. The maximally simplified case of zero magnetic shear is treated in the framework of a local shearing box. There are no linearly growing eigenmodes, so all excitations are transient. The maximal amplification factor of initial perturbations and the corresponding wavenumbers are calculated as functions of $q/\boldsymbol{\varepsilon}$ (=safety factor/inverse aspect ratio), temperature gradient and velocity shear. Analytical results are corroborated and supplemented by linear gyrokinetic numerical tests. For sufficiently low values of $q/\boldsymbol{\varepsilon}$ (<7 in our model), regimes with fully suppressed ion-scale turbulence are possible. [1] For cases when turbulence is not suppressed, an elementary heuristic theory of subcritical PVG turbulence leading to a scaling of the associated ion heat flux with q, $\boldsymbol{\varepsilon}$, velocity shear and temperature gradient is proposed; it is argued that the transport is much less stiff than in the ITG regime. The general strategy for deriving such scaling theories is also discussed. It is based on balances between the relevant time scales: driving, nonlinear, parallel streaming, shearing – this is a generalisation of the concept of critical balance originating from MHD and fluid turbulence theories [3]. The key feature of this approach is that the parallel correlation scale of the turbulence is not infinite and, via the "critical balance" between the parallel streaming time and other time scales, determines the outer scale of the turbulence and, therefore, the scaling of transport [2]. Finally, the extent to which these theoretical considerations are corroborated by turbulence measurements is discussed [4].

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Measurements of transport parameters in the near SOL by a diamond-coated probe head

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TOPIC: A) Edge - SOL turbulence and transport

Probe arrays still offer the only possibility to measure various transport parameters localized, although we have to put up with more or less perturbing the plasma. In tokamaks probe arrays have been successfully used by many authors in the far and medium Scrape-Off Layer (SOL) (see e.g. [1,2,3,4]). Radial particle transport, Reynolds stress and radial transport of poloidal momentum can be determined in this way. Although highly desired, measurements inside to the Last Closed Flux Surface (LCFS) have so far not yet been ventured due to the strong particle bombardment in this region, leading to severe damages of the probe pins as well as of the probe head as such. Usually the probe heads and pins are manufactured from graphite, which is susceptible to sputtering and evaporation. An additional unwelcome effect of the sputtering is that the sputtered-off electrically conductive graphite deposits on the material which isolates the probe pins from the probe head (usually boron nitride), thus leading to short circuits of the probe pins.

We have tested a graphite probe head coated by a layer of electrically isolating UltraNano-Crystalline Diamond (UNCD) by the KOMET RHOBEST Company in Innsbruck, utilizing a Chemical Vapour Deposition (CVD) method. The thickness of the UNCD layer was in the range of 10 to 15 μm. The UNCD coating extended over the front side and up to about 3 cm towards the rear side of the probe head. One probe head carrying 3 graphite pins was mounted on the reciprocating probe manipulator of the Experimental Advanced Superconducting Tokamak (EAST). The floating potential, the poloidal and radial electric field component and the Reynolds stress were determined up to a distance of 15 mm inside the LCFS in high confinement regimes. In a similar discharge, another 5-tip Langmuir-Mach probe coated by diamond can successfully provide measurements for plasma density, temperature, plasma potential, as well as toroidal rotation near the separatrix.

A very important preliminary result was that the UNCD coating prevented the sputtering of graphite from the probe head and the subsequent coating of the BN isolation by a layer of conductive graphite between probe pins and probe head almost completely.

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Nonlinear simulations of parallel shear flow instability in the tokamak edge

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TOPIC: **Turbulence and Transport at the transition region between core and edge (recently dubbed no man's land)**

The spontaneous stratification of the tokamak edge makes it an intrinsic potential source of instabilities. We investigate numerically the possibility of a shear-induced instability triggered by the radial gradient in parallel Mach number resulting from sheath acceleration on limiter plates, and whose presence was infered in Tore Supra to explain specific asymmetries in turbulence measurements. The simulations are performed in a geometry similar to that of the tokamak Tore Supra, with circular cross-section and axisymmetric limiter. Three-dimensional, fully nonlinear simulations of a reduced fluid model with adiabatic electrons show the possible growth of the instability in the shear layer between the core and the Scrape-Off Layer, and illustrate its nonlinear development. These simulations highlight the strong dependence on core rotation of the threshold of the instability, and of the spatial envelope of the fluctuations in the poloidal cross-section.

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Energetic Consistency and Symmetry in Gyrokinetic Field Theory

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The modern theory of gyrokinetics is briefly reviewed. Casting it as a field theory guarantees exact energy and toroidal momentum conservation at any level of ordering, which is necessary to treat a turbulent system in statistical saturation in which most of the degrees of freedom do not correspond to instabilities. It is also necessary for reliable global simulations of toroidal momentum transport. Dynamics is described in terms of a Lagrangian with canonical structure – dependent field variables appear only in the time component. The gyrokinetic and associated field equations are derived from the same Lagrangian by varying gyrocenter coordinate positions and field amplitudes. Energetic consistency follows from the general symmetry implied by the support of the equations by the Lagrangian, via the Noether theorem. Both local and global conservation forms are given. Conversion from canonical to plasma momentum uses the charge conservation equation which follows from continuity. The specific role of the time-dependent polarisation current is emphasised. All terms share the same symmetry properties, not only the lowest order ones; an example using a Lagrangian with finite ExB Mach number including third-order drift effects is given. Symmetry is dynamical/statistical, not spatial, and is evaluated using the PDF of zonal averages over a saturated turbulent state. Symmetry results from both local and global models are presented.

Overview of Intrinsic Rotation Drive Mechanisms in Fusion Plasmas

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TOPIC: D invited speaker

Toroidal rotation is observed to spontaneously develop in fusion devices, even in the absence of any externally applied momentum input, a phenomenon that has been dubbed spontaneous or intrinsic rotation. Since the applied torque in future burning plasmas such as ITER is expected to be relatively small compared to many of today's tokamaks, the study of intrinsic rotation has been an especially active area of research in the last decade. Significant effort has been devoted to elucidating the physics mechanisms responsible for intrinsic rotation, and applying such knowledge to predict, and ultimately optimize the rotation in future devices. Models to explain the generation of intrinsic rotation range from turbulent processes to orbit loss, and experimental evidence exists to support multiple mechanisms contribute to the formation of the intrinsic rotation profile. Many devices have reported strong correlations between the intrinsic drive and pedestal gradients, and such gradients have been shown to result in contributions to the toroidal angular momentum balance via the turbulent Reynolds stress. Similarly, an edge rotation layer has been observed in the toroidal rotation at the separatrix, which is semi-quantitatively consistent with thermal ion orbit loss. A review of experimental observations of intrinsic rotation and its associated drive will be reported, including modifications to the intrinsic rotation due to electron cyclotron heating, the interaction of the intrinsic drive with non-axisymmetric fields and abrupt reversals in the rotation with changes in density (seemingly related to transitions between ion temperature gradient and trapped electron mode turbulence). In addition, the scaling of the intrinsic drive to ITER will be discussed, including an assessment of its relative importance in defining the rotation profile together with the potential impact on ITER performance.

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H-mode characterization for dominant ECRH and comparison to dominant NBI heating – modeling results

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Present day fusion experiments are heated primarily by neutral beam injection (NBI). Depending on the plasma temperature and beam energy this method deposits roughly half the heating power to the electrons and half to the ions. Future plasma experiments like ITER or DEMO will be predominately electron heated. This is due to the higher particle energy of the NBI systems and the increased use of electron cyclotron resonance heating (ECRH) and alpha particle heating.

The ECRH system at ASDEX Upgrade was recently upgraded and can now provide up to 3.9 MW of electron heating power. This, in combination with the broad range of high temporal and radial resolution diagnostics available at ASDEX Upgrade offers the opportunity to analyze the influence of different ratios of electron to ion heating on important plasma parameter like confinement, kinetic profiles and radial heat transport coefficients. Experiments have been performed in high density H-modes with heating powers between 3 and 5 MW, which is about twice the H-mode threshold [1]. The total heating power was kept constant throughout the discharge, while the fraction of NBI heating to central ECRH was stepwise varied from 0% to 100% to analyze the influence of different heating mixes on global and local plasma parameter.

The analysis and the modeling of the different heating phases in these discharges by various codes are presented: An interpretative heat transport analysis is done with the ASTRA code package [2]. The electron and ion temperature and the electron density are modeled with the trapped gyro-Landau fluid transport model (TGLF) within ASTRA. Microturbulent instabilities, which are expected to be dominant and produce turbulent transport in these plasmas, are investigated with the gyrokinetic code GS2. The importance of different stabilising and destabilising terms in the calculation are analysed with respect to their impact on the differences between the heating schemes.

[1] F. Sommer et al. accepted by Nuclear Fusion
[2] G. V. Pereverzev and Y. P. Yushmanov, IPP Report 5/42 (August 1991)

Title :

Rotation of Tokamak-Plasmas out of Mechanical Equilibria, in Absence of External Torques.

Authors :

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TOPIC : D) Momentum and particle/impurity transport, and impact of rotation on transport

Text :

Rotation of tokamak-plasmas, not at the mechanical equilibrium, is investigated utilizing a theorem of thermodynamics, established by Prigogine. This theorem, suitably applied to toroidally confined plasmas, suggests that the global barycentric rotations of the plasma, in the toroidal and poloidal directions, are pure reversible processes. In case of negligible viscosity and by supposing the validity of the balance equation for the internal forces, we show that the plasma, even not in the mechanical equilibrium, may freely rotate as a rigid body in the toroidal direction with an angular frequency with an angular frequency, which may be higher than the neoclassical estimation. In addition, its toroidal rotation may cause the plasma to rotate globally in the poloidal direction at a speed faster than the expression found by the neoclassical theory. The eventual configuration is attained when the toroidal and poloidal angular frequencies reaches the values that minimize dissipation.

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Observation of Resistive Interchange Modes in a reversed-field pinch plasma

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Quasi-coherent high frequency magnetic activity has been detected to resonate at the edge region of RFX-mod reversed-field pinch plasma.
Experimental characterization of time and space periodicities of the modes reveals high frequency values around 100 kHz, high toroidal mode numbers (n>20) and a poloidal mode number m=1. These results have been performed by means of highly resolved in-vessel edge and insertable magnetic diagnostics.
Although the saturated energy spectrum of the measured modes is expected to be highly nonlinear, it is found that the spectral mode properties are in good agreement with the predictions of a linear resistive magnetohydrodynamic stability analysis.
The modes have been recognized as the first clear experimental evidence of the presence of resistive interchange instabilities (*g*-modes).
Finally, since these modes are expected to be responsible for magnetic field ergodization and enhanced diffusion and transport in RFP plasmas, some discussions on this issue are presented.

On the generation of convective cells of like-sign of vorticity in strong radial temperature gradients

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TOPIC: D (Momentum and particle/impurity transport)

Large scale cuasi-coherent structures of convective flow are supposed to be excited in the confinement region in tokamak in response to high radial temperature gradients. Even if they are manifested as intermittent events they have strong effect on the heat and angular momentum transport. At the onset they induce a fast increase of the poloidal rotation as the envelope of their peripheric velocity and this, via neoclassical polarization due to trapped ions, can be sufficient to reverse the toroidal rotation [1].

At stationary equilibrium the plasma can have sheared poloidal rotation due either to the neoclassical effect (given by the gradient of the temperature) or to a zonal flow generated by the k-space condensation from drift-wave turbulence. Both are sheared velocities with equivalent gradient of the toroidal component of the vorticity, $\omega(r)$. The stability of profiles of vorticity is examined to identify the growth of instability of breaking the annular (poloidally-axisymmetric) geometry with generation of independent rolls of convection. Three aspects are examined:

1. the role of the radial extension of the annular region of initial flow. This is because of the suggestion (coming from non-neutral plasma) that narrow layers are more unstable and generate many individual like-sign vortices which coalesce into a final small number of them
2. the role of the profile of the vorticity. This is because of the suggestion (coming from fluid experiences) that a local depression of the vorticity profile induces instability to azimuthal modes with low poloidal wavenumber
3. initial phase of hot plasma streams

It is found that the rate of growth of the nucleation instability which breaks the poloidal flow and generates isolated, like-sign cells of convection is marginally sufficient to trigger a significant neoclassical polarization effect. By contrast the streamers are faster and play the same role as in the basic bifurcation conduction-convection of the Rayleigh-Benard instability.

[1] F. Spineanu, M. Vlad, *A model for the reversal of the toroidal rotation in tokamak*, Nuclear Fusion 2012 (in print).

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Electromagnetic turbulent structures features in the edge region of toroidal plasma configurations

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Filamentary structures elongated in the magnetic field line direction have been detected in magnetized plasmas ranging from laboratory, including thermonuclear fusion devoted experiments, to astrophysical ones.
A special attention is paid to the study of turbulent features characterizing edge plasmas of toroidal devices for magnetic plasma confinement, where this represents a hot topic due to the role played by coherent structures in contributing to the transport of particles and energy.

Recently an increasing interest has been devoted also to the study of the field-aligned features of these filamentary plasma structures, including both their electrostatic and electromagnetic properties. New information is then provided beyond the standard cross-field characterization, and direct measurement of associated parallel current density and vorticity is added.

In this respect a strong experimental effort is in progress in order to provide accurate information on structure features and to gain insight on their dynamics and ultimately on their driving mechanisms. In particular a direct observation of current density filaments associated to the so called “blobs” or turbulent structures has been performed in the edge region of the RFX-mod reversed field pinch device, where drift kinetic Alfvén structures have been identified. Similar filaments have been observed also in the TORPEX experiment, a simple magnetized toroidal plasma, where blobs originated by ideal interchange waves. In this last case, for the first time the cross-field map of the parallel current density in the filaments has been revealed. Similar investigations are in progress in the edge region of the TJ-II stellarator experiment, where a range of plasma beta and different plasma equilibria can be explored.

Within this framework aim of this contribution is to present a comparison of electromagnetic properties of turbulent structures, exploiting the complementarity of different magnetic configurations. The presented data come from magnetic confinement devices including the plasma device TORPEX, characterized by open field lines, and the hotter plasmas of fusion devoted experiments represented by the TJ-II stellarator and RFX-mod, which can be operated with both reversed field pinch and ohmic tokamak configurations.
An original diagnostic concept, providing simultaneously high time resolution direct information on current density and vorticity, has been applied among different configuration in order to evidence common features of the filamentary structures and their relationship with specific dominant instabilities. Comparison will be performed in terms of the average structure features, of the electromagnetic fluctuations characteristic time scales and of their relationship with the local magnetic topology.

New technique for the accurate calculation of transport profiles in modulation experiments

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Transport codes provide a classical way to infer the profile of transport coefficients in fusion plasmas: assuming the validity of the advection-diffusion model and given functionals for the transport coefficient profiles, the free parameters in these functionals are iteratively adjusted to best reproduce the measurements. Unfortunately, this does not tell the true accuracy of the reconstructed profiles. This work introduces a new technique for the case of modulation experiments [1], the matrix approach (MA), which avoids any *a priori* constraint of the profiles, and computes them by simply inverting a 2D matrix. It provides the uncertainty on the reconstruction by a controllable smoothing of the experimental data, instead of the *ad hoc* regularization of the profile of transport coefficients by the *a priori* choice of functionals for the profiles. A relevant consequence is that transport profiles of different plasmas can be quantitatively compared, if modulation experiments are performed on all of them. In this work we present, as an example, a modeling of published JET data of momentum transport, corresponding to three discharges that share the same initial equilibrium state. While an analysis of the data by a transport code suggests that all three cases share nearly the same transport coefficients [2], the MA rules this out, within the respective error bars. On the other hand, including in the analysis also a residual stress term, on top of advective and diffusive contributions to the flux, greatly improved the agreement with the data, allowing the whole dataset to be modeled with just one common set of coefficients.

[1] D.F. Escande and F. Sattin, Phys. Rev. Lett. **108**, 125007 (2012)

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Overview of Turbulence and Transport in the Core-Edge Transition Region

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TOPIC: C invited review speaker

There are theoretical equations that have been successful at predicting the turbulence characteristics and transport in the high temperature core (gyro-kinetics, gyro-fluids) and the low temperature far edge and scrape-off layer (Braginskii fluid) regions of tokamaks. The transition between these regions has become a focus of research because of recent documented failures of the theoretical predictions. The gyro-kinetic models have been found to systematically underpredict the energy transport in the transition region of Ohmic and L-mode discharges. This has practical importance for being able to predict the control limits of the plasma during Ohmic ramp-up or the power required in order to obtain the H-mode. The evidence that the standard gyro-kinetic theory underpredicts the level of transport and the measured turbulence intensity in the L-mode transition region will be reviewed. Recent Braginskii fluid simulations in separatrix geometry have been shown to give sufficiently large turbulence at the separatrix but the resistive instabilities of the Braginskii equations are strongly stabilized as the electron temperature increases in the transition region. Some of the possible causes of the missing turbulence that have been proposed including flavours of resistive instabilities, nonlinear dynamics, zonal flow damping and violation of ordering assumptions will be summarized.

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Verification of the Spectral Shift Paradigm for ExB Shear Suppression of Transport

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TOPIC: D poster

Detailed study of the way in which shear in the mean field ExB velocity Doppler shift impacts the non-linear spectrum of electric potential fluctuations in gyro-kinetic simulations has lead to a deeper understanding of the suppression mechanism [1]. The impact of the Doppler shear can be interpreted with a simple analytic model which shows that the spectrum shifts in the direction where the Doppler shear is linearly destabilizing but non-linear mixing re-centers the spectrum about a finite radial wavenumber at reduced peak amplitude. This new paradigm leads to a model of the finite radial wavenumber shift induced by the Doppler shear. The verification of the new model, implemented in the TGLF quasi-linear transport code, with a large number of simulations with the GYRO gyrokinetic turbulence code will be presented. The spectral shift model in TGLF is shown to be more accurate that the standard quench rule paradigm based model. The average radial wavenumber shift is found to depend on the plasma flux surface shape. A Reynolds stress due to the Doppler shear is induced by the finite radial wavenumber included in the quasi-linear calculations. The verification of TGLF with parallel velocity shear is also presented. Combining both parallel and Doppler shear in the new paradigm gives and interesting asymmetry that depends on the relative sign of the two shears that is also present in the GYRO simulations.

[1] G.M. Staebler, R.E. Waltz, J. Candy and J.E. Kinsey, "A New Paradigm for Suppression of Gyro-Kinetic Turbulence by Velocity Shear," submitted to Phys. Rev. Lett. (2012).

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Dependence of properties of Geodesic Acoustic Modes (GAM) on SOL and edge flows in Tore Supra

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TOPIC: Momentum and particle/impurity transport, and impact of rotation on transport

Previous works have shown (Hennequin et al., EPS, 2010) the effects of Scrape-Off Layer (SOL) parallel flows on the edge plasma toroidal and perpendicular flows and their shearing in Tore Supra tokamak, where SOL flows were controlled by the magnetic configuration and changing the point of contact where the plasma touches the limiter surfaces. At the simplest level, those flows impose a boundary condition on core rotation.

Zonal flows and Geodesic Acoustic Modes (GAMs) are large scale sheared flow structures that are driven by, and react back on the micro-turbulence. GAMs, which have been observed in different machines, have recently been detected on Tore Supra using the MUSIC data analysis technique (Vermare et al., NF 52 063008, 2012). Here we study the effect of different SOL flow configurations on the characteristics and evolution of GAMs.

Measures are made with two Doppler backscattering devices, one viewing the equatorial plane that send O- and X-mode 50 to 100 GHz microwaves in the plasma with steerable tilt angle to the plasma and another one on the top of the machine that operates in O-mode. This setup allows measurement of the perpendicular velocity of density fluctuations in the edge and near edge regions (normalized radius of 0.7 to 1) and the wave number (3 to 20 cm-1).

Here, we will look at how the turbulence characteristics are affected depending on whether the plasma touches the wall at the top or at the bottom ('top' and 'bottom' configurations respectively). Velocity fluctuations are obtained using Fourier and MUSIC methods to detect the frequency and apparent intermittent behaviour of the GAMs. Their dynamics will be discussed, in particular the dependence of their activity with the contact point position. Correlations between turbulence intensity, perpendicular velocity, GAMs mean intensity, GAMs bursts intensity, frequency and duration will be shown as the contact point, normalized radius, and backscattering wave number are varied.

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Turbulence Driven Particle Transport Analysis in FTU Liquid Lithium Limiter Experiments

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* See Appendix of A. A. Tuccillo et al., OV/4-2, Fusion Energy 2010 (Proc. 23rd Int. Conf. Daejon) IAEA (2010).

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Abstract. Following the installation of a Liquid Lithium Limiter (LLL) in the Frascati Tokamak Upgrade (FTU), experiments exhibit significantly improved particle confinement and higher electron density peaking factors compared to standard metallic limiter scenarios (Mazzitelli et al., NF 2011).

The first gyrokinetic analysis performed with GKW (Peeters et al., CPC 2009) of the FTU-LLL discharge #30582 using a Lorentz-type collision operator was published by Romanelli et al. (NF 2011). In this work we extend the analysis and point out the importance of taking into account the full collision operator ins the simulations. We show that if the energy scattering and friction terms are included, varying the lithium concentration can change the direction of the deuterium and electron flux.

The gyrokinetic simulations are complemented by a quasi-linear fluid model that contains the necessary physics needed to capture the main aspects of the observed particle transport. The fluid approach allows us to analyse all the eigenmodes of the system and estimate their diffusive, thermodiffusive and pinch contributions to the particle flux separately (Angioni et al., PPCF 2009). Based on the fluid analysis we argue that the flux reversal observed in FTU is due to the similar spatial scales of the deuterium and lithium ITG modes.

The validity of the linear and quasi-linear analysis is confirmed by a non-linear gyrokinetic simulation of the experimental case.

Status of the studies on the effect of plasma rotation on transport and MHD

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In this paper we report about the status of the EFDA project WP12-IPH-A04-2, associated to the understanding of the effects of plasma rotation on transport and Magneto-HydroDynamics. The experimental and theoretical objectives related to this project for the year 2012 are listed, while the milestones achieved this term are summarised in this paper as well. A short outlook to the goals for 2013 is also presented.

Power deposition and SOL transport in the edge of fusion plasmas

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Edge - SOL turbulence and transport

The experimental results of the SOL power transport and deposition to the divertor and first wall plasma facing components in tokamaks are reviewed. We focus here on type-I ELMy H-Mode plasmas as the foreseen reference scenario for ITER and express our particular interest in empirical studies and their extrapolation to next step devices and the comparison to predictive modelling.

The contribution reviews three main areas of interest w.r.t recent experimental efforts and advantages in assessment of power load issues in ITER based on ASDEX Upgrade, DIII-D, NSTX, MAST, C-Mod and JET. These three areas are the inter-ELM and ELM divertor heat load and the first wall heat load induced by type-I ELMs. The principal diagnostic for these studies is IR thermography, typically providing good target resolution and high sampling rates in 10kHz range and hence provide ELM resolving data. Inter-ELM first wall heat load, though truly interesting in validation for turbulence in SOL, is hardly seen to cause any notable power load on the first wall components, e.g. in JET, possibly due to restrictions in diagnostic resolutions. However, a brief report on particle load on the first wall components, turbulent in nature, is amended.

The Inter-ELM SOL power decay length estimated from analysis of fully attached divertor heat load profiles is presented. Simple regression studies show as the main result an inversely linear dependency to poloidal magnetic field and most notably no major radius dependency. The results from the US (M.Makowski et al., PoP 2012, in print) and the EU database (T.Eich et al., PRL 215001 (2011)) agree well in both absolute magnitude and scaling. Notably, extrapolation to ITER gives a power decay length of only 1mm in the outer midplane region. Comparison to a heuristic particle drift-based model shows satisfactory agreement (R.J.Goldston, NF52, 013009 (2012)). Of course all three latter attempts do not take into account possible other constraints of the upstream SOL pressure gradients and corresponding power fall off length such as ballooning limit on open field lines, as currently discussed in the community (D.Whyte, PSI-2012).

ELMs impose transiently large heat fluxes on millisecond timescales, so far mainly assessed for the divertor target plates and only to minor extent for the first wall components, see e.g. for ASDEX Upgrade (A.Herrmann et al., PPCF 46, p.971 (2004)). Current extrapolation of the divertor heat fluxes come to the conclusion that the maximum tolerable ELM size in ITER would be as low as about 0.7MJ energy loss, about a factor of 30 lower than the predicted ELM loss for natural, unmitigated ELMs (A.Loarte, PPCF 45, p. 1549 (2003)). The talk will review the basis of the extrapolation and provide newer insights from recent JET studies. Furthermore we will try to give an overview on the achievements of reducing both, the ELM loss energy and the ELM induced peak heat fluxes with various mitigation techniques such as ELM control coils and pellet injection.

The few available data on ELM first wall heat load reveal that only about 10% of the ELM loss energy is deposited on the first wall for small type-I ELMs. However, it should be noted that the ELM related filaments impose highly localized heat fluxes and high ion temperatures on the first wall. The appearance of such ELM related filaments on the divertor targets as non-axisymmetric, helically inclined striations are compared to the results of non-linear MHD codes that provide predictions of the actual heat fluxes to the divertor and first wall.

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Gyrokinetic studies of microturbulence in transport barriers

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TOPIC: B

In the present work, the gyrokinetic turbulence code GENE [1,2] is employed to study plasma microturbulence in both edge and core transport barriers. Physically comprehensive simulations, making use of both the local and global versions of GENE, are performed.
The local version of GENE is applied to study small-scale ETG turbulence under edge transport barrier conditions as found in the ASDEX Upgrade tokamak (see also [3]), taking into account several different parameter sets, and carefully verifying numerical convergence of the simulations. It is found that ETG turbulence can under certain conditions carry a large fraction of the electron heat flux. For these parameters, the absence of radially elongated streamers within the pedestal makes ETG turbulence particularly robust with respect to shear flows.
The global version of GENE, on the other hand, has been applied to discharges from the TCV tokamak [4] exhibiting an electron internal transport barrier. In discharges with weaker barriers, TEM-type turbulence is found to be the dominant source of electron heat flux, confirming earlier findings. For steeper barriers, detailed sensitivity studies show that the transport due to small-scale ETG turbulence becomes more dominant and, for the simulations in closest agreement with experiment, is roughly equal to the large-scale TEM transport.

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Electron Heat Transport and Multi-Scale Physics : experimental characterization through fluctuation measurements and related theoretical modelling

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The origins of the anomalous electron heat transport remain uncertain while such transport could play an important role in D-T plasma in which the electron heating should be dominant. The goal of the project is to improve our understanding in multi-scale fluctuations such as ion and electron Larmor radius scales and their impact on electron heat transport. The main objectives are to perform precise characterization of density and temperature fluctuations over a wide range of spatial scales by improving diagnostics on TCV, ASDEX Upgrade, Tore Supra and MAST and to compare the observations with first principle simulations such as gyrokinetic simulations using GS2, GENE and ORB5 codes. More precisely, improvement of density fluctuations are planned in Asdex Upgrade, TCV and Tore Supra and an upgrade of the diagnostic of ECE correlation to measure electron temperature fluctuations is in progress in TCV. In parallel, the development for synthetic diagnostics for gyrokinetic codes would be made in order to compare precisely density fluctuations from specific diagnostic such as Tangential Phase Contrast Imaging, Doppler backscattering systems and temperature fluctuations from correlation ECE diagnostic.

Study of GAMs on Tore Supra using Doppler backscattering.

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Geodesic Acoustic Modes (GAMs) have only recently been detected on Tore Supra [1] by using the MUltiple SIgnal Classification (MUSIC) algorithm to access the temporal evolution of the perpendicular velocity of density fluctuations. The high resolution obtained by this method allows us to follow the temporal evolution of the characteristics of the GAMs such as the amplitude and the frequency.

The tokamak Tore Supra has three channels of Doppler backscattering [2]. Two channels covering typically the plasma edge from $r/a = 1.2$ to $r/a = 0.8$ and the gradient region $r/a = 0.9$ to $r/a = 0.6$ using respectively X-mode and O-mode polarisation are installed in the equatorial plane while the third channel is installed in vertical view with a location at a toroidal angle of 120° from the equatorial system.

Oscillations of the perpendicular velocity have been observed near the edge in numerous discharges using the different channels. Oscillations related to GAMs are generally observed with a typical frequency of about 10kHz, which is found to scale with Cs/R, when the additional heating power (ICRH) is varied.

This paper presents investigations of GAMs on Tore Supra plasmas taking advantage of the high temporal resolution given by the MUSIC algorithm and using both equatorial and vertical Doppler systems.

The dynamics of oscillations of the perpendicular velocity, in particular those related to GAMs is studied. A modulation of the frequency of the GAMs is observed and its link with fluctuation dynamics and fluctuation characteristics is studied. In addition, long-range correlation of data recorded, using both line of sight, is performed and discussed.

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Test particle study of multi-scale turbulent transport

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TOPIC: C

The studies based on test particle approach differ from the self consistent calculations mainly because the statistical parameters of the turbulence (amplitude of the potential fluctuations, correlation length and time) are not fixed by the turbulence model. The transport coefficients are calculated as functions of these parameters and transport regimes can be identified.
Drift-type turbulence determines potential fluctuations that move in the poloidal direction with the effective diamagnetic velocity and have Eulerian correlations (EC) with zero poloidal integral. We have shown that this special shape of EC has a strong influence on the transport coefficients. A complex model of the EC was considered, which accounts for non-isotropic small and large scale potential fluctuations and zonal flows.
We have shown that a rich class of anomalous diffusion regimes appears when trajectory trapping (eddying) is effective, i.e. when the combined action of the decorrelation mechanisms is weak enough. Trapping influences not only the values of the diffusion coefficients but also their scaling laws. We have obtained electron heat transport regimes with diffusion coefficients that are completely different of the sum of the transport coefficients produced separately by the small and large scale turbulence, even when the spectrum is composed by two well separated parts. The main condition for such regimes is the persistence of electron trapping in the presence of large scale turbulence, which determines local average velocities $\mathbf{V}_d$. In this condition, the average velocity makes electron diffusion non-isotropic with increased diffusion coefficient along $\mathbf{V}_d$ and also determines average flows with the relative velocity of the trapped and free electrons $\mathbf{V}_d/(1-n_{tr})$, where n_{tr} is the fraction of trapped electrons. The large scale average of these flows is zero due to the random orientation of $\mathbf{V}_d$ but it determines the amplification of the global electron heat transport.
Zonal flow effect on the electron heat transport strongly depends on the parameters of the multi-scale turbulence. In most of the cases it determines the decrease of the radial diffusion coefficient, but diffusion increase can also be produced. The physical reason for this behavior is the modification of the shape of the EC due to the zonal flow potential.
In conclusion the electron heat transport in multi-scale turbulence is a complex process with a rich class of nonlinear regimes. Consequently, the self-consistent evolution of turbulence in specific conditions that selects a path in the turbulence parameter space can determine rather different transport coefficients.
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Interplay of Turbulence and Toroidal Flow

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Interesting features observed in global gyrokinetic simulations regarding turbulence-driven plasma flow and flow shear driven turbulence in tokamak plasmas are reported with discussions on possible experimental identification. i) Turbulent residual stress driven intrinsic toroidal flow and associated **E**x**B** shearing rate are found to exhibit strong poloidal variation. Its structure is dominated by (m,n)=(1,0) mode along with the zonal mode (0,0). Nonlinear toroidal mode couplings which transfer the energy of flow fluctuations from small to large scale are shown to play a key role in the formation of such flow structure. While the total toroidal momentum appears to conserve in symmetric devices, a net (directional) toroidal flow develops when turbulence fluctuations reach the boundaries and are affected by them in the simulated plasma. The characteristics of the flow generation in various turbulence regimes are studied with focus on elucidating intrinsic rotation reversal phenomena observed in Ohmic L-mode plasmas. Moreover, the scale of the flow generation with $\rho^*(=\rho_s/a)$ will be discussed. ii) Strong flow shear, on the other hand, is found to drive the negative compressibility mode unstable in tokamak geometry in some experimentally relevant parameter regimes and the associated turbulence can produce significant momentum and energy transport, including an intrinsic torque in the co-current direction. The generic nature of flow shear turbulence in tokamak plasmas is investigated systematically, including mechanisms for its nonlinear saturation and the influence of the q-profile structure. Remarkably, strong “resonance” in turbulence and transport peaks at the lowest order rational surfaces with integer q-number (rather than fractional), consistent with theoretical calculation. As a consequence, local “corrugations” are generated in all plasma profiles, potentially impacting transport barrier formation near the rational surface. Work supported by U.S. DOE Contract DE-AC02-09-CH11466.

Investigation of edge kinetic profiles throughout the L-H transition on ASDEX Upgrade

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The density dependence of P_{thr} is non-monotonic with a minimum $\overline{n}_{e,min}$ around $4.5 \times 10^{19}\mathrm{m}^{-3}$. On ASDEX Upgrade this dependence has been investigated over a wide density range using electron cyclotron resonance heating (ECRH) with an emphasis on the low density branch. The recent extension of the ECRH system has allowed the investigation of L-H transitions at densities as low as $1 \times 10^{19}\mathrm{m}^{-3}$. Under such conditions the electron and ion heat channels are decoupled up to the plasma edge where T_e/T_i as high as 3.5 has been recorded at the L-H transition. The clear separation of the two channels allows us to demonstrate the key role played by the ions in the L-H transition physics and explains the increase of P_{thr} towards low density. In these experiments, the radial electric field profile, E_r, can be estimated from the ion diamagnetic term. The minimum of the E_r well at the L-H transition is found to be constant regardless of density and T_e/T_i over the wide range covered in this study [1]. This suggests that a minimum E_r shear rate is required at the L-H transition.

The development of the electron density profile and its dependencies after the L-H transition have been investigated [2]. Only ECRH H-modes have been analyzed to exclude core particle fueling. While the density gradient in the edge transport barrier increases significantly after the L-H transition, the pedestal top temperature rises continuously with the applied heating power and shows no pronounced change at the transition. The H-mode density saturates at a level which correlates with the neutral gas density in the divertor prior to the L-H transition. Although the density build up varies with the available deuterium inventory, the initial increase of the edge density gradient is similar.

Currently, time-dependent transport modeling of the density build up after the L-H transition is in progress to assess the respective roles of diffusion and convection in the density build up.

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Experimental measurements of residual stress and related parametric dependence for intrinsic toroidal rotation generation at the edge of TEXTOR tokamak

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TOPIC: D oral

Direct measurements of turbulent residual stress, $\Pi_{r,\phi}^{rs}$, have been carried out in the TEXTOR tokamak by using a counter NBI torque to balance existing co-current toroidal flows (V_ϕ) in the plasma edge. The radial profiles of $\Pi_{r,\phi}^{rs}$, which is part of the radial-toroidal Reynolds stress $\langle \tilde{V}_r \tilde{V}_\phi \rangle$ when V_ϕ=0, are measured by a reciprocating multitip Langmuir-Mach probe in a wide range of plasma parameters: $\langle n_e \rangle$ =(2.0–3.5) $\times 10^{19}$ m^{-3} and I_p=(200–400) kA for two different B_T (2.25 T and 2.6 T). Substantial $\Pi_{r,\phi}^{rs}$ and residual force ($-d\,\Pi_{r,\phi}^{rs}/dr$) have been observed in a narrow region just inside the LCFS, verifying the existence of the residual stress as a possible force for driving intrinsic plasma rotations.

The results show approximately a linear dependence of the residual force on the local pressure gradient in both low- and high-density plasmas. At low densities, the residual force also exhibits a correlation with the reversal of density scale length ($\nabla n_e/n_e$). These results are consistent with theoretical predictions [1, 2].

In case of high density discharges, the collisional damping effects clearly impede the development of the $\Pi_{r,\phi}^{rs}$ and its gradient, although the local pressure gradient and the reversal scale length are much larger than those in low-density discharges.

The strength of the magnetic field also shows an influence on the development of the residual force. In general, the residual force becomes smaller in higher B_T discharges.

The impact of I_p and $q(a)$ on the $\Pi_{r,\phi}^{rs}$ and residual force is quite ambiguous, which is inconsistent with theoretical expectations [2].

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Experimental validation of turbulent transport with global gyrokinetic particle simulation

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TOPIC:
C)Turbulence and Transport at the transition region between core and edge

Text

It is observed in modern gyrokinetic simulations that the heat and particle transport arising from the EXB turbulent motion is approaching to the anomalous transport level in tokamak experiments. However, most of these gyrokinetic simulations are carried out by some simplifications, such as circular cross section, approximate local temperature and density and their gradients, local flux-tube limit, etc. Eliminating these simplifications is very likely to improve the predictability of the numerical simulations. The new features lately developed in the global gyrokinetic particle simulation code GTC, such as kinetic electrons, electromagnetic effects, non-circular plasma shape and global instability drives, enable the GTC code to simulate the turbulent transport with better fidelity when comparing to real experiments. The GTC simulation is compared with DIII-D experiment and GYRO simulation with a result of consistent turbulent transport level between them. Many important physics issues in the global turbulent transport, such as the dominance of trapped electron modes, turbulence spreading, electron transport mechanism and zonal flow effects can be addressed by the new features of the GTC code with a closer relevance to the tokamak experiments. Other relevant validation processes, such as reversed shear Alfven eigenmode, will also be discussed in detail.

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Nonlinear excitations of zonal structures by Toroidal Alfvén Eigenmodes

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TOPIC: C) Turbulence and Transport at the transition region between core and edge

Zonal flows and, more generally, zonal structures are known to play important self-regulatory roles in the dynamics of microscopic drift-wave type turbulences. Since Toroidal Alfvén Eigenmode (TAE) plays crucial roles in the Alfvén wave instabilities in burning fusion plasmas, it is, thus, important to understand and assess the possible roles of zonal flow/structures on the nonlinear dynamics of TAE. It is shown that zonal flow/structure spontaneous excitation is favored including the proper trapped-ion responses, causing the zonal structure to be dominated by the zonal current instead of the usual zonal flow. This work shows that proper accounting for plasma equilibrium geometry as well as including kinetic thermal ion treatment in the nonlinear simulations of Alfvénic modes are important ingredients for realistic comparisons with experimental measurements, where the existence of zonal fields has been clearly observed.

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Experimental Evidence for Particle Transport Threshold in the Tore Supra Tokamak

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Topic D: **Momentum and particle/impurity transport, and impact of rotation on transport**

Temperature gradient threshold has been evidenced for the electron heat transport [1] and the impurity transport [2]. To investigate this effect for the particle transport, perturbation transport experiments have been performed in the Tore Supra tokamak by using the ICRH (Ion Cyclotron Resonance Heating) modulation. The modulation technique is an efficient method for the separate determination of the particle diffusivity D and convective velocity V. An analytical linear transport model [3] is used to simulate the amplitude and phase of the first harmonic of the Fourier transform of modulated density. As shown in Fig.1, the thresholds in density and temperature gradients have been clearly observed for the particle convection reversal *i.e.* the particle convective velocity direction change from inward to outward. Their values are respectively: $(R/L_n)_{crit} \approx 3.3$, $(R/L_T)_{crit} \approx 8.5$. In the same time, the turbulent particle flux defined as $\Gamma = -D\nabla n_e$ has been undergone a strong increase when the density and temperature gradient excess the same thresholds.

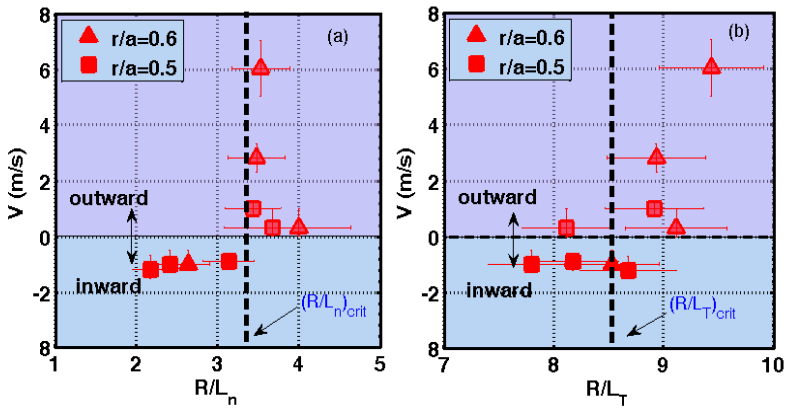

Fig.1 Particle convection velocity vs. the normalized density gradient (a) and the normalized temperature gradient (b).

Simulation with Weiland model and a quasi-linear gyro-kinetic turbulence code QuaLiKiz [4] seems to indicate that the strong particle flux increase and the convective velocity direction reverse from inward to outward correspond to the ITG/TEM transition. This scheme is consistent with that a dominant TEM exists for high values of R/L_n and R/L_T and causes an outward convection, while ITG is the dominant instability for the low values of the normalized gradients.

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Experimental Investigation of Microtearing Modes in Reversed Field Pinch Plasmas

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TOPIC: C) Turbulence and Transport at the transition region between core and edge (recently dubbed no man's land)

Experimental evidence of small wavelength instabilities (of the order of the ion Larmor radius ρ_i or shorter) in the RFX-mod reversed field pinch plasmas is presented. The analysis is performed by means of highly resolved, both in space and time, in-vessel magnetic probes.

Quasi-coherent fluctuations are revealed during the spontaneous Quasi Single Helicity (QSH) states of the plasma, which are magnetic configurations featuring a central plasma volume with good magnetic surfaces, partial but effective suppression of the magnetic chaos produced by large–scale tearing modes, appearance of transport barriers and correspondingly reduced heat transport.

The amplitude of the observed modes is well correlated to the electron temperature gradient strength in the core.

On the basis of gyrokinetic calculations an interpretation of these instabilities is proposed in terms of microtearing modes, invoked as the cause for the residual level of transport beyond collisional limits, as for a large class of toroidal fusion devices.

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