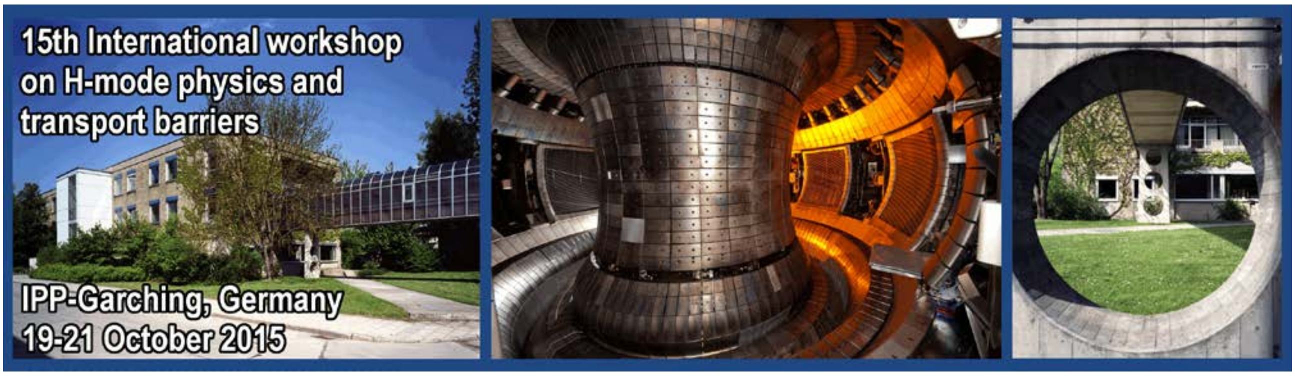

15th workshop on H-mode physics and transport barriers

IPP-Garching

19-21 October, 2015

IPP

Dear participants, dear colleagues,

I am very happy to welcome you to the 15th International workshop on H-mode physics and transport barriers in Garching.

Following the tradition of the workshop format the International Advisory Committee has identified 6 topics of high importance in the current research. For each topic an overview speaker has been invited who was asked to provide an overview of the topic and lead a discussion about the critical issues. The invited speaker is free to choose additional short oral contributions to stimulate the discussion. The subsequent poster session is also dedicated to the same topic and participants are invited to enter into discussions with colleagues from all over the world, which is the main objective of this workshop.

The main fusion experiment situated at IPP in Garching is the ASDEX Upgrade (AUG) tokamak. For those of you who are interested in having a look at AUG, a tour has been organized for Monday evening, 17:30 p.m., immediately after the poster session.

The conference dinner will take place on Tuesday evening, 18:30 p.m., at the restaurant 'Gasthof Neuwirt' in Garching.

Wishing you a pleasant stay, I remain
Sincerely yours,

Elizabeth Wolfrum

International Advisory Committee:

S. Lebedev (Ioffe Institute, Russia)
X. Gao (IPP, China)
K. Ida (NIFS, Japan)
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Local Organising Committee

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Agenda

	Monday, October 19	**Tuesday, October 20**	**Wednesday, October 21**
09.00-10.30	Session 1: *Development of reactor relevant scenarios: key physics and operational aspects*	Session 3: *Impact of magnetic perturbations on ELMs and ETB structure*	Session 5: *H-mode transition dynamics; role of flow-turbulence interaction*
	Coffee	Coffee	Coffee
11.00-12.30	Poster session 1	Poster session 3	Poster session 5
	Lunch	Lunch	Lunch
14.00-15.30	Session 2: *Turbulence in edge and core transport barriers, new experimental results and modelling*	Session 4: *ELM-free, small-ELM regimes including I-mode, QH-mode*	Session 6: *Influence of impurities and divertor conditions on transitions, pedestal and ELMs*
	Coffee	Coffee	Coffee
16.00-17.30	Poster session 2	Poster session 4	Poster session 6
18.30		Conference dinner	

Development of reactor relevant scenarios: key physics and operational aspects

Alberto Loarte

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The plasma conditions required for ITER and tokamak fusion reactor scenarios present specific characteristics which cannot be achieved, or are not routinely reproducible, in present tokamak experiments. Some of them are associated with the scale of the plasma itself, while others are linked to specific features of the heating and fuelling systems required for fusion reactors and to the characteristics of alpha heating. In addition, the core plasma conditions needed for fusion reactors must be achieved in a way which is compatible with other requirements, chiefly these associated with the control of power and particle fluxes to plasma facing components (PFCs) and the need for low impurity concentrations in the core plasma. In addition, the dominance of alpha heating introduces an additional and complex feedback loop between the plasma density and temperature and the plasma heating power that, in turn, determines them. This feedback loop makes the evolution of plasma parameters in fusion reactors complex to predict and control, in particular during confinement transients.

The present physics understanding on key issues required for the development of ITER and reactor scenarios and the integration of core plasma performance with other operational requirements in stationary and transient phases will be reviewed, including:

- Core energy, particle and momentum transport and the influence of reactor specific features, such as dominant electron heating, low momentum input, low central fuelling, etc.
- Pedestal plasma parameters in high density/low collisionality plasmas and the inter-relation between edge and core energy confinement in reactor plasmas that affect the degradation of energy confinement with increasing levels of plasma heating.
- The plasma fuelling requirements for ITER and fusion reactors, and the associated particle transport issues in reactor plasmas with low fuelling efficiency of edge neutral recycling.
- Pedestal plasma MHD stability and ELM control requirements to provide transient power fluxes compatible with the design of PFCs in fusion reactors.
- Control of core and edge impurity transport by heating, fuelling and pedestal control schemes in reactor plasmas to provide low core plasma impurity concentrations.
- Integration of helium ash, impurity source and stationary power flux control to meet PFC lifetime requirements in reactor scenarios and the inter-relation with the control of ELM transient power fluxes.
- Control of the evolution of plasma parameters during the access to and exit from high energy confinement regimes, and integration with the control of power fluxes to PFCs and core impurity content in these phases.

The paper will discuss the required R&D to address these outstanding issues for ITER and reactor scenario development by new experiments and simulations.

Fast measurements of heat flux in ELM filaments in SOL and divertor region on the COMPASS tokamak.

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The investigation of the parallel heat flux on the plasma facing components during Edge Localized Modes (ELMs) represents an important issue for the ITER tokamak in order to determine the physical sputtering and melting of the components. It requires fast measurements with microsecond time resolutions. The local and fast measurements of the parallel heat flux in SOL and divertor region were performed on the COMPASS tokamak using probes.

The combination of ball-pen probe [1, 2, 3] and Langmuir probe was used for the fast measurements of the plasma potential, floating potential, and consequently of the electron temperature and parallel heat flux during ELMy H-mode plasmas. The investigation of ELM filaments in SOL region is performed using midplane reciprocating manipulator. It allowed us to provide the temporal evolution of parallel heat flux in ELM filaments and to determine the power decay length during/inter ELMs period as well [3].

Recently, a new array of ball-pen probes and dome-shaped Langmuir probes was installed also in the divertor target on COMPASS [4] as an alternative option to triple probe technique. The first results show that parallel heat flux during ELMs reaches several MW/m^2 in peaks roughly 6 cm from outer strike point. This peak heat flux is not observed, when the measurement is acquired at lower time resolution (~10kHz), which is comparable to IR cameras time resolution. Such heat flux temporal evolutions have maxima almost one order down compare to fast measurements.

[1] J. Adamek et al., Contributions to Plasma Physics 54 3, 279-284 (2014).
[2] J. Horacek et al., Nuclear Fusion 50, 105001 (2010).
[3] J. Seidl et al., 41st EPS Conference on Plasma Physics, Berlin, P5.059 (2014).
[4] J. Adamek J. et al., 42st EPS Conference on Plasma Phys., Lisbon, P4.101 (2015).

Predicted dependence of turbulent tungsten diffusion on electron and ion heat fluxes and comparative analysis of the impact of turbulence on tungsten transport in ASDEX Upgrade and JET H-mode plasmas

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Operational constraints and impact on performance caused by the requirement of adopting high Z metallic materials such as tungsten (W) as plasma facing components are critical aspects in the development of reactor relevant scenarios. It has been widely documented in experiments that additional central heating by radio frequency (RF) waves has a beneficial effect in avoiding central accumulation, allowing stable plasma operation. The compensation of neoclassical inward convection by turbulent diffusion, which is increased by the increased turbulence level required to sustain a higher heat flux, is one of the main mechanisms at play and to be exploited in future devices in order to avoid impurity accumulation. Important questions to consider are how large can be the turbulent diffusion of heavy impurities for a given level of total heat flux, and whether this is affected by the fraction of electron to ion heating, that is whether electron or ion heating should be preferred to offset the neoclassical impurity accumulation, or whether both can be considered equally efficient. These questions are answered from a theoretical standpoint first, with a gyrokinetic study based on numerical and analytical calculations [1]. Nonlinear simulations show that the size of the turbulent diffusion of heavy impurities can vary by one order of magnitude with fixed total heat flux and is an extremely sensitive function of the electron to ion heat flux ratio. Turbulent diffusion is maximized when plasma parameters are such that the electron and ion heat fluxes are comparable. Dominant ion or dominant electron heat fluxes provide significantly lower values of the turbulent diffusion of heavy impurities, and particularly low values of turbulent diffusion are found in conditions where the ion heat flux is completely dominant. Numerical linear calculations are found to reproduce the nonlinear results. Thereby, a quasi-linear analytical approach is used to identify the physical origin of this dependence. Finally, the theoretical results are applied to a comparative analysis of ASDEX Upgrade and JET H-mode discharges, with a large fraction of ion heating provided by neutral beam injection (NBI). Heat flux levels and their impact on W transport in the two devices are compared. The role of electron heating in these operational conditions is specifically analysed.

[1] C. Angioni, in preparation for submission to Phys. Plasmas (2015).

[†]See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, San Petersburg, Russia

Selected transport studies of a tokamak–based DEMO fusion reactor

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As a next–step in the tokamak–based fusion programme, the DEMO fusion reactor, in the European design, is foreseen to produce relevant output electricity, in the order of ~ 500 MW delivered to the network [1]. Presently under investigations are a pulsed device based on standard H–mode scenarios, called DEMO1, and a steady–state device based on more advanced physics, called DEMO2 [2]. In this work, which is focused on DEMO1, scenarios are studied from the point of view of core transport, to assess plasma performance and limitations due to core microinstabilities. The role of core radiatiated power, impurities, and H–mode pedestal are discussed with respect to their impact on core energy and particle transport.

The ASTRA transport code [3, 4], coupled to turbulence quasi–linear model TGLF [5], is used to perform the several investigations.

Main results obtained in this study are summarized as: 1) low collisionality in the core of DEMO allows to reach a moderate density peaking, that favors fusion power build–up. 2) due to core profile normalized gradients being determined by threshold and stiffness of turbulence, fusion performance is strongly impacted by choice of pedestal parameters, leading to relevant fusion outcome in the range of $7-10$ keV of pedestal top temperature. 3) the impurity mix impacts fusion performance via dilution and radiation in a non–trivial way, narrowing the choice of impurity mix down to a few candidates. 4) pellet fueling in the region $r/a \sim 0.7-0.9$ would lead to a moderate increase in peaking and consequently fusion power. 5) W accumulation would most probably be prevented by the central heating source and the low collisionality regime of the core plasma. Moreover, if radiation, albeit high, remains radially de–localized, its impact on confinement would be marginal, as observed also on present experiments.

Open issues arising in this kind of simulations framework are also addressed.

References

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[2] G. Giruzzi *et al.*, to be published in Nuclear Fusion (2015)

[3] G. V. Pereverzev and Y. P. Yushmanov, IPP Report 5/42 (August 1991)

[4] E. Fable *et al.*, *Plasma Phys. Control. Fusion* **55**, 12402 (2013)

[5] G. M. Staebler *et al.*, *Phys. Plasmas* **12**, 102508 (2005)

The DIII-D high poloidal beta scenario for a Steady State Tokamak Reactor

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Recent DIII-D experiments have advanced the normalized fusion performance of the high poloidal beta tokamak regime toward reactor-relevant steady state operation. The experiments, conducted by a joint team of researchers from the DIII-D and EAST tokamaks, developed a fully noninductive scenario that could be extended on EAST to a demonstration of long pulse steady-state tokamak operation. Fully noninductive plasmas with extremely high values of the poloidal beta, $\beta_p \geq 4$, have been sustained at $\beta_T \geq 2\%$ for long durations with excellent energy confinement quality ($H_{98y,2} \geq 1.5$) and internal transport barriers (ITBs) sustained at large minor radius (≥ 0.7) in all channels (T_e, T_i, n_e, V_φ). Values of the normalized beta, β_N, up to ~4.6 have been obtained by optimizing the plasma-wall distance. The scenario is robust against several variations, including replacing some on-axis with off-axis neutral beam injection (NBI), adding electron cyclotron (EC) heating, and reducing the NBI torque by a factor of 2. This latter observation is particularly promising for extension of the scenario to a reactor, expected to have low rotation. Despite the large values of q_{95} ~10 in these DIII-D experiments, the normalized fusion performance achieved fully noninductively is comparable to that envisioned for the ARIES-ACT2 and ARIES-ACT4 fusion DEMO concepts. On the other hand, the very high safety factor strongly reduces the disruption risk, the most critical issue for the tokamak path to fusion energy. Projections of performance in a steady state reactor using theory-based 0-D modeling and full 1.5D transport modeling will be discussed.

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Issues for H-mode studies in Wendelstein 7-X

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Wendelstein 7-X is scheduled to start test operation (Operational Phase OP1.1) late summer 2015 with already >5MW ECRH heating power but yet unprotected first wall elements. The selected limiter configuration using 5 graphite limiters sets an upper limit to the dissipated energy of <2MJ. About one year later the inertially cooled island divertor will allow to explore the full range of edge configurations with discharges of the order of 10s and extended heating (OP1.2); long pulse operation (OP2) with the geometrically identical steady-state divertor is scheduled to start 2019. A dedicated aim is the exploration of a high-density divertor relevant regime with acceptable low impurity confinement such as it has been achieved in the High Density H-Mode (HDH) of the predecessor W7-AS.

L-H transition phenomena, steepened edge gradients and Edge Localized Modes (ELMs) or smaller ELM-like events have been observed in helical devices with similar phenomenology than in tokamaks. However, their phenomenology shows strong dependencies on the 3D features of the magnetic edge topology - the edge magnetic shear, edge islands, rationals and stochasticity - and there are indications for the particular role of the mean *ExB* flow shear already prior to the transition resulting from the ambipolarity condition of the convective fluxes.

Against the background of these earlier H-mode studies in helical devices the particular characteristics of the HELIAS configuration realized in W7-X are its low magnetic shear with a separatrix topology defined by an island chain and the optimization of neoclassical transport which leads to criteria resulting in a minimization of the geodesic curvature. The latter also enters the interplay between turbulence and flows. Therefore it may be anticipated that access to H-mode can happen in an early phase of the scientific programme and tools to identify and ideally quantify H-mode phenomena need to be prepared.

Therefore, among the limited set of diagnostics available already for the first operation are an ECE radiometer with a zoom device for improved edge resolution of Te-profiles, a Doppler reflectometer for fast measurements of turbulence and its flow velocity at the plasma edge and a conventional poloidal correlation reflectometer to measure correlation lengths, propagation velocities around the separatrix and identify edge instabilities. An IR thermography system together with flush mounted Langmuir probes can be used to study the loads and their dynamics at the limiter targets. For the later physics operation (OP1.2) - besides others - edge profile measurements of T_i, E_r and n_e are envisaged by Charge Exchange Recombination Spectroscopy (CXRS), Beam Emission Spectroscopy (BES) and reflectometry. For these edge diagnostics the particular challenges in W7-X are (1) to obtain a sufficient diagnostic penetration depth in scenarios expected that extend significantly beyond densities $1\ 10^{20}\ m^{-3}$ and (2) to assess on turbulence from a limited number of measurement locations despite its expected 3D behavior.

Full-f gyrokinetic simulation including kinetic electrons

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Full-f gyrokinetic simulations are important tools in studying stiff temperature profiles imposed by non-local transport, non-diffusive momentum transport leading to intrinsic rotation, interplay between neoclassical and turbulent transport, and plasma size scaling of turbulent transport [Idomura, NF09, CSD12, POP14a, POP14b, PFR14]. However, most of existing full-f gyrokinetic simulations are limited within electrostatic ion temperature gradient driven (ITG) turbulence simulations with adiabatic electrons, and electron transport problems have been still open in fill-f approaches. In this work, we develop a kinetic electron model for electrostatic ITG and trapped electron mode (TEM) turbulence simulations in the Gyrokinetic Toroidal 5D full-f Eulerian code, GT5D. In the model, a full kinetic electron model including both trapped and passing electrons is solved for collisional processes and radial electric fields. In the axisymmetric limit, this model imposes a neoclassical equilibrium with an ambipolar condition. The neoclassical transport is computed using a multi-species linear Fokker-Planck collision operator [Sugama,POP09], and the particle transport, the ion and electron heat transport, the bootstrap current, and the radial force balance condition are verified against the standard moment approach [Hirshman,NF87]. On the other hand, turbulent fluctuations are computed by kinetic (adiabatic) response of trapped (passing) electrons in order to avoid a high frequency mode, which appear as the electrostatic limit of kinetic Alfven waves. It is noted that unlike a bounce-averaged trapped electron model [Idomura,JPFR04], this model involves collisional and turbulent trapping and de-trapping processes, which are essential as physically relevant source and sink models for the trapped electron distribution. The linear ITG-TEM stability is verified against former benchmark results [Rewoldt,CPC04]. In this work, we compare ITG and ITG-TEM turbulence simulations with the same Cyclone parameters, and show qualitative differences with respect to turbulence saturation mechanisms, critical temperature gradients, and electron transport. We also discuss possible roles of kinetic electrons in hydrogen isotope effects on turbulent transport.

Systematic measurements of pedestal parameters in COMPASS tokamak

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The COMPASS tokamak has been recently equipped with a set of high resolution diagnostics for studies of pedestal parameters and their behavior. Since it operates with an ITER-like plasma cross-section, obtained results can be used to improve existing empirical scalings of pedestal for ITER and next-step devices. Such scaling are important ie. to predict the properties of ELMs.

The electron temperature and density radial profiles are routinely measured by the High Resolution Thomson Scattering powered by two 1.5 J Nd:YAG lasers (repetition rate 30 Hz each) with spatial resolution of ~4mm in the pedestal region (~a/100). In addition, the edge density profile is also measured by fast reflectometry (temporal resolution ≥30 μs, density range $4\text{x}10^{18} – 2\text{x}10^{19}$ m^{-3}) and the lithium beam emission spectroscopy (temporal resolution 4 ≥μs).

The pedestal parameters have been measured in a single null plasma configurations with plasma current range 160-330 kA, line averaged density $4\text{-}15\text{x}10^{19}$ m^{-3}, B_T = 0.9-1.15 T. H-modes with Type-I and Type-III ELMs as well as ELM-free ohmic H-modes are studied separately. The profiles were fitted using a modified hyperbolic tangent function. The resulting pedestal widths and heights were compared to existing empirical scaling laws with moderate agreement.

Controlled operation in the high density H-mode scenario

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A fusion reactor like DEMO will aim to establish a high core density in order to harvest sufficient output power. Simultaneously, the separatrix density must be adjusted to a value sufficiently high for achieving the necessary divertor detachment while avoiding confinement degradation by encountering the H-mode edge density limit. Hence, establishing a high density plasma regime compatible with confinement requirements and first wall power load restrictions was identified one of the major key physics aspects to be solved for DEMO. In addition, operational aspects must be taken into account. Due to the high fuelling efficiency, both ITER and the European DEMO project have selected pellet injection as sole actuator for core particle fuelling. However, injection of mm-sized pellets composed from frozen fuel causes strong local perturbations in the plasma. It was observed that these perturbations strongly disturb most measurements of parameters applied during standard operational control. Consequently suitable alternatives need to be identified which are compatible with both pellet actuation and control requirements.

Investigations from ASDEX Upgrade reported here focused on both physics and operational issues. Changing to a reactor relevant all-metal-wall configuration, most scenarios require now significant gas puffing in order to prevent impurity accumulation, causing in turn a distinct reduction of the energy confinement. The loss in confinement can be however recovered by seeding with nitrogen (N) once a sufficiently high concentration c_N in the plasma is established. In unseeded reference cases, showing typically a confinement factor of H98 ≈ 0.75 during the initial phase, core densities up to twice the Greenwald density n_{Gw} can be achieved applying pellet fuelling with no loss of confinement. To avoid confinement degradation due to excessive increase of the edge density, here the gas puffing was reduced during the pellet phase. Applying pellet fuelling in N seeded discharges also resulted in the achievement of high core densities. However, a strong reduction of impurities was observed in the high density regime. Thus, also the N concentration was strongly reduced cancelling the performance enhancement and dropping back the confinement to the unseeded reference level. Counteracting this N pump out via an increased N puffing rate during the pellet phase was mitigating this loss of c_N. Thus, the seeding related confinement enhancement was retained partially up to core densities of 1.5 x n_{Gw}. Proceeding with pre-programmed N puffing it turned out difficult to balance between a too low c_N and too strong puffing finally causing core accumulation and a radiative collapse. Hence, a major task is now to establish a suitable control scheme to manage the complex task of increasing the core density to the required level while keeping edge density and seeding gas concentration stationary. First steps have already been successfully taken. The neutral gas pressure in the divertor can be used as control parameter for the electron edge density. It was shown also the line averaged density derived in a sophisticated way from several available measurements is valid and available under pellet actuation and can be applied to control the core density. The next step will be to control the line averaged density to a set point by varying the pellet injection rate. After that, control of N seeding to regulate the divertor density will be integrated into the scenario, eventually aiming for a stable plasma, with high density and high confinement.

Impact of Electron Heating and Reduced Torque on Confinement and Stability in DIII-D ITER Baseline Scenario Demonstration Plasmas

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The DIII-D tokamak has the unique capability to make plasmas with the cross-section shape of ITER at the proper aspect ratio. In addition, combined co- and ctr-NBI and ECH allow systematic variation of the external torque input and ratio of electron to ion heating from the standard values in the multi-national databases used as the ITER design basis to values more typical of those expected in ITER. An overview of the operating experience in DIII-D in the ITER shape will be presented and compared with the larger DIII-D database.

Confinement degrades with respect to that with co-NBI in DIII-D as electron heating is increased or external torque input is reduced. When compared to the standard H-mode confinement scaling (IPB98y,2) at fixed stored energy and β_N=1.9, the co-NBI cases have up to 30% better confinement (H_{98y2}=1.3), while the strong electron heating and low torque cases have confinement in agreement with the scaling (H_{98y2}=1.0). Examination of the electron and ion temperature profiles indicates the confinement reduction in either case is correlated with a reduction in T_i/T_e toward unity. A limited comparison with the TGLF transport model indicates that the case with low torque and strong electron heating appears to be consistent with the model expectations. However, the magnitude of the reduction in confinement (up to 2x) and the disagreement of the confinement obtained in the co-NBI case with the ITER design basis raise questions of how to interpret and project these results for ITER.

Stability to tearing modes of the plasmas with low torque input is also a concern. Tearing modes with n>1 lead to reduction in confinement, but the m=2/n=1 tearing is dangerous since it often leads to a disruption, even at the modest β_N envisioned for the ITER baseline scenario. With co-NBI, a broad but finite operating space was found where the m=2/n=1 tearing modes were stable even as plasmas reached resistive equilibrium. As the input torque is reduced, this space is reduced and at zero torque, no stationary operating point has been found. Correction of intrinsic non-axisymmetric magnetic fields becomes increasingly important as the torque input drops. A comprehensive explanation for the stability of these plasmas that would permit a prediction of the stability of ITER remains to be found.

Tools needed in ITER such as radiative divertor operation and ELM mitigation and suppression have been explored in DIII-D ITER baseline scenario experiments. Reduction of the ELM and between-ELM heat flux to the outer divertor by a factor of 3 was achieved with radiation fraction up to 80% of the input power. Neon was the impurity seed, and the contribution to ion dilution was substantial (ΔZ_{eff}>0.5) compared to previous results in argon. ELM pacing was demonstrated using an oscillating n=1 applied field with beneficial effects on stability with reduced torque. At high collisionality and reduced torque, ELMs were mitigated by a factor of 3 with n=3 RMP. ELM suppression with n=3 applied fields was re-established at low q_{95} with co-NBI. However, reduction in torque resulted in prompt return of ELMs, consistent with measurements and modeling using M3D-C1 that indicate the null of the electron rotation and the location of the tearing response moving inward.

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Pedestal MHD stability at JET – an experimentalist's view

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Traditionally, the stability of the H-mode edge transport barrier to MHD modes is assessed by running linear MHD stability simulations. This has the drawback that results are very sensitive to the accuracy of the reconstructed equilibrium or the details of the model and that, in practice, additional assumptions have to be made to either bridge gaps in diagnostic information (such as the precise location of the separatrix or edge current density profile) or in the stability model itself (e.g which effects to include when defining a realistic threshold for instability).

The ELM precursor modes encountered on JET [1] offer an alternative and more direct source of information for studying stability. First reported with the CFC wall, the collected evidence pointed at the identification of these modes as (often saturated) peeling [2] and coupled peeling-ballooning [3] modes but not pure ballooning modes [1,4]. Since that work, there have been multiple enhancements to the edge profile diagnostics on JET. In addition, the conversion of the plasma facing materials mix from CFC to Be/W has led to unexpected changes in pedestal behaviour, which are empirically found to be plasma shape and scenario dependent. A 400 pulse ELM precursor database with good edge profile and fluctuation data covering both walls has been recently compiled. The new analysis provides confirmation for the earlier identification of these modes as peeling and peeling-ballooning modes. In addition, it provides direct experimental information about which regions of stability space are being accessed in the various scenarios and how this is connected to the observed changes in confinement.

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First pedestal MHD stability analysis of H-modes in COMPASS tokamak

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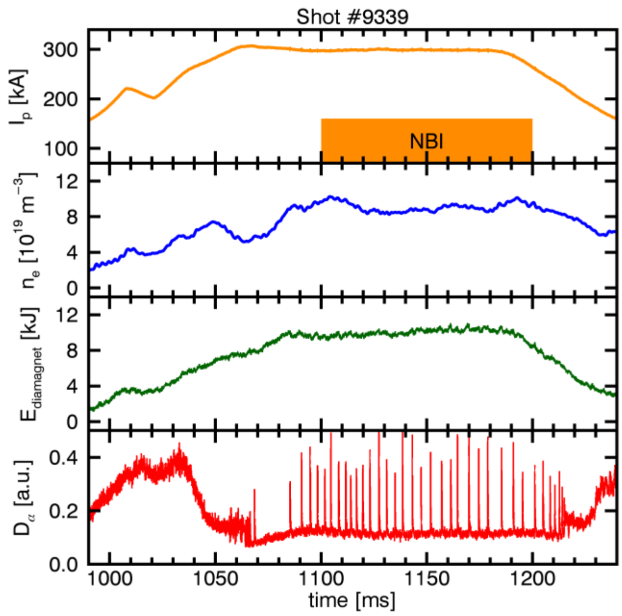
The COMPASS tokamak (R = 0.56 m, a = 0.2 m, ITER-like plasma cross-section) has undergone an extensive development since its relocation from Culham, UK to Prague, Czech Republic in 2006. Ohmic as well as NBI assisted H-modes are regularly generated at B_T = 1.2 T with plasma current in the range of I_{pl} = 200 – 340 kA, plasma elongation 1.8 and edge safety factor q_{95} ~ 2.5 at the highest plasma current. The L-H transition is usually followed either by small Type-III ELMs with frequencies in the range of 200 – 1000 Hz or by ELM-free period. Large Type-I ELMs with typical frequency in the range of 80-200 Hz are generated in case of high plasma currents or NBI-heated plasma. The figure on the left displays a temporal evolution of an ELMy H-mode discharge where the ELM frequency was stabilized by the presence of NBI heating.



The profiles of electron temperature and density are routinely measured by the High Resolution Thomson Scattering (HRTS) powered by two 1.5 J Nd:YAG lasers (repetition rate 30 Hz each). During H-modes, pedestals with height up to 400 eV in electron temperature and 10^20 m^-3 in electron density have been observed. Based on the HRTS profiles, the MHD stability analysis has been performed for COMPASS for the first time, utilizing the well-established routines using numerical codes HELENA, ELITE, and MISHKA, as well as the recently developed (within the EU Integrated Tokamak Modelling/WPCD platform) stability tool JALPHA using numerical code ILSA.

The first results of modelling of MHD stability of edge plasma of COMPASS will be presented. Standard 2D stability diagrams will be shown, which represent a systematic scan of MHD stability in dependence on the pedestal pressure gradient and the edge toroidal current density, i.e., these two quantities are varied independently in order to locate the boundary of MHD unstable region. Apart from that, influence of other experimental as well as numerical parameters will be studied, e.g. the value of total pressure in the plasma core, the alignment of HRTS profiles with respect to the magnetic equilibrium, or the amount of smoothing applied on the plasma boundary before the equilibrium reconstruction refinement by HELENA.

Analysis of fuelling requirements in ITER H-modes with SOLPS-EPED1 derived scalings

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An analysis of fuelling requirements for ITER H-mode plasmas is performed including the use of pellet injection for core plasma fuelling and ELM pacing, gas fuelling for edge density and divertor power load control and respecting the ITER pumping capabilities [1]. Plasma parameters at the separatrix and particle sources from gas puffing are derived from scalings based on SOLPS simulations [2]. The effective transport coefficients in the pedestal are derived from EPED1+SOLPS scalings for pedestal height and width [3]. The equations describing the pedestal and separatrix parameters as functions of the core plasma parameters ($\langle n_e \rangle$ and P_{SOL}) are solved numerically taking into account the ITER pumping capabilities and the divertor detachment requirements and are used for core plasma modelling with the ASTRA suite of codes. In this way, the operational space for ITER DT H-mode operation with the required performance and the level of ELM and divertor power load control compatible with the ITER fuelling and pumping capabilities has been derived. This analysis highlights the inter-relation, which was found problematic in previous studies [4], between the fuelling and ELM pellet pacing requirements (in terms of the pellet size and injection frequency) to achieve the required $\langle n_e \rangle$ and level of ELM control consistent with the ITER pumping capabilities. In particular, the present assessment shows that a reduction of $\langle n_e \rangle$ by a factor ~2 (from 11 to 5 $10^{19} m^{-3}$) in 15 MA H-mode plasmas leads to a reduction of the pellet fuelling rate by a factor of 8. Results of the analysis of the fuelling requirements for a range of ITER scenarios will be presented and compared with similar studies [5] which used the JINTRAC code involving 2-D modelling of the edge plasma.

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Prediction, Testing and Optimization of the Pedestal and the Coupled Pedestal-Core System for Reactor Relevant Scenarios*

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Prediction and optimization of fusion reactor performance requires consideration of a coupled system including both the core and edge plasma. The EPED model [1,2] predicts the H-mode pedestal height and width based upon directly calculated criticality constraints for: 1) onset of non-local peeling-ballooning (P-B) modes at low to intermediate mode number, and 2) onset of nearly local kinetic ballooning modes (KBM) at high mode number. We present a comparison to observed pedestal structure in more than 700 cases on 5 tokamaks, across a broad range of normalized parameters, typically finding agreement within a standard deviation of ~20-25% [1–6]. Because P-B stability is improved by the global Shafranov shift, the pedestal height and width are predicted to depend on the core pressure. Core confinement, in turn, is predicted to depend strongly on the boundary condition provided by the pedestal. To self consistently predict both core and pedestal profiles, we couple the EPED model to the TGYRO core transport solver [7], using TGLF [8] for core turbulent transport and NEO [9] for neoclassical transport. The models are coupled inside the OMFIT/IPS framework, using several hundred CPUs to enable EPED runs in only a few minutes, enabling efficient convergence of core-pedestal solutions from EPED/TGLF/NEO. Predictions of thermal beta and confinement time, as well as density and temperature profiles, can be made and optimized as a function of input parameters including pedestal density, plasma shape, field (B_t) and current (I_p). Initial core-pedestal predictions for ITER-like plasmas on DIII-D find good agreement with observed pressure and temperature profiles. We present comparisons of coupled core-pedestal predictions to observations on existing devices, progress on predictions for ITER, and initial optimization of ITER fusion performance as a function of I_p and pedestal density. We also present predictions and observations of the novel Super H-Mode regime [10], and an assessment of its prospects for improving performance on ITER and existing devices. Future plans include studies of the impact of impurities and coupling to the scrape-off-layer.

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Self-Consistent Modeling of ITER and DEMO with the Integrated Predictive Modeling Code BALDUR

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Self-consistent modeling of ITER and DEMO has been carried out using the BALDUR integrated predictive modeling code in which theory-based models are used for both core and edge transport. Several designs of DEMO, including China design, Indian design, Korean design, Japanese design, and European design, are considered. In these simulations, a combination of NCLASS neoclassical transport and Multi-mode (MMM95) anomalous transport model is used to compute a core transport. The boundary is taken to be at the top of the pedestal, where the pedestal values are described using a theory-based pedestal model. This pedestal temperature model is based on a combination of magnetic and flow shear stabilization pedestal width scaling and an infinite-n ballooning pressure gradient model. The time evolution of plasma current, temperature and density profiles is simulated for each design, which can lead to a comparison of fusion performance of each design, as well as the impurity behaviors such as impurity accumulation. In addition, simulations are carried out for scans in which the plasma parameters, such as plasma density and auxiliary heating power are varied, in order to improve the plasma performance of each design. Finally, the ignition test will be conducted to observe the plasma response in each design after shutting down an auxiliary heating.

Turbulence in edge and core transport barriers, new experimental results and modeling

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The formation of the transport barrier in edge and core is a key role for highly confined magnetic fusion plasma devices. The understanding of the physical mechanism is in progress experimentally and theoretically. Several models, which are based on the suppression of the turbulence, the electric field bifurcation, the steep gradient of the electric field, the effect of ripple loss, and so on, have been pointed out. The observations of them also have been reported in many tokamak and helical/stellarator plasmas. Nevertheless, there are still open questions about these non-linear phenomena. For example: What physics does decide the threshold level and the transition timing and location? How control the limit cycle oscillations and/or the edge localized modes? Which is important the electric field Er or Er shear? etc.

As for studying the behavior of turbulence, in particular multi-scale interaction of turbulence between micro-, meso-, macro-scale structure gets much attention nowadays, since higher spatiotemporal resolved diagnostics have been developed and applied in several devices. Some comparisons between the theoretical model and observation have led to new understandings. It is addressed, for example, that the role of the curvature of the electric field is important for the relationship with the turbulence intensity.

In the workshop, the current understanding of turbulence in edge and internal transport barriers will be discussed with a focus on the spatiotemporal dynamics of the plasma and the highlight areas in which more work is still needed will be pointed out.

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The global build-up to intrinsic ELM bursts and comparison with pellet precipitated ELMs seen in JET

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We perform direct time domain analysis of full flux azimuthal loops in JET. These toroidally integrating signals provide simultaneous high time resolution observation of global plasma dynamics. ELM occurrence times are identified from BeII emissions. We examine the time dynamics of these signals (i) in plasmas where a steady H-mode is sustained over several seconds during which the ELMs are intrinsic and there is no attempt to trigger ELMs and (ii) in plasmas where pellet injection is used to trigger ELMs in the presence of intrinsic ELM. Pellets of size and speed intended to provide a maximum local perturbation for the triggering are launched at pre-programmed times, hence without correlation to the intrinsic ELMs. Pellet rates were kept sufficiently low in order to prevent sustained changes of the initial plasma conditions and ELM behaviour.

We find in all these plasmas a global signature of the build-up to an intrinsic ELM in the temporal analytic phase of the full flux loops. At the time when intrinsic ELMs occur, the value of the time dependent temporal phase is clustered around the same value for all intrinsic ELMs occurring in the steady H-mode of each plasma. Before an intrinsic ELM, the signal phases align to this value on a ~2-5 ms timescale. We establish that this global build up to an intrinsic ELM occurs whilst the amplitude of the signals is at its background value- it precedes the response to the onset of ELMing. We perform the same analysis on pellet-triggered ELMs and find that these signals do not clearly phase align before the ELM in these signals, whereas intrinsic ELMs within the same plasmas do. This null result further supports the idea of a global build up phase to intrinsic ELMs; pellets can trigger ELMs even when the signal phase is at a value when an intrinsic ELM is unlikely to occur.

Lower hybrid current drive related to H-mode in EAST

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Lower hybrid current drive (LHCD) is one of effective tools achieving high confinement (H-mode) plasma in EAST. A 4.6GHz LHCD system has been firstly commissioned in EAST in 2014 campaign. To improve current drive efficiency at high density is very important to sustain LHCD H-mode plasma in EAST. Related high density experimental results will be presented, including the comparison between 2.45GHz and 4.6GHz LHCD system. In the 4.6GHz system experiments, electron internal transport barrier (e-ITB) is observed near the normalized radius of 0.3. Such formation could be related to the central power deposition calculated by C3PO/LUKE code.

In addition, repeatable H-mode plasma is obtained by either 4.6GHz LHCD system alone, or together with 2.45GHz LHCD system, NBI system. Results show different ELM features of H-modes and the related reason is under investigation. Also, LHCD efficiency in H-mode plasma is higher than that in L-mode, possibly due to the less parametric instability (PI) behaviour in H-mode plasma. High temperature in edge region is expected to improve CD efficiency at high density. Further experiments will be explored.

Formation of Large-Radius ITB in High Beta Low Torque Scenario with q_{min} Above 2

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A recent joint experiment between DIII-D and EAST has extended the previous high β_p, high q_{min} non-inductive regime, which has been tested in the 2013 DIII-D/EAST joint experiment, to significantly higher normalized fusion performance ($G = H_{89}\beta_n/q_{95}^2 = 0.16$) at higher plasma current ($I_p = 0.8$ MA). The experiment aims at exploring high performance operation with $q_{min} > 2$ and reduced torque. The effort was largely motivated by the interest in developing a feasible scenario for long-pulse high performance operation with low torque on EAST. Very high confinement, $H_{89} = 3.5$ with $\beta_n \sim 3$, has been achieved transiently in this experiment and BES data shows a significant reduction in the fluctuation levels at the location where an internal transport barrier (ITB) forms. The excellent confinement is associated with the formation of an ITB at large minor radius (normalized $\rho \sim 0.7$) in all channels (n_e, T_e, T_i, V_ϕ, especially strong in the T_e channel). In this experiment, we demonstrated that such ITB and good confinement are achievable at relatively higher plasma current with high q_{min}, finite inductive-driven current and I_p feedback control. The strong electron ITB can be triggered by a current ramp up at a ramping rate of 0.4 MA/s, accompanied by a significant change in the q profile near the ITB location. The spontaneous formation of a strong ITB in plasmas with I_p = 0.8 MA is also observed. However, triggered ITBs in the current ramp-up phase collaps shortly afterwards, perhaps as the ohmic current induced at the edge travels to smaller minor radius, changing the q-profile in an unfavorable way. The ITB collapse at 0.8 MA is induced by an ELM-triggered n = 1 MHD mode at the ITB location. Besides the general features of this experiment, the evolution of ITBs will be shown and the characteristic of turbulence before and during ITB formation will be compared with gyrokinetic simulations.

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Pedestal evolution and edge turbulence on EAST tokamak

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Edge turbulence in pedestal region on EAST tokamak have been observed and studied by using a microwave reflectometry. In lower hybrid wave (LHW) or neutral beam injection (NBI) dominated hating plasma, a coherent mode (CM) was usually observed in the ELM-free phase just after L-H transition. The CM rotated in the electron diamagnetic drift (EDD) direction in the laboratory frame with a poloidal wave number (k_θ) of 0.5 cm^{-1} – 0.7 cm^{-1} and its frequency usually chirped from 80-100 kHz down to 40-50 kHz as pedestal evolves. The appearance of this mode reduced the increasing rate of pedestal pressure, implying that CM may have an effect on outward pedestal transport. This mode can exist about several ten milliseconds and finally replaced by broadband fluctuation in the later ELM-free phase. It was found that the appearance and disappearance of the CM was correlated to the pedestal pressure. In the inter-ELM phase, the pedestal turbulence is generally dominated by broadband (BB) fluctuation with poloidal wave number from 0 to 3 cm^{-1} rotating in the EDD direction in the laboratory frame. Analysis shows that the pedestal pressure increasing rate $dp_{e,ped}/dt$ decreases with amplitude of the broadband fluctuation, implying the BB fluctuation may play an important role in pedestal evolution. The preliminary observation on the fluctuation just inside the pedestal top is also presented.

Keywords: Edge turbulence, coherent mode, broadband fluctuation

Successes and Challenges of Modeling Steady-State High Poloidal Beta Discharges on DIII-D*

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Steady-state high β_p discharges on DIII-D display ion temperature profiles consistent with dominant or exclusively neoclassical thermal transport, but electron thermal, electron particle and momentum flux that is highly under-predicted within the TGLF transport model. By "clamping" the ohmic transformer, fully non-inductive steady-state scenario discharges have been obtained that achieve high beta and high energy confinement with large bootstrap fraction and reversed q-shear associated with a transport barrier at large radius (ρ~0.7). A key challenge of projecting this regime to future experiments or reactor is predicting the self-consistent kinetic and equilibrium profiles when they are tightly coupled. Modeling of the high-performance phase of these discharges by GLF23 and TGLF display striking differences in the ability of the transport models to capture the observed transport fluxes, and in turn produce the attractive bootstrap current and q-profile features observed in the discharges. By performing time-dependent predictive transport and equilibrium simulations with TRANSP we find that the GLF23 transport model produces profiles that capture the global non-inductive current (lower by 1.5 %) and energy confinement (τ_E lower by 7%), but radial profiles that miss details of the local transport barrier and shift the bootstrap current closer to the magnetic axis, lowering q_0. TGLF includes terms that are important for obtaining this scenario including general geometry, intermediate-k modes, increased accuracy for reversed shear and internal transport barriers as well as momentum fluxes. However, with improved physics fidelity in TGLF, the ability of TGLF to model these plasmas appears worse than GLF23. In this contribution, the successes and challenges of modeling this scenario will be presented along with future directions for resolving key issues for confidence in projecting to future experiments and devices.

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ITB formation in gyrokinetic flux-driven ITG turbulence with toroidal momentum injection

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Profile stiffness is a long standing problem, which may limit the overall performance of H-mode plasmas. In the JET experiment, while strong temperature profile stiffness is observed around the nonlinear threshold of ion temperature gradient, it can be greatly reduced by co-current toroidal rotation in weak magnetic shear case [1].

To understand such a mitigation mechanism of the stiffness, we have newly developed a 5D global gyrokinetic code *GKNET* [2]. This enables us to simulate flux-driven ITG turbulence consistently coupled with neoclassical transport mechanism, where mean profiles are governed by radial force balance and can be adjusted to heat and toroidal momentum sources.

By mean of this code, it is found that a stiff temperature profile is established in the absence of momentum source. The stiffness is identified to result from not only the fast propagation of heat avalanches but also the explosive global transport coupled with the instantaneous formation of radially extended ballooning structure, whose size ranges from mezo ($\sim\sqrt{\rho_{ti}L_T}$) to even macro-scale ($\sim\sqrt{L_T}$). The radial mean electric field is found to play an important role in forming such a global structure by recovering the up-down symmetry of the ballooning structure. This indicates that the mean filed can enhance the stiffness.

Then we introduce a momentum source to control the mean field through the radial force balance. Figure 1 shows the radial ion temperature profile without momentum injection and with co/counter momentum injection around $r = 90\rho_{ti}$ in weak magnetic shear case. It can be seen that only co-current toroidal rotation leads to an ITB formation inside the momentum source region, in which the ion thermal diffusivity reduces to the same level as the neoclassical counterpart. The underlying mechanism is identified to originate from the modified radial mean electric field by the localized co-current toroidal rotation. This result is consistent with the observations in the JET experiment.

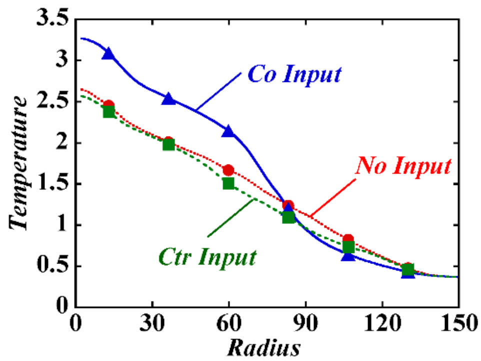

Fig. 1 Radial ion temperature profile without momentum injection and with co/counter-current momentum injection around $r = 90\rho_{ti}$.

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Observations of Fine Flow Structures and Related Turbulence Dynamics in Edge Region of LHD

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Turbulence transport in magnetized plasmas is considered to be non-diffusive, thus the hysteresis appears in macroscopic transport relation [1], and plasma turbulence can generate long distance correlation [2]. One of the keys in this problem is the mesoscopic self-organizing pattern of plasma profile (flow and pressure), for which some hints have been discussed experimentally [3] and is studied theoretically [4]. In the theoretical study, a fine structure intersperses between regions of turbulent avalanching. Observation of such fine structures and associated turbulence dynamics is one of the most challenging problems.

We applied the microwave frequency comb technique to the Doppler reflectometry (the repetition frequency of 0.31 GHz and frequency band is 26 - 40 GHz) for edge plasma turbulence diagnostic [5]. The incident and reflected wave signals are directly transferred to the digital storage oscilloscope, which has a frequency band of 33/50 GHz (the sampling frequency is 80/160 GHz), so the waveforms of the incident and reflected signals are detected in the form of digital signals with very high temporal resolution and phase delay between them is obtained by using of the FFT analysis. Formation of a fine flow structure coinciding with reduction of density fluctuations was found. The non-local bi-coherence [6] between turbulence at two distant locations has been tested to observe the avalanching of the micro-fluctuations.

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Transport Hysteresis of Core Plasma and H-mode Physics

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The violation of local closures of transport (which express the flux in terms of local mean variables and their gradients) has been reported widely these days [1]. One of the examples is the discovery of hysteresis in the gradient-flux relation for the core plasma [2]. The impact of this hysteresis on the H-mode is investigated.

We first discuss the origin of this core transport hysteresis. Theoretical consideration has been made by focusing upon the new thermodynamical force in phase space [3]. Global direct nonlinear simulation on modulational ECH, which tries to reproduce the hysteresis, is commented [4]. We next discuss the impact of this hysteresis on the transient dynamics of L-H (and H-L) transitions. One of the outstanding mysteries of the H-mode transition is the very rapid change of core transport after the L-H transition at edge [5]. This problem of rapid change in core is discussed in the light of the core transport hysteresis. We then study the possibility that the short lack of central heating can have a strong impact on the edge transport barrier via this mechanism. The scheme of control is influenced much by the presence of this hysteresis. W7-AS team has reported that the electric field in the H-mode barrier starts to change (almost immediately) after the termination of core heating [6], indicating such transient response. This process should be carefully studied in the control of fusion plasmas.

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Simulation of Neoclassical Tearing Modes in JET and DIII-D

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Effects of neoclassical tearing modes (NTMs) in standard H-mode and H-mode with the presence of ITB in DIII-D and JET are investigated by using BALDUR integrated predictive modeling code [C. E. Singer *et al.*, Comput. Phys. Commun.49, 275 (1988)]. ISLAND module [C. N. Nguyen *et al.*, Phys. Plasmas11, 3604 (2004)] which based on a quasi-linear theory approach is used to calculate for the width of the saturated magnetic island by include the module into BALDUR code. The plasma profiles at the rational surfaces in BALDUR code are flattening due to the effect of NTM which enhance the plasma transport in the radial direction. The simulation results of single and multiple magnetic islands for JET and DIII-D discharges show the reduction of plasma energy at the central region, especially the 2,1 mode when it compares against other single modes.

Analysis of 2-Dimensional Transport Mechanism in a Toroidal Plasma Turbulence Simulation

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It is important to clarify the spatio-temporal behavior of plasma turbulence for understanding anomalous transport in magnetic confined plasmas. In toroidal plasmas, poloidal flows arise with poloidal asymmetry as by Stringer spin-up [1] and dynamic shearing [2]. A mode with long range correlation has been also identified to show connection in the radial direction [3]. These 2-D structures affect transport relation between distant locations, and must be taken into account in the L/H transition dynamics. To clarify the 2-D transport mechanism, global turbulence simulations are carried out, and the energy transfer dynamics between distant locations is investigated in this research.

We have been developing the Turbulence Diagnostic Simulator (TDS) [4] to reveal the characteristic feature of the plasma turbulence. For the investigation, drift-interchange modes in helical plasmas are analyzed using a reduced 3-field MHD model. This model is used as the fundamental one including the global (broadened in the radial direction) and micro localized modes, nonlinear couplings with the Reynolds stress, and collisional transport processes. In the nonlinear saturated state, modes spreading broadly in the radial direction and localized near their rational surfaces are both excited, and couple to the others. A poloidal flow is generated near the plasma edge, due to existence of the mean gradient. Dynamical response to the source modulation can reveal the role of the mode in the transport process. We have obtained the hysteresis in the flux-gradient relation responding to the modulation [5]. Energy redistribution by nonlinear process is found to play the key role to give the hysteresis in which the pressure gradient precedes the turbulent flux. In the dynamics, the propagation to outer in the radial direction and the poloidal rotation near the edge are combined to show 2-D transport features. The energy transfer rate is calculated with the balance equation of the energy, and the time evolutions of nonlinear couplings between excited modes are studied. The correlation analyses are carried out to clarify the relation between distant locations to show the 2-D profile of the mode couplings. By changing the profile of the applied modulation, the dynamic propagation process and spatio-temporal structures of the nonlinear couplings can be investigated. The 2-D transport dynamics is clarified by the spatio-temporal analysis including the energy transfer in the wave number space.

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Investigation of MHD activity and plasma edge behavior by applying helical magnetic field and limiter bias.

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MHD behavior base on mirnov oscillations have been studied by applying an external resonant helical magnetic field (RHF) in IR-T1 tokamak. This field is produced by two winding with optimized geometry conductors wound externally around the tokamak torus with a given helicity (L=2, L=3) .The purpose of these experiments was to understand the effect of RHF on magnetic island behavior. The time-resolved frequency component analysis has been performed using morlet wavelets. Singular Value Decomposition (SVD) and the Fourier coefficient decomposition (FCD) have been used for extracting spatial and temporal mode structures m=1-4. The results show mode structure change during RHF. The amplitude mode oscillations related to m=2 suppressed and became irregular by applied RHF (L=3). The poloidal velocity which has been measured by Mach probe increased with short delay by RHF while the amplitude of mirnov oscillations decreased. Furthermore, results of the wavelet analysis of mirnov coil Illustrates that 1ms after RHF, the MHD frequency is increased from 23 kHz to28 kHz. The fluctuation in rotation increased by applying RHF but after external biasing both poloidal and toroidal rotation became smooth and edge plasma rotation increased furthermore MHD activity raised when RHF and bias use together.

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Effect of the transition to improved core confinement observed in the LHCD experiment at FT-2 tokamak

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To explain a relatively good efficiency of LHCD and improved core confinement transition obtained at the small FT-2 tokamak (R=0.55 m, a=0.08 m, $B_T \leq 3$T, I_{pl} = 35 kA, f_0 = 920MHz, Δt_{pl} = 50 ms, Δt_{RF} = from 30 ms to 36 ms) [1] a thorough modeling of experimental data has been performed. Effect of LHW on the transition into improved core confinement regime is discussed in the deuterium plasma experiment. It was observed, that in the LHCD experiment with initial OH density $<n_e>$= 1.6 10^{19} m^{-3} the central electron temperature $T_e(r = 0$ cm) increases during RF pulse from 550eV to 700eV and that is accompanied by cooling of the plasma periphery and the density rise, Fig. 1. This effect could not be explained by increase of working gas or impurity recycling because the D_β line intensity and radiation losses during RF pulse is not appreciably changed. Heating of bulk plasma electrons during RF pulse (Δt_{RF} = 6ms) could not be described by collision with LHW generated superthermal and runaway electrons with 200keV÷1MeV energy due to characteristic time $t_E \approx$ 100ms >> Δt_{RF}.

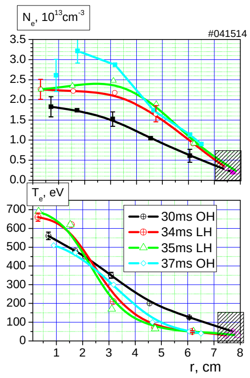

Fig. 1. Evolution of the plasma density $n_e(r)$ and temperature radial profiles $T_e(r)$ measured by Thomson scattering diagnostics in the LHCD experiment.

According to GRILL3D, FRTC and ASTRA codes modeling the increase of the density and electron temperature T_e inside of r < 3 cm (despite the decrease of ohmic heating power P_{OH} at LHCD) happens due to strong reduction of the electron transport in this region where the magnetic shear vanishes, and the value of thermal diffusivity $\chi_{e,\ eff}$ decreases. Broadening of the plasma current profile by noninductive LHCD results in flattening of the safety factor q - profile in the plasma column center. As the result, the magnetic shear $s = (r/q)(dq/dr)$ in the center became low, or even negative. In such a case the transport code (where the electron transport was described by the mixed Bohm and gyro-Bohm model) predicts a reduction of the transport [2].

Paper presents new experimental data and modeling results appropriate to the transition to improved core confinement during LHCD experiment.

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Core Turbulence Response to Controlled *ExB* Shear Variation in Advanced-Inductive Plasmas*

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Multi-scale turbulence properties are significantly altered as core toroidal rotation and resulting *ExB* shearing rate profile are systematically varied in moderately high-beta, advanced-inductive H-mode plasmas on DIII-D ($\beta_N \approx 2.7$, $q_{95}=5.1$). These measurements elucidate the mechanisms by which rotational shear affects the underlying turbulence, and reduces transport with increasing rotation. The energy confinement time increases by ~50% as the toroidal Mach number ($M= v_{TOR}/v_{th,i}$) is increased by a factor of 2.5 (to $M_o \approx 0.5$), while core turbulence, measured with BES, DBS and PCI, is altered in a spatially and wavenumber-dependent fashion. Density, electron and ion temperature profiles, and relevant dimensionless parameters (β_N, q_{95}, ν^*, ρ^*, and T_e/T_i) were maintained nearly fixed during the rotation scan, performed via feedback-control of co- and counter-current neutral beam injection. Ion thermal transport decreases significantly at higher rotation and shearing rate, while electron thermal and particle transport exhibit a more modest decrease. Low-wavenumber (ion gyroradius scale, $k_\perp \rho_S<1$) density fluctuations measured with BES near $\rho=0.5$ show significant but localized amplitude reduction. Linear GYRO growth rate calculations are broadly consistent with these low-k measurements, since localized shearing rates (ω_{ExB}) exceed growth rates near $\rho=0.5$, while this relationship is reversed at lower rotation where ω_{ExB} is well below local growth rates. Interestingly, fluctuations in the broad radial range of $0.55 < \rho < 0.85$ exhibit little change in amplitude despite a large change in local *ExB* shearing rates. The measured decorrelation rates, however, do increase (corresponding to reduced eddy lifetime) in response to increasing *ExB* shear, and these rates quantitatively match each other, as expected from fluid theory. At both low and high shear, the 2D turbulence correlation function exhibits a "tilted" eddy structure, consistent with the prevailing shear direction. Intermediate to high wavenumber fluctuations measured with DBS and PCI exhibit decreasing amplitude at higher rotation. GYRO calculations, however, show increased higher-k linear growth rates in the observed wavenumber range, which appear inconsistent with this reduction in measured high-k fluctuations. These results clarify the specific and complex mechanisms by which *ExB* shear impacts multi-scale core turbulence and related transport, including increased turbulence decorrelation rates and suppressed higher-wavenumber turbulence.

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Effects of tubulence on the edge-core coupling in tokamak plasmas with transient edge source/sink

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Recently, a nonlocal plasma response/transport to transient edge density sources corresponding to pellet injection at low field side was found in global fluid simulations of tokamak plasmas that are based on the 4-field reduced magnetohydrodynamics (RMHD) model [1,2]. The nonlocal plasma response appears in the core region far from the edge source, in which the $(m, n) = (\pm 1, 0)$ pressure perturbations input by the edge source play an essential role where m and n are poloidal and toroidal mode numbers, respectively. Although in the 4-field RMHD simulations the resistive ballooning mode (RBM) turbulence is active in the edge region, ion temperature gradient (ITG) driven turbulence which is important in the core region is not included. We have performed an electrostatic ITG turbulence simulation to investigate effects of the ITG turbulence on the nonlocal plasma response. In the electrostatic ITG turbulence simulation which is based on the 3-field Landau-fluid model [3,4], the edge density source is treated as a sink in the ion temperature equation. We have found that the ITG turbulence tends to prevent the nonlocal response of a kind observed in the 4-field RMHD simulations [5]. It is identified that the $\cos\theta$ component of the $(\pm 1, 0)$ pressure perturbations plays an important role of connecting the core region with the edge in the nonlocal response where θ is the poloidal angle. In the above simulations only the $\cos\theta$ component was put into the system by the edge source/sink. This component is stirred by the ITG turbulence in the core region and its radial wavelength is shortened considerably. Then, the $\cos\theta$ component cannot connect the core region with the edge region. On the other hand, the $\sin\theta$ component of the $(\pm 1, 0)$ pressure perturbations shows strong geodesic acoustic mode (GAM) oscillations. They are excited by zonal flows nonlinearly generated from the ITG turbulence. We investigate effects of location of the source/sink and safety factor profiles on the nonlocal plasma response and the turbulence by the global fluid simulations.

The numerical simulations were performed on the HELIOS supercomputer system at Computational Simulation Centre of International Fusion Energy Research Centre (IFERC-CSC, Aomori, Japan). This work was partly supported by JSPS KAKENHI Grant Number 23561009 and 26400538.

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Local and non-local formation of the ITB near the q=1 surface in ECRH/ECCD and OH experiments at T-10 Tokamak

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In T-10 the role of q=1 surface has been demonstrated in many papers. ITB has been recognized by analyzing the slow heat pulse propagation (HPP) induced by central ECRH-onset in a sawtooth-free plasma created by off-axis ECRH at the first and the second harmonics [1-2]. ITB has been formed near the q=1 surface. The abrupt non-local reduction of transport in central part of plasma column often occurs together with the appearance [3] (or slightly before [4]) of q=1 surface in T-10 sawteeth-free plasmas. The role of magnetic shear has been demonstrated in T-10 experiments with co/contra ECCD in the centre [5-6].

A new type of ITB created by sawteeth oscillations almost damped by off-axis ECCD has been found recently [7]. ITB exists up to 50-70% of the energy confinement time. In the present report, we focus on analysing the correlation between turbulence and transport. ITB formation occurs in a two steps. The evolution of the small-scale density perturbations has been investigated using a heterodyne correlation reflectometer (see detail in [8]). The reflectometer data shows significantly enhanced spectrum amplitude of the density fluctuations during ~1 ms after the crash in a wide spatial zone (measured at $0.5<r/a<0.8$) and in a wide range of frequencies (mainly at 60-140 kHz). A sawtooth crash causes the rise of T_e and n_e outside inversion radius r_s. The turbulence rises stronger in the region where ITB is further observed (mainly at $k_\perp$=0.5-6 cm^{-1}, pronounced peak at $k_\perp \approx 1.2$ cm^{-1} and f≈ 100 kHz). T_e and n_e decays significantly faster compared with that of in similar L-mode shots with central ECRH where the turbulence characteristics were also measured. Comparison of the transport, spectrum of turbulence and the correlation length is in the progress at present.

Later, at ITB formation, the density stops to decay, T_e rises inside r/a=0.45 to a new steady-state, turbulence level measured at ITB falls below its pre-crash value and the spectrum of the turbulence shrinks at in a wide range of frequencies (mainly at $k_\perp$=1-3 cm^{-1}). No accumulation of impurities was observed. By comparing the series of shots supported by calculations using the ASTRA/OGRAY code we demonstrate that narrow profiles of ECRH/ECCD create stronger ITB compare with the wider one (hence the importance of ECCD near q=1). ITB exists under ECCD within the narrow position (3 % of minor radius) thus reminding that of reported earlier for the case of the effective sawteeth damping [9].

The abrupt and non-local reduction of the electron heat diffusivity (ITB-event) around q=1 surface (in the zone $0.2<r/a<0.5$) is reported also. ITB-event occurs after cut-off of the gas puffing in OH discharges with an increasing high density. In this case, impurities begin to accumulate simultaneously with the ITB-event. The reflectometer data is being currently processed and analyzed. The authors are indebted to Drs N.A. Kirneva, D.A. Kislov, Yu.D. Pavlov and V.A Vershkov for fruitful discussions.

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Micro-instability analysis of pellet fueled discharge in H-mode JET tokamak

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Micro-instability analysis and plasma transport of pellet fueled in H-mode JET plasmas is carried out using BALDUR integrated predictive modeling code together with MMM 95 transport code and the NGS pellet ablation model. It is found that after launching a pellet, plasma density suddenly increases with a reduction of temperature. An increase in density results in an increase of transport throughout the plasma, leads to the destruction of an internal transport barrier. It is also found that micro instability properties are extremely sensitive to the rapid and large transient excursions of the density and temperature profiles, which also change collisionality and significantly in the region most strongly affected by the pellet ablation.

Anomalous Transport in the Alcator C-Mod H-mode Pedestal*

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Anomalous transport in the H-mode pedestal region of Alcator C-Mod discharges is analyzed. The anomalous transport is usually reduced in the H-mode pedestal region due to large magnetic shear and large $E \times B$ flow shear. However, the residual anomalous transport is important because it can change the H-mode pedestal structure and its stability. Many pedestal models are based on a combination of MHD constraints for the peeling and ballooning modes and on various assumptions for different transport mechanisms that control the plasma profile gradients in the pedestals. Marginal stability constraints for kinetic-ballooning modes (KBM) are used in the computation of the H-mode pedestal height and width [1]. The KBM modes are electromagnetic modes that are destabilized above critical value of $\beta^{\rm crit}$. Similar to the ITG modes, the stability of KBM modes are dependent on the parameter η_i that is defined as the ratio of temperature and density gradients. Other drift-wave instabilities in addition to KBM may play a role in the development of the structure of the H-mode pedestal. In particular, the drift resistive inertial ballooning modes (DRIBM) [2] might be dominant instabilities in the plasma edge region for some plasma conditions. The DRIBM modes are destabilized by the density gradient and may be stabilized by electron and ion temperature gradients. The differences in the destabilization mechanisms of KBM and DRIBM modes can be used to distinguish these modes in the analysis of experimental data. The H-mode pedestals in five Alcator C-Mod discharges that represent a plasma density scan are analyzed. The stability analysis with the TRANSP code identified that the DRIBM modes are unstable in two out of five discharges. An improved interpretive analysis is carried out for H-mode pedestal experimental data. The flux minimization technique [3] together with the guiding-center neoclassical kinetic XGC0 code [4] is used in this analysis. The neoclassical and neutral physics are simulated in the XGC0 code, and the anomalous fluxes for the five density-scan Alcator C-Mod discharges are computed using the flux minimization technique. The resulting fluxes are compared with one another. Possible candidates for the MHD instabilities that drive the residual anomalous transport for different plasma collisionality regimes are identified.

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Impact of ELMs on edge rotation, momentum confinement and ion heat transport in ASDEX Upgrade

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Edge localized modes (ELMs) are magnetohydrodynamic instabilities that occur after the edge profiles steepen up to a limit which is thought to be defined by the peeling-ballooning limit. ELMs appear as a periodic relaxation event and lead to a crash of the gradients in the plasma profiles for a few 100 μs, thus causing a transient degradation of the H-mode transport barrier.

The comprehensive edge diagnostic suite available at ASDEX Upgrade allows us to measure the edge kinetic profiles on a fast temporal (sub-ms to ms timescale) and with high spatial resolution (less than 5 mm), making it ideal to study the profile recovery after an ELM crash. In this contribution we present the temporal evolution of the edge ion temperature and toroidal rotation profiles during the ELM cycle. The relative loss of ejected toroidal momentum due to the ELM is compared to the relative thermal energy loss for a variety of H-mode plasmas with different conditions. In all analyzed discharges, the edge toroidal momentum loss is larger than the loss in thermal energy. At low collisionality, the recovery of the edge impurity toroidal rotation to its pre-ELM value is observed to be faster than the ion temperature recovery. The edge ion and electron temperature recover on a similar timescale, suggesting that first the level of momentum transport is restored after an ELM crash followed by the restoration of the ion and electron heat transport. The heat transport during the ELM cycle is analyzed in an interpretative way using power balance and compared to predictive modelling using the transport code ASTRA. The temporal evolution of the modelled temperature profiles is compared to the experiment to test whether neoclassical theory is sufficient to describe the inter-ELM edge ion heat transport.

*See http://www.euro-fusionscipub.org/eu-im

Recent Progress in Understanding ELM suppression and Pedestal Transport induced by 3D Magnetic Perturbations*

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Substantial progress has taken place since the last H-mode workshop in experiments and modeling of 3D Magnetic Perturbation (3D-MP) effects on ELM stability and pedestal transport. A key motivation for these studies is to develop ELM stable operation in ITER with 3D-MPs that are compatible with high fusion performance and edge heat flux mitigation. To achieve this goal requires fundamental physics understanding that can be used to extrapolate demonstration plasmas to ITER parameters. This presentation is divided into two parts. The first focuses on the progress made in obtaining ELM mitigation and ELM suppression across a range of facilities with low pedestal collisionality. The second is the progress made in understanding the underlying physics of the plasma response to 3D-MPs and its relation to ELM suppression. In particular, focus will be given to recent efforts validating ideal MHD predictions of the 3D plasma response to RMPs. The discovery of a large edge-localized ideal MHD response and its role in ELM suppression is particularly important as this demonstrates a fundamental breakdown of the vacuum field model. In addition, the observation of bifurcations in the plasma magnetic and pedestal response, without a significant modification in the applied external field, demonstrates the role of non-ideal MHD effects on the dynamics of ELM suppression. These advances in the validation of ideal and non-ideal MHD theory provide a new starting point for developing predictive understanding, based on realistic attributes of the plasma such as kink coupling, resonant field screening and tearing drive.

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Effects of resonant 3-D magnetic fields on pedestals*

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Introduction: This work focuses on development of a model to explain recent $n = 2$ resonant magnetic perturbation (RMP) experiments on DIII-D H-mode plasmas [1,2] that have demonstrated some key features of ELM suppression [2]: 1) abrupt bifurcation to a new pedestal state when RMPs penetrate to $q = m/n$ rational surfaces where they cause a tearing-type magnetic response $\delta B_{\rm pol}^{3D}$ and increase the edge toroidal impurity velocity V_ϕ; 2) reduction of the T_e gradient over an apparently slowly expanding radial region at the pedestal top while $\delta B_{\rm pol}^{3D}$ and V_ϕ are nearly constant; and 3) a residual T_e gradient with no evidence of RMP-induced magnetic islands. This work presents equations for $\delta B_{\rm pol}^{3D}$ and $\Omega_{\rm tor}$, and a model which is reasonably consistent with resonant 3-D magnetic field effects due to field errors (FEs [3]), neoclassical tearing modes (NTMs [4]) and RMPs.

Model Equations: The "penetration" and evolution of a 3-D magnetic field that is helically resonant at a $q = m/n$ rational surface are governed by the equations for the radial component of the resonant magnetic field $\delta B_{\rho\, m/n}(\rho, t)$ and plasma toroidal rotation frequency $\Omega_{\rm tor}(\rho, t)$: $\delta B_{\rho\, m/n}$ is obtained from the radial component of Faraday's law with an appropriate Ohm's law for the electric field; $\Omega_{\rm tor}$ is obtained from the plasma toroidal torque balance equation [5]. These equations are toroidal, kinetic-based generalizations of the cylindrical, fluid-based equations developed originally for field error effects in tokamaks [3a]. They provide criteria for 3-D resonant magnetic field penetration, resistive reconnection, island initiation and possible growth, and the induced plasma transport.

Penetration: Externally applied 3-D magnetic perturbations produce a nonzero response abruptly ($\sim$ ms) in a few mm resistive singular layer of width δ_η at a rational surface when the toroidal torque induced by the 3-D field there exceeds the torque caused by the intrinsic toroidal rotation $\Omega_{\rm tor}$ in the plasma. This applies to FEs and RMPs.

Reconnection: During penetration, the resonant m/n 3-D field reconnects field lines in the thin resistive layer δ_η around the rational surface and produces a tearing-type response and increased $\Omega_{\rm tor}$ there. This radially localized, helically resonant magnetic field then spreads radially slowly at a rate determined by resistivity and transport processses.

Islands, Transport: Reconnection at $q = m/n$ produces a magnetic island whose width w is about the resistive layer width δ_η. If δ_η exceeds the ion banana width $\mathrm{w_{ib}}$ [3b], the island can grow, expanding radially on the resistive diffusion time scale. For NTM islands a seed island of sufficient width is needed [4]. For RMPs $\delta_\eta \ll \mathrm{w_{ib}}$ and while the nascent island does not grow, the continuously driven RMP-induced helically resonant perturbation spreads radially on a slow time scale and induces flutter transport [6].

Criteria For Resonant 3-D Field Effects: Physics-based criteria for these effects will be discussed, quantified and contrasted for FEs, NTMs and RMPs in DIII-D.

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Applications of continuum drift kinetics in NIMROD *

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Abstract

To better understand kinetic effects on macroscopic dynamics in fusion plasmas, continuum solutions to drift kinetic equations (DKEs) for thermal ions and electrons and energetic ions have been implemented in the NIMROD code†. Three advantages of the implementation are (1) solutions to DKEs are fully implicit in time, (2) finite-elements in pitch-angle effectively resolve trapped/passing physics in velocity space, and (3) the full linearized Coulomb collision operators are in place for electrons and ions. In this work, we emphasize how these advantages make possible self-consistent studies of bootstrap currents in the pedestal edge and open fieldline region and the suppression of edge localized modes (ELMs). Resonant magnetic perturbations (RMPs) have been shown to eliminate large, type-I ELM events while preserving global confinement and the generic properties of the H-mode pedestal‡. NIMROD excels at calculating the plasma response to the resonant (island-forming) and non-resonant (flutter) magnetic perturbations of interest in RMP ELM mitigation. As a significant step forward, we plan to close NIMROD's extended-MHD model using parallel electron and ion heat fluxes and stresses from DKE solutions that include the full, linearized Coulomb collision operator. NIMROD's extended-MHD/kinetic model will help to quantify the effects of plasma screening, stochastic layers and magnetic flutter fields on profiles in the pedestal edge and heat loads on divertor targets. Preliminary progress along these lines will be discussed including a plan for incorporating external coil fields from ELM-suppressed discharges into NIMROD.

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Impact of magnetic island and stochastic magnetic field on plasma flow

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Impact of magnetic island and stochastic magnetic field on plasma flow is a crucial issue in the ELM suppression physics using RMP, because both transport and MHD stability at the pedestal are sensitive to the plasma flow. Recently the magnetic topology (magnetic island or magnetic stachastization) has been experimentally identified by the characteristics of the heat pulse propagation properties using the modulated electron cyclotron heating (MECH) technique in toroidal plasmas[1] and a topology bifurcation between magnetic island and stochastic magnetic field is observed[2]. Slow heat pulse propagation exhibiting a non-monotonically increasing delay time is evidence of a magnetic island, while the fast heat pulse propagation observed is evidence of the stochastization of the magnetic surfaces.

The impact of magnetic island on plasma flows has been investigated by the precise measurements of toroidal and poloidal rotation velocities with charge exchange spectroscopy. Both toroidal and poloidal flows show the damping inside the non-rotating magnetic islands. The strong damping of the flow inside the magnetic island produces a very large flow shear at the boundary of magnetic island. In experiments, the large poloidal and toroidal rotation velocity gradients are observed at the boundary of magnetic island both in tokamak and helical plasmas. The large radial electric field shear contributed by these toroidal/poloidal rotation gradients is expected to have a significant influence on the turbulence spreading at the boundary of the magnetic island. The turbulence spreading from outside to inside the magnetic island plays an important role in determining the turbulence level inside the magnetic island, because there is no source of turbulence due to the flattening of temperature and density profiles inside the magnetic island.

The impact of stochastic magnetic field on plasma flows depends on whether the magnetic field is closed (in core stochastization) or open (in the edge stochastization). In the core stochastic region, a clear evidence of the flow damping due to stochastization of magnetic field is found. Abrupt damping of the toroidal flow associated with a transition from a nested magnetic flux surface to a stochastic magnetic field is observed in helical plasmas[3]. This flow damping and resulting profile flattening are much stronger than that expected from the Rechester-Rosenbluth model. The toroidal flow shear shows a liner decay, while the ion temperature gradient shows an exponential decay. This observation suggests that the flow damping observed is not due to the enhancement of viscosity (diffusive term of momentum transport) but due to the change in the non-diffusive term of momentum transport. In the edge stochastic region, the plasma flow, especially poloidal flow, is enhanced rather than damped. This is because the non-ambipolar electron loss along the magnetic field produces a large positive electric field in the edge stochastic region, where the magnetic field is connected to the divertor or vessel wall due to the stochastization of magnetic field.

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ELM crash suppression by mixed non-axisymmetric fields in KSTAR

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Among various control methods of edge localized mode (ELM) crashes, only the non-axisymmetric magnetic perturbation (NAMP) reached complete suppression of ELM crashes beyond their mitigation thus it has attracted more attention than other methods. However, no other device has achieved the complete ELM crash suppression by NAMP except KSTAR and DIII-D [1][2]. Furthermore, the underlying mechanism of NAMP is still uncertain despites of the success of ELM crash suppression. In this research, we investigated the characteristics of ELM crash suppression when differently aligned non-axisymmetric fields are concurrently applied to ELMy H-mode discharges. It was revealed that strong n=1 non-axisymmetric field could degrade the ELM suppressed state of n=2 NAMP. The result implies the importance of underlying non-axisymmetric field, for instance, intrinsic error field, in NAMP ELM crash suppression.

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Role of collisionality on plasma response to external magnetic perturbation in tokamaks

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The interaction between tokamak edge plasmas and externally applied resonant magnetic field perturbations (RMPs) is an important subject for understanding mitigation of edge localized modes (ELMs) by RMPs in H-mode physics. The present idea is that the linear response, kink or pitch resonance, determines the efficiency of RMPs in the ELM mitigation, especially at low collisionality [1]. On the while, some experiments indicate that the details of RMP configuration are not a decisive factor at high collisionality [2]. Therefore, we investigate the role of collisionality in plasma response using four-field reduced MHD fluid simulations in shifted circular equilibria. All simulations are implemented using BOUT++ framework. Physically one can expect that the kink and resonant responses trend differently as collisionality increases. Thus, the resonant responses could be dominant beyond a critical collisionality, which may leads to ELM mitigation regardless of RMP configurations at high collisionality. Detailed study of plasma response modification by resistivity will be presented and preliminary nonlinear effect will be discussed.

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Drive of a mesocale Vortex-Flow pattern by coupling to Zonal-Flows in presence of Resonant Magnetic Perturbations

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Controlling Edge Localized Modes (ELMs) is very important for ITER, and a well-tested way to achieve this is by using external coils to generate Resonant Magnetic Perturbations (RMPs), demonstrated on several tokamaks [1-4]. The working hypothesis for the origin of ELM stabilization is that RMPs increase transport in the pedestal, thus lowering the pressure-gradient below the ideal-MHD threshold. In this work, we show that - in presence of RMPs - Zonal Flows V_{ZF} can drive a long-lived Vortex-Flow pattern ϕ_{VF}. This finding clarifies the theory of RMP-induced Zonal Flow damping [5]. Note that evidence of such a Vortex-Flow pattern has been observed experimentally [6]. We obtain a dynamical system of coupled 1D equations for Zonal Flows and Vortex-Flow profiles, which we solve numerically [7]. In our model, turbulence acts as a shear-dependent negative eddy viscosity $\nu_{eddy} \sim \nu_{eddy0}(1 - V'^2)$. As Zonal Flows are turbulence-driven, this shows that turbulence plays a major role in the plasma self-organization towards a 3D quasi-equilibrium. Our model predicts a nearly-quadratic scaling of the saturated Vortex-Flow energy v.s. RMP amplitude: $E(\nabla\phi_{VF}) \sim \frac{\delta B_r}{B}^{\alpha}$, with $\alpha \simeq 1.9$ [Fig 1]. Contrary to Zonal Flows - which act as a benign reservoir for energy - the Vortex-Flow pattern has a radial streamer-like flow associated to it and hence can drive convective transport. The associated enhancement in the particle transport - assuming the Vortex Flow has a density component - has a resonant character. This additional transport could act to limit the pressure-gradient, and is therefore a possible candidate to explain ELM mitigation.

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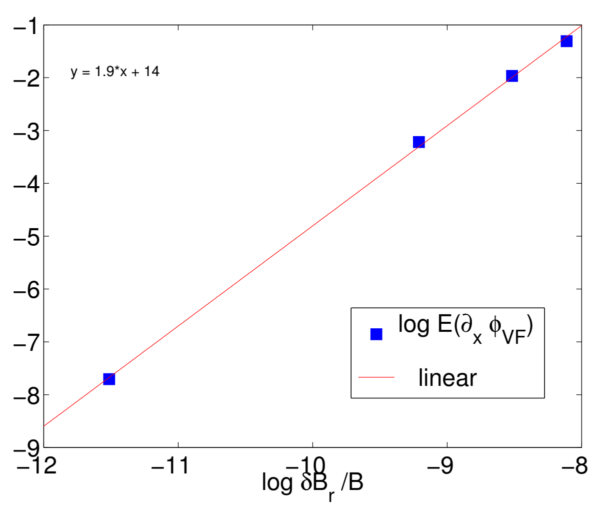

Figure 1: Scaling-law of the Vortex-flow energy v.s. RMP amplitude, in the range $\delta B_r/B = 1 \times 10^{-5} - 3 \times 10^{-4}$.

Non-linear modeling of the plasma response to RMPs in ASDEX Upgrade: towards quantitave predictions for the ELM mitigation with JOREK

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Characteristic shots of the 2014 ASDEX Upgrade – MST1 1.2-4 campaign on ELM mitigation by Resonant Magnetic Perturbations at low collisionality are modeled with the non-linear resistive MHD code JOREK. Modeling was performed using the realistic geometry and profiles of the ASDEX Upgrade discharges. In particular, the experimental toroidal rotation profile and the neoclassical poloidal rotation used in modeling induce a radial electric field profile similar to the experimental one. In addition, the realistic RMP field applied at the boundary of the computational domain allows to model the RMP penetration while taking into account the self-consistent plasma response.

This work aims at assessing the role that both the resonant response and the "kink response" have on the ELM mitigation, in order to move towards more quantitative understanding of current experiments and better predictive capabilities for future experiments. The coil configuration (differential phase between upper and lower coils) leading to the best ELM mitigation in the experiment does not correspond to the largest resonant field component according to our simulations. Instead, the "kink response" is maximal for this configuration, suggesting that it might play an important role for ELM mitigation. In our simulations, the large perpendicular electron velocity at the plasma edge prevents the seeding of magnetic islands at the top of the pedestal for all coil configurations in these discharges. Experimentally, such an island is also not observed, however within the measurement uncertainties a small island cannot be excluded entirely.

Current and future works focus on direct simulations of the non-linear interaction between ELMs and RMPs. Through detailed comparisons against experiments, we aim at further understanding the underlying mechanism of ELM mitigation and suppression by RMPs, depending among others on the resonant and kink responses.

Change of the radial electric field by magnetic perturbations and impact on pedestal

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A model for the radial electric field variation and pump out of the pedestal in the presence of magnetic field perturbations is presented. Resonant magnetic perturbations (RMPs) can form a stochastic layer inside the edge transport barrier (ETB) and cause additional electron current in the radial direction. To compensate it radial neoclassical current of ions arises and radial electric field becomes less negative (or even positive) than the neoclassical electric field. Particle and convective flux reduces density in the pedestal region causing pump out. The level of the effect depend on the plasma screening and is more pronounced at low densities (low collisionalities) and strong magnetic fields, i.e. for tokamak reactors ITER, DEMO etc. Similar effect is predicted during ELMs event when stochastic layer is formed by the currents flowing inside the filaments. Here dynamics of penetration of the perturbed magnetic field is important. It is demonstrated that penetration is fast enough with respect to the filaments life time. The drop of the pedestal density and temperature is attributed to the rise of the radial convective particle and energy fluxes due to modified radial electric field.

Enhancement of High-k Fluctuations by External Magnetic Field Perturbations as a Mechanism for ELM Mitigation

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The physical mechanisms for edge localized modes (ELMs) mitigation and control are the subject of great interest in experimental [1] and theoretical research. Mitigation of ELMs by external magnetic field perturbations requires a predictive understanding of ELM physics. Recent simulation studies highlights the role of nonlinear processes for ELM crashes such as: (1) The phase coherence time between potential and pressure [2]; 2) the stochastization of an edge pedestal by a nonlinear interaction of adjacent ballooning modes (BM) [3]. JOREK simulations [4] show $n = 2$ externally imposed magnetic field perturbations can couple nonlinearly with BM and drive additional higher n modes, which mitigates the ELM-released energy.
In this work, we study the impact of external magnetic perturbations on linear stability of ballooning modes. A unique feature of our analysis is that we employ a two-step parametric process [5] which enables us to evaluate contributions from all harmonics. Analyses show that externally applied magnetic field perturbations can modify the linear dispersion characteristics of ballooning modes (BM). Specifically, the growth rate spectrum $\gamma(k_\theta)$ of BM becomes broader in k_θ-space ($k_\theta = nq/r$; q is the safety factor, r is the radial location), implying the excitation of high-k fluctuations. This indicates the emergence pedestal turbulence before it hits the ballooning mode boundary to trigger an ELM crash. Further, the increase of high-k fluctuations may reduce (or eliminate) ELM crash by the decrease of the phase coherence of the most unstable modes, as presented in previous study [2]. Details of mode characteristics and results of a parametric study will be presented at the Conference.

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New results on RMP ELM suppression in EAST

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ELM mitigation and suppression by RMP have been observed recently on EAST. ELM suppression has been achieved by using the *n*=1 and 2 coil configuration with $\nu_* \sim 1$. The best phase for ELM suppression with *n*=1 is also shift away from the vacuum peak in the spectrum. The best spectrum for ELM mitigation with higher *n*=2-4 is the non-resonant dominant one, not the resonant one. No obvious phase dependence has been observed during the application of rotating *n*=2 RMP. Density pump out and magnetic braking are often observed in the ELM mitigation and suppression phases. The best phase for ELM mitigation or suppression is typically correlated with the maximal density pump-out and magnetic braking effects.

3D Effects and plasma response measurements of non-axisymmetric magnetic perturbations on ASDEX Upgrade via ECE

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One method to suppress or to mitigate edge localized modes (ELMs) is the application of non-axisymmetric magnetic perturbation (MP)-fields [1, 2]. Recent experiments at ASDEX Upgrade demonstrated ELM mitigation at low collisionality $\nu^{\star}$ [3].

To investigate MP induced 3D effects, we used rigid rotating MP-fields and toroidal localized edge diagnostics. Experiments show that the external MP-fields do not only distort the separatrix (shown in [4]), but also change the edge gradients (in space) of the kinetic profiles like n_e, T_e, T_i and v_{tor} depending on the toroidal angle of the applied MP-field. This is seen even when the MP-fields do not cause ELM mitigation.

The best parameter to quantify the plasma response due to a non-axisymmetric MP-field is the electron temperature. Because of the large anisotropic thermal conductivity ($\chi_{II} >> \chi_{\perp}$), changes in the electron temperature profile reflect changes in magnetic structure. We used edge electron cyclotron emission (ECE) and ECE imaging (ECEI) measurements during one rigid rotating MP-fields with even and n=2 configuration (not resonant and no ELM mitigation) to detect variations in magnetic structure. During one full turn, ECEI measurements reveal a poloidal propagating structure. From the poloidal velocity, one can determine the poloidal number m using the given toroidal velocity and mode number (n=2). Additionally, the measured distribution of the amplitude indicates a poloidal asymmetry, which is not expected from ideal MHD. Both, the measured number m and the poloidal distribution will be compared with the results of 3D ideal equilibrium calculations, and vacuum field calculations. Experimental difficulties with rotating MP-fields, like the feedback of the plasma control system or the interpretation of ECE data within the gradient region due to varying optical thickness will be discussed.

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Nonlinear multi-scale multi-physics simulations of a full ELM cycle

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Nonlinear ELM simulations show three stages of an ELM event: (1) a linear growing phase; (2) a fast crash phase; and (3) following by a slow inward propagation phase until heating flux from core finally balances the ELM energy loss and the ELM is terminated. The pedestal profiles rebuild, so long as the heating power is maintained. The turbulence transport phase is a slow encroachment of electron temperature perturbation due to the ELM event into pedestal region. The inward propagation is mainly caused by the ExB convection. The relative cross-phase between density, temperature, and potential perturbations plays a major role in turbulent transport. Nonlinear simulations show that the electron wave-particle resonances provide a relatively strong parallel damping effect on the electron temperature

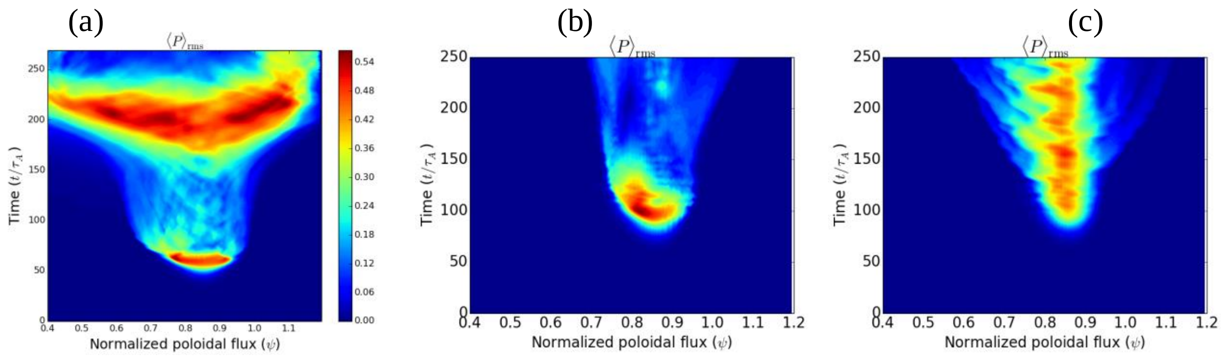

Fig. 1 The time evolution of turbulence intensity: (a) without Landau damping, with zonal perturbations; (b) with Landau damping and zonal perturbations; (c) with Landau damping, without zonal perturbations.

perturbation in comparison of Fig. 1(a) with (b) and can induce a relative cross-phase shift of smaller than $\pi/2$ angle between ExB velocity and the electron temperature perturbation for large electron temperature gradient, which yields a large spreading for electron. The relative phase for ions is about $\pi/2$ and has no turbulent spreading effect on it. Figure1 also shows that the quasilinear effects can reduce the inward turbulence spreading in comparison of figure 1(b) to 1(c).

In order to improve the computational efficiency for a full ELM cycle with ELM dynamics, the basic set of dynamical equations has been separated into equations in the fluctuating and averaged parts over binormal direction. The averaged quantities (such as $\langle P \rangle$, $\langle A_{||} \rangle$ and $\langle \omega \rangle$) are evolving on slow transport time scale and make no contribution to the averaged the ELM flux and the averaged quantity $\langle P \rangle$ contributes to ELM dynamics through the flattening of the background pressure profile. In addition, the averaged vorticity $\langle \omega \rangle$ contributes through the zonal flow and the averaged magnetic potential $\langle A_{||} \rangle$ contributes through the zonal field. The non-ELM radial transport of averaged quantities is determined 'interpretively' from their initial H-mode profiles by dividing the given transport fluxes at inner core boundary by the appropriate plasma gradients. The fluxes in parallel direction (along the magnetic field B) are assumed to be classical with flux limits. The basic idea of a coupling scheme is to pass the ELM radial energy flux $\mathbf{\Gamma}_\kappa = \langle P_k \mathbf{v}_r \rangle$ to the averaged pressure and pass Reynold stress $\prod_\kappa = \langle \omega_k \mathbf{v}_r \rangle$ to the averaged vorticity, where v_r is the fluctuating ExB velocity calculated from ELM fluctuation. The transport equations with sources and sinks are of the form of a convection diffusion system and are evolving on large time steps. Similarly, the profiles used for the turbulence simulations are updated from an average over the previous transport iterations.

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ELM-free, small-ELM regimes including I-mode, QH-mode

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It is now clear that large Edge Localized Modes, such as those characteristic of Type I ELMy H-modes, cannot be tolerated in a burning plasma, due to their transient heat pulses. Active mitigation methods such as Resonant Magnetic Perturbations and pellet injection are thus planned for ITER. These methods are proving challenging to implement, and their range of applicability is unclear; they may not extrapolate to a fusion reactor. Stationary regimes which have the high energy confinement of H-mode, but are naturally free of large ELMs are thus of great interest and quite possibly required. Several such regimes do exist and important progress has been made in the last few years in extending them towards conditions for burning plasmas and in understanding their transport barrier physics. This review session will focus on I-mode, QH-mode, EDA H-mode and related regimes with quasicoherent modes.

The I-mode regime is unique in that it has a barrier in energy but not particle transport, which is both advantageous for impurity control and interesting for transport physics. It has now been accessed on Alcator C-Mod, ASDEX Upgrade and DIII-D, over very wide ranges of parameters. The L-I threshold increases with both current and density, similar to L-H thresholds. An important difference is that it has weak or no dependence on magnetic field. The I-H threshold does increase with B_T, leading to a wider range of power for I-mode at higher B_T, now up to 8 T. Energy confinement is in the range of τ_{98y2} but has much less degradation with input power. More detailed measurements of turbulence and flows in I-mode, on both C-Mod and AUG, show the existence of a GAM which is coupled to the weakly coherent mode, playing a role in the transition as well as WCM spectrum. The turbulence has an intermittent character. An important challenge for extrapolation of any confinement regime is integration with power handling solutions. To this end the I-mode has recently been extended to near double null configurations, reducing heat flux, and seeding is being studied, though detachment has not yet been obtained.

Another stationary regime which has been studied for several years is the EDA H-mode, in which a quasicoherent QC mode provides particle transport to maintain stationary density. More detailed measurements of the mode structure identify it as an electron drift wave with interchange drive and EM contributions. Actuators to actively control transport in the barrier would be beneficial in extending the range of this and other regimes. New results showing stimulation of the QC mode with a 'shoelace antenna' are promising in this regard. A number of interesting quasicoherent fluctuations have recently been reported on EAST which result in stationary H-mode periods.

The regime of "quiescent H-mode" (QH-mode) operates at ITER's values of collisionality and beta, and provides excellent energy confinement even at the very low plasma rotation expected in ITER, while operating without ELMs and with adequate impurity transport via the edge harmonic oscillation (EHO). QH-mode was originally discovered on DIII-D and was subsequently observed on ASDEX- Upgrade, JT-60U, and JET. Recent DIII-D experiments have achieved stationary QH-mode operation for many energy confinement times at simultaneous ITER relevant values of beta, confinement, and safety factor, in an ITER similar shape. The operating space has also been extended to densities exceeding 80% of the Greenwald limit, consistent with peeling-ballooning theory of QH-mode density thresholds. At these higher densities, the coherent EHO is often replaced by broadband MHD oscillations with similar frequencies, but different rotation characteristics. First non-linear MHD simulations of the pedestal show saturation and coupling of low-n kink-peeling modes, reproducing many EHO characteristics and opening the way to developing a predictive understanding of QH-mode for ITER operations.

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Impact of ion diamagnetic drift effect on MHD stability at edge pedestal of rotating tokamaks

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In H-mode tokamaks, edge-localized modes (ELMs) sometimes appear and enhance heat/particle transport periodically. The large amplitude ELM, called the type-I ELM, can induce unacceptable heat load to divertor, and hence, it is necessary to predict correctly the threshold pressure gradient triggering the ELM. Fortunately, many past works identified that the ideal MHD mode called peeling-ballooning mode is the strongest candidate of the type-I ELM [1], and the stability analysis with ideal MHD codes has been explaining experimental results successfully. However, the pressure gradient of the type-I ELMy H-mode in experiments sometimes exists far below the stability boundary obtained numerically with ion diamagnetic correction. For example, the type-I ELM in JET with metal wall (ILW) can appear with the pressure gradient smaller than that predicted numerically with ion diamagnetic correction, though the numerical analysis has explained the ELM stability in JET with carbon wall successfully [2].

In this paper, we pay attention to the plasma rotation effect on ion diamagnetic correction as the key physics resolving the discrepancy between numerical and experimental results. With the new drift MHD model with Frieman-Rotenberg form and the update MHD stability code MINERVA [3], the impact of ion diamagnetic effect on MHD stability at tokamak edge pedestal has been analyzed in rotating plasmas. The result, shown in Fig.1, indicates that MHD modes can become unstable in rotating plasmas even when these modes are stabilized by ion diamagnetic effect in the static case, and the MHD stability depends on the direction of plasma rotation. From this viewpoint, we will revisit the MHD stability at pedestal of JT-60U type-I ELMy H-mode plasmas whose pedestal stability is affected by rotation[4], and report the results at the workshop.

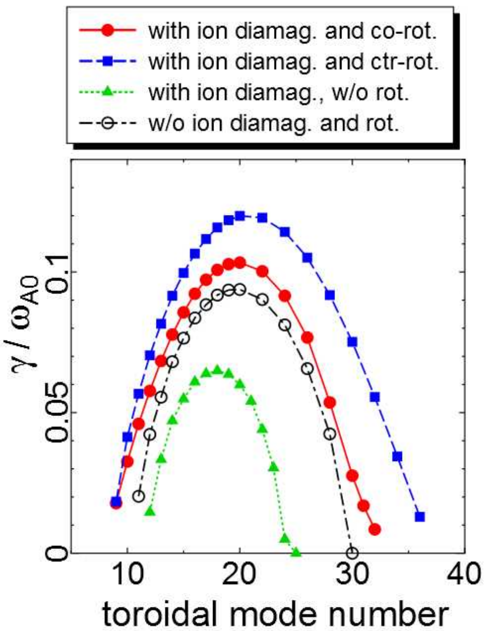

Fig.1) Dependence of growth rate on toroidal mode number with/without ion diamagnetic effect and plasma rotation.

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High Frequency ELM Pacing by Lithium Pellet Injection on DIII-D*

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Full-shot, high-frequency pacing of edge localized modes (ELM) by lithium pellet injection has been demonstrated recently in DIII-D. Periodic, unmitigated ELMs are likely to cause unacceptable damage to wall components in fusion devices like ITER, which might require a 20-50x reduction in peak ELM heat flux [1]. While this could be achieved by fast ELM pacing with deuterium pellets [2], use of non-fuel particles would reduce gas load to the pumping system. A simple device to inject non-fuel granules (lithium) was shown to trigger ELMs in EAST [3]. An upgraded version of the Lithium Granule Injector (LGI) was recently installed on DIII-D, to study pacing efficiency dependence on granule size and velocity, and characterize LGI induced ELMs. The LGI was tested in a number of different ELMy scenarios (b_N=1.2-2.0) injecting granules of nominal diameter 0.3, 0.5, 0.7 and 0.9 mm, with injection speed 50-120 m/s and injection rates up to 500 Hz. Robust ELM pacing was documented on long time windows (up to 3.5 s), with triggering efficiency close to 100% obtained with 0.9 mm diameter granules, lower with smaller sizes, and weakly depending on granule velocity. Paced ELM frequencies up to 100 Hz were achieved, with a 2-5 fold increase over the natural ELM frequency and a consequent reduction of divertor peak heat flux (Fig. 1). Li was found to penetrate the plasma core, but concurrent reduction of core metallic impurities consistently was observed. Overall, LGI high frequency pacing, appeared to be compatible with high plasma performance, in terms of global confinement and pedestal characteristics.

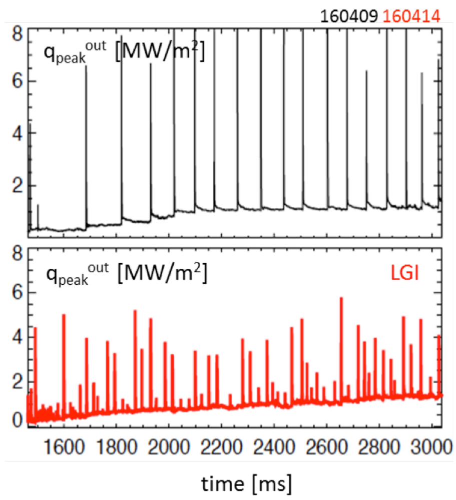

Fig. 1. Divertor peak heat flux during two DIII-D discharges with (top) and without (bottom) ELM pacing by injection of 0.5 mm diameter granules at 105 m/s.

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New Discoveries in QH-mode Plasmas from Experimental and Numerical Studies on DIII-D*

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The physics of the edge harmonic oscillation (EHO) – the key to quiescent H-mode (QH-mode) – is being investigated using two MHD codes. Linear M3D-C1 [1] modeling of the EHO shows rotation shear destabilizes low-n modes while stabilizing high-n modes, consistent with experiments and the theory of EHO being a kink-peeling mode destabilized by edge rotational shear [2]. Nonlinear simulations by JOREK without toroidal rotational shear show unstable low-n kink-peeling modes grow into a saturated stationary state [3], also consistent with experiments and the theory of EHO being a saturated kink-peeling mode. QH-mode is a high confinement operation regime without edge localized modes and with strong impurity transport via the benign EHO, which drives additional transport allowing the plasma edge to operate just below the ideal-MHD stability limit [2]. The calculated linear eigenmode structure from M3D-C1 exhibits similar features to those measured for the EHO by magnetics, ECE, BES, ECE-Imaging and microwave imaging reflectometer: ~2 cm radial width, located at the edge steep gradient region, and poloidal wavenumber increasing with toroidal mode number in the range of 0.02~0.2 cm^{-1}. In the saturation phase of JOREK simulations, the linearly independent modes become locked in phase resulting in a single non-sinusoidal oscillation containing multiple toroidal harmonics, consistent with experiment. In addition, nonlinear coupling of medium-n modes excites the low-n modes [3].

An edge broadband MHD fluctuation sometimes co-exists with the EHO and may also contribute to successful QH-mode. The broadband MHD and EHO appear to be distinct modes as they have different rotational characteristics. An unexpected, rapid improvement in the pedestal pressure height and width along with increased edge turbulence is observed at low toroidal rotation, when the EHO goes away and only broadband MHD fluctuation remains. After the transition, the electron pedestal pressure increases by ~ 60% and the overall energy confinement improves, which is surprising given the higher edge turbulence. Even with the increased pedestal pressure in the enhanced state, the peeling-ballooning (P-B) stability calculations show that the edge operating point can be below the peeling boundary owing to the significantly decreased edge gradients. The stronger broadband MHD and density fluctuations suggest that the pedestal widening is due to increased turbulence-driven transport, possibly caused by decreased ExB shear; thus, the pedestal conditions may be set by transport, not P-B stability. These findings advance the physics basis for developing stationary ELM-free operation at low rotation for ITER and beyond.

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The Shoelace Antenna: An Actuator to Induce Continuous Edge Fluctuations on Alcator C-Mod

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The Shoelace antenna ($k_\perp = 1.5$ cm^{-1}, $50 \lesssim f \lesssim 300$ kHz, Figure 1) is built to induce the same continuous edge fluctuations implicated in providing the impurity exhaust mechanism that maintains steady-state, ELM-free regimes. In particular, the antenna matches the perpendicular wave number and frequency of the Quasi-Coherent Mode (QCM, $k_\perp \sim 1.5$ cm^{-1}, $50 \lesssim f \lesssim 150$ kHz) belonging to the Enhanced D$_\alpha$ (EDA) H-mode, as well as the Weakly-Coherent Mode (WCM, $k_\perp \sim 1.5$ cm^{-1}, $200 \lesssim f \lesssim 500$ kHz) associated with I-mode. Previous experiments showed that the Shoelace antenna was able to excite a resonance resembling the QCM in the edge plasma; however, measurements of transport driven by the induced fluctuation were not available. Recent experiments have now probed the level of transport induced by the antenna, and we report those results here. In addition, improvements to the power and control systems provide not only higher power levels than available in early experiments, but also the ability to lock to the phase of the intrinsic density fluctuation signal, promoting or suppressing the background signal or operating at intermediate relative phase. This makes it possible to explore nonlinear interaction between the antenna and intrinsic edge fluctuations. This research informs the feasibility of developing actuators to actively control edge transport via exciting the fluctuations normally responsible for achieving a particular confinement regime.

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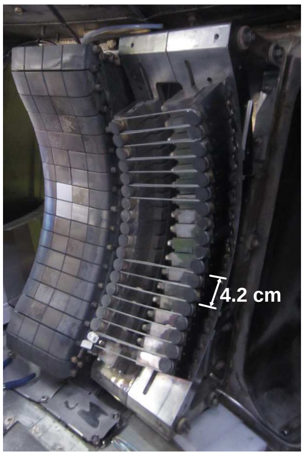

Figure 1: The Shoelace antenna mounted inside the Alcator C-Mod vacuum vessel.

Access conditions for the I-mode regime on Alcator C-Mod and prospects for extrapolation

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Experiments on C-Mod have shown an extended operating range for I-mode at higher magnetic fields, offering options for high-performance, ELM-suppressed operation in future devices. Stationary regimes without significant ELMs are a requirement for ITER and other large burning devices. The I-mode regime offers one potential solution, and has been extensively explored over increasingly wide parameter ranges. It features a strong T_e and T_i pedestal, up to 1 keV, without a density pedestal. Global energy confinement is comparable to H-mode, with H_{98} between 0.7 and 1.2. Scaling of τ_E with power is more favorable than H-mode [1]. This lack of saturation and the natural stability to ELMs can now be understood in terms of pedestal stability, with pressure and current gradients well away from stability limits [2].

Key questions for extrapolation to other devices are the conditions for L-I transitions and for avoiding transitions to H-mode. L-I thresholds increase with both density and current [3]. An important new result is that the L-I threshold is independent of field, while the upper range of power for I-mode increases with B_T , leading to a wider operating space; at 5 T and above, many discharges remain in stationary I-mode with the full heating power of 5 MW. Scaling thresholds with size suggests that I-mode should be obtainable on ITER [4]. Some I-modes have been observed up to 8 T; this range will be explored further in the 2015 campaign. Another key question for any regime is compatibility with boundary solutions. In usual operation with Bxgrad drift away from the X-point, heat flux is predominantly to the inner divertor leg. Impurity seeding is used to reduce the flux, taking advantage of low τ_{imp}. I-modes have now been extended to near-balanced double null.

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NIMROD Modeling of QH-mode: Reconstruction Considerations and Saturation Mechanism

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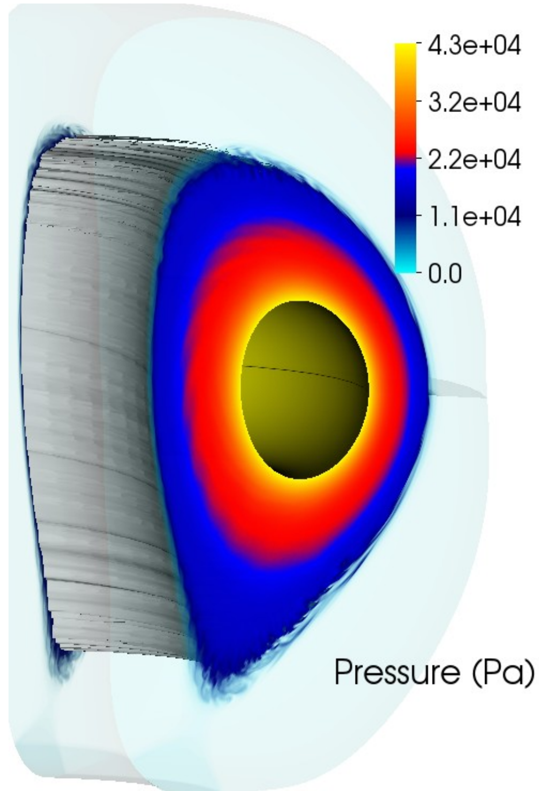
It is desirable to have an ITER H-mode regime that is quiescent to edge-localized modes (ELMs). ELMs deposit large, localized, impulsive, surface heat loads that can damage the divertor. One such quiescent regime with edge harmonic oscillations (EHO) is observed on DIII-D, JET, JT-60U, and ASDEX-U [Garofalo et al, PoP (2015); Burrell et al., PoP (2012); Garofalo et al, NF (2011) and refs. within.]. These ELM-free discharges have the edge-plasma confinement necessary for burning-plasma operation on ITER. The EHO is characterized by small toroidal-mode numbers (n≈1-5); measurements from beam-emission spectroscopy, electron-cyclotron emission, and magnetic probe diagnostics show highly coherent density, temperature and magnetic oscillations. These measurements show that the EHO is a saturated macroscopic mode with perturbations peaking in the pedestal region. The particle transport is enhanced compared to discharges without EHO, leading to essentially steady-state profiles in the pedestal region.



A toroidal cut of pressure contours from a NIMROD simulation of EHO on DIII-D

High quality equilibria are essential for extended-MHD modeling with the initial-value codes such as NIMROD [Sovinec et al., JCP 195, 355 (2004)]. Typically the spatial resolution requirements for extended-MHD modeling, which must resolve singular-layer physics and highly anisotropic diffusion, are more stringent than the resolution of equilibrium reconstructions from experimental discharges. Additionally, reconstructions typically assume that the region outside the last closed flux surface (LCFS) is current free. We relax this assumption and include temperature and density profiles outside the LCFS which generate associated currents. We solve the Grad-Shafranov equation with open-flux regions using the NIMEQ solver [Howell and Sovinec, CPC 185, 1415 (2014)] to generate a new equilibrium while using the mapped results for both an initial guess and to specify the boundary conditions. This regenerated equilibrium is consistent with all of the available profiles that the high quality diagnostics on DIII-D can gives: electron and ion temperatures, electron density, and the rotation profiles. The details of how this consistency is performed, and quantitative comparisons with experiment, will be shown.

Results from nonlinear NIMROD simulations of EHO are presented. The full (toroidal and poloidal) rotation profiles based on Carbon impurity rotation measurements are included in the simulations as experimental observations indicated that the operation regime of the QH-mode is dependent on the rotation profile. These simulations develop into a saturated state. The saturation mechanism of the EHO is explored and comparisons to the magnetic coil measurements are made with a synthetic diagnostic. A summary of the state of fluid modeling to be able to predict EHO is given.

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Nonlinear MHD simulations of QH-mode plasmas in DIII-D

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The quiescent H-mode (QH-mode) regime originally developed at the DIII-D tokamak [1] provides high confinement without transient energy fluxes to plasma facing components associated with edge localized modes (ELMs). This operational regime has been extended to conditions suitable for ITER operation such as low torque input [2] and high normalized density operation [3]. In the QH-mode, the edge harmonic oscillation (EHO) is found to provide a continuous edge particle transport which replaces the periodic expulsion of particles and energy by ELMs. The JOREK [4] non-linear MHD simulations, showing that the unstable low-n modes grow to a saturated kink-peeling mode(KPM), are in good agreement with the theoretical hypothesis of EHO [5] and the experimental observations[6].\

To evaluate the feasibility of the QH-mode regime as an alternative ELM-free regime for ITER high Q operation it is essential to establish under what conditions the plasma develops into an H-mode with ELMs (ballooning modes) or a QH-mode plasma with an EHO (kink modes). In this paper the role of high-n modes and the effect of plasma rotation are investigated.

For this purpose, simulations of QH-mode plasmas have been carried out with the JOREK code with toroidal modes including high-n (up to n=20) modes. In these simulations with high-n modes, it is found that both low-n kink-peeling modes and high-n ballooning modes co-exist in the phase where their amplitude is saturated; i.e. without triggering and ELM. The influence of the pedestal plasma parameters and pedestal gradients on the evolution of the modes has been is evaluated. In order to study the effect of toroidal and poloidal plasma rotation on QH-mode edge MHD stability and to reproduce properly the pedestal radial electric field, the neoclassical poloidal rotation and diamagnetic rotation as well as the effect of the vacuum vessel wall on the destabilization and saturation of edge modes will be evaluated for experimental QH-mode conditions in DIII-D. The nonlinear MHD modelled results of JOREK will be quantitatively compared to experimental measurements in DIII-D.

This work was supported in part by the US Department of Energy under DE-FC02-04ER54698 and DE-AC03-09CH11466.

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I-mode studies at ASDEX Upgrade: L-I and I-H transitions, confinement and pedestal properties

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The I-mode results obtained recently in ASDEX Upgrade will be presented and discussed. The I-mode has been achieved with NBI, ECRH or ICRH, under the high H-mode power threshold conditions with the ion ∇B drift away from the X-point. After the L-I transition, the typical temperature pedestal develops and the global confinement time which can reach values as high as $H_{98y2} = 1$. As in Alcator C-Mod, the transition from L to I mode is revealed by the development of the temperature pedestal, accompanied by the typical signatures: weakly coherent mode and geodesic acoustic mode which seem to play a key role in the transition.

In ASDEX Upgrade P_{L-I} increases linearly with the density, such that P_{L-I} and P_{L-H} (for the favorable ion ∇B drift) are similar at the density minimum of P_{L-H} ($\approx 4 \cdot 10^{19} m^{-3}$), but P_{L-I} is significantly higher than P_{L-H} at higher density. In contrast to P_{L-H}, the magnetic field dependence of P_{L-I} is very weak, suggesting that the physics mechanisms of the L-I and L-H transitions are different.

In ASDEX Upgrade, even at fixed input power, the temperature pedestal often develops gradually over two or three confinement times and ends with a transition to H-mode. In this process, the edge radial electric field well becomes gradually more negative while the overall turbulence level is reduced, seemingly due to a positive feed-back loop. This is in agreement with the assumption that the E_r well plays a key role in the transition to H-mode but that it is perhaps not important, or at least not the only player, in the L-I transition. This will be discussed on the basis of our E_r measurements from Doppler reflectometry and charge exchange recombination spectroscopy.

We will also show how 3D edge magnetic perturbations, n=2 resonant and non-resonant configurations, affect the I-mode. The non-resonant perturbation has almost no effect on P_{L-I}, pedestal development and confinement, while with the resonant setting P_{L-I} increases by about 30%. Our edge measurements indicate that this difference is caused by a flattening of the edge pressure gradient induced by the resonant perturbation, such that more heating power is required to establish the conditions for the L-I transition.

Impact of the Pedestal on Global Performance and Confinement Scalings in I-mode

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The I-mode [1] is a novel high-confinement regime pioneered on Alcator C-Mod, notable for its formation of an H-mode-like temperature pedestal without the accompanying density pedestal found in conventional H-modes. This separation in transport channels gives the necessary improvement in energy confinement while maintaining desirable L-mode-like particle confinement, avoiding excessive impurity accumulation and radiative loss. Moreover, I-mode operation is naturally free of large, deleterious Edge-Localized Modes (ELMs). Recent experiments on Alcator C-Mod have provided an initial characterization of the pedestal structure in I-mode [2,3]. The impact of the pedestal response (particularly to fueling and heating power) and core profile stiffness on global performance and confinement has been characterized, demonstrating confinement metrics competitive with H-mode operation on Alcator C-Mod, and consistent with concepts for I-mode access and operation on ITER. Following the practice of the ITER89 and ITER98 scaling laws for L-mode and ELMy H-mode energy confinement, an initial, illustrative attempt at an I-mode confinement scaling has also been developed. The initial characterization from C-Mod data is consistent with the observed pedestal transport properties in I-mode, particularly the weak degradation of energy confinement with heating power, and comparatively strong positive response to fueling and increased magnetic field. A full empirical characterization of I-mode energy confinement will benefit from the inclusion of multi-device I-mode data, particularly from medium- and large-radius devices.

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H-mode Transition Dynamics - Role of Flow-turbulence Interaction

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A physics-based L-H transition model is important for confidently extrapolating auxiliary heating requirements for burning plasmas. Recent experimental and simulation work has advanced understanding of the interaction of L-mode turbulence and plasma flows preceding the L-H transition. L-mode turbulent structures exhibit characteristic changes in topology and temporal and radial correlation as they tilt in the L-mode $\boldsymbol{E}\times\boldsymbol{B}$ seed flow layer preceding the L-H transition. $\boldsymbol{E}\times\boldsymbol{B}$ flow acceleration and shear flow amplification via the turbulent Reynolds stress have been directly observed in several devices using multi-tip probe arrays, beam emission spectroscopy (BES), and gas puff imaging (GPI). L-H transitions characterized by limit cycle oscillations allow probing the trigger dynamics and the synergy of turbulence-driven and pressure-gradient driven flows with high spatio-temporal resolution. Simultaneous measurements of main ion flow (via main ion CER), $\boldsymbol{E}\times\boldsymbol{B}$ flow, and turbulence level $\tilde{n}/n$ (via Doppler backscattering) in the DIII-D tokamak show that the initial turbulence collapse occurs when the turbulence-generated main ion flow (and $\boldsymbol{E}\times\boldsymbol{B}$ flow) opposes the equilibrium (L-mode) edge plasma $\boldsymbol{E}\times\boldsymbol{B}$ flow related to the edge ion pressure gradient. As the LCO evolves, the periodic reduction in edge turbulence and edge transport enables a gradual, periodic increase of the pressure gradient and mean flow $\boldsymbol{E}\times\boldsymbol{B}$ shearing rate, eventually sustaining fluctuation suppression and securing the LCO-H-mode transition. Modeling of the L-H trigger dynamics has progressed from 0-D and 1-D heuristic predator-prey models to extended models including neoclassical ion flow damping and pressure gradient evolution. Initial results from 2-D and 3-D first-principles fluid codes have been obtained for specific regimes. Predictive modeling of the L-H transition power threshold will require linking the outer core L-mode turbulence properties and energy flux in D, H, and He plasmas to the edge turbulence/flow interaction across a large plasma density/collisionality range. Recent isotope scaling studies show that hydrogen L-mode plasmas exhibit higher radial transport rates and a narrower shear layer compared to deuterium plasmas, potentially contributing to or explaining the observed difference in L-H transition threshold power.

The magnetic structure of the I-phase at ASDEX Upgrade

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The I-phase [1], sometimes referred to as limit-cycle oscillations [2] between perpendicular flow velocity and the turbulence amplitude, appears close to the L- to H-transition and shows pulsations with frequencies in the low kilohertz range. At ASDEX Upgrade, it is shown that the I-phase - typically measured with Doppler reflectometry - is accompanied by a magnetic response visible in pick up coils measuring $\dot{B}_\theta$. This magnetic response seems to originate from the X-point region and propagates from the bottom to the top in lower single null plasmas. In upper single null configuration, the propagation is from top to bottom.

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

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

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Radial electric field dynamics at the L-H and H-L transition on ASDEX Upgrade

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The interplay between turbulence and flows is the key to understanding the transition from the low (L-) to the high confinement mode (H-mode) in toroidally confined plasmas. An H-mode takes place when an edge transport barrier is established in which plasma turbulence is reduced by the shear of the **E**×**B** velocity ($v_{E\times B}$). $v_{E\times B}$ is the sum of two contributions: the neoclassical flow, which is roughly equal to the diamagnetic velocity of the plasma ions ($v_{\mathrm{dia,i}} = \nabla p_i/Z_i e n_i B$), and the turbulence induced flow, also called zonal flow (ZF). Experimental observations show that the neoclassical term is the dominant component in H-mode [1]. Moreover, a correlation between the ion heat channel and the H-mode onset [2] has been recently found pointing out the importance of $v_{\mathrm{dia,i}}$ in the L-H transition mechanism. At the same time, zonal flows are debated to be the trigger of the H-mode, [5, 6]. In particular, a pulsating phase of the edge E_r and of the turbulence amplitude (originally called dithering H-mode [3] and more recently limit cycle oscillation or "I-phase" [4, 5]) is often observed at the L-H transition where turbulence induced flows are discussed to be the actuators.

A recent upgrade of the charge exchange recombination spectroscopy (CXRS) diagnostic in the ASDEX Upgrade tokamak provides simultaneous measurement of the impurity density, temperature and, through the radial force balance, E_r profiles with a time resolution down to 50 μs. This allows to address the evolution of these profiles during the L-H transition. The fast dynamics of E_r and the ion profiles during the L-H transition will be presented for discharges with different L-H power thresholds P_{thr} obtained via a B_t-scan as well as a change of plasma isotopes. The **E**×**B** velocity shear just before the transition is studied as a function of P_{thr}. A comparison of neoclassical and measured E_r profiles together with the evolution of the turbulence fluctuations will be shown in the different phases of the L-H and H-L transition process.

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Reduction of heating power for accessing the H-mode with a kink-like MHD crash in the HL-2A tokamak

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Considering the present ITER power capabilities (in the range of 70 MW), the reduction of the L-H power threshold (P_{L-H}) would have great impact on ITER plasma operation scenarios. Based on ITPA scaling laws, H-mode operation is expected to be marginally feasible in H but likely in D and He [1]. For the tight margin of ITER power threshold, an improved understanding of the L-H transition at reduced power is highly desirable. Experimental studies of stimulated transitions have been reported in KSTAR using a supersonic molecular beam injection (SMBI) system [2-3]. Further research should be centred on identifying the key ingredients of the L-H transition in order to reduce the power threshold. In this paper, we firstly report the reduction of heating power for accessing the H mode with a kink-like MHD crash in the HL-2A tokamak.

The H mode experiment was performed with a lower single-null divertor configuration and following parameters: B_t=1.3-1.4T, I_p=180-190 kA, n_{el} = (1.5-2.8)×10^{19} m^{-3}, P_{NBI}=0.8-1.0 MW, P_{ECRH} = 0.4-1.6 MW. A MHD mode routinely occurs at a low heating power and it crashes rapidly prior to the low to intermediate (L-I) and intermediate to high mode (I-H) transitions [4]. The mode crash evokes substantial energy release from the core to the plasma boundary and hence increases the edge pressure gradient and E_r shear, which further suppresses turbulence by the enhanced flow shear and leads to confinement improvement into the H-mode. With increasing heating power by the ECRH added to the NBI, the kink-like MHD mode disappears and the plasma enters into the H-mode with an overall rising in density and temperature profiles. Meanwhile, the life time of limit cycle oscillation decreases. The statistical result over 50 shots shows that the heating power for achieving H mode with a kink-like MHD-mode crash is significantly reduced, in comparison with that without a kink-like MHD crash. This fact indicates the critical role of the additional energy released by the kink-like MHD crash on achieving the H mode at the low heating power case. In addition, under the same NBI heating power, with the increase of plasma density, the magnitude of kink-like MHD modes increases as well for the I-H transition, suggesting the larger energy release needed for accessing the H-mode regime, in accordance with the empiric scaling of the H threshold power [5].

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Nonlinear Interactions and Transitions of Edge Transport-Barrier Regimes

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Transitions of tokamak confinement regimes are studied with a focus on interactions between turbulence and zonal flows (ZF) or geodesic-acoustic modes (GAM). Results show that access to improved confinement regimes is profoundly affected by these interactions and clarify the role of GAM and ZF in different types of transitions.

In order to understand the dynamics of these transitions, both their trigger mechanism and the parametric dependence of nonlinear processes are studied using gas-puff-imaging. For the L-H transition, this work shows that the stress mediated transfer rate of kinetic energy from turbulence into ZF leads in the changes, the turbulence collapses, and finally the pressure gradient forms – establishing the trigger as flow organization. For the I-mode, turbulence is studied with the aim of understanding *access* to the improved confinement regime, which exhibits an edge temperature pedestal, but a relaxed density profile. L-to-I and I-to-H transitions are analyzed in a time-resolved manner analogous to the L-H transition. For the L-to-I transition, a difference is found in the onset of the regime's typical edge fluctuation, the Weakly Coherent Mode (WCM), and GAM, known to be essential in shaping the WCM; and regime access is found to be sensitive to the GAM drive and damping. Parametric dependences of nonlinearities are examined in steady state discharges from a range of toroidal field, plasma current, and density in both H-mode-favorable and –unfavorable configurations; and interactions between flows and turbulence in both L-mode and I-mode are estimated using bispectral methods. Results advance our progress toward predicting the parametric dependences of transition conditions.

E×B Shearing of Tilted Turbulent Eddys and Its Dependence on Diverted Plasma Configurations

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It is widely believed that the L-H transition and transport reduction are closely related to the E×B flow shear [1]. E×B shear induced suppression of turbulence has been characterized by reduction in radial correlation length of turbulent eddys from two point nonlinear decorrelation theory [2-4]. This is supported by fluctuation measurements using the phase contrast imaging [5] and the correlation reflectometry [6]. Recently, we have addressed effects of initial eddy tilting on E×B shear suppression in toroidal geometry extending the work by Hahm and Burrell [4]. Reduction in radial correlation length of an eddy in the presence of E×B shear flow can be understood in terms of E×B shear induced scale reduction and eddy rotation. It is found that the same direction of initial eddy tilting and E×B shear, rather than the opposite direction, is desirable for effective suppression [7]. This sign dependency is more pronounced for highly elongated eddys in radial direction. With a proper model for magnetic shear induced eddy tilting [8], our results predict different levels of threshold E×B shear for H-mode transition depending on the ∇B drift direction with respect to the single-null location of diverted plasmas.

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Access to high-confinement regimes on Alcator C-Mod and the complex influence of divertor geometry

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The placement of X-point and strike points in a diverted tokamak can have a remarkable impact on properties of the discharge, including thermal and particle confinement. The distinctive divertor of Alcator C-Mod [1] allows us to demonstrate these effects experimentally, as we vary equilibrium shaping to obtain substantial variation of divertor leg length, field line attack angle and divertor baffling. In response to these changes, we observe differences in both L-mode confinement and access to high-confinement regimes (*e.g.* ELMy H-mode and I-mode). With the ion grad-B drift directed toward the divertor, scanning the strike point can induce ~2x reductions in H-mode power threshold [2], and can produce a window for I-mode operation with $H_{98}>1$ [3]. Recent and ongoing experiments seek to explore these effects using improved diagnostics, taking data over a range of plasma density and input power. Detailed high-resolution measurements, spanning the last closed flux surface, provide profiles of key quantities — density, temperature, plasma potential — and their gradients, which are of likely importance in determining whether a discharge evolves an edge transport barrier, or remains in an L-mode state. Advances in Langmuir probe development [4] have enabled not only the characterization of profiles in L-mode at varying values of input power approaching the L-H threshold power, but also the fast (<1MHz) fluctuations in those fields. These data allow new tests of models for H-mode access, especially those attempting to explain the non-monotonic density dependence of the H-mode power threshold through density-related changes in transport and/or turbulence [5,6,7].

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Origin and structure formation of solitary radial electric field in the H-mode

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Various mechanisms to form the steep electric field structure in H-mode have been pointed out, and the nonlinearities in the radial currents due to ion-orbit-loss, neoclassical transport and turbulence Reynolds stress play important roles [1]. Spatio-temporal evolution of localized radial electric field is precisely measured on JT-60U and JFT-2M [2, 3]. Study on JFT-2M by using the direct measurement of radial electric field has shown that the L-H transitions can occur without unstable zonal flows [3]. The structure formation mechanisms are discussed in the system that includes ion-orbit-loss, neoclassical transport and turbulence Reynolds stress (but without zonal flows). The spatial scale of the steepness of electric field is discussed, referring to edge biasing experiments [4]. We then extend the study on the critical condition for bifurcation [5] so as to find the structural transitions. It is shown that the curvature, rather than the shear, of the radial electric field plays a decisive role in forming the transport barrier. We then compare the theoretical models for the radial current, the nonlinearity of which induces the L-H transition, with experiments [6]. Theoretical models show order-of-magnitude agreement with observations in the L-H transition of JFT-2M plasma. In this case, the ion-orbit-loss and neoclassical damping term play dominant role. Discrepancy in the L-mode is also described.

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Self-consistent Electromagnetic Simulations of Edge Transport Barrier Formation in Tokamaks

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To understand the basic physics mechanism for the L-H transition and associated edge transport barrier (ETB) formation, a flux-driven simulation model of tokamak edge turbulence is developed, where profiles, turbulence-driven flows, and neoclassical coefficients are evolved self-consistently. In a recent study based on a two-field electrostatic model [1], it was shown that turbulence collapses and ETB transition begins when energy transfer from the turbulence onto the flow is larger than energy input into the turbulence. In this work, we extend the previous study by employing a three-field electromagnetic model. An ETB forms once input power exceeds a threshold value as in Ref. [1]. A notable difference, however, is found in the electromagnetic case, where the ETB transition is followed by reduction in cross phase between pressure fluctuation and fluctuating radial velocity rather than the turbulence collapse. The turbulent transport reduction by dephasing of fluctuating fields was observed in some experiments [2]. It is observed that avalanche-like heat flows increase neoclassical coefficient at the edge, leading to a strong mean shear flow formation. Details of barrier dynamics including the appearance of hysteresis will be presented.

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Characteristics of low frequency oscillation during L-H dithering phase in high density plasmas of Heliotron J

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In this study, we describe the characteristics of low frequency oscillation observed before the H-mode transition in high density plasmas of Heliotron J. Heliotron J is a medium sized (R/a=1.2/0.16m) heliotron device with L=1 helical winding coil. An H-mode transition was observed in the high density NBI plasmas with the density around 1×10^{20} m^{-3} using short-pulsed high intensity gas puffing (HIGP) [1,2]. In the H-mode phase, an improvement in the energy confinement time normalized to the international stellarator scaling law ($\tau_E^{exp}/\tau_E^{ISS95}$ ~ 2) has been found in conjunction with increase in the edge electron and ion temperatures.

Before the transition, so-called "dithering" phenomenon was seen in the H_α line emission intensity and the density fluctuation level by beam emission spectroscopy (BES). The BES system installed in Heliotron J measured the radial structure of the density fluctuation in the whole plasma region using 16 sightlines [3]. During the dithering phase, n=2 (or 6, 10, …) bursting MHD mode was occurred with the frequency from f = 5kHz to 40kHz. The repetition frequency of the bursting mode is about 1-3kHz. The density fluctuation measurement by BES shows that: (1) the low frequency mode is located at the peripheral (r/a > 0.7) region. (2) cross-correlation function of the low frequency (f=1-3kHz) density fluctuation has correlation length of around 2-3cm in the radial direction and (3) the low frequency fluctuation propagates outward direction. This result indicates particle exhaust phenomena in the peripheral region. The envelope analysis is applied to the BES signals. The envelope of the high frequency (f = 40-150 kHz) turbulent fluctuation at the edge region has a significant coherence (0.2-0.3) to the low frequency oscillation, while the phase difference among the two is almost zero. It is supported by the experimental observation that a relatively high-coherent auto-bicoherence has been seen between the low and high frequency fluctuations. These features indicate that the low frequency oscillation are coupled with the turbulence. To understand the physical mechanism between the low frequency oscillation and the H-mode transition, the 2-dimensional BES measurement is being prepared, which will allow us to obtain propagation and phase relations of the oscillations in the radial and poloidal directions.

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Pelet triggered LH transition in the TUMAN-3M

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Pellet injection is a widely used as fueling tool in fusion devices [1,2]. It is regarded as an effective mean of ELM frequency control in modern tokamaks [3] and in ITER [4]. Besides these applications several experiments were conducted to explore influence of pellet injection on LH transition. For the first time LH transition triggering by shallow pellet ablation was observed on TUMAN-3 [5]. Later studies have shown that average density at which the transition occurred in those experiments was well below a low density margin of H-mode operational diagram [6]. Drawback of the experimental setup in [5] was the use of LiD as pellet material, which poses a question of possibility to trigger H-mode with cryogenic hydrogen isotope pellets. On DIII-D the possibility of pellets to reduce the H-mode power threshold was demonstrated [7]. MAST experiments [8] had shown that high field launch of pellets simplifies H-mode triggering compared with low field launch.

The paper will present results of first experiments on TUMAN-3M with newly build injector capable of launching from low field side cryogenic H/D pellets of half-mm scale with velocity from 150 to 1000 m/s. In the above setup a possibility to trigger H-mode in ohmically heated plasma was demonstrated, see fig.1. LH transition took place at average density of $1\cdot10^{19}$ m^{-3}, which is below low density margin of H-mode operational diagram. According to simulations pellet penetration depth is shorter than half of minor radius.

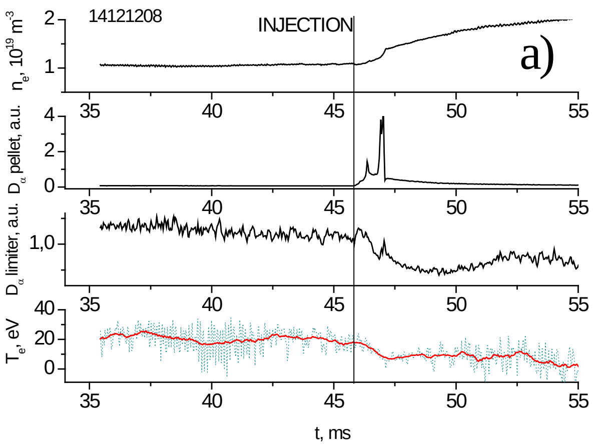

Fig.1 Evolution of plasma density, H-alpha/D-alpha emission in injector and limiter cross-sections, edge electron temperature in the shot with LH-transition triggered by cryogenic hydrogen pellet

Steep density gradient arising in peripheral region after pellet ablation is regarded as a main cause of the transition. Establishing of a sheared radial electric field E_r in response to density gradient formation is conjectured as a main driving force of turbulence suppression causing H-mode triggering. Damping of turbulence was observed using microwave Doppler reflectometer.

Model of E_r development in presence of density gradient was developed in [5]:

$$E_r = \frac{T_i}{e}\left(\frac{\partial \ln n}{\partial r} + k_T \frac{\partial \ln T_i}{\partial r}\right).$$

Numerical simulation of E_r development in the experiments with pellet injection confirmed possibility to trigger H-mode with the above model.

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Physics of the Power Threshold Minimum for L-H Transition

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Recently, significant progress has elucidated the micro-dynamics of L→H transition [1–7]. However, the question of the physics of the micro-scopic $P_{\mathrm{th}}(n)$ scaling – and specifically the minimum in density – remains. Here, we study the physics of $P_{\mathrm{th}}(n)$, with the aim of linking microscopics and macroscopics. The roles of the electron/ion heating ratio and electron-ion coupling in the threshold physics of the L→H transition are the primary foci. A motivation for this is the C-Mod observation of the close relation between the Ohmic saturation density and the density minimum in the power threshold [8]. By extending a numerical 1D model to evolve both electron and ion temperatures, including collisional coupling, we find that the decrease in $P_{\mathrm{thr}}(n)$ along the low-density branch is due to the combination of an increase in collisional electron-to-ion energy transfer and an increase in the heating fraction coupled to the ions. Both processes strengthen the edge diamagnetic electric field needed to lock in the mean electric field shear for the $L \to H$ transition. The increase in $P_{\mathrm{thr}}(n)$ along the high-density branch is due to the increase with ion collisionality of the damping of turbulence-driven shear flows. Turbulence driven shear flows are needed to trigger the transition by extracting energy from the turbulence. Thus, we identify the critical transition physics components of the separatrix ion heat flux and the zonal flow excitation. The model reveals a power threshold minimum in density scans as a crossover between the threshold decrease caused by a rise in heat fraction coupled to ions (directly or indirectly, from electrons) and the threshold increase (at higher n) supported by the rise in shear flow damping. The electron/ion heating mix emerges as important to the transition, in that it, together with electron-ion coupling, regulates the edge diamagnetic electric field shear [9]. The importance to threshold scaling of collisionless turbulent electron-ion heat transfer processes [10] which is very relevant to electron heated discharges at low collisionality, is under study. Predicted modifications of the power threshold curve $P_{\mathrm{th}}(n)$ in collisionless regimes will be discussed.

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Magnetic Oscillations near L-H transition: experimental observations and comparisons with MHD theory.

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**See Appendix of F. Romanelli et al., 25th IAEA Fusion Energy Conference, 2014, Russia*

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We present a description of magnetic oscillations observed at JET near all L to H transitions (easier to observe with slow power ramps). The transitions take place in 3 steps:

1. Before: in the ohmic and L phases, High Frequency broad band axisymmetric magnetic oscillations (HFO) are observed [2];. Their frequency is of order 80 kHz, depending on plasma current, with a width of the order of 20 kHz.
2. At the L-H transition: start of an M-phase, with an n=0, m=1 magnetic oscillation (the M-mode, frequency of order 1 kHz), with clear pedestal density rise and weak temperature pedestal, medium confinement [1]. The HFO amplitude is modulated by the M-mode [2];
3. Conventional H-phase: both of the above oscillations disappear, density and temperature pedestals develop, confinement is improved and conventional ELMs are observed.

Additionally, dithering transitions between L and M phases are sometimes observed as well as an intermediate phase with type III ELMs between M and H phases.

First we present detailed experimental observations on the M-mode: changes in density and temperature are synchronised with apparent up-down plasma motion. Soon after the plasma reaches its top apparent position, particles and energy are released. The HFO is characterised magnetically, but it has not been observed so far in other diagnostics.

The frequency dependency of both M-mode and HFO scales with the poloidal Alfven wave velocity, both in Deuterium and Hydrogen plasmas. A theoretical model of the M-mode is presented, matching the observations. No model of the HFO is available yet.

Both observations and model indicate an electromagnetic distinction between L, M and H confinement phases, not explained by purely electrostatic fluctuation models.

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The Role of the Viscous Boundary Layer in the H-mode Threshold

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The transition from open to closed magnetic surfaces at the separatrix creates a viscous boundary layer that governs the E×B and parallel velocities. The toroidal and parallel momentum transport equations are solved in order to explore the role of different physical processes in the L-mode plasma leading up to the H-mode threshold. The H-mode threshold condition from the mean field transport model is shown to agree with observed turbulence conditions [1]. The Reynolds force build up at the separatrix prior to the H-mode transition is shown to be due to the poloidal ion velocity being driven away from its neoclassical value in the viscous boundary layer. The influence of the collisional poloidal flow damping and ion orbit loss on closed flux surfaces are considered. In the scrape off layer, the parallel flows and sheath boundary at the divertor are shown to have important influences on the momentum balance. The L-mode velocity profile solutions will be compared with Langmuir probe and Charge Exchange Recombination data from DIII-D. Time dependent 1-D simulations of particle, electron and ion energy, toroidal and parallel ion momentum transport equations [2] are also presented. A simplified model for the transport fluxes due to turbulence and Coulomb collisions is used to illustrate the types of solutions possible. The suppression of turbulence by E×B velocity shear is the critical physics mechanism that causes a dynamic bifurcation to H-mode or limit cycle oscillations (LCO) that compare well with dithering H-mode transitions. Constraining the transport model with data from a DIII-D discharge, a reasonable fit to the observed oscillations [3] in the E×B velocity, density fluctuation amplitude and diamagnetic velocity are obtained. The frequency of the dithering can be matched with the LCO solutions.

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Near-Unity Aspect Ratio H-mode and ELM Studies

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The Pegasus Toroidal Experiment is an ultra-low aspect ratio (A < 1.2) spherical tokamak, enabling exploration of the unique plasma characteristics of the tokamak at near-unity A. Ohmic H-mode is attained in both limited and diverted magnetic geometries via high-field-side fueling and low edge recycling. The features of this regime are: reduced D_α emissions; formation of a quiescent edge and an edge current pedestal; increased rotational edge shear; increased central heating; energy confinement consistent with the ITER98pb(y,2) scaling; and the presence of ELMs.

The H-mode power threshold, P_{LH}, behaves quite differently at low-A compared to high-A operations. This threshold power has been studied in both limited and favorable SN diverted plasmas in Pegasus. It is found that Pegasus requires P_{LH} to be 10–20× higher than projected by the conventional ITPA08 scaling. This continues and emphasizes the trend indicated from NSTX and MAST that increasingly more power than predicted by the scaling is required as A decreases. Since the ITPA08 P_{LH} scaling is derived from high-A tokamak H-mode results, these findings hint at missing underlying physics in our understanding of the L-H power threshold that manifests at low-A. The power threshold on Pegasus is observed to increase with density in both topologies. However, unlike at higher-A, no minimum P_{LH} with density is observed. Also in contrast to higher-A tokamaks, where P_{LH} is ~2× higher in limited plasmas than diverted plasmas, the threshold in approximately the same in both limited and favorable SN diverted Pegasus plasmas.

Some of these results are consistent with the FM^3 model for the L-H transition.[1] This model predicts the density at which the minimum power threshold exists for Pegasus to occur at ~$1\text{x}10^{18}$ m^{-3} ($n_e/n_G << 0.1$), which is too low to be routinely accessed. The P_{LH} insensitivity to magnetic configuration on Pegasus is related to the model's prediction that $P_{LH} \sim q_{edge}^{-7/9}$. At low-$A$, q_{edge} is approximately the same in both limited and favorable SN plasmas. Hence, the P_{LH} for limited and diverted plasmas would be similar, as observed.

Two classes of ELMs have been observed on Pegasus. Small, Type III-like ELMs are present at input power $P_{OH} \sim P_{LH}$ and have toroidal mode number $n \leq 4$. At $P_{OH} >> P_{LH}$, large, Type-I-like ELMs with intermediate $5 < n < 15$ appear. The mode numbers for Type III ELMs at low-A are opposite those seen at large-A, which likely reflects an increased J/B peeling drive at $A \sim 1$. The unique edge plasma parameters afforded by near-unity A operations allow long-sought measurements of the edge current profile dynamics during an ELM. Such measurements on Pegasus with a multi-channel magnetic probe array show a complex, multimodal pedestal collapse and the subsequent ejection of a current-carrying filament.

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The formation, maintenance and collapse of the negative radial electric field during the L-H transition

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Bifurcation of the negative radial electric Er is found based on the ion orbit loss model in the tokamak edge [1]. This bifurcation mechanism provides a possible explanation for the formation of strong radial electric field during the transition from the Low (L) to the High (H) confinement regime observed in tokamak edge plasmas, including threshold power, transition time, isotope effect, width of H mode, etc.

In our model, the initial Er can be built up by ion orbit loss, than the negative Er will change the ion loss orbit in return and lead some new ion losses. As a result, Er can saturate at either a low or a high value depending on plasma parameters. When the ion temperature and density in the plasma edge exceed a threshold condition and there are enough ion losses inside the width Lr, the radial correlation length of plasma edge turbulence, of the last closed flux surface (LCFS), a self-sustaining growth in the negative Er can be triggered due to the interaction between the ion orbit loss and the radial electric field, leading to a strong negative Er in milliseconds, which are corresponding to the requirement of heating power threshold, the width of edge H mode, the structure of Er and the transition time as can be seen in the experiments. The isotope effect is also found in the bifurcation phenomena of the ion orbit loss and Er, for single-charge state element discharge a larger ion mass is found to correspond to a lower threshold for the self-sustaining growth, while for the multi-charge state element charge there can exhibit more multiple phenomena because of the incomplete ionization. The results are the same as the isotope scaling of the H mode experiment in Ref. [2] which dedicated that the power threshold of mixture HD is less than that of pure H and greater than that of pure D. The results also explain successfully the electron density dependence of the power threshold of ^{4}He in Ref. [3].

While the formation of the negative Er, the radial particle flows, the ion radial inward flow Γ_{iin} and radial outward electron flow Γ_{eloss}, are also formed in the same area. In the self-sustaining growth, the radial flow velocity Vr is easily deduced from the equations (11) and (13) in Ref [4]. It is only of the order Vr ~ 10^{-1} cm/s which is much less than the ion orbit loss velocity of the order V_{loss}~10^2cm/s, so they can be ignored. However, after the formation of the strong negative Er, the radial flow velocity Vr can reach 10^1cm/s order. On the effect of these radial flows the Er will become smaller, while ion loss orbit will correspondingly be changed. Thus the changed loss condition can lead to some new ion losses $d\Gamma_{iloss}$. Without other instabilities, if $d\Gamma_{iloss} < d\Gamma_{eloss} + d\Gamma_{iin}$, then the Er structure will collapse, otherwise the Er structure can be maintained.

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Impact of impurities and divertor conditions on transitions, pedestal, and ELMs

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That the divertor conditions and plasma impurity content have an impact on transitions and pedestal properties is well established. Experiments on many devices with both low- and medium-Z impurities have shown a generally positive impact of impurity content on global performance. These impurities are added in one of two main methods; pre-discharge machine conditioning (typically boron or lithium), or active extrinsic seeding (mainly nitrogen and neon) for divertor heat load control.

The installation of metal walls in several devices has allowed much lower impurity contents to be reached, facilitating a wide range of new experiments in recent years. In particular, the increase of confinement with impurity seeding in these devices seems to counteract the negative effect of increased density operation, which is required to reduce high-Z influx. Extensive analysis of these plasmas has revealed that the confinement improvement stems from improved pedestal stability, with core gradient lengths remaining constant.

The latest modelling of these results, focussing on predictive pedestal models, is presented, showing the key role of the pressure profile location relative to the separatrix. For fixed machine parameters the movement of the pressure profile, or even temperature and density separately, appears to be a dominating factor determining the pedestal performance in both carbon- and metal-walled devices. Several mechanisms are thought to be responsible for this, ranging from SOL/divertor cooling to turbulence excitation.

In addition to the impact on confinement, impurities have also been seen to alter the ELM characteristics in metal-walled devices. A typical observation in JET and AUG is that Type-I ELMs consist of a rapid event followed by a ”slow transport event” which further degrades the pedestal. Impurity seeding has been shown to reduce the duration of, and even eliminate, this second ELM phase. Although the mechanism for this remains unkown, observations on ELM filaments and divertor temperatures seem to point towards a scrape-off layer (SOL)-pedestal mixing phase after an initial MHD crash.

Both the change of pedestal structure and ELM behaviour points towards the SOL being an important boundary condition on the pedestal and, hence, main plasma performance; moving towards a fully predictive model of SOL-pedestal interactions is therefore of great importance to predict the performance of future devices.

Effect of varying number of ELM filaments on the behavior of divertor heat flux profile

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The behavior of wetted area (A_{wet}) of divertor heat flux footprints during the ELM is crucial for the determination of ELM mitigation requirements for ITER. Compared to the inter-ELM profile, A_{wet} has been observed to increase by the ELM in several tokamaks, including JET and ASDEX-U [1]. Also important is that A_{wet} increased with the size of ELM, *i.e.* the amount of energy released by the ELM, which keeps the peak heat flux (q_{peak}) from increasing substantially by ELMs. Formation of filamentary structures is common during ELMs; typically 10 – 15 filaments are formed during ELMs in JET, observed in the heat flux profile by the high speed IR camera, and the heat flux carried by these filaments is dispersed over a larger divertor surface area than the inter-ELM profiles. However, the number of filaments observed during ELMs in NSTX is significantly lower, typically below ~10 [2]. In NSTX the ELM heat flux tends to be more peaked near the strike point with a few (0 – 3) filaments, leading to a reduced A_{wet}, exacerbating the heat flux exhaust problem. When more ($\geq$ 3) filaments are present, the A_{wet} increases, similar to JET, but the increase is only by up to ~50% and is not sufficient for effective heat dispersal. As the ELM energy loss increases, A_{wet} rapidly decreases and q_{peak} increases, contrary to the trend seen in JET. Stability analysis confirms that current driven kink/peeling modes with low toroidal mode number are dominant for ELMs in NSTX [3], whereas pressure driven intermediate-n peeling-ballooning modes are usually observed for ELMs in other tokamaks [4]. Non-linear ELM footprint simulation using BOUT++ is in progress to compare to the observed divertor heat flux footprints. Experimental data for both NSTX and DIII-D ELMs will be presented for comparison.

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Behaviors of impurity in standard H-mode discharges and H-mode discharges with the presence of ITB in JET and DIII-D

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The behaviors of impurity in standard H-mode discharges and H-mode discharges with the presence of ITB in JET and DIII-D are investigated using self-consistent modeling of BALDUR integrated predictive modeling code in which theory-based models are used for both core and edge transport. In these simulations, a combination of NCLASS neoclassical transport and Multi-mode (MMM95) anomalous transport model is used to compute a core transport. The boundary is taken to be at the top of the pedestal, where the pedestal values are described using a theory-based pedestal model. This pedestal temperature model is based on a combination of magnetic and flow shear stabilization pedestal width scaling and an infinite-n ballooning pressure gradient model. The time evolution of plasma current, temperature and density profiles is simulated for each discharges including the impurity behaviors such as impurity accumulation and impurity transport.

Type I ELM characterization in JET with the ITER-like wall

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**See Appendix of F. Romanelli et al., 25th IAEA Fusion Energy Conference, 2014, Russia*

Experiments in JET with the new ITER-like wall (JET-ILW) have revealed that in conditions of high neutral recycling (with high external D_2 gas input and/or reduced divertor pumping) the change in wall materials (Be, W) can have a significant impact on H-mode plasma performance, not only affecting the pedestal parameters but also the pedestal recovery in between ELMs[1-2]. In order to develop a sufficient physics understanding of the impact of the wall materials on ELM dynamics, type I ELM characteristics in JET-ILW have been examined for a wider range of plasma conditions than in previous studies[3] and compared to those observed in JET-C. To this end, a database of low triangularity ILW H-mode plasmas over an expanded plasma current range (I_p=1.4-3 MA, B_T=1.7-2.8 T), with varying heating power (β_N=1.4-2.8) and plasma density ($n_{e,ped}$=2-6×10^{19}m^{-3}), has been compiled and analysed. Analysis of the JET-ILW dataset has shown that, while type I ELM characteristics (ELM losses and their parametric dependencies, ELM affected region and ELM duration) in H-modes with low D_2 gas rate (low recycling) are very similar to those observed in JET-C, the ELM behaviour in high recycling H-mode plasmas can be significantly different. In high density H-mode plasmas ($n_{e,ped}$>5×10^{19}m^{-3}), ELMs are larger and their frequency is smaller than in JET-C for similar pedestal parameters. Moreover, the pedestal collapse time after the ELM becomes longer (up to 10 ms)[1,3] than the ELM-related MHD event duration (Δt_{MHD}~0.3-0.4 ms, from magnetics) and the response of the neutral recycling to the ELMs in the divertor region does not match the standard behaviour observed at low density The different deuterium recycling properties of the W divertor, compared to the carbon surfaces, may be responsible of the different ELM dynamics seen in JET-ILW[4]. The evolution of the pedestal profiles during the ELM cycle will be examined alongside a set of sub-ms divertor and pedestal measurements to gain understanding of the physics mechanisms determining the ELM particle and energy losses and pedestal recovery after Type-I ELMs in JET-ILW.

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Pedestal Saturation and the Onset of the Quasi-Coherent Fluctuations between ELMs on the DIII-D tokamak

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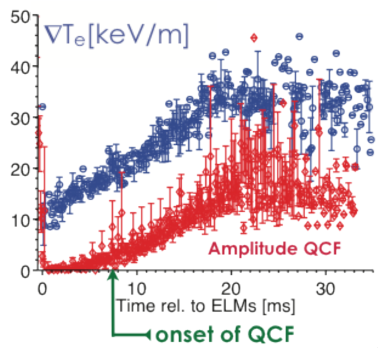

Figure 1: Evolution of the magnetic signal of the QCF and temperature gradient.

State-of-the-art measurements of the H-mode edge transport barrier recovery following edge-localized modes (ELMs) on DIII-D reveal new evidence that turbulent fluctuations play an important role in the saturation of the edge gradient in the inter-ELM period. Accurate reconstruction of the pedestal gradient recovery for density and temperature has been obtained, which show the faster recovery of the density gradient compared to the temperature gradient. Similar results have been observed on AUG [1]. Furthermore, identification of edge quasi-coherent fluctuations (QCFs) on multiple diagnostics is observed when the pressure gradient in the edge pedestal region of the plasma saturates following the ELM. This supports the hypothesis advanced in recent theoretical models that the threshold for the onset of kinetic ballooning modes (KBMs) sets the criteria for the saturation of the pressure gradient. Figure 1 shows a correlation between the onset of QCFs and the saturation of the edge temperature gradient following the ELM. The fluctuations are of the order of the ion gyroradius and are localized to the plasma edge based on beam emission spectroscopy (BES) measurements on DIII-D [2]. Similar results were observed on C-Mod: the QCFs are determined to be edge localized based on the reflectometry and the gas-puff-imaging measurements [3]. Magnetic measurements confirm the MHD nature of the fluctuations as expected for KBMs. The pedestal predictive EPED [4] model indicates that the pedestal pressure gradient reaches KBM critical gradient when the fluctuations are observed. In addition the EPED model predicts saturation of the pressure gradient, i.e., the observed gradient does not exceed the prediction after the onset of the instability. These results provide additional data toward validation of key theoretical predictions for the physics of the pedestal, which is essential for performing reliable predictions for the fusion performance of ITER plasmas.

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ELM energy losses in AUG with & without Nitrogen seeding

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Nitrogen seeding is typically used to reduce the heat loads on the divertor. Recently, it has been observed that nitrogen seeding can improve the confinement in metal wall machines [1,2,3] and can affect the ELM behaviour [4,5]. This work investigates the ELM behaviour in terms of energy losses and time scales of the ELM collapse in AUG with and without nitrogen seeding.

Without nitrogen seeding, two types of ELMs can coexist in the same AUG discharge. The first type (“fast” ELM) has a duration $\Delta\tau_{ELM}\approx0.5$ms and is characterized by energy losses in the range $\Delta W_{ELM}/W_{ped}\approx3$-10%. The second type (“slow” ELM) is significantly longer, $\Delta\tau_{ELM}\approx2.0$ms, and has higher energy losses, in the range $\Delta W_{ELM}/W_{ped}\approx6$-15%. The “slow” ELMs seem to be correlated with the expulsion of more filaments [6].

The “fast” ELMs tend to follow the standard trend with pedestal collisionality [7]. Due to the increased pedestal temperature produced by the nitrogen seeding, the energy losses of the “fast” ELMs are increased. Regardless of this, the injection of nitrogen significantly modifies the ELM behaviour. With a sufficiently high nitrogen level, the “slow” ELMs tend to disappear and, on average, the energy losses are reduced.

The “slow” ELMs are characterized by a divertor temperature in the pre-ELM phase that is higher by a factor 1.5-2.0 than the pre-ELM divertor temperature of the “fast” ELMs. JOREK simulations done on MAST shows that a low SOL temperature slightly reduces the ballooning growth rate and so the energy losses [8]. This might suggest that the disappearance of the “slow” ELMs is related to the cooling effect of the nitrogen in the SOL region.

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Effect of nitrogen and neon seeding in confinement and pedestal structure in JET with carbon and Be/W wall

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The reference scenario for achieving Q=10 in ITER is a type-I ELMy H-mode and an integrated scenario that combines both plasma performance of $H_{98(y,2)}$~1, β_N~1.8, $\langle n\rangle/n_{gw}$ ~0.85 (n_{gw} being the Greenwald density), high fuel purity Z_{eff}~1.6, together with edge parameters compatible with the Be/W plasma facing components. Achieving this plasma performance requires high pedestal pressure at high $n_{e,ped}/n_{gw}$, which is generally obtained at high triangularity through improved edge stability at high plasma shape (δ~0.4). While nitrogen seeding is planned for ITER, to achieve high divertor radiation and reduce the power reaching the divertor plate, a non-reactive divertor radiator, such as neon, is preferable. The pedestal is key in the challenging integration of plasma core performance and divertor conditions. This paper aims at establishing our current physics understanding of the role of low and medium-Z impurity on pedestal confinement which is critical in predicting the pedestal pressure in ITER.

It has been widely reported that on JET when operating with a metallic wall as opposed to a carbon wall there is a 30-40% reduction in performance [1,2].. Reintroducing low-Z impurities such as nitrogen can help recover the thermal stored energy. This recovery is largely due to a recovery of the pedestal pressure, which propagates to the core through profile stiffness. In JET this has so far been investigated in low β_N<1.5 plasmas at low and high triangularity, where with N_2 seeding the pedestal pressure (mainly temperature) was increased by 10% and 40% respectively. In AUG, seeding N_2 and CD_4 in β_N~2 plasma lead to a pedestal pressure improvement of up to 40% at low and at high plasma triangularity, and resulting from a temperature pedestal increase at similar net input power [3]. More recent JET results, using neon as seeding impurity, show no improvement in performance [4] with respect to the unseeded plasmas.

The focus of this paper will be to document the difference between Ne and N-seeding on the global and pedestal confinement at JET, looking critically at inter-ELM pedestal evolution, pedestal structure, Z_{eff}, divertor conditions to assess reasons for this difference in pedestal confinement. A similar study will also be done in N-seeded plasmas in low and high-shape to gather evidence on the mechanisms that leads with N-seeding and high-shape to higher pedestal pressure. An investigation of the JET-C seeded discharges will help in the identification of plasma conditions in which Ne behaves similarly to N and leads to pedestal improvement in JET-ILW.

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Role of zonal flow in the edge pedestal collapse

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A recent study [T. Rhee *et. al*., Nucl. Fusion, **55** 032004 (2015)] shows unequivocally that nonlinear dynamical processes play a key role in the edge pedestal collapse. A prominent example of this nonlinear interaction is the stochastization of field lines during the collapse. Stochastization occurs due to the growth of tearing modes by extracting kinetic energy of an adjacent unstable ballooning mode, eventually leading to the island overlap. This energy conversion between disparate parity modes happens via secondary tearing parity modes (STM) which are generated through a coherent nonlinear interaction between adjacent ballooning modes. In this way, an STM plays as an ***agent*** in the nonlinear energy transfer process delivering the kinetic energy of a ballooning mode to the magnetic energy of an adjacent tearing mode. In the present work, we extend the previous simulation study. Specifically, we focus on the role of zonal flow (ZF) in the stochastization process. When ZF is present, kinetic energy of unstable ballooning modes are distributed between STM and ZF. Thus, the growth of STM is hampered by ZF, leading to a potential prolongation of the ELM crash process. A key parameter in this process is the ratio of energy transfer to STM and ZF, the value of which will be presented. The implication of the present results to the phase dynamical interpretation of an ELM collapse [P. W. Xi *et. al.*, Phys. Rev. Lett., **112** 085001 (2014)] is also presented in detail.

The inter-ELM evolution of electron temperature and density H-mode pedestal profiles on JET with a metallic wall

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The current best understanding of the H-mode pedestal inter-ELM evolution is captured by the EPED model [1]. This model predicts the H-mode pedestal width and height when given a set of scalar input parameters. It assumes the pedestal will grow indefinitely until the onset of kinetic ballooning (KB) modes and peeling-ballooning (PB) modes. These two constraints can be solved for the two unknowns, the width and height. More specifically, after an ELM crash the pedestal can evolve unconstrained until reaching the KB stability boundary i.e. a critical gradient. After this for the pedestal height to increase further, the pedestal must widen at a fixed gradient to follow the KB stability boundary towards the PB stability boundary. This is consistent with measurements on DIII-D, MAST, NSTX and C-MOD [2, 3]. EPED is a key tool for both future and current devices. It facilitates predictions for ITER but also provides a platform to test and expand our understanding of the H-mode pedestal.

Inter-ELM measurements of the pedestal structure on JET with the carbon wall (JET-C) for a low deuterium fuelled plasma show the pedestal narrowed from 2.3+/-0.1 cm early in the ELM cycle to 1.6+/-0.1 cm just before the ELM crash [4]. This is not inconsistent with EPED as it is possible the pedestal is constrained very late on in the ELM cycle by KB modes. However, it is still challenging for the model as this is not apparent with the time resolution of the JET high resolution Thomson scattering (HRTS) system and furthermore this narrowing is not seen on other machines. A key aim of this study is to provide further context for these JET-C measurements. The pedestal measurements on JET with the ITER-like-wall (ILW) reported to-date have focused on the pre-ELM measurements. This study explores the inter-ELM evolution of JET-ILW HRTS pedestal profiles and quantifies the trajectory towards the PB stability boundary. This study critically assesses the significance and accuracy of the HRTS measurements. Initial analysis of a JET-ILW fuelling and seeding database [5,6] suggests the JET pedestal typically narrows or shows no significant change during the ELM cycle; consistent with previous JET-C results. However, at high collisionality, the measurements suggest the pedestal can also widen; this is particularly prominent for the density pedestal.

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Bifurcation to Expanded H-mode Pedestal Width and Improved Performance with Lithium Injection into DIII-D Discharges with Pre-existing Pedestal Localized Instabilities

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Lithium (Li) was injected into the DIII-D tokamak in discharges with an existing edge-localized instability. The pedestal gradients were reduced near the separatrix, inducing long ELM-free phases. The pedestal top pressure and energy confinement increased by 100% and 60% above the ELMy H-mode values during these phases. The pre-existing edge-localized instability increased the pedestal pressure width and reduced the average pressure gradient[1, 2]. This mode bursts in amplitude, up to ñ/n~8%, chirps in frequency, in the range of 40-150 kHz ("Bursty Chirping Mode" or BCM), and exists very near the separatrix in certain DIII-D discharges. The poloidal wavelength of this mode, $k_\theta \rho_s \sim 0.1$–0.2, and its electron drift direction propagation in the plasma frame are consistent with both trapped electron modes and micro-tearing modes, and it may be related to the "edge coherent mode" reported in EAST during active Li injection[3]. The BCM is typically observed in only 5-10% of ELM cycles, with subsequent ELMs terminating the mode. Injection of low levels of Li (45 μm spheres via a simple apparatus[4]) doubles the probability that the BCM will appear within ELM cycles, but only modestly alters ELM dynamics. When sufficiently high Li rates are injected into discharges with the BCM, however, the ELMs that terminate the BCM are delayed, leading to long ELM-free phases (duration < 350 ms) with controlled impurity content and steady radiated power, due to the enhanced particle transport from the BCM itself. In these cases the Li concentration at the pedestal top can exceed 15%, although the carbon concentration is reduced in such a way that the Z_{eff} increase is modest. Ideal MHD calculations including both the measured carbon and Li density indicate that the plasma is unstable to peeling/ballooning modes at the time of giant ELM onset. The change in the profiles with the BCM and lithium decreases the kink/peeling stability limit, but increases the ballooning limit, and more importantly, the maximum pressure gradient and current at the onset of peeling-ballooning modes.

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Effect of Helium on pedestal and stored energy in JET-ILW

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Helium ashes might have a significant effect on ITER, in part because of the dilution of the main ions, but also because of a degradation of the stored energy. The present work describes the impact of helium on the JET-ILW stored energy (W_{th}), focusing on pedestal structure and how the effect on pedestal affects the total W_{th}.

The work has been carried out on two sets of low δ baseline JET-ILW plasmas with I_p= 2.5MA, $q_{95}\approx3.0$ and two gas levels: $\Gamma_{D2} \approx 1.5\cdot10^{22}$ (e/s) and $\Gamma_{D2} \approx 3.5\cdot10^{22}$ (e/s). For both gas levels, the helium concentration is varied in the range 0-20%.

The increase of the helium concentration produces the reduction of the stored energy by approximately 5-10%, from $W_{th}\approx4.2$MJ to $W_{th}\approx3.9$MJ. The pedestal stored energy is mainly unaffected by the helium and the performance degradation is driven only by the core energy reduction (10-15%).

At the pedestal, the increase of the helium concentration produces the reduction of the pedestal temperature and the increase in the pedestal density. As a result, the pedestal pressure is almost unaffected but the collisionality is increased by a factor 3. The temperature profiles are stiff and do not show any trend with collisionality. Instead, the density peaking shows a clear reduction at high collisionality, as also typically observed in JET and in other devices [1,2].

Due to the temperature profile stiffness, the reduction of the pedestal temperature is reflected into a reduction of the core temperature. On the other hand, the increase of the pedestal density is compensated by the reduction of the density peaking due to the higher collisionality. Therefore, no major changes in the core density are observed. The overall process leads to the reduction of the core pressure.

The work will then investigate the pedestal structure, in particular the dependence of the density and temperature pedestal width on the Helium concentration.

The pedestal behaviour is further investigated by studying the peeling-balooning stability to verify if the effect of helium is consistent with the peeling-balooning model. The pedestal structure behaviour is then investigated by comparing the experimental results with the prediction from a EPED-like model [3].

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Impact of detached divertor on the pedestal region

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Modeling of detached regimes for ASDEX Upgrade performed with B2SOLPS-ITER code demonstrates existence of cold and dense highly radiating region in the *X*-point vicinity in qualitative agreement with experimental observations. In this region strong potential and strong electric fields are obtained in the simulations. The corresponding ExB drifts along equipotentials leads to mixing of density in detached SOL and core plasma.The increase of the density on the coreflux surfaces in the pedestal region takes place as a result of this mixing.

Pressure perturbation in the vicinity the *X*-point leads to redistribution of the parallel flows on the coreflux surfaces which changes the radial electric field. As a result the radial electric field inside the edge transport barrier becomes smaller in absolute value than the neoclassical electric field in contrast to the results obtained for high recycling regimes.

Extended pedestal width in JET H-mode plasmas with a metallic Be/W wall

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In high δ H-modes on JET-ILW, the pedestal pressure remains constant similarly to that observed at low δ. The pedestal pressure width is observed to be approximately consistent with the $\beta_{\mathrm{p,ped}}^{1/2}$ dependence. However, with increasing D_2 gas rate, the pedestal is found to broaden at constant $\beta_{\mathrm{p,ped}}$ [1].

Recent edge stability analysis of low δ H-modes at high D_2 gas injection [2] indicates that the pedestal before the ELM crash is in many cases unstable against the ideal infinite n ballooning mode. The ideal infinite n ballooning mode is a very localised instability with a zero mode width and is not likely to cause MHD events such as ELMs. Therefore, it could be presumed that while ELMs are ultimately triggered as a result of the increased edge current at high n ballooning instabilities, the pressure gradient at the pre-ELM state is constrained by the ideal infinite n ballooning stability limit.

According to the simulation of the pedestal stability based on artificial pressure profiles with a fixed pedestal width, a larger pressure gradient induces a larger bootstrap current which is enough to destabilise the pedestal by an intermediate n ballooning mode. This is likely to correspond to the low D_2 puff case. On the other hand, a lower pressure gradient with the same pedestal width leads to only a small bootstrap current, which is not enough to destabilise the pedestal. Under the condition where the pressure gradient is constrained by high n ballooning mode, the pedestal could be destabilised only when the pedestal width extends inwards to increase the bootstrap current. This is likely to correspond to the high D_2 puff case. The extension of pedestal width with this physics picture has also been observed in high density H-modes on JT-60U [3]. The analysis is underway based on JET experimental data to confirm if this hypothesis can explain the broadening pedestal width at high D_2 puff case.

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