Progress in understanding the physics of the H-mode pedestal and ELM dynamics

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The height of the edge transport barrier, or pedestal, sets the boundary condition for high confinement (H-mode) operation in tokamaks. In H-mode plasmas the edge transport barrier generally coexists with and is limited by edge instabilities, the Edge Localised Modes (ELMs). Despite significant progress both in experiments and models, the uncertainties associated with the H-mode pedestal conditions are such that the fusion performance of burning plasmas, such as ITER, can be predicted at best within a factor of two.

The paper reviews recent progress in the understanding of H-mode pedestal physics and ELM dynamics. In particular, recent results on multi-machine pedestal scaling with various plasma parameters, such as normalized ion gyroradius and beta, are summarized and discussed in light of advances in pedestal models. Significant improvements in edge diagnostics, such as fast visible and IR cameras, high spatial and temporal resolution Thomson scattering and edge CXRS, allow studying profile dynamics in inter-ELM phases as well as during the ELM crash. Recent measurements of the temporal evolution of pedestal parameters in inter-ELM phases are also reviewed. All these findings provide stringent tests to current pedestal models, improved confidence for extrapolations to future devices and highlight areas where experimental and modelling work needs to be intensified.

Effect of Anomalous Transport on Simulations of H-mode Pedestal Growth

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Simulations are carried out using the XGC0 gyrokinetic code [1] to investigate the effects of anomalous transport on H-mode pedestal growth at the edge of tokamak plasmas. Reduced models for anomalous transport are needed in the XGC0 code in order to complement the neoclassical and neutral particle effects that are computed in the kinetic part of that code. Three classes of reduced anomalous transport models, with increasing levels of complexity, have been implemented in XGC0. For the simplest class, particle and thermal diffusivities are prescribed with values that can be different in the pedestal, just inboard of the pedestal, and in the scrape-off-layer parts of the edge plasma. For the next level of complexity, simple analytic models are used to investigate the effects of transport stiffness and flow shear stabilization in a way that can be carefully controlled. Finally, stiff, physically relevant, theory-based models such as the Multi-Mode [2,3] transport models are used to compute anomalous thermal and particle transport. The theory-based transport models have been implemented in XGC0 using the Framework for Modernization and Componentization of Fusion Modules (FMCFM). In these models, transport is suppressed in the pedestal by high values of the flow shear rate $\partial(E_r/B)/\partial r$, in which the radial electric field, E_r, is self-consistently calculated in the XGC0 code, B is the toroidal magnetic field and r is the minor radius. There is a competition between the strong flow shear suppression of anomalous transport and the strong driving force for the stiff transport models resulting from the steep temperature and density gradients in the H-mode pedestal. XGC0 simulations are used to provide insight into how thermal and particle transport, together with the sources of heat and charged particles, determine the shape and growth rate of the temperature and density pedestal profiles.

[1] C.S. Chang, S. Ku and H. Weitzner, Phys. Plasmas **11** (2004) 2649

[2] G. Bateman, *et al,* Phys. Plasmas **5** (1998) 1793

[3] F.D. Halpern, PhD thesis, Lehigh University (2008)

Edge Stability Studies at high <j_{edge}/B> in the PEGASUS Toroidal Experiment

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Large-scale, coherent, high-m filamentary edge instabilities are routinely observed under conditions of high edge current density in the PEGASUS Toroidal Experiment. These instabilities exhibit properties strikingly similar to Edge Localized Mode observations in large, high-performance advanced tokamak plasmas. In particular, the filaments are observed via high-speed imaging and local magnetic field fluctuation measurements to have low- to intermediate-*n*, large poloidal coherence lengths (over the majority of the poloidal cross-section), to rotate in the poloidal direction, and to explosively detach from the plasma edge region and propagate radially outward. Local edge measurements with scanning magnetic and electrostatic probes indicate these ELM-like structures have both magnetic and electrostatic turbulence properties. A coherent electromagnetic signature is particularly evident in the 100-200 kHz spectral range. This signature vanishes rapidly with distance from the last closed flux surface, consistent with a MHD origin and high *m*. These ELM-like structures may be explained by peeling-ballooning stability theory. The extremely low-**B** ($B_{t,0} \leq 0.1$ T at $R_0 = .45$ m) and high edge current density ($j_{edge} \approx 100$ kA/m^2) present in PEGASUS leads to high peeling instability drive, proportional to <j_{edge}/B> , that is comparable to that achieved in H-mode operation on larger experiments. It is thus reasonable to expect peeling modes in PEGASUS, although the large relative <j_{edge}/B> is due to the naturally very low magnetic field and strong dI_p/dt (≤ 50 MA/s) driving j_{edge} as opposed to the presence of a strong pressure gradient and bootstrap current in the edge. PEGASUS, as a very low-field ST, offers a unique opportunity to study detailed properties of peeling-ballooning instabilities, in that the edge current and pressure profiles can readily be measured in detail via insertable probes. To that end, a new magnetic probe array and a scanning Langmuir probe assembly are being installed on PEGASUS. They will provide measurements of $P_e(R,t)$, $B_z(R,t)$ with high spatial and temporal resolution for comparison to peeling-ballooning stability theory with direct experimental constraint on the both the edge current and pressure profiles in equilibrium reconstructions.

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Creation of Quiescent H-Mode Discharges in DIII-D with Edge Rotation Ranging from Strong Counter to Strong Co-Rotation*

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In recent experiments in DIII-D, we have investigated the behavior of quiescent H-mode (QH-mode) plasmas as a function of plasma rotation. These investigations have produced two significant discoveries. For the first time on any tokamak, we have created QH-mode plasmas with strong edge co-rotation; previous QH-modes in all tokamaks had edge counter rotation. This result demonstrates that counter neutral beam injection and edge counter rotation are not essential conditions for QH-mode. Second, in discharges with edge counter rotation, we have found that we can control the edge pedestal density and pressure by altering the edge particle transport through changes in the edge toroidal rotation. This allows us to adjust the edge operating point to be close to, but below the edge localized mode (ELM) stability boundary, maintaining the ELM-free state while allowing up to a factor of two increase in edge pressure. The ELM boundary is significantly higher in more strongly shaped plasmas, which broadens the operating space available for QH-mode and leads to improved core performance. Both of these investigations benefited from the edge stability predictions based on peeling-ballooning mode theory. The broadening of the ELM-stable region with plasma shaping is predicted by that theory. The theory has also been extended to provide a model for the edge harmonic oscillation that enhances edge transport in the QH-mode. Many of the features of that theory agree with the experimental results. One notable example is the prediction that co-rotating QH-mode is possible provided sufficient shear in the edge rotation can be created.

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Analysis Of Pedestal Transport*

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Background. While 1.5D transport models are used in the hot core, 2D models are usually used in the separatrix and divertor regions. Both models can be extended into the H-mode pedestal region. To clarify plasma transport properties in the pedestal and determine which are most important there, we have undertaken an H-mode Edge Pedestal (HEP) Benchmarking Exercise (BE) for a single DIII-D pedestal. Codes used include 1.5D interpretive (ONETWO,WMS), 1.5D predictive (ASTRA) and 2D (SOLPS,UEDGE) codes.

DIII-D Pedestal Case. The particular DIII-D discharge considered is 98889, which is in the ITER H-mode profile database. The modeled pedestal is a typical low density case in near transport equilibrium; plasma profiles for it are obtained from Thomson and CER data averaged over the last 20 % of the $\sim$ 36 ms repetition time between Type I ELMs. The top of this pedestal has $T_e \simeq 750$ eV, $n_e \simeq 3\times10^{19}$ m^{-3} with electron collisionality $\nu_{*e} \simeq 0.35$, at $\rho \simeq 0.95$. The maximum T_e gradient point (midpoint) is at $\rho \simeq 0.978$ ($R_{\rm sep} - R \simeq 6$ mm) where T_e, n_e are a factor of about two smaller and ν_{*e} is a factor of 2 larger. At the separatrix $T_e \simeq 78$ eV and $n_e \simeq 0.7\times10^{19}$ m^{-3}. Convective heat transport is found to be a small fraction of the electron (10 %) and ion (25 %) heat flows in this pedestal.

Modeling Issues. The 2D transport analysis codes determine the variation of plasma parameters on a flux surface. They use a combination of Braginskii (collisional) transport along field lines and a Fourier heat flux law $\mathbf{q} \equiv -n\chi(\rho)\boldsymbol{\nabla}T$ for radial transport. Modeled temperature variations are sinusoidal (Pfirsch-Schlüter-type) at all radii up to within about 1 mm ($\rho \simeq 0.996$) of the separatrix. The neutral density is largest in the divertor X-point region and varies by a factor $\lesssim 10^3$ on the separatrix. This causes neutral fueling, electron density and potential to vary substantially on flux surfaces in the bottom half of the pedestal ($0.978 \lesssim \rho \lesssim 1$). Radial heat flows vary poloidally by factors of 2–3 in the pedestal region [1] and are appropriately averaged for comparisons to 1.5D results; they are largest on the outboard midplane where flux surfaces are bunched and local radial gradients are largest.

Transport Inferences. The inferred diffusivities are smallest near the midpoint of the pedestal. Their minimum values are about 0.2–0.3 (electron heat), 0.1–0.2 (ion heat) and 0.02–0.04 (particle) m^2/s. Predictive transport modeling with ASTRA has shown (see Fig. 8 in [2]) that the pedestal T_e profile can be modeled using an ETG-induced $\chi_e^{\rm ETG}$ in the top half of the pedestal and a paleoclassical $\chi_e^{\rm pc}$ in its bottom half. The minimum ion heat diffusivity is of order the neoclassical value but has a different profile. The small effective particle diffusivity could be the result of an inward particle pinch nearly balancing a diffusive outward radial particle flux. These and other pedestal transport properties will be discussed, along with what measurements are needed to facilitate better pedestal transport modeling.

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[1] See for example W.M. Stacey, Phys. Plasmas **15**, 122505 (2008).

[2] T. Rafiq, A.Y. Pankin, G. Bateman, A.H. Kritz, F.D. Halpern, Phys. Pl. **16**, 032505 (2009).

Limits to H-mode Pedestal Pressure Gradient in DIII-D*

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The temporal evolution of the total pedestal pressure profile has been measured during the full edge localized mode (ELM) cycle of Type I ELMing H-mode discharges in DIII-D in order to test models of pressure-gradient limiting phenomena. Scaling studies with linear peeling-ballooning theory predict that the pressure gradient at an ELM crash scales approximately as the product I_pB_T [1]. This scaling is a good description of the maximum pressure gradient in scans of I_p and B_T, with measurements made just before an ELM crash. For the inter-ELM period, a new model predicts that kinetic ballooning (KB) modes are excited during build-up of the pedestal and cause saturation of the pressure gradient prior to an ELM [2]. Measurements made during the inter-ELM period show that the pressure gradient varies by a factor of ~3–10 across the pedestal. The general trend is for gradients to increase with time during the inter-ELM cycle; an increase in pedestal width is often observed as well. However, some regions of the profile, particularly in the outer half of the pedestal, can reach an approximate steady state long before an ELM crash. Even when this happens, the pressure gradient often continues to increase in other parts of the pedestal. The saturation of gradients might be a sign of gradient limiting phenomena, but further analysis is required to determine if KB modes are responsible.

[1] P.B. Snyder et al., 2004 *Plasma Phys. Control. Fusion* **46** A131.
[2] P.B. Snyder et al., 2008 *Phys. Plasmas* **16** 056118.

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H-mode pedestal regulation experiments on Alcator C-Mod

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Recent research on Alcator C-Mod has achieved greater leverage on global confinement through both optimization and active modification of the edge pedestal. In particular, regimes are being explored which break from the typical robust linear dependencies of pedestal density (n_{ped}) and temperature (T_{ped}) on plasma current. In H-mode, pedestal parameters show a striking sensitivity to the ion ∇B drift direction, relative to the active x-point position, with considerable variability observed when the distance between separatrices is on the order of the pedestal width (≈5mm) or less, *i.e.* near double null (DN). Near DN H-modes with favorable ∇B drift direction can have improved confinement factors ($H_{98}>1$) as a result of elevated T_{ped}, with the edge regulated by benign small ELMs or continuous modes, regimes desirable for ITER and other future devices. If, instead, the magnetic balance is biased slightly toward the unfavorable ∇B drift direction, a 20—30% reduction in pedestal density n_{ped} is observed.

The reduced density H-modes realized through regulating magnetic balance have provided accessible targets for lower hybrid range of frequency (LHRF) waves. Application of LHRF has induced further H-mode density reduction, accompanied by strong relaxation of pedestal ∇n and increases in T_{ped}, all at fixed or even slightly increasing pedestal pressure. Contrary to usual experience, steady EDA H-modes with no ELMs are maintained despite edge collisionality reductions of 2—3. Changes in edge density fluctuations, along with elevation of scrape-off layer density, accompany the application of LHRF (at levels as low as 400kW) with a fast time response (~10^{-2} s), suggesting prompt response of edge particle transport, presumably via direct interaction of the LHRF with the edge plasma. Full density pedestal relaxation, core density reduction, and global temperature rise occur on longer time scales (~10^{-1} s), conveniently relaxing the discharge to a state more conducive to wave penetration and damping. In all cases, strongly modified pedestals modify core properties, often including surprising effects on core rotation. Understanding the responsible physical mechanisms and applying them to a broad range of H-mode discharges would provide a tool for improving density control, affecting edge MHD stability and applying modulation for transport studies.

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Dependence of plasma performance and ELM behaviour on the transport characteristics of the H-mode pedestal

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This paper presents a systematic study of how the shape of the edge pressure gradient profile within the H-mode pedestal affects plasma performance, the shape and localization of the eigenfunctions of the unstable modes and ELM behaviour. Initially, different systematically varying edge pressure profiles have been obtained in a series of predictive transport simulations by introducing tiny edge transport perturbations within the pedestal. These transport perturbations can be thought of as resulting from e.g. toroidal magnetic field ripple or edge ergodization.

Ideal linear MHD stability analysis of the series of predictive transport simulations indicates that plasmas with the maximum pressure gradient located near the top of the pedestal generally sustain a considerably higher level of pressure gradient than plasmas with the maximum pressure gradient occurring just inside the separatrix. As a result of this, plasmas of the former kind feature considerably better pedestal performance. It has been shown that the improved performance can be attributed to the fact that the bootstrap current is effectively suppressed in the vicinity of the separatrix in these plasmas, whereby kink and peeling modes remain stable and stability is controlled by medium n ballooning modes. The simulation results are compared against plasmas from recent JET experiments, such as experiments with ELM mitigation by means of vertical kicks [1]. It is shown that even small shifts of the experimental data, say a radial shift of the order of 1% in terms of normalized poloidal flux, can change the MHD stability of the pedestal dramatically.

The structure of the eigenfunctions of the unstable modes in the simulation plasmas with different edge pressure gradient profiles has been studied. It has been found that the maxima of the eigenfunctions typically coincide with the radial location of the maximum pressure gradient and that the widths of the eigenfunctions depend on the pedestal width and the width of the region with the steepest pressure gradient within the pedestal.

Making use of the above results, the effect on ELM behaviour has been studied. Using a theory-motivated ELM model, the ELM amplitude and ELM duration have been calculated self-consistently in predictive transport simulations. It has been found that in plasmas with the pressure gradient maximum occurring near the top of the pedestal, the ELMs become less frequent and more violent. The opposite effect has been observed in plasmas with the pressure gradient maximum near the separatrix. The results seem to go in line with the experimental trend deduced in experiments with enhanced toroidal magnetic field ripple at JET that there is a trade-off between confinement and the severity of ELMs [2].

[1] E. de la Luna *et al*, 36th EPS Conference on Plasma Physics 2009.
[2] G. Saibene, N. Oyama, J. Lönnroth *et al*, Nucl. Fusion **47** 969 (2007).

Pedestal studies in co- and counter-current NBI discharges on MAST

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The avoidance or mitigation of edge localised modes (ELMs) is currently a high priority research goal for the fusion community, due to the incompatibility of ELMs with plasma facing components in future large devices such as ITER. This makes control of the edge transport barrier (ETB) necessary either by regime development or active mitigation techniques. The physics determining the strength of, or the mechanisms affecting the ETB are, however, not well understood yet. A key role is attributed to the edge radial electric field, E_r, because turbulent transport can be suppressed by a sheared $E \times B$ flow. Another important player may be the impact of recycling on the density pedestal, in particular for smaller devices.

On MAST, experiments have been performed to study the relationship between edge electron density, n_e, and temperature, T_e and E_r. New high resolution measurements of the edge ion temperature by charge exchange of C^{6+} with excited $\mathrm{D}^{\star}$ in a thermal gas jet augment the set of edge diagnostics. Pedestal characteristics were also measured in discharges with He as the main ion species and in discharges with counter-current neutral beam injection (cntr-NBI).

The cntr-NBI H-modes behave quite differently from the co-current (co-NBI) NBI H-modes. Despite the prompt loss of about $2/3$ of the injected fast-ion population with cntr-NBI similar plasma energy $W_{\mathrm{pl}} \approx 0.1$ MJ as with co-NBI is achieved. However, these discharges have no clear pedestal structure, but show large ELMs despite the low pressure gradient. Also the electric field well just inside the last closed flux surface is less pronounced in cntr-NBI than in co-NBI with E_r becoming more negative towards the plasma core. An edge localised continuous mode similar to the edge harmonic oscillation has been observed in these cntr-NBI H-modes without showing the other signs of the attractive quiescent H-mode regime.

The L/H threshold has been compared between He discharges and D discharges and nearly twice the injected power $P_{\mathrm{NBI}} = (2.6 \pm 0.2)$ MW is needed to enter H-mode in He compared to D. The pedestal profiles show no marked differences despite the different recycling of these two ion species. This seems to be different to recent results on ASDEX Upgrade.

With the application of resonant magnetic perturbations, E_r becomes more positive in L-mode cases where a clear density pump-out is observed. This is implies achange in the field line structure at the plasma edge. Below a certain threshold perturbation no change in E_r is observed. The effect of the applied perturbation, however, seems to vary with time as the density is pumped-out. In H-mode so far no effect on E_r of the perturbation field is observed.

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Characterization of type I ELM filaments on JET and ASDEX Upgrade using magnetic signals

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It is now a well accepted fact that an ELM results in a medium number of filamentary structures being expelled from the plasma pedestal into and through the scrape off layer (SOL). The energy and particle loss by ELMs has in the past been the focus of investigations, while less is known about losses of momentum and current. This contribution is focused on investigating the magnetic signatures of type I ELM filaments using the perturbation of the magnetic field they cause. By applying magnetic pick-up coils we measure the magnetic perturbations induced by the moving filaments and in term estimate the current carried by the filaments.

On JET a limited number of high time resolution magnetic coils were used to derive essential ELM filament parameters. The method uses forward modeling and simultaneous fitting of a number of magnetic pickup coil signals to a simple model, motivated by observations. Key parameters such as quasi toroidal mode number, radial and toroidal velocity of the filaments as well as their peak current can be fitted. The resulting values are in good agreement with other observations [1].

Using the same method, ELM-postcursors, as f.x. the Palmtree mode [2], were investigated and found to consist of localized rotating current structures.

While measurements on JET are limited to wall mounted pickup coils, a new diagnostic in the form of a reciprocating probe with three magnetic pickup loops was developed for ASDEX Upgrade. All three spatial components of the magnetic field perturbations can be measured rather localised due to the smallness of the coil system [3]. ELM and inter-ELM phases show significantly different signatures in the perturbation signals from the three magnetic field components. Detailed measurements of the magnetic field perturbation during the passage of type-I ELM filaments show that these carry substantial amounts of current [4]. The actual values are in rough agreement with the values found at JET.

[1] P. Migliucci and V. Naulin, submitted to Nuclear Fusion (2009).
[2] H. Koslowski et al., Nuclear Fusion 47, 201, (2005).
[3] C. Ionita, N. Vianello, H.W. Müller, et al., *J. Plasma Fusion Res. Series*, in print (2009).
[4] N. Vianello, V. Naulin, R. Schrittwieser et al., to be submitted to PRL (2009).

Scaling of the H-mode Pedestal Characteristics with Gyro-radius in the DIII-D and JET Tokamaks*

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The dependence of the H-mode edge transport barrier width on ion gyro-radius ($\rho^*=\rho/a$) in discharges with Type I ELMs was examined in experiments combining data from the JET and DIII-D tokamaks. The plasma shape, q, normalized pressure (β), collisionality (ν^*), Mach number, and the ratio of ion to electron temperature at the H-mode pedestal top were kept constant, while ρ^* was varied by a factor of four. ρ^* scans were carried out in both low and high triangularity shapes. The width of the steep gradient region of the electron temperature (T_e) and density (n_e) profiles showed only a weak if any dependence on ρ^*, $\Delta/a \sim (\rho^*)^{0.0+/-0.15}$. In particular a dependence of $\Delta/a \sim (\rho^*)^{0.5}$ was ruled out to an 80% confidence level. The pedestal pressures and widths were consistent with predictions of the EPED1 model [1] where $\Delta/a \sim (\beta_P^{PED})^{1/2}$, including an observed increase in width at higher triangularity. In DIII-D, the n_e profiles shifted outward relative to T_e as pedestal n_e increased with decreasing ρ^* consistent with a particle source effect, however on JET the profiles remained aligned. The ELM energy loss normalized to the pedestal energy increased from 10% to 40% as ρ^* increased by a factor of 2 in DIII-D, but the trend did not continue in the smaller ρ^* JET discharges where the ELM energy loss was relatively fixed. Although the ELM depth increased at high ρ^*, the peeling-ballooning eigenmode width was relatively unchanged.

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Comparing 1.5D ONETWO and 2D SOLPS Analyses of Inter-ELM H-mode Plasma in DIII-D[*]

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A 1.5D radial transport analysis of the DIII-D inter-ELM H-mode plasma of discharge 98889 is compared to 2D full-plasma (core, edge, SOL and divertor) simulations in order to investigate the effects on pedestal transport of divertor and SOL processes and of poloidal asymmetries that are not explicitly included in a 1D interpretative core analysis. The 1.5D code ONETWO solves a complete plasma/neutrals transport model inside the separatrix in cylindrical geometry. External particle and energy sources from neutral beam injection are calculated with a Monte Carlo beam deposition package. SOLPS is a suite of codes, the main component of which is the 2D plasma transport code B2.5 coupled to the Monte Carlo neutrals code Eirene. Radial profiles of the beam particle and energy sources and the interpretative transport coefficients D, χ_e and χ_i are taken from the ONETWO simulations, assumed to be flux surface quantities, and mapped to the 2D SOLPS grid inside the separatrix.

The two codes give almost identical upstream radial profiles of main ion densities and temperatures. Good agreement of the C^{6+} density is obtained with a constant chemical sputtering yield at the divertor plates. Flux surface compression on the low field side leads to significant radial and poloidal flux asymmetry in the pedestal, but flux surface averaged SOLPS fluxes agree with those from ONETWO. Divertor fueling across the X-point is the dominant source of poloidal asymmetry in the ion and neutral density distributions. Plasma temperature asymmetries in the pedestal are small. Shallower fueling (in ρ or ψ space) in the flux-expanded X-point region is partly compensated by the energy gain resulting from multiple charge exchange in the divertor.

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Effects of edge collisionality on ELM characteristics in grassy ELM regime

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Establishment of H-mode operation with small ELMs is one of the important and urgent issues for ITER. The grassy ELM regime found in JT-60U has been considered as one candidate for the H-mode operation with small ELMs, since grassy ELMs can be obtained in plasmas with low collisionality and low toroidal rotation [1]. Small ELMs similar to grassy ELMs in JT-60U have been reproduced in ASDEX Upgrade only when edge collisionality was less than unity [2], suggesting an importance of the edge collisionality (ν_e^*) to determine the ELM characteristic. Based on these experimental results, effects of ν_e^* on ELM characteristics have been investigated in grassy ELM regime.

The experiments were performed with the toroidal magnetic field of B_T = 2.5 T for a low q case (q_{95} ~ 4.3) and B_T = 3.9 T for a high q case (q_{95} > 6) at the plasma current of 1.0 MA. The plasma triangularity, which is one of the important parameter to obtain grassy ELMs, was higher than 0.5 and well inside the operational regime for grassy ELMs [3]. The dedicated comparison between plasmas with similar β_p, the edge toroidal rotation and the pedestal pressure indicates that the ELM amplitude increases with increasing ν_e^* toward unity in both high and low q regimes. For larger grassy ELMs, larger losses of the edge density evaluated near the top of pedestal are confirmed by fast edge density profile measurement using a lithium beam probe. This collisionality dependence for grassy ELMs is opposite to the dependence for type I ELMs, where the ELM amplitude decreases with increasing the edge collisionality. In the previous stability analysis, both type I ELM and grassy ELM can be considered as the same MHD instability of peeling-ballooning mode having different radial structure of the eigenfunction of the most unstable mode. The different edge stability due to different edge plasma current density is a possible candidate of the reason for the observed collisionality dependence in grassy ELM regime. Therefore, the results of edge stability analysis will also be presented.

[1] Oyama, N., et al., Plasma Phys. Control. Fusion **49** (2007) 249.
[2] Oyama, N., et al., Plasma Phys. Control. Fusion **48** (2006) A171.
[3] Oyama, N., et al., Nucl. Fusion **45** (2005) 871.

Kinetic neoclassical scaling of the H-mode pedestal including ELM stability

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The pedestal width and structure are critical components of H-mode pedestal models [1, 2]. The multi-scale nonlinear nature of the problem makes development of such a scaling very challenging. Existing models for the pedestal width are based on simplified theoretical approaches or on experimental scaling. In this study, first principles' kinetic simulations of the neoclassical pedestal dynamics are combined with the MHD stability conditions for triggering ELM instabilities that limit the pedestal width and height in H-mode plasmas. The neoclassical kinetic XGC0 code [3] is used to produce systematic scans over plasma parameters including plasma current, elongation, and triangularity. As plasma profiles evolve, the MHD stability of these profiles is analyzed with the ideal MHD stability ELITE code [4]. The scaling of the pedestal width and height is presented as a function of the scanned plasma parameters. Simulations with the XGC0 code, which include coupled ion-electron dynamics, yield predictions for both ion and electron pedestal profiles. Differences in the electron and ion pedestal scalings are investigated. This study includes reduced models for several important physical effects at the plasma edge. In summary, this study should be considered as a first step towards the goal of developing a full first principles' model for width and structure of the H-mode pedestal.

[1] T. Onjun, G. Bateman, A.H. Kritz, and G. Hammett, Phys. Plasmas **9** (2002) 5018.

[2] P.B. Snyder, R.J. Groebner, A.W. Leonard, T.H. Osborne and H.R. Wilson, Phys. Plasmas **16** 056118 (2009).

[3] C.S. Chang, S. Ku and H. Weitzner, Phys. Plasmas **11** (2004) 2649.

[4] P.B. Snyder, H.R. Wilson, J.R. Ferron, Phys. Plasmas, **9 (**2002) 2037.

Inter-machine study of the baseline neoclassical scaling law on H-mode pedestal width from XGC0 kinetic simulation[1,2]

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In the H-mode pedestal before the ELM onset, nonlocal neoclassical self-organization is an important physical effect, to set the baseline pedestal width scaling law. Deviation from the neoclassical scaling will define the anomalous scaling. The neoclassical self-organization includes effects from the self-consistent radial electric field shear, strong magnetic field shear, ion orbit loss across the last closed magnetic surface, finite ion banana width, particle source from neutral ionization, heat flux from the core plasma, and collisional transport. XGC0 code is used to perform an inter-machine study of the neoclassical pedestal scaling law between two representative devices DIII-D and C-Mod. DIII-D is chosen to represent the low B-field, low collisionality, and high temperature devices, and C-Mod is chosen to represent the high B-field, high collisionality, and low temperature devices. The numerical scaling law will be compared with experimental data from the two machines. Anomalous component in the experimental pedestal width scaling will be separated out from the neoclassical component. Prediction for ITER pedestal will be attempted based upon the combined neoclassical (theoretical) and anomalous (empirical) scaling laws obtained in this study.

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[2] Work supported by US DOE Office of Fusion Energy and Office of Advanced Scientific Computing Research

Characterization of magnetic perturbation spectra of Edge Localized Modes in JET plasmas

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Edge Localized Modes (ELMs) are quasi-periodic oscillations involving bursts of MHD activity occurring in improved confinement regimes (H-mode). lasting on JET typically less than 1 ms. ELMs appear with distinct features on different devices, so that - despite the number of theories available [1] - only a phenomenological description can be done at present [2]. Using a wavelet analysis combined with a two-point correlation technique, we reconstruct the toroidal mode number of ELMs during the burst and during the phases that immediately precede [3]. This method allows us to extract the coherent part of fluctuations from the incoherent background and to follow the evolution of the toroidal mode number spectrum with a time resolution comparable to the wave period. The magnetic perturbations spectra of type-I and type-III ELMs on JET are presented and discussed, and compared with those of ELMs triggered by pellets. A coherent mode number structure is measured for both type-I and type-III ELMs during a time window of approximately 0.4 ms before the burst, also in those cases where a coherent precursor to the ELM is not detected. The number of coherent modes involved increases in time until the burst, when the mode structure is destroyed. We find that type-I ELMs on JET start from low toroidal mode numbers, typically n=1,2 and that during the phases that immediately precede the crash the toroidal mode number increases in absolute value up to |n|>15. In experiments with pellet injection for ELM mitigation, triggered events have spectral features similar to ELMs that naturally occur in the same plasma background suggesting that the properties of triggered ELMs are determined more on plasma background parameters rather than on the pellet mass and velocity [4].

[1] JW Connor, Plasma Phys. Control. Fusion (1998) **40** 191.
[2] H.Zohm, Plasma Phys. Control. Fusion, (1996) **38** 105. *Ibid*. **38** 1213
[3] F.M. Poli *et al*, Plasma Phys. Control. Fusion, **50** 095009 (2008). FM Poli *et al*, JPFR |Series, in press.
[4] F.M. Poli *et al*, submitted to Nucl. Fusion

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[1] See the Appendix of F. Romanelli *et al*., Fusion Energy 2008 (Proc. 22nd Int. Conf. Geneva, 2008) IAEA.

Temporal evolution of electron density and temperature profiles in between type-I ELMs at ASDEX Upgrade.

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At ASDEX Upgrade the ECE diagnostic and the Lithium beam diagnostic deliver data with high spatial and temporal resolution. The alignment of the profiles in space is done via mapping to the midplane and comparison to Thomson scattering profiles, which delivers data for both, the electron density and electron temperature, from the same scattering volume. An equilibrium reconstruction on a 1 ms time base is used for mapping to the normalized poloidal radius.

A study of the profile behaviour for electron density and electron temperature in ELMy H-modes with varying gas puff levels is presented. The gas puff is changed in four discharges from $9 \cdot 10^{21}$ particles/s to $6 \cdot 10^{21}$, $4 \cdot 10^{21}$ and 0 particles/s. For all four cases the electron pressure gradient reaches the same value, a strong indication for a ballooning limit. When this upper pressure gradient is reached, the ELM does not yet break out, but a phase with large fluctuations in density and temperature is observed. Although the pressure gradient evolution is very similar in these discharges, the temporal behaviour of density and temperature occurs on different time scales. The maximal temperature gradient breaks down with the ELM, then recovers very quickly, i.e. within 1.5 ms to a steady value. At 4.5-5 ms after the ELM the maximal temperature gradient increases again and the phase with large fluctuation starts, indicating the start of a second, different transport mechanism. A detailed analysis of these temporally highly resolved data will be presented.

Pedestal Density Fluctuation Properties in H-mode Plasmas*

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The spatially resolved density fluctuation characteristics of the H-mode pedestal are measured in stationary Type I ELMing discharges and ELM-free quiescent H-mode on DIII-D with beam emission spectroscopy in order to characterize the pedestal structure and properties. ρ^* was varied by a factor of 2, while the other dimensionless parameters (β, collisionality ν^*, Mach number, and T_e/T_i at the pedestal top) were held constant. The fluctuation power spectra were found to vary significantly with ρ^*, while the radial correlation lengths were 1.5–2 cm and exhibited little variation with ρ^*. It is also observed that the pedestal width has little dependence on ρ^* [1]. Two distinct bands of fluctuations are observed to propagate in opposite poloidal directions: one low frequency band near 20–150 kHz in the ion-diamagnetic drift direction, and a higher frequency band around 200–400 kHz in the electron diamagnetic drift direction. The fluctuation amplitudes of both bands are modulated with the ELM cycles, rising monotonically between ELMs and crashing at the ELM. These features of the pedestal turbulence are compared with expected characteristics of theoretically predicted pressure-gradient limiting instabilities.

Related measurements in ELM-free "quiescent H-mode" (QH) discharges exhibit a set of coherent modes in the pedestal region ($0.90<r/a<1.0$) when the pedestal pressure exceeds a relatively high value. These modes appear in a band from 50–250 kHz, peaking in amplitude around 150 kHz, and have uniform frequency separation of about 10 kHz. These modes have significantly different spectral structure than the edge harmonic oscillation (EHO) often observed in QH discharges. The EHO typically terminates when these high frequency modes appear. Further analysis is required to determine if these modes are related to the kinetic ballooning modes that are predicted to limit the pedestal pressure. A detailed analysis of the characteristics of these modes will be performed and compared with ELITE calculations of pressure-gradient limiting peeling-ballooning modes.

[1] M.N.A. Beurskens, et al., EPS invited talk, Sofia, Bulgaria, 2009.

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