Annual Report of the ITPA Pedestal and Edge Physics Topical Group, 2012

Guido Huijsmans, Alberto Loarte, Rajesh Maingi and Naoyuki Oyama

The ITPA Pedestal and Edge Physics Topical Group has met twice during the year under the chairmanship of Naoyuki Oyama (JAEA, Japan) and strong assistance from the Deputy-Chairs Rajesh Maingi (JAEA, Japan), Guido Huijsmans (ITER Organisation) and Alberto Loarte (ITER Organisation). The first meeting was hosted by ASIPP (China) during 2-4 April, and the second was hosted by General Atomics (USA) during 15-17 October. Each meeting had around 40-50 participants from EU, US, China, Japan and S Korea. The experiments, modelling and simulation for ELM physics, ELM control methods, pedestal structure & evolution are progressed. In both meetings, joint session with Transport and Confinement Topical Group discussing L-H transition physics and 3D physics including the effect of RMP. In the autumn meeting, a dedicated session discussing ITER divertor strategy was organized jointly with Transport and Confinement Topical Group. This report gives the headlines of the progress and provides a list of publications related to the research in 2012. The detail of the progress can be found in two summary reports for the year.

Pedestal structure

- Featured collaboration between C-Mod, DIII-D and NSTX and collaboration between experimentalists, modelers and theorists in US provided improved quantitative understanding of peeling-ballooning stability, bootstrap current and width scaling. Confidence in the EPED model was improved, particularly by an extension of the range of pressures for testing by a factor of two.
- A new theory based on a turbulent particle pinch, which is proposed to explain the rapid formation of sharp density gradients in tokamak edge plasmas, in particular the pedestal region has been proposed and tested against experimental data from DIII-D and JET similarity experiments.
- Gyrokinetic analysis of DIII-D H-mode pedestal instabilities indicated ITG and micro-tearing modes (MTM) were the dominant instabilites at ψ_N =0.95. In MAST, kinetic ballooning modes (KBM) are close to marginal stability near the knee of the pressure profile, and MTM dominate the plateau/near pedestal top region. In JET, KBM are closer to marginal stability near the knee of P(r). KBM would be unstable in pedestal and at knee, if J_{bs}=0. MTM are unstable in plateau with significant growth rates, but they are subdominant to ITG/TEM.

ELM Physics

- Progress of several nonlinear MHD codes was reported. JOREK was applied for the analysis of the experimentally observed broadening of the ELM energy deposition and reproduced a broadening of the power deposition profile during the ELM in JET-like plasma. The stabilizing effects of edge current density on pedestal instabilities with resistive MHD were investigated by NIMROD and it was found that a strong dependence of the low-n edge localized instabilities on edge current density distribution. BOUT++ ELM simulations for a DIII-D discharge showed that the power split between inner and outer divertor target plates depends on the magnitude of parallel heat diffusivities. To validate the results of non-linear MHD simulations, it is proposed to collect the data for a small set of well-diagnosed cases from several machines and make it available for MHD simulations.
- In JT-60U, ELM frequency f_{ELM} increased monotonically together with the power across the separatrix and f_{ELM} became higher in the case of counter-NB at a given power across the separatrix. Global confinement and ELM characteristics in KSTAR plasmas were summarized and large type-I ELMs, intermediate ELMs and a mixed ELM with type-I and small ELM peaks were identified.
- A new model for small ELMs was proposed, which is relevant when the critical gradient for instability to the isolated mode is exceeded. The pedestal only has access to this mode when

the complex growth rate is stationary in radius. If such a point occurs as the pedestal parameters evolve between the ideal MHD limit and the isolated mode stability boundary, then a small ELM crash would be expected, driven by the isolated mode instability.

- The kinetic particle code XGC0 has been used in full-f mode to study various edge physics. The simulation of DIII-D plasma qualitatively reproduced particle transport, electron and ion heat transport, pedestal shape, plasma rotation, ExB shearing rate, perpendicular electron flow and floating potential behaviour in front of the divertor plate.

ELM control

- In ASDEX Upgrade, ELM mitigation is observed for n=2 with odd (resonant) and even (non-resonant) parity with eight of sixteen coils as observed in 2011. However, the use of all 16 coils for n=2 fields leads to reduction of type-I ELM frequency, but not their complete suppression. ELM mitigation is observed with single rows of either four upper or four lower coils, albeit with stronger gas puff. ELM mitigation occurs as well with n=1 (12 coils, resonant or non-resonant configurations), but has so far not been achieved with n=4 fields.
- In MAST, ELM mitigation has been obtained in LSN plasmas using an RMP with n=3, n=4 or n=6 and in DN plasmas with n=3. Scans of various parameters have shown that f_{ELM} can be increased by up to a factor of 8 but ELM suppression has not been obtained.
- In DIII-D, analysis of RMP ELM suppression results suggests that a necessary condition may be to have a resonant island (the 10/3 island in many of the n=3 RMP experiments) located at a position where the electron perpendicular velocity is near zero (for strong field penetration) and at the top of an edge pedestal that is narrower than needed to trigger the ELM instability.
- QH-mode was sustained at q_{95}=3.4 up to the ITER target $G=\beta_N H_{89}/q_{95}^2$=0.4 at small negative NBI torque using NTV torque from NRMFs applied by the external C-coil plus the internal I-coil in DIII-D.
- Significantly reduced energy fluxes by a factor of 12 to the divertor than the natural ELMs by pellet pacing were demonstrated in DIII-D. JOREK non-linear MHD code was applied to DIII-D plasmas and found that the pressure in the high density pellet cloud heated by the parallel conduction can be large enough to trigger a ballooning type mode.
- Some enticing results with a 5 times increase in ELM frequency were shown in JET, despite some difficulties with pellet delivery to the plasma. Improvements to the pellet transmission system are planned for the current shutdown.
- New results from EAST with Li granule injection were shown that indicate a definite capability to trigger ELMs. Future work with D2 and Li injection is planned.
- Extreme edge heating ($0.95<\rho<0.98$) in TCV showed a reliable way to increase the ELM frequency. A series of experiments were conducted to assess the use of pulsed ECH for ELM pacing, indicating that ELM triggering via pulsed ECH requires as much integrated power than in case of continuous power injection.

LH transition physics

- Various L-H transition models were compared with experimental observations using Doppler reflectometer and Langmuir probe. The role of the nonlinear energy transfer among turbulence, low-frequency zonal flows (ZFs) and geodesic acoustic modes (GAMs) on L-H transition was also discussed.
- Dedicated joint experiments related to L-H transition physics (PEP-26, 27, 28, 32 and 33) provided a variety of conditions of L-H transition across devices. Systematic analysis will be needed to find a common physics for better prediction in ITER plasmas. Thus, the community has moved beyond simple 0D scaling laws for P_{th} projection, and most work now focuses on local “macroscopic” threshold parameters (e.g. the critical E_r shearing rate needed to suppress L-mode turbulence, and the local profile characteristics needed to obtain this), and also the local “microscopic” behavior (e.g. the rapid oscillatory interplay between edge turbulence and poloidal flow sometimes observed near a L-H transition).

- The investigation of L-H and H-L transitions over a large density range indicated that the density dependence of the threshold power of the L-H and H-L transitions is very similar.
- In JET, a reduction of P_{thr} by ~ 30% with the ILW and the reappearance of the roll-over of P_{thr} at low density, which was not found with C wall in the present JET MkII-HD divertor geometry, were observed.
- The evolution of plasma density after the L-H transition with low core fuelling at JET indicated no major difficulty in access to burning plasma conditions in ITER. More experiments across devices with low core source are required for further confirmation. Core particle transport mechanisms are reasonably well understood within the theoretical framework of TEM and ITG turbulence, with contrasting behaviours of density peaking, particularly in response to electron heating.

Pedestal evolution between ELMs

- In ASDEX Upgrade, the recovery from an ELM crash can be subdivided into several distinct phases, with first a partly recovery of the electron temperature gradient, which stalls as the edge density gradient recovers quickly. During the final recovery of the electron temperature gradient, the density gradient is already at the maximum value found in between ELMs.
- In C-Mod, pedestal pressure clearly is seen to reach a maximum in the latter portion of the ELM cycle, with a crash evident from examination of the first 20% of the ELM cycle. There are signs of crash and rebuild in the density pedestal, at least in some conditions. The final pedestal pressure achieved during the ELM cycle was independent of ELM frequency, and that then pressure may actually saturate midway through the slow ELM cycles.
- In DIII-D, there is a general trend for the total pedestal pressure to grow in width during the ELM cycle. The KBM physics in the EPED model provides a good description of the evolution of the maximum pedestal pressure gradient during the ELM cycle. For some discharges, the paleoclassical model provides a good description of the evolution of the T_e profile.
- In JET, EPED1 model predicts the pre-ELM pedestal height within 25%, but the pedestal evolution seems inconsistent with KBM theory, in that the pedestal narrows during the ELM cycle. Ideal MHD n=infinity stability is a good proxy for KBM stability, and GS2 calculations show no unstable KBMs in the JET pedestal.
- In JT-60U, after the rapid recovery for ~10ms, the pedestal temperature linearly increases toward next ELM, while keeping the pedestal density constant. Nevertheless, core density continuously increases toward next ELM. Although the ELM characteristics are very sensitive to the edge toroidal rotation, profiles after ELM crash are similar between co- and ctr-rotating plasmas.
- In MAST, the pedestal pressure height increases and the width gets wider meaning that the pressure gradient remains roughly constant through the ELM cycle. The width scales as $\Delta = C.\beta_{pol}^{0.5}$. The width evolution is consistent with KBMs setting a constant pressure gradient (with $n=\infty$ ballooning modes being a good proxy). At low collisionality the temperature pedestal also increases during the ELM cycle.
- In NSTX, the pedestal pressure builds up in the early part (first 30-40%) of the ELM cycle, mainly due to T_e buildup. The pedestal n_e remains flat or even decreases in some cases.

ITER divertor strategy

- From the transport and confinement point of view, it is expected that W concentration in ITER L-mode plasmas will be low as it is dominated by strong anomalous transport so that the risk to ITER operation in terms of accumulation is not very high. The main outstanding issue is the quantification of the maximum acceptable W concentrations for a range of typical L-mode plasma conditions in ITER.
- Present experimental evidence shows that metallic walls favour H-mode access and this seems to apply to all hydrogenic isotopes and helium. While the physics behind this is not

well understood, the W divertor does not seem to represent a risk but rather an advantage regarding H-mode access.

- The competition of inwards W transport and expulsion by ELMs is a key to determining the level of edge W contamination to be expected in ITER. Two issues remain to be clarified in the short term to make a solid physics-based evaluation of the risks that this entails for ITER: one is the determination of the expected transport between ELMs and the other is the required ELM control for the expulsion of the edge accumulated W in ITER.
- Present experimental evidence indicates that the presence of W (or Molybdenum in C-Mod) can cause a decrease of energy confinement compared to a carbon divertor and thus may be a risk for ITER. In general it is observed that operation with W PFCs leads to lower pedestal pressure and that low Z impurity seeding can lead to a recovery of the energy confinement but only in some conditions.
- The major outstanding issues for helium plasmas ITER concern are as follows: a) the nature of W transport between ELMs with respect to D plasmas, b) the ELM control requirements to prevent edge W accumulation, c) core W transport and accumulation and power requirements for its control in comparison with D plasmas and d) H-mode and W behavior in He H-mode plasmas with H pellet injection for ELM control.
- After further discussion in the spring TG meeting on April, the final report will be submitted to ITPA-CC.

Publications linked to the activities of the ITPA pedestal group in 2012

[1] J. Rossel et. al. *Edge-localized mode control by electron cyclotron waves in a tokamak plasma.* Nucl. Fusion **52** (2012) 032004

[2] Y. M. Jeon et. al, *Suppression of Edge Localized Modes in High-Confinement KSTAR Plasmas by Nonaxisymmetric Magnetic Perturbations.* Physical Review Letters **109** (2012) 035004

[3] P. Sauter et. al. *L- to H-mode transitions at low density in ASDEX Upgrade.* Nucl. Fusion **52** (2012) 012001

[4] Y. Ma et. al. *Scaling of H-mode threshold power and L-H edge conditions with favourable ion grad-B drift in Alcator C-Mod tokamak.* Nucl. Fusion **52** (2012) 023010

Conference presentations in 2012:

[1] P.B. Snyder et. al, *The EPED Pedestal Model: Extensions, Application to ELM-Suppressed Regimes, and ITER Predictions.* IAEA Fusion Energy Conference 2012, TH/P3-17

[2] M.R. Wade et. al, *Advances in the Physics Understanding of ELM Suppression Using Resonant Magnetic Perturbations in DIII-D.* IAEA Fusion Energy Conference 2012, EX/3-1

[3] Y. Liang et. al, *Mitigation of Type-I ELMs with n=2 Fields on JET.* IAEA Fusion Energy Conference 2012, EX/P4-23

[4] G. Spizzo et. al, *Ambipolar edge electric field with energy dependence.* APS-DPP 2012, JP8.00169

[5] A. Loarte et. al, *Progress on the Application of ELM Control Schemes to ITER.* IAEA Fusion Energy Conference 2012, ITR/1-2

[6] A. Kirk et. al, *Understanding ELM Mitigation by Resonant Magnetic Perturbations on MAST.* IAEA Fusion Energy Conference 2012, EX/3-2

[7] Y. M. Jeon et. al, *ELM Control in Application of Non-Axisymmetric Magnetic Perturbations in KSTAR.* IAEA Fusion Energy Conference 2012, EX/3-3

[8] W. Suttrop et. al, *Mitigation of Edge Localised Modes with Small Non-axisymmetric Magnetic Perturbations in ASDEX Upgrade.* IAEA Fusion Energy Conference 2012, EX/3-4

[9] F. Ryter et. al, *L-H Transition, Pedestal Development and I-mode Studies in the ASDEX Upgrade Tokamak.* IAEA Fusion Energy Conference 2012, EX/P4-03

[10] Y. Ma et. al, *Study of H-mode Access in the Alcator C-Mod Tokamak: Density, Toroidal Field and Divertor Geometry Dependence.* IAEA Fusion Energy Conference 2012, EX/P2-04

[11] C. Maggi et. al, *The H-mode threshold in JET with the ITER-like wall.* EPS Conference 2012, O3.118

[12] H. Mayer et. al, *Dynamics of the L-H transitions at different density in MAST.* EU-US TTF 2012, P3.3

[13] D. Battaglia et. al, *Dependence of the L-H Power Threshold on X-point Geometry.* IAEA Fusion Energy Conference 2012, EX/P5-28

[14] E. de la Luna et. al, *The Effect of ELM Mitigation Methods on the Access to High H-mode Confinement (H98~1).* IAEA Fusion Energy Conference 2012, EX/6-1

[15] L. Baylor et. al, *Experimental Demonstration of High Frequency ELM Pacing by Pellet Injection on DIII-D and Extrapolation to ITER.* IAEA Fusion Energy Conference 2012, EX/6-2

[16] A. Hubbard et. al, *Progress in Performance and Understanding of Steady ELM-free I-modes on Alcator C-Mod.* IAEA Fusion Energy Conference 2012, EX/1-3

[17] J. Hughes et. al, *Pedestal Stability and Transport on the Alcator C-Mod Tokamak: Experiments in Support of Developing Predictive Capability.* IAEA Fusion Energy Conference 2012, EX/P4-15

[18] P. Lang et. al, *Pellet Induced High Density Phases during ELM Suppression in ASDEX Upgrade.* IAEA Fusion Energy Conference 2012, EX/P4-01