Pedestal Group Annual Report 2010

H R Wilson, M Fenstermacher, J Hughes, P Lang, A Loarte, N Oyama, R Sartori, P B Snyder and the ITPA Pedestal Group

1. Introduction

The ITPA Pedestal group has enjoyed another very active year, with substantial progress being made in a wide range of important issues for fusion, and ITER in particular. This is reflected in the large number of publications in refereed journals during 2009/10, with a total of 24 related to the activities of the ITPA pedestal group. We have held two meetings during the year: a joint meeting with the Transport and Confinement Group at Princeton Plasma Physics Laboratory in September, 2009 and another at JAEA, Naka in April 2010. Eruptions from the Icelandic volcano meant that many of our colleagues were unable to travel to the Naka meeting but it was nevertheless very productive, with extensive use being made of videoconference facilities. This report gives an overview of the group's activities over the past year. The following section describes the work related to the PEP joint experiments and the database development activity. In Section 3 we review the progress made towards the ITER urgent issues, before closing in Section 4 with a summary of future meetings.

2. Joint Experiments and database activity

The following is the list of joint experiments that the Pedestal and Edge group is coordinating:

PEP-1+3	Dimensionless identity experiments in JET and JT-60U: studies of ripple effects and rotation
PEP-2	Pedestal gradients and ELM energy losses in dimensionally similar discharges and their dimensionless scaling
PEP-6	Pedestal structure and ELM stability in DN
PEP-13	Comparison of small ELM regimes in JT-60U, AUG and JET
PEP-14(TP-5)	QH/QDB Comparison in JT-60U and DIII-D (COMPLETE)
PEP-16	C-Mod/ MAST/ NSTX small ELM regime comparison (COMPLETE)
PEP-17	Rotation effect on high β_p small ELM regimes (COMPLETE)
PEP-18	Comparison of Rotation Effects on Type I ELMing H-mode in JT-60U and DIII-D
PEP-19	Basic mechanisms of edge transport with resonant magnetic perturbations in toroidal plasma confinement devices
PEP-20	Documentation of the edge pedestal in advanced scenarios (COMPLETE)
PEP-21	The spatial and temporal structure of type II ELMs
PEP-22	Controllability of pedestal and ELM characteristics by edge ECH/ECCD/LHCD
PEP-23	Quantification of the requirements for ELM suppression by magnetic perturbations from off mid-plane coils
PEP-24	Minimum pellet size for ELM pacing
PEP-25	Inter-machine comparison of ELM control by magnetic field perturbations from mid-plane RMP coils
PEP-26	Critical edge parameters for achieving L-H transition (NEW)
PEP-27	Pedestal profile evolution following L-H transition (NEW)
PEP-28	Physics of H-mode access with different X-point height (NEW)

The full summary report for each of the experiments is provided on the ITER portal at https://portal.iter.org/departments/FST/ITPA/CC/IEAITPA/default.aspx?InstanceID=8, so we refer the interested reader to that report. One of the main motivations for the joint meeting with the Transport and Confinement group in Princeton was to identify a research programme to advance our understanding of the LH transition for ITER. Three new joint experiments were proposed as a consequence (PEPs 26-28). Four other joint experiments were closed during the year, having achieved their aims: PEPs 14-17 and 20.

Turning to the database activity, the main development here is the definition of the structure of the new LH transition database, that is being developed as a joint project between the Pedestal Group and the Transport and Confinement group. The activity is led by Jerry Hughes of MIT. Access to the International Global Threshold DataBase (IGDBTH), used for many years to derive empirical scaling laws for the H-mode power threshold, is being made available from MIT beginning in the fall of 2010. The database schema will be largely consistent with prior implementations, and access will be granted to ITPA and IO members who request it. In the near future, the group will also implement a new database, which will allow the archiving of edge profile information for the study of H-mode thresholds in local parameters. Several devices are expected to populate this database with an initial set of data taken from experiments with density scans on individual devices.

3. Urgent R&D issues for ITER

A number of urgent R&D issues have been identified by the ITER Organisation. This Section identifies those that the ITPA pedestal group is best-placed to address, proposes an updated work plan and reports progress over the past year. This work plan assumes that adequate resources are provided by the organisations of the ITER partners. It will remain flexible and will continue to be modified as new devices around the world reach maturity and begin to contribute H-mode data, and as knowledge improves. The first plan was constructed in December, 2008. This is version 3, taking account of developments and summarising progress over the past year. It will continue to be a “live” document, to be updated each year.

The focus here is on *urgent* ITER issues; less urgent, but nevertheless important, issues will be addressed in parallel with this programme (aiming to avoid them becoming urgent). These important areas include, for example, alternative ELM control techniques, such as plasma jolts, although this is becoming urgent. The interested reader should consult the summaries of the Pedestal group meetings for progress in these areas. There are five main areas (urgent issues) that the group will address:

1. Conditions for ELM suppression using resonant magnetic perturbations
2. Conditions for ELM pacing using pellets
3. Impact of the TF ripple on the pedestal characteristics
4. The impact of heating source on pedestal structure and ELM size
5. L-H transition physics

We have established five working groups to drive these areas forward under the leaderships of (1) Max Fenstermacher, (2) Peter Lang, (3) Naoyuki Oyama, (4) Phil Snyder and (5) Roberta Sartori. The ITPA group will discuss adjustments to this working group structure at its next meeting.

We have defined a number of objectives to address these ITER urgent issues. These in turn will be met through a set of specific tasks that will involve both theory and experiment. In some cases, the necessary data and theoretical models/codes will already exist while in others new experiments and theoretical models will need to be defined.

3.1 ELM suppression with RMP coils

Objective	Task	Q1-10	Q2-10	Q3-10	Q4-10	Q1-11	Q2-11	Q3-11
1.1	(a) Suppress ELMs using RMPs on MAST							
1.1	(b) Suppress ELMs using RMPs on AUG							
1.1	(c) Explore potential to mitigate/suppress ELMs with mid-plane coils (NSTX, JET)							
1.2	(a) Model and compare vacuum RMP field for MAST and DIII-D with suppressed ELMs							
1.2	(b) Test model based on min stochastic width and alignment of perturbation with q against MAST and DIII-D data. Identify other important parameters							
1.2	(c) If 1.2(b) is successful, predict scenarios for ELM suppression in advance of AUG expts 1.1(b)				CLOSE			
1.2	(d) Compare RMP data for on and off-mid-plane coils (JET, MAST, DIII-D, NSTX, AUG)							
1.2	(e) Interpret data from 1.2(d) using model developed in 1.2(b)							
1.2	(f) Predict ELM suppression criteria/regimes for ITER; optimise ITER coil design							
1.2	(g) Quantify the impact of torque and plasma rotation on ELM mitigation and suppression (DIII-D, JET, MAST, NSTX, AUG)							
1.3	(a) Compare pedestal height with and without RMP ELM suppression on DIII-D, AUG and MAST							
1.3	(b) Compare measured pedestal height with RMP with EPED1 model predictions (JET,MAST,NSTX,AUG,DIII-D)							
1.3	(c) Demonstrate the ability to maintain the required edge density during ELM suppression (DIII-D, MAST, AUG)							
1.3	(d) Quantify impact of RMP on core transport and H-factor (JET,MAST,NSTX,DIII-D, AUG)							
1.4	(a) Quantify impact of RMP-suppressed ELM regimes on divertor power loading (DIII-D, MAST)							
1.4	(b) Make recommendations on need to rotate RMPs: input to AUG design (DIII-D, MAST)							
1.4	(c) If necessary, explore impact of rotating RMPs on ELM suppression (JET, NSTX, AUG, MAST,DIII-D)							
1.5	(a) Quantify ability to suppress or mitigate ELMs with RMP in current ramp (NSTX,JET.AUG, MAST, DIII-D)							
1.5	(b) Quantify ability to suppress or mitigate ELMs close to LH transition threshold (NSTX, JET,AUG, MAST, DIII-D)							
1.6	(a) Demonstrate RMP ELM suppression with ITER-like pellet fuelling (DIII-D, AUG, MAST)							
1.7	Demonstrate ability of modulated RMP fields to mitigate ELM size by factor needed to meet ITER requirements							
1.8	(a) Model the performance of the ITER RMP coil set, calculate divertor/wall power loads and optimise design							

Figure 1: Work plan for RMP coil suppression/mitigation of ELMs.

Motivation:

It is extremely likely that control of Type I ELMs will be necessary for ITER to meet its objectives fully. Coils to provide resonant magnetic perturbations (RMPs) are presently the only tool available known to suppress the ELMs in such high performance regimes. However, ELM suppression has only been proven on DIII-D to date and the physics remains uncertain. RMP ELM control also has the potential to mitigate ELM impulsive energy sufficiently for ITER requirements by pacemaking. The work plan presented here aims to improve our understanding, and so reduce uncertainties in ELM control scenarios for ITER, quantifying the conditions and requirements for suppression, mitigation and pacemaking.

Working Group:

Max Fenstermacher (Chair)
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Andrew Kirk
Oliver Schmitz
CS Chang
John Canik
Andrea Garofalo

Objectives:

The objectives for this working group remain largely as originally defined. There is, however, one additional objective, inserted as 1.7, to explore the impact of modulated RMPs on ELMs.

1.1 Reproduce ELM suppression with RMPs on at least one tokamak other than DIII-D.
1.2 Identify the criteria for ELM suppression from experimental data and theoretical models.
1.3 Quantify the impact of ELM suppression by RMPs on the pedestal pressure and core confinement and develop/validate theoretical models
1.4 Quantify the power loading on the walls and divertor with RMP-suppressed ELMs; make recommendations on any requirement for rotating RMPs
1.5 Explore the capability to suppress or mitigate ELMs during the current ramp phase (ie close to the L-H transition threshold, and with q95 varying with time).
1.6 Demonstrate ELM control with ITER-like pellet fuelling
1.7 Demonstrate the ability of modulated RMP fields to mitigate ELM impulsive energy by the factor needed to meet ITER requirements
1.8 Model the performance of the ITER ELM control coil set, and propose changes to the design as appropriate. This is likely to require further developments in modelling the plasma response, which is very challenging.

Capability:

A large number of tokamaks have coils suitable for ELM control, including DIII-D, MAST, NSTX and JET. Of these, only DIII-D and MAST have internal coils off the mid-plane, as planned for ITER, and therefore these have a particularly key role to play in this area. In addition, ASDEX Upgrade will have a reduced set (2 rows x 4 coils) of ITER-relevant internal RMP coils from late-2010 to early-2011, and a full set (3 rows x 8 coils) from early 2012, that should provide important input on the required time-scale. A number of codes exist that can calculate the vacuum response to the RMPs. Fluid codes (eg M3D, JOREK, BOUT++) and kinetic codes (e.g. XGC0, XGC1) also exist that can analyze the effects of the plasma response.

Work plan, time-scales and assumptions

Figure 1 shows the present work plan and time scales for the tasks related to ELM control by RMP coils. The original work plan was based on a number of assumptions, but is adjusted as assumptions are proven or falsified. These original assumptions were:

1. The *complete* suppression of ELMs on DIII-D by RMPs, while not on JET, for example, is because the DIII-D coils are off the mid-plane, as presently designed for ITER. Thus only MAST and DIII-D are presently in a position to test ITER-relevant coils. AUG will also be in this position from late 2010.
2. Appropriate machine time, experimental and theoretical manpower are made available.
3. The criteria (to be validated) based on a minimum stochastic layer region and alignment of the perturbation with $q(r)$, are the main requirements for ELM suppression. If this proves not to be the case, other model development (including plasma response) and tests will be required.
4. The target date for input to ITER Organisation on RMP coil design is Sept 2010, but results will be communicated as they are produced in advanced of this date.

Although the initial target date specified in assumption 4 has passed, there is still time to provide input to ITER, so the work programme (with extended timescales) remains valid.

Progress

Progress is being made in understanding parameters that appear to influence ELM suppression and mitigation. These include q95 resonance, collisionality, density pump-out, beta, net electron perpendicular velocity, and island overlap width. DIII-D initially suggested that vacuum island overlap width was a good ordering parameter for maximum ELM size and that ELM suppression was correlated with achieving a minimum island overlap width. Calculations with Fourier harmonic field representations (SURFMN, ERGOS) for cases from MAST, JET and NSTX now demonstrate that while this may be a necessary condition, it is not sufficient. Comparative analysis of field line loss fractions (e.g. with TRIP3D) should also be done. A major task is to quantify the importance of each of the key parameters, and to understand that importance in terms of a physically-motivated theoretical model. Although both MAST neutral beams are now operational, providing reliable ELMing H-modes, complete ELM suppression has not yet been observed in MAST, so it will be necessary to adjust tasks and timescales in the light of this result. Installation of 6 additional coils in the below-midplane row and modification of the PF coils set wiring to allow LSN ITER Similar Shape (ISS) plasmas should bring the MAST experiments closer to DIII-D conditions. Plans are progressing for the installation of a very flexible coil set on AUG for operation in 2011 (the full capability is expected to be available from 2012). Finally, experiments in DIII-D, MAST and NSTX have shown that the L-H power threshold increased when applied RMP fields produced a threshold vacuum island overlap region width, and the threshold width was lower for dominantly resonant fields vs. non-resonant fields.

Related joint experiments

A number of the joint experiments play an important role in meeting the objectives:

- PEP-19 "*Basic mechanisms of edge transport with resonant magnetic perturbations in toroidal plasma confinement devices*" DIII-D, MAST, NSTX, TEXTOR-DED
- PEP-23 "*Quantification of the requirements for ELM suppression by magnetic perturbations from off mid-plane coils*" ASDEX Upgrade, DIII-D, JET, MAST, NSTX
- PEP-25 "*Inter-machine comparison of ELM control by magnetic field perturbations from midplane RMP coils*" ASDEX Upgrade, DIII-D, MAST, JET, NSTX

3.2 ELM pace-making with pellets

Motivation: If pellets can be used to trigger ELMs and increase their frequency by a factor of ten or more, then provided the ELM size falls by a similar factor, the ELMs on ITER will be tolerable. This programme of work will explore whether or not the increase in ELM frequency is possible through pellet pace-making, and then whether or not this results in a corresponding drop in ELM size. The compatibility with fuelling will also be explored. The main devices that can contribute to this R&D in the next two years are AUG, DIII-D and JET. JET provides a unique tool for pellet pace-making demonstrations as it is the only device large enough such that the fuelling of the pellets will not be the dominant effect. This package of work will also strive to develop a physics understanding of the mechanism by which pellets trigger ELMs, thus helping to minimise uncertainty in extrapolating the technique to ITER. A high frequency pellet injector is probably not required for this physics study and a number of other tokamaks can contribute to this work.

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Objective	Task	Q1-10	Q2-10	Q3-10	Q4-10	Q1-11	Q2-11	Q3-11
2.1	(a) Demonstrate pellet-triggered ELMs at ten times the natural ELM frequency in JET in a low natural ELM frequency regime							
	(b) Demonstrate pellet-triggered ELMs at ten times the natural ELM frequency in JET in ITER-relevant scenarios							
2.2	(a) Quantify the dependence of ELM size on frequency for pellet triggered ELMs and constant, ITER-relevant density (JET)							
2.3	(a) Quantify the minimum pellet size required to trigger an ELM (AUG, DIII-D, JET)							
2.3	(b) Quantify the minimum penetration required to trigger an ELM (AUG, DIII-D, JET)							
2.4	(a) Explore whether ELMs can be triggered by pellets arbitrarily close to the L-H transition (JET, AUG, DIII-D)							
2.4	(b) Compare pellet-triggered and natural ELM phenomenology (JET, AUG, DIII-D)							
2.4	(c) Measure edge flow profiles at the time of pellet injection (JET, AUG, DIII-D)							
2.4	(d) Compare proximity to peeling-ballooning boundary for cases when pellets do, and do not, trigger ELMs (JET, DIII-D, AUG)							
2.4	(e) Based on above measurements, develop a model for pellet-triggering by ELMs (modelling)							
2.5	(a) Explore ability to trigger ELMs at different injection angles and compare (JET, DIII-D)							
2.6	(a) Explore compatability of pace-making/fuelling; do ELM-triggering pellets fuel same as fuelling pellets? (JET, AUG, DIII-D)							
2.6	(b) Compare pedestal structure with and without pellet pace-making (JET, AUG, DIII-D)							
2.7	(a) Explore alternative pellet options, such as C, B, etc, for triggering ELMs (AUG)							
2.7	(b) Assess impact of alternative pellets on edge impurities and confinement (AUG)							
2.8	(a) Model pellet pace-making in ITER and provide input to ITER pellet launcher							

Figure 2: Work plan for pellet pace-making studies for ITER.

Objectives:

2.1 Achieve a frequency of pellet-triggered ELMs that is greater than ten times the natural ELM frequency with minimal density rise in an ITER-relevant scenario (e.g. shape, *q*, etc).
2.2 Explore the dependence of the ELM size on frequency for pellet-triggered ELMs
2.3 Quantify the minimum pellet size for triggering ELMs
2.4 Develop a model for the ELM-triggering mechanism
2.5 Optimise the injection angle
2.6 Study the compatibility of ELM pacing by pellets with the required bulk plasma fuelling (by pellets) in ITER reference scenarios
2.7 Explore alternative options for pellet material
2.8 Recommend pellet pace-making options for ITER

Capability:

At present, there are three tokamaks with the capability to inject pellets at sufficiently high repetition rate to increase the frequency of ELMs above the natural frequency: AUG, JET and DIII-D. The capabilities of all three of these devices will improve further during 2010/11, aiming at pushing up the triggered ELM frequency without excessive fuelling. A pellet dropper that was employed on DIII-D failed to penetrate sufficiently deeply into the plasma to trigger an ELM, so this has now been removed. It is important to note that experiments that aim to understand the physics processes that lead to the triggering of ELMs by pellets do not require a high repetition rate and may be performed with lower frequency injectors. A number of additional tokamaks have this capability, including the MAST spherical tokamak. In addition, a new solid state launcher is being commissioned on AUG that will test the feasibility of ELM triggering with a range of pellet materials.

Work plan and time-scales

Figure 2 shows the work plan and time scales for the devices that are expected to contribute. JET is a key device for ELM pellet pace-making experiments (high volume, so minimal fuelling from small pellets), but it will be unavailable for experiments until towards the middle of 2011. It is anticipated that its new high speed pellet injector will then be available, and this assumption has been factored into the schedule. DIII-D will also contribute new data with upgrades to its pellet injector towards high repetition rates and smaller pellet sizes planned to be in operation from spring, 2011. Meanwhile, AUG will also have an improved capability with a more reliable centrifuge system becoming available (compared to the gas gun system that has been used to date). Tests with a room temperature solid state pellet launcher at AUG have started, with installation at the torus expected for late 2010.

These new developments provide much optimism that progress can be made in the coming year, and the workplan and timescales reflect this.

Progress

Pellet pace-making investigations at JET were concluded in October 2009 due to the shutdown which will last until mid-2011 for the installation of the ITER-like wall (ILW). The objective to increase the ELM frequency by a factor of 10 compared to the natural ELM frequency was not achieved due to technical difficulties with the new high frequency pellet injector. Nevertheless, some data was taken from the lower frequency fuelling pellets, and analysis of this has progressed through the year, providing six pellet related contributions at the EPS 2010, two for the IAEA FEC 2010 and several journal papers are in preparation. The main results from JET are summarised here. Using fuelling size pellets, JET confirmed pellet pacing in a large tokamak. ELMs triggered by pellets are observed to expel the plasma energy in just one filament (or sometimes a few), as expected from recent modelling using the nonlinear MHD code JOREK, as well as modelling with the JINTRAC code package. A large proportion of the pellet mass is ejected to the divertor target plates. Small pellets that only penetrate a few millimetres into the JET plasma do not trigger ELMs, indicating that there is a minimum pellet size and/or penetration

depth required for a pellet to trigger an ELM. This is also expected from MHD modelling. This threshold was reached in the baseline scenario for a D particle content of 1-3 10^{19}, corresponding to a pellet penetration close to the pedestal top. Consistent with this, experiments on AUG found that low field side pellets must penetrate close to the pedestal top in order to trigger an ELM.
New experiments this year on DIII-D show significant promise for the technique, demonstrating pacemaking with a five-fold increase in ELM frequency, with negligible additional fuelling. A moderate decrease in confinement of ~10% was experienced. Like JET, the experiments indicate a single filament is formed from the pellet ablation plasmoid. The higher spatial resolution of the camera system on DIII-D showed that the filament forms in front of the LFS pellet. This is interpreted as a steepening pressure gradient there, which provides the trigger mechanism. DIII-D experiments also indicate a threshold for ELM triggering, with smaller pellet fragments failing to trigger ELMs, although this remains to be quantified.

Related joint experiments:

- PEP-24 "Minimum pellet size for ELM pacing" ASDEX Upgrade, DIII-D, JET, MAST

3.3 Impact of TF ripple

Motivation: Toroidal field (TF) ripple can affect the confinement of energetic particles (alpha and beam ions) and result in local heat deposition on plasma facing components. In addition, recent experimental results from JT-60U and JET show that a large amplitude of the TF ripple can degrade the pedestal performance. However, the acceptable level of TF ripple required to achieve the ITER mission of Q=10 has not been confirmed. Since the TF ripple increases the loss of fast and thermal ions, which can produce counter-current plasma rotation, the influence of the ripple through its effect on toroidal rotation should also be examined.

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Tony Leonard
Toshihiro Oikawa
Peter de Vries
Johnny Lonnroth
CS Chang

Objectives:

3.1 Survey the relation between TF ripple amplitude and pedestal performance in existing devices.
3.2 Survey the relation between toroidal rotation and pedestal performance in existing devices.
3.3 Identify the experimental conditions for the degradation of pedestal and H-mode performance with the TF ripple amplitude expected in ITER.
3.4 Develop and validate the model of ripple induced losses of energetic and thermal particles, and ripple induced toroidal rotation.
3.5 Assess the effects of TF ripple on the LH power threshold
3.6 Recommend the acceptable ripple for ITER.

Capability:

Since the pedestal performance is sensitive to the plasma configuration through MHD stability, the effect of ripple should be investigated at fixed plasma shape. JET can contribute to dedicated ripple experiments. In particular, the unique capability of the JET TF system, which can change the ripple amplitude actively, provides the potential for many dedicated ripple experiments. DIII-D has a capability to change the toroidal rotation/torque input while keeping the heating power and TF ripple amplitude fixed. The analysis of JT-60U data will help to separate the effects of ripple amplitude and toroidal rotation. JT-60U data on the non-uniform TF ripple amplitude associated with ferritic steel tiles can also contribute to our understanding of the impact of local ripple due to TBMs in ITER. Additional data supporting the tasks of this working group can be obtained from a single machine by using radial displacements of the plasma to vary the ripple. A new capability this year has been provided by the tritium breeding blanket module (TBM) mock-up coil installed on DIII-D to allow the study of a toroidally localised source of ripple, as will be produced by the TBMs that will be installed on ITER.

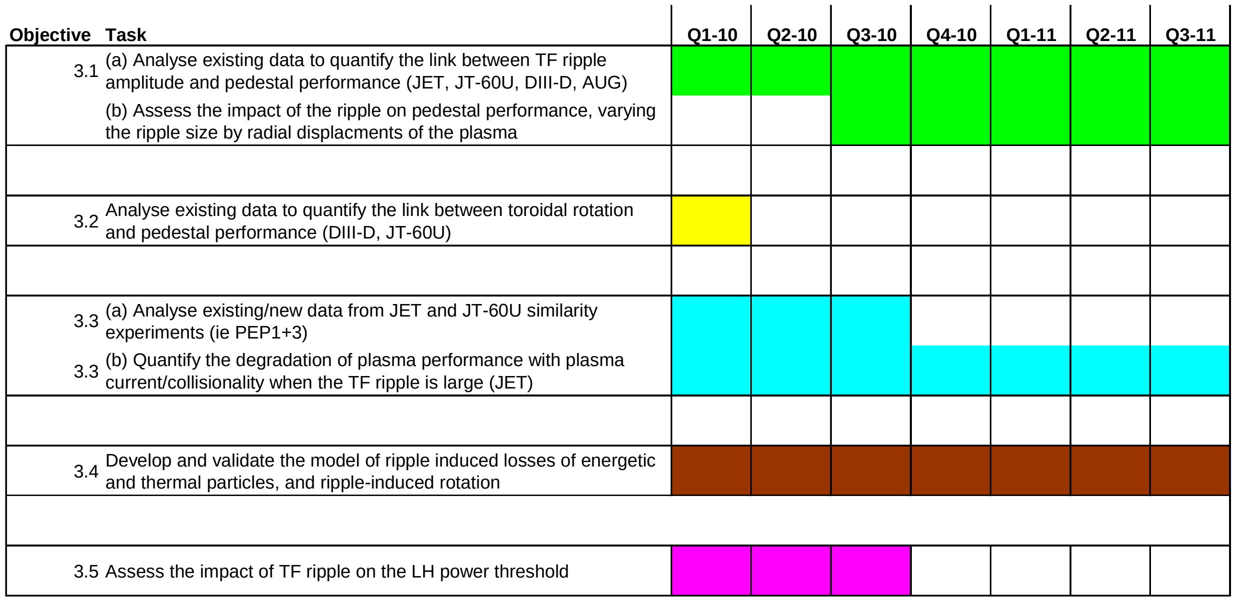

Figure 3: Work plan for TF ripple related issues for ITER.

Work plan and time-scales

Figure 3 shows the work plan and time scales. The target date for input to the ITER Organisation on the acceptable ripple amplitude is ~2012 in order to finalise the design of the first wall and blanket modules. By that time an initial assessment of the effects of local ripple due to TBMs is also expected. Results will be communicated to the ITER team before these target dates if they become available.

Progress

In order to understand the impact of the effects of ferromagnetic error fields similar to those expected from proposed ITER Test Blanket Modules (TBMs), a TBM mock-up coil was installed in a DIII-D horizontal port and dedicated experiments were performed. The local ripple amplitude in DIII-D can be controlled up to a size ~3 times larger than the local ripple amplitude expected in ITER. However, this local ripple is only created at one port on DIII-D, while on ITER there will be three ports for TBMs. The spectrum of the ripple therefore differs between the two. The *maximum* mock-up field, which produces a local ripple amplitude of >4%,was observed to reduce H-mode energy and confinement by almost 20% at high normalized beta, β_N>2, which is enough to raise concern for the high power-gain ITER mission. The TBM mock-up field showed significant *non*-resonant braking on plasma toroidal rotation across the whole radial cross section. On the other hand, the effects on RMP ELM suppression, L-H transition, fast ion losses and pedestal properties, (except for pedestal density) were smaller. These results will be presented at 23rd IAEA Fusion Energy Conference. The remaining issues for extrapolation to ITER are to identify a suitable definition of ripple amplitude taking account of its 3D structure and the difference between a single local ripple source in DIII-D compared with three local ripple sources in ITER.

The analysis of experiments to explore the impact of ripple on ELM characteristics and confinement in JET and JT-60U is also continuing. The ELM frequency normalised to the power across the separatrix is found to gradually decrease with edge toroidal rotation in both devices, while the pedestal performance and global plasma parameters are kept constant. In a ripple scan in 1.1MA JET plasmas, the change in the ELM characteristics is not so large. However, the ELM behaviour in a 2.6MA JET ripple scan experiment is clearly modified with ripple amplitude, accompanied by a large variation in the toroidal rotation. As reported in a number of papers, the effect of TF ripple is larger in higher plasma current discharges in JET. However, it is noted that the change in the edge toroidal rotation is also larger in these plasmas. Further analysis for the influence of the ripple through its impact on toroidal rotation will be presented at 23rd IAEA Fusion Energy Conference.

Related joint experiments
A number of the joint experiments play an important role in meeting the objectives:

- PEP-1 + PEP-3 "*Dimensionless identity experiments in JET and JT-60U: studies of ripple effects and rotation*", JET, JT-60U
- PEP-18 "*Comparison of Rotation Effects on Type I ELMing H-mode in JT-60U and DIII-D*", DIII-D, JT-60U

3.4 Pedestal structure

Motivation: The overall performance of ITER will depend to a large extent on the pressure at the top of the pedestal, or "pedestal height". Ideal MHD stability of intermediate wavelength modes imposes a constraint on the pedestal height as a function of the width of the edge barrier (or "pedestal width"). [In certain regimes two-fluid effects like diamagnetism may significantly alter the ideal stability boundaries]. However, a physics understanding of the pedestal width is required to combine with the MHD constraint to predict pedestal height and width. Recent experimental data suggest that the pedestal width scales approximately as the square root of β_p, and weakly with ρ_*. Together, these results provide a prediction for the pedestal height on ITER. One issue where uncertainty remains is whether or not the pedestal height depends on the heating source. It is important to test this before a final decision on the mix of heating power for ITER is taken, so this is an urgent issue. Developing a theory-based model for the pedestal structure in parallel to the experimental activity reduces uncertainty in extrapolations to ITER.

Another aim of this Working Group which is believed to be linked to the structure of the pedestal, is to quantify both experimentally and theoretically, the requirements for and characteristics of ELM-free Quiescent H-Mode (QH) operation. QH Mode has been observed on DIII-D, JT-60U, AUG and JET, primarily in low collisionality discharges with edge toroidal rotation in a direction opposite to the plasma current. QH mode operation has many characteristics that are desirable for ITER. Notably, it allows operation with good global confinement and high pedestal pressure, in the absence of ELMs. The QH mode edge provides density and impurity control in the low collisionality regime of interest to ITER and future reactors, over a broad range of input power. This particle transport appears to be associated with an edge mode known as the Edge Harmonic Oscillation (EHO).

Working Group

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Lorne Horton	Jerry Hughes
Rajesh Maingi	Hajime Urano
Roberta Sartori	Andrew Kirk
Nobuyuki Aiba	Alberto Loarte

Objectives:

4.1 Explore whether the pressure pedestal height and width depend on the heating source, quantify any differences and interpret in terms of emerging models for pedestal height

4.2 Explore whether the density pedestal properties depend on heating source (e.g. through modified fuelling sources; i.e. enhanced core fuelling with NBI compared to that with ICRF)

4.3 Assess the impact of heating source on ELM size and explore prospects for interpretation in terms of peeling-ballooning theory

4.4 Quantify the impact of torque on the pedestal structure and ELMs

4.5 Assess the potential viability of QH mode as a high pedestal, ELM-free regime for ITER

4.6 Develop theoretical models for the observed scaling of pedestal width with plasma parameters

Capability

Several devices have the capability to address the urgent issue of the impact of heating mix on pedestal structure and ELMs. Ideally experiments would be done on a single machine to keep other variables fixed, but joint experiments may be appropriate in the future to develop understanding further. ASDEX Upgrade has ICRH, NBI and ECRH; Alcator C-Mod has LH and ICRH; DIII-D has ECRH and NBI (balanced and unbalanced); NSTX has NBI and HHFW; JET has ICRH and NBI, and JT-60U has data from negative and positive ion neutral beams (balanced and unbalanced). MAST heating is dominated by NBI, but also has a small amount of EBW. A number of gyro-kinetic turbulence codes are beginning to emerge that can treat the transport processes in the pedestal region and may provide some understanding on the pedestal width scaling with β_p in the future. Efficient MHD codes are widely

Objective	Task	Q1-10	Q2-10	Q3-10	Q4-10	Q1-11	Q2-11
4.1	(a) Compare pedestal width scaling with different mixes of heating power (DIII-D, JET, AUG, NSTX, CMod,JT-60U)						
4.1	(b) Test EPED model for pedestal height holds independent of heating power mix (theory, All H-mode tokamaks)						
4.2	(a) Compare density pedestal structure with different mixes of NBI and RF heating (DIII-D, AUG, JET, NSTX)						
4.3	(a) Quantify impact of heating mix on ELM type (DIII-D, JET, AUG, NSTX, CMod, JT-60U)						
4.3	(b) Interpret experiments in 4.1(a) and 4.4(a) in terms of peeling-ballooning theory						
4.4	(a) Quantify impact of torque input on pedestal structure for beam-heated discharges (DIII-D, JT-60U)						
	(b) Quantify impact of torque input on ELM type for beam-heated discharges (DIII-D, JT-60U)						
4.5	(a) Identify the required range of density expected to allow QH mode operation in ITER						
	(b) Identify the required range of flow (or radial electric field) shear required for accessing the QH mode						
4.6	(a) Provide a theoretical/computational model for observed scaling of pedestal width with plasma parameters.						

Figure 4: Work plan for Urgent Pedestal Structure issues for ITER

available for the calculation of peeling-ballooning stability. High resolution edge diagnostics have seen continued improvement across all the major devices, allowing more accurate characterization of the pedestal structure.

Several tokamaks have operated in QH mode, including DIII-D, JT-60U, AUG and JET. In most cases, this has involved operating with edge toroidal rotation in the counter-current direction. In some cases this requires changing the plasma current from its usual direction. JT-60U has substantial QH mode data in a variety of neutral beam configurations. DIII-D has recently changed the direction of 2 neutral beam lines, so that it can continuously vary neutral beam torque from counter- to co- current direction. AUG, JET and DIII-D can vary torque by exchanging neutral beam for EC or RF heating. Several machines have error correction or other external coils which can be used to generate non-resonant magnetic perturbations, which can drive edge rotation through neoclassical toroidal viscosity (NTV). NSTX has recently identified a regime similar to QH mode, in that an EHO is present, though very small ELMs are also present in this regime.

Progress

Stability calculations have continued to provide a useful way of exploring the pedestal structure and ELM characteristics in terms of the peeling-ballooning theory, and peeling-ballooning stability calculations have now been carried out on over 200 discharges. Experimental observations continue to suggest weak or no dependence of the pedestal width on gyroradius, and most observations suggest a strong dependence of the pressure width in poloidal flux space on β_p, roughly as $\beta_p^{1/2}$, though variation in the widths of different profiles (density, electron temperature, ion temperature) has been observed in some cases. There are, however, differences in the scaling with β_p of the pedestal width in real space between the different machines, and this remains to be resolved.

JET, DIII-D and AUG experiments have been conducted to investigate the dependence of pedestal height, width and ELM behavior on type of heating source. Neutral beam power was exchanged for RF or EC power. In all cases, as long as input power was sufficient to maintain core beta, both pedestal height and width were approximately constant, independent of power source. The observed ELM behavior is complex, but not dramatically different with changing heating source on JET or DIII-D. An exception is the recent observations on AUG that modulated ECH can be used to lock the ELM frequency, and observations on JT-60U that ELM frequency can significantly increase with ECH power. LHCD power has been found, on Alcator C-Mod, to decrease the pedestal density and increase the temperature.

A theoretical model (EPED) has been developed which combines the MHD peeling-ballooning constraint with a local kinetic ballooning mode (KBM) constraint to predict the pedestal height and width. The current version of the model (EPED1.6) calculates both constraints directly, has no fitting parameters, and incorporates a model of diamagnetic stabilization. The model has been tested on a range of Type I ELM and QH-Mode discharges on DIII-D, JET, JT-60U, and Alcator C-Mod, finding generally good agreement (within ~20%) between predicted and observed pedestal height.

The impact of rotation on pedestal structure has been studied. One result is that JT-60U finds a slightly lower pedestal height in counter injection, while DIII-D results indicate a weak, or no, effect of rotation on pedestal structure at fixed global β (JT-60U experiments were at fixed power, not fixed β).

The operational space of QH mode has been substantially extended in several parameters. QH mode operation with all co-injected beams has been demonstrated on DIII-D, as has QH mode operation in a continuous torque range from all counter-injection to nearly balanced injection. Using non-resonant magnetic perturbations (which generate torque through NTV), QH mode operation with no net neutral beam torque (balanced beams) has been demonstrated on DIII-D. High density QH mode operation, at pedestal densities above half the Greenwald density, has been demonstrated using strongly shaped discharges, and ramping down rotation to reduce particle transport from the EHO. NSTX has continued to explore a QH-mode like regime, with an EHO, but also small ELMs, as well as enhanced pedestal H-mode in which very high global confinement is associated with high Te and Ti pedestals. Alcator C-Mod has found that operation in I-mode can yield high energy confinement with an edge heat barrier, but no particle transport barrier.

A theoretical model of the QH mode has been developed which posits that the EHO is a saturated kink/peeling mode, and that strong rotation shear aids mode saturation and prevents mode locking. This model allows predictions of the maximum density possible in QH mode, which have been successfully tested on DIII-D. The model predicted that high density QH operation would be possible in high triangularity near-double null discharges, and this was later achieved. It also predicts that ITER's planned density will be well within the QH operational regime (max ~1.2 10^{20} m^{-3}). However, this is a necessary but not sufficient condition for QH mode operation. The requirements on rotation remain to be precisely quantified.

Computational studies of neoclassical transport in the edge barrier find that neoclassical ion heat transport is significant, but that neoclassical transport, by itself, is insufficient to explain the observed pedestal structure. Edge gyrokinetic codes are under development to study turbulent transport in the edge barrier. Paleoclassical theory has developed a set of testable predictions for the structure of the electron temperature profile in the outer edge barrier.

Related joint experiments

A number of the joint experiments make important contributions towards meeting the objectives:

- PEP-2 "*Pedestal gradients and ELM energy losses in dimensionally similar discharges and their dimensionless scaling*" JET, DIII-D and ASDEX Upgrade
- PEP-6 "*Pedestal structure and ELM stability in DN*" MAST, AUG, NSTX, (JET and C-Mod for analysis of existing data)
- PEP-18 "*Comparison of Rotation Effects on Type I ELMing H-mode in JT-60U and DIII-D*", JT-60U (analysis of existing data) and DIII-D
- PEP-20 "*Documentation of the edge pedestal in advanced scenarios*" AUG, DIII-D, JET, JT-60U (analysis of existing data)
- PEP-22 "*Controllability of pedestal and ELM characteristics by edge ECD/ECCD/LHCD*" AUG, C-Mod, DIII-D, JT-60U (analysis of existing data)

3.5 L-H Transition

Motivation: The aim of this Working Group, in collaboration with the Transport and Confinement ITPA group, is to reduce the level of uncertainty in achieving and maintaining H-mode on ITER.

The mechanism(s) responsible for the LH transition remain poorly understood. While it is thought that sheared flows play an important role, the mechanism for the spontaneous generation of flows remains unclear. There is therefore considerable uncertainty related to the trigger mechanism for the LH transition and, as a consequence, the power threshold for ITER. This is important as the heating power available to ITER may be marginal for accessing the H-mode, according to some scaling laws. There are three key issues that this group will address: (1) Does ITER have sufficient power to access H-mode and how can this be optimised? (2) Can it stay in high performance H-mode as density and current are increased to achieve the fusion performance? (3) Is the quality of the H-mode with the heating power available on ITER sufficient to access Q=10 regimes? In the second issue, the group will document and aim to understand the circumstances under which there is a transition to a lower confinement (Type III ELMing or dithering) H-mode, or indeed L-mode (e.g. due to the density increase, large ELM events, etc). These questions need to be addressed for each of the ion species planned for ITER.

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Objectives

5.1 Develop an understanding of the impact of radiated power on the L-H transition power threshold
5.2 Identify any possible dependence of the LH transition power threshold on the plasma heating mechanism and the impact of momentum injection.
5.3 Determine the characteristics of the H-mode when the power is marginally above threshold.
5.4 Characterise the conditions under which a high performance H-mode plasma makes a back-transition to a regime of reduced performance (e.g. Type III or dithering H-mode, L-mode) for fixed global plasma parameters (power, fuelling, etc)
5.5 Determine whether, and how, the LH power threshold is modified by current ramps.
5.6 Determine the dependence of the LH transition and pedestal characteristics on the plasma ion species
5.7 Provide a first-principles model of the LH transition.

Capability

There are many tokamaks around the world that can provide data on the LH transition: JET, DIII-D, JT-60U, MAST, TCV, ASDEX-Upgrade, NSTX, Alcator Cmod and, most recently, HL-2A. These have available a wide range of heating mixes: electron and/or ion heating: beam and/or rf; co, counter and balanced beams, etc. In addition, there are new diagnostics that are probing the pedestal characteristics with ever increasing spatial and temporal resolution. The international fusion community is therefore well-placed to make a renewed attack on this long-standing issue for fusion to address urgent issues for ITER, particularly related to the level and mix of heating power, dependence on ion species, and scenarios to take the ITER plasma from L-mode, through the L-H transition and up to full performance, Q=10 H-mode.

Objective	Task
5.1	(a) Quantify the impact of radiated power on the L-H transition power threshold and local parameters at the transition
5.2	(a) Compare the power threshold and pedestal/edge parameters required to enter H-mode for dominant electron and ion heating schemes
	(b) Quantify the impact of momentum injection on the L-H power threshold, and develop an understanding in terms of local parameters
5.3	(a) Determine the H-factor as a function of the fractional power above the expected power threshold
5.3	(b) How do the pedestal characteristics depend on the fractional power above threshold, and can the observed dependence of the confinement be understood in terms of
5.4	(a) Document situations which cause a back-transition to reduced performance H-mode or L-mode as a function of fractional power above threshold
5.4	(b) Determine which factors affect how rapidly the pedestal and core plasma (in particular density) build up after the L-H transition, and the implications for the fusion power in ITER
5.5	(a) Document the influence of current ramps (up and down) on the L-H power threshold
5.6	(a) Document the dependency of the LH transition power threshold on ion species
5.6	(b) Characterise and compare the quality of the pedestal for different ion species
5.7	(a) Provide a first-principles model of the LH transition and power threshold

Figure 5: Work plan for LH transition issues for ITER. Timelines to be defined at Seoul ITPA meeting

Summary of progress:
Although subtracting the bulk radiated power, and using the power across the separatrix is not seen to make a difference in the L-H threshold trends (5.1), and does not help in reducing the scatter of the L-H threshold, it does help to order the data describing the H-factor evolution with increasing power. In particular, it brings together H-modes with different characteristics (EDA and ELMy H-modes) and correlates with the pedestal temperature. The result deserves further work in situations where either the radiation profile (i.e. bulk vs core) or the power deposition profile is varied. More work is still required to answer questions 5.3 and 5.4, part (b) in particular. Although in most machines H=1 can be achieved at low power above the threshold, and H is seen to increase with power, this depends on specific conditions and therefore documentation and understanding of these conditions is needed. The questions

are covered by the joint experiments TC-3 and PEP-26 but additional discussions will be required to propose new experiments that could allow us to make progress beyond documenting conditions (though more work on this is required) and analyses based on scaling predictions (H and Pth), which have associated uncertainties. One focus of JET will be on studying the conditions that produce back transitions to lower confinement H-mode with the largest power requirements. C-Mod confirms a favourable hysteresis in the L-H-L cycle, observing that the power required to maintain H-mode is comparable to, or lower than, the L-H transition requirement. Documentation of the effect of current ramps on the L-H threshold is still missing. Since the L-H threshold varies with a number of parameters that are not included in the scaling laws (such as mass, divertor/X-point geometry, momentum injection/rotation, etc) it is important to systematically document the L-mode conditions immediately before the L-H transition with a focus on the effect of vaying these parameters. Thus a new objective is proposed to meet this requirement, which will benefit from the input of PEP-26. The observed differences in the isotope dependence of the L-H transition (e.g. between H, D and He plasmas) remain unexplained, and require further analysis.

Progress Report:

On Task 5.1: *Quantify the impact of radiated power on the L-H transition power and local parameters at the transition"* C-Mod finds that radiated power fractions in L-mode are typically in the 10—20% range, and so do not have a significant impact on experimental power threshold results. Conventionally one uses the loss power P_{loss} as the figure of merit for the power threshold. If, on the other hand, one subtracts core radiated power from P_{loss} to obtain P_{net}, no significant change is observed in the experimental trends; only the magnitude of the power threshold is changed. Unfortunately, accounting for the radiation generally does not help reduce the large scatter that is prevalent in threshold power databases. In its next experimental campaign, JET will address the question of whether different radiation profiles resulting from the changes in the vessel wall affects the power threshold.

On Task 5.2 (a): *Compare the power threshold and pedestal/edge parameters required to enter H-mode for dominant electron and ion heating schemes"* ASDEX-U finds no measurable difference between P_{th} with NBI and ICH heating in He and D. In DIII-D, a different density dependence of P_{th} with zero torque NBI and NBI+ICH could explain the higher threshold that they observe with ECH at low density. The decrease of P_{th} with decreasing applied beam torque (5.2 (b): "*Quantify the impact of momentum injection in the L-H power threshold and develop an understanding in terms of local parameters"*) is also observed in Hydrogen plasmas, with at least a factor of two larger P_{th} in H than in D for all the range of torque explored, as well as when P_{th} is varied by varying the X-point height. Work towards an understanding in terms of local parameters is ongoing. Very recent analysis of JET experiments shows P_{th} decreasing with reduced torque. There will be further analysis of old data, as well as new experiments in order to confirm and clarify this result.

On Tasks 5.3(a*),"Determine the H-factor as a function of fractional power above the expected L-H threshold power"*, and 5.3(b), *"How do the pedestal characteristics depend on the fractional power above the threshold, and can the observed dependence of the confinement be understood in terms of pedestal physics?*, recent dedicated work was performed in C-Mod to study H98 as a function of power above the threshold power in both EDA and ELMy H-modes. It was found that H98 increases with the ratio of heating power to the threshold power. The data is best correlated with net power across the separatrix, and shows that H98≥1 is achieved for $P_{net} \geq 0.9 P_{th}$. The core confinement is tightly linked to the edge temperature, independent of the type of edge fluctuations. These confinement results are reproduced with impurity seeding. Both JET and ASDEX-U see a trend of H increasing with P_{loss}/P_{th} for specific discharges or sets of discharges, although there is a large variation on the P_{loss}/P_{th} at which H=1 is reached. For example, recent analysis for the ITPA joint experiment TC-3 in JET, in a situation when stationary H-mode conditions are achieved for $P_{loss}/P_{th}=1.1$, shows that nevertheless H98 continues to increase with P_{loss}/P_{th}, reaching H=1 for $P_{loss} \geq 1.5 P_{th}$. The observed trend is correlated with an increase in pedestal pressure. A set of different JET experiments shows the same trend, but with H=1 achieved for $P_{loss} \geq 1.1 P_{th}$, while in other JET experiments H=1 is reached only when $P_{loss} \geq 2 P_{th}$ because for lower powers the H-mode is not stationary. The ASDEX-U analyses also show that the evolution of the H-mode after the L-H transition depends on plasma parameters such as heating ramp rate, n_e, q_{95}. NSTX finds that H=1 is achievable with loss power equal to the measured threshold power in ELM free discharges, although the conditions to achieve this are not clear. Both ASDEX-U and JET do not find any correlation between H and P_{loss}/P_{th} from database information. These results indicate that:

i) the analysis of H vs P_{loss}/P_{th} depend on two scaling predictions that have associated error bars and that do not include all the experimentally observed trends, such as the well known dependencies of H on density and triangularity. Therefore this analysis can only highlight trends for specific situations in which discharge parameters, such as shape, I_p, B_t, density, are not varied and where, ideally, P_{th} is the measured threshold (including P_{th} density dependence) in those conditions;

ii) even when conditions are carefully controlled, there can be variations of the results depending on the specific set of parameters, or on the device.

The ITPA TC-3 joint experiment will provide further documentation of the H-mode behaviour at low power above the threshold in controlled conditions. Since TC-3 is not completed (analysis ongoing or experiment planned) the task should be extended into 2011 with an emphasis on 5.3 (b).

On task 5.4 (a): "*Document situations which cause a back-transition to reduced performance H-mode or L-mode as a function of fractional power above threshold" ,* back transitions to reduced performance H-mode seem at present to be an observation specific to JET. In a region of power up to αP_{th}, transitions to reduced performance H-mode (Type III ELMs) or to L-mode are observed. α is an empirical parameter and can vary from ~1.1 to ~2.5. Factors that affect this variation, and hence the variation in power requirements for a stationary H-mode with H=1, have been identified although are not yet understood. Increased triangularity tends to reduce α. There is also experimental evidence correlating increased collisionality with reduced α. Experiments are being planned for the next JET experimental campaign, aimed at investigating the factors that affect the variation of α to understand the physics of these phenomena. Therefore it is proposed that the task should be extended to 2011.

The characterisation of the pedestal evolution is covered by the joint experiment PEP-27, with significant progress made, as presented in the status report at the last ITPA (5.4 (b), which did read "*Quantify how rapidly the pedestal builds up to achieve H=1 following the L-H transition, and assess the implications for fusion power on ITER")*. There was some discussion at the expert group meeting on the formulation of this question and on the meaning of "how rapidly". Here the main emphasis is on the density evolution after the L-H transition and there are also commonalities with question 5.3 (b). Therefore this task has been re-formulated more explicitly to read: "Determine which are the factors that affect how rapidly the pedestal and core plasma (in particular density) build up after the L-H transition, and what are the implications for the fusion power in ITER".

There is no recent result on 5.5 (a) *"Document the influence of current ramps (up and down) on the L-H power threshold"*. In a developed H-mode both DIII-D and JET observe that a current ramp up induces a transition from H-mode to L-mode (inversely a current ramp down induces a transition from L-mode to H-mode).

A review of the dependence of the H-mode threshold on ion species (5.6 (a) and (b)) was presented by P Gohil at the 2009 ITPA meeting in Princeton. The most recent JET and ASDEX-U helium experiments showed very little, if no, difference between P_{th} in He and D, in contrast to previous results in both machines. The difference between the two sets of JET data is partially explained by invoking different density dependencies in He and D, that are not seen in the ASDEX-U experiment. The variability of these results in most devices still needs to be explained and requires more analysis.

Related Joint Experiments

PEP-2	*Pedestal gradients and ELM energy losses in dimensionally similar discharges and their dimensionless scaling* (JET, DIII-D and ASDEX Upgrade)
PEP-26	*Critical edge parameters for achieving L-H transition* (C-Mod, AUG, DIII-D, MAST, NSTX)
PEP-27	*Pedestal profile evolution following L-H transition* (C-Mod, AUG, DIII-D, MAST, NSTX)
PEP-28	*Physics of H-mode access with different X-point height* (AUG, DIII-D, C-Mod, JET, MAST, NSTX, TCV)

4. Future meetings

The next ITPA Pedestal Group meeting will be held in Seoul, S Korea 18-20 October, 2010. Following that, it is proposed that in 2011 the meetings will be at MIT, US from March 30 to April 1 and then in York, UK in September. Both of the 2011 meetings require formal approval before final confirmation.

September, 2010