Version 2: July 2009

ITER IO Urgent Tasks: Pedestal Group Response

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A number of urgent R&D issues have been identified by the ITER IO. This note identifies those that the ITPA pedestal group is best-placed to address, proposes an updated work plan and reports progress since the previous note. This work plan assumes that adequate resources are provided by the organisations of the ITER partners. The plan 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 2, taking account of developments and summarising progress over the past 6 months. It will continue to be a "live" document, to be updated each six months.

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). 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. Note that area (5), the physics of the L-H transition, is a new area. It will be performed in collaboration with the Transport and Confinement group; this note identifies those tasks for which the Pedestal Group has the main responsibility.

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. More detailed descriptions of the progress towards meeting the objectives of the Working Groups is described in the summary reports of the ITPA meetings. These, together with individual presentations made at the meetings, can be accessed from the pedestal group web-site at http://itpa.ipp.mpg.de/.

1. ELM suppression with RMP coils

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, the technique has only been proven on DIII-D to date and the physics remains uncertain. The work plan presented here aims to improve our understanding, and so reduce uncertainties in ELM control scenarios for ITER.

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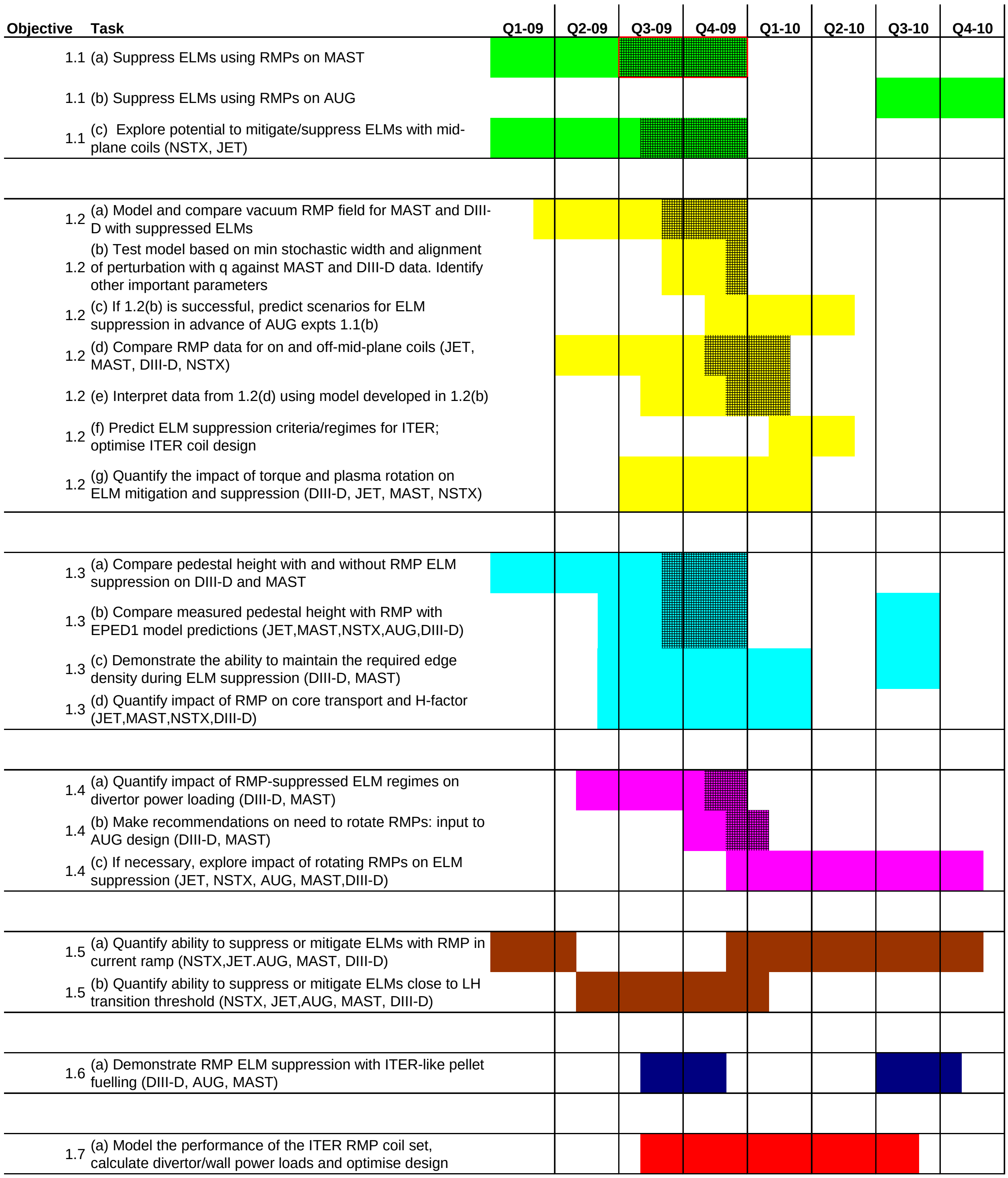

Figure 1: Work plan for RMP coil suppression/mitigation of ELMs (hashed areas indicate an extension compared to the previous work plan.

Objectives:

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 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 ELM control coils, including DIII-D, MAST, NSTX and JET. Of these, only DIII-D and MAST have 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 ITER-relevant RMP coils from mid (to late)-2010, 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++) also exist that can calculate 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 hashed areas indicate additional time is required for the tasks, mainly because ELM suppression has not yet been observed on MAST (despite a substantial effort in this direction). The original work plan was based on a number of assumptions, but must remain flexible 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 mid-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 IO on RMP coil design is Sept 2010, but results will be communicated as they are produced in advanced of this date.

Progress

Progress is being made in understanding parameters that appear to influence ELM suppression. These include q95 resonance, collisionality, density pump-out, beta, and island overlap width. DIII-D initially suggested that 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. Recent results from MAST now demonstrate that while this may be a necessary condition, it is not sufficient. A major task is to quantify the importance of each of the important 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. Plans are progressing for the installation of a very flexible coil set on AUG for operation in 2010 (the full capability is expected to be available from 2011).

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 internal 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

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 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 (otherwise the rise in density would itself modify ELM frequency and mask the effect of the pellets). 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.

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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 only two tokamaks with the capability to inject pellets with the necessary high repetition rate to increase the frequency of ELMs above the natural frequency: AUG and JET. DIII-D can drop pellets from above the plasma at the required frequency, but so far these pellets have failed to penetrate deep enough into the H-mode pedestal region to trigger ELMs. It is important to note that experiments that aim to understand the physics processes that lead to the triggering of ELMs do not require a high repetition rate and may be performed with lower frequency injectors.

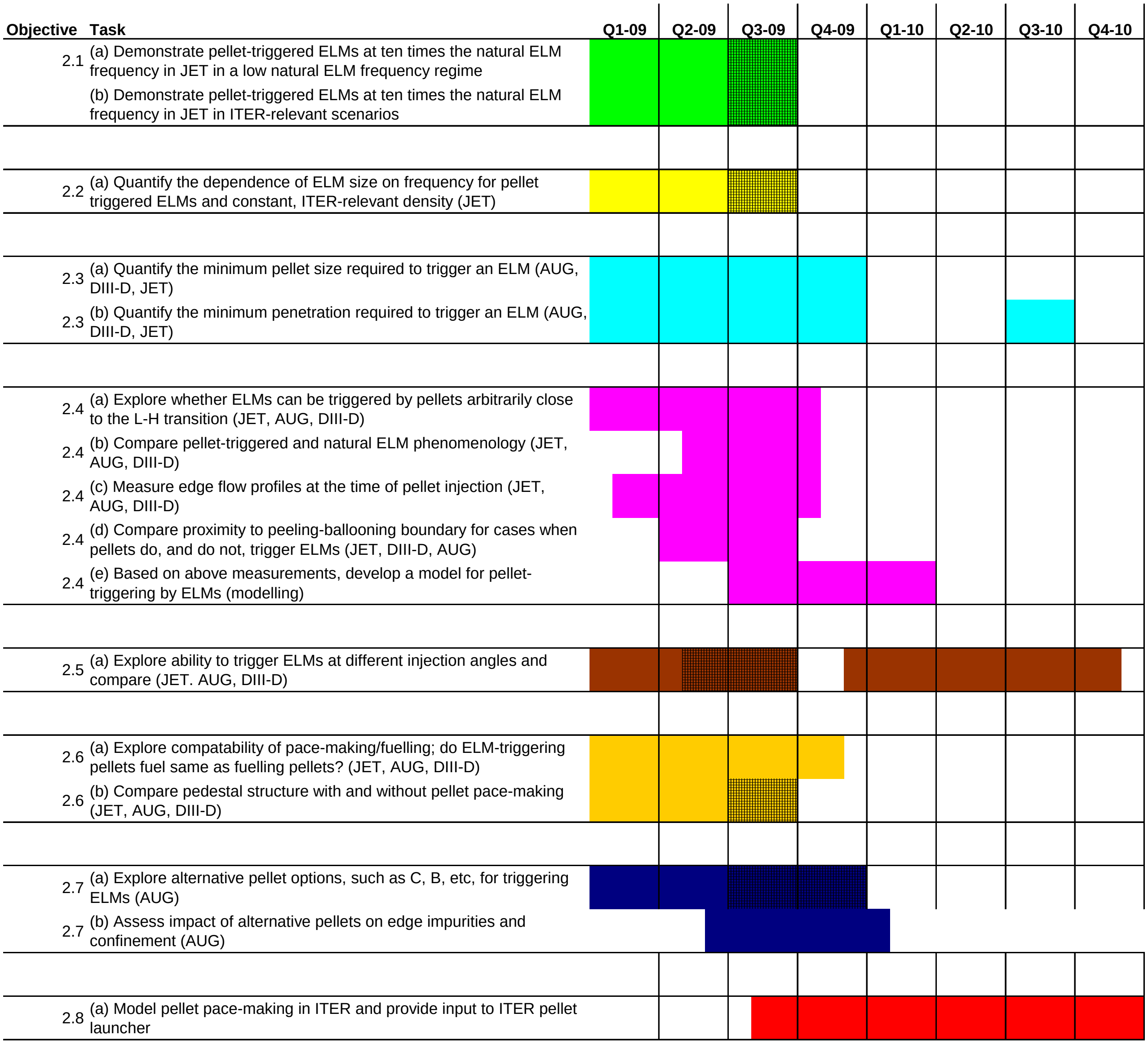

Figure 2: Work plan for pellet pace-making studies for ITER. Hashed areas denote extensions to deadlines.

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 is expected to be unavailable for experiments from autumn 2009 to the end of 2010. It is important, therefore, to carry out the necessary JET experiments in the next few months so that the key results for ITER are obtained and further research to firm up/expand these findings can progress in ASDEX-Upgrade and DIII-D until the end of 2010.

Progress

Delays in the new pellet-pacemaking system on JET have meant that experiments have been confined to using the fuelling pellets. Results confirm those found on AUG. On DIII-D, the pellet dropper has yet to successfully trigger ELMs. The high frequency pellet injector is expected to be available on JET towards the end of the summer to enable a campaign directed towards the objectives of this working group before JET shuts down for an extended period. There is information on the minimum pellet depth required to trigger an ELM: the pellet triggers the ELM before it is half way into the pedestal region. On DIII-D, when RMPs are applied, the pellets must penetrate a little deeper into the pedestal to trigger the ELM.

Related joint experiments

A joint experiment has been proposed that makes a substantial contribution to the objectives:

- PEP-24 “Minimum pellet size for ELM pacing” ASDEX Upgrade, DIII-D, JET

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 the large amplitude of the TF ripple can degrade the pedestal performance. However, the acceptable level of the 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 toroidal rotation should also be examined.

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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.

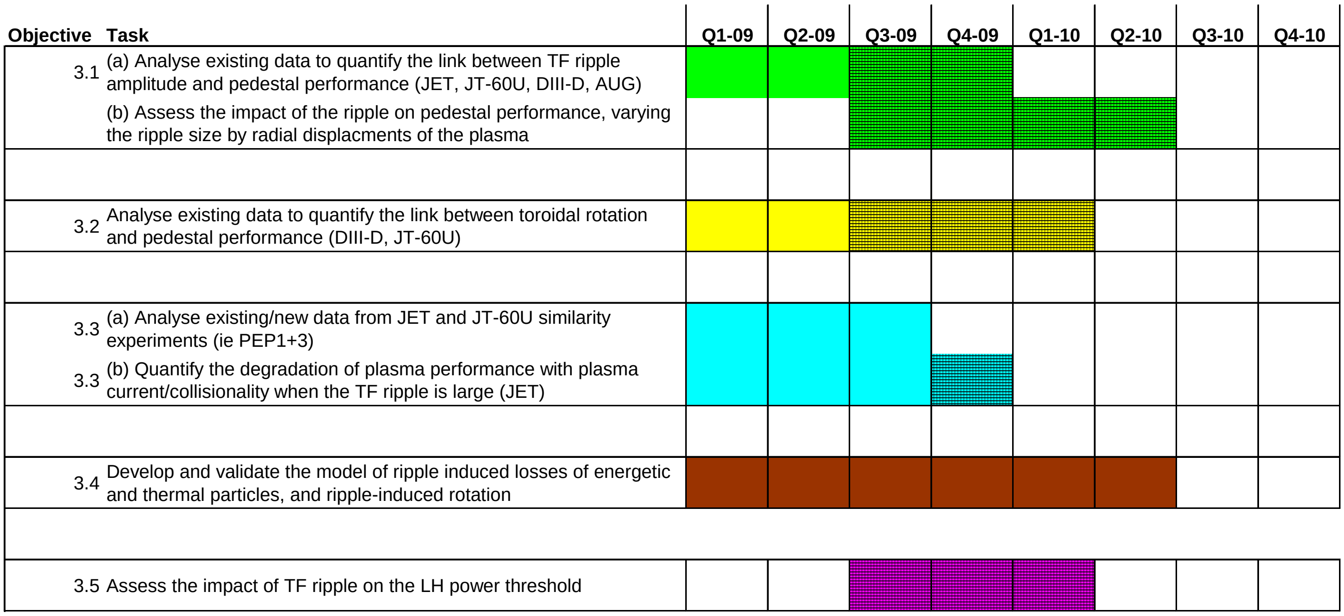

Figure 3: Work plan for TF ripple related issues for ITER. Hashed areas denote extensions to existing tasks, or new tasks

Work plan and time-scales

Figure 3 shows the work plan and time scales. The work plan assumes that new ripple experiments will be performed in JET before the shutdown in 2009 for installation of the ITER-like wall and other enhancements. In particular, we strongly recommend JET experiments to quantify the degradation of plasma performance with plasma current/collisionality at large TF ripple.

The target date for input to ITER IO on acceptable ripple amplitude is December 2009, and on losses by the TF ripple is end 2010 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

From the dedicated ripple experiments in JET, it is found that the effect of ripple on H-mode properties (stored energy and density) varies depending on plasma background parameters. The effect of ripple was seen in plasmas with lower density (or collisionality?) at 1.7MA and 2.5MA, while no significant difference was seen in plasmas with gas fueling. Therefore, there is no simple correlation between fast ion losses/torque/rotation and confinement explaining the JET results. The inter-machine experiment between JET and DIII-D demonstrates that it is possible to achieve the matched pedestal structure and the same H-mode quality (H_H~1), although the ripple amplitude of these devices was different, 0.08% in JET and 0.35% in DIII-D. Therefore, it is suggested that the ripple amplitude of 0.35% might not affect the H-mode quality.

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

4. Pedestal structure

Motivation: The overall performance of ITER will depend to a large extent on the pressure at the top of the pedestal. Two effects influence this: the pedestal width and the pressure gradient in the pedestal region. Ideal MHD is likely to set the maximum achievable gradient (though it is possible that two-fluid effects like diamagnetism may permit higher gradients in certain regimes). Recent experimental data suggest that the pedestal width scales 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. A related issue is how ELM type/size depends on the heating power mix. Other, less urgent (but nevertheless important), issues to address include characterising the transport processes in the pedestal, and developing an understanding of the density and temperature pedestal heights.

Working Group

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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.

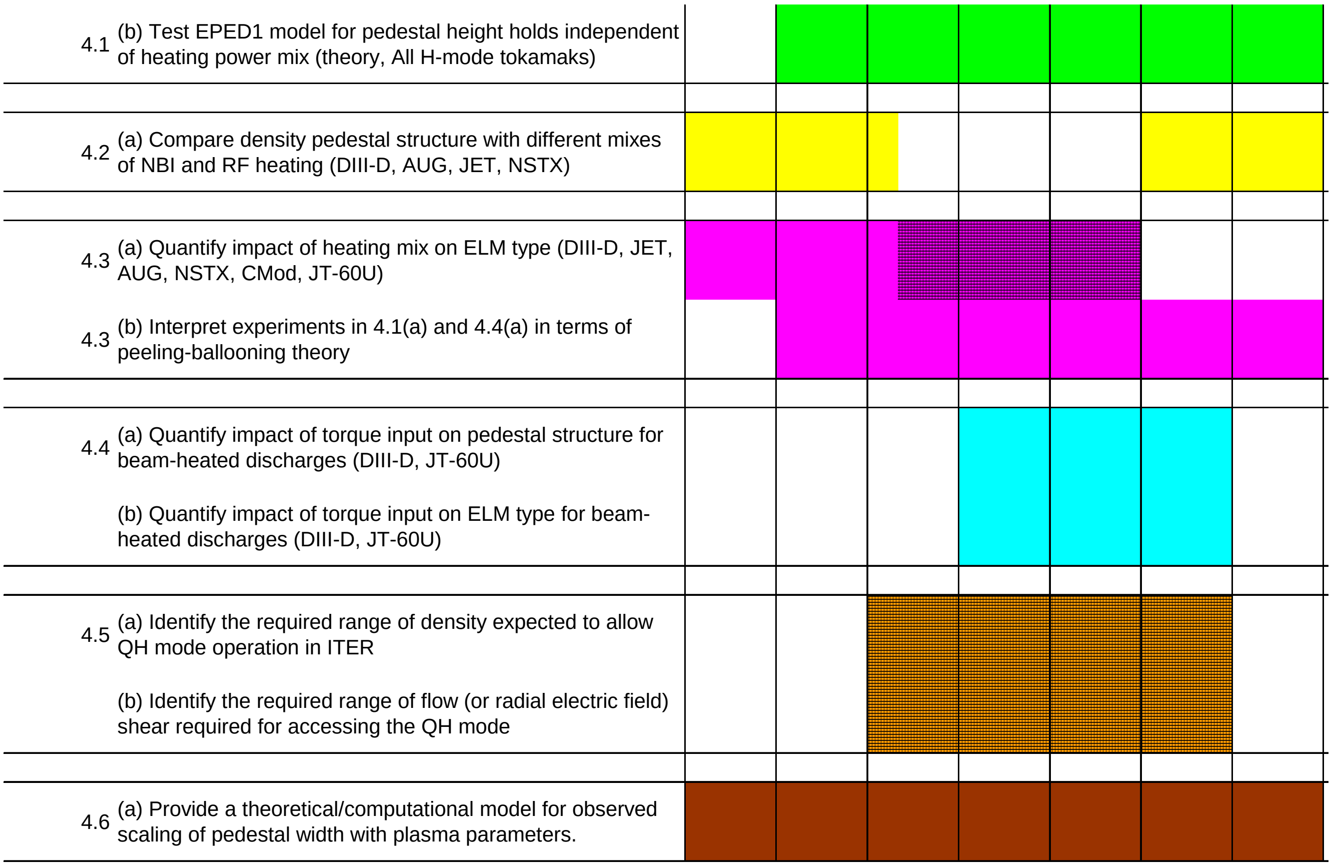

Figure 4: Work plan for Urgent Pedestal Structure issues for ITER

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. Experimental observations continue to suggest weak or no dependence of the pedestal width on gyroradius. Plans have been discussed, including a range of tokamaks and lead people, to initiate experiments to explore how (or whether) pedestal structure depends on heating source. Some data is available on the impact of torque on the pedestal structure and ELMs, but more work is planned. 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 at fixed β (JT-60U experiments were at fixed power, not fixed β). In light of recent progress in extending the parameter range of Quiescent H-Mode (QH) to a broad range of input torque, rotation, and density values, we have created a new objective focused on determining the potential viability of QH mode as a high pedestal, ELM-free regime for ITER.

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)

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	Q1-09	Q2-09	Q3-09	Q4-09	Q1-10	Q2-10	Q3-10	Q4-10
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 pedestal physics?								
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) 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								
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 impurity 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

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)

July, 2009