IAEA
International Atomic Energy Agency

22nd IAEA Fusion Energy Conference
Geneva, Switzerland Oct. 13-18, 2008

ELM physics and ELM mitigation in ITER

P. R. Thomas 1) for the ITER Organization, ITER9 Domestic Agencies, and ITER collaborators
1) Fusion for Energy, Josep Pla no. 2, Torres Diagonal Litoral - B3, 08019 Barcelona, Spain

---

This page intentionally left blank

ELM physics and ELM mitigation in ITER

P R Thomas 1) for the ITER Organization, ITER Domestic Agencies and ITER collaborators
1) Fusion for Energy, Josep Pla no. 2, Torres Diagonal Litoral - B3, 08019 Barcelona, Spain

email contact of main author: paul.thomas@f4e.europa.eu

Abstract. Edge Localised Modes are characteristic of the high performance, H-mode plasmas that are required for the attainment of Q = 10/500MW fusion power in the first phase of ITER operation. The energy released by a type I ELM, in good confinement plasmas, is typically 5-10% of the plasma stored energy; with low collisionality plasmas at the upper end of the range. Dimensional analysis, experiment and modeling all show that the thermal load limit of, where evaporation or sublimation of the divertor surface occurs, is likely to be exceeded by at least an order of magnitude by ELMS in ITER. The consequence this will be unacceptably rapid erosion of the divertor target, core plasma pollution and, possibly, increased disruption frequency. Thus it is required that ELMs be eliminated or mitigated in ITER. This paper details the background to this requirement, the physical basis for the available mitigation methods and the technical measures that have been undertaken, so far, to implement them on ITER.

1. Introduction

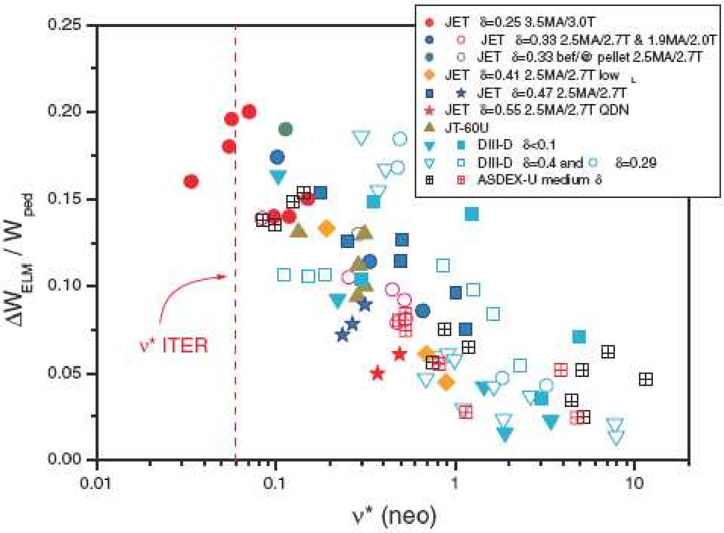

FIG. 1. The pedestal stored energy in ITER for the baseline high performance H-mode scenario is ~100MJ, implying that the energy loss per ELM can be ~20MJ at the collisionalities expected in ITER edge [1].

One of the physics requirements, subjected to close scrutiny during the ITER Design Review [2], was that of the thermal loads imposed on the divertor target by ELMs. New data, contributed by the ITPA and collaborators, showed that the disparity between unmitigated ELMs and the material properties of the target is anticipated to be even wider than had been presumed in the special issue of Nuclear Fusion, “Progress in the ITER Physics Basis” [3]. Methods of ELM mitigation or suppression were studied and it was concluded that the foreseen pellet injection system must be supplemented by a Resonant Magnetic Perturbation system. The ITER Science and Technical Advisory Board concurred with this conclusion and an intensive effort was undertaken to prepare the physics specification of an RMP system and, in parallel, to design a suitable installation for ITER

Extrapolations from existing experiments to ITER indicate that unmitigated ELMs on ITER could correspond to ~20MJ energy loss per ELM as indicated in figure 1. There is considerable scatter in the ELM energy loss at a given collisionality and there is dependence of ELM amplitude on such parameters as TF ripple and rotation velocity at the separatrix [4]. Nonetheless, the best confinement correlates with the largest amplitude ELMs and without counter-measures it cannot be excluded that ELMs corresponding to the upper limit in figure 1 will occur.

2. The Requirement to Reduce Divertor Heat Loads due to ELMs

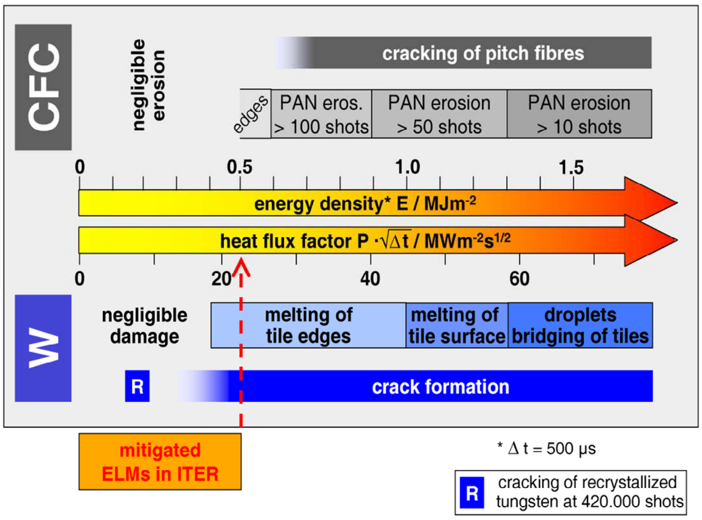

FIG. 1. Overview of damage to carbon fiber composite and tungsten divertor targets by ELMs. This analysis indicates that the transient heat load from ELMs needs to be reduced to about $0.5MJ/m^2$*. For comparison, unmitigated ELMs correspond to ~10* MJ/m^2 *[5 and references therein].*

Recent analyses by the ITPA [6] of divertor heat loads due to ELMs indicate that the peak heat loads are projected to be greater than used in the analysis in the ITER Physics Basis because the inboard/outboard asymmetry is larger and the losses to the wall are less than had been assumed. In addition the new information about material damage for both carbon fibre composite and tungsten divertor targets has become available as shown in figure 2.

The conclusion is that the release ~0.3% of the total thermal plasma energy (~1MJ) can cause tile fatigue and cracking as well as erosion, and larger energy losses can ablate or melt divertor materials potentially degrading the purity of ITER plasmas and greatly reducing the lifetime of the ITER divertor. These results imply a need to reduce the energy loss by a factor of ~20 and being able to do so very reliably. For 1000 high power shots, the 20MJ ELMs would have to be reduced to ~10^7 1MJ ELMs, corresponding to 0.5 MJm^{-2}. Occasional ELMs beyond the 0.5 MJm^{-2} are acceptable if limited to ~ 1.0-1.5 MJm^{-2} (CFC) and ~ 1.0 MJm^{-2} (W melting occurs). The consequences of thermal fatigue of 10^7 1MJ ELMs remains to be established since cracks are observed after material testing of both tungsten and CFC targets

Tools that can either eliminate or greatly reduce ELM energy losses without significantly degrading confinement are therefore critically important for successful operation of ITER and have stimulated worldwide research on ELMs [7-21]. Two approaches, pellet pacing and application of helically resonant magnetic perturbations (RMP), are current areas of experimental and theoretical research that were evaluated as part of the ITER design review. In addition, vertical position "joggling", first used to pace ELMS on TCV [22] and AUG [23], has recently been exploited on JET and is reported at this conference [24]. Whilst it is not clear what PF power would be required to do this in ITER, nor indeed if it would work at all, the JET results have important implications for other ELM triggering schemes, such as pellet pacing, because of the range over which the ELM frequency could be increased.

3. ELM Mitigation by Pellet Pacing

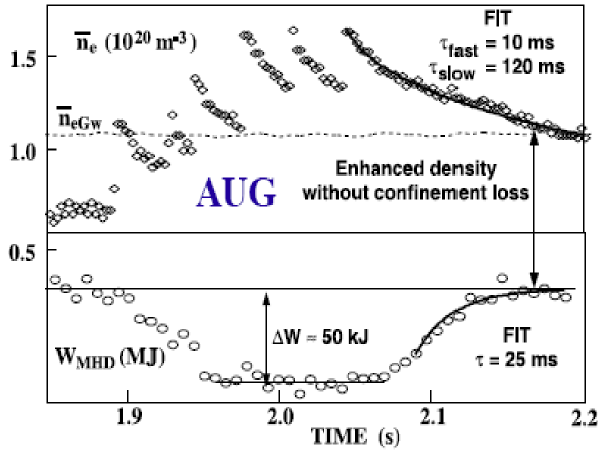

FIG. 3. Impact of pellet injection in ASDEX Upgrade on confinement time, showing a modest degradation in the energy confinement, which is attributed to convective energy loss [25].

Experiments on ASDEX Upgrade, DIII-D and JET have demonstrated that pellets can trigger ELMs, enabling the production of more frequent smaller ELMs. A factor of 0.6 reduction in ELM size was achieved by the application of pellet pacing to control the ELM frequency though even larger reductions have been observed in uncontrolled experiments in which the pellet was injected right after a naturally occurring ELM. The present experiments are accompanied by a small degradation in the energy confinement time [25]; which is associated with increased convective loss, as shown in figure 3. Pellet pacing to control ELMs on ITER is a significant extrapolation from current experiments in that the ratio of the pellet repetition time to the energy confinement time is much smaller. The JET "vertical joggling" experiments show that ELMs can be paced to a frequency at least an order of magnitude greater than the “natural” frequency. However, it is not evident that the continued inverse proportional reduction of ELM energy with frequency can be depended upon.

The frequency of pellet injection required on ITER is estimated to be about 40Hz with pellets penetrating to the top of the pedestal. For these conditions, it is possible to estimate the convective energy loss taking into account that the particle confinement time decreases with minor radius as observed on MAST [26] and existing pellet technology. For these assumptions, the convective power loss is most of the heating power. To decrease the adverse effects of the accompanying convective energy loss at this frequency and depth of penetration will require the development of a higher speed pellet injector [10]. Further experimental results are needed to refine the requirements for the depth of penetration required to trigger ELMs and evaluate the impact on energy confinement when using higher frequency pellet injectors.

To provide for the capability to incorporate a pellet pacing on ITER, the gas throughput requirements were updated. The gas throughput requirements for 400 s standard burn pulses were increased from 120 to ~200 Pam^{3}s^{-1}. For 1000s pulses the gas throughput was increased from 120 to 160 Pam^{3}s^{-1} The requirement for 3000s pulses were maintained at 120 Pam^{3}s^{-1}. The requirements for the pellet injector will be updated after further experimental results from existing machines become available.

4. ELM Mitigation by Resonant Magnetic Perturbation

The application of resonant magnetic field perturbations (RMP) to control ELMs began with early work on JFT-2M [7], was first discussed as a possibility for ITER in [8] and is currently a very active area of research. Different experimental results have been obtained, depending on the applied perturbation mode spectrum [9 and references therein, 12]. These include 1) triggering ELMs in a previously ELM-free discharge (COMPASS, JFT-2M and NSTX) with n=3 fields from large aperture, external (far from the plasma) RMP coils on the outer midplane, 2) increasing the frequency of ELMs and reducing the amplitude on DIII-D and JET using n=1 or n=2 perturbations from both large aperture, external, midplane coils and smaller aperture, internal off-midplane rows of coils, to 3) fully suppressing ELMs on DIII-D with n=3 RMPs from small aperture, internal, off-midplane rows of coils. The ability to completely suppress ELMs has major implications for the reliability of plasma facing components and has motivated including the capability of applying resonant magnetic perturbations into the ITER design.

The use of resonant magnetic perturbations for ELM control to suppress ELMs on DIII-D involves applying helically resonant magnetic perturbations to the plasma boundary to increase the plasma transport near the edge to limit the edge pressure gradient of the H-mode. This technique has been shown to be capable of completely suppressing ELMs at ITER-relevant collisionality while maintaining the energy confinement times consistent with the predictions of the ITER database ($H_{98y,2}$=1) provided the magnetic perturbations are sufficiently localized to the plasma edge region.

The DIII-D data, in combination with the results from the other devices, provide four guidelines toward the requirements for ELM suppression coils on ITER: 1) the coils should be as close as possible to the plasma to maximize the edge perturbation while minimizing the core perturbation, 2) the coil rows should be on the outboard side but not solely on the outboard midplane, 3) the perturbation should be as pitch aligned with the unperturbed equilibrium field lines as possible, and 4) the width of the edge region having good overlap of magnetic islands calculated with the vacuum fields from the coils should be greater than a threshold value. Good overlap of magnetic islands can be characterized by a Chirikov parameter (magnetic island width / island spacing) being greater than 1.0. The maximum ELM size in the DIII-D experiments at q95 ~ 3.6 is correlated with the width of the edge region having Chirikov parameter > 1 (figure 4). The threshold value for the ELM suppression range from these experiments was used to guide the requirements for the currents in the ITER coil design.

With the existing geometry of the internal plus external coils on DIII-D, the requirement for field line alignment results in suppression being achieved in a relatively narrow range of the safety factor, $3.2<q_{95}<3.8$ when the two rows of internal coils are configured with up down symmetric perturbations, in combination with n=1 fields from the external coil, which are typically used to correct error fields. For up/down asymmetric perturbations from the internal coils theory predicts, and the experiments show, suppression for $q_{95} \sim 7.2$, confirming the requirement for pitch alignment of the perturbation fields. Outside these pitch aligned resonant windows in q_{95}, ELM energy loss is reduced when the perturbations are applied, but ELMs are not suppressed.

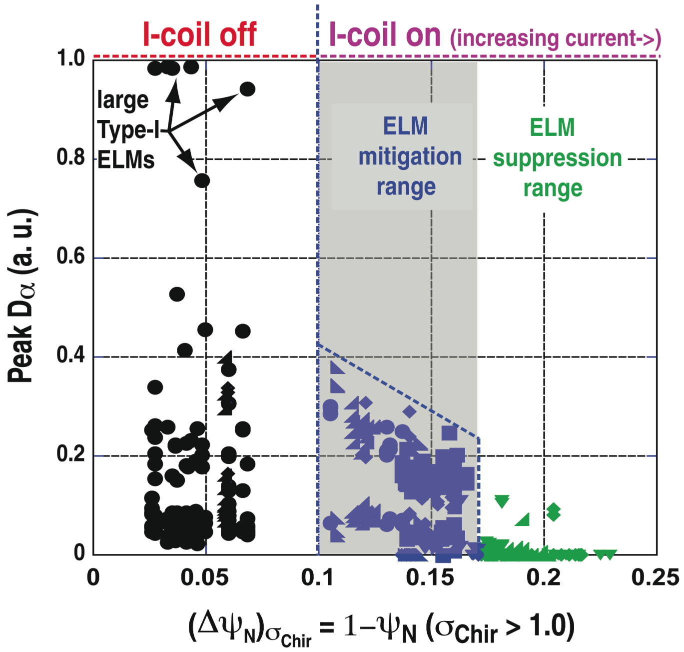

FIG. 4. Results from DIII-D experiments at q_{95}~3.6 for the ITER shape and edge collisionality. The maximum ELM size is correlated with the width of the edge region having Chirikov overlap parameter greater than 1.0 and ELM suppression is correlated with the overlap width exceeding a threshold value [9].

The DIII-D experiments utilized two rows of off-midplane coils to create an n=3 helical pattern. In contrast, other experiments, including experiments on DIII-D, which utilized one row of distant midplane coils did not succeed in suppressing ELMS before generating locked modes. However, in DIII-D a single row of off-midplane in-vessel coils did suppress ELMs before locking, perhaps because the coil set close to the plasma has less non-resonant spectral content relative to resonant than fields from more distant coils. On MAST and NSTX, experiments using their outboard midplane error field correction coils failed to suppress ELMs though the Chirikov parameter was estimated to satisfy the criteria developed on DIII-D. These results suggest the importance of tailoring the perturbation spectrum.

A comprehensive understanding of the underlying physics is still emerging, motivating additional experiments, including the role of edge pumping and pellet injection. Variation of the location of the strikepoint with respect to the DIII-D cyropanels demonstrated that edge pumping is an important consideration. Furthermore, the effective particle confinement time decreased in DIII-D experiments with the application of RMP coils decreasing the plasma density but that should, in principle, be able to be compensated with increased core pellet fueling. Pellet injection into discharges with resonant magnetic perturbations has in some cases but not always triggered ELMs. Since pellet fueling is integral to achieving the required densities in ITER, this needs to be studied further. This has also motivated further theoretical work on the role of resonant and non-resonant magnetic perturbations, which is important not only for ELM suppression but, more broadly, for error field correction and avoidance of locked modes [11, 27]. A closely related issue that needs to be more thoroughly explored is not only the impact of the magnetic perturbations on plasma rotation but the role of plasma rotation in the penetration of the magnetic field and altering transport preferentially in the edge pedestal [28, 29].

5. An RMP System for ITER

The case for ELM mitigation or suppression measures in ITER was conclusively demonstrated by the studies undertaken during the ITER Design Review, as described above. Whilst ELM pacing by pellet injection was foreseen for ITER, the uncertainty of extrapolation to ITER and the difficulty of some of the technical requirements made a second system mandatory. Since RMP acts on ELMs in an entirely different way to pellet pacing, it was seen as the most useful alternative. Also, the difficulty of mounting an RMP system on ITER meant that a retro-fit would not be possible, so the decision to proceed with RMP had to be taken immediately.

In support of the ITER in-vessel coil design, experimental and theoretical assessments were performed for different coil configurations to evaluate the magnetic spectrum and the coil current requirements. A number of different locations were considered for the coils, such as the exterior of the vacuum vessel, the inter-space between the vessel shells and between the blanket-shield and the vacuum vessel. In the end, the latter was found to be the only feasible solution and the adopted coil layout is shown in figure 5. It should be stressed that a significant driver for the adopted configuration and its technical specification is that of the need for internal coils to improve vertical stability, as described elsewhere in this conference [30].

As discussed above, this analysis indicates that multiple (3) rows of in-vessel coils provide greater flexibility to attain the minimum conditions for ELM suppression and minimize the deleterious effects of plasma rotation damping. As shown in figure 5, three rows of coils above and below the midplane as well as on the midplane are proposed for each of the nine vessel sectors. The mid-plane coils primarily trim the spectrum to minimize toroidal braking of the plasmas, whilst the upper and lower windings provide most of the resonant contribution. These coils would be located behind the blanket shield module and provisions are included to enable remote maintenance of the coils. The interfaces between the coils, the vessel and the blanket shield are not straightforward and much innovative design has gone into the proposed solution, ranging from the conductor cooling to the transitions between the coil windings and the feeds for water cooling and the supply of electrical current.

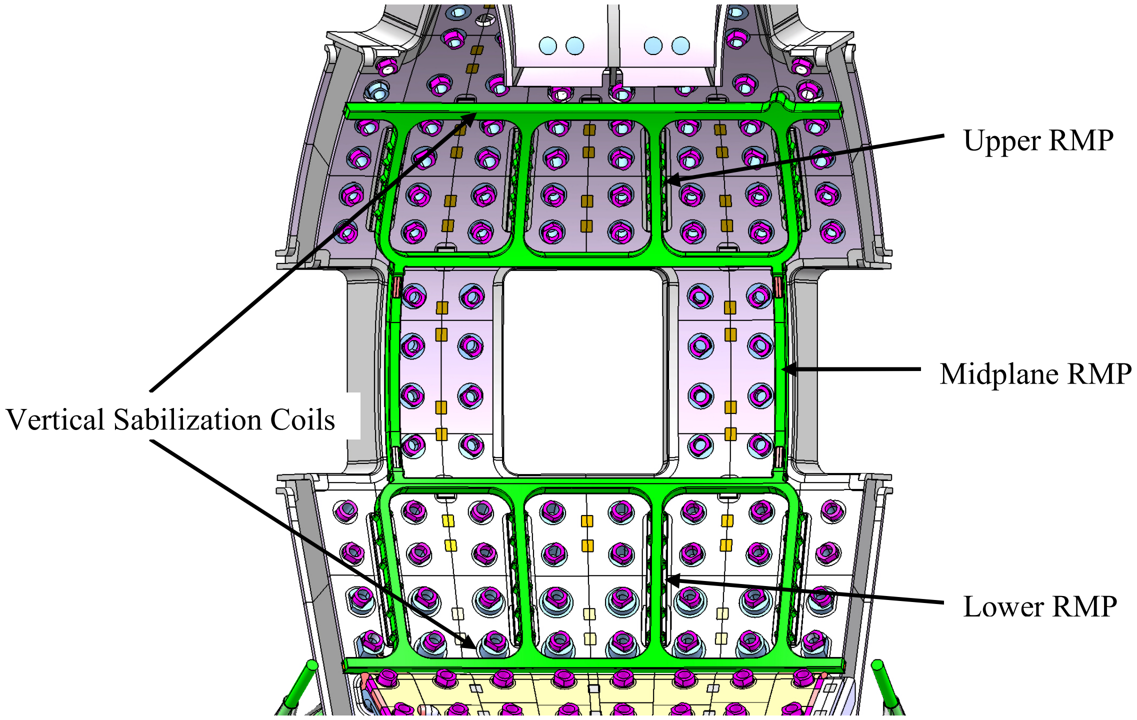

FIG. 5. Proposed design of in-vessel coils for vertical stabilization and ELM control. The ELM control windings can also be used for resistive wall stabilization.

Though there has been substantial progress in defining the physics and engineering requirements for the coils design, the criteria for field line alignment and mode spectrum as well as magnitude of the perturbed field remains an active area of research.

Acknowledgement

The material presented in this paper is the outcome of work by colleagues that was carried out under extreme time pressure because of the urgent need to conclude the ITER design. The presenter would like to express sincere thanks for this incredible effort.

References

[1] LOARTE, A. *et al* 2007 Progress in the ITER Physics Basis Nucl. Fusion **47** S203
[2] HARWYLUK, R. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) *et op. cit.*. IT/1-2
[3] Editors of 'Progress in the ITER Physics Basis' *et al* 2007 Nucl. Fusion **47** S1
[4] OYAMA, N, (2008) Journal of Physics: Conf. Series **123** 012002.

[5] LINKE, J. *et al* 2007 Proc. 13th International Conference on Fusion Materials, Nice, December 10-14, 2007.
[6] ITPA PEP and SOL/DIV Task Groups communication June 2007.
[7] MORI, M. *et al* 1992 Proc. 14th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research 1992 (Wurzburg, 1992) vol 2 (Vienna: IAEA) 567
[8] ANE, J-M. et al. 2002 Proc. 19th Int. Conf. on Fusion Energy 2002 (Lyon, France) (Vienna, IAEA)
[9] FENSTERMACHER, M.E. *et al* 2008 Phys. Plasmas 15, 056122
[10] BAYLOR, L. R. *et* al 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) IT/P6-19
[11] BECOULET, M. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) TH/2-1Ra
[12] EVANS, T. E. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) EX/4-1
[13] FUNDAMENSKI, W. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) EX/4-3Ra
[14] GAL, K. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) TH/P4-5
[15] HAYASHI, N. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) TH/P9-14
[16] IZZO, V. A. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) TH/P4-19
[17] LANDMAN, I. S. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) IT/P6-11
[18] LANG, P. T. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) EX/4-5
[19] KIRK, A. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) EX/P6-3
[20] MAINGI, R. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) EX/P6-4
[21] TERESHIN, V. I. *et* al 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) IT/P6-12
[22] MARTIN,Y *et al.* 2004 Proc. 31st EPS Conf. on Plasma Phys.(London), ECA 28G P4-133
[23] DEGELING, AW et al., 2003, Plasma Phys. Control. Fusion **45** 1637
[24] ROMANELLI, F. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) OV/1-2
[25] LANG, P.T. *et* al 2002 Nucl Fusion **42** 388
[26] VALOVIC, M. *et al* 2008 Nucl. Fusion **48** 075006
[27] PARK, J-K. *et* al 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) EX/5-3Rb
[28] PARK, G. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) TH/P4-10
[29] SHAING, K. C. . *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) TH/P9-30
[30] PORTONE, A. *et al* 2008 Proc. 22nd Int. Conf. on Fusion Energy 2008 (Geneva, Switzerland) (Vienna, IAEA) IT/2-4Ra