EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(02)07/21

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in
Proceedings of the 19th IAEA Conference, (Lyon, France 14-19 October 2002)

ABSTRACT.

The investigation of methods for a reduction of divertor heat loads in order to increase the lifetime of divertor tiles in future fusion reactors is the main objective of this paper. Special emphasis is given to the reduction of transient heat loads due to Edge Localised Modes (ELMs). Two methods are compared: Argon seeded type-I ELMy H-modes and Nitrogen seeded type-III ELMy H-modes. In both scenarios the impurity seeding leads to a reduction of the pedestal energy and hence a reduction of the energy released by the ELM. This consequentially reduces the power load to the divertor targets. At high radiative power fractions in type-III ELMy H-modes part of that released ELM energy (25kJ) is dissipated by radiation in the Scrape Off Layer (SOL). Modelling of the ELM mitigation supports the experimental findings. Both scenarios might be compatible with an integrated ITER scenario, with respect to acceptable divertor lifetime and acceptable confinement.

1. INTRODUCTION

One of the most severe problems for fusion reactors is the power load to the divertor target plates. Technically only steady state power loads of less than 10 MW/m^2 are acceptable with margin. In order to reduce the power load in the divertor to those values radiation cooling by seeding of impurities is essential. Furthermore transient heat loads due to ELMs have to be reduced to values below 40 MJ m^2 $s^{1/2}$. Presently unseeded type-I ELMy H-modes seem to be problematic. Alternative operating scenarios with tolerable transient heat loads have to be developed. One of the potential alternative scenarios is the ELMy H-mode with impurity seeding. The present paper summarises the work aimed at the reduction of the heat load to the target plates, both during, and inbetween ELMs, using the radiation of a purposely injected 2 impurity. Two scenarios are described, type-I ELMy H-modes with impurity seeding and type-III ELMy H-modes with impurity seeding.

2. RESULTS

In the first scenario described Nitrogen is seeded in type-III ELMy H-modes up to radiative power fractions of 90%. In low triangularity configurations [1] this regime leads to a par-tially detached H-mode at 85% of the Greenwald density, confinement enhancement factors of $H_{98(Y,2)} \approx 0.7$-0.8 with a normalised plasma pressure of $\beta_N \approx 1.3$-1.4. The steady state heat flux density is reduced to less than 1MW/m^2 and electron temperatures in the divertor of less than 10eV even during ELM peaks are feasible. There is an indication of radiative dissipation of ELM energy at high radiative power fractions (90%), which reduces the ELM power load by a factor of 2 and leads to transient power loads due to ELMs of less than 5MW/m^2 at the outer divertor target plate [1]. Although the heat load can be reduced significantly, the confinement of these discharges is reduced as well. However, increasing the triangularity from $\delta = 0.2$ to $\delta = 0.47$ leads to improved confinement at high densities (see figure 1a), resulting in $H_{98(Y,2)} \approx 0.76$ at densities close to the Greenwald density $\bar{n}_e/n_e^{GW} = f_{GDL} = 1$. This increase in absolute density ($Z_{eff} \propto P_{rad}\ n_e^2$) also leads to a reduction of the plasma core impurity content ($Z_{eff} \approx 1.6$). No impurity accumulation has been observed. The profile of the fully ionised nitrogen, as derived from CXRS, is hollow during the highest radiative power fractions.

This radiating type-III ELMy H-mode might enable an integrated ITER scenario for Q = 10 operation with acceptable steady state and transient target power loads. For a slightly degraded confinement ($H_{98(Y,2)}$=0.75-0.8) a Q = 10 operation will be possible at a plasma current of 17 MA ($\beta_N \approx 1.5$, f^{GDL}= 1, q_{95} = 2.6) [2, 3]. Though operation at low q_{95} might be difficult due to MHD, experiments at low triangularity have been extended to low q_{95} with no apparent drawback due to MHD. The confinement ($H_{98(Y,2)}$=0.77) is acceptable even at lowest edge safety factors (see figure 1b).

As alternative to the nitrogen seeded discharges, argon is seeded in type-I ELMy H-modes in order to reduce the transient heat flux due to larger ELMs (energy losses due to ELMs of ΔW_{ELM} $\geq$0.2 MJ) since it has the potential to radiate at higher temperatures. In this scenario a confinement of $H_{98(Y,2)}$= 1 can be maintained at densities of f_{GDL} = 0.85 up to radiative power fractions of 65%, provided an accurate adjustment of both the Argon and Deuterium fuelling rates [4]. In the series of experiments reported here, emphasis has been given to the analyis of the ELM heat flux in discharges, which have not been performance optimised ($H_{H98(Y,2)} \approx$ 0.87, f_{GDL} = 0.78 which is 5% less than in Deuterium Reference pulse, and f_{rad} = 0.6): detailed measurements of the pedestal parameters (edge LIDAR and ECE data) and of the power fluxes to the target plates (IR camera) have been obtained. In these experiments, the frequency of the type-I ELMs decreases slightly as the power crossing the pedestal is decreasing (due to enhanced radiative power from the plasma core), and the transient divertor power load is reduced by a factor of ≈2 (figure 2a). The resulting peak value at the outer divertor target is ≈ 15MW/m^2 , i.e. a factor of 3 higher when compared to the type-III ELMy H-mode with similar heating power. This reduced transient heat flux with Argon seeding stems from a reduced pedestal electron temperature (figure 2b). This is furthermore illustrated in figure 3a, which shows the energy rise at the divertor target versus the loss of stored plasma energy: no difference between data from Argon seeded and non-seeded discharges is observed, demonstrating the lack of additional dissipation in the SOL and divertor plasma under the present conditions. However, for similar ELM losses $\Delta W_{ELM}/W_{ped}$ Argon seeded discharges have a lower ELM frequency (by up to a factor of two lower), which is beneficial for the divertor lifetime.

Argon seeding in type-I ELMy H-modes would enable an integrated ITER scenario for Q = 10 operation at 15 MA (q_{95} = 3). Confinement and density are well within the ITER requirements [5]. However, the aimed radiative power fraction of f_{rad} = 0.75 is difficult to reach in this scenario. This is consistent with the observation that the steady state heat flux to the divertor is not significantly reduced in those pulses. The maximum radiative power fraction has to be limited in order to avoid accumulation of argon in the plasma center, although the application of central heating might enable high impurity concentrations without accumulation in the plasma core [6].

Modelling of the effect of impurity seeding on the transient power load on the divertor tiles has been carried with MIST, B2/Eirene and EDGE2D. The calculations with MIST suggest that Krypton is the best element for the reduction of the divertor power load. However, since high-Z elements radiate strongly in the plasma core the acceptable impurity concentration of those elements is less than for low-Z impurities.

EDGE2D modelling of the ELM mitigation by nitrogen seeding (f_{rad} =0.75) demonstrates that roughly half of the ELM energy can be dissipated by radiation for small ELMs (25kJ). Increasing the ELM energy to 60 kJ diminishes the effect of radiative dissipation in those highly radiative plasmas to negligible values of ≈16%. Without the cooling of extrinsic impurities (here Nitrogen) ELM mitigation of small ELMs (25 kJ) is also less effective (≈25 % gets dissipated). This is consistent with B2/Eirene simulations for ITER [7], which show that only very small ELMs can be dissipated by a radiating layer. A comparison of recycling impurities versus non-recycling impurities has been carried out (1% recycling versus 90% recycling), which showed essentially no significant difference in the effect of radiative dissipation.

In order to assess the applicability of both impurity seeding scenarios the expected ELM size in ITER has to be estimated. Figure 4 shows the dependence of the ELM energy loss on the collisionality. Both, in type-I ELMy H-modes [9] and in type-III ELMy H-modes the ELM energy loss ΔW_{ELM} / W_{ped} increases with decreasing pedestal collisionality. Argon seeded type-I ELMy H-modes have the same ELM energy loss $\Delta W_{ELM}/W_{ped}$ as unseeded type-I ELMy H-modes for similar collisionalities. For type-III ELMy H-modes also no difference between impurity seeded and non-seeded discharges with respect to the ELM energy losses $\Delta W_{ELM}/W_{ped}$ is observed. One should note that the values of $\Delta W_{ELM}/W_{ped}$ used in Fig. 4b for type-III ELMs are upper boundary estimates of the real ELM losses, since the noise level in the magnetic measurements is comparable to DWELM. Even considering this upper boundary estimate, the energy loss in type-III ELMy H-modes is a factor of ≈2 lower than in type-I ELMy H-modes. The real ELM losses can be up to a factor of two lower than these estimates, as some kinetic measurements of ΔW_{ELM} indicate [1]. For ITER, an ELM size of $\Delta W_{ELM}/W_{ped}$ of 9±5% (assumingW_{ped} = 30%W_{dia} seems to be just acceptable [8, 9]. As shown in figure 4a, the contribution of the pedestal stored energy to the total stored energy is generally lower for type-III ELMs than for type-I ELMs, remaining within the ITER reference of W_{ped} = 30%W even at high stored energy (and triangularity, up to $\Delta \approx 0.5$). As in figure 4b demonstrated the type-III ELM losses are within the ITER acceptance even for the lowest collisionality, whereas for the ITER edge collisionality too large type-I ELM losses are observed. However, if the ELM size in ITER is not determined by the edge collisionality but rather by the parallel transport times in the SOL, type-I ELMy H-modes might be just acceptable [9].

3. CONCLUSION

By seeding impurities the steady state heat flux to the divertor target plates can be reduced significantly. Radiative power fractions of 90% did lead to steady state power fluxes of less than 1 MW/m^2. For both type-III ELMy H-modes and type-I ELMy H-modes a reduction of the transient heat flux was observed. This reduction of the heat flux is mainly due to a decrease of the pedestal energy in the presence of impurity fuelling. In addition ELM mitigation by radiative dissipation of the ELM energy was observed for the smallest type-III ELMs. This radiative dissipation of ELM energy is not expected for ITER, since the ELM energy will be likely in excess of several MJ.

Hence, the ELM energy loss has to be limited. It is expected that for ITER-like pedestal collisionalities type-III ELMs are acceptable, whereas type-I ELMs are not. However, if the ELM losses are not determined by the pedestal collisionality type-I ELMy H-mode might be acceptable [10].

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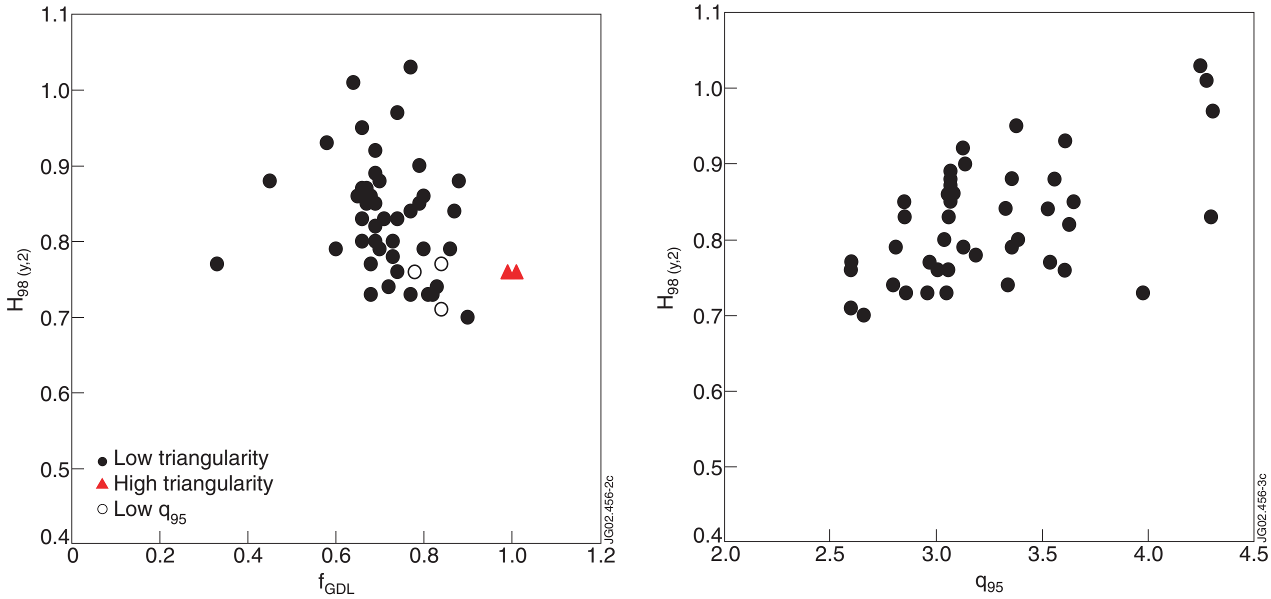

Figure 1: $H_{98(Y,2)}$ versus the normalised density $\bar{n}_e/n^{GW} f_{GDL}$ (a), and versus the edge safety factor q_{95} (b), type-III ELMy H-modes with $f_{rad} \geq 0.7$.

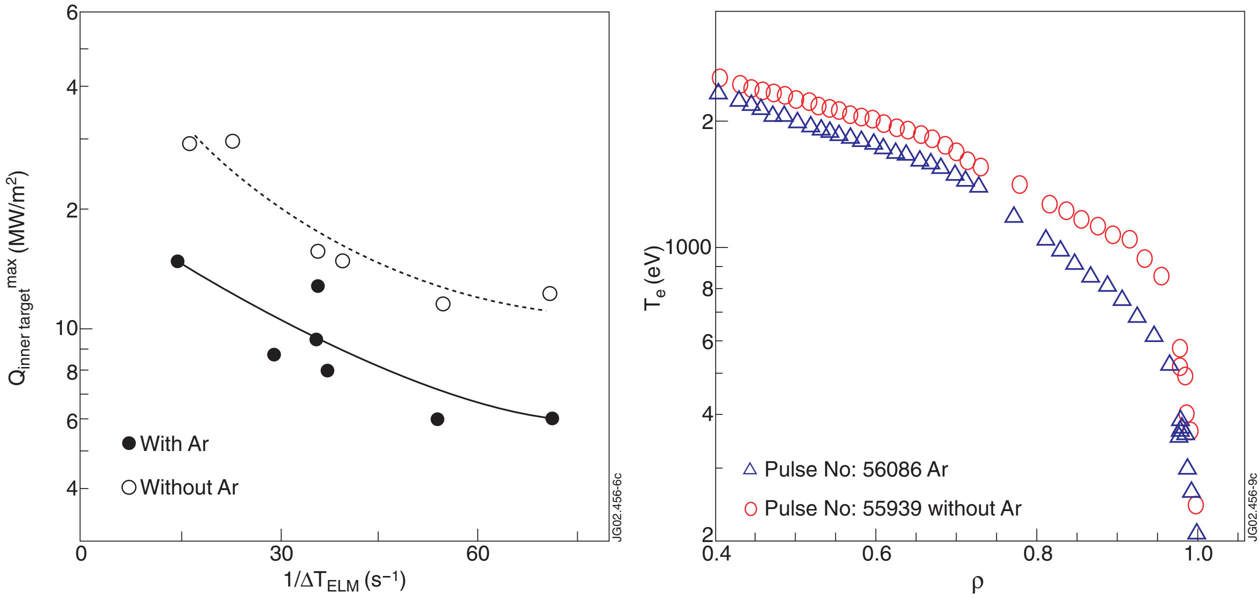

Figure 2: (a) Comparison of power fluxes to the inner divertor target with ($f_{rad} \approx 0.6$) and without Argon fuelling, (b) comparison of the electron temperature profiles with and without Argon seeding.

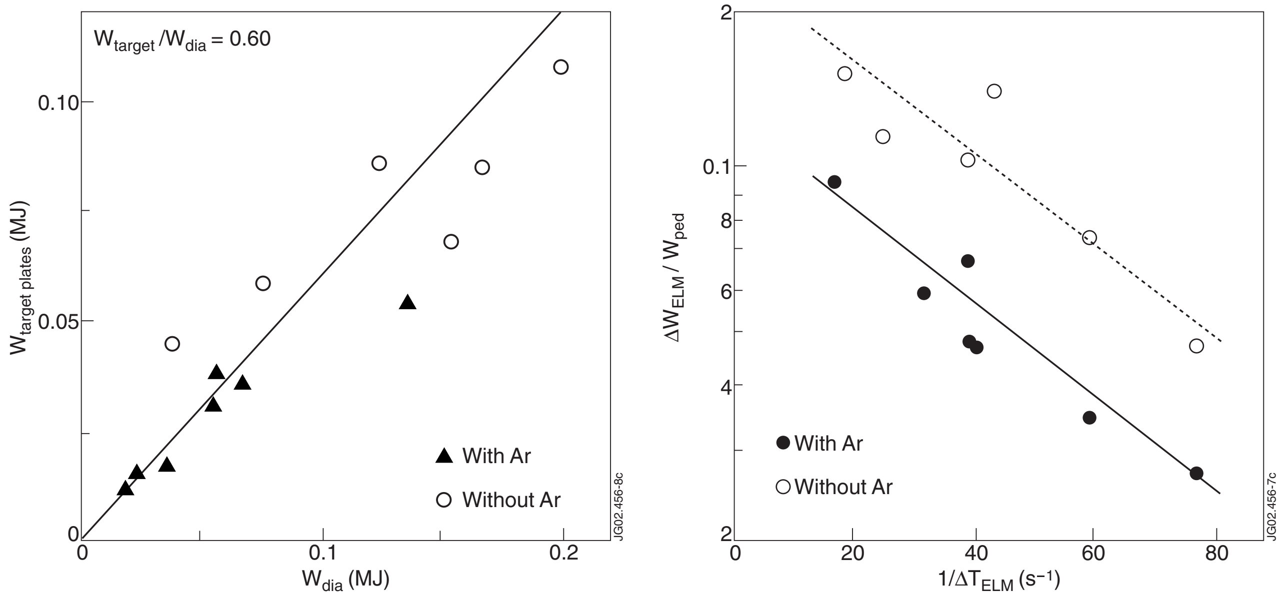

Figure 3:(a) Reduction of target energy load due to ELMs versus energy lost from plasma due to ELMs, (b) dependence of ELM energy losses versus ELM frequency.

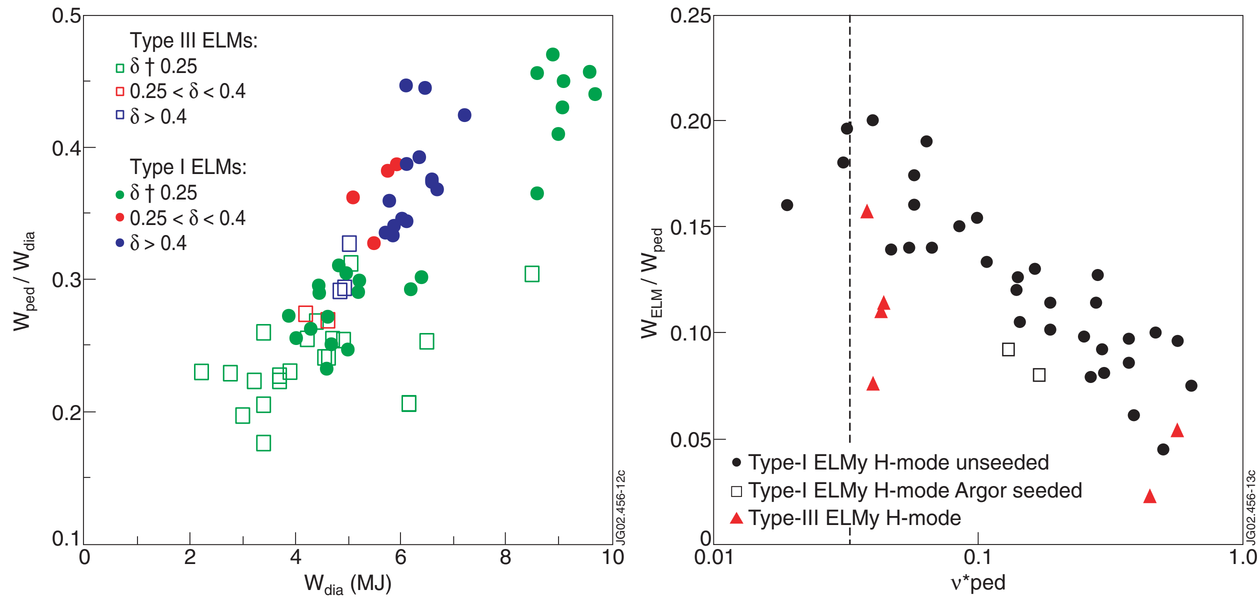

Figure 4: Comparison of type-III ELMy H-modes to type-I ELMy H-modes: (a) Ratio of pedestal to total stored energy versus stored plasma energy; (b) plasma energy loss due to ELMs normalised to pedestal stored energy versus pedestal ion collisionality; non-seeded type-I ELMy H-modes (black solid circles), seeded type-I ELMy H-modes (black open squares), seeded and non-seeded type-III ELMy H-modes (red solid triangles); the ITER collisionality (dashed line).