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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).*

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ABSTRACT.

One of the most severe problems for the operation of next step fusion devices in H-mode is the transient power load to the divertor target plates due to Type I ELMs. The purpose of this paper is to assess the use of impurity seeding to reduce Type I ELM heat fluxes through enhanced radiation, either in a narrow region just inside the separatrix, or in the SOL and divertor regions, while maintaining good core confinement. An analysis of the divertor heat load during Type I ELMs in argon seeded H-modes on JET has already been reported. In these discharges, with Ar and P_{rad}/P_{tot} $\approx$0.6, the peak heat flux due to Type I ELMs was reduced by a factor of $\approx$2, and the confinement was $\approx$5% less than in the deuterium reference pulse. This effect is due to a reduced pedestal energy, and hence a reduced ELM energy release. From the limited set of data analysed in, no clear evidence of any additional radiative dissipation in the SOL and divertor region was observed. In the present paper, the previous analysis of argon seeded H-modes is compared with new experiments where nitrogen is used as radiating species as a means to change the localisation of the radiation from the region just inside the separatrix to the SOL and divertor, the underlying physics idea being that, in that case, some fraction of the ELM energy might be radiated before reaching the target plates. The results are modelled using the time-dependent SOLPS5.0 code. Previous calculations of this possible buffering effect have been reported for JET and ITER, both predicting it to be large (> factor 2) only for small ELMs (ΔW_{dia} <20kJ in JET).

1. EXPERIMENT.

1.1. EXPERIMENTAL SCENARIO AND REDUCTION OF THE TRANSIENT DIVERTOR ENERGY LOAD DURING ELMS.

Low levels of N or Ar impurity have been injected in H-mode plasmas with Type I ELMs in the Diagnostic Optimized Configuration (DOC-L, $\delta \approx 0.26$) with q_{95} = 3.8 (2.0MA/2.4T) or q_{95} =3.0 (2.5MA/2.4T). The low q 95 experiments correspond to a higher electron density ($n_e^{ped} = 5.0 \times 10^{19}$ m^{-3} for N experiments, 7.0×10^{19} m^{-3} for Ar experiments, whereas $n_e^{ped} = 3.7 \times 10^{19}$ m^{-3} for the high q_{95} case). Figure 1 shows a summary of the variation of the global confinement, when impurities (N or Ar) are injected. A noticeable difference is found between the high and low density cases, the observed degradation of confinement with increasing impurity concentration in the plasma core being much weaker at high density.

The heat load to the target plates, during and in between ELMs, is measured using a fast infra-red camera [4]. The presence of a codeposited layer on the inner target is taken into account to calculate the deposited energy and heat fluxes from the surface temperature measurement [5]. Figure 2 shows the outer target plate energy increase ($\Delta W_{outer\ target}$) versus the plasma energy loss (ΔW_{dia}) during an ELM, for a reference pulse without impurity seeding and a pulse with n_N/n_e = 0.3 or 0.8% respectively for the low and high density experiments. For a given plasma energy loss, the energy increase on the outer target plate during an ELM is 18% lower with N seeding ($\approx$ 24kJ less on the target plate for $\delta\Delta W_{dia} \approx$ 400kJ). On the inner target, a reduction of 24% of the energy increase is measured (≈ 36kJ less on the target for $\delta\Delta W_{dia} \approx 400$kJ). Experimental evidence of what actually happens to this 'missing' energy which is no more accounted for on the target plates in presence of N is difficult to get. The time resolution of the available bolometric measurements is too low to tell us if this energy (or part of it) is radiated by N in the SOL and divertor. Therefore, time-dependent SOLPS calculations have been performed and are reported in Section 3 (see Fig.5).

1.2. DISCUSSION ON HIGH EDGE DENSITY, LOW Q 95 EXPERIMENTS.

The ELM frequency increases slightly with increasing radiation. Radiation increases mainly in the divertor region (about 65% increase of the radiation emissivity for the highest N injection level, $n_N/n_e = 0.8\%$), only a 10% increase of the edge radiation inside the separatrix being measured. No modification of the electron temperature profile is observed up to 5% loss of confinement, which may correspond to the highest N core concentration, depending on the experimental point actually considered. In conclusion, the pedestal region and hence the confinement properties are only weakly affected by N in this high edge density case.

1.3. DISCUSSION ON LOW EDGE DENSITY, HIGH q_{95} EXPERIMENTS.

As in the previous case, f_{ELM} increases slightly with increasing radiation. However here, the radiation increases not only in the divertor, but also in the edge region inside the separatrix (40% increase for the highest injection level), which is consistent with a deeper penetration of the N radiating ions at low edge density. This is also qualitatively consistent with the observed reduction of the pedestal temperature as shown in Fig.3, and the observed degradation of confinement.

2. MODELLING

The core plasma is described using the MIST and SANCO impurity transport codes. These include an ELM model in which impurities are assumed to be instantaneously expelled into the SOL from the ELM-affected region and then recycled. The edge region (both the SOL and pedestal) is modelled using the time-dependent SOLPS5.0 code. Deuterium plus two impurity species, C and N are included. ELMs are described by increased heat and particle perpendicular diffusivities compared to steady-state values. Enhancement factors of 50 and 100 have been used : these values correspond to the same ELM energy loss in the experiment (there is a fixed amount of ΔW_{dia} which can be removed, 350-400 kJ in the case considered), but the higher enhancement case removes the energy faster, and the time to remove it is smaller. Figure 4 shows the calculated electron energy hitting the divertor target normalized to that crossing the separatrix, versus the time needed to remove the energy from the pedestal (τ_{ELM}, determined by the enhancement factor). The background plasma conditions are those of the high density pulses described above, Pulse No: 58135 reference case without impurity seeding, and Pulse No: 58139 with N seeding. Although the calculated fraction of the ELM energy reaching the target is smaller than that actually observed, the reduction of ≈ 15% of $\Delta W_{target} / \Delta W_{SOL}$ with N seeding which is calculated for $\tau_{ELM} \approx 150\mu$s is consistent with the experimental findings, and with previous code results [2]. Note that a stronger reduction is predicted for a longer ELM. SOLPS5.0 has also been used to perform a study of the sensitivity of the bolometric measurements to the expected increase of N radiation associated to ELM buffering. Figure 5 shows that this increase is likely to be too small and localised in time to be detected by the bolometers with a 20ms integration time.

CONCLUSION.

In the low triangularity configuration analysed here, $\Delta W_{target} / \Delta W_{dia}$ during a Type-I ELM is found to be reduced by 18 - 24% (on the outer and inner targets respectively) with low levels of N or Ar seeding. Corresponding SOLPS calculations for N suggest that the fraction of the ELM energy which is radiated before it reaches the target plates depends on the ELM duration, and a small fraction » 15% consistent with the experiment is calculated for tELM » 150ms . This small fraction is also consistent with previous code results [2]. However, more work is needed to understand the discrepancy which is found between present SOLPS calculations and experiment for the absolute values of $\Delta W_{target} / \Delta W_{SOL}$. The reduction of the target plate energy load with N seeding is obtained with a loss of confinement that may be limited to 5% when the edge electron density is high, favouring low core penetration of the radiating ions, and high divertor radiation. To this respect, the high triangularity of ITER plasmas is beneficial, since even higher edge densities are then achieved with no loss of confinement. Experiments at high triangularity and high density are planned on JET at the end of the year to determine whether $\Delta W_{target} / \Delta W_{dia}$ can be further reduced.

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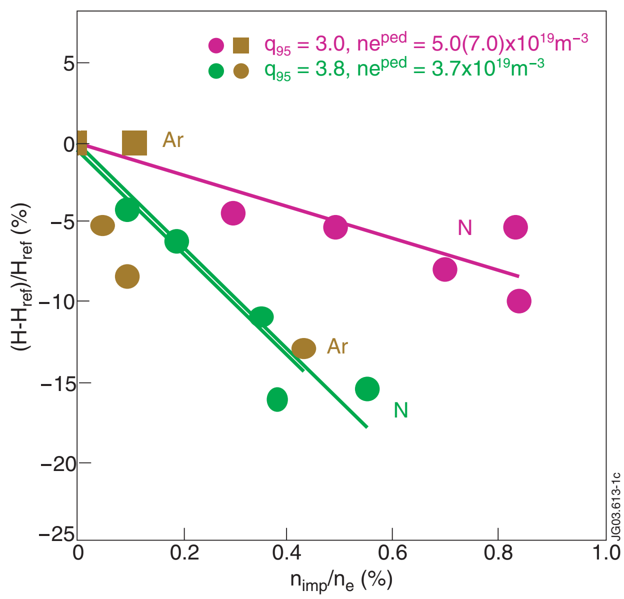

Figure 1: Variation of confinement versus impurity concentration in the core measured by charge exchange recombination spectroscopy (n_{Ar18+}/n_e, n_{N7+}/n_e).

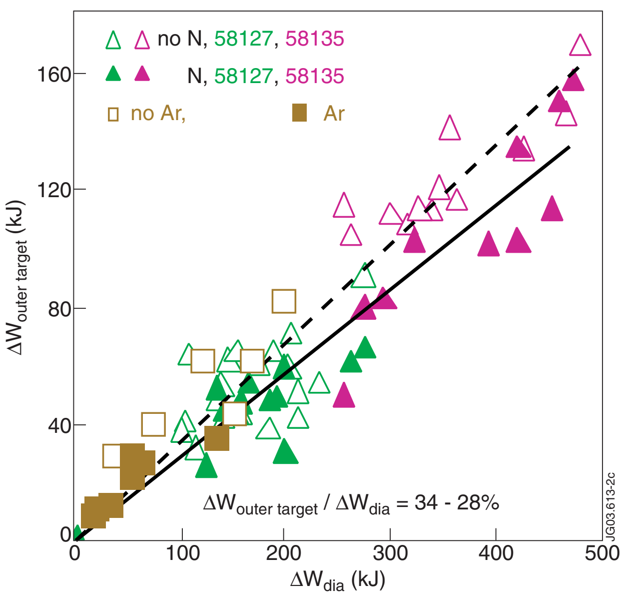

Figure 2: Energy increase on the outer divertor target versus plasma energy loss during an ELM. Purple solid triangles: 5% loss of confinement. Green solid triangles: H is reduced by about 13%.

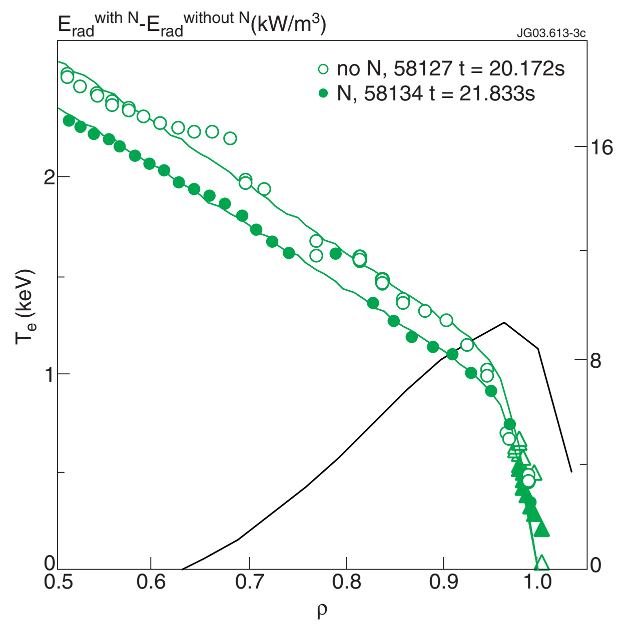

Figure 3: Te profiles without and with Nseeding in the case q_{95} =3.8 (H is reduced by about 15% in Pulse No: 58134, full symbols). The difference of the radiation emissivity profiles is also shown in black (left axis).

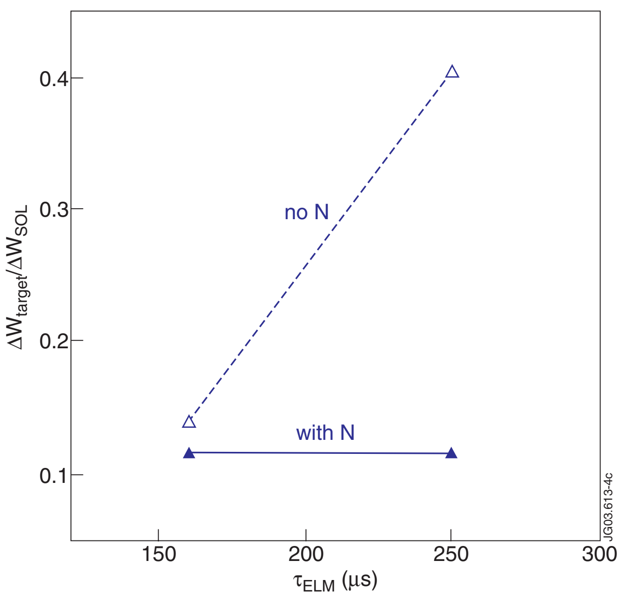

Figure 4: Integrated electron energy on the target plate normalized to that in the SOL, versus time needed to remove a given energy from the pedestal. Solps5.0 calculation for Pulse No's: 58135 (no N) and 58139 (with N).

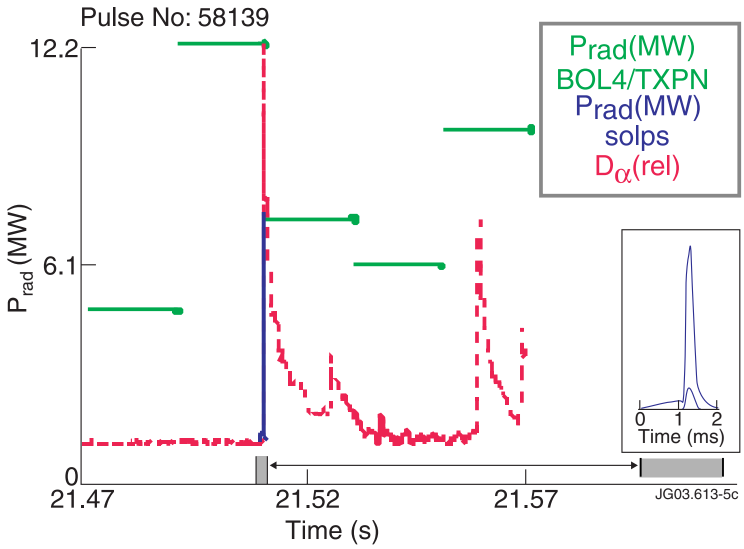

Figure 5: time evolution of the measured divertor Hα signal (red), radiation in the X-point and divertor regions from bolometry (green), and N divertor radiation from Solps5.0 (blue).