

## Comparison of core and edge characteristics of NB and ICRH ELMy H-modes in JET

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### 1. Introduction

Previous JET experiments highlighted differences in the ELM behaviour in NB and ICRH ELMy H-modes, the latter being in general characterised by more frequent and lower amplitude ELMs than NB heated discharges. One proposed explanation of the different ELM behaviour [1] is based on a semi-empirical model [2] that attributes the suppression of the edge turbulence between Type I ELMs to the fast ion population in the edge of the plasma. In this model, Type I ELMs occur at the ideal ballooning limit, and the critical pressure gradient is approximated by  $p_{crit}/\Delta_{ped}$ , where the edge pedestal width  $\Delta_{ped}$  is proportional to  $\sqrt{\epsilon \cdot \rho_{\theta,fast}}$  ( $\epsilon$ = inverse aspect ratio,  $\rho_{\theta,fast}$ = poloidal Larmor radius of fast ions).

The analysis of gas fuelled ELMy H-modes with NB heating and type I ELMs showed that the critical pressure at the top of the pedestal  $P_{ped}$  before an ELM is well described by a similar model: Type I ELMs occur at the ideal ballooning limit, but the pedestal width is  $\propto \sqrt{mTi}$  or  $\rho_{\theta,Th}$  (poloidal Larmor radius of thermal ions) [3,4].

This paper reports on the results of two new experiments, designed to separate the effects of fast and thermal ions in the plasma edge on ELMy H-mode pedestal parameters. In the first experiment, the fast ion concentration  $n_i/n_F$  in the plasma edge was changed, at approximately constant  $\rho_{\theta,fast}$ , while the second was designed to achieve a variation in  $\rho_{\theta,fast}$  at approximately constant  $n_i/n_F$ .

### 2. ELMy H modes with combined NB and ICRH heating

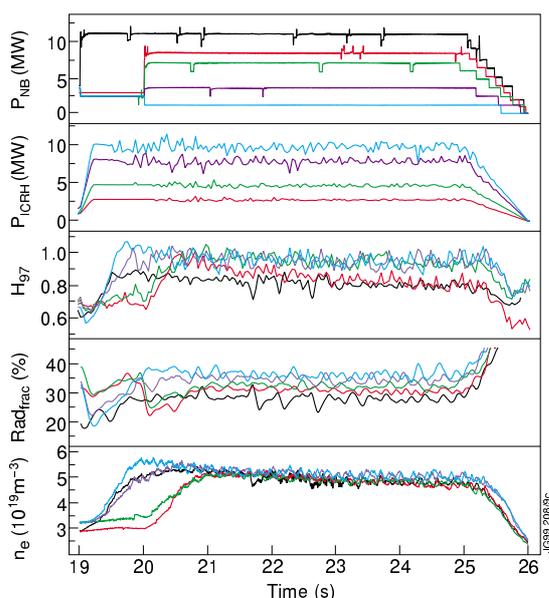


Fig. 1: NB and ICRH power, H97, radiated fraction and central line averaged density for the NB/ICRH power scan experiment.

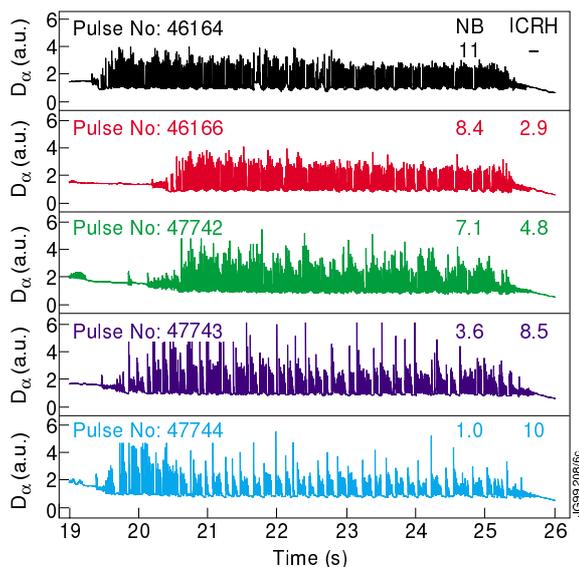


Fig. 2: Divertor Balmer- $\alpha$  emission for same set of discharges as Fig. 1. All discharges are fuelled with D+5%H, at a constant rate of  $1 \times 10^{22} \text{ s}^{-1}$ .

A series of ELMy H-modes at 2MA/2.6T was carried out at constant total input power ( $\sim 11$  MW), varying the proportion of NB and ICRH (H minority, resonance at the normalised minor radius  $\rho \sim 0.2$ , h.f.s.), as shown in Fig. 1, from pure NB heating to 10 MW ICRH + 1 MW NB heating. Whilst in NB H-modes the additional heating provides fuelling to the plasma, external gas fuelling is required in ICRH H-modes to obtain the same edge and core density. In contrast to previous experiments, we achieved a very good match of edge and core density throughout the NB/ICRH scan, by imposing a constant gas fuelling of  $\sim 1 \times 10^{22} \text{ s}^{-1}$  during the additionally heated phase of all discharges.

Fig. 1 shows that the plasma average density in steady state is very similar for all discharges ( $\sim 75\%$  of the Greenwald density limit  $n_{Gr}$ ), and that the global energy confinement ( $H97$ ) is comparable (within 10%), independent of the heating scheme used. As expected, increased ICRH power results in higher central  $T_e$  ( $\sim 20\%$  higher central  $T_e$  for pulses 47743 and 47744, with 8.5 and 10 MW ICRH respectively), while no increase is observed at larger major radius ( $\rho > 0.75$ ), resulting in a peaking of the temperature profiles. The plasma impurity content increases with ICRH power, with  $Z_{eff}$  going from  $\sim 1.7$  for the NB case up to 2.7 at the highest ICRH power, with the radiated power fraction increasing from about 25% to 35%.

TRANSP analysis shows that the dominant energy losses are due to ion conduction in all cases, and that the  $\chi_i$  profiles are similar, independent of the proportion of ICRH and NB heating. The electron transport is enhanced at high ICRH powers, but it remains small and does not significantly affect the global energy balance. The temperature peaking compensates for the increased plasma dilution, and the plasma pressure profile is very similar for all the discharges in the scan.

### 2.1 Pedestal parameters

As is shown in figure 2, the ELM frequency  $\nu$  and magnitude are similar for all discharges. This is consistent with the measured edge parameters. In fact, the edge density of the discharges is constant, independent of the NB/ICRH mix. The edge temperatures are also very similar, as shown in Figs. 3 and 4. Fig. 3 shows the edge  $T_e$  profiles for 3 discharges of the series, and we note that both the top of the pedestal  $T_e$  and the width are the same for the three discharges ( $\sim 4\text{-}5$  cm, by linear extrapolation). This observation applies also to the  $T_i$  profiles. Within the resolution of the measurement, the ion and electron temperature pedestals in this regime are the same, and independent of heating scheme. The variation of the amount of injected NB power (from 11 to 1 MW) corresponds to a decrease of  $n_i/n_F$  in the pedestal region by an order of magnitude (from  $\sim 2\%$  to  $\sim 0.2\%$ ), to compare to a critical  $n_i/n_F$  of  $\sim 1\%$  [2]. Note that  $n_i/n_F$  may be overestimated, as the CX losses are not included in the calculations. The addition of the ICRH does not change the fast ion population of the edge, as shown by the modelling of ICRH, including the finite orbit effects, with the PION code [5]. The average ICRH fast ion distribution in the plasma is peaked at  $\rho \sim 0.3$  and becomes negligible for  $\rho > 0.8$ , so that the fast ion content in the plasma edge is entirely determined by the NB component of the

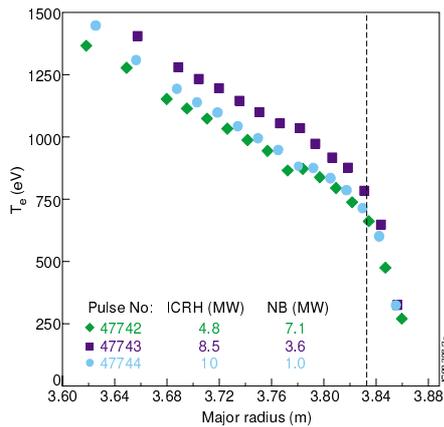


Fig. 3: Edge  $T_e$  profiles measured with ECE heterodyne radiometry. The dotted line marks the top of the pedestal

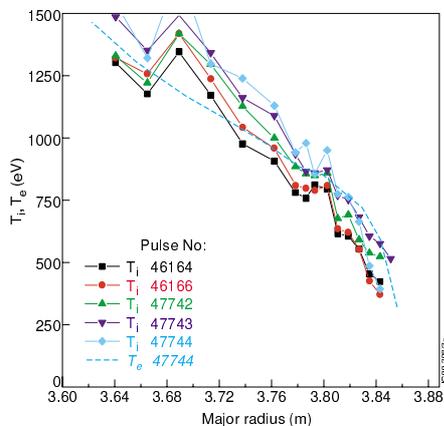


Fig. 4: Edge  $T_i$  profiles measured with CXS.  $T_e$  profile for pulse 47744 is superimposed for comparison.

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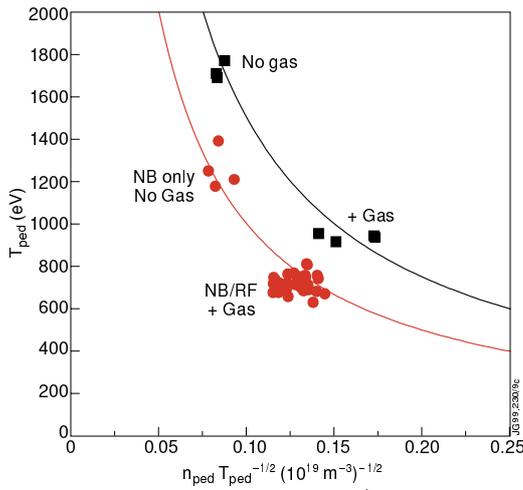


Fig. 5:  $T_{ped}$  as a function of  $n_{ped}/\sqrt{T_{ped}}$  (densities are corrected by  $Z_{eff}$ ), for the ICRH/NB experiment (points labelled NB/RF + gas), compared to NB only discharges. Details in the text.

and  $T_{ped}$  obtained in the ICRH/NB experiment are consistent with the pedestal parameters of the NB heated discharges, and in both cases the pedestal pressure before an ELM decreases with  $\sqrt{T_{ped}}$ . In other words, the reduced pedestal pressure in the gas fuelled ICRH/NB experiment is consistent with a degradation of the edge confinement with  $\sqrt{T_{ped}}$  [3,6]. In the approximation  $(\nabla P)_{crit} \sim p_{crit}/\Delta_{ped}$ , these data suggest a scaling of the pedestal width with  $\rho_{\theta, Th}$ .

additional heating. The average energy  $\langle E_{fast} \rangle$  of the fast ions in the pedestal region is about 38 keV for the first two pulses of the series, and around 30 keV for the others. In spite of the variation of  $\langle E_{fast} \rangle$  and of the number of the fast ions in the pedestal region, it is found that the edge pressure (average and before an ELM) is essentially the same for all discharges.

$T_{ped}$  vs.  $n_{ped}/\sqrt{T_{ped}}$  at the top of the pedestal (just before an ELM) are shown in Fig. 5 for the ICRH/NB experiment (NB/RF+gas, in red). Fig 5 also includes data for a reference 2MA/2.6T NB only case (11 MW NB, no gas, in red) and for a NB only gas scan at 2.5MA/2.5T (black squares). The lines are constant  $n_{ped}\sqrt{T_{ped}}$ , scaled by the ratio of the plasma currents. The reduced values of  $n_{ped}$

### 3. Pedestal scaling experiments in H and D plasmas

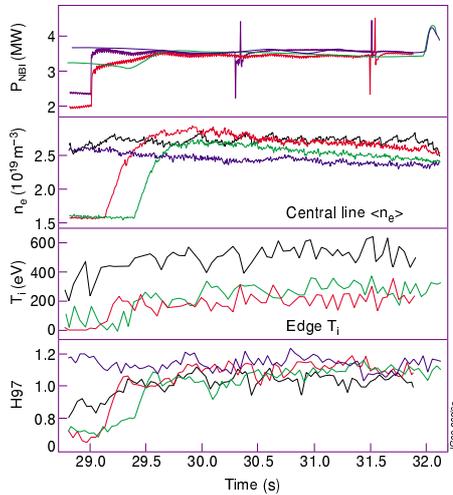


Fig. 6: NB power, line average  $n_e$ , edge  $T_i$  ( $H \rightarrow D$  data missing) and H97 for the 4 pulses of the isotope experiment described in the text.

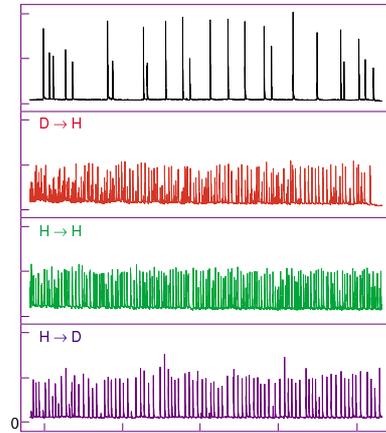


Fig. 7: Balmer- $\alpha$  divertor emission for the 4 pulses of the isotope experiment. Note the variation of the plasma composition.

Another way to vary the fast/thermal ion composition at the plasma edge is to change the mass of the background plasma and of the injected NB ions. This was done in JET in an experiment where steady state ELMy H-modes were studied, with  $D$  and  $H$  NB injection (without gas fuelling) in  $D$  and  $H$  target plasmas. Four combinations of injected isotope/target plasma were studied ( $D \rightarrow D$ ,  $D \rightarrow H$ ,  $H \rightarrow H$  and  $H \rightarrow D$ ), Figs. 6 and 7. Due to limitations in the NB power available, a complete set of data was obtained only at reduced plasma current and

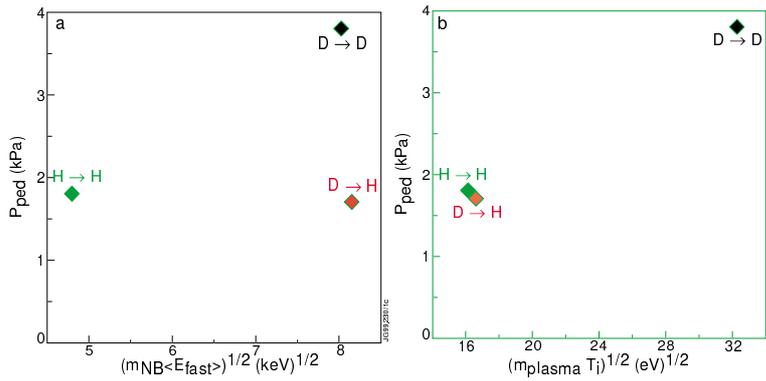


Fig. 8: (a)  $p_{ped}$  vs. fast ion Larmor radius and (b)  $p_{ped}$  vs. thermal Larmor radius.  $m_{plasma}$  is the effective mass number of the plasma

do not confirm this hypothesis: as shown in Fig. 8a, the 2 discharges with D NB injection have  $P_{ped}$  differing by a factor of 2, for the same  $\rho_{\theta,fast}$ . From the same graph, we also see that  $P_{ped}$  for D→H and H→H are very similar, although  $\rho_{\theta,fast}(D \rightarrow H) \approx 1.6 \rho_{\theta,fast}(H \rightarrow H)$ . In contrast, as shown in Fig. 8b, the variation of  $P_{ped}$  are consistent with  $\Delta_{ped} \propto \rho_{\theta,Th}$ . Unfortunately, edge  $T_i$  data are missing for the H→D case, limiting the extent of the analysis. The changes in ELM frequency do not correlate with  $\rho_{\theta,fast}$ , whilst a better correlation is found when the effective mass of the plasma and the average thermal energies are considered.

#### 4. Conclusions

Experiments have been carried out to determine the physical mechanisms that influence the width of the edge transport barrier. ELMy H-modes with varying proportions of NB and ICRH power have been compared, taking care to match the gas fuelling and edge densities, since these quantities are known to affect the pedestal parameters in standard NB heated discharges. We find that, as we substituted ICRH for NB at constant input power, the core and edge parameters of the plasma remain largely independent of the heating scenario, in agreement with results reported by AUG on ICRH/NB ELMy H-mode comparisons [7].

The reduction of  $n_i/n_F$  in the edge by a factor of 10 (down below the critical concentration of  $\sim 1\%$ ) does not change significantly the pedestal, indicating that the controlling mechanism for the pedestal width does not change as the NB/ICRH mix changes. In the range of density investigated ( $\sim 75\%$  of  $n_{GR}$ ) we find that the pedestal pressure before an ELM is proportional to  $\sqrt{T_{ped}}$ , in agreement with previous analysis of gas fuelled NB ELMy H-modes [3] and isotope scans experiments [4]. This implies that, in this regime, fast ions do not play a dominant role for the edge stabilisation between ELMs. Further analysis is in progress to assess the magnitude of charge-exchange neutral losses in the edge, and their effect on the fast ion concentration.

The role of fast ions in the edge has been also investigated by changing the mass of the NB particles and of the target plasma. We find that the edge pedestal pressure and ELM frequency variations observed in the experiment do not correlate with the changes in the Larmor radius of the fast ions (at approx. constant fast ion density), and the pedestal parameters vary with the average Larmor radius of the thermal ions. These results have to be confirmed by new experiments carried out at higher NB power with the full complement of diagnostics.

[1] V P Bhatnagar et al., Nuclear Fusion 1999 39(3) pp353 - [2] V V Parail, H Y Guo and J Lingertat, Nuclear Fusion 1999, 39(3) pp 369 - [3] G Saibene et al, submitted to Nuclear Fusion - [4] J G Cordey et al., 17<sup>th</sup> IAEA Conference, Yokohama, Japan 1998, paper F1-CN-69/EX/7/1 - [5] L-G Eriksson, T Hellsten and U Willen, Nuclear Fusion 33(1993) pp 1037 - [6] L D Horton for the JET Team and the AUG Team, this conference - [7] J M Noterdaeme et al., 17<sup>th</sup> IAEA Conference, Yokohama, Japan 1998, paper F1-CN-69/CDP/11