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** See annex of M.L. Watkins et al, "Overview of JET Results ",*
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1. MOTIVATION.

The main goal of ITER is to produce plasmas with high fusion gain ($Q_{DT}>10$), where a large fraction of the plasma heating is supplied by the α-particles from fusion reactions. To first order, this requires both thermal and fast ion confinement to be at least as good as predictions. The plasma H-mode energy confinement time estimates for ITER are based on extrapolation from a wide database from existing Tokamaks [1], while the projected α-particle confinement is based mainly on theoretical predictions but also on experimental data [2, 3].

In all tokamak devices, the finite number and toroidal extension of the Toroidal Field (TF) coils causes a periodic variation of the toroidal field from its nominal value; called toroidal field ripple ´BT. In this paper, we use the definition of $\delta_{BT} = (B_{\Phi Max} - B_{\Phi min})/(B_{\Phi Max} + B_{\Phi min})$, that is the same adopted by ITER. The δ_{BT} values quoted in the paper are always maximum values at the plasma separatrix. It is well known that ripple in the toroidal field adversely affects fast ion confinement, and in the case of ITER, this has been accounted for by including in the design Ferritic Insets (FI) compensation, reducing δ_{BT} from ~1.2% to ~0.5%, to reduce first wall power loads. Analysis [4] shows that the main α-particle loss mechanism in ITER will be ripple banana orbit diffusion, and that the magnitude of these losses is expected to be in the 1% region, therefore negligible in terms of α-particle confinement.

Recent experimental results from JT60-U [5] and H-mode dimensionless H-mode experiments in JET and JT-60U [6] have indicated that ripple may also affect the H-mode confinement and plasma rotation. Although the physics mechanisms at the root of the reduced energy confinement with δ_{BT} was not identified unambiguously, the implication of a reduction of energy confinement on projected ITER performance due to ripple stimulated a series of experiments at JET. This paper reports the results of these experiments and briefly discusses the implications for the ITER design.

2. THE RIPPLE EXPERIMENT

The JET tokamak is equipped with a set of 32 TF coils, normally fed an equal current. Uniquely to JET, the TF system can also be configured in such a way to feed different currents to the odd and even set of coils. In this operation mode, δ_{BT} can be increased in a controlled way, by selecting the appropriate differential current between each set of coils.

In the experiments described in this paper, the average TF was set at 2.2T and 1.7T, and the ripple changed, from pulse to pulse, form the standard JET δ_{BT} of 0.08% to a maximum of 1%, in steps (0.3%, 0.5% and 0.7%). Most of the H-mode studies were carried out at 2.6MA/2.2T (q_{95}~2.9), in a low triangularity shape (´ ~ 0.22), while a subset of the experiments was carried out at 2.0MA/1.7T. In all cases, additional heating was provided by Neutral Beam (NB) co-current injection. The ripple experiments required careful preparation: predictive fast ion loss analysis simulations with the OFMC and ASCOT codes were carried out for the range of ripple and plasma parameters foreseen during the experiments, to evaluate the magnitude and location of power loads on first wall components, for assessing limits for safe plasma operations.

3. GENERAL EXPERIMENTAL RESULTS

The effect of ripple on H-mode plasmas was investigated first by establishing a H-mode with Type I ELMs at δ_{BT} of 0.08%, and then increasing the ripple in steps, pulse by pulse. The NB input power was adjusted as function of the ripple amplitude, to account for the predicted fast ion losses and to maintain the net input power P_{net} ~ constant in the scan. No external gas fuelling was applied during the H-mode phase of the discharges. The plasma response to increased ripple is quite obvious and dramatic, as shown in figures 1, 2 and 3, for a ripple scan with ~12.5 to 13MW P_{net}. The most obvious effect of increasing δ_{BT} is the large plasma density reduction in the H-mode phase. In fact, both the plasma average density (figure 1, 2nd box) and the edge density (not shown) show a pronounced "pump-out" with a ~30% loss for δ_{BT} = 0.5%. At higher TF ripple amplitude of δ_{BT} = 1%, the density loss is in excess of 40% of that of the reference "no ripple" H-mode. At the same time, we observe that the plasma electron temperature remains, in average, approximately constant, as the ripple is increased ($T_{e,ped}$ is shown in figure 1, box 3).

In contrast, T_i across the whole plasma profile is substantially higher with ripple than in the reference case, as shown in figure 2. At the plasma edge, the measured Ti for pulse 69635 (1% δ_{BT}) is, in average, up to ~50% higher compared to T_i of pulse 69624 (´BT = 0.08%, see $T_{i,ped}$, see also figure 1, box 4). The increase of T_i with ripple does not compensate entirely the density loss and this result in a decrease of the plasma stored energy with ripple amplitude (figure 3), by ~20% in the scan. It is interesting to note the most of the loss of Wth with ripple is already observed for δ_{BT} = 0.5%, that is the projected ripple level at the ITER plasma separatrix. Increasing the ripple also results in a marked change of the plasma toroidal rotation V_{TOR}. A substantial plasma braking is observed, with the reduction of the positive (co-current) plasma rotation measured across the whole profile. The last box of figure 1 shows that, at the plasma edge, V_{TOR} becomes counter-current (negative) for ripple of 1%. The relation between ripple, fast ion losses and plasma rotation is discussed further in section 6, as well as in [8]. Increased values of the toroidal field ripple also affect the ELM behaviour, as illustrated in figure 4. In fact, when the ripple is increased from 0.08% to 0.5%, the type I ELM frequency almost doubles, going from ~12Hz to ~20Hz. When the ripple is increased further to 0.7% and finally to 1%, ELMs become irregular, with Type I, Type III and long ELM-free phases, in spite of the fact that power across the separatrix remains approximately constant.

All observations above originate from plasmas with no gas fuelling in the H-mode phase, resulting in low pedestal density and collisionality (n_{ped} ~ 30% n_{GR} and ν^*_{ped} ~ 5 – 7 10-2). The effect of fuelling was investigated by adding increasing amounts of gas to the reference plasmas described above. Although the most striking effect of ripple is the strong density pump out, the plasma response to external gas fuelling is similar, independent of the ripple value. These findings are summarized in figure 5, showing the plasma average density as function of gas fuelling rate in the H-mode phase, for 3 values of δ_{BT} (0.08%, 0.5% and 1%). As the fuelling is increased, the steady state density achieved in the discharges becomes more and more similar, in spite of the increased ripple. At the highest fuelling rates (corresponding to nped~ 60 – 70% n_{GR}) the difference between an H-mode with 0.08% and 1% ripple becomes very small in terms of achievable density, edge temperature and, as it is discussed in the next section, energy confinement.

4. PLASMA CONFINEMENT AND PEDESTAL BEHAVIOUR WITH RIPPLE

As mentioned in section 1, concerns about the possible impact of toroidal field ripple on plasma thermal confinement are relatively recent, and an acceptable ripple for ITER was evaluated only in terms of fast ion loss minimization. One of the main aims of the experiments described in this paper was to quantify, for a range of plasma condition, the impact of ripple on confinement, and to attempt to identify an acceptable "maximum ripple" for ITER. The results presented in this section summarize the results on confinement (and pedestal pressure) when varying ripple and plasma density (increased with edge gas puff). The evaluation of the thermal confinement was carried out based on the kinetic plasma energy calculations from interpretative analysis carried out with the JETTO code, for selected time slices. For a sub-set of discharges, these results were validated against TRANSP analysis. Finally, the ASCOT code was used to calculate fast ion losses (required for the confinement analysis) and torque profiles. A comparison of the thermal stored energy calculated with JETTO and TRANSP for 2.6MA discharges indicate that the relative variations of Wth with ripple are very similar for both estimates, while there are differences (up to 10%) in the absolute values of W_{th}, probably due to different treatment of impurities. We therefore will not discuss here absolute values H98, while the analysis concentrates on the relative variations with ripple.

Figure 6 shows H98 as function of ripple amplitude, for the complete dataset of ELMy H-modes at 2.6MA/2.2T. The dataset includes both un-fuelled and gas fuelled plasmas; note that the variation of H98 at fixed ripple is due to density variations, "amplified" by the $n^{0.4}$ dependence of the scaling. Discharges with NTMs (3/2 and 4/3) are excluded form the dataset. The data indicate a different behaviour of the confinement with ripple, depending on the plasma fuelling/density. For plasmas without gas fuelling in the H-mode phase, we observe a gradual decrease of H98 with ripple, with up to ~20% confinement loss for $\delta_{BT} = 1\%$. Figure 6 also shows that the variation of H98 for high density discharges (given by the trend of the low H98 points vs ripple) is very small and, within the uncertainties of the measurements, the confinement enhancement factor appear to be independent of ripple at higher density and/or higher pedestal collisionality. These results are consistent with the observation of a much-reduced density pump-out as the density is increased, independent of ripple (section 3). The reduction of plasma thermal confinement with ripple amplitude is confirmed by the behaviour of the pedestal pressure P_{ped} with ripple, illustrated in figure 7. P_{ped} is calculated as $P_{ped} = (n_{e,ped}T_{e,ped} + n_{i,ped}T_{i,ped})$, so it properly includes the increase of ion temperature at the edge observed for increasing ripple. Note that figure 7 does not include he high density data points since T_e measurements are not available because of ECE emission cut-off. Nonetheless, the decrease of P_{ped} with δ_{BT} (approx – 20% in average comparing P_{ped} at 0.08% and 1%) is entirely consistent with the results from the confinement analysis. Figure 8 shows the ion and electron pedestal pressure (normalized to the max pressure at 0.08%) as function of δ_{BT}. The data confirm the unexpected result that the loss of pedestal pressure with ripple occurs mainly in the electron component, associated to the observed clamping of T_e with ripple. Finally, the confinement behaviour at low ripple values deserves particular scrutiny, since the present design target in ITER is $\delta_{BT} \sim 0.5\%$. To clarify this issue, a second "no gas" ripple scan was carried out with reduced I_p/B_t. The reduction of H98 is confirmed to be ~5% at $\delta_{BT} = 0.3\%$ (well within the uncertainly of the estimate of H98) and ~ 10-15% at $\delta_{BT} = 0.5\%$.

5. ELM LOSS ANALYSIS.

As mentioned in the general results section, increasing δ_{BT} at constant power across the separatrix makes the ELMs activity more irregular, with increase of the type I ELM frequency as well as in the appearance of ELM-free and Type III ELM phases. In general, type I ELMs appear to be smaller, at least in terms of the D_α emission form the divertor. To quantify this observation, the normalized ELM energy loss (normalized to the pedestal energy W_{ped}) is shown, in figure 9, as function of ν^*, for Type I ELMs. Unfortunately, the range of ν^* is rather limited, since for many discharges, T_e is not available due to ECE emission cut-off. Nonetheless, the plot indicates that, for similar collisionality, the size of the ELM energy loss is reduced as the ripple increases. The normalized Te drop at the ELM is shown in figure 10, for the same dataset of figure 9. The scatter of the data is large, but the data suggest that the temperature drop tends to be lower for higher δ_{BT}, even at low pedestal densities, suggesting that ELM losses become more convective as the ripple is increased, even at low ν^*.

DISCUSSION.

The flexibility of the JET TF system allowed the study of H-mode behaviour at δ_{BT} values around the design values of ITER. Nonetheless, fast ion sources and confinement in JET are very different from those expected in ITER. In particular, α-particles losses in ITER, for $\delta_{BT}<1\%$ are expected to be ~ few %, while in JET the NB fast particle losses at 1% ripple are up to 20% of the injected power. As discussed in detail in [7], ASCOT analysis of the JET ripple experiments shows that fast particle losses generate a negative torque in the plasma, qualitatively consistent with the observed reduction of the co-current plasma rotation. On the other hand, torque balance analysis shows that the total NBI-induced torque and plasma rotation should remain positive, while experimentally we observe plasma negative rotation at the plasma edge, for 1% ripple (figure 1). It has been suggested [8] that toroidal field ripple could also enhance thermal ion transport, and that these additional losses could be responsible for the extra negative torque. Indications that thermal ion losses may play a role with ripple come from comparing the time evolution of V_{TOR} at the edge in a H-mode discharge with 0.08% ripple with one with 1% δ_{BT}. For $\delta_{BT} =0.08\%$, V_{TOR} at the edge is positive and goes up between ELMs, consistently with the increased energy and momentum confinement. In contrast, for $\delta_{BT} =1\%$, that VTOR becomes more negative during ELM-free phases, although fats ion losses do not change appreciably. This behaviour could be due to an increase of thermal ion losses as the pedestal collisionality decreases in the ELM free phase, providing an extra. negative torque, The considerations above could imply that the behaviour we observed in JET H-mode with ripple is not entirely driven by fast ion losses.

CONCLUSIONS

The JET ripple experiments show that increasing toroidal field ripple has a detrimental effect on plasma confinement and density, especially at low pedestal collisionality. Specifically, increasing δ_{BT} from the standard 0.08% level to 1% causes a reduction of the H factor of ~20%. Within the measurement uncertainty, the deterioration of plasma confinement with ripple magnitude is continuous (although not necessarily linearly proportional to δ_{BT}). The very non-linear dependence of Q_{DT} on the H factor ($\sim H^{3.3}$) implies that even "small" reductions of the plasma confinement would result in a reduction of the fusion power not acceptable for ITER.

The effect of the density reduction associated to ripple has to be evaluated carefully for the projected ITER $Q_{DT}=10$ plasma conditions. In fact, at the ITER temperature, the fusion power output is ~ n (at constant β), therefore the impact of density pump-out on Q_{DT} is even more severe than what is deduced from the reduction of the H factor.

The analysis of the JET data also shows that toroidal field ripple affects ELM frequency and size. In particular, the data indicate that Type I ELM size is reduced, for 1% ripple, by about a factor of two and that the ELM losses seem to become more convective. Although a reduction of the ELM size may look attractive for ITER, this would come at the price of significant confinement deterioration. Moreover, the ripple in ITER cannot be adjusted or reduced after construction, so the use of ripple for ELM size reduction is not advisable.

Further analysis is required to understand in detail the physics mechanisms at the root of the observed plasma behaviour with ripple. This includes the understanding of the plasma pump-out effect, of the role of fast and thermal ion losses, both on confinement and rotation, and the dependence on the observed density and confinement loss on plasma edge parameters, especially collisionality.

With the present understanding, minimization of the ripple in ITER at full toroidal field is recommended, to minimize the uncertainty of the confinement extrapolations and reduce the risk associated to possible reduction of plasma rotation.

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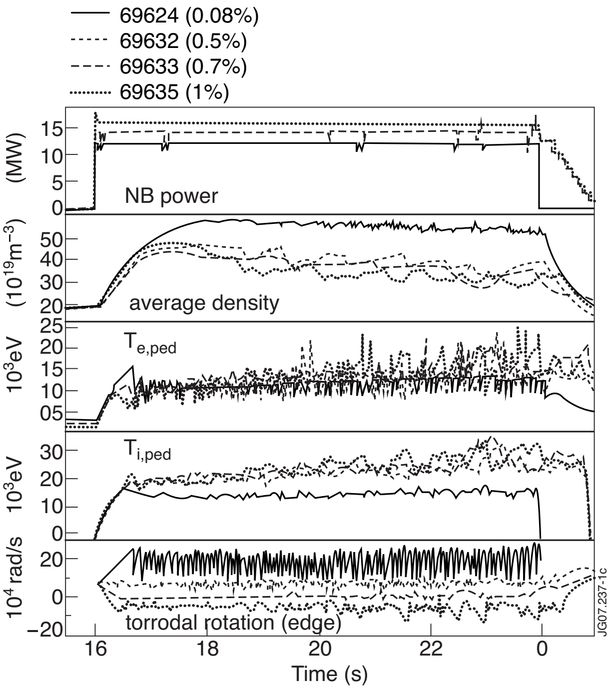

Figure 1: from top to bottom: NB input power, average density, pedestal T_e and T_i and edge toroidal rotation for a 4-steps ripple scan at constant Pnet(2.6MA/2.2T)

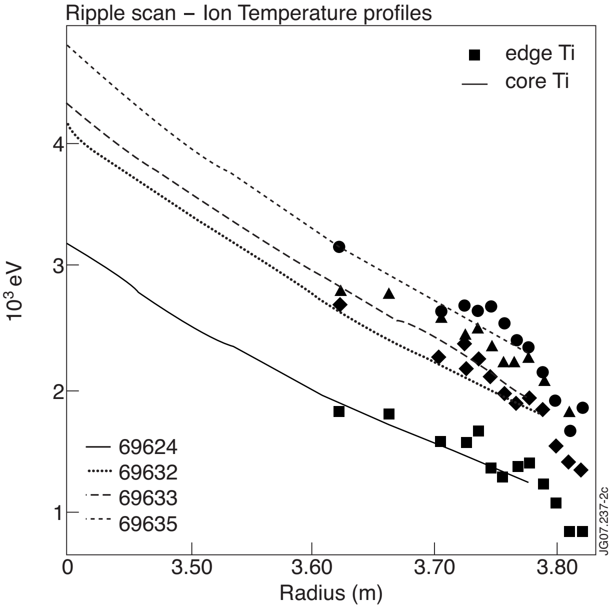

Figure 2: Ion temperature profile (core and edge CX), for a the ripple of figure 1

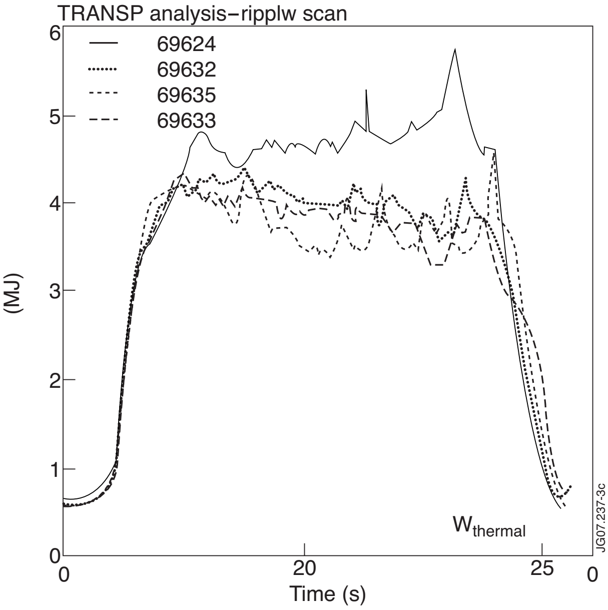

Figure 3: Plasma thermal stored energy, as calculated with TRANSP, for the 4-steps ripple scan in figure 1.

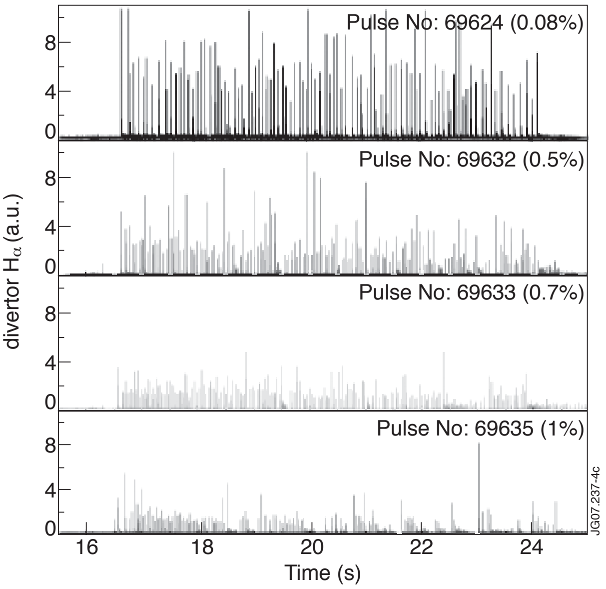

Figure 4: Divertor H-a traces for the 4 plasma discharges in figure 1.

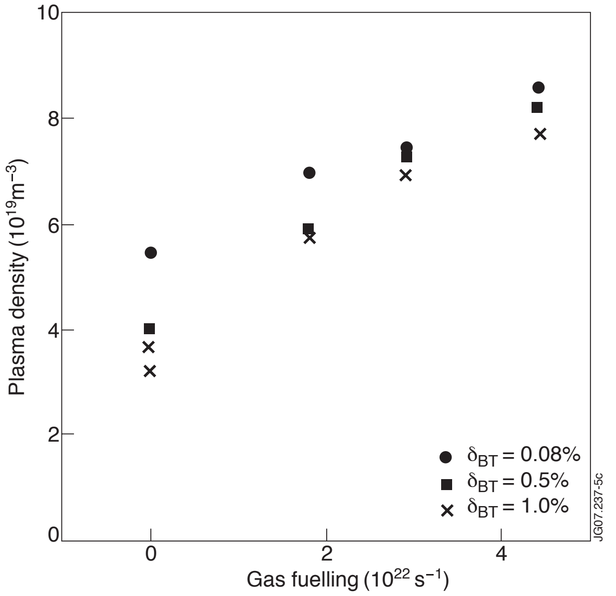

Figure 5: plasma density as function of gas fuelling, for 3 values of ripple.

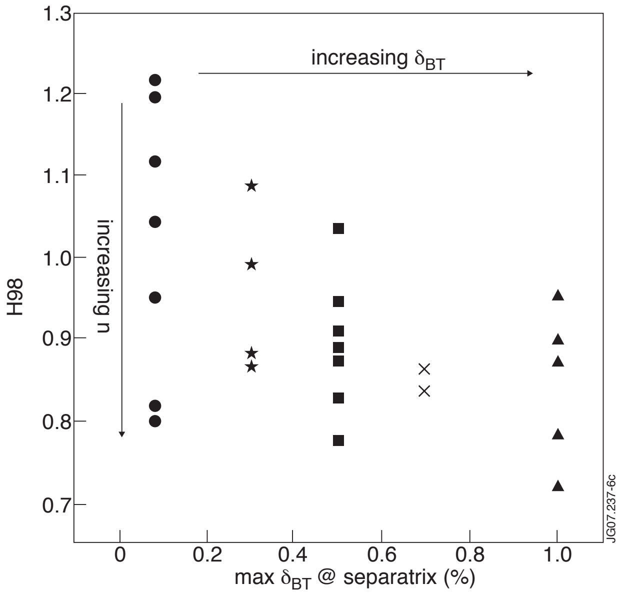

Figure 6: H98 versus δ_{BT} @ separatrix for the 2.6MA/ 2.2T dataset.

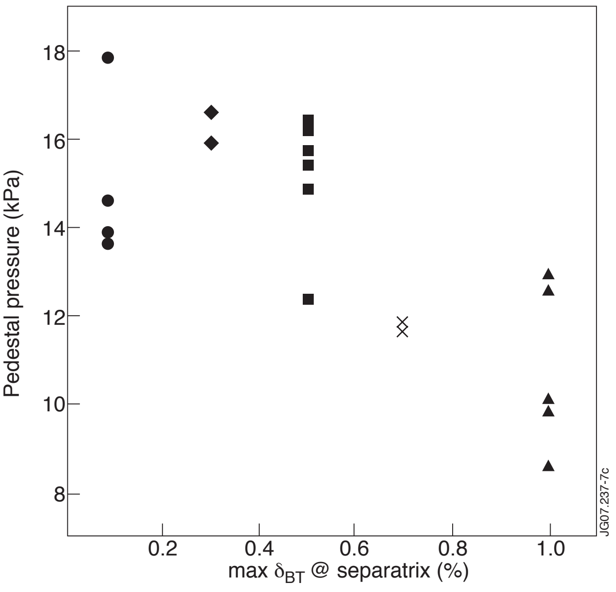

Figure 7: Pedestal pressure as function of δ_{BT}, 2.6MA/ 2.22T.

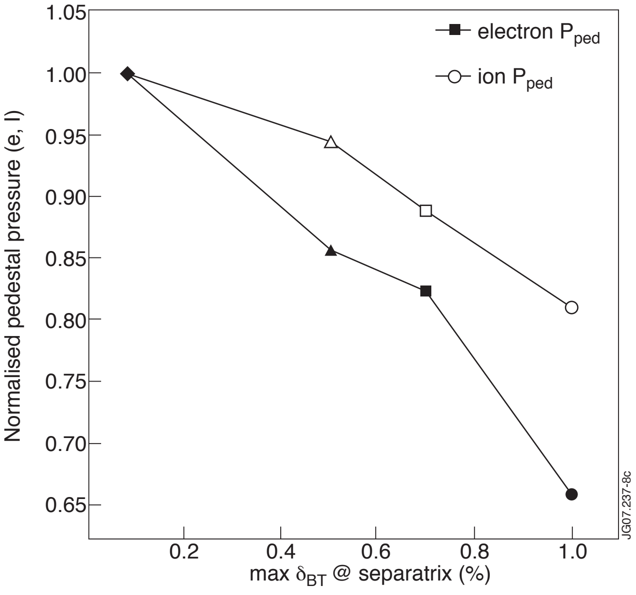

Figure 8: $P_{e,ped}$ and $P_{i,ped}$ variation with δ_{BT}, same pulses as figure 1.

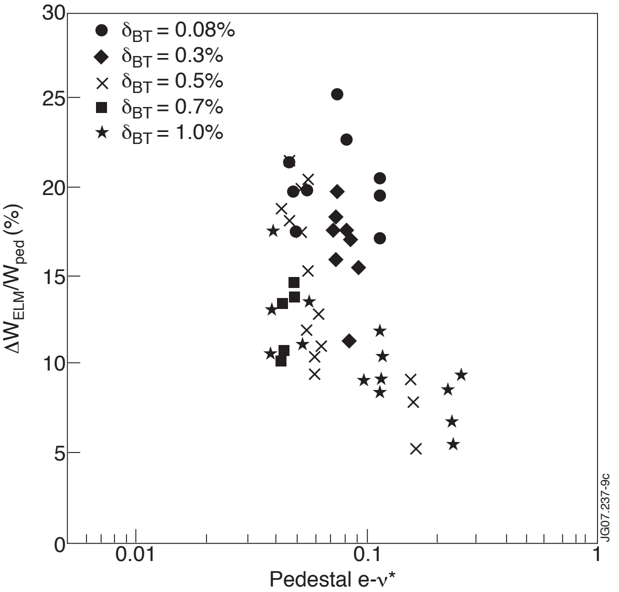

Figure 9: ELM energy loss (normalized to W_{ped}) versus pedestal collisionality – 2.6MA/2.2T.

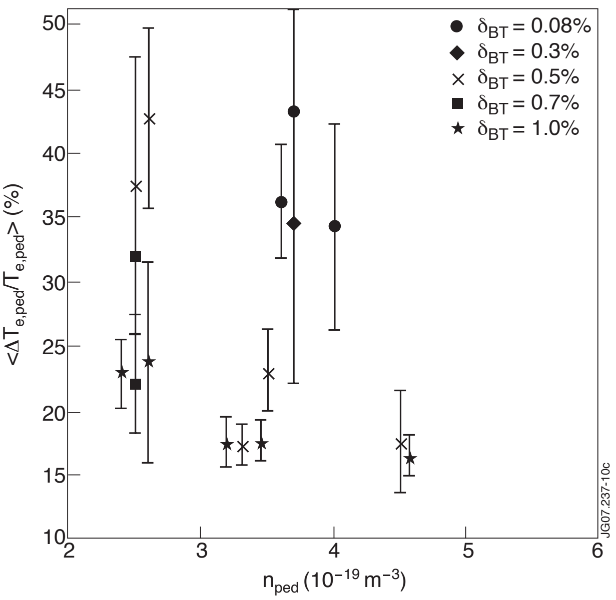

Figure 10: average prompt ELM T_e drop, normalized to $T_{e,ped}$ versus n_{ped} 2.6MA/2.2T.