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# Results of the Variable Toroidal Field Ripple Experiments in JET

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## ABSTRACT.

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  $\delta_{BT}$ . Ripple in the toroidal field adversely affects fast ion confinement, and in the ITER design, this is mitigated by including Ferritic Insets (FI) compensation, reducing  $\delta_{BT}$  from  $\sim 1.2\%$  to  $\sim 0.5\%$ . With this correction, the magnitude of  $\alpha$ -particle losses in ITER is expected to be in the 1% region, negligible in terms of  $\alpha$  particle confinement and power load to plasma-facing components. On the other hand, experimental results from JT60-U and H-mode dimensionless identity experiments in JET and JT-60U indicated that ripple may also affect the H-mode confinement, pedestal height, ELM size and plasma rotation. This paper describes the results of dedicated experiments carried out in JET, where H-mode plasmas properties were studied for varying levels of toroidal field ripple, in the range from 0.08% (natural  $\delta_{BT}$  for JET) up to  $\sim 1\%$ . The experiments were carried out in the ELMy H-mode regime with  $q_{95} = 3$  to 3.6, to investigate the effect of  $\delta_{BT}$  on pedestal and core properties of the plasma. These experiments show that toroidal field ripple has a clear effect on H-mode properties, although the physics mechanisms at the root of the reduced energy confinement with  $\delta_{BT}$  have not been identified unambiguously. Plasma density pump out and reduction of the global energy confinement is found for  $\delta_{BT} \sim 0.5\%$ , but the magnitude of this effect depends on plasma parameters. Ripple may also affect pedestal pressure, as well as size and frequency of ELMs. Plasma toroidal rotation was also strongly affected by ripple: the toroidal velocity is reduced for increased ripple and may become negative at the edge for  $\delta_{BT} \sim 1\%$ . These results are discussed and implications for ITER outlined.

## 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  $\alpha$ -particles from fusion reactions. To first order, this requires both thermal and fast ion confinement to be at least as good as predictions, based on the H98(y,2) [1] scaling. The plasma H-mode energy confinement time estimates for ITER are in fact based on extrapolation from a wide database from existing Tokamaks [1], while the projected  $\alpha$ -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  $\delta_{BT}$ . 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  $\delta_{BT}$  values quoted in the paper are always maximum values, calculated at the nominal radius of the plasma separatrix and at the low-field side equatorial plane, in the case of JET located at  $R = 3.8\text{m}$ ,  $Z = 0\text{m}$ . It is well known that ripple in the toroidal field adversely affects fast ion confinement, by modifying their guiding centre orbit. Two mechanisms contribute to the enhanced transport: ripple-banana diffusion and ripple-trapped transport. Orbit-following Monte Carlo codes have been used both in the preparation and for the analysis of the JET experiments [4]. For the

plasma conditions of the experiments described in this paper, this analysis showed that the dominant loss mechanism is ripple-banana diffusion. ITER is equipped with 18 Toroidal field coils, and the basic level of ripple is relatively high,  $\sim 1\%$  at the nominal separatrix position in the outer midplane. This level of ripple may cause excessive heat loads to limiters and other plasma-facing components [5], therefore Ferritic Insets (FI) compensation is included in the design, reducing  $\delta_{BT}$  from  $\sim 1.2\%$  to  $\sim 0.5\%$ . With FI, analysis [5, 6] shows that the main  $\alpha$ -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 both in terms of  $\alpha$ -particle confinement and wall loads. While the main preoccupation with ripple has always been focused on fast ion losses, recent experimental results from JT60-U [7] and H-mode dimensionless identity experiments in JET and JT-60U [8] 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  $\delta_{BT}$  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. EXPERIMENTAL CONDITIONS

The JET tokamak is equipped with a set of 32 Toroidal Field (TF) coils, normally fed with an equal current. In these conditions, the toroidal field ripple in JET is very small,  $\delta_{BT} \sim 0.08\%$  at the nominal separatrix radius in the outer midplane. 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,  $\delta_{BT}$  can be increased in a controlled way, by selecting the appropriate differential current between each set of coils.

This paper discusses experiments where the effect of ripple was studied in dedicated experimental campaigns, in 2007 and 2008. Series of plasmas discharges were carried out with average TF varying from 2.4T down to 1T. The plasma current was also changed in the range from 2.6MA to 1MA with  $q_{95}$  varying from  $\sim 3$  to  $\sim 3.6$ . The selected plasma shape was a low triangularity  $\delta$  plasma with average  $\delta \sim 0.22$ . This plasma parameter variation allowed studying ripple effects for a range of pedestal and core temperature and densities, achieving a variation of the normalized plasma parameters ( $\rho^*$  and  $v^*$ ) of a factor of  $\sim 2$ .

The toroidal field ripple was varied, from pulse to pulse, from the standard JET  $\delta_{BT}$  of 0.08% to a maximum of 1%, in steps (0.3%, 0.5% and 0.7%). Fine  $\delta_{BT}$  scan in H-mode were carried out at 2.6MA/2.2T ( $q_{95} \sim 2.9$ ) and at 1MA/1T ( $q_{95} \sim 3.6$ ), while coarser scans were performed at 2.6MA/2.4T and 1.7MA/1.6T ( $q_{95} \sim 3$ ). 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 calculations with the OFMC and ASCOT codes were carried out for the range of ripple and plasma parameters foreseen during the experiments [4], to evaluate the magnitude and location of power loads on first wall components, for assessing limits for safe plasma operations. After the

experiments, the calculated power loads to the limiters obtained by simulations using the actual experimental parameters were compared measured power loads to limiters obtained with an IR camera, showing an excellent agreement [4].

The effect of toroidal field ripple was studied in JET on H-mode plasmas with different values of average toroidal field and plasma current, showing that the effect of ripple on plasma properties depends on the plasma parameters. The results of the experiments at 2.6MA are described in section 3, while section 4 discusses results at reduced current and field. Section 5 discussed and compares the experimental observations, and these are finally summarized in section 6.

### 3. EXPERIMENTAL RESULTS – 2.6MA

#### 3.1. GENERAL RESULTS.

The effect of ripple for plasmas with 2.6MA/2.2 and 2.4T was investigated first by establishing a H-mode with Type I ELMs at  $\delta_{BT}$  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  $P_{net} \sim$  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, and 2, for a ripple scan with  $\sim$ 12.5 to 13 MW  $P_{net}$ . The most obvious effect of increasing  $\delta_{BT}$  is the 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  $\sim$ 30% loss for  $\delta_{BT} = 0.5\%$ . At higher TF ripple amplitude of  $\delta_{BT} = 1\%$ , 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, on average, approximately constant, as the ripple is increased ( $T_{e,ped}$  is shown in figure , box 3). In contrast,  $T_i$  across the whole plasma profile is substantially higher with ripple than in the reference case. At the plasma edge, the measured  $T_i$  for pulse 69635 (1%  $\delta_{BT}$ ) is, on average, up to  $\sim$ 50% higher compared to  $T_i$  of pulse 69624 ( $\delta_{BT} = 0.08\%$ , 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 results in a decrease of the plasma stored energy with ripple amplitude (figure 2), by  $\sim$ 20% in the scan. It is interesting to note the most of the loss of  $W_{th}$  with ripple is already observed for  $\delta_{BT} = 0.5\%$ , 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 reduction of  $V_{TOR}$  is observed as the ripple increases at  $\sim$  constant  $P_{net}$ , with a 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  $\delta_{BT} = 1\%$ . The relation between ripple, fast ion losses and plasma rotation is discussed further in section 5, as well as in [9].

All observations above originate from plasmas with no gas fuelling in the H-mode phase, with low pedestal density and collisionality ( $n_{ped} \sim 40\% n_{GR}$  and  $n_{ped}^* \sim 4 \cdot 10^{-2}$  for the reference  $d_{BT} =$

0.08% H-mode) 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 3, showing the plasma average density as function of gas fuelling rate in the H-mode phase, for 3 values of  $\delta_{BT}$  (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  $n_{ped} \sim 60-70\% n_{GR}$ , for the high pumping plasma configuration of the 2.6MA/2.2T series of pulses) the difference between an H-mode with 0.08% and 1% ripple becomes very small in terms of achievable density and temperature ( $v_{ped}^* \sim 4 \cdot 10^{-1}$  for all ripple values) as well as, as it is discussed in the next section, energy confinement.

### 3.2. IDENTITY EXPERIMENT

The effect of ripple on the global plasma confinement was explored further by producing identical plasmas without additional ripple and with  $\delta_{BT} = 0.5\%$  (JET Pulse No: 74623 and 74617, respectively). The plasma parameters for this pair of discharges were 2.6MA/2.4T ( $q_{95} = 3$ ), while the NB input power was feedback-controlled to obtain  $\beta_N \sim 1.6$  in both cases. The plasma density was controlled by gas injection to achieve the same density in both discharges, and the target  $\rho^*$  and  $v^*$  at the pedestal top were  $\rho_{ped}^* \sim 0.1$  and  $v_{ped}^* \sim 0.2$ . As figure 4 shows, a very good match in the plasma parameters was indeed obtained at the two ripple values, but  $\sim 17$  MW of input power were required with  $\delta_{BT} = 0.5\%$  to match the target  $\beta_N$  of the reference  $\delta_{BT} = 0.08\%$ , achieved with  $\sim 10$  MW NB injection. When accounting for fast ion losses in the ( $\sim 2$  MW for the  $\delta_{BT} = 0.5\%$  discharge),  $\sim 50\%$  more absorbed power is required at 0.5% ripple to reproduce the same plasma core and edge parameters of the  $\delta_{BT} = 0.08\%$  reference. Plasma rotation and ELM frequency were not matched, and the plasma with ripple showed, as expected, a strong reduction of  $V_{TOR}$  due to the counter-torque resulting from ripple losses [9], and much higher ELM frequency ( $\sim 10$  versus  $\sim 20$  Hz).

### 3.3 PLASMA CONFINEMENT AND PEDESTAL BEHAVIOUR

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 reference design had been evaluated only in terms of the fast ion loss minimization. One of the main aims of the experiment 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 concentrate on the high current/high field ripple scans, since these are the conditions where substantial changes in confinement and high convective losses are observed.

The ASCOT code was used to calculate fast ion losses (required for the confinement analysis) and torque profiles. Then, 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 sub-set of discharges, these results were validated against TRANSP analysis. A comparison of the thermal stored energy calculated with JETTO and TRANSP for 2.6MA discharges indicate that the relative variations of  $W_{th}$  with ripple are very similar for both estimates, while there are differences ( $<10\%$ ) in the absolute values of  $e$  to different treatment of impurities. We therefore will not discuss here  $f_{H98}(y,2)$ , and the analysis concentrates on the relative variations of  $W_{th}$  with ripple.

Figure 5 shows  $f_{H98}(y,2)$  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  $f_{H98}$  at the fixed ripple is due to density variations, although “amplified” by the  $n^{0.4}$  dependence of the scaling. Discharges with NTMs (3/2 and 4/3) are excluded from 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  $f_{H98}(y,2)$  with ripple, with up to  $\sim 20\%$  confinement loss for  $\delta_{BT}=1\%$ .

Figure 5 also shows that the variation of  $f_{H98}(y,2)$  for high density discharges (given by the trend of the low  $f_{H98}(y,2)$  points versus ripple) is very small and, within the uncertainties of the measurements ( $\sim 5\%$ ), 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. 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 6.  $P_{ped}$  is calculated as  $P_{ped} = (n_{e,ped}T_{e,ped} + n_{i,ped}T_{i,ped})$ ,  $T_i$  at the edge observed for increasing ripple. Note that figure 6 density data points since  $T_e$  measurements were not available due of ECE emission cut-off. The decrease of  $P_{ped}$  with  $\delta_{BT}$  (approx  $-20\%$  in average  $P_{ped}$ ) is consistent with the confinement analysis.

### 3.4. ELM energy loss analysis.

Increasing  $\delta_{BT}$  at constant power across the separatrix makes the ELM 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, as illustrated in figure 7. When is  $\delta_{BT}$  increased from 0.08% to 0.5%, the type I ELM frequency almost doubles, going from  $\sim 12\%$  to  $\sim 20\text{Hz}$  while, for a further increase in ripple amplitude to 0.7% and finally to 1%, ELMs become irregular, with mixed Type I, Type III and long ELM-free phases.

In general, type I ELMs appear to be smaller, at least in terms of the  $D_\alpha$  emission from the divertor. To quantify this observation, the normalized (to the pedestal energy  $W_{ped}$ ) type I ELM energy loss is shown, in figure 8, as function of  $v_{ped}^*$ . The plot indicates that, for similar collisionality, the size of the ELM energy loss is reduced as the ripple increases. In particular, the reduction of the ELM energy loss is due to a reduction of the relative prompt  $T_e$  drop for higher  $\delta_{BT}$ , suggesting that ELM losses become more convective as the ripple is increased, even at low  $v^*$ .

## 4. RESULTS AT REDUCED $I_p/B_T$ .

The effect of ripple on H-mode characteristics seems to reduced as the plasma current and field are

reduced. This is illustrated by the results of a fine ripple scan (0.3%, 0.5%, 0.7% and 1%), carried out on reference H-mode plasma at 1MA/1T ( $q_{95} = 3.6$ ), with plasma shape identical to that of the 2.6MA/2.4T H-modes just discussed. The method used to test ripple effects was to select a reference plasma and then, using real time control of the NB input power to keep constant  $\beta_N$ , to attempt to produce identical plasmas for increasing ripple. The reference plasma was a 1MA H-mode obtained in a pedestal identity experiment between JET, DIII-D and ASDEX-Upgrade. This target plasma was selected to test the effects of ripple on the identity (since DIII-D and ASDEX-Upgrade have higher ripple at the separatrix than JET) as well as to obtain data on ripple effects at reduced current and field, or higher  $\rho^*$  (the reference discharge has  $\rho_{ped}^* \sim 1.7 \cdot 10^{-1}$  and  $v_{ped}^* \sim 0.23$ , at the pedestal top). Figure 9 shows that, in contrast to the results obtained at higher field and current, the global and pedestal parameters of the 1MA/1T series of H-modes do not change significantly for increasing ripple, and in particular the plasma stored energy is only slightly reduced at high ripple at constant input power. Quite interestingly, the effect of ripple on  $V_{TOR}$  is still observed, and the plasma rotation is reduced as the ripple is increased, with  $V_{TOR}$  approaching 0 at the plasma periphery for  $\delta_{BT} = 1.0\%$ .

## CONCLUSIONS

The JET ripple experiments show that increasing toroidal field ripple may have a detrimental effect on plasma confinement and density, in particular at lower pedestal normalized gyro-radius and/or collisionality in the range explored. At high field, low density, increasing  $\delta_{BT}$  from the standard 0.08% level to 1% causes a reduction of the H factor of  $\sim 20\%$ . Within the measurement uncertainty (although not necessarily linearly proportional to  $\delta_{BT}$ ). The confinement reduction with ripple is associated to a strong increase of convective losses that can reduce the density in extreme cases by almost a factor of two. Plasma background parameters, in addition to fast ion losses, seem to play a role in determining the effect of ripple on the H-mode properties.

Given the very non-linear dependence of  $Q_{DT}$  on the H factor ( $\sim H^{3.3}$ ), the possible impact of toroidal field ripple on ITER confinement has to be considered carefully. The density pump out observed with ripple in JET at high current may, if not properly compensated, have an impact on the projected ITER  $Q_{DT} = 10$  plasma conditions. In fact, at the ITER temperature, the fusion power output is  $n$  (at constant  $b$ ), and therefore a reduction of density would also impact of  $Q_{DT}$ .

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 may 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 background plasma parameters, especially in the pedestal region.

Based on the present understanding, minimization of the ripple in ITER to values  $<0.5\%$ , at full toroidal field, has been recommended as part of the ITER design review of 2007-2008, to minimize the uncertainty of the confinement extrapolations and reduce the risk associated to possible reduction of plasma rotation.

## REFERENCES

- [1]. ITER Physics Basis, *Nucl Fusion* **39** (1999), Ch 2
- [2]. Thomas P.R., et al., *Phys Rev Lett* **80** (1988), 5548
- [3]. Zwben S.J., et al., *Nucl Fusion* **40** (2000), 9
- [4]. Johnson T., et al, Proc 10th IAEA TM on Energetic Particles in Magnetic Confinement Systems, 8-10 October 2007, Kloster Seeon, Germany.
- [5]. Kurki Suonio T., et al., IAEA FEC 2008, IT/P6-2
- [6]. ITER Physics Basis, *Nucl Fusion* **39** (1999), Ch 5
- [7]. Urano H., et al., IAEA FEC 2006, EX/5-1 –317
- [8]. Saibene G., et al., *Nucl. Fusion* **45** (2005) 297
- [9]. de Vries P., et al., *Nucl. Fusion* **48** (2008); 035007
- [10]. Parail V., et al., IAEA FEC 2006, TH/P8-5
- [11]. Salmi A., et al., *Contrib. Plasma Phys.* **48** (2008) 7
- [12]. Mantica P., et al., IAEA FEC 2008, EX/2-4 .

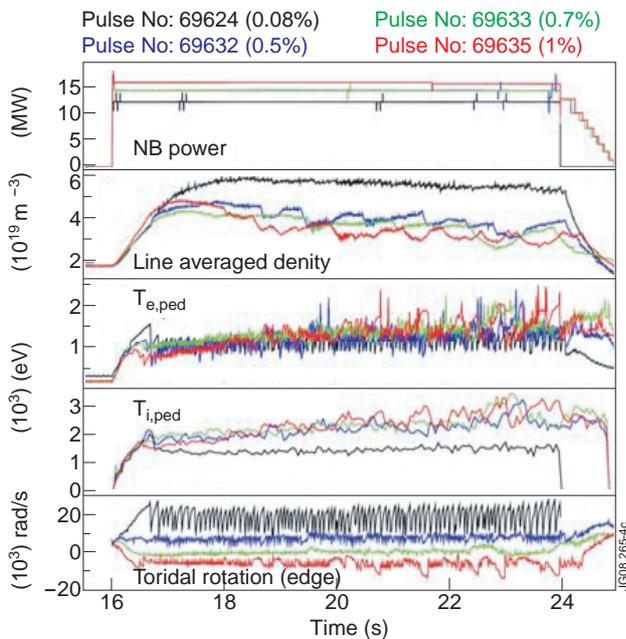


Figure 1: From top to bottom: NB input power, average density, pedestal  $T_e$  and  $T_i$  and edge toroidal rotation for a 4-steps ripple scan at constant  $P_{net}$  (2.6MA/2.2T).

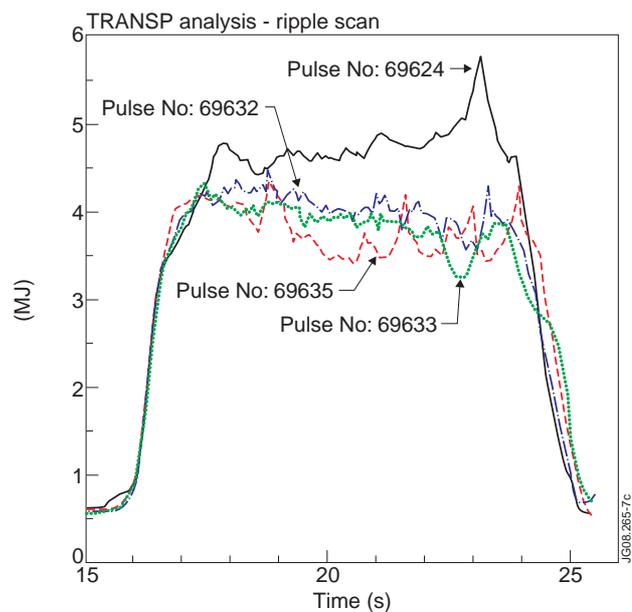


Figure 2: Plasma thermal stored energy, as calculated with TRANSP, for the 4-steps ripple scan in figure 1.

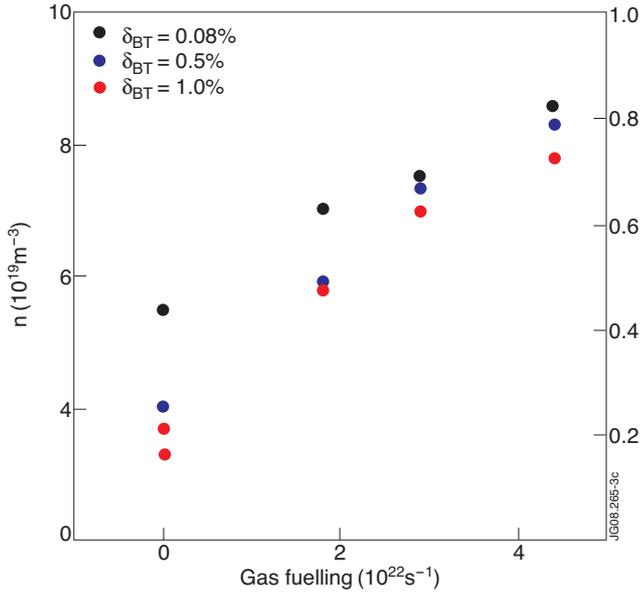


Figure 3: Plasma density (line average and normalized to  $n_{GR}$ ) as function of gas fuelling, for 3 values of ripple.

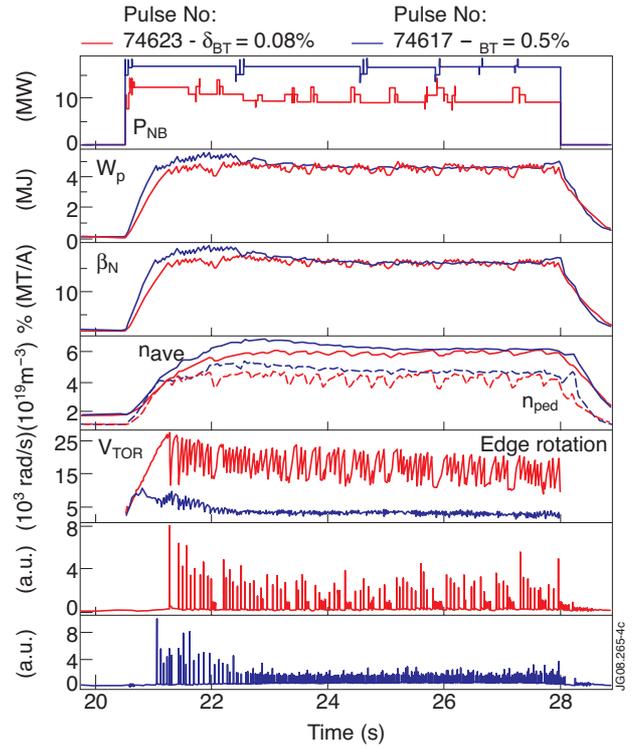


Figure 4: selected time traces for the identity pulses at 2.6MA/2.2T, ripple of 0.08% (red) and 0.5% (blue). From top to bottom: NB input power, plasma stored energy (MHD), normalized  $\beta$ , line average density (core, full) and edge (dashed), plasma toroidal rotation frequency at the plasma edge (3.77m) and divertor  $H_{\alpha}$ .

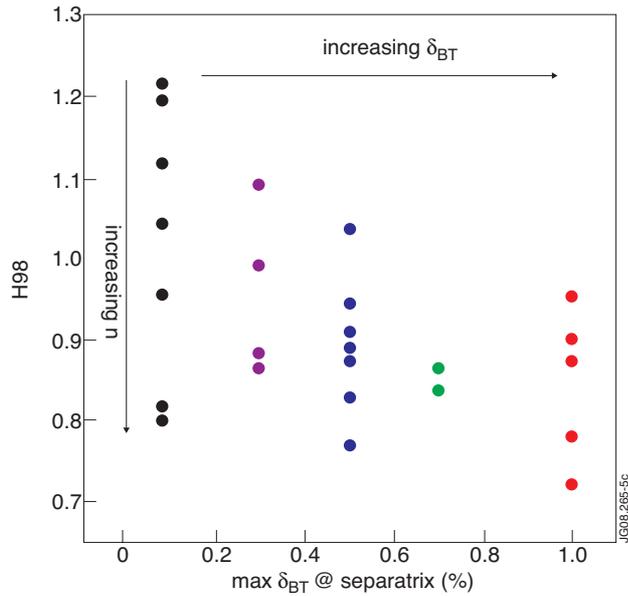


Figure 5: H98 as function of  $\delta_{BT}$  the separatrix. 2.6MA/2.2T dataset

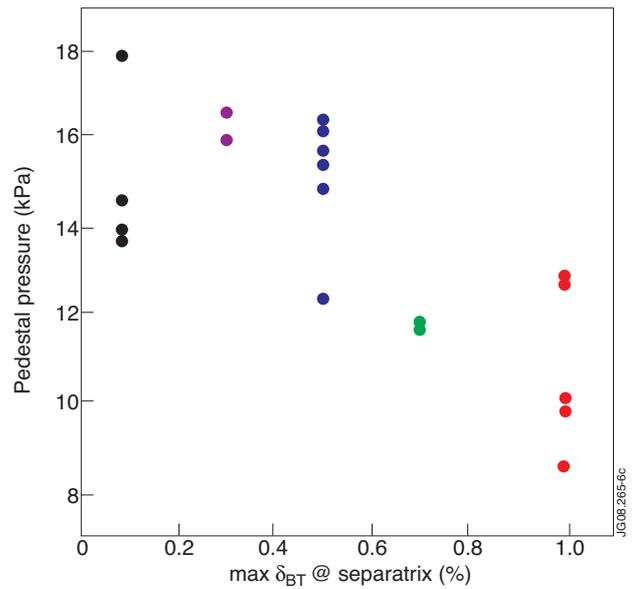


Figure 6: pedestal pressure as function of  $\delta_{BT}$ , 2.6MA/2.2T dataset

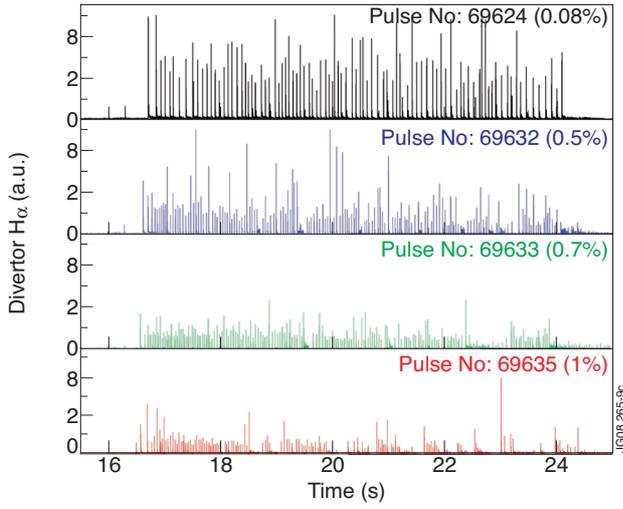


Figure 7: Divertor  $H\text{-}\alpha$  traces for the 4 plasma discharges in figure 1.

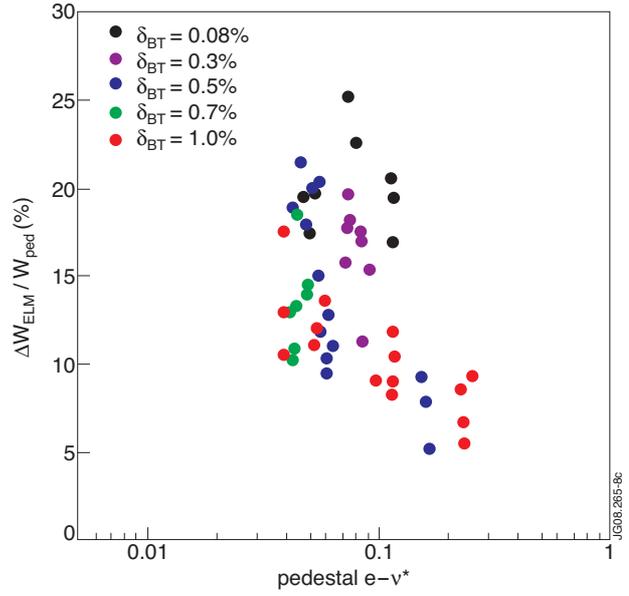


Figure 8: Energy loss per ELM (normalized to the pedestal energy  $W_{ped}$ ) versus  $v_{ped}^* \cdot 2.6MA/2.2T$ , fine ripple scan.

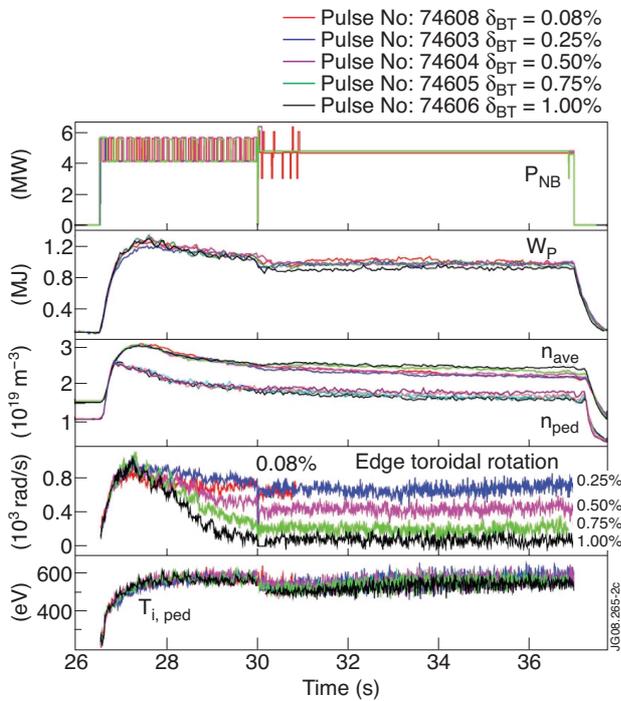


Figure 9: Ripple scan at IMA/IT – From top to bottom: total NB input power, plasma stored energy, line average density (core and edge), and plasma toroidal rotation frequency, at  $\sim 3.77m$

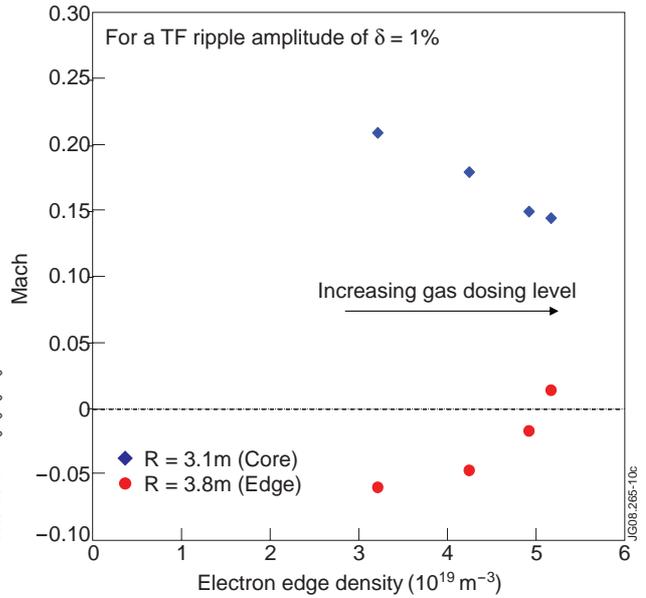


Figure 10: Mach number at the edge (dots) and core (lozenges) at constant 1% ripple as function of density [9]. Data from the gas scan at 2.6MA/2.2T of figure 4.