IAEA
INTERNATIONAL ATOMIC ENERGY AGENCY
22nd IAEA Fusion Energy Conference
Geneva, Switzerland, 13 - 18 October 2008

IAEA-CN-165/EX/2-1

RESULTS OF THE VARIABLE TOROIDAL FIELD RIPPLE EXPERIMENTS IN JET

G SAIBENE(1), R SARTORI(1), DC MCDONALD(2), M BEURSKENS(2), A SALMI(3), J LÖNNROTH(3), V PARAIL(2), P DE VRIES(2), Y ANDREW(2), R BUDNY(4), A BOBOC(2), I COFFEY(2), E DE LA LUNA(5), A LOARTE(6), PJ LOMAS(2), S GERASIMOV (2), C GIROUD(2), J HOBIRK(7), S HOTCHIN(2), T JOHNSON(8), C LESCURE(2), I NUNES(9), N OYAMA(10), V RICCARDO(2), H URANO(10), AND JET EFDA CONTRIBUTORS(*)

JET-EFDA, Culham Science Centre, Abingdon OX14 3DB, UK.

1 FUSION FOR ENERGY Joint Undertaking, 08019 Barcelona, Spain.
2 EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon OX14 3DB, UK.
3 Association EURATOM-Tekes, Helsinki Univ. of Techn., Finland
4 Plasma Physics Laboratory, Princeton University, Princeton, USA.
5 Association EURATOM-CIEMAT, Avda Complutense – Madrid, Spain
6 ITER-IO, Cadarache 13108 Saint Paul Lez Durance, France.
7 Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-85748, Garching, Germany.
8 Association EURATOM-VR, Fusion Plasma Physics, EES, KTH, 10044 Stockholm, Sweden
9 Euratom/IST Fusion Association, Centro de Fusao Nuclear, Lisboa, Portugal.
10 Japan Atomic Energy Agency, 801-1 Muko-yama, Naka, Ibaraki 311-0193, Japan.

*See the Appendix of F. Romanelli et al., paper OV/1-2, this conference

Results of the Variable Toroidal Field Ripple Experiments in JET

G Saibene(1), R Sartori(1), DC McDonald(2), M Beurskens(2), A Salmi(3), J Lönnroth(3), V Parail(2), P de Vries(2), Y Andrew(2), R Budny(4), A Boboc(2), I Coffey(2), E de la Luna(5), A Loarte(6), PJ Lomas(2), S Gerasimov (2), C Giroud(2), J Hobirk(7), S Hotchin(2), T Johnson(8), C Lescure(2), I Nunes(9), N Oyama(10), V Riccardo(2), H Urano(10), and JET EFDA contributors(*)

1 FUSION FOR ENERGY Joint Undertaking, 08019 Barcelona, Spain.
2 EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon OX14 3DB, UK.
3 Association EURATOM-Tekes, Helsinki Univ. of Techn., Finland
4 Plasma Physics Laboratory, Princeton University, Princeton, USA.
5 Association EURATOM-CIEMAT, Avda Complutense – Madrid, Spain
6 ITER-IO, Cadarache 13108 Saint Paul Lez Durance, France.
7 Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-85748, Garching, Germany.
8 Association EURATOM-VR, Fusion Plasma Physics, EES, KTH, 10044 Stockholm, Sweden
9 Euratom/IST Fusion Association, Centro de Fusao Nuclear, Lisboa, Portugal.
10 Japan Atomic Energy Agency, 801-1 Muko-yama, Naka, Ibaraki 311-0193, Japan.

e-mail contact of the main author: Gabriella.Saibene@f4e.europa.eu⊗

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 δ_{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 δ_{BT} from ~ 1.2% to ~ 0.5%. With this correction, the magnitude of α particle losses in ITER is expected to be in the 1% region, negligible in terms of α 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 δ_{BT} for JET) up to ~1%. The experiments were carried out in the ELMy H-mode regime with q_{95}=3 to 3.6, to investigate the effect of δ_{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 δ_{BT} have not been identified unambiguously. Plasma density pump out and reduction of the global energy confinement is found for δ_{BT} ~ 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 δ_{BT} ~ 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 α-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 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 δ_{BT}. In this paper, we use the definition of $\delta_{BT} = (B_{\Phi Max} - B_{\Phi min})/(B_{\Phi Max} + B_{\Phi min})$,

---

⊗ *The views expressed in this publication are the sole responsibility of the author and do not necessarily reflect the views of Fusion for Energy. Neither Fusion for Energy nor any person acting on behalf of Fusion for Energy is responsible for the use which might be made of the information in this publication* that is the same adopted by ITER. The δ_{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=3.8m, Z=0m.

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, ~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 δ_{BT} from ~1.2% to ~0.5%. With FI, analysis [5, 6] 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 both in terms of α-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 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. 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, δ_{BT} ~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, δ_{BT} can be increased in a controlled way, by selecting the appropriate differential current between each set of coils.

This paper discusses experiments were 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 ~3 to ~3.6. The selected plasma shape was a low triangularity δ plasma with average δ~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 (ρ^* and ν^*) of a factor of ~ 2.

The toroidal field ripple was varied, from pulse to pulse, from the standard JET δ_{BT} of 0.08% to a maximum of 1%, in steps (0.3%, 0.5% and 0.7%). Fine δ_{BT} scan in H-mode were carried out at 2.6MA/2.2T (q_{95}~2.9) and at 1MA/1T (q_{95}~3.6), while coarser scans were performed at 2.6MA/2.4T and 1.7MA/1.6T (q_{95}~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 to 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.

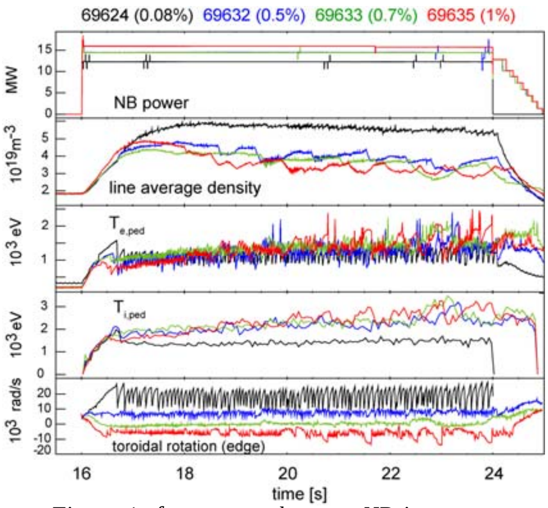

Figure 1: from top to bottom: NB input power, average density, pedestal T_e and T_i and edge toroidal rotation for a 4-steps ripple scan at constant P_{net} (2.6MA/2.2T).

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 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, and 2, for a ripple scan with ~12.5 to 13 MW P_{net}. The most obvious effect of increasing δ_{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 ~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, 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% δ_{BT}) is, on average, up to ~50% higher compared to T_i of pulse 69624 (δ_{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 ~20% in the scan. It is interesting to note the most of the loss of W_{th} with ripple is already observed for δ_{BT} = 0.5%, that is the projected ripple level at the ITER plasma separatrix.

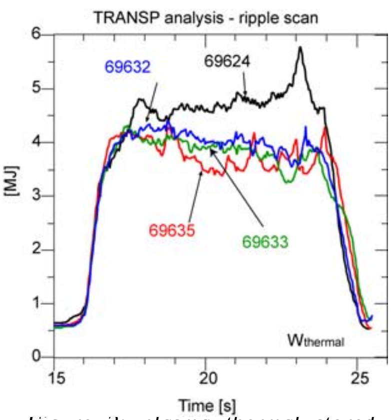

Figure 2: plasma thermal stored energy, as calculated with TRANSP, for the 4-steps ripple scan in figure 1.

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 ~ 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 δ_{BT} = 1%. The relation between ripple, fast ion losses and plasma rotation is discussed further in section 5, as well as in [9].

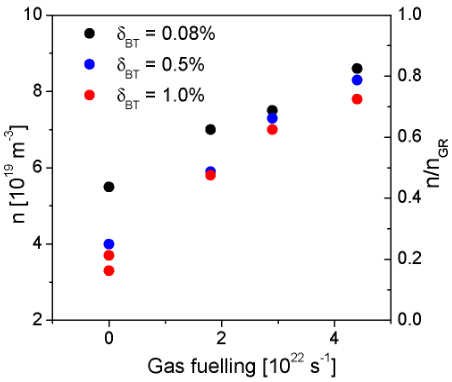

Figure 3: plasma density (line average and normalized to n_{GR}) as function of gas fuelling, for 3 values of ripple.

All observations above originate from plasmas with no gas fuelling in the H-mode phase, with low pedestal density and collisionality (n_{ped}~ 40% n_{GR} and ν^*_{ped}~ 4 10^{-2} for the reference δ_{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 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 n_{ped}~ 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 (ν^*_{ped}~ 4 10^{-1} for all ripple values) as well as, as it is discussed in the next section, energy confinement.

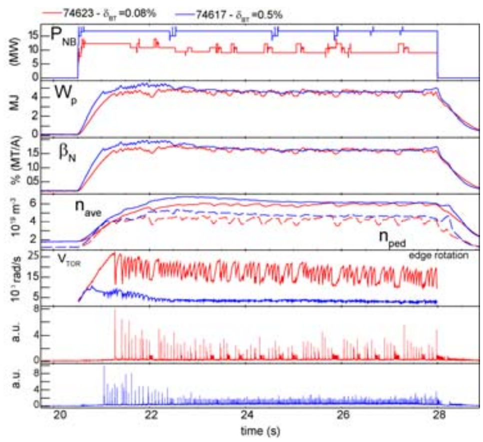

Figure 4 selected time traces for the identity pulses at 2.6MA/2.T, ripple of 0.08% (red) and 0.5% (blue), From top to bottom: NB input power, plasma stored energy (MHD), normalized β, line average density (core, full) and edge (dashed), plasma toroidal rotation frequency at the plasma edge (3.77m) and divertor $H\alpha$.

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 δ_{BT} = 0.5% (JET pulse 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 β_N~1.6 in both cases. The plasma density was controlled by gas injection to achieve the same density in both discharges, and the target ρ^* and ν^* at the pedestal top were ρ^*_{ped} ~0.1 and ν^*_{ped} ~ 0.2. As figure 4 shows, a very good match in the plasma parameters was indeed obtained at the two ripple values, but ~17MW of input power were required with δ_{BT} =0.5% to match the target β_N of the reference δ_{BT} =0.08%, achieved with ~10MW NB injection. When accounting for fast ion losses in the (~2MW for the δ_{BT} = 0.5% discharge), ~50% more absorbed power is required at 0.5% ripple to reproduce the same plasma core and edge parameters of the δ_{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 (~10 vs. ~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 the ITER reference design had been evaluated only in terms of fast ion loss minimization. One of the main aims of the experiments

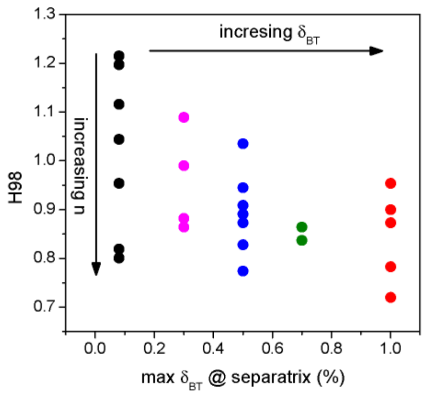

Figure 5: H98 as function of δ_{BT} at the separatrix. 2.6MA/2.2T dataset

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 time slices. Finally, for a 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 W_{th}, probably due to different treatment of impurities. We therefore will not discuss here absolute values of H98(y,2), and the analysis concentrates on the relative variations of plasma properties with ripple.

Figure 5 shows 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 H98 at 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 H98(y,2) with ripple, with up to ~20% confinement loss for δ_{BT} =1%. Figure 5 also shows that the variation of H98(y,2) for high density discharges (given by the trend of the low H98(y,2) points vs. ripple) is very small and, within the uncertainties of the measurements (~ 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 $P_{ped} = (n_{e,ped}T_{e,ped} + n_{i,ped}T_{i,ped})$, so it includes the increase of T_i at the edge observed for increasing ripple. Note that figure 6 does not include the highest density data points since T_e measurements were not available due of ECE emission cut-off. The decrease of P_{ped} with δ_{BT} (approx –20% in average comparing P_{ped} at 0.08% and 1%) is consistent with the confinement analysis.

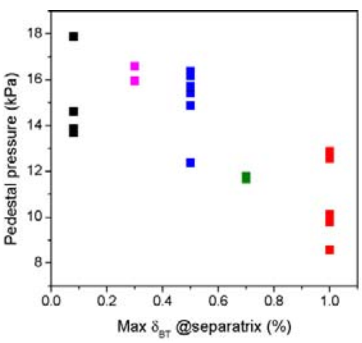

Figure 6: pedestal pressure as function of δ_{BT}, 2.6MA/2.22T dataset

3.4. ELM energy loss analysis. Increasing δ_{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 δ_{BT} is increased from 0.08% to 0.5%, the type I ELM frequency almost doubles, going from ~12Hz to ~20Hz while, for a further increase in ripple amplitude to 0.7% and finally to 1%, ELMs

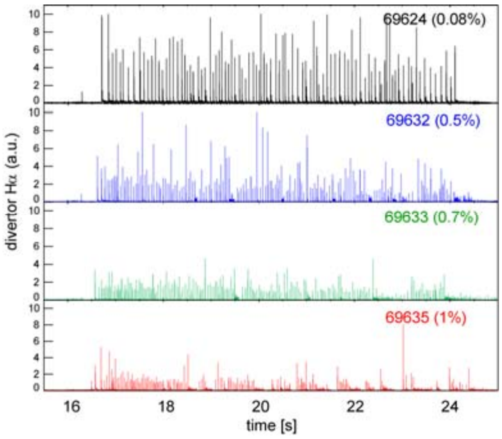

Figure 7 divertor H-α traces for the 4 plasma discharges in figure 1

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_α 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 ν^*_{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 δ_{BT}, suggesting that ELM losses become more convective as the ripple is increased, even at low ν^*.

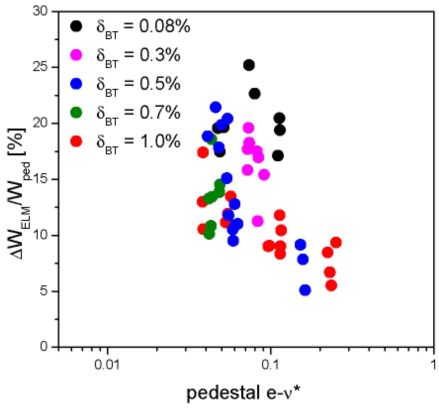

Figure 8: energy loss per ELM (normalized to the pedestal energy W_{ped}) vs ν^*_{ped} . 2.6MA/2.2T, fine ripple scan.

4. Results at reduced I_p/B_T.

The effect of ripple on H-mode characteristics seems to be 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 β_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 ρ^* (the reference discharge has ρ^*_{ped} ~1.7 10^{-1} and ν^*_{ped} ~ 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 δ_{BT} = 1.0%.

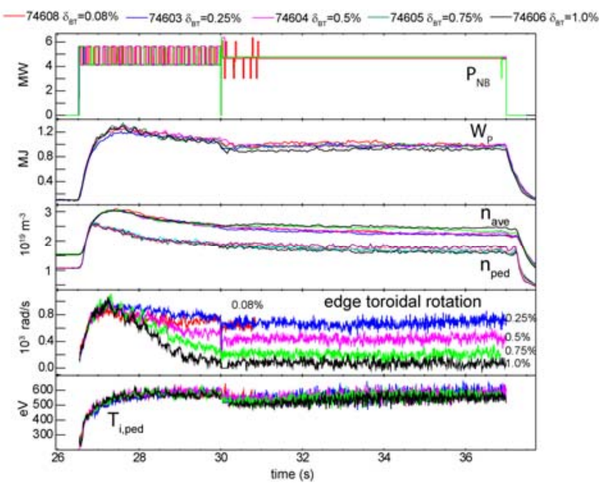

Figure 9: ripple scan at 1MA/1T – From top to bottom: total NB input power, plasma stored energy, line average density (core and edge), and plasma toroidal rotation frequency, at ~3.77m

5. Discussion.

The flexibility of the JET TF system has 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 δ_{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. It is therefore important to examine the JET results to see if the observed plasma behaviour is entirely attributable to the (relatively) high fast ion losses or if there are indications that other effects may be playing a role in determining the plasma parameters with ripple.

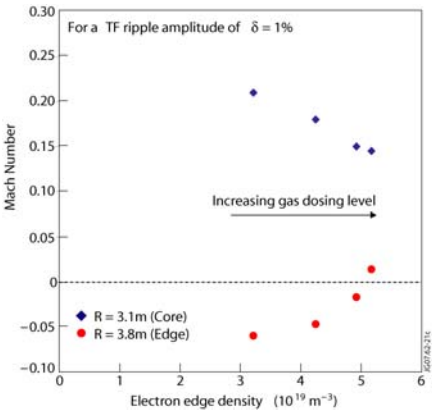

Figure 10: Mach number at the edge (dots) and core (lozenges) at constant 1% ripple as function of density [9]. Data from the gas scan at 2.6MA/2.2T of figure 4.

The changes in V_{TOR} with ripple were studied in detail, as described in [9, 10 and 11]. 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, detailed torque balance analysis also shows that the total torque on the plasma is reduced but still positive, and therefore plasma rotation should remain positive, while experimentally negative rotation at the plasma edge is observed, for 1% ripple (figure 1). It has been suggested that toroidal field ripple could also enhance thermal ion transport, and that these additional losses could be responsible for the extra negative torque required to explain the observed toroidal rotation.

Further indications that local background plasma parameters play a role in determining plasma rotation 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 δ_{BT} =0.08%, V_{TOR} at the edge is positive and increases between ELMs, consistently with the increased energy and momentum confinement. In contrast, for δ_{BT} =1%, V_{TOR} becomes more negative during ELM-free phases, although fast ion losses do not change appreciably. This behaviour could be attributed to an increase of thermal ion losses as the pedestal collisionality decreases in the ELM free phase, providing an extra negative torque. Similar indications can be drawn from the observation of the change in V_{TOR} with density at constant δ_{BT}=1% [9]. As shown in figure 11, the edge toroidal rotation changes (at approximately constant fast ion losses) when the n_{ped} is increased (and T_{ped} reduced) by external gas puff. This observation suggests a link between the source of the counter-torque and the background plasma properties, in particular with the local collisionality.

The reduced impact of ripple on plasma confinement and the absence of density pump-out in the low current/low field H-modes compared to the 2.6MA cases, also suggests that the "background" plasma parameters play a role in determining the plasma response to ripple. Given the rapid decay of the ripple perturbation (~25cm), the plasma region that is of interest is the periphery, including the pedestal. The pedestal collisionality and normalized Larmor radius of these discharges are higher then for the 2.6MA discharges, but the difference is modest, of the order of a factor 2.

Finally, it is interesting to note that strong reduction of the plasma co-rotation was always observed when applying ripple to an H-mode in JET, while plasma confinement reduction and density pump were not observed for all plasma conditions. This observation provides further indications of the complex link between rotation and thermal transport [see, for instance, ref 12], and will be analyzed in detail in the near future.

6. 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 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 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 (~$H^{3.3}$), 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 β), 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 Fu*sion **39** (1999), Ch 2
[2] PR Thomas et al., Phys Rev Lett **80** (1988), 5548
[3] S.J.Zwben,et al., *Nucl Fusion* **40** (2000), 91
[4] T Johnson et al, Proc 10th IAEA TM on Energetic Particles in Magnetic Confinement Systems, 8-10 October 2007, Kloster Seeon, Germany.
[5] T Kurki Suonio et al., IAEA FEC 2008, IT/P6-2
[6] ITER Physics Basis, *Nucl Fusion* **39** (1999), Ch 5
[7] H Urano et al., IAEA FEC 2006, EX/5-1
[8] G Saibene et al., *Nucl. Fusion* **45** (2005) 297–317
[9] P de Vries et al., *Nucl. Fusion* **48** (2008); 035007
[10] V Parail et al., IAEA FEC 2006, TH/P8-5
[11] A Salmi et al., Contrib. Plasma Phys. **48** (2008) 77
[12] P Mantica et al., IAEA FEC 2008, EX/2-4