*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, O-4.002 (2007)*

Toroidal Field Ripple and the formation of Internal Transport Barriers

P.C. de Vries[1], E. Joffrin[2], X. Litaudon[3], C.D. Challis[1], K-D. Zastrow[1] J. Brzozowski[4], J. Hobirk[5], M. Brix[1], N.C. Hawkes[1], C. Giroud[1], Y. Andrew[1], M. Beurskens[1], K. Crombé[6], T. Johnson[4], J. Lönnroth[8], A. Salmi[8], V. Yavorskij[9] and JET EFDA Contributors[§]

[1]*EURATOM/UKAEA Fusion Association, Culham Science Centre,. OX14 3DB, Abingdon, UK*
[2]*EFDA-JET CSU, Culham Science Centre, ABINGDON, Oxfordshire, OX14 3DB, UK*
[3]*Association EURATOM-CEA, DSM/DFRC, CEA Cadarache, 13108, St. Paul lez Durance, France*
[4]*Association EURATOM - VR, Fusion Plasma Physics, EES, KTH, Stockholm, Sweden*
[5]*Max-Planck-Institut für Plasmaphysik, Euraton Association, 85748, Garching, Germany*
[6]*Departement of Applied Physics, Ghent University, Ghent, Belgium*
[7]*VTT Technical Research Centre of Finland, EURATOM-Tekes, Espoo, Finland*
[8]*Association Euratom-Tekes, Helsinki University of Technology, P.O. Box 4100, 02015 TKK, Finland.*
[9]*Institute for Theoretical Physics, Association EURATOM-OEAW, University of Innsbruck, Austria*
[§]*See Appendix of M.L. Watkins, et al., Fusion Energy 2006 (Proc. 21th Int Conf. Chengdu) IAEA (2006)*

1. Introduction

The toroidal field (TF) ripple of ITER will differ from JET due to a lower number of TF coils, with *18* and *32* coils in these devices, respectively. Ferrite material will be mounted between the ITER coils in order to reduce the ripple. Nevertheless, the estimated TF ripple in ITER is in the order of δ~*0.5*% (the maximum toroidal variation of the magnetic field at the separatrix) which is higher than that at JET (δ~*0.08*%). The question arises if a larger TF ripple may affect the formation and performance of internal transport barriers (ITBs). Firstly, because a larger TF ripple is expected to reduce the toroidal rotation and consequently affecting the rotational shear. Secondly, the TF ripple may act on the H-mode pedestal and Edge Localised Modes (ELMs) which have been found to degrade ITBs. Internal Transport Barriers are an important feature of advance tokamak scenarios, which provide the possibility of steady state, non-inductive tokamak operations with improved confinement. Before, extrapolating such scenarios to ITER, the effects of an enhanced TF ripple on ITBs should be understood.

2. TF Ripple experiments at JET

Standard operations at JET are carried out with a set of *32* toroidal field coils all carrying equal current. However, at JET it is possible to vary the TF ripple amplitude by independently powering the *16* odd and *16* even-numbered coils. The imbalance current between the two coils set can be changed arbitrarily increasing the toroidal field ripple up to δ~*3*%. A series of experiments has been carried out analysing the effect of TF ripple by increasing its value on a shot-to-shot basis from the standard JET value of δ~*0.08*% to δ~*1.0*%.

Two distinct scenarios were used, shown in figure 1. Both scenarios heated early in the current ramp-up phase in order to optimise the current profile and used a low triangularity plasma configuration. In the first scenario, however, prelude Lower Hybrid Current Drive (LHCD) heating was applied in order to create negative or reversed magnetic shear (RS). The second scenario used a delayed start of the heating and omitted the use of LHCD in order to create plasmas with low positive or optimised magnetic shear (OS). For those discharges where the TF ripple amplitude was enhanced, the amplitude was ramped during first few seconds of the discharge and kept constant after $t=4$s, i.e. during the main experimental phase.

The plasmas were heated by a combination of Neutral Beam (NB) and Ion Cyclotron Resonance Heating (ICRH). A power scan was performed in each scenario for each ripple-amplitude in order to modify the ELM properties and to analyse the power threshold for ITB formation. Because of TF ripple induced particle losses, part of, predominantly NBI, power is lost. The ripple induced power loss fraction and the total absorbed power for each ripple-amplitude have been determined using the JAEA Orbit Following Monte Carlo (OFMC) code [1]. Shine-through losses are not included in these calculations, but similar for each of these discharges. For these scenarios it was found that typically *17*% of the NBI power is lost with a TF ripple of δ~*1.0*%. All discharges in this experiment were carried out with sufficient power to achieve H-mode.

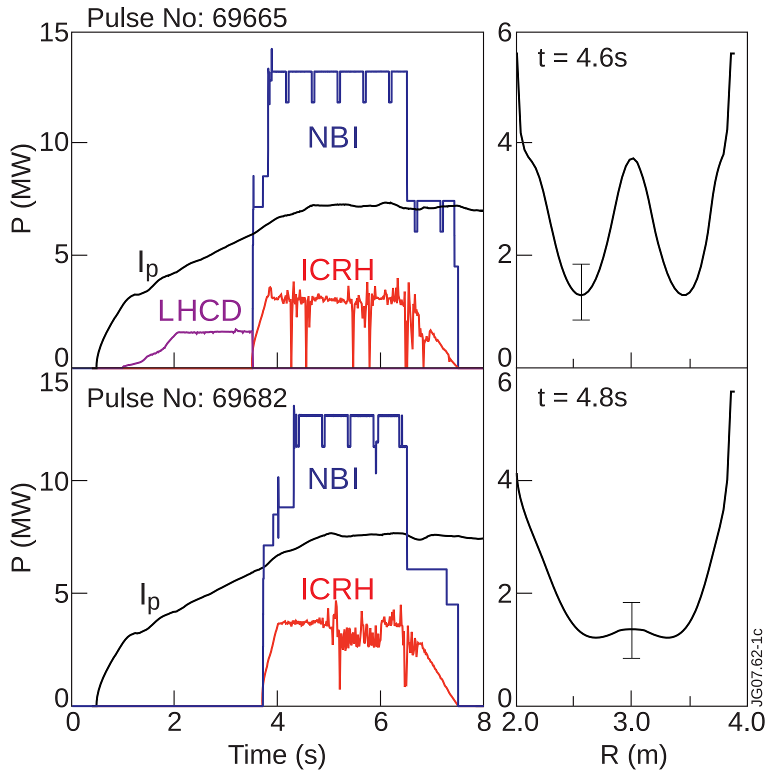
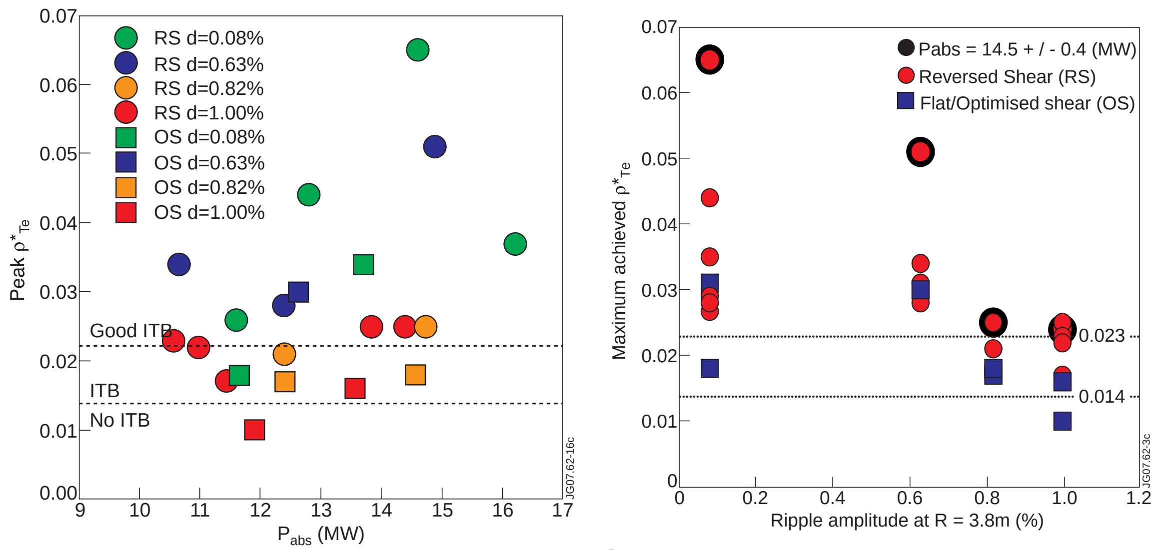


Figure 1: (top) *First scenario (RS) with LHCD prelude (t=1*s*-3.5*s*) during the current rise phase and NBI (blue) and ICRH (red) switched on at t=3.5*s*. The obtained q-profile in this is shown on the left with negative/reversed shear in the core and q_{min} at approximately R=2.6 and 3.5*m. (bottom) *Second scenario (OS) with later NBI and ICRH heating (t=3.8*s*). The q-profile is flat in the centre. The plasma current time traces* [a.u.] *are shown in black in the left graphs with the flat top starting at t=5*s*. Both scenarios used* B_t=2.2T, I_p=1.8MA *and* q_{95}=4.1.

3. Observations

In this paper an ITB is said to be triggered when ρ^*_T exceeds *0.014*, a criterion based on the temperature profile gradient, as described in [2]. ρ^*_T is defined as $\rho^*_T \equiv \rho_s/L_T$, the ratio of the ion Larmor radius and the temperature gradient length. After being triggered, the ITB does not always grow to cause a significant improved performance of the tokamak discharge and sometimes the criterion is only touched briefly. Here a well developed, high-performance ITB is defined as having a $\rho^*_T > 0.023$. In figure 2a the peak ρ^*_T values obtained with these experiments are shown as a function of total absorbed power. ITBs are triggered in most discharges ($\rho^*_T > 0.014$). Both the electron and ion temperature profiles showed increased gradients and peak ρ^*_T values were comparable. Those discharges with larger TF ripple, however, only had weak ITBs. This is more clearly visible figure 2b which shows the ITB strength versus the TF ripple amplitude. Mainly weak, $\rho^*_T < 0.023$, and short-lived ITBs are observed in discharges with a TF ripple of $\delta > 0.8\%$.
The ITB trigger is found to be independent of the applied power in the scenario with reversed central magnetic shear (RS), but stronger and ITBs developed in discharges with a larger absorbed power. Generally more power is required to form an ITB in the OS scenario [3]. In this scenario, ITBs were observed above an absorbed power threshold. Nevertheless, those ITBs in the presence of a large TF ripple remained weak. A higher NBI particle loss fraction and lower absorbed power for larger TF ripple amplitude could however not explain the observed degradation of the ITB strength with ripple amplitude. For example in figure 2b RS discharges with different TF ripple but similar total absorbed power, $P_{abs}=14.5 \pm 0.2$MW, have been indicated. The discharges with smaller TF ripple develop stronger transport barriers.

As mentioned in the introduction the TF ripple affects the plasma rotation [4]. Although the discharges shown in black circles in figure 2b may have similar absorbed powers, the total torque on these plasmas is reduced with TF ripple amplitude.



a b

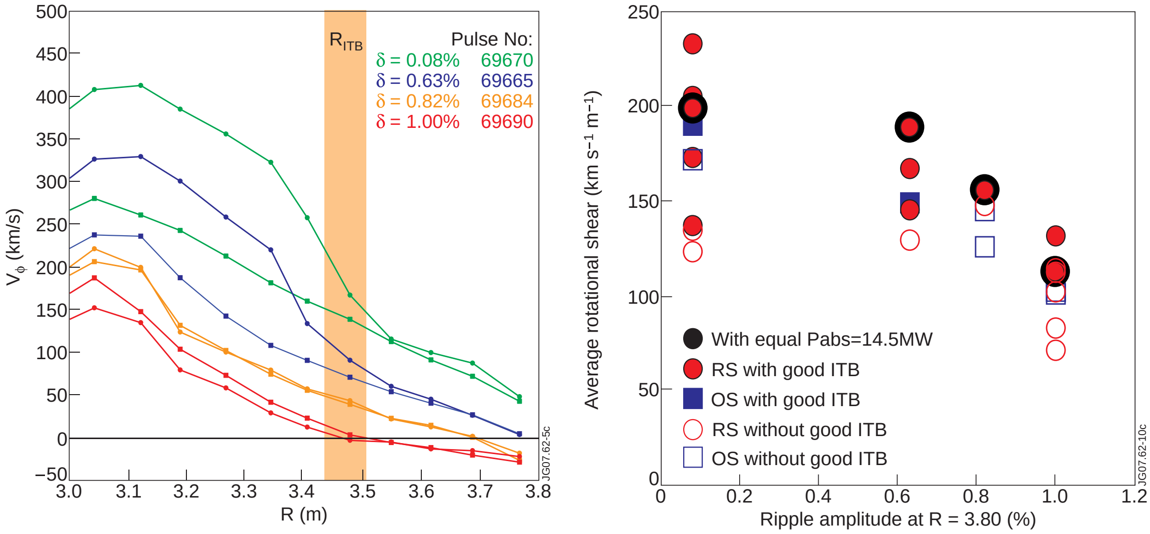
Figure 2: a) *The maximum achieved* ρ^*T_e *in each discharge as a function the total absorbed power for the two scenarios, with RS (circles) and OS (squares), respectively. The different colours indicate the TF ripple amplitude.* b) *The maximum achieved* ρ^*T_e *as a function of TF ripple amplitude. The red circles represent the scenario with reversed central shear (RS) while blue squares show the results with the optimised flat shear (OS). Four discharges (RS scenario) with equal absorbed power* P_{abs}*=14.5*MW *have been circled in black.* a) *The toroidal rotation profiles for these four discharges (RS scenario) taken at two times, at the time the ITB is triggered (~ t=4.5*s*)(squares) and at the time of its maximum strength (circles).*

This results in significantly different toroidal rotation profiles as shown in figure 3a. The toroidal rotation is lower for higher TF ripple amplitude and even reverses sign at the outer part of the plasma. For $\delta=1\%$ a region outside $R=3.48$m ($\rho=0.55$) rotates in counter current direction (negative) while the JET NB system injects in co-direction. For the two discharges that form strong ITBs ($\delta<0.8\%$) the transport barrier causes a peaking of the central rotation. No measurable change was observed in poloidal rotation at the time the ITBs were triggered, although a significant deviation from neo-classical poloidal rotation values has been observed during the further development of the ITB similar as has been reported before at JET [5].

The position of the ITBs was found in the region of zero magnetic-shear or the outer edge the low shear region in the RS and OS scenario, respectively. In figure 1b these regions are at approximately R~3.45-3.5m. The position where the toroidal plasma rotation is zero moves deep into the plasma (up to ρ~0.6) for $\delta>0.8\%$ and almost reaches the foot of the ITB in these discharges. However, the question arises if this is the parameter that determines the development of the ITB. Figure 3a and 3b show that the toroidal rotation gradient at the location of the ITBs (R~3.45-3.5m) reduces with ripple amplitude. The gradients are determined just before the trigger of the ITB and averaged over $R=3.4$-3.5m. Strong ITBs *(i.e.* $\rho^*_T > 0.023$*)* only formed in discharges with a large toroidal torque and sufficient gradient in the toroidal rotation.

4. Discussion

Besides the plasma rotation ELMs may affect the development of ITBs. The influence of TF ripple on the JET H-mode pedestal and ELMs is discussed in detail in [6]. In the experiments discussed in the paper, an increased TF ripple amplitude led to irregular and smaller ELMs. The penetration of the pedestal crash was studied by comparing the temperature profile prior and after the ELM. For large ELMs the profile is modified deep in the plasma. For standard ripple amplitude (δ~0.08%) more ELMs were able to affect the plasma at position of the ITB while for larger ripple amplitude ($\delta>0.5\%$) the number of ELMs that affected this position was significantly reduced. Nevertheless, up to δ~1% the reduction of the ELM size did not seem to have a beneficial effect on the development of the ITB.



a

b

Figure 3: a) *The toroidal rotation profiles for the four discharges (RS scenario) with equal absorbed power (P_{abs}=14.5±0.2*MW*) taken at two times, at the time the ITB is triggered (~ t=4.5*s*)(squares) and at the time of its maximum strength (circles).* b) *The averaged gradient in the toroidal rotation profile at the foot of the ITB, versus the TF ripple amplitude. The discharges with closed symbols did develop strong ITBs (i.e. ρ^*_T > 0.023), while the open symbols indicate weak or non ITBs (ρ^*_T > 0.023). The four discharges in figure 3a are circled in black.*

The TF ripple experiments enabled to study the formation of ITBs with different amounts of toroidal torque as discussed in [3]. Disregarding the TF ripple amplitude, ITBs were triggered in all RS discharges, suggesting that the trigger mechanism of this scenario may not depend on plasma rotation. Similar observations have been made in other experiments at JET [7]. The barrier formation in this reversed shear scenario is often associated with minimum q reaching an integer value [8]. More power is required to form ITBs in the optimised or flat shear scenarios. A larger fraction of the NBI power was lost in discharges with a higher TF ripple hence a larger input power was required to achieve ITBs. Nevertheless, comparing discharges with similar total absorbed power, it was again found that those with a larger TF ripple and lower toroidal rotation shear formed only weak ITBs.

These experiments have shown that, although the ITB trigger was unaffected, the further development of the ITB may be degraded due to larger TF ripple. The TF ripple reduced the toroidal rotation and modified the toroidal rotation profile while the poloidal rotation was not affected. It suggests that stronger barriers form in the presence of a larger rotational shear. The ITB trigger and the positive feedback mechanism responsible for the further development may be related to different parameters.

This research was funded partly by the United Kingdom Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was carried out within the framework of the European Fusion Development Agreement.

References

[1] K. Shinohara, *et. al.*, *Nucl. Fusion* 43 (2003) 586.
[2] G. Tresset, *et al.*, *Nucl. Fusion* 42 (2002) 520.
[3] C.D. Challis, et al., *Plasma Phys. Control. Fusion* 44 (2002) 1031.
[4] P.C. de Vries, *et al.*, in Proc. of this conference
[5] K. Crombe, *et al., Phys. Rev. Letters* 95 (2005) 155003.
[6] G. Saibene, *et al.*, in Proc. of this conference.
[7] N.C. Hawkes, *et al.*, in Proc. of this conference.
[8] E. Joffrin, et al., *Plasma Phys. Control. Fusion* 44 (2002) 1739.