34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-1.122 (2007)

Effect of Toroidal Field Ripple on Plasma Rotation in JET

P.C. de Vries[1], A. Salmi[2], V. Parail[1], C. Giroud[1], Y. Andrew[1], T.M. Biewer[2], K. Crombé[4], I Jenkins[1], T. Johnson[5], V. Kiptily[1], A. Loarte[6] J. Lönnroth[2], A. Meigs[1], N. Oyama[7], R. Sartori[5], G. Saibene[5], H. Urano[7], K-D. Zastrow[1] and JET EFDA Contributors[§]

[1]*EURATOM/UKAEA Fusion Association, Culham Science Centre,. OX14 3DB, Abingdon, UK*
[2]*Association Euratom-Tekes, Helsinki University of Technology, P.O. Box 4100, 02015 TKK, Finland.*
[3]*Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[4]*Departement of Applied Physics, Ghent University, Ghent, Belgium*
[5]*Association EURATOM - VR, Fusion Plasma Physics, EES, KTH, Stockholm, Sweden*
[6]*EFDA Close Support Unit, c/o MPI für Plasmaphysik, 2 Boltzmannstrasse, 85748 Garching, Germany*
[7]*Japan Atomic Energy Agency, Naka, Ibaraki-ken 311-0193, Japan*
[§]*See Appendix of M.L. Watkins, et al., Fusion Energy 2006 (Proc. 21th Int Conf. Chengdu) IAEA (2006)*

1. Introduction

Plasma rotation is thought to play an important role in the stability properties of tokamak plasmas. Hence it is relevant to accurately predict the rotation properties of ITER plasmas. Because of the finite number of Toroidal Field (TF) coils, a toroidal variation (ripple) of the main magnetic field exists in Tokamaks. 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 $\delta{\sim}0.5\%$ at the outer separatrix while this value in JET is only $\delta{\sim}0.08\%$. A larger TF ripple will have a non-negligible effect on the plasma rotation. In order to extrapolate rotation properties of present experiments to that of ITER plasmas, toroidal field ripple effects should be understood.

The TF ripple could affect the toroidal plasma rotation in two ways. Firstly, rotation can be reduced by friction between the circulating particles and those locally trapped in the toroidal field ripple [1]. Secondly, the TF ripple causes diffusion of the banana orbits of high-energy trapped particles in radial direction [2]. This radial ion flow induces a $j{\times}B$ torque on the plasma. The toroidal torque due to ripple banana orbit diffusion is in counter-current direction. The first effect tends to relax the plasma rotation to zero, while the second mechanism could drive rotation in counter-current direction. This has been observed in JT-60U where, with near perpendicular neutral beam injection (NBI) and, hence, little NB driven torque, significant plasma rotation in counter direction was measured in the presence a TF ripple of $\delta{\sim}1\%$ [3]. Rotation in co-current direction was observed after the TF ripple was reduced using Ferrite inserts [4].

By means of the Orbit Following Monte Carlo code ASCOT, the trajectories of energetic ions, for example those injected by the NB system and those accelerated by ICRH, can be accurately traced in the presence of TF ripple [5]. This enables the determination the fraction of energetic particles trapped in the TF ripple and the strength of the TF ripple induced torque due to banana-orbit diffusion.

At JET it is possible to vary the TF ripple amplitude by independently powering the odd and even-numbered TF coils. The imbalance current between the two sets of coils can be changed arbitrarily increasing the TF ripple up to $\delta{\sim}3\%$. A series of experiments has been carried out analysing the effects of TF ripple by increasing its value on a pulse-to-pulse basis from the standard JET value of $\delta{\sim}0.08\%$ up to $\delta{\sim}1.5\%$. This paper presents the effects of an enhanced TF ripple on the plasma rotation in JET. The plasma rotation has been measured by means of charge exchange spectroscopy (CXS). The experimental observations will be compared with the results from the ASCOT modelling.

2. Experimental observations

The mechanism of TF ripple affecting plasma rotation can be illustrated by comparing discharges with different angles of NBI. At JET the NB system can apply near tangential injection with a tangency radius of $R_T=1.85$m ($\theta_{inject}{\sim}25°$) and so-called normal injection with $R_T=1.31$m ($\theta_{inject}{\sim}17°$) with $R_o=2.95$m. In figure 1, two discharges are compared both with a TF ripple of $\delta=0.5\%$ but one with predominantly tangential and the other normal NBI. Higher normal NBI power was applied in order to keep to total toroidal torque applied by NBI ($T_{NBI}=15.1\pm1$Nm) the same in both discharges. The plasma with tangential NBI still has significantly larger (*20*%) angular momentum. If this would be repeated with a standard JET ripple the difference would disappear.

The observed difference in rotation can be explained by the fact that normal NBI produces more ions that are trapped in banana orbits, which are affected by the TF ripple. The higher density of trapped particles in the presence of a large TF ripple, results a larger counter torque induced by the particle losses, hence reducing the rotation. ASCOT indeed calculates a larger loss fraction for case with normal bank injection, *13*% compared to *9*%. ASCOT determined that these extra losses resulted in a lower torque (by *2.7*Nm) for plasma with normal NB. The calculated torques, including TF ripple losses were $T_{ASCOT}=9.1$Nm and $T_{ASCOT}=11.8$Nm for the normal and tangential case, respectively.

Note that the torque on the plasmas with TF ripple ($\delta=0.5\%$), shown in figure 1, is also reduced by approximately *40*% compared to the applied NBI torque. Hence the overall rotation of these two discharges is reduced considerably compared to a case with minimum ripple ($\delta=0.08\%$). In order to be able to compare rotation properties of various experiments, it is convenient to use the dimensionless thermal Mach number, defined as the ratio of the rotation velocity and the thermal velocity [6]. In figure 2a, the Mach numbers measured at the plasma centre and edge are shown as a function of TF ripple amplitude. The central Mach number decreases from standard values of $M=0.40\text{-}0.55$ to $M=0.25\text{-}0.35$ for $\delta=0.5\%$ and $M=\text{-}0.1\text{-}0.3$ for $\delta=1\%$. For higher TF ripple amplitudes ($\delta\sim1\%$) negative Mach numbers, i.e. counter rotation, is observed in various discharges while the core kept its co-current rotation. The overall poloidal rotation at the edge was found to be unaffected by TF ripple.

In figure 2b a dedicated TF ripple scan is shown, where beside the TF ripple, the other plasma parameters are kept unchanged in a series of ELMy H-mode discharges. Again the Mach number and total angular momentum are found to decrease with TF ripple amplitude. Furthermore the momentum confinement time, defined as the ratio of the total angular momentum and the applied torque by NBI, is found to be much smaller than that of the energy confinement time.

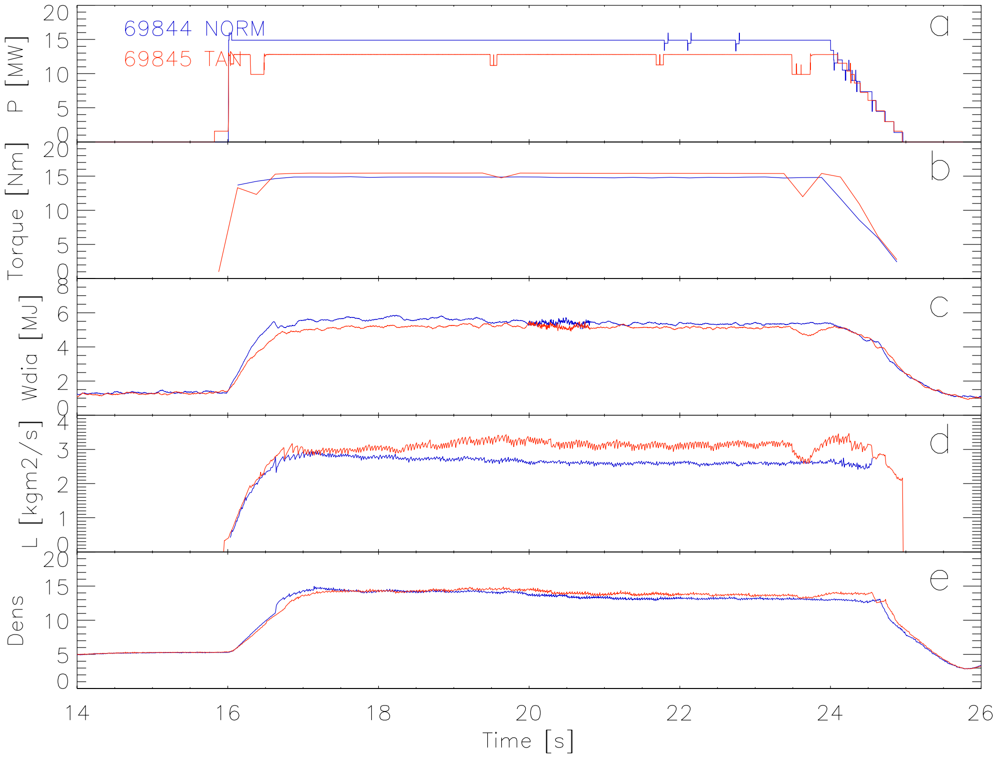
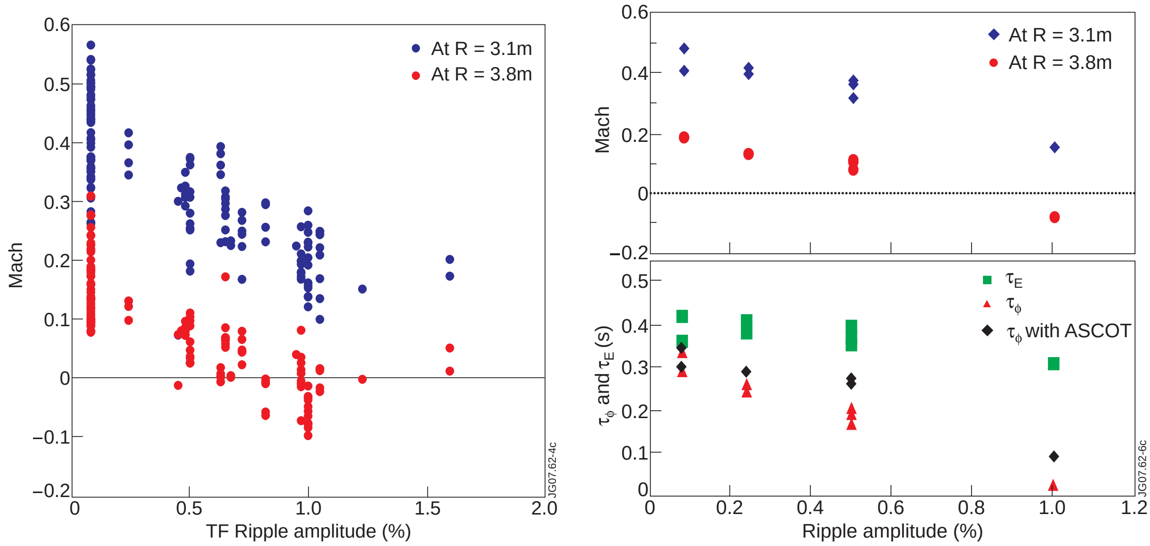


Figure 1: a) *NBI Power for the two JET discharges with predominantly normal and tangential injection in blue and red, respectively. The TF ripple in both discharges was* $\delta=0.5\%$. b) *The toroidal torque applied by NBI.* c) *The diamagnetic energy.* d) *The total angular momentum.* e) *The line-integrated density in* 10^{19} m^{-2}.



a b

Figure 2: a) *Mach numbers measured at the plasma centre (R=3.1*m*) and edge (R=3.8*m*) are shown as a function of TF ripple amplitude at the outer separatrix. The data have been taken over various scenarios and plasma conditions*. b) *Series of identical Type I ELMy H-modes pulse but with increasing TF ripple. The top graph shows again the centre and edge Mach number, while the bottom graph presents the energy (green squares) and momentum (red triangles) confinement times. The black diamonds show the momentum confinement times with the toroidal torque calculated by ASCOT.*

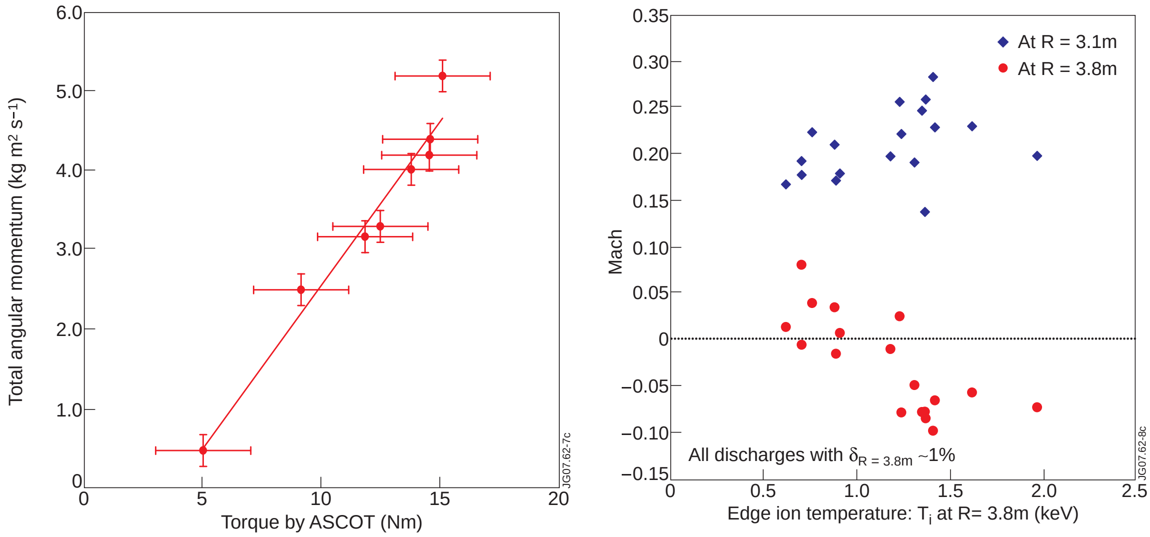
In JET for a standard TF ripple (δ=*0.08*%) these parameters are found to be of the same order of magnitude. The drop in energy confinement time with TF ripple is due to the degradation of the H-mode pedestal for larger TF ripple as discussed in detail in [7].

The momentum confinement time can be calculated using the torque as calculated by ASCOT, which include the effects of TF ripple on energetic ions. These values are shown in figure 2b to be larger than the original confinement times but the values still drop with ripple amplitude and are considerably lower than those of the energy confinement. In figure 3a shows that the angular momentum for these discharges scales with the torque as calculated by ASCOT. Note that these discharges all had approximately the same NBI torque. The offset scaling indicates that either the momentum confinement is strongly affected by the TF ripple or the TF ripple induced counter torque as calculated by ASCOT is too small. Similarly negative or counter rotation is observed at the edge in discharges for which ASCOT still calculates a positive total torque.

Negative edge rotation in the presence of large TF ripple was found to correlate with the local temperature as shown in figure 3b. Discharges with very high edge temperatures such as those for advanced tokamak scenarios showed the fastest edge counter rotation with the area with counter rotation extending up to ρ=*0.5* into the plasma for δ~*1.0*%. It was also found that the edge counter rotation could be reduced or reversed by gas dosing, which causes a lower edge temperature.

3. Discussion

Friction with particles trapped in the TF ripple cannot explain counter rotation. Furthermore, ASCOT calculations have shown that the fraction of particles trapped by the TF ripple is negligible (less than *0.1*%) for the levels of TF ripple discussed in this paper δ<*1.0*%. The dominant mechanism that drives the observed counter rotation in JET discharges with a large TF ripple δ>*0.5*% can be associated with banana orbit diffusion of trapped energetic ions (by NBI). However calculations of the induced torque due these losses do not fully explain the observations. The edge rotation in the presence of a large TF ripple in JET depended on the local ion temperature, suggesting that other ion losses, possibly those of thermal ions, may be involved. The effect of TF ripple on thermal ions has so far not been included in the ASCOT calculations shown in this paper.



a b

Figure 3: a) *The total angular momentum as a function of the torque as calculated by ASCOT (including TF ripple effects) for the discharges shown in figure 2b* b) *The centre and edge Mach number (R=3.8*m*) for all JET discharges with a TF ripple of δ~1% (at R=3.8*m*) as a function of the local ion temperature.*

Even for small TF ripple amplitudes of *δ~0.5*%, which is expected in ITER, the JET plasma rotation was significantly reduced compared to normal levels. In JET discharges with a TF ripple of *δ~0.5*% the counter current torque was found to be in the order of *20-30*% of that supplied by the JET NBI system in co-current direction. In JT-60U with almost perpendicular NBI and larger ripple *δ~1*% the ripple induced ion losses may have been the dominant drive for the observed counter current plasma rotation [4]. This shows that the orientation of the NBI, e.g. tangential versus normal/perpendicular injection, at these ripple amplitudes is of importance.

Predictions for plasma rotation in ITER often assume that the momentum and energy confinement times are proportional and do not include TF ripple effects [8]. It has been shown in this paper that such assumptions do not hold. Predicting plasma rotation in ITER by extrapolating from present devices, like JET, which have significantly lower TF ripple may be more complicated. The TF ripple induced torque is always in counter current direction and will reduce the NBI co-current torque, yielding a lower rotation in ITER than presently expected. To quantify these effects detailed modelling of TF ripple effects on ITER rotation are required. The effect of thermal ion losses on the torque is being investigated, modelling these losses with ASCOT. Initial results indicate that these losses indeed contribute to the counter-current torque on the plasma [5].

This research was partly funded by EURATOM and the UK Engineering and Physical Sciences Research Council.

References

[1] A. B. Mikhailovskii, *Physics Letters A* 198 (1995) 131.
[2] R.J. Goldston, R.B. White and A.H Boozer, *Phys. Rev. Lett* 47 (1981) 647.
[3] Y. Koide, *et al.*, *Plasma Phys. Control. Nucl. Fusion Research* 1 (1993) 777.
[4] M. Yoshida, et al., *Plasma Phys. Control. Fusion* 48 (2006) 1673.
[5] A. Salmi, *et al.*, in the Proc. of the 11th Intl. Workshop on Plasma Edge Theory in Fusion Devices, Takayama, Japan (2007).
[6] P.C. de Vries, *et al.*, *Plasma Phys. Control. Fusion* 48 (2006) 1693.
[7] G. Saibene, *et al.*, in the Proc. of this conference.
[8] A.R. Polevoi, *et. al.*, in the Proc. of the 19th IAEA Fusion Energy Conference 2002, Lyon, France (IAEA, Vienna, 2006), Paper No. CT/P-08.