PUBLICATION II

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In: Contributions to Plasma Physics 48,
pp. 77–81, 2008.

Contrib. Plasma Phys. **48**, No. 1-3, 77 – 81 (2008) / **DOI** 10.1002/ctpp.200810013

# ASCOT Modelling of Ripple Effects on Toroidal Torque

**A. Salmi***[1], **T. Johnson**[2], **V. Parail**[3], **J. Heikkinen**[4], **V. Hynönen**[1], **T. P. Kiviniemi**[1], **T. Kurki-Suonio**[1], and **JET EFDA Contributors**[**]

[1] Helsinki University of Technology, Association Euratom-Tekes, Finland
[2] Association EURATOM-VR, Fusion Plasma Physics, EES, KTH, 10044 Stockholm, Sweden
[3] Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK
[4] VTT, Association Euratom-Tekes, Helsinki, Finland
[**] See appendix of M.L. Watkins, et al., Fusion Energy 2006 (Proc. 21th Int Conf. Chengdu) IAEA (2006)

Received 23 May 2007, accepted 17 November 2007

**Key words** MC, GC orbit following, ripple, torque.

**PACS** 52.25.Fi, 52.55.Fa, 52.65.Pp

Toroidal field ripple, $\delta$=(B$_{max}$-B$_{min}$)/(B$_{max}$+B$_{min}$), in ITER will be relatively large, about 0.5% at the outer midplane. Due to the importance of toroidal rotation on plasma stability and confinement it is important to understand the consequences of a non-negligible ripple field on rotation. Guiding centre following Monte Carlo code ASCOT is used to evaluate the torque on plasma from co-current NBI in presence of toroidal magnetic field ripple. Simulations are made for a JET discharge from 2007 Ripple Campaign aimed to clarify the effect of ripple on fusion plasmas in preparation for ITER. ASCOT results show large reduction of torque from co-NBI and negative torque from thermal ions, which together could create a counter rotating edge plasma.

## 1 Introduction

Toroidal magnetic field ripple is known to have an effect on plasma density, rotation and confinement. Energetic ions, e.g. fusion alphas and NB and RF heated ions are most vulnerable to ripple and it has been studied much before. The increased losses of fast ions naturally lead to both; decreased heating efficiency and increased heat load on the vessel first wall. However, they may also play a crucial role in the loss of confinement through ripple reduced toroidal rotation. Toroidal field ripple breaks the axi-symmetry of the magnetic field which allows the ions and the toroidal field coils to exchange toroidal momentum. As ITER, having 18 toroidal field coils, will be operating in relatively strong ripple field it is important to understand the effect that ripple has on plasma toroidal rotation.

Recognising the importance of ripple on ITER and its design, JET launched its third ripple campaign in 2007 to study these effects in a controlled way. JET has the capability to drive uneven currents in the adjacent coils thus gaining control over the level of ripple. In JET Ripple Campaign 2007 (RIP3) some discharges have shown that with increased level of ripple the toroidal rotation can reverse to counter direction (relative to the current and NBI injection angle) [1]. Although fast ions and ripple have an important role when explaining experimental observations it is generally not possible to limit the analysis for fast ions only. The ripple can namely also affect thermal ions. For thermal ions, however, the effect of ripple is much affected by the radial electric field in the plasma in particular close to the separatrix where the thermal energy is comparable to the potential well depth.

In this contribution plasma discharges from the JET RIP3 Campaign are analysed with a guiding centre following Monte Carlo code ASCOT [2]. Toroidal torque in presence of magnetic ripple is calculated from both fast (NBI) and thermal ions. ASCOT results show that NBI heated JET plasma can produce torque that can give rise to counter rotation if ripple is high enough and/or torque from the thermal ions is taken into account.

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*Corresponding author: e-mail: antti.salmi@tkk.fi

## 2 Torque from NBI in presence of ripple

NBI ions usually have much greater kinetic energy than the electrostatic potential difference that they encounter during their orbit. Radial electric field is then not expected to more than make a small perturbation on fast ion orbits. We will therefore neglect the electric field when estimating the torque from NBI. The experimental set-up for the discharge, #69648 (60s), being investigated is: 15.4 MW of co-current NBI with an average injection energy of 75 keV, central electron density $n_{e,0} = 5 \times 10^{19}$ m$^{-3}$, central electron temperature $T_{e,0} = 5$ keV, density and temperature at the pedestal top $n_e = 3 \times 10^{19}$ m$^{-3}$ and $T_{e,i} = 1$ keV. With these parameters the plasma is in the banana regime.

ASCOT simulations use EFIT reconstructed magnetic equilibrium and experimental plasma density and temperature profiles. As an NBI source for ion birth profile ASCOT uses Fokker-Plank code PENCIL. Ion birth profiles are sampled to generate typically $10^4$ test particles. The ripple model in ASCOT uses a numerical poloidal 2D map of the toroidal field ripple and sinusoidal harmonics in toroidal direction.

To illustrate the agreement between ASCOT and PENCIL when ripple is not present Fig. 1 shows a comparison between the codes. The scenario used for this is the JET shot #69648 which had $\delta = 1\%$ ripple at the outer midplane separatrix but which was set zero in the simulation to allow for comparison. As can be seen the agreement is very good especially in the middle of the minor radius[1] where also most of the power goes. The difference close to the separatrix is due to orbit losses, which PENCIL does not evaluate. The reason for the difference in the central plasma is attributed to the fact that in PENCIL all of the power and torque end up on the same flux surface where the neutrals were first ionised. ASCOT, however, accounts both collisional transport effects and the shift in radius between ion birth point and the bounce average GC position. The beam deposition being mostly off axis and injection in co-current direction means that both these and volumetric effects tend to enhance the power density in the central plasma as compared to PENCIL.

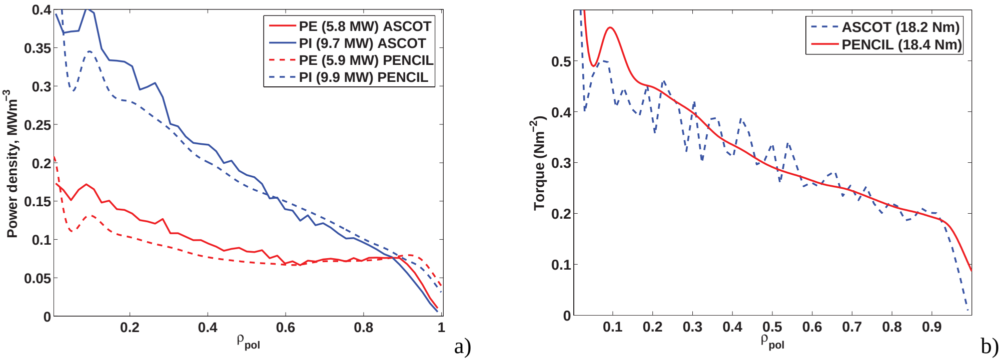

**Fig. 1** a) Power and b) torque density profiles comparing PENCIL and ASCOT for #69848 without ripple. Positive sign in torque refers to co-current direction. (Online colour: www.cpp-journal.org.)

In axi-symmetric field torque from NBI is transferred to the plasma either through particle collisions on through the *instantaneous* current originating from the difference in particle birth point and its bounce averaged position. To maintain quasi-neutrality the plasma sets up a return current, which leads to torque through $j \times B$ force.

In the presence of ripple the canonical angular momentum is not conserved and ions can exchange momentum with the toroidal field coils. This leads to non-ambipolar radial current of ions, usually directed radially outwards. One can interpret this radial current as externally driven which can then induce torque on the plasma. As for the instantaneous (or direct) torque generation it is the requirement of quasi-neutrality that ensures that non-ambipolar radial current leads to torque.

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[1] Minor radius co-ordinate used here is $\rho_{pol} = \sqrt{(\Psi_{pol} - \Psi_{pol}(0))/(\Psi_{pol}(a) - \Psi_{pol}(0))}$, i.e. the square root of the normalised poloidal flux.

In ASCOT simulations the radial current includes both the instantaneous current and the ripple induced radial current and also the orbit loss current. We do not make a difference where the current originates. The $j \times B$ torque we quote is the sum of all these components. Figure 2a shows ASCOT results of momentum transfer into the plasma for #69648 without ripple. Torque has been split explicitly into two parts; a friction due to collisions between NBI ions and bulk plasma and a $j \times B$ part. More specifically the torque density is defined as $T = Rj_rB_{pol}$, where $R$ is the major radius, $j_r$ is the current density induced into the plasma and $B_{pol}$ is the poloidal component of the magnetic field.

It can be seen that in the centre of the plasma, due to the small trapping fraction, only collisions can transfer toroidal torque from fast ions into the plasma. However, at outer part of minor radus, where the number trapped ions increases the radial current becomes larger and the $j \times B$ force becomes the dominating momentum exchange mechanism. Figure 2b shows the total torque profiles for three levels of ripple for a JET plasma #69648 with 15.8 MW of NBI which in axi-symmetric and lossless case would generate 18.4 Nm of co-current torque. It is seen that with increasing ripple the torque becomes negative at the edge; first only close to the separatrix but with $\delta = 1.69\%$ already at $\rho_{pol} = 0.7$. In the central part of the plasma, where the ripple is small and collisions dominate, the momentum transfer is almost unaffected by the ripple.

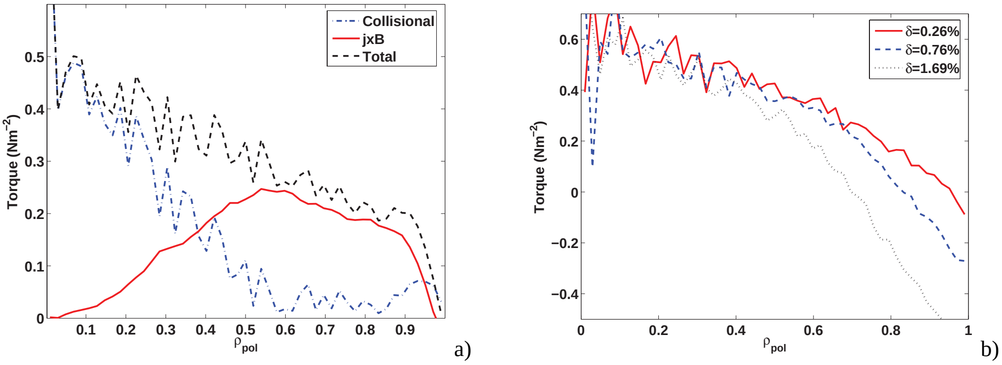

**Fig. 2** a) Torque profile split into collisional and $j \times B$ parts and b) total torque for 3 levels of ripple. Co-current torque is defined as positive. (Online colour: www.cpp-journal.org.)

**Table 1** Total torque from a ripple scan for NBI heating case similar to #69648. Here *Wall* denotes the torque lost through separatrix along with escaped NBI ions, *Colls* is the torque received by the plasma through collisional slowing down of fast ions, $J \times B$ is the torque on plasma due to non-ambipolar radial current of fast ions, *Co-torque lost* is the loss of co-current initial torque and *Power lost* is the lost NBI power. Initial torque evaluated from ion birth profile for all cases is 18.4 Nm.

| Ripple (%) | Wall (Nm) | Colls (Nm) | JxB (Nm) | Co-torque lost (%) | Power lost (%) |
|---|---|---|---|---|---|
| 0.0 | 0.2 | 6.3 | 12 | 2 | 2 |
| 0.26 | 0.8 | 6.5 | 11 | 7 | 7 |
| 0.51 | 1.5 | 6.9 | 7.2 | 24 | 11 |
| 0.76 | 2.3 | 6.7 | 2.0 | 54 | 16 |
| 1.00 | 2.9 | 6.7 | -3.2 | 82 | 21 |
| 1.69 | 3.8 | 6.5 | -15 | 150 | 30 |
| 3.26 | 4.2 | 6.0 | -39 | 280 | 45 |

Table 1 shows the volume integrated values of the profiles shown in Fig. 1b together with other levels of ripple which were not plotted to keep the figure readable. Table 1 separates also the amount of momentum transferred through collisions and through $j \times B$ force. This split shows clearly that collisional torque is almost independent of ripple. The torque from $j \times B$ force, which in modest ripple levels stays co-current becomes negative between $\delta = 0.76\% - 1\%$. This is because with small level of ripple the instantaneous current, which is directed radially inwards, dominates. With higher level of ripple radial current becomes more and more outward and negative total torque can result as also depicted in Fig. 3. Generally ripple induced torque is always counter current thus reducing torque from co-injected NB.

From momentum balance equation one finds that the total torque on the plasma must be negative if counter rotation at the edge is to be expected as observed in experiments [1]. According to ASCOT one finds that 18.4 Nm torque from 15.4 MW of NBI is reduced by 82% due to ripple. Although greatly reduced the total torque from NBI is still positive and can not alone explain why the edge was counter rotating. The missing negative torque is believed to arise from the thermal ions and it is studied in the next section.

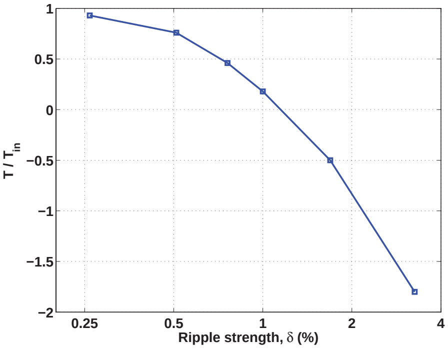

**Fig. 3** ASCOT calculated torque divided by input NBI torque. For small ripple levels the total torque is close to the beam input but as the ripple is increased more and more of co-torque is lost dominantly through the ripple induced outward radial current. With ripple exceeding 1% the total torque becomes counter NBI. As expected ripple reduces the torque near quadratically for ripple levels up to 0.8% after which the increase of counter torque slows down to near linear since relatively weak collisions do not continue to maintain pure stochastic behaviour of ripple diffusion.

## 3 Torque from thermal plasma in presence of ripple

Estimating the torque from thermal ions due to ripple is more complicated than for fast ions due to the existence of radial electric field. Radial electric field perturbs the orbits of thermal ions relatively strongly because usually the depth of the potential well is of the order of thermal energy. Ripple generated torque from the thermal ions is tightly coupled with the radial electric field.

To study this effect one should, in principle, solve the radial electric field self-consistently using *full-f* techniques and collisions that conserve energy and momentum because of the importance of the edge region where ripple is strongest and particle distributions asymmetric. In addition when interpreting experiments one really should have a simulation system, which is not sensitive to initial conditions. To make plasma profiles consistent with experimental heat and particle fluxes, recycling and radial electric field, transport time scale simulations would be needed. One also might need to include the effect from ELM's and turbulence to match simulations and experiments.

To avoid these complications and the noise from time varying electric field, which are likely to confuse the interpretation of the ripple effects, we fix the radial electric field in these simulations. We use the equation [3] with zero toroidal rotation condition:

$$E_r = \frac{T}{e}\left(\frac{n'}{n} + \gamma\frac{T'}{T}\right) \tag{1}$$

to solve the electric field. Although this estimate clearly does not produce the correct electric field it will serve for our purposes in estimating the effect of electric field on the torque generated by the ripple.

We set up the simulations by loading 250 000 thermal test particles between $\rho_{pol} = 0.8 - 1.0$ homogeneously in phase space while maintaining the experimental temperature and density profiles. Test particles collide against fixed Maxwellian background and are allowed to escape the plasma. No recycling is used. Maxwellian collisions used here are expected to be more efficient in providing ion flux into ripple trapped region of phase space than conserving collisions due to asymmetric distribution close to the edge. In the end, even in this case we lose at most 0.2% of the particles due to ripple trapping justifying the use of non-conserving collisions for this analysis.

Figure 4 shows the torque from thermal ions in the presence of ripple as a function on radial electric field strength. The torque shown is only due to ripple and it is separated from the torque arising from orbit losses. Note that without ripple $j \times B$ torque and collisional torque cancel each other exactly due to ambipolarity except close to the edge where orbit losses occur. In 1% ripple field but without electric the resulting torque (-40 Nm) is more than twice and counter of what can be achieved with 15.4 MW of NBI in the absence of ripple and about 10 times and counter of what remained from NBI in the ripple field. From experiments we know that total torque on the plasma must be very small as edge rotation was marginally counter. From Fig. 4a we can read that ASCOT results indicate that thermal torque would be of the correct order ($\sim -5$ Nm) if the NC electric field was enhanced by a factor of 3.5. This enhancement could result, e.g. from ripple itself. Without self-consistent evaluation of electric field one can not say quantitatively if the ripple acting on the thermal component explains the counter rotation observed but these calculations indicate that it is indeed a good candidate.

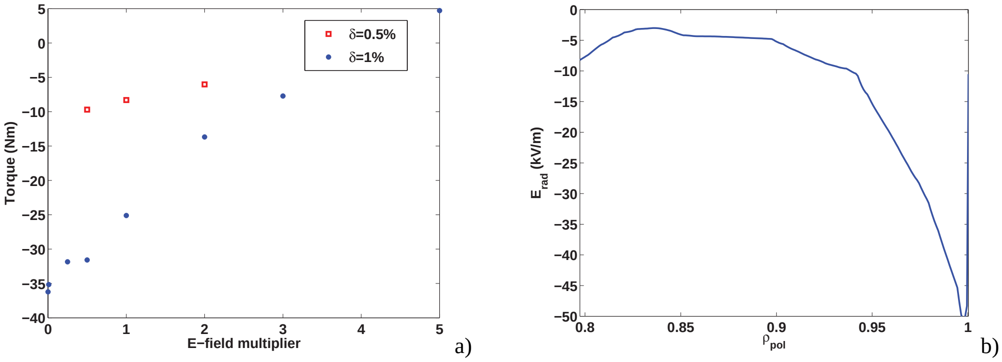

**Fig. 4** a) Torque from thermal ions with ripple and b) radial electric field without scaling factor.

## 4 Conclusions and Discussion

Ripple effects on toroidal torque generation have been modelled using GC following Monte Carlo code ASCOT. Simulations show that with $\delta = 1\%$ ripple the co-current torque from NBI is reduced by 82% from what would be achieved without ripple. Despite this large reduction of torque from NBI, the volume integrated torque remained positive. Main mechanism for the loss of co-torque is the increased ripple diffusion of fast ions leading to outward radial current. Due to the nature of momentum balance it could be concluded that torque from NBI alone could not explain experimentally observed counter rotating plasma edge.

Simulations with thermal ions showed large counter torque for smaller levels of radial electric field. With increasing (negative) electric field the amount of torque dropped to a level that could explain the measured counter rotation. Self-consistent evaluation of radial electric field with ripple, however, is needed to make quantitative conclusion of the thermal ion torque.

**Acknowledgements** This work has been partly funded by Fortum Säätiö

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