Momentum transport studies in JET H-mode discharges with an enhanced toroidal field ripple

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1. Introduction

The study of plasma rotation and momentum transport has gained interest over the last few years as rotation is thought to play an important role in the stability of Tokamak plasmas while it may also affect transport properties via the stabilization of turbulence. A proper understanding of all aspects that affect the rotation of Tokamak plasmas, in particular rotation sources and momentum transport, is important if one wants to make an accurate prediction of the rotation in ITER.

The assumption that momentum transport is similar to the turbulence driven ion heat transport is a strong simplification and usually in JET it is found that the effective momentum diffusivity is significantly smaller than the ion heat diffusivity [1]. This observation can be attributed to the existence of an inward momentum pinch [2,3]. Clear experimental evidence for such a momentum pinch in JET was obtained in earlier experiments [4].

JET has the unique capability to change its toroidal field (TF) ripple. It was shown that an increased TF ripple has a strong impact on the overall toroidal rotation at JET [5]. This paper will not deal in detail with mechanisms of TF ripple induced torque on the plasma, which is described elsewhere [5], but utilize TF ripple as a tool, in order to reveal the impact of the momentum pinch on the rotation profiles in H-mode JET discharges. Besides this an estimation of the magnitude of the momentum pinch can be made for each entry in the JET rotation database [1], which enables us to look into the basic scaling of this parameter.

2. Experiments using TF ripple

A series of experiments were performed to investigate the impact of the TF ripple on the H-mode pedestal properties [6] for which the TF ripple was increased from the standard JET level of δ_{BT}=0.08% up to 1.0%. In total 16 discharges were analysed which were standard type I ELMy H-modes with a plasma current of I_p=2.6MA, a toroidal magnetic field of B_T=2.2T and q_{95}=3, using a plasma configuration with a low triangularity and standard elongation (δ=0.23, k=1.65). The auxiliary heating came from NBI only which in JET is injected near tangentially, in the direction of the plasma current. The NBI power ranged from 13-19MW and supplied a toroidal torque of the order of 15Nm. Generally, these plasmas had equal ion and electron temperatures (T_i/T_e~1) and density profiles with a typical inverse gradient length of R/L_n~2. More details on these discharges can be found in ref. [6, 7].

For the purpose of transport studies it is important to understand the energy and momentum sources, or torque deposition profiles, which will be affected by the varying TF ripple. The ASCOT code was used to determine the TF ripple induced losses of NBI ions and the resulting torque, of which the details are described in ref. [5, 8]. In figure 1a, the ASCOT calculated torque deposition profiles are shown for 4 cases with increasing levels of TF ripple. Two features can be seen.

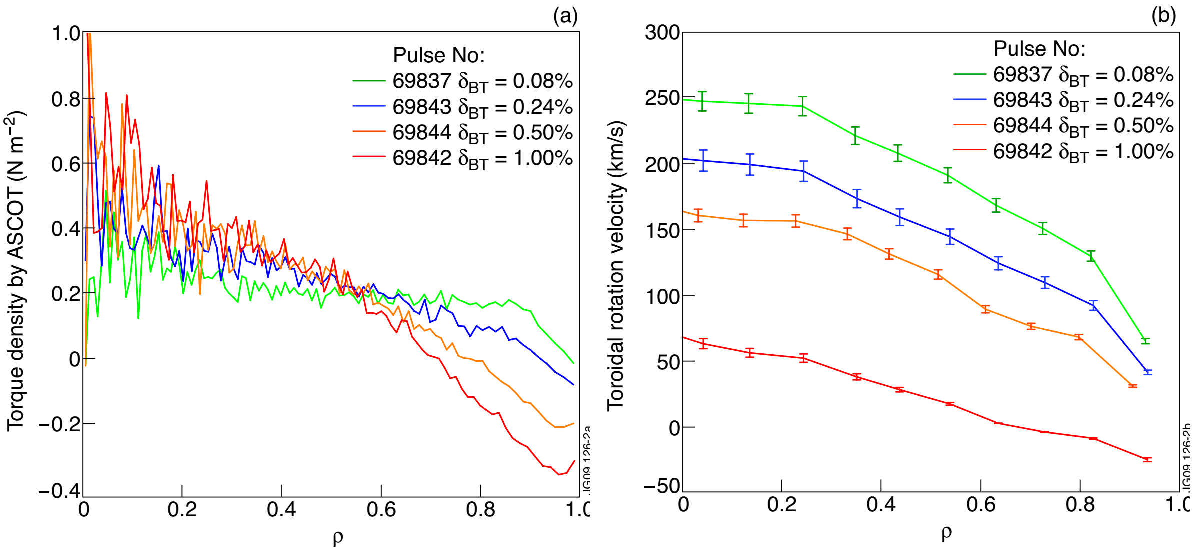

Figure 1a: (left) Torque deposition profiles for 4 identical discharges, however, with increasing levels of TF ripple. **1b:** (right) The changes in the toroidal rotation profiles for the same 4 discharges, as measured by Charge Exchange Spectroscopy.

Firstly, with increasing TF ripple a large area in the outer part of the plasma ($\rho>0.6$) will experience a counter current (negative) torque due to the TF ripple induce non-ambipolar ion losses [5]. Secondly, a small variation of the centrally ($\rho<0.5$) deposited NBI torque is found. In order to compensate for the TF ripple induced power losses and keep the total absorbed power constant, the requested NBI power was often slightly higher (up to about 15%) for the higher TF ripple cases, resulting in a higher torque density in the core.

If one considers momentum transport at $\rho=0.5$, one expects for cases with a higher TF ripple a slightly increased torque flux, however, the figure 1b shows that at the same time, the gradient of the rotation profiles decreases. It was found that the ion heat diffusivity did not vary significantly for these plasmas, nevertheless, the observations indicate a large difference in momentum transport. In figure 2a, the ratio of the effective momentum diffusivity, assuming only diffusive momentum transport, and the ion heat diffusivity, or effective Prandtl number (P_r^{eff}), is found to increase towards unity with increasing TF ripple amplitude.

The effective momentum diffusivity does however not consider inward momentum convection. But the observations are consistent with the presence of an inward momentum pinch, V_p, with a momentum transport equation:

$$\Gamma_\phi = -\chi_\phi \nabla\Omega - V_p \Omega \tag{1}$$

Here the symbols Γ_ϕ the torque flux (i.e. the amount of torque deposited within a certain region divided by the surface), Ω and $\nabla\Omega$ give the momentum density and its gradient and χ_ϕ is the momentum diffusivity. The TF ripple reduces the momentum in the outer part of the plasma, hence, for increasing TF ripple, the second term on the right-hand-side is reduced. Even if χ_ϕ, together with Γ_ϕ , are more or less unaffected, the increasing TF ripple may indirectly reduce $\nabla\Omega$. One can rewrite eq. (1) to:

$$\frac{\nabla\Omega}{\Gamma_\phi} = -\frac{V_p}{\chi_\phi}\frac{\Omega}{\Gamma_\phi} - \frac{1}{\chi_\phi} \tag{2}$$

In figure 2b, this equation is plotted and the normalised gradient, $\nabla\Omega/\Gamma_\phi$, is clearly found to scale with Ω/Γ_ϕ. The slope is determined by the pinch velocity, while the off-set is equal to $1/\chi_\phi$.

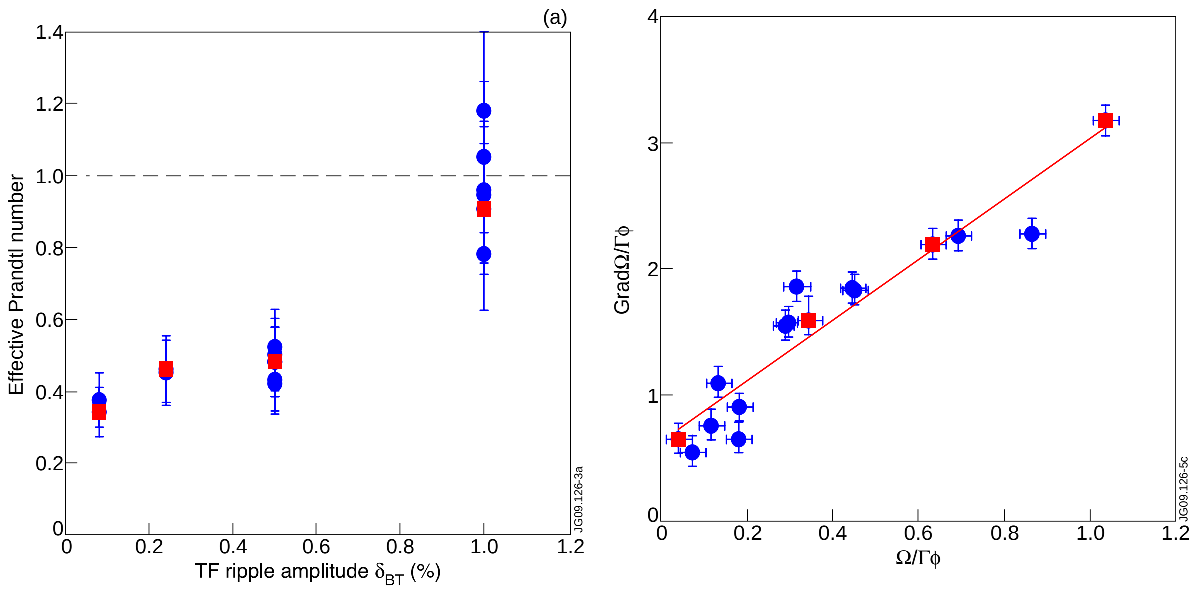

Figure 2a: (left) Effective Prandtl number for various discharges as a function of TF ripple. **2b:** (right) The normalised momentum density gradient versus the normalised momentum for the same discharges. The four discharges shown in figure 1 are indicated by the red squares.

This gives an estimate of the average pinch velocity and momentum diffusivity for this set of discharges. An important parameter is the average normalised pinch velocity, RV_p/χ_ϕ~6.6, where R is the major radius, which can be compared to the theoretical predictions [3]. The average momentum diffusivity was χ_ϕ=1.5±0.2(m^2/s). The latter is close to the average ion heat diffusivity of χ_i^{eff}~ 1.3(m^2/s) for these the discharges. Hence the diffusive transport of momentum was found to be approximately the same as the ion heat diffusivity.

3. Database analysis

The JET rotation database contains entries from various operational scenarios, such as type I and III ELMy H-modes or plasmas with internal transport barriers (ITBs) for which the average rotation and momentum source and transport properties are determined in steady-state phases of the discharge [1]. All the entries have a standard TF ripple (δ_{BT}=0.08%) and generally an effective Prandtl numbers considerably less than unity. If one considers the observations in the TF ripple experiments and assume the presence of an inward momentum pinch and that $\chi_\phi \equiv \chi_i$, one can estimate the magnitude of such a pinch by rewriting equation 1 as :

$$\frac{V_p}{\chi_i} \approx (1 - P_r^{eff})\frac{\nabla\Omega}{\Omega} \qquad (3)$$

Using this equation the normalised momentum pinch, RV_p/χ_ϕ, was calculated for all database entries, averaged over ρ=0.3-0.7, as shown in figure 3. The plot gives an idea of the levels of the average momentum pinch in JET plasmas which are plotted as a function of the inverse density gradient length R/L_n. The Higher values are found in discharges with more peaked density profiles (i.e. a larger R/L_n). The magnitude and scaling is consistent with the simplified fluid description of the Coriolis momentum pinch theory that gives: RV_p/χ=4+(R/L_n) [3]. The normalised momentum density gradient (∇Ω/Ω) used in equation 6 was found to be predominantly determined by the gradient in the rotation profile, and the density gradient played only a minor role. The values found for the TF ripple experiments (as indicated by the black start) match nicely within the other H-mode entries in the database.

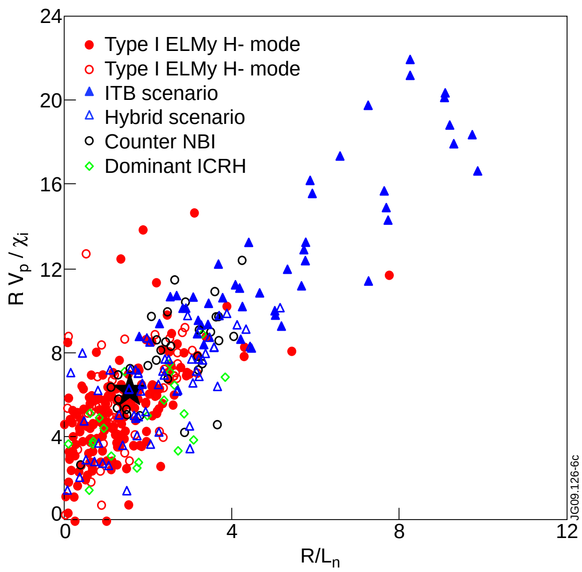

Figure 3: The normalised momentum pinch from the rotation database estimated using eq. (3) under the assumption the ion and momentum diffusivities are equal. The black star shows the value of normalised pinch derived from the analysis of the TF ripple experiments shown in figure 2b.

4. Conclusions

Although TF ripple is unlikely to be able to affect the core momentum viscosity (levels at (ρ<0.6 are δ_{BT}<0.001%), indirectly the lowering of the momentum in the outer part of the plasma has a strong impact on the core gradient as less momentum can be pinched inward. These experiments showed directly the importance of the momentum pinch standard H-mode JET discharges. Values of RV_p/χ<=6.6 were found, which are in agreement with earlier experiments and theoretical predictions [2,3].

Under the assumption that the heat and momentum diffusivities are equal in the core, an estimate of the levels of the momentum pinch in all discharges in the JET rotation database was made. For H-mode discharge these ranged from 0.3(m/s)<V_p<17(m/s), with a normalised momentum pinch of 2<RV_p/χ<10. The magnitude of the (normalised) momentum pinch was found to scale with density profile gradient length as expected from theory [3]. To conclude this analysis shows that in order to make an accurate prediction of the core rotation, detailed knowledge of the processes that determine the edge rotation is essential. Beside TF ripple or other external magnetic perturbations or even MHD instabilities, these may also include charge exchange friction with neutrals [9].

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