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Highly spatially resolved measurements of JET edge toroidal rotation in Type-I ELMy H-mode plasmas

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1. Introduction

Type-I ELMy H-mode operation have been pointed out as a reference operational scenario for ITER (Q=10) [1]. However, the heat and particle flux produced by Type-I ELMs would lead to a rapid erosion of the divertor plates. In this way, several approaches have been made to control Type-I ELMs, such as in DIII-D [2], in TCV [3] and in ASDEX-Upgrade [4]. Reports from JT-60U [5] have shown that neutral beam injection (NBI) in counter-current direction alters the toroidal velocity (v_φ) decreasing the frequency of Edge Localized Modes (ELMs). Turbulence is thought to be suppressed by **E**x**B** shear for which rotation is a key parameter. As a result, plasma rotation may have a direct effect on the overall plasma performance. Therefore further understanding of ELM behavior and the relationship with ripple and toroidal velocity is relevant for ITER.

Due to the finite number of toroidal field (TF) coils the magnetic field varies toroidally. The TF ripple amplitude (δ) is defined as the variation of the magnetic field, $\delta = (B_{max} - B_{min}) / (B_{max} + B_{min})$. The values shown in this paper are the maximum values at the plasma separatrix. For standard JET operation at midplane $\delta = 0.08\%$, while for ITER it will be of $\delta = 0.5\%$ with the inclusion in the design of Ferritic Insets (FI) compensation. JET tokamak has 32 TF coils, which can be fed with equal current or powered independently with different current in the odd and even-numbered coils, allowing to vary TF ripple amplitude up to $\delta \sim 3\%$. The TF ripple breaks the axisymmetry of the magnetic field, enhancing particles losses of fast and thermal ions [6,7] and affects the toroidal rotation velocity (v_φ).

In this paper the effect of the TF ripple on localized measurements of edge plasma toroidal rotation, close to the top of the ion temperature pedestal (T_i^{ped}), and its influence on ELM frequency is examined on JET Type-I ELMy H-mode plasmas.

2. Experimental results

The pulses used in this paper were performed at JET, in 2007 and 2009, in dedicated experimental campaigns for ripple studies. The following analysis has been performed for several Type-I ELMy H-mode plasmas with varying amounts of TF ripple (from the standard JET ripple δ=0.08% up to a maximum of 1%) and edge plasma densities. The set of pulses was carried with a plasma current from 2.6 MA down to 2.4MA, while the strength of the

* See the Appendix of F. Romanelli et al., Fusion Energy Conference 2008 (Proc. 22nd Int. FEC Geneva, 2008) IAEA, (2008)

toroidal magnetic field ranged from 2.2 T to 2.4 T. In all cases, additional heating was provided by co-current NBI input power ranging from 8.6 to 15.9 MW, and for some pulses Ion Cyclotron Resonant frequency Heating (IRCH) was applied between 0.7 and 1.5 MW. Detailed measurements of the edge plasma toroidal rotation velocity (v_φ) and ion temperature (T_i) have been carried out using the edge Charge eXchange Recombination Spectroscopy (CXRS) diagnostic system at JET, with a temporal resolution of 50 ms and a spatial resolution up to 2 cm [8]. The measured quantities are those of the fully ionized carbon impurities at wavelength λ = 529.1 nm. It is assumed in the paper that the deuterium ions have the same velocity and temperature.

Figure 1 shows time traces of plasma current a-b), magnetic field c-d), volume averaged electron density e-f), diamagnetic energy g-h), D_α emission on the outer divertor i-j) and additional heating power k-l) for pulses 77108 (δ=0.08%) and 77110 (δ=0.75%).

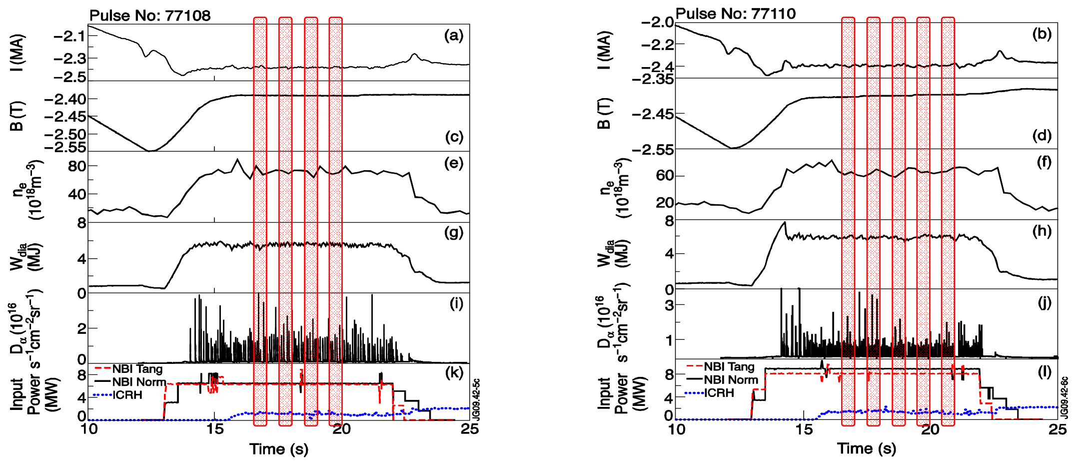

Figure 1: *Time traces of plasma current a)-b), magnetic field c)-d), volume averaged electron density e)-f), diamagnetic energy g)-h),outer divertor D_α i)-j) and additional heating power k) -l) for pulses 77108 and 77110.*

For each of the analyzed pulse several time windows of 0.5s were selected, represented by the red boxes in figure 1. During each time window the ELM frequency (f_{ELM}) was determined, using the D_α signal of the outer divertor. Toroidal velocity at the top of the pedestal (v_φ^{ped}) has been averaged over the selected time windows. The ion temperature profiles (figure 2a), given by the edge CXRS, were used to determine the T_i^{ped} location, allowing to retrieve, at the same radial position, v_φ^{ped} from the toroidal velocity profiles given by the edge CXRS diagnostic (figure 2b).

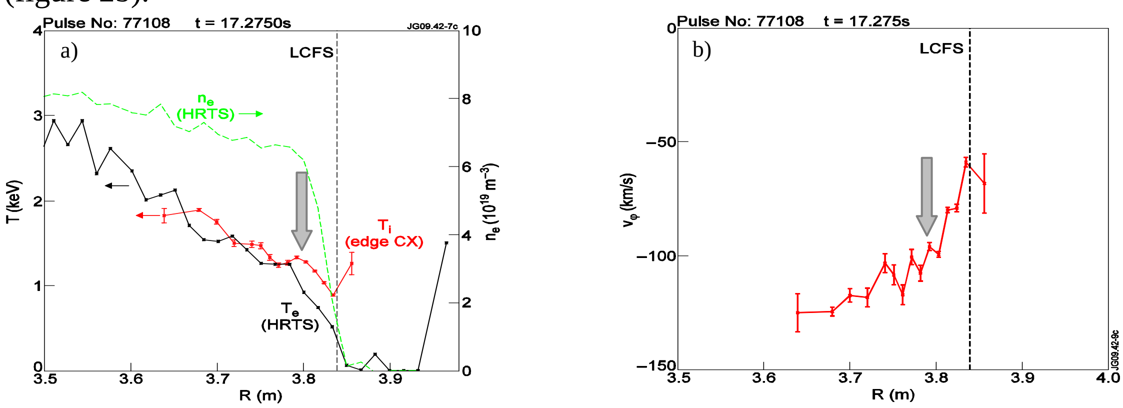

Figure 2: *Profile of ion temperature (—) given by edge CXRS, electron temperature (—) and density (—) given by HRTS (a) and toroidal velocity profile given by edge CXRS (b) for JET pulse no 77108 at t= 17.275s.*

Figure 3 shows the f_{ELM} plotted against $\bar{v}_\varphi^{ped}$. Negative values of toroidal rotation velocity are in co-current direction. The values range from -100 to +50 km/s. Counter-current rotation at the edge of the plasma is observed for higher ripple values, namely δ=1%, due to thermal and fast ion losses. As shown in figure 3a), a trend is visible between f_{ELM} and $\bar{v}_\varphi^{ped}$ for pulses with similar edge density and low collisionality regime (ν^* ~6 10^{-2}). The f_{ELM} seems to increase as the $\bar{v}_\varphi^{ped}$ decrease and reaches values close to 0km/s for δ=0.75%. For a higher value of TF ripple (δ=1%) $\bar{v}_\varphi^{ped}$ is in counter-current direction and f_{ELM} decreases as the toroidal velocity increase.

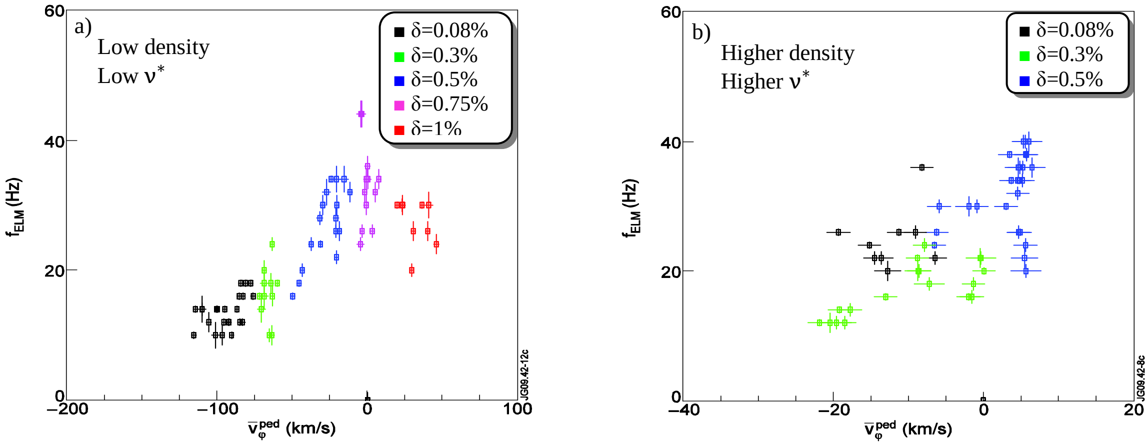

Figure 3: *Plots of ELM frequency versus toroidal velocity at the top of the pedestal region for JET pulses with similar edge density a) and for pulses with higher values of edge density b).*

Figure 3b) show the results for pulses with higher edge density and collisionality (ν^* ~0.5). In this set of pulses $\bar{v}_\varphi^{ped}$ ranges from -20 to +8km/s. A similar relationship between the f_{ELM} and $\bar{v}_\varphi^{ped}$ has been found, f_{ELM} increases with decreasing $\bar{v}_\varphi^{ped}$, however the values of toroidal rotation velocity are considerably lower than for the low density cases.

The effect of the density on the edge rotation has been investigated further. As an example two pulses, 69837 (n_e^{ped}~3.6x10^{19} m^{-3}) and 69858 (n_e^{ped}~6.1x10^{19} m^{-3}) with $\bar{v}_\varphi^{ped}$ of -100 and -9 km/s respectively are compared. Both pulses have δ=0.08% and are represented in black dots in figure 3.

Figure 4a) shows the angular momentum density profile (L_φ) for both pulses.

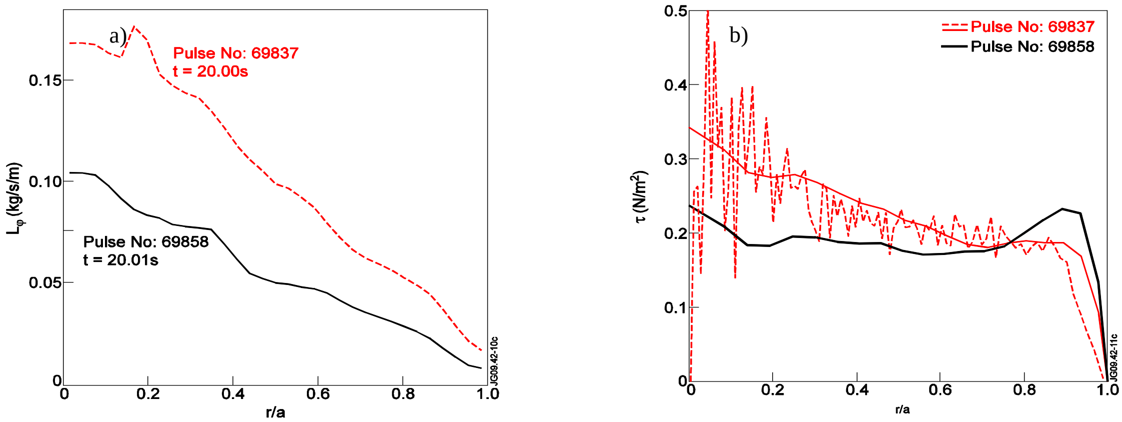

Figure 4: *(a) Angular momentum density profiles for pulse 69858 (▬) and 69837 (▬). (b) torque profile calculated by PENCIL, for pulse 69858 (▬) and 69837 (▬), and calculated by ASCOT for the latter (- - -).*

It can be seen that L_φ is lower over the whole profile for the high density pulse, which implies that v_φ for pulse 69858 must be considerably lower than for pulse 69837, which is consistent with the obtain values for $\bar{v}_\varphi^{ped}$, which are of -100 and -9 km/s respectively.

In both pulses, the same PINIs configuration was used. The difference in total torque applied to the plasma is less than 1%. The torque profiles calculated by the neutral beam deposition code PENCIL are compared in figure 4b). For the pulse 69837 the torque profile given by the orbit following Monte Carlo code ASCOT [9] is also shown and agrees with Pencil calculation. A higher edge density leads to a higher beam deposition at the edge and lower deposition in the core, as it can be seen in figure 4b). The slightly higher torque at the edge of the plasma for the higher density case (69858) might enhance slightly the edge rotation, but the large difference in mass results in lower $\bar{v}_\varphi^{ped}$ values.

3. Conclusions and Discussion

The JET ripple experiments clearly show that increasing TF ripple lead to counter rotation at the plasma edge due to fast and thermal ion losses. It has been found that the toroidal velocity at the pedestal location and the ELM frequency are related. As the toroidal velocity approaches values close to zero, for TF ripple of δ = 0.75%, the ELM frequency increase. However, for δ = 1% the toroidal velocity at the top of the pedestal become counter-current and the ELM frequency decreases. The plasma density has a large influence on the range of rotation values that can be reached with changing TF ripple.

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