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** See annex of F. Romanelli et al, "Overview of JET Results", (Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).*

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INTRODUCTION

In present day tokamak experiments, rotation is often driven by the torques of Neutral Beam Injection (NBI), while in an alpha-heated reactor the momentum input is expected to be small [1]. In reactors with high NBI power, the torque is still expected to be small due to the high injection energy needed for the beam to penetrate deep into the plasma, which reduces the torque per MW of injected power. Predicted toroidal rotation velocities for ITER with NBI power of 50MW, around 70km/s in the core and 8kms/s at the edge [2], are lower than currently observed at JET for the same Prandtl number and wit NBI powers less than 20MW [3]. Thus, there has been a growing interest in the intrinsic rotation of the plasma, which is observed to occur in the absence of momentum sources such as NBI. The extrapolation from intrinsic plasma rotation data observed in several machines has suggested that a substantial rotation in the co-current direction, i. e. in the direction parallel to the plasma current, will occur in ITER [4]. In order to contribute to this multimachine intrinsic rotation scaling, referred to as the "Rice scaling", the angular velocity of the plasma column was measured at JET in Ion Cyclotron Resonance Frequency (ICRF) heated H-mode plasmas.

Intrinsic rotation in H-modes with pure ICRF heating (except for short NBI pulses for diagnostic purposes) were studied with JET in its standard low toroidal magnetic ripple configuration, and during a special experimental campaign when the ripple was increased [5]. The ICRF experiments were performed with hydrogen minority heating in deuterium plasmas using a dipole antenna phasing. Toroidal angular frequency profiles reported here were obtained from charge exchange recombination spectroscopy of C^{+6} [6] during short NBI pulses (P_{NBI}~1.5MW). JET has 32 toroidal field coils and, therefore, a very low ripple level. However, ripple can be increased by reducing the current carried in every second coil. The ripple is largest in the outboard of the plasma where the plasma is close to the toroidal magnetic field coils. The ripple values quoted in this paper are taken at R = 3.80m, Z = 0 m, which is close to the maximum value. In standard operation with 32 coils the ripple amplitude is $\delta = 0.08\%$. This was increased to $\delta = 1.5\%$.

1. OBSERVATIONS

With its usual ripple value, i. e. $\delta = 0.08\%$, JET plasmas with ICRF heating [7-9] are observed to rotate with small toroidal angular frequencies, typically less than $\omega_\phi \leq 10$krad/s. For this low ripple level the edge is clearly always co- rotating, while the core of ICRF heated plasmas is either counter- or co-rotating depending on plasma current [9], confinement regime [7] and heating details [8]. An extensive investigation of intrinsic rotation in ICRF heated L-mode plasmas was reported in [9]. A smaller database of H-mode plasmas includes a few measurements done in 1994-95 with the newly installed MarkI divertor [9] and more recent data obtained at different ripple levels with bN values up to 1.3. The early 1994-95 measurements were done with an X-ray crystal spectrometer that observed the spectrum near the resonance line of the helium-like nickel (Ni^{+26}) of the plasma [7]. Core co-rotation of 20krad/s were obtained [7]. These were included in the intrinsic rotation scaling of [4]. Those high rotation values have not been observed with subsequent divertor models (the reason is not understood). Although in the same plasma pulse there is an increase in co-current rotation from L to H mode, when several pulses are compared there are no significant differences in the range of measured angular frequencies in L-mode and Hmode. We found no correlation between toroidal rotation and ICRF power. In addition there is no correlation with bN values. No correlation has been found between sawtooth period and core rotation [9], however increasing ICRF power as required for H-modes, leads to the observation of MHD modes such as fishbones, and core tae modes which reduce core corotation. Figure 1 shows an H-mode with type I-ELMs with bN=1.3. The angular frequency profiles are hollow, with core and edge rotation values similar to observations in L-mode plasmas as reported in [9].

Since the toroidal field ripple can induce high heat fluxes of fast ICRF accelerated ions to plasma facing components [10] ripple experiments were restricted to modest ICRF powers, less than 4MW, and to cyclotron resonances near the plasma centre, oron the high field side of the plasma [5]. As the TF ripple increased, both the edge and the core of the plasma counter rotated. In experiments with plasma current, $I_p = 1.5$MA, H-mode plasmas with the whole plasma column counter rotating were obtained. Counter-current rotation was found to depend on ripple and, on fast ion losses associated to MHD modes (fig.2), as well as on local plasma conditions and heating details. Core counter-rotation was observed to be larger in phases with type III ELMS as shown in fig.3b. It is not clear if this is a pedestal or a density effect.

CONCLUSIONS

With the standard low ripple value of 0.08%, JET plasmas with large ICRF heating power and normalized b≈1.3, have a very small co-current rotation, in clear contradiction with the Rice scaling law [4] that would extrapolate to roughly 10 times higher Alfven-Mach number for the same b value (Figure 3). JET experiments showed that ripple has a significant effect on the plasma rotation even in the absence of external momentum sources. As the ripple in the toroidal magnetic field increased, both the edge and the core of JET plasmas counter rotated. Core counter-rotation was observed to be larger in phases with type III ELMs, but even type I-ELM plasmas with normalized $\beta \approx 1$ were counterrotating. At ITER-relevant ripple values of 0.5% [11], JET H-mode plasmas with ICRF heating are hardly rotating, while at 1%, H-modes were observed to counter-rotate. These results do not fit the multi-machine intrinsic rotation scaling of [4]. JET results suggest that ripple will affect rotation in ITER and, it should be taken into account in extrapolation from present data.

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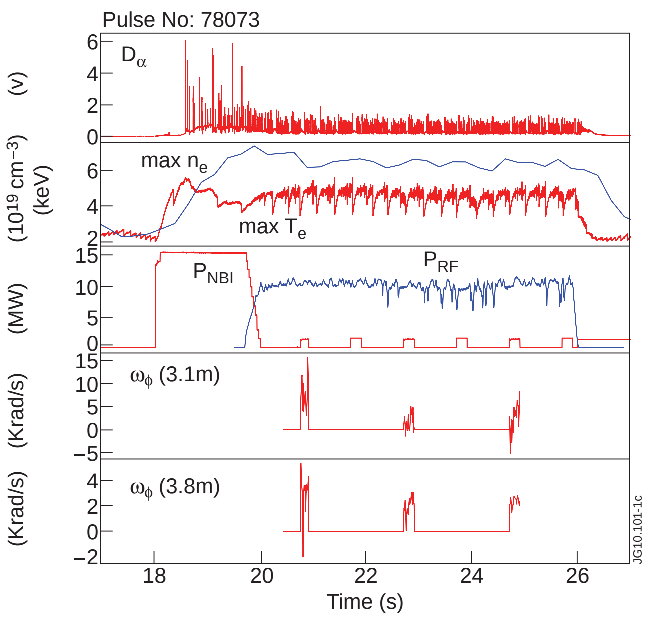

Figure 1: H-mode with ICRF heating (except for NBI blips) with P_{ICRF} ~ 10MW, I_p = 2.5MA, B_T = 2.6T , β_N ~ 1.3.The first NBI blip is too close to a large NBI pre-heating phase so it should be ignored. ICRF rotation is measured in the first 10ms of blips n.2 and n.3.

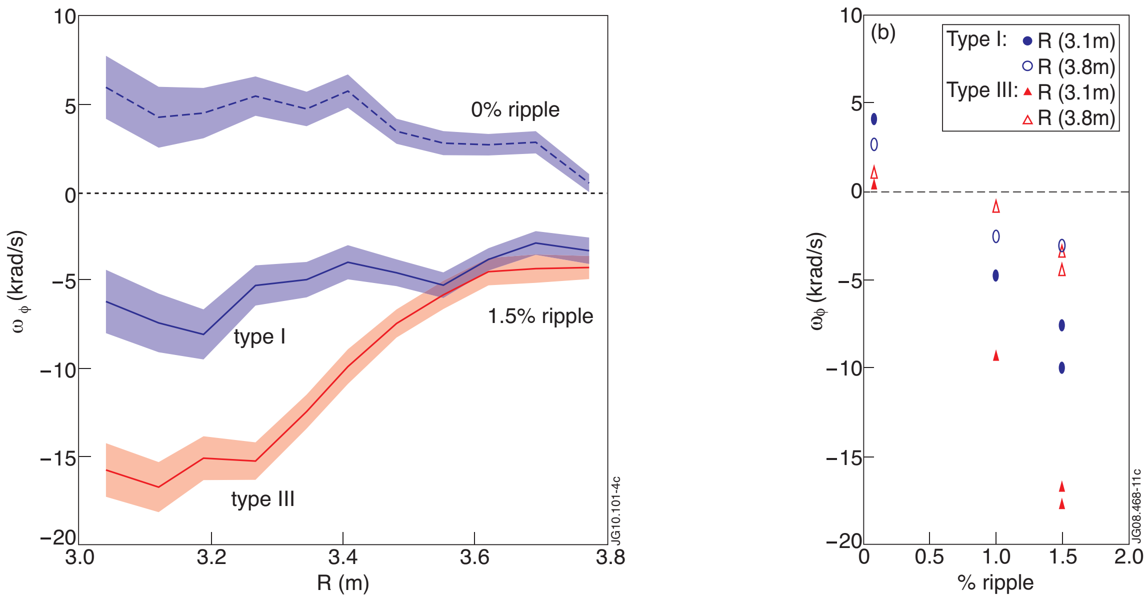

Figure 2: (a) - Toroidal rotation angular frequency profiles for ICRF heated H-mode plasmas with I_p=1.5MA, $<B_T>$=2.2T, P_{ICRF}~3MW for two ripple levels. Top: Pulse No: 74688 with δ = 0.08% and P_{ICRF}=3.1MW; bottom: Pulse No: 74686 δ = 1.5% and P_{ICRF}= 2.9MW. The plasma centre is at R_0=3.02m, the ICRF resonance is slightly off-axis on the high-field side at R_{res}= 2.71m . (b)- Toroidal rotation angular frequency as a function of ripple for ICRF pulses with 1.5MA, for the centre (3.1 m, solid symbols) and the edge (R=3.8 m, open symbols). Circles are measurements during type I ELM phases, while triangles are during type III-ELM phases

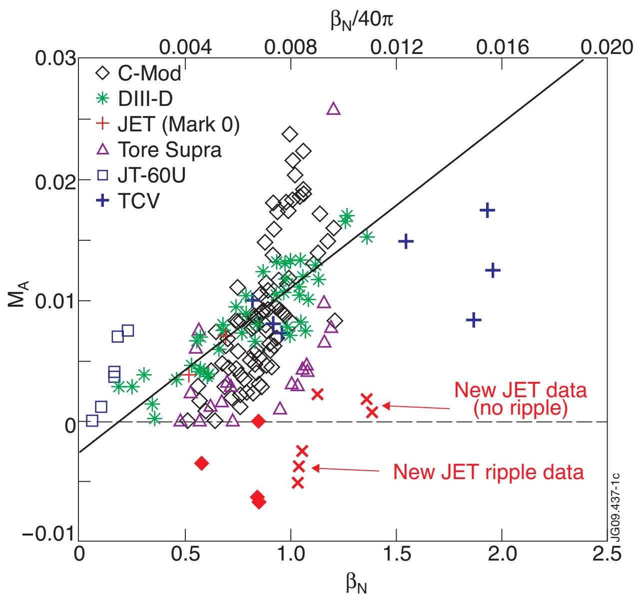

Figure 3:Plot of Alfven Mach number versus β_N taken from Rice et al [4] with new JET H-mode data.