

Toroidal rotation in JET ICRF heated H-mode plasmas

M.F. F. Nave¹, T. Johnson², L.-G. Eriksson³, C. Giroud⁴, T. Hellsten², M.-L. Mayoral⁴, J. Ongena⁵, G. Sabeine⁶, R. Sartori⁶, F. Rimini⁸, T. Tala⁷, M. Tsalas⁸, P. de Vries⁹, JET-EFDA Contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

¹*Associação EURATOM/IST, Instituto de Plasmas e Fusão Nuclear-Laboratório Associado, Instituto Superior Técnico, P1049-001, Lisbon, Portugal*

²*Association EURATOM - VR, Fusion Plasma Physics, EES, KTH, Stockholm, Sweden*

³*European Commission, Research Directorate General, B-1049 Brussels, Belgium*

⁴*CCFE/Euratom Fusion Association, Abingdon, U. K.*

⁵*ERM-KMS, Association EURATOM-Belgian State, Brussels, Belgium*

⁶*Fusion For Energy Joint Undertaking, Barcelona, Spain*

⁷*VTT Association Euratom-Tekes, VTT, Finland*

⁸*EFDA-JET CSU-Culham, Abingdon, U.K.*

⁹*FOM Institute for Plasma Physics, Rijnhuizen, Association EURATOM-FOM, Nieuwegein, the Netherlands*

**See the Appendix of F. Romanelli et al., Proc. 22nd Fusion Energy Conf. Geneva, Switzerland, 2008*

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 50 MW, around 70 km/s in the core and 8 kms/s at the edge [2], are lower than currently observed at JET for the same Prandtl number and with NBI powers less than 20 MW [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 multi-machine 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 ($P_{\text{NBI}} \sim 1.5$ MW). 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 $R=3.80$ m, $Z=0$ 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 $\delta=1.5\%$.

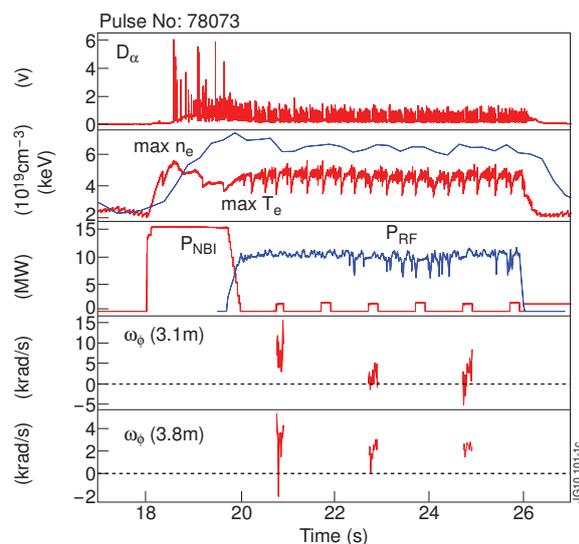


Fig. 1 - H-mode with ICRF heating (except for NBI blips) with $P_{\text{ICRF}} \sim 10$ MW, $I_p = 2.5$ MA, $B_T = 2.6$ T, $\beta_N \sim 1.3$. The first NBI blip is too close to a large NBI pre-heating phase so it should be ignored. ICRF rotation is measured in the first 10 ms of blips n. 2 and n.3. The angular frequency profile measured at the beginning of blip n.2 is shown in figure 2.

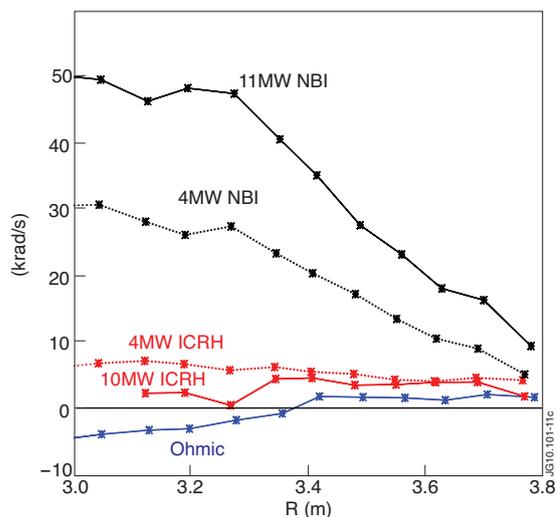


Fig. 2 - Toroidal angular frequencies measured with charge exchange diagnostic for two ICRF heated plasmas (an H-mode with $P_{\text{ICRF}} = 10$ MW and a L-mode with $P_{\text{ICRF}} = 4$ MW) and NBI and Ohmic heated pulses for comparison.

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 in ELM-free plasmas done in 1994-95 with the newly installed MarkI divertor [7] and more recent data obtained in ELMy discharges at different ripple levels with β_N 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 20 krad/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 H-mode. We found no correlation between toroidal rotation and ICRF power. In addition there is no correlation with β_N 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 tearing modes which reduce core co-rotation.. Figure 1 shows an H-mode with type I-ELMs with $\beta_N=1.3$. The angular frequency profiles are hollow, with core and edge rotation values similar to observations in L-mode plasmas as reported in [9] and illustrated in figure 2.

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 4 MW, and to cyclotron resonances near the plasma centre, or on 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 observed (figure 3). Core counter-rotation was observed to be larger in phases with type III ELMS as shown in figures 3 and 4. It is not clear if this is a pedestal or a density effect.

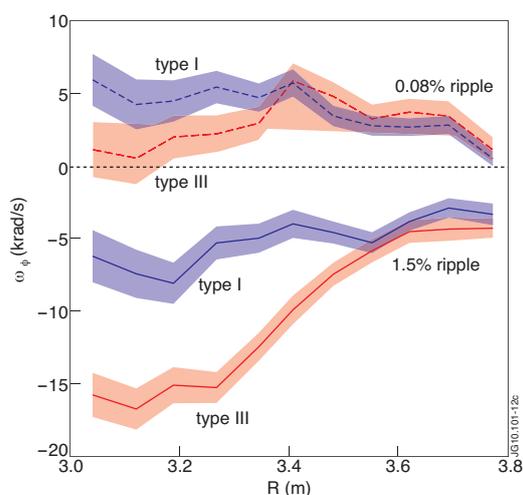


Fig. 3 – Toroidal rotation angular frequency profiles for ICRF heated H-mode plasmas with $I_p=1.5$ MA, $\langle B_T \rangle=2.2$ T, $P_{ICRF} \sim 3$ MW for two ripple levels. Top: pulse # 74688 with $\delta=0.08\%$ and $P_{ICRF}=3.1$ MW; bottom: pulse # 74686 $\delta=1.5\%$ and $P_{ICRF}=2.9$ MW. The plasma centre is at $R_0=3.02$ m, the ICRF resonance is slightly off-axis on the high-field side at $R_{res}=2.71$ m.

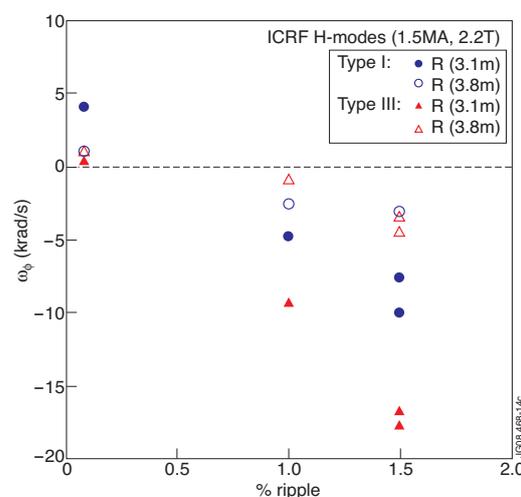


Figure 4 - Toroidal rotation angular frequency as a function of ripple for ICRF pulses with 1.5 MA, for the centre (3.1 m, solid symbols) and the edge ($R=3.8$ m, open symbols). Circles are measurements during type I ELM phases, while triangles are during type III-ELM phases

Conclusions

With the standard low ripple value of 0.08%, JET plasmas with large ICRF heating power and normalized $\beta \approx 1.3$, have a very small co-current rotation, in clear contradiction with the Rice scaling law [4] that would extrapolate to roughly 10 times

higher Alfvén-Mach number for the same β value. 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 counter-rotating. 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.

Acknowledgments This work was supported by EURATOM and carried out within the frameworks of the European Fusion Development Agreement. It received financial support from Fundação para a Ciência e Tecnologia (FCT), Portugal. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

- [1] M.N.Rosenbluth and F.L.Hinton, Nuclear Fusion **36**, 55 (1996)
- [2] R. Budny, Nuc Fusion 49, 085008 (12009)
- [3] P.C. de Vries, et al. Nucl. Fusion **48** (2008) 065006
- [4] J.E.Rice et al, Nuclear Fusion **47**, 1618 (2007)
- [5] M.F.F.Nave et al., submitted to PRL (2010)
- [6] C. Giroud et al, Review of Scientific Instruments 79, 10F525 (2008)
- [7] L-G Eriksson, E. Righi and K-D Zastrow, Plasma Phys. Control Fus. **39**, 27 (1997)
- [8] J.-M. Noterdaeme et al. NF **43**, 274 (2003)
- [9] L.-G. Eriksson et al., Plasma Phys. Control. Fusion **51** (2009) 044008
- [10] T. Johnson et al., 10th IAEA TM Energetic Particles in Mag. Conf. Systems, Kloster Seeon, Germany (2007)
- [11] G. Sabeine, 34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.31F, O-4.001 (2007)