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The influence of magnetic field ripple on JET Intrinsic Rotation

M.F. F. Nave[1], T. Johnson[2], L.-G. Eriksson[3], C. Giroud[4], K. Crombé[5], M.-L. Mayoral[4], J. Ongena[6], A. Salmi[7], T. Tala[7] , M. Tsalas[8] and JET-EFDA Contributors*
JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]*Associação EURATOM/IST, Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal*
[2]*Euratom-VR Association, EES, KTH, Stockholm, Sweden*
[3]*Association EURATOM-CEA, CEA/DSM/DRFC, CEA-Cadarache,F-13108 St. Paul lez Durance, France*
[4]*UKAEA/Euratom Fusion Association, Abingdon, U. K.*
[5]*Department of Applied Physics, Ghent University, Gent, Belgium*
[6]*ERM-KMS, Association EURATOM-Belgian State, Brussels.*
[7]*Association Euratom-Tekes, VTT, P.O. Box 1000, FI-02044 VTT, Finland*
[8] *EFDA-JET CSU-Culham, Abingdon, U.K.*
**See the Appendix of F. Romanelli et al., Proc. 22nd Fusion Energy Conf., Geneva, Switzerland (2008)*

Introduction - In tokamaks, a finite number of magnetic field coils creates a variation of the toroidal magnetic field known as "ripple". In the presence of ripple the canonical angular momentum is not conserved and fast ions as well as thermal ions can exchange momentum with the toroidal field coils. It is well known that ripple affects rotation in tokamak plasmas with neutral bean injection (NBI) heating [1, 2]. In JT-60 experiments with perpendicular NBI, the observed edge counter-rotation (i.e. rotation anti-parallel to the plasma current) has been explained by a torque induced by ripple losses of fast-ions [2]. Experiments with NBI at JET have shown that ripple reduced rotation in plasmas with injected momentum parallel to the plasma current and, in some cases, counter-current rotation was observed at the edge [1]. Fast-ion losses were not enough to completely explain the JET observations [1], leaving open the question of the role of ripple on thermal ions [3]. In order to separate ripple induced fast ion effects from thermal ion effects, intrinsic plasma rotation (i.e. rotation without momentum input) was measured in JET Ohmic and Ion-Cyclotron Radio Frequency (ICRF) heated plasmas with different ripple levels. Extrapolation to ITER from intrinsic rotation measurements from present day tokamaks [4] is quite uncertain since each machine has a different ripple level. As ITER will have 18 toroidal magnetic field coils, a ripple of 0.5% at the edge [5], is expected to affect the magnetic confinement of plasma ions as well as the plasma rotation.

Since JET has 32 toroidal field (TF) coils, the usual ripple levels are low, however ripple can be increased by reducing the current carried in every second coil. The TF ripple amplitude $\delta(R,Z)=[B_{max}(R,Z)-B_{min}(R,Z)]/[Bmax(R,Z)+Bmin(R,Z)]$ depends strongly (approximately exponentially) on the ratio between the distance from (R,Z) to the TF coils-system and the distance between two coils. B_{max} and B_{min} are the maximum and minimum magnetic field along the circle for which the major radius R and the

vertical coordinate *Z* are constant. The highest ripple inside the plasma is found at the separatrix near the outboard equatorial plane. 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 this amplitude is δ=0.08%. Ripple values were enhanced up to 1.5%.

II- JET experiments with small ripple- Without ripple enhancement i.e. with δ=0.08%, JET plasmas with low momentum input, namely with ICRF, Lower Hybrid and Ohmic heating [6, 7] are observed to rotate with small toroidal angular frequencies, typically $\omega_\phi \leq 10\text{krad/s}$. Toroidal angular frequency rotation profiles were measured from charge exchange recombination spectroscopy (CXRS) of C^{+6} [8] during short NBI pulses of 1.4 MW. Since NBI at JET provides a co-current toroidal momentum source, only measurements taken within the first 20 ms were used. In the convention used here, positive means co-current rotation. For this low ripple level the edge is clearly always co- rotating independent of heating scenario. However the core of JET plasmas without NBI has been found to be either co- or counter-current rotating. The core of Ohmic plasmas is found to be counter-rotating [7], while the core of ICRF heated plasmas is either counter- or co-rotating depending on plasma current, I_p, and heating details [6].

III- JET experiments with enhanced ripple - The intrinsic rotation ripple experiments were performed in deuterium for two I_p values: 1.5 and 2.1 MA, with an average toroidal field at the centre of $\langle B_T \rangle$=2.2 T. For the study with ICRF heating, hydrogen minority heating in deuterium plasmas was used with the antennas in dipole phasing, with ICRF powers up to 4 MW. Ripple was found to affect the rotation of both Ohmic and ICRF heated plasmas. In both cases ripple drives counter rotation.

Ohmic plasmas - The ripple effect on the rotation of Ohmic plasmas is illustrated in figures 1-2. The typical central ω_ϕ values, that for δ=0.08% were negative, that is counter-current rotating, became more negative as ripple increased, whilst the edge co-rotation decreased and for ripple values $\geq$ 1% edge counter-current rotation is observed. Charge exchange rotation profiles indicated that the edge and core effects are of the same order. Charge exchange measurements in the plasma core are consistent with measurements of the frequency and direction of propagation of sawtooth pre- and post-cursor oscillations (fig. 2). There is no significant difference between 1.5 and 2.1 MA.

ICRF heated plasmas - Figures 3- 4 illustrate the observed effect of TF ripple on ICRF heated plasmas. As the TF ripple increases both the edge and the core of the plasma counter rotate. The effect is larger in the plasma core. Experimentally, counter-current rotation was found to depend on ripple, fast ion losses associated to MHD modes, as well as on local plasma conditions and heating details. Increased core

counter-rotation was when core-tae modes were present and fast-ion losses observed. For the lower plasma current, I_p=1.5 MA, L-mode and H-mode phases were obtained. Core counter-rotation was larger in the L-mode phases (fig. 4). It is not clear if this is a pedestal or a density effect. For a given TF ripple value, counter-rotation in the core of L-mode plasmas is larger when compared with plasmas with I_p=2.1 MA, confirming a result previously obtained with zero ripple where co-rotation increased with plasma current [6]. The largest edge and core counter rotation was observed when the ICRF resonance position, $R_{res,}$ was on the low-field side. With R_{res}=3.13 m, the magnetic axis R_0 =2.92 m and, δ=1.5%, the central $\omega_\phi \sim$ -20 krad/s. For a fixed resonance position overall counter rotation increased with ICRF power.

IV- Interpretation and Conclusion - Observation of increased counter-rotation in Ohmic plasmas indicates a strong torque due to non-ambipolar transport of thermal ions. In ICRH plasmas the rotation change in the plasma core is larger indicating that the torque source in this case would be less edge localised and that ripple induced fast-ion as well as thermal ion effects may be involved. Modeling is being performed with the Monte Carlo codes ASCOT [9] and SELFO [10]. Preliminary results for plasmas with ICRF show that torque driven by ripple effects on the fast ions, although still smaller when compared with NBI, are 5 times larger with δ=1.5% than without ripple. Modeling for different ICRF resonance positions, confirm that the distance in major radius from resonance to ripple region is important. The torque from the diffusive transport, roughly proportional to the density gradient of fast ions, increases as the resonance on the low-field side is closer to the ripple region. In Ohmic pulses, the toroidal torque driven by non-ambipolar transport of thermal ions is influenced by the radial electric field. For a neo-classical calculation, the torque driven by thermal ions for 1.5% ripple is around 1.2 Nm (equivalent to torque driven by 1-1.5 MW of NBI).

In conclusion, ripple has a significant effect on plasma rotation in the absence of external momentum sources. Ripple was found to affect the rotation of both Ohmic and ICRF heated plasmas. In both cases ripple drives counter rotation. The effect was seen both in the edge and core. JET results suggest that ripple will affect rotation in ITER, and should be taken into account in extrapolation from present data.

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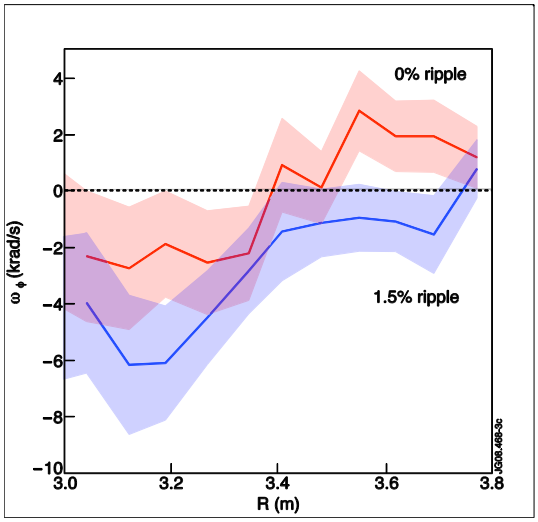

Fig. 1 Toroidal rotation profiles from charge exchange measurements for Ohmic pulses # 74758 with 0% ripple and # 74599 with 1.5% ripple, I_p=2.1 MA and $<B_T>$=2.2 T. Here and in the following figures, the profiles shown are the average over the first 20 ms. Error-bars are indicated by the shaded areas.

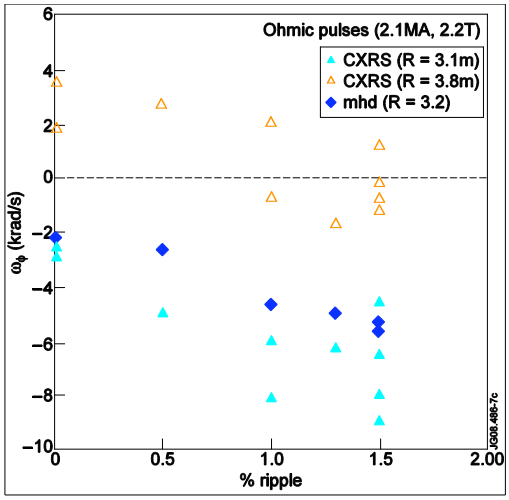

Fig.2 - Toroidal rotation frequencies as a function of ripple for Ohmic pulses with 2.1 MA. Plot shows: the charge exchange toroidal rotation frequency at the centre (R=3.1 m, blue triangles) and the edge (R=3.8 m, red triangles) and the frequency of sawtooth postcursors (solid blue kites). The sawtooth inversion radius and period remained unchanged with ripple.

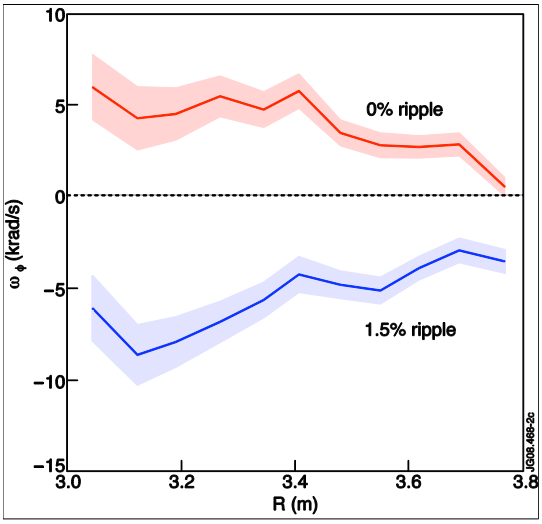

Fig. 3 – Toroidal rotation profiles from charge exchange measurements for ICRF heated pulses with I_p=1.5 MA and $<B_T>$=2.2 T, P_{ICRF}~3 MW for two ripple levels. Top: pulse # 74688 with 0% ripple and P_{ICRF}=3.1 MW; bottom: pulse # 74686 with P_{ICRF}= 2.9MW bottom). R_0=3.02 m, the ICRF resonance is off-axis on the high-field side at Rres= 2.71 m.

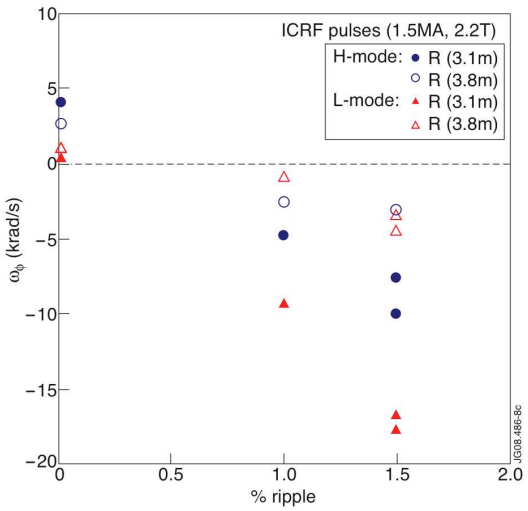

Fig. 4 - Toroidal rotation as a function of ripple for ICRF pulses with 1.5 MA, off-axis Rres=2.71 m, for the centre (3.1 m, solid symbols) and the edge (R=3.8 m, open symbols). Blue circles are measurements in H-mode and red triangles are L-mode.

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