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Toroidal Rotation in Ohmic and RF heated JET Plasmas

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**See the Appendix of of M.L.Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA, (2006)*

I – Introduction - Understanding the origin of rotation in ICRF heated plasmas is important for predictions for burning plasmas sustained by alpha particles, as both are characterised by a large population of fast ions and no external momentum input. Recent experiments performed at JET investigated rotation in Ohmic and purely ICRF heated plasmas. The aim of recent experiments with ICRF heating was to establish under which conditions co and counter rotation arise and to build up a database on how intrinsic rotation in JET scales with the plasma current and ICRF heating details. Determination of the rotation induced with ICRF heating requires taking into account the rotation in Ohmic heated plasmas. Previous studies of rotation with Ohmic heating were in limiter plasmas, here studies in the divertor configuration are reported.

II – Measurement Tools- Plasma rotation was determined from charge exchange recombination spectroscopy, X-ray crystal spectroscopy and the observed frequency of MHD modes. (a) Toroidal angular frequency profiles were obtained from charge exchange recombination spectroscopy (CXRS) of C^{+6} [1] during short NBI pulses (typical duration of 200 ms and P_{NBI}~1MW). In the normal JET configuration, i.e. $\vec{B}_T // \vec{I}_p$ and no toroidal field ripple, NBI provides a toroidal momentum source in the direction of the plasma current (co-current rotation). Thus, for diagnostic purposes with ohmic and ICRF heating, only measurements taken within the first 50 ms have been used. (b) The toroidal angular frequency in the plasma core has also been measured with a high resolution X-ray crystal spectrometer (XCS) that observes the spectrum near the resonance line of the helium-like nickel (Ni^{+26}) [2]. In JET divertor configuration, where the level of impurity is reduced and, for the low frequencies studied here, both CXRS and XCS measurements are at the limit of detection. Special consideration was taken in improving measurement statistics. (c) Further information on plasma rotation at different radial positions was obtained from MHD modes' frequency and mode number analysis.

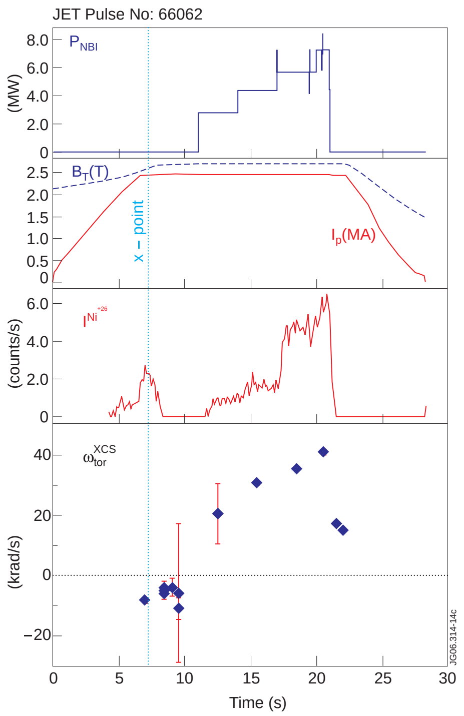

Figure 1- Typical discharge used for XCS calibration (B_T=2.T, I_p=2.5MA, P_{NBI}=2.5-11.3 MW) with a flat top Ohmic phase, after X-point formation (indicated by vertical dotted line) with 2-3 s duration.(a) NBI Power; (b) B_T and I_p, (c) Intensity of Ni^{26+} obtained with an integration time of 30 ms; (d) Core angular frequency time determined from XCS.

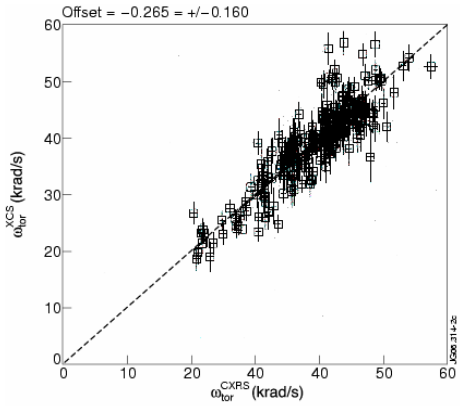

Figure.2 - Comparison of measurements of toroidal angular frequency of C^{+6} and Ni^{+26} at the same radius (Ni^{+26} <R> =3.2-3.8 m.).

III – Ohmic heated plasmas-. Early studies with X-ray crystal spectroscopy indicated that the core of JET Ohmic limiter plasmas rotated counter to the toroidal plasma current [3]. In the present study XCS was used to analyse pre-heating phases in the divertor configuration (fig. 1). The method of spectral and Doppler shift analysis is described in detail in [4]. In the early rotation frequency measurements, the wavelength scale was calibrated by comparison with the observed sawtooth precursor frequencies [1]. In the present analysis, a reference wavelength for the Doppler shift of the Ni^{+26} line was obtained by comparison with the derived CXRS measurements of C^{+6} at different NBI power levels (fig. 2). During the Ohmic divertor phase Ni levels are too low. In order to improve measurement statistics, spectra analysed with an integration time of 30 ms have been added over extended phases lasting up to 2 s under steady state conditions. Fig. 1 shows that the core of Ohmic plasmas in the divertor configuration are counter rotating. In the convention used here, positive frequency means co-current and negative means counter-current rotation. The observation of core counter rotation is consistent with angular frequency profile measurements with charge exchange recombination spectroscopy that show hollow counter rotating profiles (as illustrated in fig. 4). In contrast, the outer half of the plasma is co-rotating.

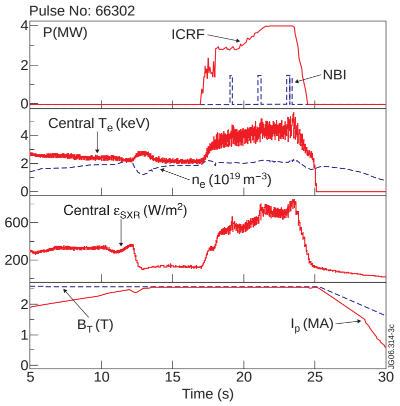

Figure 3 Typical discharge with ICRF off-axis heating and dipole phasing (B_T=2.6T, I_p=2.6T). The rotation profiles obtained during the first NBI blip, t=19 s, are shown in figure 4.

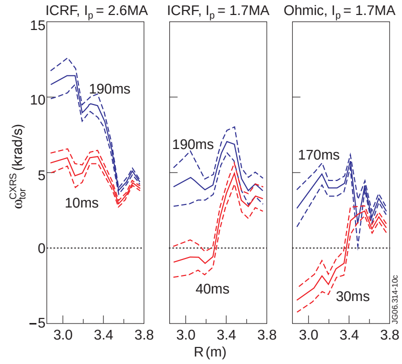

Figure 4 - CXRS Toroidal Angular Frequency Profiles for similar discharges: (a) Ip=2.6MA with ICRH (see fig. 3), (b) Ip=1.7 MA with identical ICRH (c) reference Ohmic plasma with NBI blips but no ICRH. The 1st reliable profile is shown in red and a profile at the end of the blip is shown in blue. The times are from the start of the blip.

IV – ICRF heated Plasmas: ICRF heated plasmas have been previously observed to either co or counter rotate [5,6]. Recent JET experiments studied rotation in L-mode plasmas with B_T=2-2.75 T, I_p=1.2-2.6 MA and ICRF heating (P_{ICRF}=3-6MW, resonance position 40 cm off-axis on the high field side). The object was to establish under which conditions co- and counter-current rotation arises and to establish a database on how rotation in JET scales with various parameters such as the plasma current, position of the cyclotron resonance and the antenna phasing A typical discharge is shown in figure 3. Short NBI pulses were used intermittently for rotation profile measurements with charge exchange recombination spectroscopy. CXRS angular frequency profiles obtained at the beginning of the NBI blips indicate that the core rotation depends on the value of the plasma current (as illustrated in figure 4). At the lowest plasma currents, I_p~1.2-1.7 MA, hollow profiles with the core counter rotating, similar to observations in the Ohmic plasmas were observed. At the high plasma current, I_p~2.6MA, peaked co-rotating profiles, were observed, even though ICRH was applied off-axis. Figure 5 shows the central angular frequency as a function of I_p from a database of 21 discharges. At the higher plasma currents where sawtooth precursors were clearly identified, MHD mode frequencies indicated significant plasma acceleration in the co-current direction as the ICRF power is stepped up (fig. 6). The increase in the observed MHD mode frequency could neither be attributed to an increase in ω^*_i, as T_i remained constant, nor to a radial shift in the mode location. In order to study the possible influence of MHD instabilities on rotation profiles, discharges with and without sawtooth crashes (with q_0>1) were produced. These were either obtained by early X-point formation and RF heating applied before the plasma current was fully penetrated or in a few cases by application of 2 MW of Lower Hybrid Current Drive (LHCD) [7]. The range of central rotation frequency values (-6 krad/s to +10 krad/s) was the same in discharges with or without sawtooth. In addition, no correlation was found between profile shape and sawtooth period. The edge as in the Ohmic cases was co-rotating in all cases, with the edge frequency scaling with $W_{DIA}/\bar{n}_e$, where W_{DIA} is the plasma stored energy and $\bar{n}_e$ is the line integrated density [7].

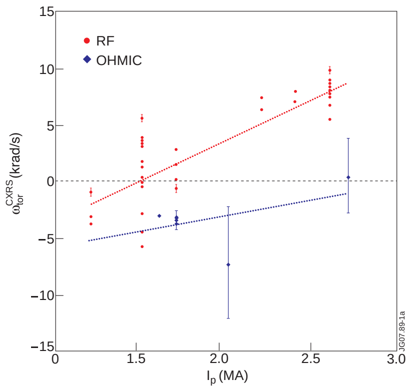

Figure 5 – Central Toroidal Angular Frequency from CXRS measurements vs Ip.

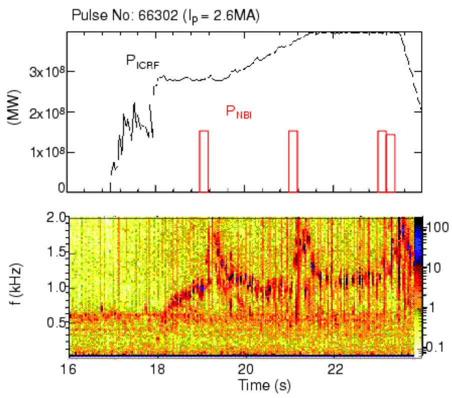

Figure 6 – Spectrogram of magnetic pick up signal showing frequency ofsawtooth precursors that increase with P_{ICRF}.

IV – Summary -: The central region of Ohmic plasmas in the JET divertor configuration are counter rotating with toroidal frequencies up to -8 krad/s. ICRF heated plasmas have been found to either co or counter- rotate with central angular frequencies ranging from -6 krad/s to +10 krad/s. Once the Ohmic rotation is subtracted, one finds in most cases co-current acceleration when ICRF power is applied. In addition, the ICRF induced rotation appears to originate in the plasma core and it was found to be sensitive to the plasma current. The differences in frequency profile shape cannot be attributed to differences in sawtooth instability. The outer part of the plasma is observed to rotate in the co-current direction independently of heating scenario.

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