Spontaneous Rotation in JET plasmas with LHCD

M.F. F. Nave[1], K. Kirov[2], J. Bernardo[1], B. Chouli[3], C. Giroud[2], J. Mailloux[2], J. Ongena[4] and JET-EFDA Contributors*

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

[1]Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, P1049-001, Lisbon, Portugal

[2]CCFE/Euratom Fusion Association, Abingdon, U. K.

[3] CEA-Cadarache, 13108 St.-Paul-lez-Durance, France

[4]ERM-KMS, Association EURATOM-Belgian State, Brussels, Belgium

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I - Introduction - Spontaneous rotation that flows mainly along the magnetic field has been measured on virtually all tokamaks, nevertheless understanding its origin remains a challenge. At JET, with the previous Carbon-wall, toroidal rotation was measured in plasmas with ohmic heating, lower hybrid and with ion cyclotron heating [1, 2]. This paper reports on observations of spontaneous rotation in JET plasmas with Lower Hybrid Current Drive (LHCD). The JET LHCD system is mainly used to control the q-profile in advanced plasma scenarios. Rotation with LHCD has been measured as the q-profile evolved from reversed shear, to monotonic q-profiles, for LH powers, P_{LH}, up to 4 MW.

Toroidal rotation is measured by Charge Exchange Recombination Spectroscopy (CXRS) of C^6, using a diagnostic NBI blip (a low power, short duration pulse of NBI) [3]. This provided measurements of toroidal angular frequencies and ion temperatures in 12 radial positions that cover from the plasma center (typically at R~3m) to close to the edge (R~3.8), with a time resolution of 10 ms. Data from the first 10-30 ms, when momentum from NBI was negligible, is used.

II - The JET LHCD System - The LHCD system at JET [4] is capable of launching about 6MW in L-mode plasmas at 3.7GHz. The microwave power is coupled into the plasma by a phase-array antenna commonly referred to as a launcher, which is fed via a complex waveguide structure by the available 24 klystrons. The spectrum of the launched LH wave, which is measured as the RF power density versus the parallel refractive index $N_{||}$, can be changed by phase shifting (or phasing) the power delivered by each klystron. Most commonly used phasing modes provide relatively narrow RF power spectrum peaked at about $N_{||}$=1.84. In some of the experiments discussed here an alternative phasing was used with spectrum peaked at about $N_{||}$=2.1 or 2.3.

III - Rotation Studies with LHCD - Rotation measurements in discharges with LHCD have been made in two types of L-mode plasmas: (a) LHCD applied early in the plasma for the control of the q-profile evolution, such as in the study of discharges with reversed magnetic shear and hybrid discharges [5]. In those early phases the plasma current, I_p, is still being ramped-up and $q_0>1$; (b) LHCD applied later when the plasma current is fully penetrated, q-profile is monotonic and $q_0<1$ in agreement with the observation of sawtooth instabilities. Rotation near the edge is always in the co-current direction, typical values of ω(R=3.8m)~2 krad/s, however in the core both co-current and counter-current rotation has been found, with |ω(R=3.0m)|~5-10 krad/s. In the case of core counter-rotation the direction of rotation changes at mid-radius, similarly to what has been observed in JET discharges with Ohmic heating and in some cases with ICRF heating [2].

Figure 1 shows the effect on rotation when 2MW of LHCD is added to a discharge with continuous 1.8 MW of NBI heating. NBI at JET drives momentum in the co-current direction, the angular velocity increases with time (fig. 1, traces in blue). LHCD has a strong effect on the plasma rotation in the plasma center (fig. 1, traces in red) that appear to depend on the magnetic shear. Early in the discharge with LHCD, when magnetic shear is reversed and q is above unity, co-rotation is observed. With LHCD, the angular frequency value is larger than observed with NBI-only. As the q-profile evolves into a monotonic q-profile, co-rotation with LHCD decreases, indicating that the plasma core might be moving in the counter-current direction. These observations are consistent with observations of intrinsic rotation, i.e. in plasmas without NBI except for a CXRS diagnostic blip, where we observed co-rotation when LHCD is applied early in the discharge during the current ramp-up phase, while core counter rotation is seen in most cases with LHCD applied later, when the current is fully penetrated and a q=1 surface present. This is illustrated in figure 2, for two discharges with P_{LH}~2MW and similar collisionality. The examples in figures 1 and 2 suggest that the direction of rotation may be determined by the magnetic shear [6].

Core co-rotation has also been observed in a discharge with monotonic q-profile with q0<1. Figures 3-5 compare two discharges with P_{LH}=3.4 MW applied at the same plasma current, sawtooth instabilities exist in both cases, in one we observe a peaked co-rotation profile, in the other a hollow counter-rotation. Here differences in magnetic shear are insignificant. The only apparent difference is a 10% lower density in the case of co-rotation. Further analysis is needed to understand if a difference in density or density gradient could be influencing the direction of the rotation.

A detailed assessment of the observed changes in the rotation profile with LHCD power has been started. Two possible causes related to LH waves which can affect the ion rotation [7]: (*i*) direct momentum input from the waves or; (*ii*) in a more complex way as a result of LH driven current impact on the magnetic shear which modifies the turbulence and thus affects the rotation.

In both cases LH wave power deposition profiles and driven current needed to be calculated by means of a ray tracing / Fokker-Plank code. The power deposition profile was calculated for each pair of discharges shown in figures 2 and 3. In each case the power deposition is similar (see figure 5).

Transport simulations, assuming a Prandtl number of unity, estimate the angular frequency originating from torque driven by LH waves to be an order of magnitude smaller than the observed frequency. This in any case would be in the counter-direction providing no explanation for the observed co-rotation.

IV- Discussion - When comparing pulses with and without LHCD a clear impact of LHCD on rotation is seen. The changes in core rotation can be either in the co- or counter-current directions. What determines the direction of rotation is still under investigation.

A change from co- to counter-rotation as the q-profile evolves from above unity to below unity, suggests that processes associated to magnetic shear could be important. A similar correlation between direction of rotation and magnetic shear was found in C-MOD discharges [9], while in Tore-Supra a dependence with plasma current was observed [10]. However in JET, application of LHCD can drive either co or counter rotation in discharges with similar magnetic shear and at the same plasma current. No striking features in plasma profiles could be associated with co-rotation. It is not clear if a slightly lower density is significant. However we note a possible similarity with Ohmic rotation observation in TCV [11] and C-MOD [12] where a rotation reversal from co to counter direction has been observed at a critical density.

The effect that the LH waves deposition profile might have on rotation has been assessed. The power deposition has been calculated with a ray tracing code coupled to a Fokker Plank code. The differences between peaked and hollow rotation profiles is not correlated with changes in LH accessibility. The estimated counter-torque from the LH waves, would not explain the observed angular frequencies, neither would it explain the observation of co-rotation.

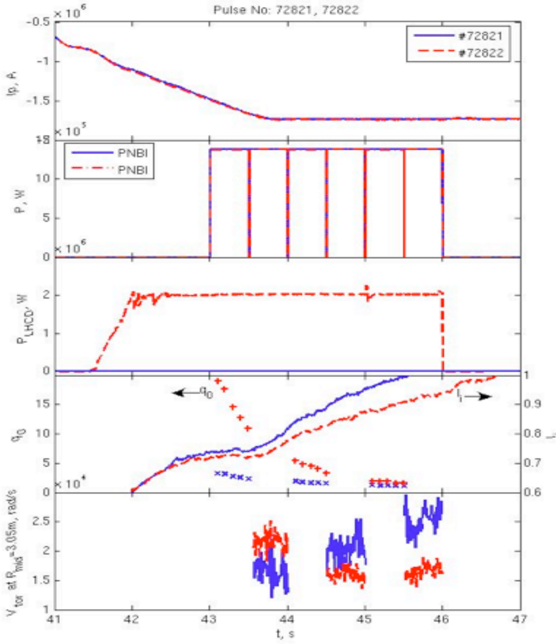

Figure 1 – Comparison of pulses with LHCD (red) and without LHCD(blue). The boxes show: (a) I_p, (b) Continuous application of P_{NBI}, consisting of alternate blips for measurements of MSE and CXRS, (c) P_{LH}; (d) q_0 and l_i, (e) central angular frequency.

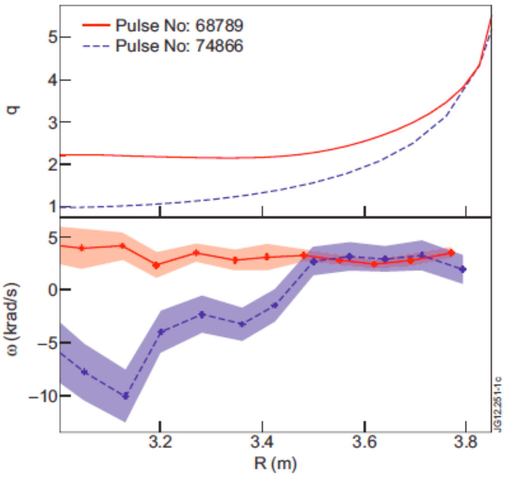

Fig. 2 - Plasmas with LHCD (Pulse 68789 with P_{LH}~1.97MW applied during the I_p-ramp, I_p=1.93MA, B_T=2.78T, <ne>=1.98E19 m-3 and; Pulse 74866 with P_{LH}=2.52 MW applied later during I_p flat-top, I_p=1.96 MA, B_T=2.44T, <n_e>=2.09E19m-3). (top) Safety factor profiles. and (bottom) C^6 angular frequency profiles.

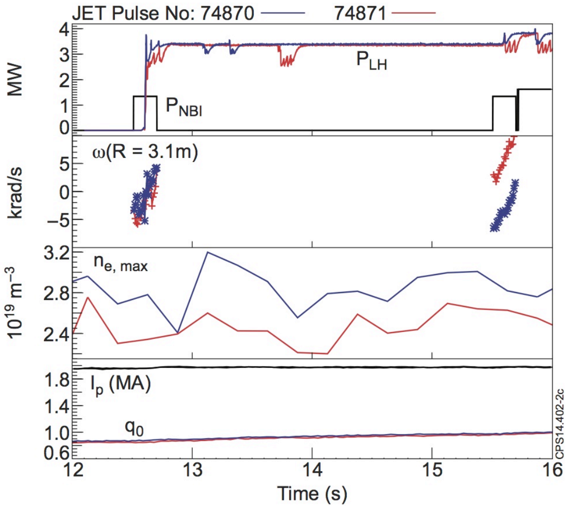

Figure 3 – Plasmas with monotonic q –profiles at the same I_p=2MA, B_T=2.45T. (a) P_{LH}=3.5 MW, P_{NBI} to measure CXRS, the 1st blip in Ohmic phase, the 2nd blip in LHCD phase, (b) angular frequency near the centre (R=3.1 m), (c) Maximum n_e from LIDAR, (d) I_p and EFIT q_0.

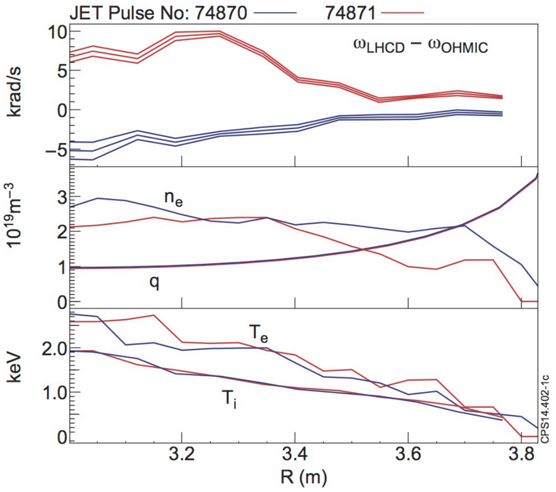

Figure 4 – Profiles just before or at the beginning of the NBI blip at 55.515s. (a) ω_{LH}-ω_{Ohmic}, angular frequency profile measured with LHCD on at 55.515s with Ohmic rotation profile,at 52.515s beginning of 1st blip, subtracted. (b) LIDAR n_e profiles and EFIT q profiles, (c) LIDAR T_e and CXRS T_i.

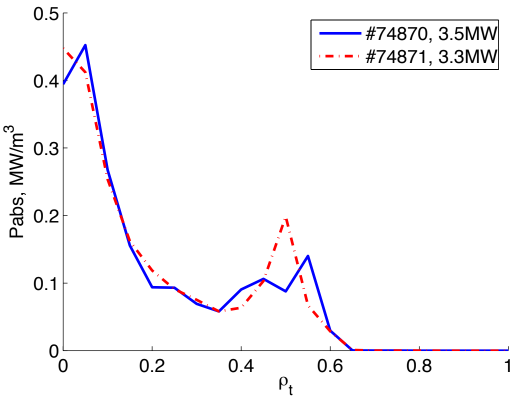

Figure 5 – Absorbed power density profiles in the normalized toroidal flux coordinate, for pulses shown in figures 3-4.

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