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J.-M. Noterdaeme, E. Righi, J. de Grassie, V. Chan, M.F.F. Nave,
K-D. Zastrow, R. Budny, R. Cesario, A. Gondhalekar, N. Hawkes,
T. Hellsten, Ph. Lamalle, F. Meo, F. Nguyen
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J.-M. Noterdaeme[1], E. Righi[2], J. de Grassie[3], V. Chan[3], M.F.F. Nave[4], K-D. Zastrow[5], R. Budny[6], R. Cesario[7], A. Gondhalekar[5], N. Hawkes[5], T. Hellsten[8, 9], Ph. Lamalle[8,10], F. Meo[1], F. Nguyen[11]
and JET EFDA Contributors*

[1]*Max-Planck-Institut für Plasmaphysik, Euratom Association, Garching, Germany,*
[2]*EFDA-CSU Garching, Germany,*
[3]*General Atomics, USA,*
[4]*Associacao Euratom/IST, Instituto Superior Tecnico, Lisbon, Portugal,*
[5]*UKAEA, Euratom Association, UK,*
[6]*PPPL, Princeton, USA,*
[7]*ENEA, Euratom Association, Frascati, Italy,*
[8]*EFDA-CSU JET, UK,*
9NFR, Euratom Association, Sweden,
[10]*Association Euratom-Belgian State, LPP-ERM/KMS, Belgium*
[11]*CEA Cadarache, Euratom Association, France*
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ABSTRACT
ICRF only heated plasmas show distinct structures in the toroidal rotation profile, with regions where $d\omega/dr > 0$ when the minority cyclotron resonance layer is far off-axis. The rotation is dominantly co-current. MHD modes can strongly affect the rotation profiles. In H-mode, the profiles become centrally peaked.

1. INTRODUCTION
Plasma rotation plays an important role in several areas: from transport, where shear in the rotation can lead to reduced losses, to MHD where rotation will increase the stabilizing effect of a wall. In magnetized plasmas, rotation can have various causes. For ion cyclotron heating, the direct momentum input due to the wave is negligible, but in the case of minority heating, radial transport or trapping/detrapping of the fast particles can lead to radial currents and thus to rotation. The scarcity of experimental data up to now, leads to a large number of often contradicting theoretical predictions for the rotation profiles due to ICRF heating only, the influence of the position of the resonance layer and the effect of the antenna spectrum.

For the first time on JET, spatially resolved toroidal rotation profiles were measured systematically for L and H mode, for a high field side and low field side position of the resonance layer, for a symmetric and asymmetric launched spectrum and for a large and small minority concentration.

2. EXPERIMENTS
The experiments were conducted at a plasma current of 2MA (in JET, clockwise and co-linear to B). Several ICRF frequencies (37, 42.5, 51MHz) at a constant magnetic field (2.8T) as well as a ramp of the magnetic field (between 2.3T and 3.1T) at constant frequency (42.5MHz) were used to position the resonance layer of the H minority (n_H/n_D = 0.01-0.05) at various locations (2.5m < R_{res} < 3.5m) in the plasma. The JET A2 antennas have four straps which can be phased arbitrarily, yielding symmetric spectra or asymmetric directed spectra.

3. MEASUREMENT METHOD
The toroidal rotation is obtained from the Doppler shift of the charge exchange resonance line of C, whereby Be -assumed to be non rotating in the scrape off layer- is used in each shot as a wavelength reference. To measure the Doppler shift, the spectrum of the C is fitted with one Gaussian after deducting a background spectrum without beams.

Since the rotation measurements need short (Δt = 200ms) pulses “blips” of neutral beam injection (E_{beam}= 140kV) care was taken through design of the experiment and subsequent experimental check that the NBI momentum input did not interfere with the toroidal rotation to be measured. Indeed, the analysis of the evolution of the rotation profile during one beam blip (three to four profiles can be recorded) and from one beam blip to another (with different timing), indicate that the *central* rotation is the first to react to the beam [1]. The evolution of this central rotation on the other hand, can be tracked continuously and independently from the beam injection, by the looking at the rotation of a mild central MHD mode. From this, we can conclude that the first measurement of the first beam blip is sufficiently little affect by the beam and depicts faithfully of the rotation as it was before the turn on of the beam.

4. RESULTS

The rotation in L-mode with only ICRF is smaller than with neutral beam injection. But, whereas the profiles with NI are monotonically decreasing from the center to the edge, profiles with ICRF only, can for particular conditions show clearly non-monotonic "hollow" profiles (with regions where $d\omega/dr > 0$). A distinct off-axis maximum in the co-current direction is seen for a far off-axis position of the resonance layer (R = 2.5m or R =3.5m). For the high field side position of the resonance layer, the off-axis maximum is modestly (20%) higher than for the low field side position [1]. The differences due to the direction of the antenna spectrum (co or counter – meant is the direction of the wave in relation to the plasma current) are small. If the hollowness of the rotation profiles for a far off-axis location of the resonance layer is interpreted as a central counter-torque, then there are some indications that this torque may be lightly larger (in absolute value) for a co-direction launch of the wave. The indications come from the difference in central rotation between discharges with different spectra and from the different evolution of this central rotation with beam input. This does not seem to be dependent whether the resonance layer is far on the high field side or the low field side. Further confirmation comes from the result that the rotation profile for a discharge with simultaneously a HFS position of the resonance layer (with a co-launched spectrum) and a LFS position of the resonance layer (with a counter-launched spectrum) is within 20% of the rotation profile of a discharge with the opposite spectra (HFS resonance with the counter-launched spectrum and a LFS with a co-launched spectrum). A change of the H concentration from 1% to 5% reduces the off-axis peak in the case of far HFS position of the resonance layer from typically 6krad/sec to 5krad/sec.

By varying the magnetic field (B = 2.3T to 3.1T) at constant frequency (f = 42.5MHz), the resonance position is varied, from far high field side (R = 2.5m), to central, to low field side. As the resonance layer location becomes more central, the hollowness of the rotation profile decreases (Fig. 2). The spectrum was symmetric $(0, \pi, \pi, 0)$. When the resonance layer is central, the sawteeth become stabilized and, after a big sawtooth crash, neoclassical tearing modes appear which completely flatten the rotation profile (Fig. 3). In H-mode, the rotation profile becomes is more peaked (Fig. 4). The fast evolution seen in Fig. 4 from one profile to the next (within the 200ms blip) is partly due to the development of the H-mode, partly due to the larger beam power used in this blip.

4. CONCLUSIONS

Rotation profiles with ICRF only, show different structures depending on the position of the resonance layer, the presence of MHD modes or the status of the plasma (L-mode or Hmode). The differences however between a far high field side and a far low field side position of the resonance layer are small as are those due to the antenna spectrum. These results provide the first data against which to test the existing theories [2].

AKNOWLEDGEMENT

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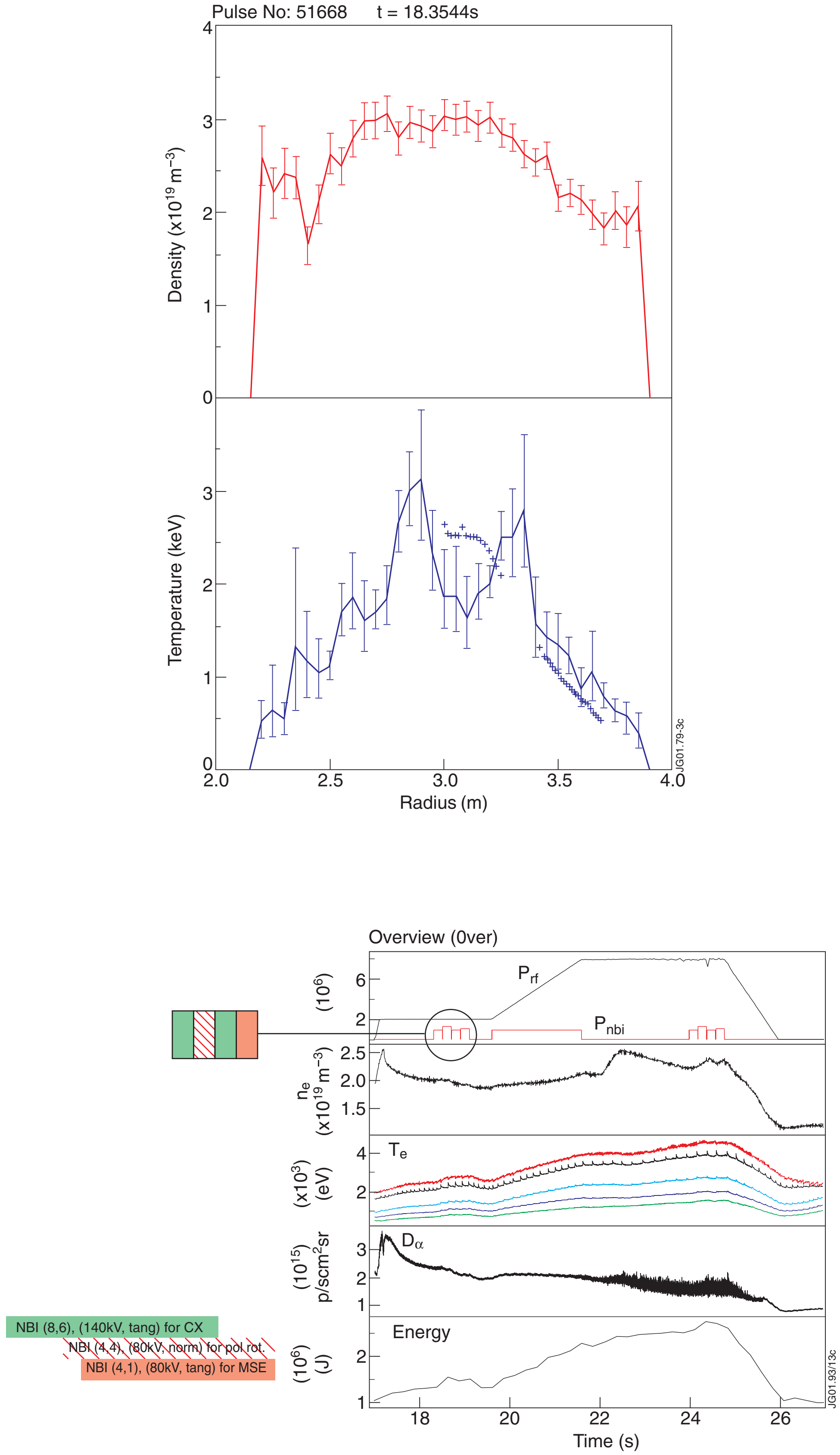

Figure 1: Top: typical time traces of ICRF and NI power, plasma density and temperature, D_α signal and plasma energy. Bottom: In the sequence of beam blips, the first and third (a and c) in each series of 4 blips, is used to measure the toroidal rotation. On the left, profiles of the density (top) and of the temperature (bottom).

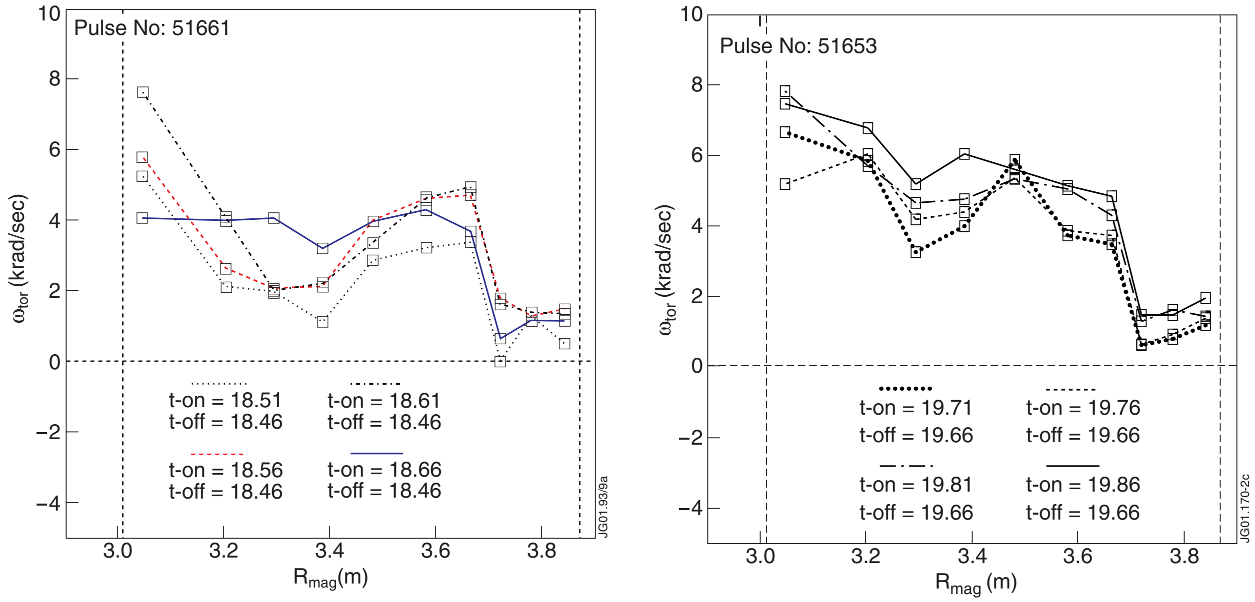

Figure 2. On the left (a), rotation profile for a location of the resonance layer at R = 2.5m, P_{IC} = 2.85MW, on the right (b) for a location of the resonance layer at R= 2.65m, P_{IC} = 2.9MW. In both cases the plasma was in the L-mode. Four rotation profiles taken during a time interval of 200ms are show. As discussed in the text, the first profile is not markedly influenced by the momentum input of the beam.

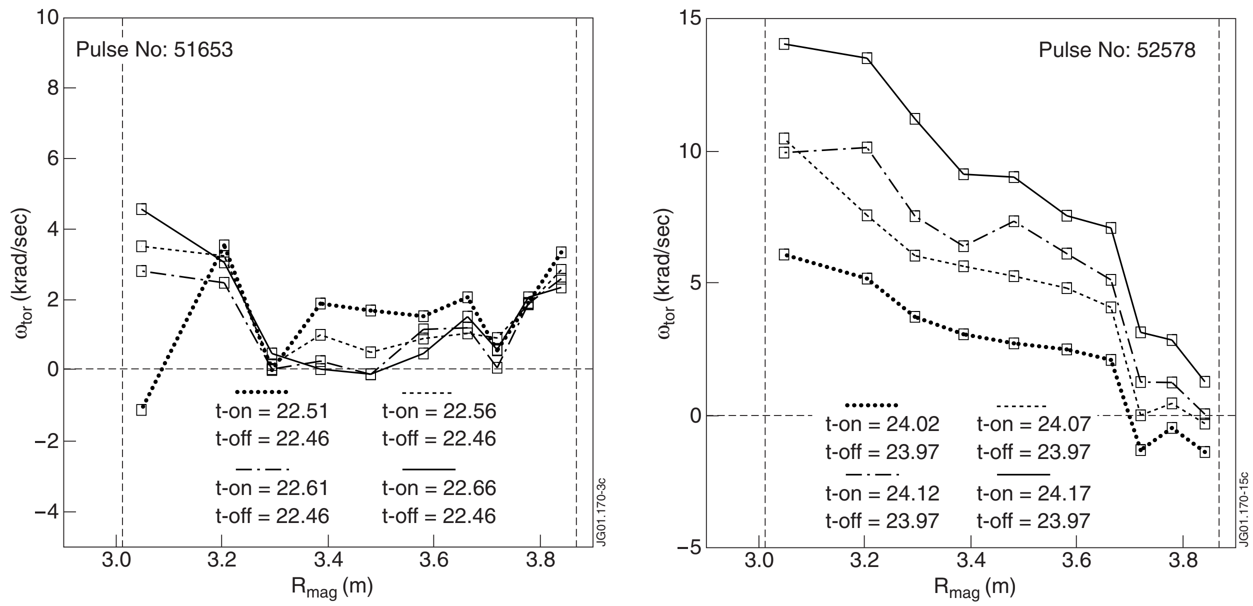

Figure 3: Toroidal rotation profile for the same discharge as Fig 2b, at a later time, R = 2.95m, P_{IC} = 2.9MW, after a period of sawtooth stabilization and subsequent large sawtooth crash.

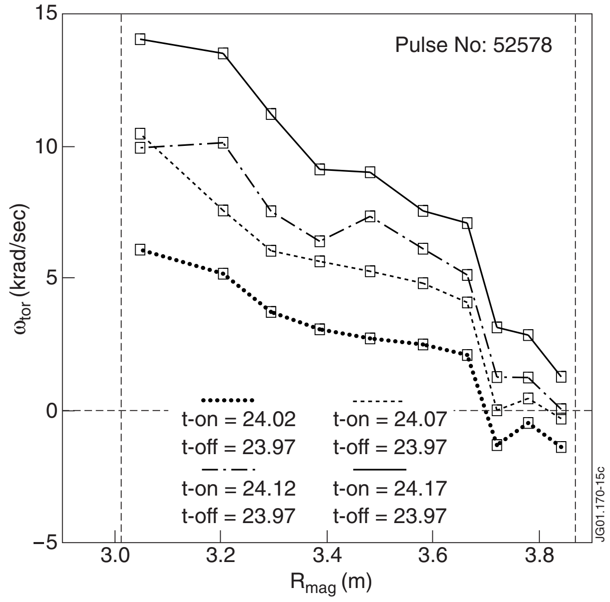

Figure 4: Toroidal rotation profile for B = 2.45T, f = 42.5MHz, (R = 2.60m), P_{IC} = 9MW, the plasma is in the H-mode.