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L.-G. Eriksson, T. Hellsten, F. Nave, J. Brzozowski, K. Holmström,
T. Johnson, J. Ongena, K.-D. Zastrow, JET-EFDA Contributors

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L.-G. Eriksson[1], T. Hellsten[2], F. Nave[3], J. Brzozowski[2], K. Holmström[2],
T. Johnson[2], J. Ongena[4], K.-D. Zastrow[5], JET-EFDA Contributors*

[1] *Association EURATOM-CEA, CEA/DSM/DRFC, CEA-Cadarache, F-13108 St. Paul lez Durance, France*
[2] *Euratom-VR Association, EES, KTH, Stockholm, Sweden*
[3] *Associação EURATOM/IST, Lisbon, Portugal*
[4] *ERM-KMS, Association EURATOM-Belgian State, Brussels.*
[5] *UKAEA/Euratom Fusion Association, Abingdon, U. K.*
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ABSTRACT

Experiments have been carried out on JET aimed at studying rotation in RF heated plasmas with low external momentum input. Both plasmas with Ion Cyclotron Resonance Frequency (ICRF) heating and Lower Hybrid Current Drive (LHCD) have been investigated. The rotation profiles are measured by Charge Exchange recombination spectroscopy, using short diagnostic Neutral Beam Injection (NBI) pulses. Moreover, the temporal evolution of the central rotation could in some cases be deduced from MHD activity. While most of the measurements were focussed on ICRF heating, the profiles measured in plasmas with LHCD are interesting since they are the first reported from JET in such plasmas. In particular, they allowed for studies of rotation in RF heated plasmas with $q > 1$. The experimental results are presented together with an analysis of the torque from ICRF heated fast ions.

INTRODUCTION

Rotation in plasmas can have a beneficial effect. For instance, it can enhance the stabilizing effect of a resistive wall. Shear in the rotation is also believed to be an important factor for transport barriers. Recent results from JT-60U [1] and D-IIID [2] indicate that the velocity needed to stabilize resistive wall modes (RWMs) is lower than previously thought. In view of this and the fact that Neutral Beam Injection in ITER is not expected to give rise to strong plasma rotation, it is interesting to consider other mechanisms with a potential to produce rotation useful for RWM stabilization. Intriguing observations of rotation in plasmas heated by Radio Frequency (RF) waves with little or no external momentum input have been made in several machines [3-11]. There is as yet no complete understanding of the mechanisms behind the observed rotation. Effects due to fast ions, MHD and transport have been proposed, see e.g. [13-15], but reliable theoretical predictions of rotation in ITER or a reactor with low momentum are not yet available. Instead work on establishing a multi machine data base has been undertaken [16]. Nevertheless, detailed experimental information is still needed to shed light on the underlying mechanism, especially for improving predictive capabilities. In this respect, measurements of rotation profiles are crucial.

Here we report on JET experiments with RF heating where toroidal rotation profiles have been measured by Charge Exchange Recombination Spectroscopy (CXRS). In contrast to previous studies using this technique on JET [5, 12], we focus some effort on providing statistics on rotation at the edge and centre of the plasma. Furthermore, a quantitative assessment of the influence of the wave accelerated fast ions is made.

MEASUREMENT TECHNIQUE

The use of CXRS to measure rotation in plasmas with low external momentum input is discussed in detail in Ref [5]. Essentially a short NBI pulse (typically 200ms) is applied a few times during a discharge, and the rotation profiles are deduced from the first collected charge exchange spectrum at the beginning of each pulse; this should minimize the perturbation introduced by the NBI. An overview of a discharge typical of those reported here is displayed in Fig. 1. Furthermore, the temporal evolution of the rotation has in some cases been deduced from MHD activity.

EXPERIMENTAL RESULTS

The discharges reported here were all in L mode and the majority were heated by Ion Cyclotron Resonance Frequency (ICRF) heating, but there were also a few with Lower Hybrid Current Drive (LHCD). In all the discharges the edge region of the plasma was found to rotate in the co-current (co-I_p) direction. Both profiles with a slight peaking of the rotation toward the centre of the plasma and hollow ones were measured. Two typical examples are shown in Fig. 2, where the rotation profiles are taken at the last NBI pulse before the ICRF switch-off for two discharges with an ICRF power around 6 MW. The discharge with the lower I_p has a hollow rotation profile and with a counter- I_p velocity in the centre while the one at higher I_p has a relatively flat rotation profile. The latter is consistent with an analysis of MHD activity, which indicates a central co-I_p acceleration in the ICRF power phase.

In fact, the hollowness of the rotation profile seems to be related to I_p. The rotation velocity in the centre for a database of about 20 discharges is shown in Fig. 3 as a function of I_p It appears that a necessary but not sufficient condition for a hollow rotation profile is low I_p. Regarding the co-rotation in the edge region of the plasma, it scales fairly well with the diamagnetic stored energy, W_{DIA}, divided by the line-averaged density. These results are interesting since they do not follow the scaling of the type W_{DIA}/I_p reported e.g. in Ref [7]. A possible reason is that the discharges here were in L mode whereas those in Ref [7] were in H mode. Moreover the mechanism in Ref. [15] could be relevant.

The discharges with ICRF only heating had monotonic q-profiles and sawteeth. To investigate rotation profiles with $q > 1$ everywhere, discharges with LHCD were carried out. Figure 5 shows the rotation profiles for two discharges with I_p=1.5 MA, one with only LHCD, the other with combined LHCD and ICRF heating. The discharge with LHCD only shows a slightly peaked co- I_p rotation profiles while the addition of ICRF drives to profile hollow and even counter I_p in the centre. If one looks at the evolution of the rotation during the NBI pulse in the discharge with ICRF, one finds that the centre of the plasma accelerates in the co-I_p direction, but at the next NBI pulse a hollow profile is recovered. Thus, there is really an effect associated with the application of ICRF power that drives the profile hollow.

DISCUSSION

A contributing factor to the hollow rotation profiles observed during ICRF heating could be the influence of the resonating fast ions. Their typically wide orbits lead to differential torques [13] and losses of them to counter-I_p torque. In order to evaluate these effects the SELFO code [17] has been used. It calculates the ICRF power deposition and the distribution function of the resonating ions, including finite orbit width, self-consistently. The discharge with I_p = 1.5 MA in Fig. 2 has been simulated, and the resulting fast ion induced toque is shown in Fig. 6. This torque has been inserted in a radial diffusion equation with a diffusion coefficient giving a momentum confinement time equal to the energy confinement (c.f. [13]) and with the same radial variation as in [12]; the measured rotation at normalized radius $\rho = 0.95$ was used as boundary condition. The simulated rotation frequency is displayed in Fig. 6. As can be seen, the model does not quite reproduce the bulk of the hollowness of the rotation profile. On the other hand the error bars are large, e.g. due to uncertainties in the momentum transport. Nevertheless, there is likely room for other effects, e.g. linked to the transport in the bulk plasma, to play a role for the observed rotation profiles.

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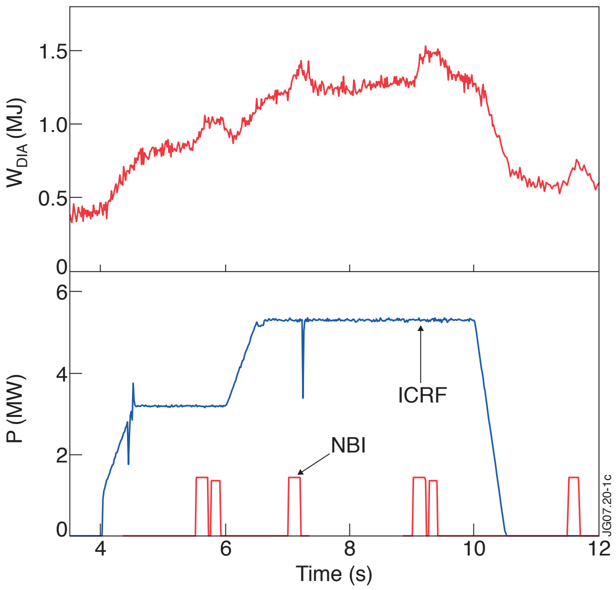

FIGURE 1. Typical power wave form (from discharge #66310) and diamagnetic stored energy.

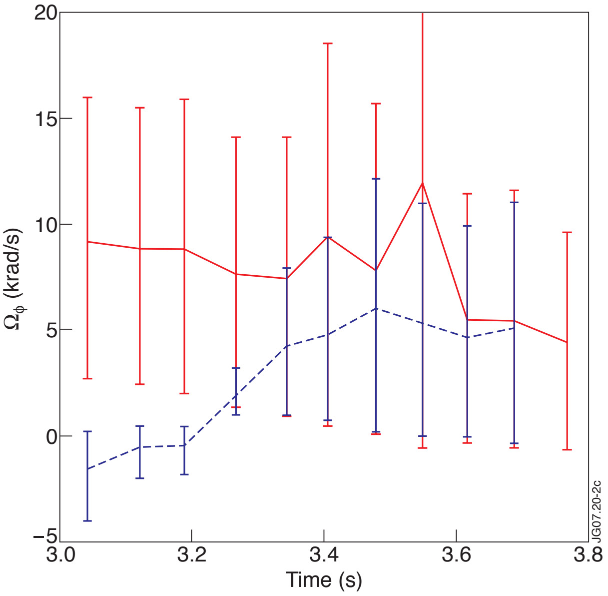

FIGURE 2. Rotation profiles for two ICRF heated discharges: solid line, I_P = 2.6MA (#66315); dashed line I_P= 1.5 (#66309). MA.

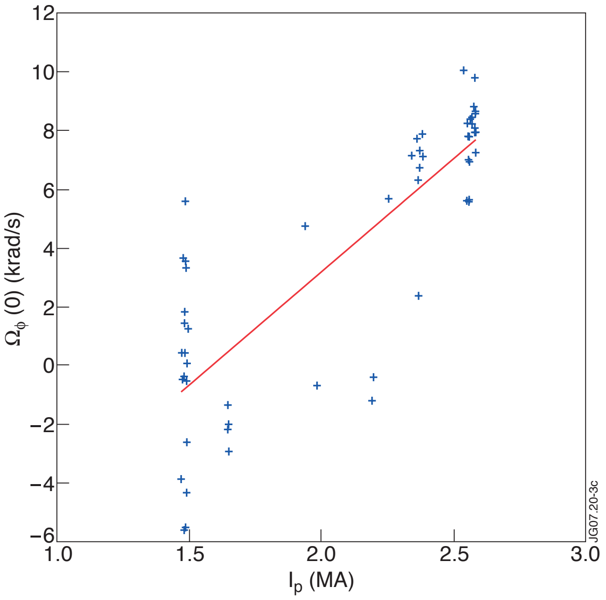

FIGURE 3. Central rotation frequency, at R ≈ 3.1 m, as a function of the plasma current.

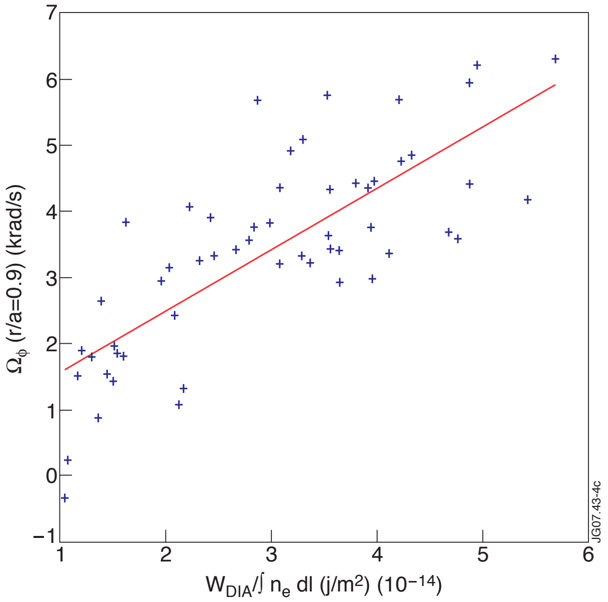

FIGURE 4. Edge rotation frequency, at R ≈ 3.7m, as a function the diamagnetic energy over the line integrated electron.

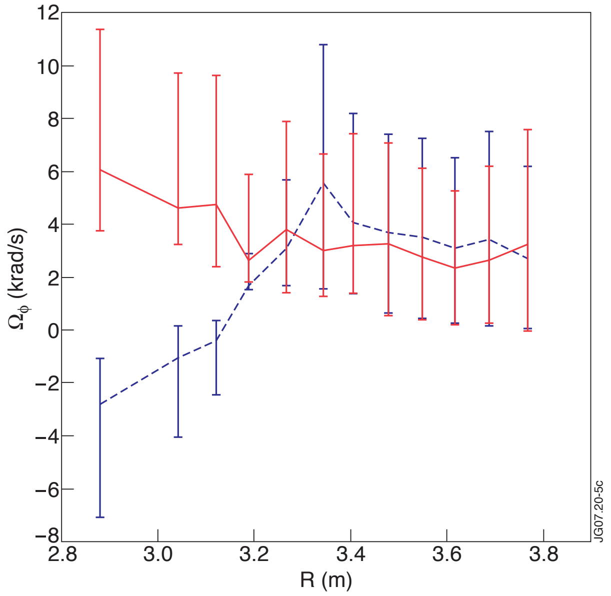

FIGURE 5. Rotation profiles for two discharges: (i) LHCD only (#68789) solid line and; (ii) combined ICRF and LHCD (#68782) dashed line.

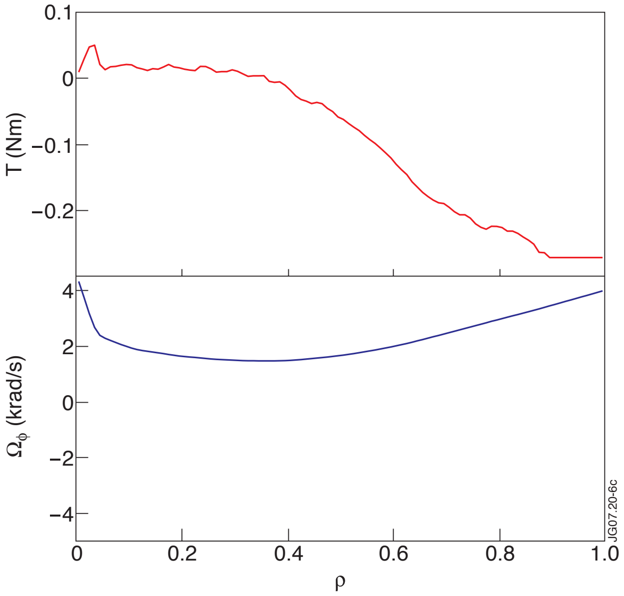

FIGURE 6. Simulated volume integrated torque profile for the low I_p case in Fig. 2 and its estimated influence on the toroidal rotation frequency.