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1. INTRODUCTION.

Plasma rotation can have beneficial effects on tokamak fusion plasmas. For instance, plasma rotation can enhance the stabilising effect of a resistive wall. Recent experimental results [1, 2] suggest that the required speeds could be relatively modest. In contrast to in present day devices, heating by Neutral Beam Injection (NBI) is not expected to induce strong plasma rotation in ITER and future reactors. It is therefore of interest to consider other mechanisms that can give rise to plasma rotation. Intriguing observations of plasma rotation have been made in ICRF heated plasmas with little or no external momentum input, often referred to as intrinsic rotation [3-7]. The mechanism behind the rotation is not yet well understood. Recent work aiming at developing a multi machine database indicates that the rotation velocity extrapolated to ITER conditions could provide a useful contribution to restive wall mode stabilization [8]. However, there are large uncertainties, the dependence on many important factors (fast particles, ripple etc) is not clear. It is therefore of interest to investigate in more detail the origin of the intrinsic rotation.

Since most of the early observations of plasma rotation with little external momentum input were made in ICRF heated plasmas, where fast resonating ions are generally generated, much of the initial theoretical effort aimed at explaining the observed rotation was concentrated on the effect of non-thermal ions on bulk plasma rotation, see e.g. [9-11]. However, theories based on fast ions were not able to explain all the experimental observations. Instead much effort has recently been concentrated on bulk plasma effects that could influence the plasma rotation. There are most likely several mechanisms that contribute to the observed intrinsic rotation, and the fast ion effect is one of them. Consequently it is important to assess their influence on the rotation, even if it is not dominating.

2. EXPERIMENTAL RESULTS.

A number of experiments dedicated to rotation studies in ICRF heated L-mode plasmas were carried out on JET in 2006/2007. In many of these the cyclotron resonance of the resonating hydrogen minority ions, in deuterium plasmas, was located on the high field side of the magnetic axis (30-40 cm), which should give rise to ICRF heated fast ions with relatively wide orbits, a central factor for the influence of the fast ions on the plasma rotation. Furthermore, in order to vary the orbit width, discharges with different plasma currents, I_p, were carried out. The rotation profiles were measured by Charge eXchange Recombination Spectroscopy (CXRS). Short Neutral Beam Injection (NBI) pulses were used. To minimize the perturbation from them, only the first CXRS spectrum at each of them was used as a measure of the intrinsic rotation profiles. The rotation profiles for two discharges with I_p = 1.5 and I_p =2.6MA, are shown in Fig.1. Both had an ICRF power of around 5MW, the magnetic field was 2.8T and the ICRF frequency 42MHz, placing the minority hydrogen cyclotron resonance around 40cm on the high field side of the magnetic axis. As can be seen, both have a finite rotation frequency in the direction of I_p in the outer region of the plasma. While the discharge at high I_p has a slightly peaked rotation profile, the low I_p one has a hollow profile. In a larger set of L-mode discharges, the rotation in the outer region, always in the co-I_p direction, was found to scale relatively well with the stored plasma energy. Consequently, it appears that an effect, most likely, acting in or near the edge plasma, is responsible for the rotation in the outer region of the plasma. The question is now to which extent the difference in rotation profiles in the more central parts of the plasma are influenced by the fast ions, a question addressed in the next section.

3. SIMULATION OF THE INFLUNCE OF THE FAST IONS ON THE ROTATION.

In order to assess the influence the fast ions on the plasma rotation, the torque they exert on different parts of the plasma must be calculated. There are two mechanisms by which fast ions give rise to a torque on the bulk plasma: collisions and radial currents associated with the fast ions. Owing to finite orbit width, a fast ion exerts a torque locally on the bulk plasma through collisions. Since a trapped ion, typical of ICRF heated ones, always travels in the counter I_p direction on its inner leg, the torque is of a dipolar nature with a lobe in the counter I_p direction closest to the plasma centre. Furthermore, the fast ions move radially. This movement is induced by collisions with the bulk plasma and due to wave induced transport. In a quasi neutral plasma the fast ion radial current must be compensated by a radial bulk plasma current, giving rise to a $\vec{j}\times\vec{B}$ torque on the bulk plasma. It is obviously quite involved to evaluate the fast ion torque in ICRF heated plasmas accurately. For the present study we have used the SELFO code [12]. It combines a full wave code with a Monte Carlo solver for the orbit averaged Fokker-Planck equation. The latter includes finite orbit width effects and fast ion transport due to collisions and wave interaction.

In order to assess the rotation, the simulated fast ion torque must be inserted in a transport equation for the toroidal angular momentum, we assume it to have the form.

$$n_i\, m_i\, \frac{\delta\langle RV_\phi\rangle}{\delta t} = g^{-1/2}\, \frac{\delta}{\delta\rho}\left[g^{-1/2}\, n_i\, m_i \left(\alpha + D\, \frac{\delta\langle RV_\phi\rangle}{\delta\rho}\right)\right] + t$$

where ρ is a flux surface label, V_ϕ is the toroidal velocity (assumed to be the same for all species, a rough approximation), $g^{1/2}$ is the Jacobian, $\langle ...\rangle$ denotes flux surface average, t is the torque density of the fast ions, D a momentum diffusion coefficient and the term a represents momentum transport due to off-diagonal terms in the transport matrix and possible pinch terms. The coefficient D is assumed to increases with radius as, $D = D_0\, [q(\rho)/q_0]^2$, c.f. [9], where D_0 has been adjusted to give a momentum confinement time equal to the energy confinement. Moreover, since recent studies suggest that the Prandtl number (D/χ_E) can be significantly lower than unity, at least in the central plasma, we have also simulated cases with a momentum confinement twice that of the energy. The simulated fast ion torque and the resulting rotation frequency are shown in Fig.2 for $\alpha = 0$. The measured rotation at R = 3.7m was used as a boundary condition. The volume integrated torque is finite at the plasma boundary for the low I_p discharges because of fast ion orbits intersecting the wall. As can be seen, the fast ions can explain much of the hollowness of the rotation profile at low I_p, especially for the weaker D. However, the observed slight peaking of the rotation in the high I_p discharge is not well reproduced, but it can be matched by adding a pinch term, $\alpha = \alpha_1\, \langle RV_\varphi\rangle$, of the form indicated in Fig/3.

CONCLUSION

Depending on the assumption on D, fast ion effects can explain from 50% to most of the observed hollowness of the rotation profile in low current discharge. The slight peaking in the high current discharge suggests that a momentum pinch could be present.

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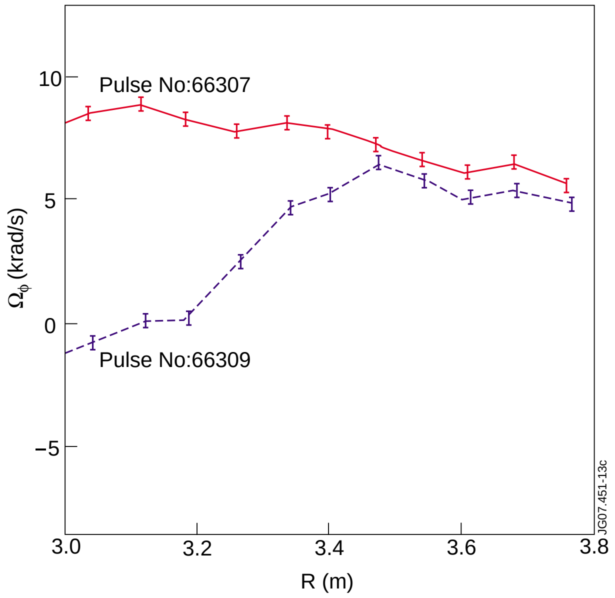

Figure 1: Measured rotation profiles for Pulse No's: 66307 (solid line) and 66309 (dashed line). The former had a plasma current of 2.6MA while the latter had a current of 1.5MA

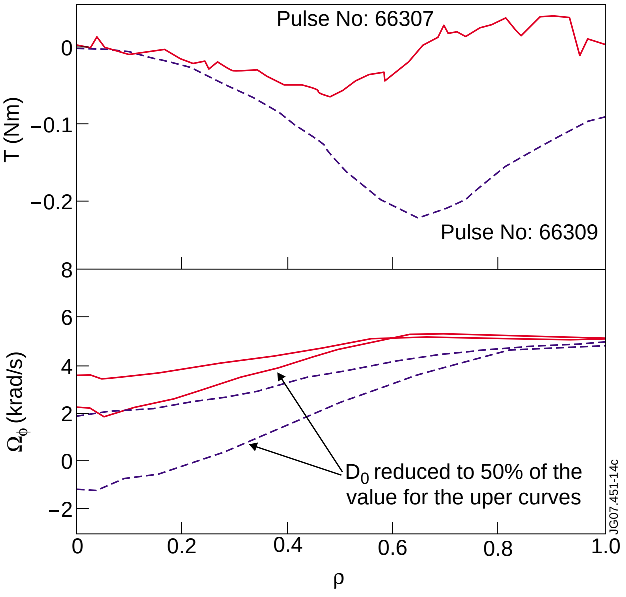

Figure 2: Top panel: simulated volume integrated torque densities on the bulk plasma due to ICRF heated fast ions for the Pulse No's: 66307 (solid line) and 66309 (dashed line). Bottom panel: the effect of the simulated torques on rotation profiles

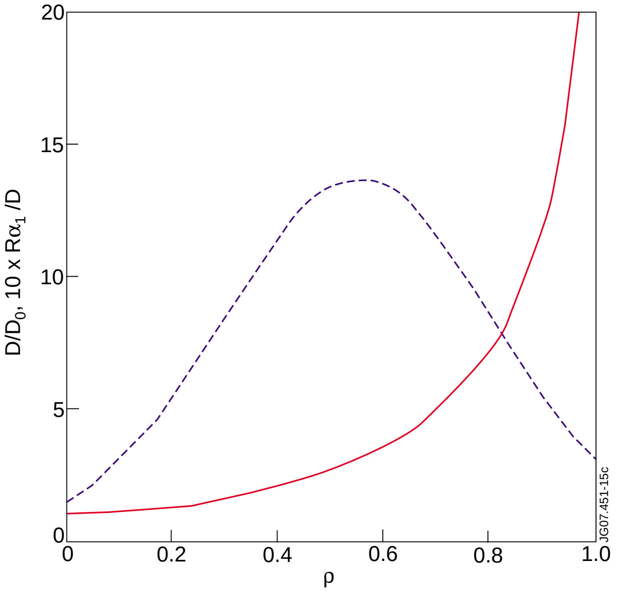

Figure 3: Diffusion coefficient (solid) and pinch term (dashed) used for obtaining the match in the top panel of the measured rotation profile.