EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

EFDA–JET–CP(03)03-02

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives",*
Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).

Preprint of Paper to be submitted for publication in Proceedings of the
15th Topical Conference on Radio Frequency Power in Plasmas
(Moran, Wyoming, USA 19-21 May 2003)

ABSTRACT.

Experiments with directed ICRF waves have for the first time in JET demonstrated the influence of absorbed wave momentum on bulk plasma rotation. Resonating fast ions acted as an intermediary in this process, and the experiments therefore provided evidence for the effect of fast ions on the plasma rotation. Results from these experiments are reviewed together with results from ICRF heated plasmas with symmetric spectra in JET and Tore Supra. The relevance of different theoretical models is briefly considered.

1. INTRODUCTION

Plasma rotation can have beneficial effects on the performance of a tokamak plasma. For example, it is widely believed that the shear in the toroidal velocity component associated with the radial electric field is an important factor for the formation of transport barriers [1, 2]. Furthermore, plasma rotation can influence MHD activity, and enhance the stabilizing effect of a resistive wall [3]. It is therefore important to understand the mechanisms behind plasma rotation.

Strong toroidal plasma rotation is normally induced by Neutral Beam Injection (NBI) heating in present day tokamaks. In a burning reactor plasma, however, there might not be any NBI or it will be used for current drive purposes. In the latter case, the injection energy must be very high for the injected neutrals to penetrate towards the center of the plasma. Since the injected momentum scales like $P_{NBI}/E_{INJ}^{1/2}$, the toroidal torque on the plasma could be relatively modest.

As a result, it is relevant to investigate other mechanisms that can give rise to plasma rotation. Interesting observations of rotation in plasmas heated by waves in the Ion Cyclotron Range of Frequencies (ICRF) have been made in several tokamaks since the early nineties [4-9]. The presence of often very fast resonating ions is such plasmas means that there are significant similarities to alpha particle heated plasmas. It is therefore of particular interest to investigate the origin of the observed rotation. Especially intriguing is the fact that little or no external momentum injection has been involved in most of the reported cases of rotation during ICRF heating. Furthermore, rotation predominantly in the same toroidal direction as the plasma current has been observed in these conditions, excluding losses of fast ions as a source for the rotation. Nevertheless, fast ion effects have been proposed as a possible source for the rotation [10]. On the other hand, scalings of the experimentally measured rotation indicate that a bulk plasma effect could be involved [4-9], especially since rotation in ohmic H modes have been observed to generally follow the scaling of the rotation in ICRF heated plasmas in Alcator C-Mod [6, 7]. In fact, there is probably a combination of effects involved, with fast ions being one of them. Consequently, it is useful to identify and quantify their effect on plasma rotation experimentally.

In recent experiments on the JET tokamak with directed (or travelling) ICRF waves, the effect of fast ions on the rotation has been clearly identified for the first time. Furthermore, the use of directed waves offer a possibility to control the rotation. The principal part of this paper is therefore devoted to JET experiments with directed waves.

MHD activity has been observed to have a strong influence on ICRF heated JET plasmas. Such experiments are briefly discussed in the second section of this paper. In the last section, rotation in plasmas with little or no external momentum injection are discussed and new results from Tore Supra are reported together with a brief look at theoretical models.

2. PLASMA ROTATION IN THE PRESENCE OF DIRECTED ICRF WAVES

It would of course be advantageous to control plasma rotation. In principle this could be achieved by directed waves in the Ion Cyclotron Range of Frequencies (ICRF). Although such waves would globally provide much less torque than NBI injected ions, the maximum torque density would not necessarily be small since the power deposition profile for ICRF is much narrower than for NBI. Furthermore, the location and direction of the provided torque could be controlled by moving the cyclotron resonance and changing the spectrum of the waves. Directed waves are discussed in for instance [11]. The first clear evidence of an influence of directed ICRF waves on rotation has been observed in recent experiments on JET. Since the momentum carried by the waves is initially absorbed by resonating fast ions and subsequently transferred to the background plasma, the JET results provide evidence for fast ion influence on rotation. By monitoring the fast ions with a gamma-ray diagnostic, it has been possible to identify the relative importance of ions on topologically different orbits in the discharges with directed waves.

The equation of motion for a resonating ion combined with Maxwell's equations shows that a particle receiving a change in its energy ΔE during a resonant interaction with a wave also experiences a change in its toroidal angular momentum $\Delta P_\varphi = (N/\omega)\ \Delta E$ (c.f. quantum mechanics, absorption of wave quantum $\Rightarrow \Delta E = \hbar\omega$ *and* $\Delta P_\varphi = \hbar k_\varphi = R = \hbar N$). The amount of toroidal momentum imparted to the plasma per unit time is therefore given by:

$$\sum_N (N/\omega)\, P_{ICRF}\,(N),$$

where $P_{ICRF}\,(N)$ is the power into the toroidal mode number N. Thus, by exciting directed waves, i.e. waves with an asymmetrical toroidal mode number spectrum, toroidal angular momentum can be imparted to the plasma.

In order to investigate the possibility of influencing toroidal rotation with directed ICRF waves, a set of experiments was carried out in JET. According to the formula above, a scenario with a low frequency should be used to maximize the imparted momentum for a given power. In the JET experiments discussed here, ^{3}He minority heating in deuterium plasmas, (^{3}He)D, was the chosen scenario. The ICRF frequency was 37MHz and the central toroidal magnetic field 3.4T, placing the cyclotron resonance slightly on the high field side of the magnetic axis (~0.15m). The JET four strap antennas had a phasing between the currents in two neighboring straps of either +90^o or −90^o o , producing waves propagating predominately in the toroidal direction parallel or anti-parallel to the plasma current, respectively. Characteristic toroidal mode number spectra for the two phasings, typically peaking at N±15 for ± 90^{o} phasing, can be found in Ref. [13]. An overview of two discharges with +90^{o} and −90^{o} phasing respectively is given in Fig.1. The rotation profiles for the two discharges are displayed Fig.2. Neutral Beam Injection (NBI) blips and charge exchange spectroscopy, described comprehensively in [20], were used to measure the rotation in these discharges. The resulting profiles measured at t = 21sec are shown in Fig.2.

As can be seen, the two discharges are very well matched in terms of the applied ICRF power and plasma density, whereas there is a small difference in the stored energy and a somewhat larger difference in the central electron temperature. These differences are consistent with the absorption of wave momentum and the concomitant inward/outward pinch effect on the resonating ions [14, 15]. While both discharges rotate in the co-current direction, there is a significant difference: the +90 o discharge rotates much more strongly in the center.

The stronger co-current rotation of the +90^{o} discharge is consistent with theoretical expectations since the waves in this case carry momentum in the co-current direction. In order to increase the confidence in that the absorbed wave momentum was the critical factor and not more efficient central heating in the +90^{o} case, a discharge where 2 MW of +90^{o} ICRF power was replaced by 2MW of LH power was carried out in an otherwise similar discharge (the LH wave also carries momentum, but is much smaller than for the ICRF waves, around a tenth). The stored energy for this discharge was somewhat lower (~10%) than for the −90^{o} case, the rotation profile is shown in Fig.2. In spite of having a lower stored LH power rotates more strongly in the co-current direction than the −90^{o} discharge. This is a strong indication that it is the wave momentum and not the power deposition or the efficiency of the heating that is the cause of the difference in rotation velocity between the +90^{o} and −90^{o} phasing discharges. Important information on the fast ion behavior in these discharges has been provided by the gamma-ray measurements [12]. Figure 3 shows the line integrated emission, normalized to its maximum value, from the vertical lines of sight as a function of the major radius where the sight line crosses the mid-plane. As can be seen, the −90^{o} discharge has an asymmetrical emission with respect to the magnetic axis whereas it is almost symmetric for the +90^{o} case. Thus, the fast ion characteristics are clearly different in the two discharges. The asymmetrical emission for −90^{o} is consistent with a strong population of trapped fast ions and the more symmetric for +90^{o} with a significant presence of passing ions in the potato regime (i.e. they have orbits not covered by the small banana width limit [16]).

The presence of non-standard passing ions in the center should have an important effect on the torque provided by the fast ions to the bulk plasma in the central region. This is particularly interesting since the presence of such ions has been found to be an essential factor for co-current rotation driven by fast ions in the absence of external momentum injection [17, 18].

To gain further insight and to check in more detail if theory can explain the experimental observations it is necessary to carry out rather comprehensive simulations. For this purpose we have used the SELFO code [19], which self consistently calculates the ICRF power deposition and the distribution function of the resonating ions, including finite orbit width effects and wave induced transport in real space. From the simulated distribution function we have calculated line integrated gamma-ray emissions corresponding to the measured vertical channels. The results of these simulations have been added to Figs.3(a) and (b). As can be seen, the spatial distribution of the measured and calculated gamma-rays have very similar features. Only in the relative level is there a difference, the ratio between of the emissions at the normalization points for $+90^o$ and -90^o phasing is roughly 4 experimentally and 2 in the SELFO simulations. This is probably due to a too low concentration of ^{3}He ions in the -90^o simulation (there is a pump out of resonating ions due to the outward drift of ions in the -90^o case). The simulations confirm that the asymmetrical shape of the emission seen in Fig.3(b) is caused by a dominating presence of fast trapped ionswhereas the more symmetric emission in Fig.3(a) is the consequence of a large fraction of co-passing orbits in the potato regime.

The SELFO code has also been used to calculate the torque density absorbed from the ICRF waves by the resonating ions and subsequently transferred to the thermal background plasma. This torque has been inserted in a simple momentum diffusion equation of the type:

$$n_i m_i \frac{\partial V_\varphi}{\partial t} = \frac{\partial}{r}\frac{\partial}{\partial r}\left[r n_i m_i D \frac{\partial V_\varphi}{\partial t}\right]$$

where V_φ is the rotation velocity, m_i and n_i are the mass and density of the plasma ion species (summation over repeated index is assumed), D is a momentum diffusion coefficient. The momentum transport is likely to be anomalous, and in our estimates we simply take $D = a^2/(\alpha_M \tau_M)$, where a is the minor radius, τ_M the momentum confinement time assumed to be related to the energy confinement time ($\tau_M \sim \tau_E$), and α_M is a parameter adjusting the transport so that the global confinement, τ_M, time is obtained (in reality α_M depends on the rotation profile, but it should be of the order 5). Inserting the torque profile calculated by SELFO in the diffusion equation above using $\tau_M = \tau_E = 0.3$s and $\tau_E = 2$ results in the rotation profiles shown in Fig.4. As can be seen, the difference in the simulated toroidal rotation is of the order 4krad/s , in good agreement with the experimental finding. However, the underlying co-current rotation cannot be explained by the fast ion effects included in SELFO.

From the combination of experimental observations and numerical simulations with the SELFO code, a rather clear picture emerges. In the case of ICRF waves propagating in the direction of the toroidal current, the absorbed wave momentum is transferred from the resonating ions largely by an inward wave-induced drift of trapped ions and via collisions with co-passing ions in the potato regime. The presence of the latter is a consequence of the inward drift, as the turning point of a trapped ion reaches the equatorial plane it de-traps and is transformed into a co-passing orbit. The presence of co-passing orbits is important because they provide a co-current torque in the central part of the plasma. On the other hand, for waves propagating in the toroidal direction opposite the plasma current, the momentum transfer is mainly due to the outward drift of the resonating ions.

In earlier experiments reported in [20], very small differences were seen between $+90^o$ and -90^o

phasing. There could have been several reasons for this. Two important factors were the lower power levels used and the fact that the cyclotron resonance was placed much further off-axis, leading to a significantly lower predicted change of the rotation (~5) and greater uncertainties in the central rotation due to dependence on the momentum transport.

3. ON THE INFLUENCE OF MHD ACTIVITY ON PLASMA ROTATION

A number of JET experiments have been carried out to investigate if the position of the cyclotron resonance has an influence on the plasma rotation during ICRF heating. In a particular series of experiments, the magnetic field was ramped during the application of the ICRF power so that the cyclotron resonance was moved from the Low Field Side (LFS) to the High Field Side (HFS) in one discharge and vice versa in another. During the course of the magnetic field ramp the cyclotron resonance passed through the centre, and the resulting central fast ion pressure led to the creation of monster sawteeth. At a monster sawtooth crash MHD activity was triggered, and locked modes appeared. The rotation profiles before and after the appearance of locked modes for the two discharges with increasing and decreasing magnetic field ramps are shown in Fig.5. The MHD activity is found to wipe out the rotation over almost the whole plasma radius. This observation is consistent with similar observations in NBI heated plasmas [21].

4. PLASMA ROTATION FOR SYMMETRIC ICRF ANTENNA SPECTRA

We have shown above that the change in toroidal rotation induced by directed waves can be understood in terms of the absorbed wave momentum and its subsequent transfer from fast resonating ions to the background plasma. However, we have not explained the underlying co-current rotation shown in Fig. 3 or the observed rotation in the discharges in Fig.5, where symmetric antenna spectra were used. These are all in L mode and are all rotating predominantly in the co-current direction, but with rather modest rotation velocities. This observation is confirmed by the larger study presented in [20]. An important aspect to note in Fig.5, and which has also been found to be a general feature in [20], is that there is little difference between HFS and LFS resonance. In particular, there is no change in the direction as is predicted by the most basic theory for fast ion induced rotation [10]. A key point of the theory in Ref. [10] is that the differential torque produced by the fast ions (i.e. separated regions of positive and negative torque) is sufficient to drive rotation even if the total torque from them on the background is zero. However, preliminary results from SELFO simulations for discharges similar to those in Fig.3 but with symmetric spectra suggest that the differential torque created by the fast ions is not enough to explain the observed rotation when inserted into the momentum diffusion equation with the same momentum confinement used for Fig.4.

It is especially interesting that rotation in the same toroidal direction as the plasma current has been observed in the three machines JET, Alcator C-Mod and Tore Supra [4-9]. Furthermore, a scaling of the co-current rotation with bulk plasma parameters (stored energy and/or bulk ion pressure) has been reported from all three machines. The JET and Alcator C-mode results showing this feature are all from H-mode plasmas. The recent rotation experiments carried out in JET investigated the effect of the resonance location mostly in L-mode at constant power [20]. Therefore they did not provide additional information on the relation between bulk plasma parameters and plasma rotation. New results from Tore Supra on this aspect are reported below. Comparing results from the different machines is especially interesting in view of their significant differences. One should first note that JET and Alcator C-Mod are equipped with divertors whereas limiter discharges are operated in Tore Supra. Furthermore, the collisional regimes in Alcator C-Mod and JET can be quite different due to the high densities with which Alcator C-Mod is normally operated. Tore Supra is in this respect in between the two other machines but closer to JET.

As was reported in [8, 9], Tore Supra plasmas have been found to be accelerated in the co-current direction during hydrogen minority ICRF heating with high concentrations of hydrogen. On the other hand, plasmas with low H concentrations are normally found to be accelerated in the counter current direction. A theory put forward in [8] is that the counter current rotation could be due to ripple losses of fast ions, which can be quite significant in Tore Supra due to the relatively large ripple, 7% at the plasma boundary. At lower concentrations the resonating ions become on average more energetic and thus more subjected to ripple transport. Thus, the counter torque produced by ripple lost ions could explain the counter current rotation at low H concentrations. This picture has been reinforced by results from recent 3 He minority heating experiments carried out in Tore Supra. The ^{3}He minority scenario creates few fast ions in Tore Supra, and the ripple losses are therefore very low. As is shown in Fig.5, the Tore Supra discharges with ^{3}He minority heating are accelerated in the co-current direction, and the change in rotation velocity scales well with the diamagnetic energy content divided by the plasma current, c.f. similarities with Alcator C-Mod H-mode discharges. Another factor is the stronger ion heating expected during ^{3}He minority heating. Its role has not yet been clarified, but it is possible that it could have an influence on the rotation as well.

With in many respects fairly similar results for the observed toroidal rotation during ICRF heating with symmetric antenna spectra in three rather different tokamaks, it is quite a challenge for theory to explain the observations. There are currently mainly three theoretical explanations put forward for the observed co-current rotation during ICRF heating, fast particle effects [10], neo-classical effects [22], and the so-called accretion theory [23]. The influence of fast resonating ions on the JET experiments has already been discussed above, and this influence does not seem sufficient to explain the bulk of the observed rotation. While it is not explicitly stated in the paper, the neo-classical theory of rotation developed in [22] for ohmic H-mode plasmas should be an important component also for ICRF heated H-modes. There are two key factors in the this theory. Firstly the plasmas, and particularly the outer part, are assumed to be in the Pfirsch-Schlüter regime; secondly, the main contribution to the rotation comes from the strong ion pressure gradient in the pedestal region of the H-mode. The theory is therefore particularly suited to Alcator C-Mod H-mode plasmas, where plasmas with very high densities are operated, and fits the experimental measurements in this machine quite well. However, it is not clear that this theory can explain the bulk of the plasma rotation observed in JET and Tore Supra. For example, Tore Supra is a machine without divertor and consequently does not have an H-mode (at least not in the normal sense of a machine with a divertor). Furthermore, the collisional regimes in JET and Tore Supra are quite different from Alcator C-Mod. In fact both JET and Tore Supra are closer to the banana regime, where neo-classical theory predicts rotation in the counter current direction [24]. The accretion theory for toroidal rotation [23] predicts a reversal of the central toroidal rotation direction during a transition to H mode, with the plasma rotating in the co-current direction while in H mode. As can be seen from the JET rotation profiles presented here, the plasma often rotates in the co-current direction also in the L mode phase. This does not necessarily mean that the theory in [23] is wrong. It could well describe the co-current acceleration of the plasma in H modes. However, one then needs another theory to explain the co-current rotation in L mode plasmas seen in JET.

We can conclude this section by saying that no single theory appears to explain all the observations of toroidal rotation during ICRF heating in JET, Alcator C-Mod and Tore Supra. It is possible that several effects are involved which conspire to give results which appear similar on the three machines. Alternatively, a more general explanation, yet to be clarified, exists.

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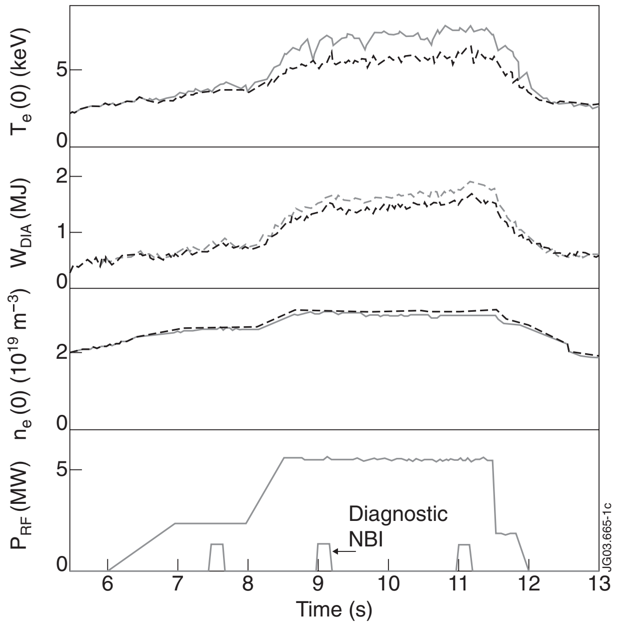

Figure 1: Overview of two discharges with +90^o (solid line) and −90^o phasing (dashed line).

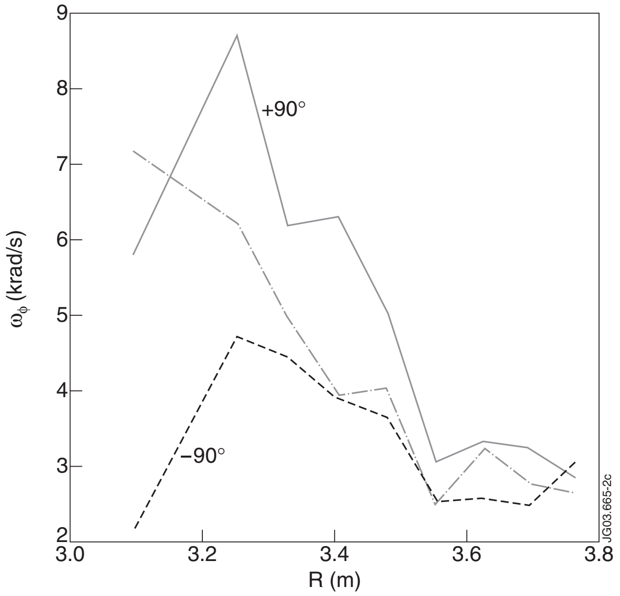

Figure 2: Rotation profiles for the discharges with +90^o and −90^o phasing. The rotation profile for a discharge where 2MW of +90^o ICRF power was replaced by 2MW of LH power is also shown (dot dashed line)

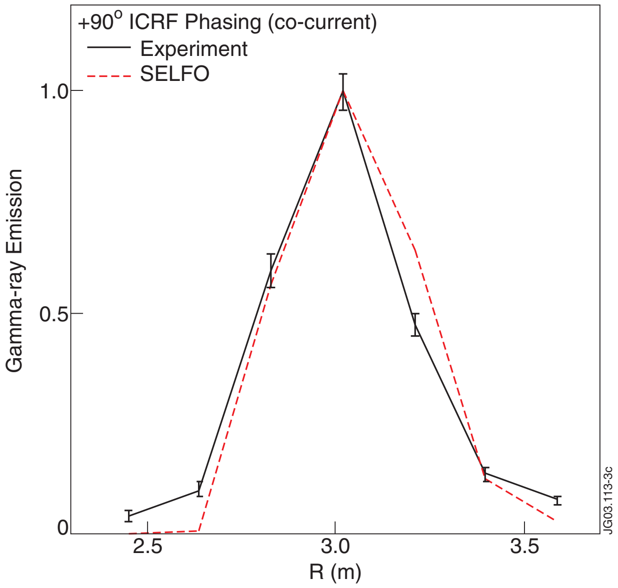

Figure 3(a): Measured and simulated gamma ray emission as a function of the major radius for +90^o

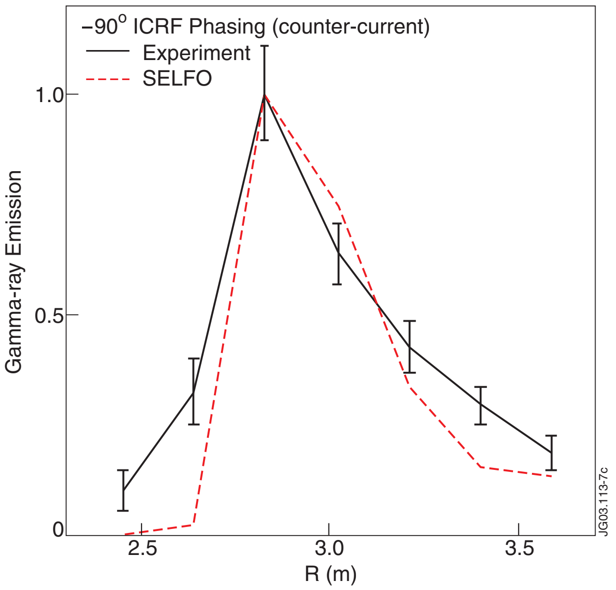

Figure 3(b): Measured and simulated gamma ray emission as a function of the major radius for −90^o

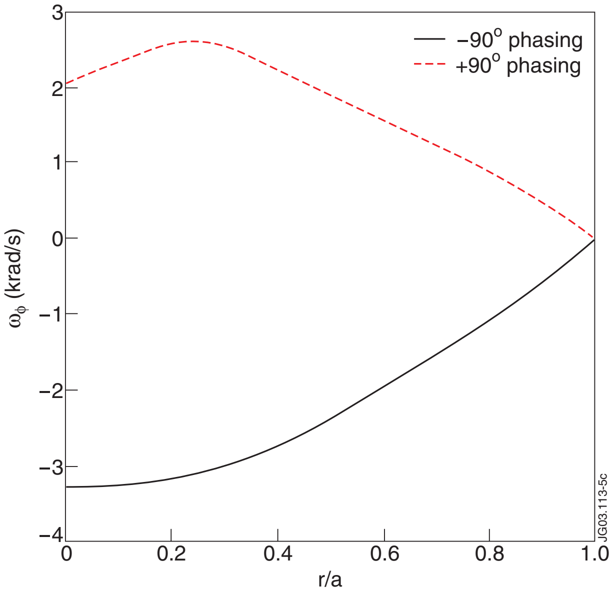

Figure 4: Rotation profiles obtained with the torque from SELFO simulations inserted in to a momentum diffusion equation.

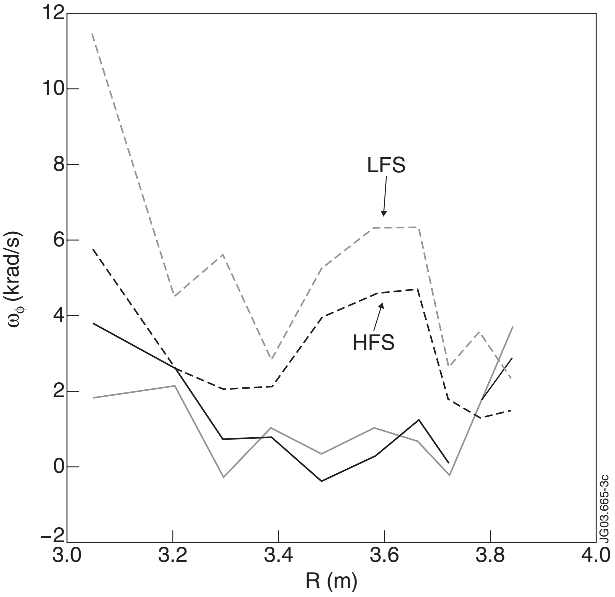

Figure 5: Measured rotation profiles before onset of MHD activity, dashed lines, and after, solid lines.

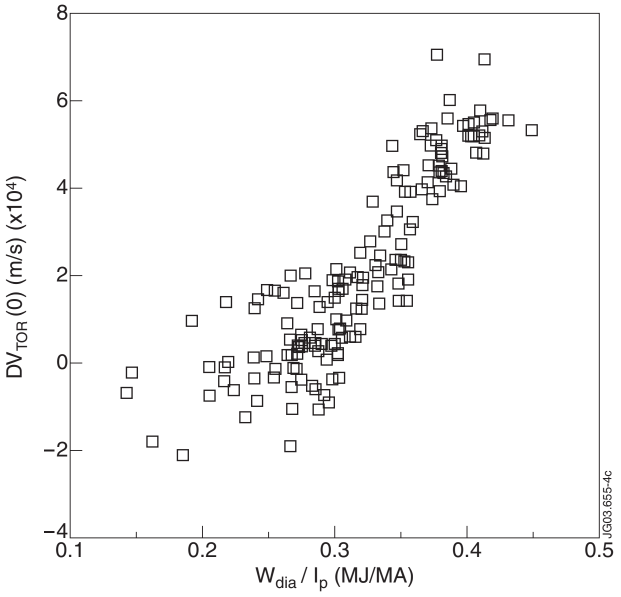

Figure 6: Change in toroidal rotation velocity as function of W_{DIA}/I_p during ^{3}He minority ICRF heating.