Toroidal plasma rotation in ICRF heated Tore Supra discharges

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INTRODUCTION. Plasma rotation can have beneficial effects on a tokamak plasma. For example, a strong shear in the component of the rotation associated with the radial electric field is widely believed to be an important factor for the formation of transport barriers. Significant toroidal plasma rotation is normally induced by Neutral Beam Injection (NBI) heating in present day tokamaks. However, in a reactor there might not be any NBI or it will be used for current drive purposes, in which case the input momentum might be rather modest because of the high injection energies required. Consequently, it is useful to consider other mechanisms leading to plasma rotation. Intriguing observations of plasma rotation in ICRF heated plasmas with very little or no external momentum injection have been made in several tokamaks, especially JET, Alcator C-Mod and Tore Supra [2-5]. New data on rotation in ICRF heated Tore Supra plasmas are reported here.

MEASUREMENT TECHNIQUE FOR TOROIDAL ROTATION ON TORE SUPRA.

High-resolution, time-resolved X-ray spectra of He- and Li-like heavy ions are obtained on Tore Supra using a Johan-type cylindrically curved crystal spectrometer, for details see Ref. [1]. The present study is based on the measurements of strong intrinsic impurities Fe and Cr spectra (1.85 - 2.2 Å region). For the 1s–2p resonance line-w (the most prominent feature in the spectrum), the line of sight makes an angle of 57° with the magnetic axis, so that the Doppler shift of the line from its position during the non ICRF heated plasma phase gives the averaged (differential) toroidal velocity $\Delta V_\phi$. A negative/positive variation in the toroidal rotation corresponds to a change in the direction parallel/anti-parallel to $I_p$ (plasma current).

EXPERIMENTAL OBSERVATIONS. ICRF heated Tore Supra discharges with symmetric antenna spectra have in the past been observed to accelerate toroidally both in the counter-$I_p$ and co-$I_p$ directions [5]. In particular there was evidence that co-$I_p$ acceleration occurred during hydrogen minority heating, (H)D, with fairly high concentrations of minority ions. In lower concentration discharges, counter-$I_p$ acceleration was observed. The concentration of the minority ions affects their averaged energy, and the resonating ions tend to be more energetic at low concentrations. The averaged energy of the resonating ions influence two important factors in Tore Supra, the fraction of the ICRF power going to bulk
ion heating and the level of ripple losses. When the averaged energy of the resonating ions is below the so called critical energy, most of the power absorbed by them is transferred to the background thermal ions via collisions. One possibility is therefore that transport in the ion channel could have an influence on the rotation.

A more easily identifiable effect is the ripple losses. The ripple in Tore Supra is fairly large, about 7% at the plasma boundary. The resulting losses, which increase with the averaged energy of the resonating ions, can therefore be significant. In response to the outward current of ripple lost fast ions, an inward current flows in the background thermal plasma to preserve quasi-neutrality. The resulting $\mathbf{j} \times \mathbf{B}$ force on the thermal plasma is in the counter-$I_P$ direction. In Ref. [5] it was thus conjectured that ion heating and small ripple losses were crucial factors for having co-$I_P$ acceleration in Tore Supra. Simulations of the $^3\text{He}$ minority heating scenario, ($^3\text{He})D$ in Tore Supra shows that the ripple losses should be very small, and that the ion heating should be significant [6]. Thus if the conjecture is right one would expect discharges with $^3\text{He}$ minority heating to accelerate in the co-$I_P$ direction.

Both (H)D and ($^3\text{He})D$ was used for plasma heating in recent experimental campaigns on Tore Supra,. The measured rotation characteristics for discharges in these campaigns are
consistent with the conjecture above, i.e. discharges with (\(^3\)He)D were found to rotate in the co-\(I_P\) direction whereas most discharges with (H)D were found to rotate in the counter-\(I_P\) direction. Figs. 1 and 2 show overviews of two typical discharges, one with (\(^3\)He)D heating with \(B_T=3.86\)T, \(I_p=1.4\) MA, \(f_{ICRF} = 42\)MHz, and the second with (H)D heating with \(B_T=3.64\)T, \(I_p=1.2\) MA, \(f_{ICRF} = 57\)MHz. The cyclotron resonances were at around 15 and 5 cm on the high field for \(^3\)He and H respectively. When the ICRF power is switched on, the plasma is accelerated in the \(I_P\) direction for the \(^3\)He discharge and in the counter-\(I_P\) direction for the discharge with hydrogen minority heating. In contrast to earlier reported cases of co-\(I_P\) rotation in Tore Supra [5], the \(^3\)He minority case has normal L-mode confinement, i.e. an improved confinement regime does not seem to be necessary for having co-\(I_P\) rotation in Tore Supra (c.f. JET L-mode plasmas [7]).

The discharges with co-\(I_P\) rotation are particularly interesting since rotation in this direction is rather difficult to explain and has been observed on both JET [2] and Alcator C-Mod [3, 4]. We have constructed a data base comprising 15 discharges, with several points per discharge, from the series with \(^3\)He minority heating. The change in the toroidal rotation velocity is found to correlate well with the diamagnetic stored energy divided by \(I_P\), see Fig. 3. The statistics, although a bit limited, are sufficient to establish the \(1/I_P\) correlation, Fig. 4.

**DISCUSSION.** It is interesting that co-\(I_P\) rotation has been observed in three quite different tokamaks [2-5]. Important differences between the machines include that both JET and Alcator C-Mod are equipped with divertors while limiter plasmas are operated in Tore Supra. Moreover, the collisional regimes are quite different. Alcator C-Mod is normally operated with high plasma densities. This leads to highly collisional plasmas, especially in the edge region which can easily be in the Pfirsch-Schlüter regime [8]. JET is normally run with moderate densities, and its plasmas are mostly in the banana regime. Tore Supra falls in between JET and Alcator C-Mod in this respect, but is closer to JET. The scaling displayed in Fig. 3 is interestingly the same as reported for H-mode plasmas in Alcator C-Mod, and also similar to findings in ICRF heated H-mode plasmas on JET [2]. If the origin of the co-current rotation is the same in the three tokamaks, this would suggest that it is not related to the existence of a divertor or strongly linked to the collisional regime.

Let us now briefly look at three possible theoretical explanations for co-current rotation in plasmas without external momentum injection. The basic form of the theory for fast ion induced rotation [9] predicts counter \(I_P\) rotation for cyclotron resonances located on the high field side, which is not consistent with co-\(I_P\) rotations shown in Fig. 1. The neo-classical
theory used to explain co-current rotation in Ohmic H-mode plasmas in Alcator C-Mod [8] should be an important component also for ICRF heated plasmas. However, the presence of an H-mode and an edge plasma in the Pfirsch-Schlüter regime are important factors in this theory. Since the discharges presented here were in L-mode and Tore Supra is closer to the banana regime, this theory does not seem applicable to them.

![Fig. 3 Change in rotation velocity as a function of $\Delta W_{\text{dia}}/I_p$.](image1)

![Fig. 4 Change in rotation velocity as a function of $W_{\text{dia}}$ for different currents.](image2)

The so called accretion theory for plasmas rotation [10] explains co-current rotation in H-mode plasmas with a change in the turbulent activity at the plasmas edge. For L mode plasmas it predicts counter current rotation. Hence, the co-$I_p$ rotation in Tore Supra L-mode plasmas cannot be explained by the theory. It does not necessarily mean that the theory is wrong, it could well explain the acceleration of the plasma at an L-H transition.

In conclusion none of the theories referred to above seems capable of explaining all the reported observations of co-current rotation in JET, Alcator C-Mod and Tore Supra. It is possible that several mechanisms are involved, coincidentally leading to similar scalings in the three machines. Alternatively, a more general explanation, yet to be clarified, exists.

**References**