Co- and Counter-Current Rotation Induced in Tore Supra Plasmas with LHCD

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Introduction

Plasma rotation in tokamaks has been an area of active interest in the past few years, because of its impact on magneto-hydrodynamic (MHD), transport and plasma performance. In particular, if the rotation is associated with sufficiently large E×B shear, it could stabilize turbulence [1] and lead to enhanced energy and particle confinement as observed in plasmas with transport barriers. Also, large enough toroidal rotation may help to stabilize resistive wall modes instabilities [2]. Strong plasma rotation is often provided by Neutral Beam Injection (NBI). However, NBI induced torque is expected to be low in ITER [4] (partly due to the high injection energy E_{inj} required, since the injected momentum scales as P_{NBI}/E_{inj}^2). Hence, exploring the mechanisms underlying "intrinsic rotation", i.e. a plasma rotation that develops in the absence of any externally applied torque, is of prime interest in order to be more confident with predictions for plasma rotation in ITER and future machines. Intrinsic plasma rotation can be understood as resulting from the competition between several effects: MHD effects, turbulent transport processes, fast particle effects and 3D effects such as those induced by resonant magnetic perturbations or ripple. We focus here on intrinsic plasma rotation behaviour in lower hybrid current drive (LHCD) plasmas. Dedicated experiments have been performed in Tore Supra, a large size tokamak ($R_0 \sim 2.4$m, $a \sim 0.7$m) with negligible external momentum input ($P_{DNBI} \sim 350$kW), a strong magnetic field ripple (~5% at the last closed magnetic surface) and a large radio frequency (RF) heating capability with up to 9 MW of ICRH power and 5 MW of lower hybrid (LH) power.

Experimental results

The plasmas to be discussed here were performed in L-mode in a limiter configuration, at magnetic field $B_t = 3.8$ T, plasma current I_p up to 1.22 MA, line averaged electron density n_l up to 6×10^{19} m^{-2} , LH power up to 5MW, q_{edge} ranging from 2.5 to 8. Toroidal rotation profiles are measured by charge exchange recombination spectroscopy. The system uses a NBI diagnostic and provides radial profiles of T_i and V_φ from C_{VI} spectral line analysis. Fifteen tangential viewing lines are used, with spatial resolution ranging from 2cm at the plasma edge, to 6cm in the core [5], the typical time resolution being set between 10 and 50ms.

Plasma rotation is investigated in two sets of plasma discharges, at high (1.2 MA) *resp*. low (0.7 MA) I_p, with $n_l = 5.3\text{-}5.9 \times 10^{19}$ m^{-2} *resp*. $n_l = 3.5 - 3.9 \times 10^{19}$ m^{-2}, $P_{LH} = 1 - 4.8$ MW, $n_{//} \sim 1.8$. When the LH power is applied, a significant increment of plasma toroidal rotation appears in the co- or counter-current direction, depending on the plasma current amplitude. At low plasma current (0.7 MA) a co-current increment is observed (Figure 1.a), increasing with the injected LH power. Also, it is worth noting that the profile is affected across the whole plasma minor radius, with a maximum effect observed in the core plasma region with an increment of about +15 km/s. The plasma core velocity remains in the counter-current direction, while the edge plasma rotation (r/a > 0.8) is co-current in the highest power case. There is no sawtooth activity (according to the ECE measurement) in this set of LHCD plasma discharges (sawteeth are stabilized when LH power is applied), the q profiles are slightly reversed in the plasma core with q_0 above 1 according to CRONOS [6] simulations (Figure 2).

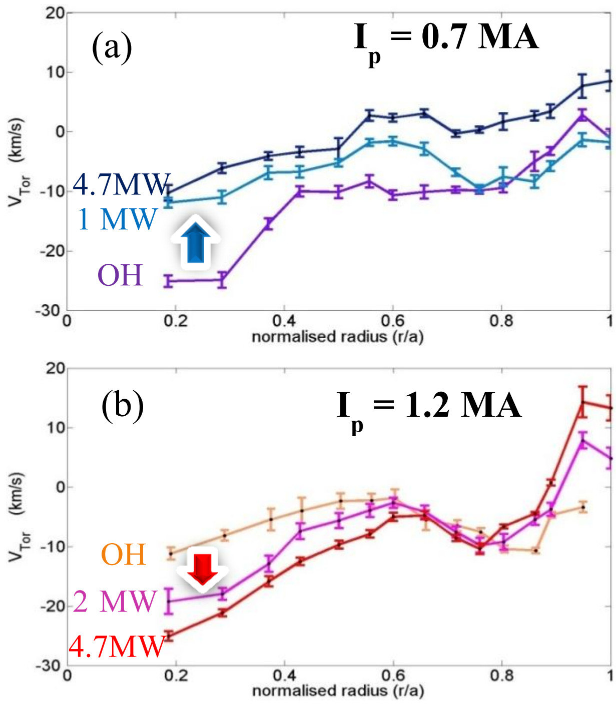

Figure 1. Toroidal rotation profiles modifications with LH power injection from ohmic to LHCD plasmas, at low plasma current (**a**) and high plasma current (**b**).

At high plasma current (1.2 MA), an opposite trend is observed. The core plasma rotation increment is in the counter-current direction with a maximum effect of about -15 km/s in the core plasma region (Figure 1b) at high LH power. It is worth noting that in this case, the profile remains unaffected for 0.6<r/a<0.9. At the very plasma edge (r/a > 0.9) the velocity increases in the co-current direction with the LH power (similar trend observed in the low plasma current case). This time, sawteeth are observed in this set of plasma discharges (ECE), and the q profiles are monotonic with q_0 slightly below 1 (Figure 2).

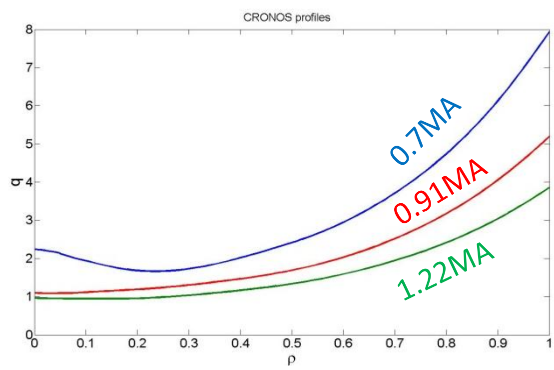

Figure 2. Typical q-profiles simulated by CRONOS for high, intermediate and low plasma current discharges during the LHCD phase, for the plasma set discussed here.

In order to investigate further such a bi-directional effect of LH on plasma rotation, the core plasma rotation (r/a<0.35) behavior at different plasma currents (ranging from 0.6 MA to 1.22 MA) is illustrated in Figure 3. It shows the change in the core rotation (the velocity difference between the LHCD and the ohmic phases) as a function of the plasma current, for discharges with B_t = 3.8 T, $n_l \sim 3.8 \times 10^{19}$ m^{-2} and LH power between 2 MW and 4.5 MW. A threshold in the plasma current amplitude is observed, the rotation increment switching from co- to counter-current when the plasma current increases. The observed stagnation point (i.e. where the core rotation is not affected by LH injection, velocity change ~ 0 km/s) corresponds to $I_p \sim 0.95$ MA for this range of parameters.

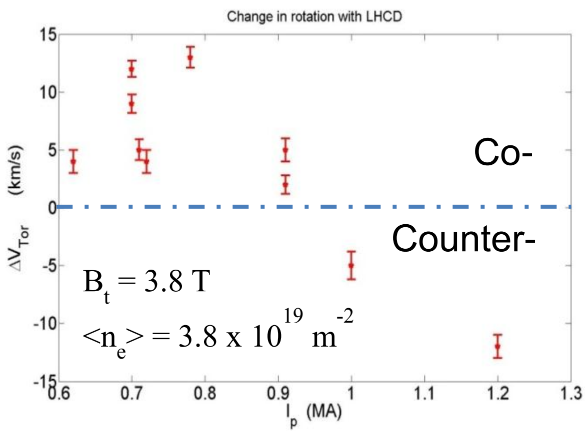

Figure 3. Core rotation change due to LHCD injection versus plasma current. All data are at fixed density. Experimental position of the intrinsic plasma rotation reversal is at **I_p ~ 0.95 MA.**

Discussion

Core plasma observations at low plasma current are similar to those of C-Mod [7], JET [8], JT-60U [10] and EAST [9]. However, the counter-current increment of plasma rotation (high plasma current case) has only been reported in C-Mod so far [7]. In C-Mod, the core velocity stagnation point is found at I_p = 0.4 MA, in LSN (0.6MA in USN) plasmas with very different plasma conditions: B_t =5.4T, $n_e = 6.6\times 10^{19}$ m^{-3} and P_{LH} = 0.8MW [7].

Significant theoretical efforts are made to understand the LH induced rotation at low and high plasma currents. In Tore Supra LH heated discharges, the rotation behavior likely results from the competition between several possible mechanisms at play, as fast electron effects, turbulence driven mechanism effects, ripple-induced effects, MHD effects, and direct LH wave effects. As mentioned above, Tore Supra operates at high ripple amplitude (typically, up to 5 % at the plasma boundary). The ripple-induced fast electron ripple losses yield to a return current directed inward, carried by ions, in order to maintain the ambipolarity condition. This return current induces a $J_{ripple} \times B$ torque in the co-current direction. However, despite the strong ripple amplitude in Tore Supra, experimental measurements of ripple loss current [11] indicate that such a mechanism has an overall weak effect, and cannot by itself explain the co-current increment observed at low I_p. Another ripple-induced term contribution comes from the ripple-induced neoclassical friction associated to thermal particles, due to the friction on trapped particles in ripple wells. The toroidal friction can be written as $-n_s m_s \nu_{neo}\big(V_{s\varphi} -$

kV_T^*) with n_s, m_s the density and the mass of the particle, ν_{neo} the friction rate and k the proportionality coefficient (detailed expressions can be found in [12, 13]) and $V_T^* = \frac{\nabla_r T_i}{eB_\theta}$ is the toroidal diamagnetic velocity. For the plasma parameters discussed here, the latter term can be responsible for a toroidal rotation increment in the counter-current direction of about -10 km/s. Another possible mechanism deals with momentum transfer between the LH waves and electrons. The input torque from the LH wave can be approximated as $T_{LH} \sim \frac{R n_{\|} P_D}{c}$ [8] with $n_{\|}$ the parallel refraction index of the antenna, P_D the injected power and c the phase velocity which can be approximated by the speed of light. The absorbed wave momentum in plasma region up to r/a = 0.7 (i.e. where the hard-X ray absorption occurs) leads to a change in the toroidal rotation directed in the counter-current direction of about -3 km/s, which is not negligible. Momentum fluxes can also be driven by turbulent transport processes. In this case, the radial direction of the fluxes depends on the dominant turbulent modes present in the plasma, such as ion temperature gradient (ITG) or trapped electron mode (TEM). This mechanism could partly explain the rotation increment reversal observed between low and high plasma current configurations. Different q profiles are observed for low / high plasma current discharges as reported above. A change in the sign of the turbulent Reynolds stress, through a change in the sign of the residual stress (which depends on the plasma magnetic shear as detailed in [2]), could also be considered. Finally, the link between the observed rotation behavior and the presence or not of sawteeth is not clear. Those theoretical mechanisms and quasi-linear gyro-kinetic simulations with QualiKiz [14] are presently under investigation.

References

[1] Burrell K.H. 1998 *Science* 281 1816
[2] A.M.Garofalo *et al* 2001 *Nucl. Fusion* 41 1171
[3] P.H. Diamond et al. PD/P8-19 (2013)
[4] E. Doyle, 2007 *Nucl. Fusion* 47 S18–S127
[5] C. Gil *et al,* 2009 *Fusion Sci. Technol.* 56 1219
[6] JF. Artaud et al, 2010 Nucl. Fusion 50 043001 doi:10.1088/0029-5515/50/4/043001
[7] Y.A Podpaly et al. PSFC/JA-11-30 (2011)
[8] L.-G. Eriksson et al. EFDA-JET-PR(08) 10
[9] Y.Shi et al., Phys. Rev. Lett. 106 (2011) 235001
[10] Y.Sakamoto *et al.*, 2006 *Plasma Phys. Control. Fusion* 48 A63
[11] V. Basiuk et al., Nucl. Fusion 41, No. 5 (2001)
[12] X. Garbet et al., Physics of Plasma 17, 072505 (2010)
[13] C. Fenzi et al., Nucl. Fusion 51,103038 (2011).
[14] C. Bourdelle *et al.*, *Phys. Plasmas*, **14 (**2007**)** 112501.