Investigations on LHCD induced plasma rotation in Tore Supra

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Introduction

Toroidal rotation is recognized to play an important role in heat transport and magnetohydrodynamic (MHD) stability in tokamaks plasmas. The $E \times B$ shear component due to toroidal flow influences turbulence in the plasma and contributes to the improvement of heat and particle transport, while toroidal rotation helps on MHD instability stabilization such as resistive wall modes and neoclassical tearing modes. Even in the absence of any applied torque, the plasma can still exhibit finite so-called intrinsic rotation. It is supposed to result from the competition between several effects: MHD effects, turbulent transport processes, fast particle effects and 3D effects such as ripple. Hence, exploring the mechanisms underlying intrinsic rotation is of prime interest in order to improve the predictions for plasma rotation in ITER and future machines where the external momentum input will be negligible [1].

Experimental and theoretical investigations are reported in order to understand the plasma rotation increments induced by lower hybrid current drive (LHCD) in Tore Supra [2]. Counter current toroidal rotation profiles ($V_\varphi < 0$) are reported in ohmic and LHCD discharges. During the LHCD phase (with P_{LH} up to 4.8 MW), an acceleration ($\Delta V_\varphi < 0$) of about -15 km/s is observed in the core plasma rotation (r/a < 0.3) at high plasma current (I_p = 1.2MA). At lower plasma current (I_p = 0.7MA), an opposite trend is observed with a deceleration ($\Delta V_\varphi > 0$) of the plasma rotation of about +15 km/s [2]. Starting from the momentum balance equation and a detailed description and evaluation of all the possible mechanisms at play in Tore Supra LHCD plasmas, a theoretical approach is proposed in this paper.

Momentum balance

The toroidal plasma rotation of ions is described by the toroidal momentum balance equation which is composed by different contributions: Laplace force, neoclassical friction, external sources and the toroidal angular momentum which counts for momentum transport. In the following, the evolution of all these mechanisms during LHCD will be reviewed.

Ripple induced force contributions

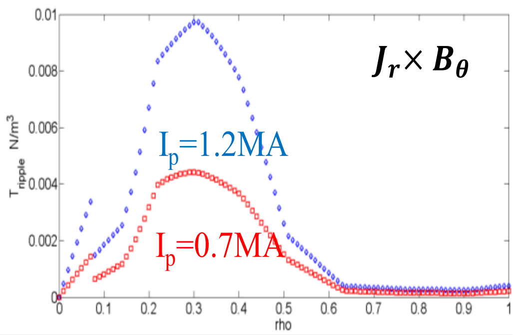

Figure 1 : Toroidal momentum due to the Laplace force at high and low plasma current discharges. As expected, the Laplace force effect is larger at high plasma current.

Ripple induced forces are namely the neoclassical friction and the Laplace forces. Two plasma regions depending on particle trajectories and whether they are or not affected by ripple, can be distinguished. First, the locally trapped particles region where the dominant mechanism is related to the Laplace force $j_r \times B_\theta$ induced by the fast electron ripple losses (generated during the LH phase and experimentally measured [3]) and carried by ions in order to ensure the plasma ambipolarity. As illustrated in Figure 1, the toroidal momentum component due to the Laplace force peaks at *r/a* ~ 0.35 with an amplitude of $M_{Jripple \times B} \approx 4.10^{-3} N/m^3$ *resp.* $9.10^{-3} N/m^3$at I_p = 0.7MA *resp.* 1.2 MA. The ripple induced momentum is larger at high I_p, which is consistent with larger fast electron ripple losses at high I_p. A simple estimation of the toroidal rotation which can be driven by this mechanism can be obtained balancing the ripple induced momentum by the total momentum stored into the plasma and yields $M_{ripple} = 2V_\varphi m_i n_i / \tau_\phi$, which corresponds to a rotation increment of about ΔV_φ = + 4 - 7 km/s in the co-current direction ($\Delta V_\varphi > 0$, e.g. deceleration). Second, the plasma banana trajectory particle domain is related to particles following banana orbits. The banana tips can be perturbed when entering the ripple well regions, and experience a vertical drift. Thermal particles are particularly sensitive to this mechanism, and collisional processes will allow them to be de-trapped eventually. In order to compensate the resulting thermal ion radial current loss and maintain ambipolarity, the radial electric field E_r adjusts itself and yields a ripple-induced neoclassical toroidal damping force reading as T_{neo} =

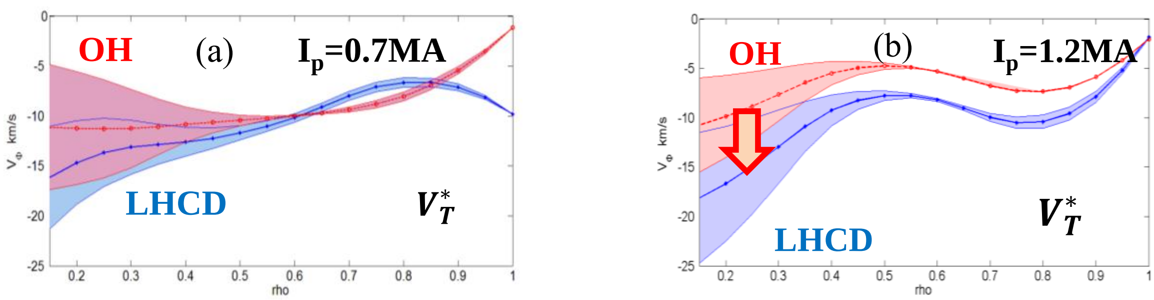

Figure 2 : Toroidal diamagnetic velocity $V_T^* = \frac{\nabla_r T_i}{e B_\theta}$ for OH and LHCD discharges at low Ip (a) and high Ip (b). A clear counter-current increment is observed at high plasma current.

$-n_i m_i \nu_{neo}\left(V_{i\varphi} - k_T V_T^*\right)$ where k_T is a constant related to the collisionality regime, $V_{i\varphi}$ the ion toroidal velocity, $V_T^* = \frac{\nabla_r T_i}{eB_\theta}$ is the toroidal diamagnetic velocity (with T_i, the ion temperature, $B_\theta$the poloidal magnetic field and e the proton charge) and ν_{neo} is the damping rate [5, 6]. As illustrated in Figure 2, the diamagnetic toroidal rotation profiles (inferred from experimental measurements) are non-monotonic, in the counter-current direction, and rather consistent (shape, magnitude, direction) with the experimental toroidal velocity profiles [3]. At high I_p, a significant counter-current change (ΔV_φ ~ -10km/s e.g. acceleration) in V_T^* is observed (Figure 2b), likely due to an increase in T_i during the LHCD phase, hence suggesting that the thermal neoclassical ripple-induced friction could play an important role in those type of plasmas.

Wave momentum source contribution

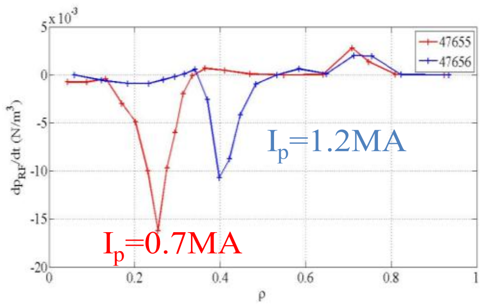

Figure 3 : LH wave momentum transferred to the plasma calculated by LUKE at low (0.7 MA) and high (1.2 MA) plasma current, consistent with calculated power deposition profiles.

This mechanism deals with the momentum transfer S_{LH} between the LH waves and the plasma through the electrons. The absorbed wave momentum in the core plasma region (i.e. where the LH wave deposition occurs) leads to a very localized change in the toroidal rotation directed in the counter-current direction of about -8 km/s, as highlighted by LUKE simulations in Figure 3.

Turbulent momentum transport (Reynolds stress) contribution

The parallel momentum flux consists of both a particle transport driven term and the Reynolds stress. In the following, only the Reynolds stress is taken into account and the

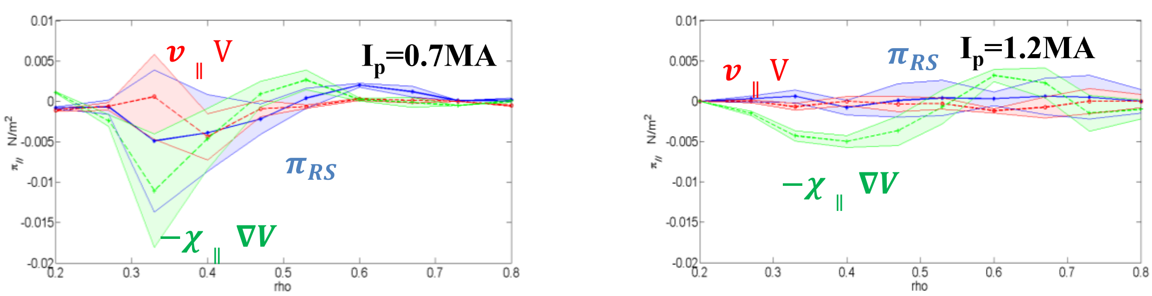

Figure 4 : Reynolds stress components at low (a) and high (b) plasma current. At high plasma current the momentum flux is purely diffusive, while at low plasma current the residual stress term rises.

parallel momentum flux can be formally written as: $\pi_{i\parallel} = -\chi_{\parallel}\nabla_r V_{\parallel} + \upsilon_{\parallel} V_{\parallel} + \pi_{RS}$ where $\chi_{\parallel}$ is the turbulent viscosity, $\upsilon_{\parallel}$ the velocity pinch and π_{RS} is the residual stress source. The different contributions to the Reynolds stress calculated by the quasi-linear solver code TGLF [7] are shown in Figure 4. At low I_p, the residual stress term clearly rises comparing to the high I_p case where it remains negligible. The divergence of the residual stress acts as a force in the co-current direction. This term can be responsible for a change in rotation of about ~ +15km/s (co-current direction, i.e. deceleration).

Momentum balance and resulting effects

In this section, all the analyzed contributions to the intrinsic toroidal rotation during the LHCD scenarios are put together. The results are illustrated in Figure 5 . The subtle competition between the mechanisms described above shows that in LHCD plasmas, the toroidal torque is governed by the neoclassical mechanisms at high I_p with a resulting net torque increment in the counter-current direction (red curve, Figure 5a), while it is dominated by turbulent transport processes through the residual stress source at low I_p with a net rotation torque in the co-current direction (red curve, Figure 5b). Moreover, transport simulations performed by CRONOS (including all the torque contributions describes above) confirm that all the major ingredients at play have been taken into account, the inferred rotation profiles being consistent with the experimental observations.

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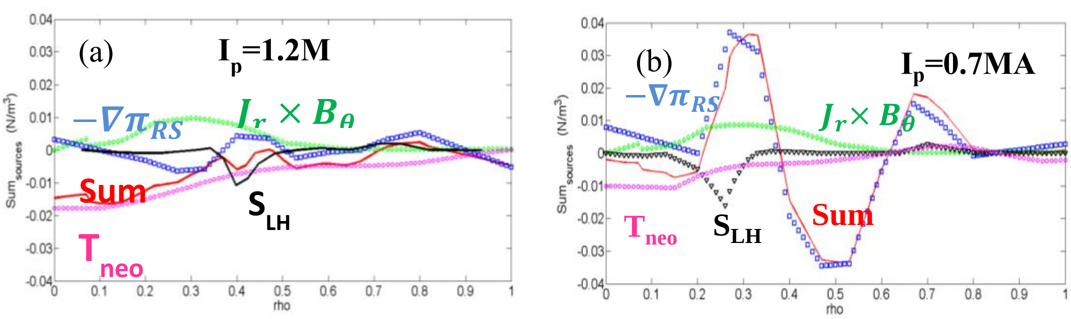

Figure 5 : The different sources (Laplace force, residual stress, neoclassical friction and LH wave source) contributing to the momentum balance equation during the LH-heating. The total source is also showed (red solid curve). We can see that at high I_p *the total source is close to the neoclassical force (a), while at low plasma current it is close to the residual stress (b).*