Toroidal magnetic field ripple and fast particle effects on plasma rotation in Tore Supra

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INTRODUCTION. Intrinsic plasma rotation (with no external momentum input as driven by NBI) can be understood as resulting from a competition between turbulent transport processes, MHD effects, fast particle effects and the ripple-induced toroidal friction. We focus here on the ripple-induced toroidal friction effect on plasma rotation, in Ohmic L-mode and RF heated plasmas. Whether or not the ripple induced particle fluxes could have a non negligible effect on plasma rotation remains a critical issue, in particular in view of ITER where external momentum input will be negligible. Consequently, understanding plasma rotation with low momentum input and its relationship to TF ripple, fast particles and associated neoclassical effect is particularly important. Tore Supra appears to be well suited to address those issues: it is a large size tokamak with negligible external momentum input (P_{DNBI} ~350kW), a strong magnetic field ripple (up to 7% at the plasma boundary) and a large RF heating capability (up to 8 MW of ICRH and 5 MW of LHCD). Recent results on intrinsic plasma rotation are reported here.

MEASUREMENT TECHNIQUE FOR PLASMAS ROTATION IN TORE SUPRA. Rotation profiles are measured with the Charge eXchange Recombination Spectroscopy (CXRS) system, assuming that the carbon impurity has the same velocity and temperature as the main ions. Fifteen tangential viewing lines are used, with 2 cm spatial resolution at the plasma edge and 6 cm in the core. Short and low power beam pulses are used for the measurements (300ms beam pulse, injected energy E_{inj} ~ 55keV, power P ~ 350kW, perpendicular injection), so that the momentum carried out by injected particles can be neglected. Additional information on the central average velocity is provided by high resolution time-resolved X-ray spectra of heavy He-like ions (mainly Cr and Fe intrinsic impurity spectra, 1.85 – 2.2Å spectra), measured with a Johan type cylindrically curved crystal spectrometer.

RIPPLE EFFECT IN OHMIC PLASMAS. The plasmas to be discussed here were performed in Ohmic *L*-mode (no fast particles, we focus here on ripple-induced thermal particle loss effect), at B_T = 2.1T, the toroidal magnetic field and plasma current being directed clockwise. In order to vary the ripple amplitude, the size of the plasma was varied with a minor radius ranging from 55cm to 72cm, while the plasma current was adjusted between 0.5MA and 0.85MA with central density $n_{e0} = 4 – 4.5\times10^{19}\mathrm{m}^{-3}$ in order to keep the edge safety factor q_a~3.3 constant and similar plasma edge properties. In consequence, the TF ripple magnitude could be varied from ~ 0.5% to 5.5% at the plasma boundary (Figure 1). As illustrated in Figure 1, the whole plasma appears to rotate in the co-current direction (positive velocity) at low ripple amplitude (δ = 0.56%). When the ripple amplitude increases, the toroidal rotation velocity evolves towards a pure hollow counter-current rotation at the highest ripple amplitude (δ= 5.52%) [1]. This behaviour is consistent with JET [2] and JT-60U [3] observations, and similar to static non resonant error field perturbation effect on toroidal rotation reported in DIII-D [4]. Comparisons with neoclassical predictions accounting for the ripple-induced thermal toroidal friction ($V_\phi = k_T \nabla T_i / eZ_i B_\theta$ with k_T = 1.67, "ripple-plateau regime", see [5] for more details) are detailed in Figure 2 for ripple amplitudes δ= 0.56%, 1.62%, 5.52%. When the ripple amplitude increases, the toroidal velocity clearly evolves towards the neoclassical prediction with a good agreement in term of magnitude and direction in the highest ripple case [1]. A coherent picture can be clearly illustrated by the evolution of V_Φ with δ_{loc} (Figure 3), δ_{loc} being the local TF ripple at the CXRS measurement locations. At low ripple value (δ= 0.56% case) V_Φ is co-current (hence not neoclassical, see [5]) and can be understood as dominated by turbulence driven contributions. When the ripple amplitude increases, the ripple-induced thermal toroidal friction becomes strong enough to overcome turbulence driven terms and the velocity converges towards the counter-current neoclassical value (δ= 5.52% case) [1].

FAST PARTICLE EFFECT IN RF HEATED PLASMAS. The observations above are modified in presence of fast particle effects, as in RF heated plasmas. In Tore Supra ICRH plasmas with standard ripple amplitude (~5.5% at the plasma boundary), toroidal velocity profiles are found to be peaked and increase with the ICRF power in the counter-current direction (Figure 4) as observed in JET [6] and JT60U [3], not mentioning here some particular plasma cases with high H-minority fraction (~6%) and ion improved confinement (hence reduced ripple losses), where the averaged central toroidal rotation was observed to increase in the co-current direction [7-8]. The former behaviour (leading to larger counter-current rotation) is consistent with fast ion loss mechanisms (although other mechanism can not be excluded). Fast ion losses increase with the averaged energy of the resonating ions, and lead to the onset of a radial current J directed outwards, which must be compensated for by an opposite current in the background plasma to ensure quasi neutrality. As a result, the background plasma experiences a $J\times B$ torque in the counter-current direction, so that the total toroidal momentum is conserved. Fast ion effect has been previously investigated in Tore Supra during H-minority and He_3 minority ICRH plasma experiments aiming at varying the fast ion ripple loss fraction [9]. More recently, it has been investigated during dedicated experiments with giant sawteeth events. Preliminar results suggest that the velocity profile is relaxed inside the q=1 surface as the fast ion population is expelled from the q=1 surface (sawteeth crash), then increases in the counter-current direction while the fast ion population is rebuilding (Figure 5). MHD data and magnetic shear are being investigated to better characterize the rotation behaviour. Finally, fast electron effect on plasma rotation has been investigated on LHCD plasmas. As illustrated in Figure 4, adding LH heating usually strongly affect plasmas rotation profiles, leading to a clear toroidal velocity increment in the co-current direction over a plasma region consistent to that of LH deposition layer (according to hard X-ray measurements), which is consistent with JET [6] but opposite to C-Mod [10].

SUMMARY AND CONCLUSION. The ripple induced thermal loss effect on plasma rotation has been investigated in a set of Tore Supra Ohmic L-mode plasmas, and first comparisons with neoclassical predictions including ripple have been performed. The toroidal velocity agrees well with the neoclassical prediction at high ripple value, while it is found to be not neoclassical at low ripple. More generally, the toroidal flow dynamics can be understood as being likely dominated by turbulence transport driven processes at low ripple amplitude, while the ripple induced toroidal friction becomes dominant at high ripple. In RF heated plasmas, the rotation profile is generally found to be peaked and counter-rotating with ICRF, while it is found to increment in the co-current direction in LHCD plasmas. Additional experiments and transport code simulations are foreseen to better investigate the mechanism underlying those observations.

References

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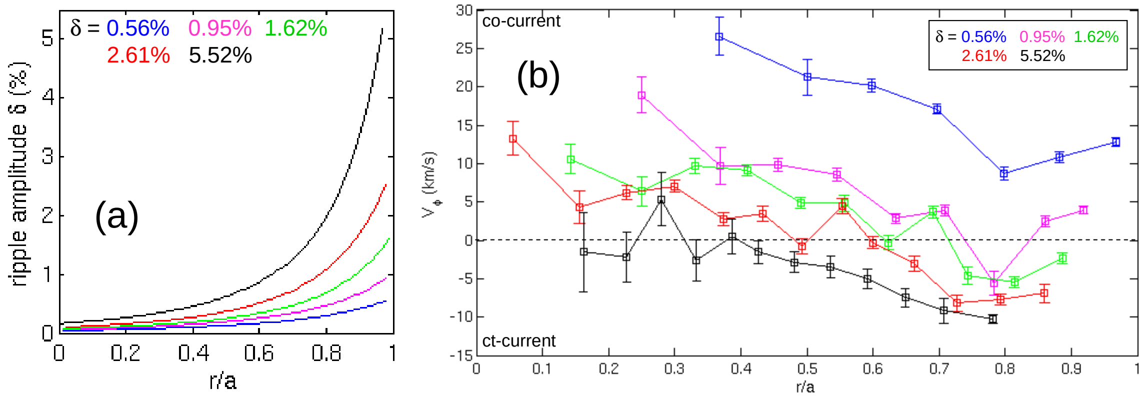


Figure 1 : Ripple amplitude profiles (a) and toroidal velocity profiles evolution (b) with increasing ripple amplitude.

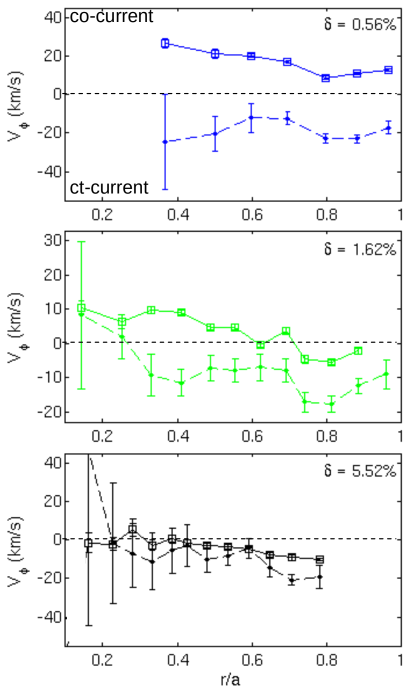


Figure 2 : Neoclassical prediction of toroidal plasma rotation with increasing ripple amplitude and comparison with measurements.

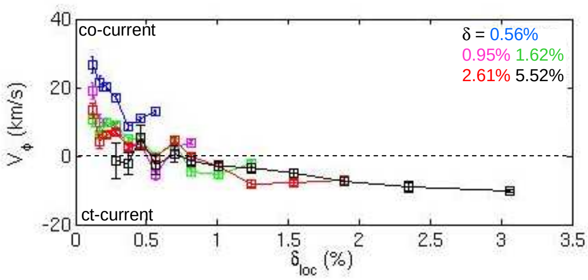
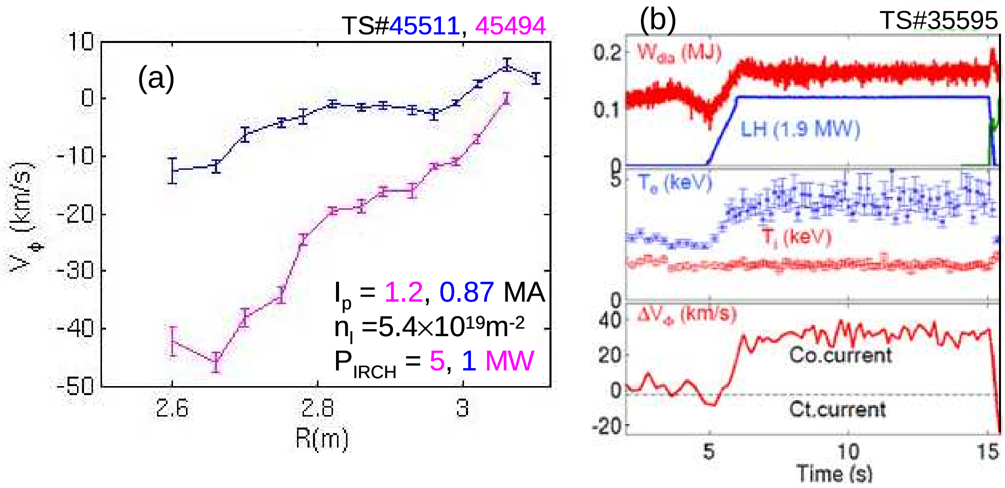


Figure 3: Toroidal velocity evolution with the local ripple amplitude (at the measurement location) δ_{loc}.



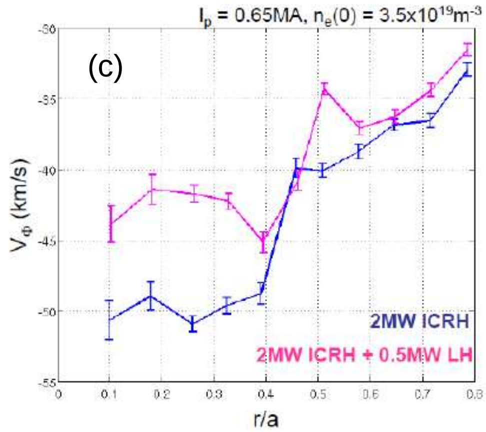
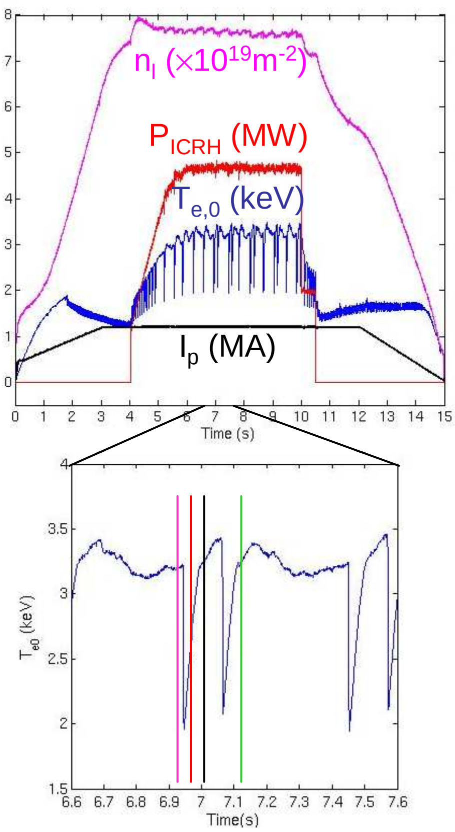


Figure 4 : Peaked and counter-rotating profiles in standard ICRH plasmas (a), and co-current velocity increment with LH heating as observed with X-ray spectroscopy measurements (b) and CXRS measurements (c).



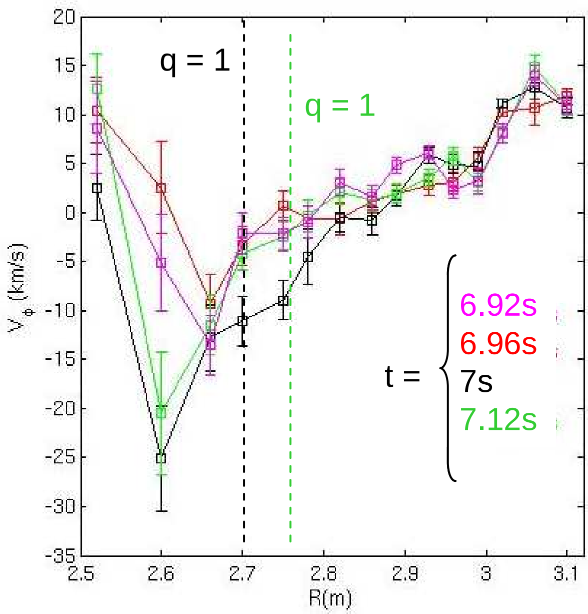


Figure 5: Typical toroidal velocity evolution over a giant sawteeth crash, just before (t=6.92s), just after (t=6.96s), after (t=7s, 7.12s).