Interplay between plasma rotation and magnetic field perturbations in RFX-mod tokamak plasmas

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Introduction. Plasma rotation can have a beneficial effect on plasma stability and confinement. For example, it is important to stabilize neoclassical tearing modes [1] and resistive wall modes [2]. Moreover, a plasma rotation shear is a key factor for turbulence suppression and the formation of transport barriers, which are important to realize high-performance regimes [3]. In present day devices, a significant external momentum source can be provided by Neutral Beam Injection (NBI). However, in ITER and future reactors, NBI is not expected to provide much external momentum. Consequently, it is of interest to consider other mechanisms to inject momentum, as those underlying the intriguing so-called intrinsic plasma rotation [4]. The RFX-mod device, operated as a tokamak [5,6], can contribute to the study of the various effects responsible for momentum injection and transport. This study investigates how the plasma rotation behaviour can be affected by magnetic field perturbations due to MHD instabilities, such as resistive wall modes and tearing modes, or externally applied through magnetic feedback. In such plasmas, the spectrum of magnetic perturbations is obtained by Fourier analysis of 192 radial, poloidal and toroidal magnetic field measurements. The flow has been measured by passive Doppler spectroscopy. The considered impurities are C VI, the main impurity coming from the graphite first wall, and O V. The reconstruction of the ion emissivity is obtained by a 1-D collisional-radiative code [7]. The simulations suggest that the C VI emissivity is rather spread over the minor radius with a broad peak at about mid radius, $r/a \approx 0.35$. Instead, the O V emissivity is relatively sharply peaked near the edge, $r/a \approx 0.8$.

Plasma rotation in presence of a 2/1 RWM. RFX-mod can operate as a tokamak with safety factor $q(a)<2$ thanks to magnetic feedback control of the 2/1 RWM [5,6]. Such mode can be completely stabilized when the magnetic feedback variable is the 2/1 edge radial magnetic field amplitude, $b_r^{2/1}$, de-aliased by sideband contributions which are inevitably present due to the finite number of actuators. If such harmonics are not taken into account in the feedback algorithm, the magnetic feedback control is not optimized: the 2/1 RWM grows in amplitude, finally leading to a plasma disruption. Passive spectroscopy reveals that the toroidal rotation is affected by the 2/1 RWM. Figure 1(a) shows the 2/1 edge radial magnetic field amplitude normalized to the equilibrium field, $b_r^{2/1}/B_t$, as a function of toroidal plasma rotation, deduced from C VI and O V impurities marked in the graph with square and triangle symbols, respectively. In the plasmas highlighted in magenta, which are characterized by the presence of an unstable 2/1 RWM, as the amplitude of the mode increases, the toroidal flow at first decelerates and then reverses from counter- to co-I_p direction (negative values correspond to rotation in counter-I_p direction). This rotation dependence is governed only by the 2/1 RWM amplitude and not by other plasmas parameters, since in the set of analyzed discharges very similar values of q(a) and density have been chosen. The plasma rotation braking, detected both in C VI and O V measurements, is also observed when the 2/1 RWM is kept at finite amplitude by mean of externally applied magnetic field perturbations with 2/1 helicity, as shown by the plasmas highlighted in green in the figure. A 1-D momentum transport model has been developed taking into account the physical mechanisms that can play a role in these plasmas, such as the neoclassical toroidal viscosity force, the radial electric field due to stochasticity induced at the plasma edge, and the friction force due to neutrals coming from the wall, which will be described in more detail elsewhere [8]. The model suggests that the stochastic force gives the largest contribution in determining the toroidal flow reversal in the plasmas under investigation. The radial

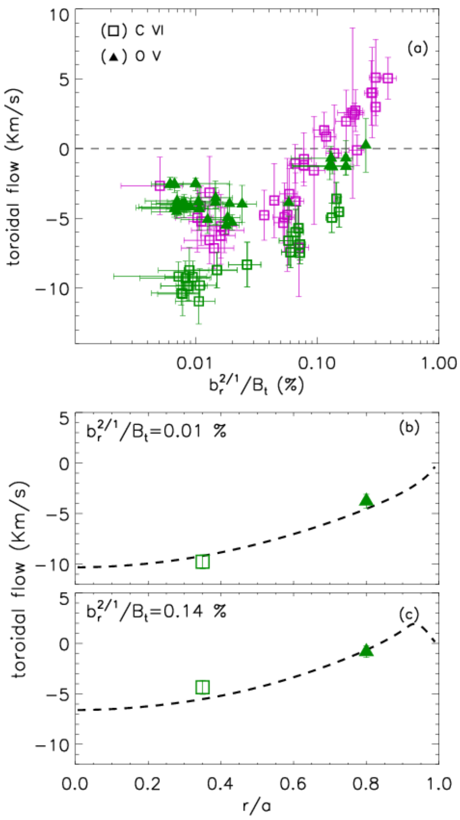

Figure 1. (a) Toroidal rotation as a function of $b_r^{2/1}/B_t$ for two sets of similar q(a) < 2 tokamak discharges. The shots in green indicate discharges with externally applied magnetic field perturbations, the magenta ones discharges with an uncontrolled 2/1 RWM. (b)-(c) Radial profile of the toroidal rotation, solution of the 1D momentum transport model described in the text, with and without 2/1 magnetic field perturbations applied.

profiles of the toroidal flow, solutions of the model for the cases without and with externally applied magnetic field perturbations, are plotted in Figure 1(b)-(c) respectively with dashed line, the mean rotation from C VI and O V measurements with symbols. Note the good agreement between the model and the experiment.

Plasma rotation in presence of a 2/1 tearing mode. Plasma experiments with q(a)>2 have been performed in RFX-mod. A 2/1 rotating tearing mode is present in these plasmas and can lock causing a disruption. Magnetic feedback interacts with this mode. For example, it has been observed experimentally that the 2/1 tearing mode can transit from the fast rotation branch (some kHz) to the slow one, imposed by magnetic feedback control (some Hz), depending on the amplitude of the radial magnetic field at the resonant surface, as predicted theoretically in [9]. The plasma rotation is affected by the 2/1 tearing mode dynamics when it rotates in the slow frequency branch (or it has non negligible amplitude). An example is the plasma experiment reported in Figure 2 on the left. As the magnetic equilibrium is approaching the q(a)=2 resonance, the 2/1 tearing mode increases in amplitude (in black) and the plasma rotation (in blue) decelerates. As soon as the mode jumps in the fast rotation branch, the plasma rotation accelerates in counter-I_p direction towards its unperturbed value (-4km/s). Instead, in conditions where the plasma is less resilient to error fields (low-density regimes) or in experiments aiming at exploring high-density scenarios (near the Greenwald density limit), the plasma rotation brakes due to the presence of a locked 2/1 tearing mode. As reported in Figure 2 on the right, as the plasma density reaches the Greenwald limit, the

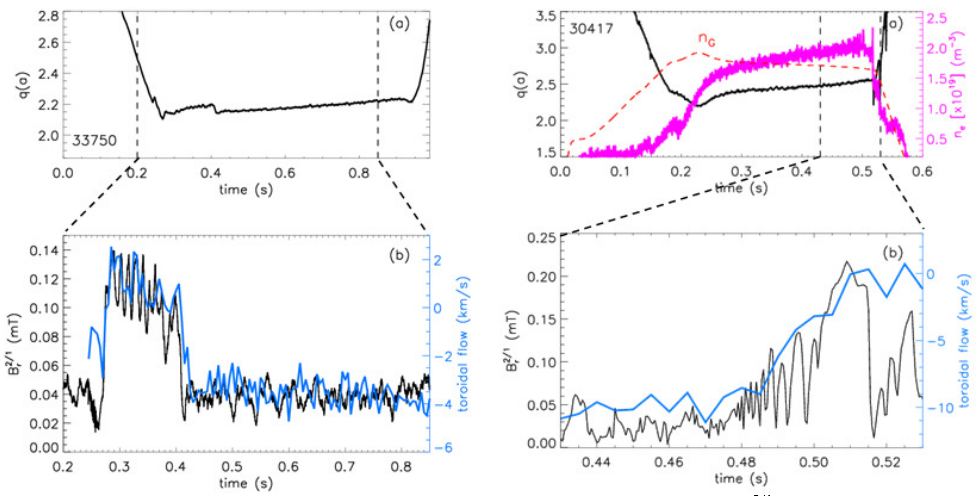

Figure 2. Left figure: (a) time behaviour of the edge safety factor and (b) $b_r^{2/1}$ of the tearing mode (in black) and plasma rotation (in blue). Right figure: (a) time behaviour of the edge safety factor, plasma density (in black), Greenwald density (in red) and (b) $b_r^{2/1}$ of the tearing mode (in black) and plasma rotation (in blue).

2/1 tearing mode, which is rotating at about 4kHz, slows down. Meanwhile, the tearing mode amplitude increases (in black) leading to a plasma rotation braking (in blue) and finally a plasma disruption. In this case, the mode frequency drop during mode locking is mainly governed in the momentum transport balance by the electromagnetic torque, induced by the presence of a localized singular current in the vicinity of a resistive layer, as discussed in [10,11]. Note that these q(a)>2 experiments confirm the existence of a synergy between the tearing mode activity and plasma rotation in RFX-mod plasmas. A similar connection has been observed for the 2/1 RWM case, as described in the previous section, even if the mechanisms which govern the momentum transport are different.

Plasma rotation modulation in presence of externally applied magnetic fields. Owing to the flexibility of RFX-mod feedback control system, magnetic field perturbations with a wide range of m, n harmonics can be applied through magnetic feedback. In the q(a)=1.7 plasma experiment reported in Figure 3, a magnetic field perturbation with m=1, n=1 helicity is applied. As shown in panel (a), the toroidal flow is oscillating at 10Hz frequency, the same as the external magnetic field. Moreover, oscillations coherent with the m=1 mode are present in the poloidal flow signal, as reported in panel (b). This evidence could be the signature of a helical flow pattern, which is predicted by non-linear simulations of these plasmas performed with the PIXIE-3D code [13].

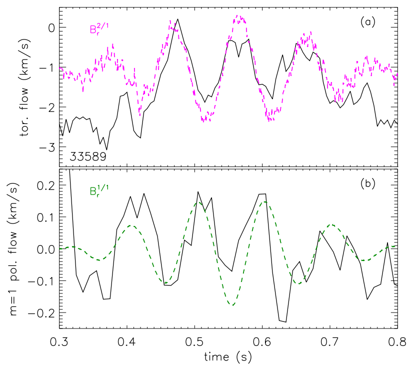

Figure 3. Time behaviour of (a) toroidal flow in black and the radial magnetic field of the 2/1 mode (in magenta) and (b) m=1 poloidal flow in black and the radial magnetic field of the 1/1 mode (in green) reconstructed at the diagnostic position.

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