Role of flow in the formation of helical states in RFX-mod

D. Bonfiglio, F. Bonomo, P. Piovesan, L. Piron, B. Zaniol

Consorzio RFX – EURATOM/ENEA Association, Padova, Italy

In the RFX-mod reversed field pinch (RFP) experiment, the magnetic feedback control of the MHD instabilities has permitted to reach and overcome 1 MA plasma currents, observing the emergence of a new helical state [1]. This state, spontaneously appearing and increasing in amplitude as the current *Ip* increases, is characterized by a single tearing mode ($n=7$) largely dominating the $m=1$ spectrum, while the secondary ones are decreasing [2]. The topology changes deriving from m=1 modes behavior are characterized by the restoration of helical magnetic flux surfaces in the plasma core by the formation of a helical internal transport barrier in the electron temperature profile (eITB). This leads to an increase of the energy confinement time by a factor of 4 with respect to the chaotic low-current multi-helical regime. In particular, the confinement properties of this regime have been found to scale with the plasma current increase [2], suggesting promising perspectives for improved plasma performances at the higher plasma currents planned for the next future.

In tokamaks and stellarators, a crucial role in triggering and sustaining ITBs is played by the plasma flow shear. It becomes therefore of great impact to study the behavior of the plasma flow on RFPs helical regimes. This paper reports passive poloidal flow measurements performed by spectroscopic techniques at 1.5MA plasma currents, to reconstruct the poloidal flow pattern in presence of such helical states. The impurities considered for these analyses are carbon, the main impurity present in RFX-mod due to the graphite first-wall, and boron, available as a consequence of the boronization first-wall conditioning process. A proper set of lines of sight has been arranged in a poloidal section in order to optimize simultaneous Doppler shift measurements of both B V (4944.6 Å, mainly centered at 0.6 r/a at the considered plasma current) and C V (2271 Å, centered at 0.85 r/a), thus gathering information from different radial positions. In order to maximize the helical state persistence during plasma flat-top and to suit the constraints in temporal resolution and low-signal level of the passive flow measurements, a finite value of the radial magnetic amplitude for the *1,7* mode ($b_r^{1,7}$) has been stimulated at the plasma boundary [3] by means of active coils, with a defined poloidal rotation frequency, from the static case up to ± 30 Hz. This acts as a seed for the corresponding mode to increase, and permit to externally control its phase position in the torus. All the considerations stated in the following are referred to discharges with an external

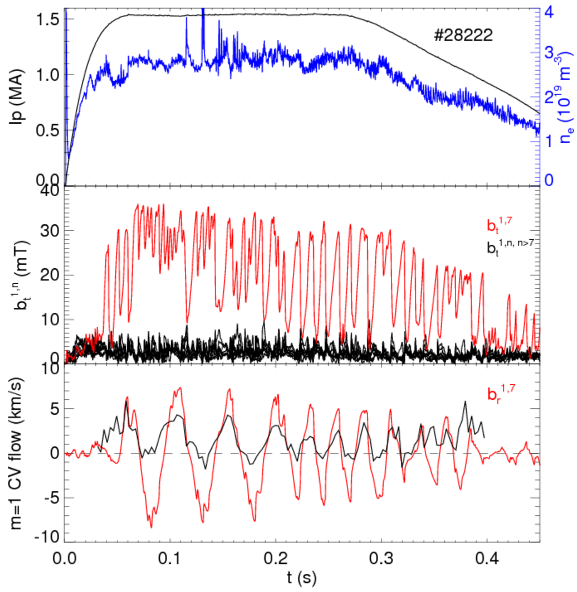

Figure 1 *Example of 1.5MA shot with external rotating $b_r^{1,7}$ reference: plasma current and electron density (in blue) (a), magnetic m=1 spectrum (b); in (c) the CV m=1 flow component (blue) for an external chord and the $b_r^{1,7}$(a) amplitude (red).*

rotating perturbation applied, but additional measurements show that they remain valid also in case of helical states spontaneously appearing in the plasma.

An example of a 1.5 MA RFX-mod plasma with a finite $b_r^{1,7}$ is displayed in Figure 1, where the plasma current and the electron density (in blue) are shown (a), together with the amplitude of the $b_t^{1,n}$ spectrum (b) (in red the *(1,7)* mode, in black the secondary ones). In panel (c) the amplitude of the fluctuation of $b_r^{1,7}$ calculated at the diagnostic toroidal position (red line) on equatorial plane (low field side) and the *m=1* component of the C V flow for an off-axis line of sight, with positive versus upwards, are displayed. The strong dependence between $b_r^{1,7}$ and flow becomes clear when the *(1,7)* mode amplitude increases, saturating at a value corresponding to the establishment of the helical state [2]. This evidence is strongly confirmed for all the externally applied rotation frequencies, including the static case. Similar behaviors and correlations have been also identified for B V measurements. In particular, almost in-axis lines of sight show a non-negligible B V flow radial component in the plasma core.

Flow reconstructions in 1.5MA plasmas have been performed by fitting all the experimental measurement signals. An example of the resulting *m=1* flow pattern (red arrows) is displayed in Figure 2, together with the reconstruction of the helically deformed magnetic flux surfaces (black solid lines). Most of the flow in the core is radially directed, pointing towards the helical axis, while at the plasma edge the flow is mainly poloidal, thus closing the flow circuit. So, in a fixed toroidal and poloidal position, it is observable an inversion of the poloidal flow at the edge,

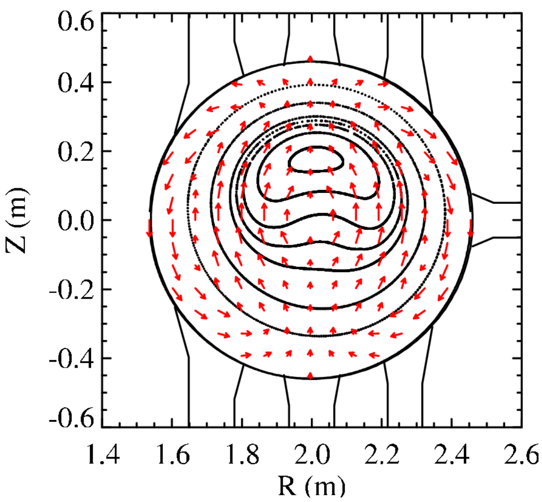

Figure 2 *Experimental flow pattern in the poloidal cross-section as obtained by C and B measurements.*

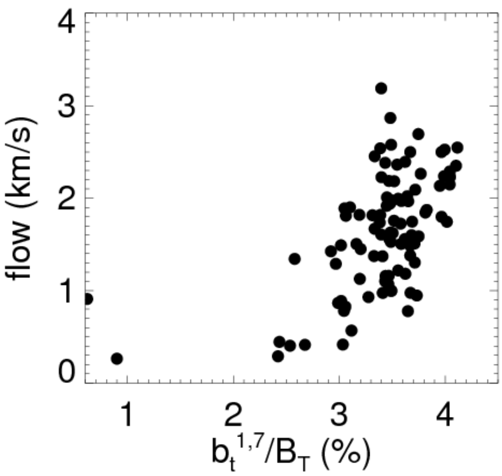

Figure 3 *Dependence of the m=1 CV flow measurement with the* $b_r^{1,7}$ *amplitude, normalized to* $B_T(a)$.

where it maintains a *(1,7)* periodicity, as detected also by means of a Mach probe diagnostic [4].

The *m=1* flow dependence with the radial magnetic perturbation has been investigated at various plasma current values, i.e. at various amplitudes of the *(1,7)* mode. A strong correlation between flow and $b_t^{1,7}$ amplitude is found, as shown in Figure 3. This suggests that the flow, which increases with the size of the helical plasma core deformation, is playing a role in the formation and sustainment of the helical equilibrium. In particular, the increase of the flow with the *(1,7)* mode amplitude suggests the possibility that a shear flow may trigger and sustain the observed internal transport barriers, in a way similar to what has been observed in tokamaks [5]. In RFX-mod, the eITB foot radial position has been found to be located in proximity of the maximum of the *q* profile [6], being located on average at r/a≈0.55-0.6, but moving outwards in some cases at r/a=0.7. In the cases considered in this work, the inversion of the poloidal flow pattern is found to be located at r/a ≈0.7, accounting for the barrier sustainment by means of the velocity shear. Further and more spatially resolved flow measurements are needed to deeply investigate the region of poloidal flow inversion, in order to better study the possible effect of the sheared flow in the formation of the eITBs.

It is interesting to compare the reconstructed experimental plasma flow in the helical RFP regime with the dynamo flow predicted by the MHD model in similar conditions, as already done for similar measurements obtained in the MST device [7]. Nonlinear visco-resistive MHD simulations of the RFP show the existence of a helical dynamo velocity field associated with the helical deformation of the magnetic surfaces, which requires a sustaining electrostatic potential and an associated electrostatic drift velocity [8]. An example of the MHD flow pattern in a pure single helicity state (no secondary modes considered) is displayed on the poloidal cross-section in Figure 4(a). This flow pattern is similar to the experimental one (shown in Figure 2), being characterized by a radial flow in the core which is pointing towards the helical axis, even though the inversion of the poloidal flow at the edge is not observed in the MHD simulations. This can be due to the constraints of the simulations (which assume a pressureless cylindrical plasma with uniform density and vanishing flow at the boundary) as well as to additional edge plasma physics processes (such as the presence of

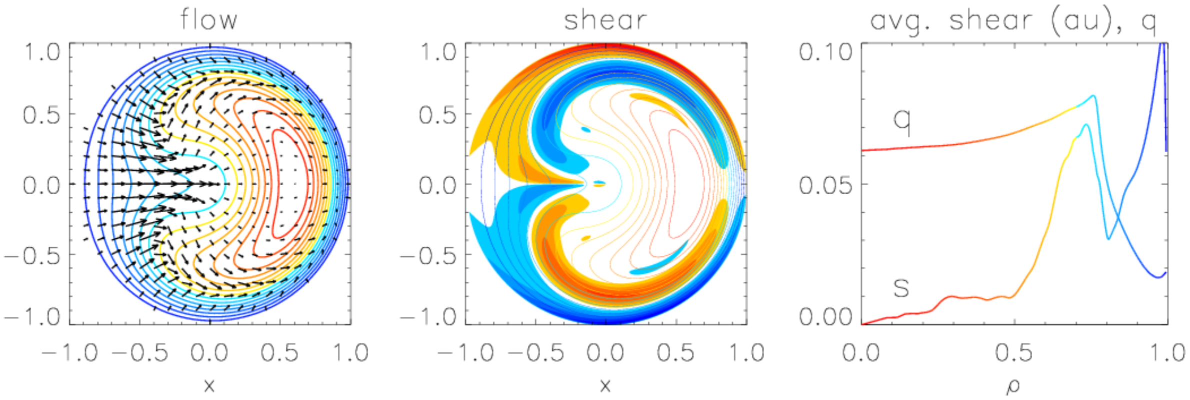

Figure 4 *(a) Flow pattern (arrows) in a pure SH state, as predicted by Specyl for a SH state, and the corresponding shear flow (b) and its correlations (c) with the helical q factor.*

ambipolar electric fields) which are not taken into account by the visco-resistive MHD modeling. The velocity field provided by MHD simulations has been processed to compute the shear in the $\nabla\chi$ direction of the flow component in the $\nabla\chi\times\mathbf{B}$ direction, where χ is the helical flux function, being constant on magnetic surfaces. This definition of the flow shear is a generalization of the standard definition $s=dv_\theta/dr$, which is valid for a tokamak with nested cylindrical magnetic surfaces. The flow shear is depicted in Figure 4(b) with orange and blue colors referring to positive and negative shear values, respectively. The absolute value of the flow shear averaged on magnetic surfaces is found to show a peak in correspondence of the maximum of the helical q profile [9], as displayed in Figure 4(c). Since the maximum of the helical q profile has been found to be located where the eITB is experimentally established [10] (i.e. at r/a≈0.3-0.4), this result suggests that the flow shear associated to the *(1,7)* dominant mode could play a stabilizing effect on the RFX-mod eITB, thus allowing for the sustainment of the barrier in the helical equilibrium state. Further experimental measurements are needed to better investigate this aspect; in particular, measures of the shear flow in the plasma core (i.e., at a radius approximately close to the electron transport barriers) are fundamental to better understand what are the trigger and sustainment mechanisms of the helical RFP regime.

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