The role of the magnetic topology in the Reversed Field Pinch edge physics

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Introduction. A better understanding of the edge phenomena regulating plasma transport and the global machine performance is of primary importance for the whole fusion community. In the RFX-mod Reversed Field Pinch (RFP) experiment [1], the edge properties are found to have a strong relation with the magnetic topology. This latter is defined by the typical RFP safety factor profile $q(r)$ (shown in fig.1) featuring an inversion from positive to negative values in the extreme edge. Due to the presence of a $q = 0$ surface in this region, a chain of poloidally symmetrical $m = 0$ magnetic island arises. This fact has a turn of relevant consequences for the global RFX-mod physics as demonstrated, among the different studies, by the analysis of the high density regimes [2, 3]. When the core density approaches n_G (the Greenwald density), in fact, an upper density limit has been observed causing the so called "soft landing" of the discharge for the increased plasma resistivity. This behaviour has been ascribed to the modifications in the edge magnetic topology and in the radial electric field causing the toroidal flow to reverse and density to accumulate at the edge producing typical hollow profiles (as shown in fig.3). Starting by these accurate studies, in this contribution, we first examine in depth the relation between electric field, flow and magnetic topology by presenting direct measurements obtained on RFX-mod by an electrostatic probe. In the second part, we focus on the density dynamics and we propose an experimental method to avoid the edge accumulation in the medium high density regimes.

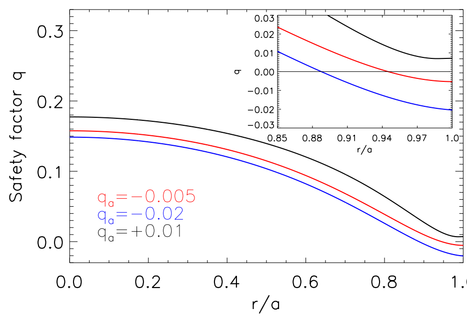
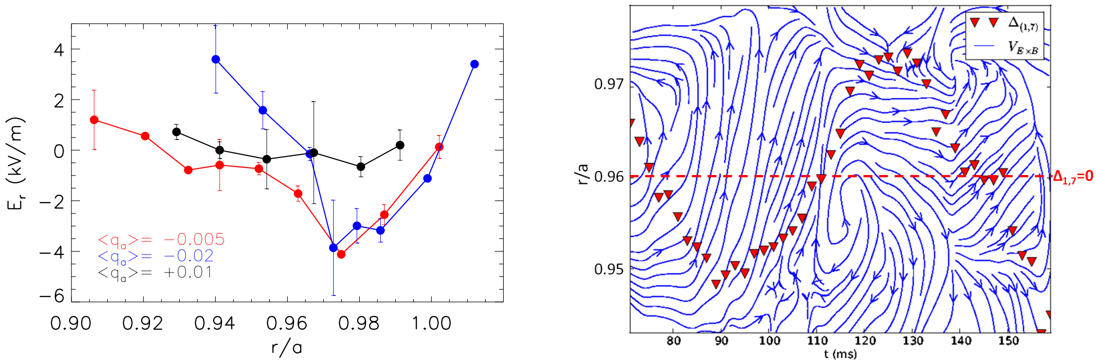


Figure 1: Radial profile of the safety factor q for a shallow (red line), a deep (blue line) and a positive (black) q_a discharge. In the inset: zoom of the inversion region

Electric field and topology. Electric field measurements have been performed by the insertion in the vacuum chamber (up to the 10% of the minor radius $a = 459$ mm) of the so called U-probe [4] equipped with a 2D array of electrostatic sensors. The radial electric field E_r profile has been evaluated by accounting for the radial derivative of the plasma potential V_p and by moving the probe at different radial positions in a set of reproducible discharges in which the plasma current I_p was kept below 400 kA. The results have been finally averaged over the plasma current flat-top phase. In fig.2(a) we show the E_r radial profiles for three different values externally imposed of the edge safety factor q_a. Changing this parameter is equivalent to move inward (deep q_a) or outward (shallow q_a) the radial position of the $q = 0$ surface (see fig.1) and, thus, of the $m = 0$ islands whose the field lines can eventually intercept the first wall. In [5, 6] this has been



(a) (b)

Figure 2: (a) Radial profile of radial electric field E_r as measured by the U-probe for three different q_a values; (b) #31267: $v_{\mathbf{E}\times\mathbf{B}}$ flow map as measured by the U-probe and the local deformation $\Delta_{1,7}$ of the edge flux surface.

also demonstrated to be crucial for defining the Last Closed Flux Surface (LFCS) and for the global plasma-wall interaction (PWI). In fig.2(a) we show how the edge magnetic topology can influence the E_r profile. Both the shallow and the deep q_a curves display a similar behaviour, featuring a negative E_r minimum for $r/a \simeq 0.97$ and an inversion from negative to positive values in the more internal regions. This can be interpretated in the light of the associated connection lengths L_c (the distance from the wall of each point along the corresponding field line): for $r/a > 0.96$ in both the equilibria a region with short L_c acting as a kind of Scrape Off Layer is present (at shallow q_a this is represented by the edge islands intercepting the first wall) and there we find the E_r minima; the inversion of E_r appears instead associated to the entrance in a region with long L_c analogously to the separatrix in Tokamaks. At deep q_a (blue curve) this occurs around $r/a \simeq 0.95$ because of the presence of the edge islands featuring well conserved flux tubes; at shallow q_a (red curve) the inversion coincides with the entrance in more internal LCFS for $r/a \simeq 0.90$. Particularly interesting is the case with positive values of q_a (black curve). This corresponds to the situation, rather unnatural for a RFP configuration, in which the $q = 0$ surface is pushed outside the first wall and the edge topology does not feature the presence of magnetic islands. This condition has been achieved transiently during the discharges in order to study the related electrostatic properties modification. Even if the radial range covered by the probe is smaller with respect to the negative q_a equilibria, one can easily notice that, within the error bars, the E_r profile (black curve) zeros almost everywhere at the edge. If on the one hand this finding highlights the interaction between edge islands and electric field (and, thus, flow), on the other hand suggests important implications for the particle dynamics and confinement in the positive q_a regimes. We will come back in the next section to this point. We focus, now, our attention to the flow pattern associated to the RFX-mod edge magnetic topology. Important information, in this sense, can be inferred by the toroidal and radial electric field E_ϕ,E_r measurements carried out in the same discharges by the U-probe. Fig.2(b) shows the $v_{\mathbf{E}\times\mathbf{B}} = (E_r/B_\theta)\hat{\phi} + (E_\phi/B_\theta)\hat{r}$ flow map as evaluated during the flat-top phase of a single deep q_a discharge. To highlight the relation with the edge topology, in the same time window, a toroidally rotating helical perturbation has been applied from the external stimulating in the whole plasma the transition to a 3D helical configuration. This allows the probe measuring at a fixed toroidal position to explore a wider topological region according to the rotation frequency of the externally imposed perturbation. In the case shown in fig.2(b), a 15 Hz $m/n = 1/7$ (being m,n the poloidal and the toroidal mode numbers respectively) perturbation was applied enabling the U-probe to see $1/7$ of the whole topology structure (the local deformation $\Delta_{1,7}$ of the flux surfaces is superimposed to the same figure) in 60 ms. The analysis of the $v_{\mathbf{E}\times\mathbf{B}}$ map reveals the presence of a self-organization in the modulation induced in both the radial and toroidal flow components and a convective cell-like structure. In particular, the E_r minimum (i.e. maximum of the toroidal flow) shown in the average profiles in fig.2(a) moves inward ($r/a \simeq 0.95$) or outward ($r/a \simeq 0.98$) according to the $\Delta_{1,7}$. A complementary behaviour is instead observed in the radial flow component. Numerical simulations [7], predicting such a structure, suggested a comparison with the mechanism acting in the RFX-mod high density regimes. At present, we have not further elements to undertake such an ambitious analysis.

Edge density dynamics in positive q_a regimes. The difficulty to operate at medium-high density represents one of the most severe limitations for RFX-mod. As mentioned in the introduction, in the worst cases ($n_e/n_G > 0.6$), a turn of detrimental effects can lead to the "soft landing" of the discharge. However, even for $n_e/n_G > 0.4$ any attempt to raise the density through gas puffing injection usually produces hollow density profiles (fig.3, red curve), increased edge resistivity and a general deterioration of the global confinement properties. Indeed, the best machine performance (in terms of energy confinement time) has been achieved by fueling the plasma core through pellet injection. In this section we propose an experimental method preliminary tested on RFX-mod and aiming to allow a better control of the medium-high density regimes. The basic idea takes the cue from two experimental observations related to the positive q_a discharges: the zeroing of the edge E_r radial profile (fig.2(a)) and the density profile peaking (due to an edge density drop, fig.3). These observations appear consistent with the hypothesis proposed in [2, 3] ascribing, through a complex mechanism, the edge density accumulation to an increased amplitude of the $m = 0$ islands at high n_e/n_G values. On the contrary, when the islands are suppressed ($q_a > 0$), the electric field zeros and the edge particles are rapidly lost to the wall. To this respect,the $m = 0$ islands are the key of the RFP confinement and, if at high n_e/n_G values they seem to act as a hole for the incoming particles (from wall recycling or gas puffing), their temporary suppression can open a "corridor" for a better plasma core fueling. Coherently, simulations by the Monte Carlo code NENE [8] showed a core penetration increasing of the puffed neutral particles over a peaked density profile (obtained at positive q_a values) with respect to a hollow one. To test this conjecture we performed an experimental campaign in which the density has been raised by puffing particles in narrow time windows in which the discharges were temporary run with a slightly positive q_a value. The result is summarized in fig.3: if the gas is puffed over a negative q_a phase (traditional scheme) a hollow profile is produced (red curves); when a positive q_a window is applied, density profile gets first peaked (dashed blue curve) and then, upon the gas puffing, grows almost evenly (dotted dashed blue curve) until getting basically flat (continuous blue curve) after q_a is turned negative. This preliminary experiment demonstrates how medium density regimes can be obtained without edge density accumulation and could open new perspectives in the study of the RFP density limit. As a final remark, we mention that the density profiles obtained with this method are not totally stationaries and evolve towards the traditional high density hollow ones in some tens of *ms*. However, while density profile keeps flat, a 25% reduction in the ohmic input power needed to sustain the discharge is observed. More accurate analysis and dedicated experiments are mandatory to better explain this behaviour.

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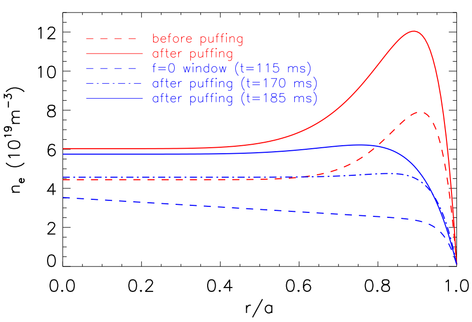

Figure 3: Time evolution of the density profiles for two different discharges