Investigation of edge transport properties in helically shaped RFP discharges

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Background. Understanding how edge phenomena influence transport and plasma performance is a subject of great interest for a better comprehension of plasma-wall interaction (PWI). The edge region of the RFX-mod RFP device [1] is characterized by the presence of a chain of $m = 0$ islands resonating close to the wall at the reversal surface ($q = 0$) and resulting in a rather complex topology. The topology is affected also by $m = 1$ magnetic modes resonant throughout the plasma radius. In this framework, it has been found [2] that local transport and kinetic properties are spatially modulated by the presence of a small residual helical ripple at the edge which arises at high current regimes ($I_p > 800$ kA) when a helical core in the plasma is revealed [3]. In order to obtain a detailed analysis of these effects, we exploited the insertion of a probe array in the vacuum chamber, the so-called U-probe [4] equipped with a 2D array of electrostatic sensors. The insertion of the probe is doable only at low current regimes (in our case $I_p < 400$ kA) due to a reduced power load. Nonetheless it is possible to mimic the high current configuration by applying a helical boundary ($m = 1$, $n = -7$) via the saddle coil feedback system. At low current the magnetic topology shows a wide spectrum of tearing modes with the same poloidal number ($m = 1$) but different toroidal periodicity that resonate in the plasma core giving rise to multiple helicity (MH) states. When an external boundary condition is imposed, the externally applied *m/n* harmonics become the dominant components of the B_r spectrum. In this paper we will focus on the effects of $(1,-7)$ helical perturbation on the properties of the plasma edge. In particular, we will explain how its induced deformation modulates quantities such as the electron density n_e and temperature T_e, as well as the particle and energy fluxes derived as the averaged product of local fluctuations of density or pressure and radial velocity:

$$\Gamma_e = \langle \tilde{n}_e \tilde{v}_r \rangle \qquad \text{and} \qquad Q_e = \frac{3}{2}\langle \tilde{p}_e \tilde{v}_r \rangle \qquad \text{where} \qquad \tilde{p}_e = \tilde{n}_e \tilde{T}_e \tag{1}$$

The helical angle, defined by $u(\theta,\phi;t) = m\theta - n\phi + \phi_{m,n}(t)$ [2], is then used to map edge measurements in the correct frame of reference based on the helical field structure set by the application of the toroidally rotating perturbation. We will enlighten also the link between the magnetic topology and local transport measurements. The evaluation of the temporal evolution of the parallel connection lengths L_c computed by the field line tracing code FLiT [5] will be part of this analysis.

Experimental setup and discussion. Results presented hereafter are obtained in deuterium discharges for two different equilibria: two different edge safety factor values ($q_a = \frac{a}{R_0}\frac{B_\phi(a)}{B_\theta(a)}$, a is the plasma radius and R_0 the major radius of the torus) were imposed, a *shallow* one ($q_a = -0.003$) and a *deep* one ($q_a = -0.01$). Modifying q_a corresponds to a change in the radial position of the reversal surface and has as an effect also on the radial location of the chain of $m = 0$ islands whose field lines can eventually intercept the first wall. In the shallow q_a discharge, the U-probe is located 20 mm inside the chamber while for the deep q_a equilibrium it is fixed at 30 mm in the vacuum chamber. The sampling frequency is 5 MHz. We are taking into account the measurements of the first two rows of electrostatic pins correctly being acquired and arranged as two five-pins balanced triple probe. As anticipated, we want to relate the local measurements to the helical field structure set by the external magnetic boundary. The ($m = 1$, $n = -7$) applied helical perturbation is slowly rotating in the laboratory frame of reference; to map the probe's measurements (functions of time) on the topology of the island, it is convenient to use the definition of helical angle. Furthermore, the U-probe is located at fixed $\theta = 0°$ and $\phi = 247.5°$ and we will take this into account to derive a consistent description of the behaviour of transport properties in this scenario. The helical angle phase $\phi_{1,-7}$ is defined so as to have a maximum of the helical flux perturbation $\delta\chi_1 sin u$ at the O-point ($u = \pi/2$) and a minimum at the X-point ($u = 3\pi/2$).

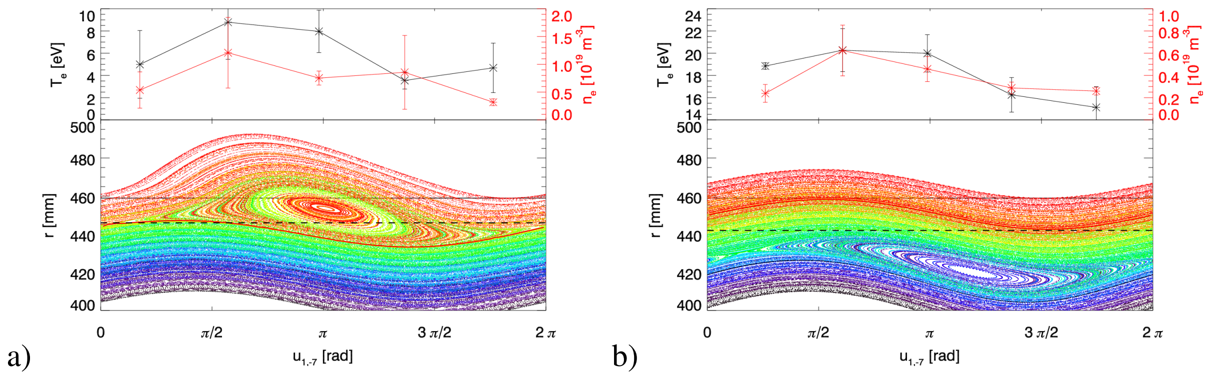

Figure 1: For shallow *(a)* (shot # 35755) and deep q_a *(b)* (shot # 35789) we show in the upper panel the modulation of T_e and n_e as function of $u_{1,-7}$ and in the lower panel the reconstructed Poincaré plot.

The interest for transport preperties in the plasma's external region is highly correlated to the observation of similarities between the edge region of helical RFPs and RMP experiments in tokamaks. Electron temperature and density as functions of the helical angle are reported in the upper panels of Fig. and while in the corresponding lower panels, the Poincaré plots of ($m = 0, 1$ and $n = -7$) modes are drawn in order to better evaluate the link with the magnetic edge topology. The dashed black line shows the radial position of the U-probe in each discharge: $r_{probe} = 446\ mm$ at $q_a = -0.003$ and $r_{probe} = 442\ mm$ at $q_a = -0.01$. The solid red line indicates the reconstructed *last closed flux surface* and the black one represents the edge of the chamber. Particle and energy fluxes are shown in Fig. 2: if compared to the reconstructed Poincaré plot shown under temperature and density profiles, it is possible to see that both fluxes obtained from Eq.1 are affected by the underlying magnetic topology.It is known [8] that electrostatic fluxes present peaked radial profiles around $r/a = 0.95$ and then present a decrease that can be accounted for by parallel losses due to the presence of the first wall.

However, any dependence on the $m = 0$ islands is subject of ongoing investigation. The study of the parallel connection length to the wall is carried out with the field line tracing code FLiT. L_c is a standard metric used in the context of tokamak stochastic edge studies, to determine the topology and width of the scrape-off layer (SOL). As defined on TEXTOR [6, 9], short connection length regions (*laminar* zones) are characterized by large plasma wall interaction and low electron temperatures, while long connection length regions (*ergodic* zones) more connected to the core are characterized by large heat fluxes and high temperature. In order to use a common paradigm with [9] to evaluate L_c, we show in Fig. 3 for each equilibrium the electron density $n_e(t)$ and temperature $T_e(t)$ under the connection length time profiles. As in TEXTOR-DED, we see that the modulation in both n_e and T_e can be connected to an alternating connection length layer when applying an external helical boundary.

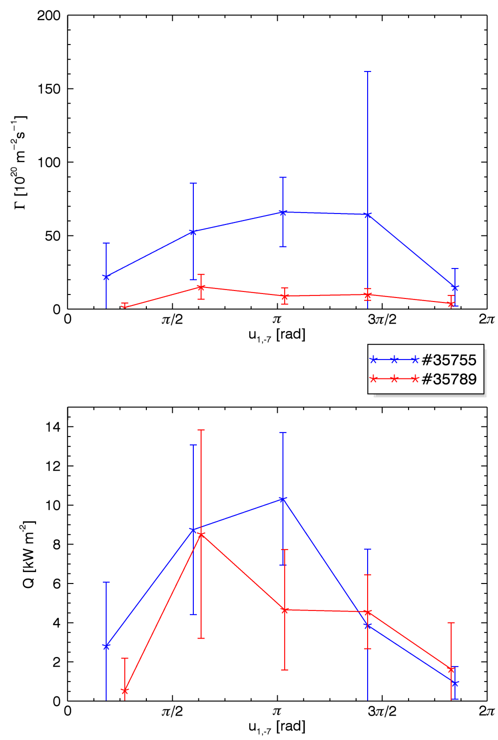

Figure 2: Modulation of Γ_e and Q_e as function of the helical angle for shallow q_a (blue line) and deep q_a (red line) dicharges.

Conclusions. We have seen that kinetic plasma properties at the edge in presence of an externally applied helical perturbation reflect the underlying magnetic topology. The particle flux itself is found to follow the helical modulation: at the edge of RFP devices Γ_e and Q_e are mainly

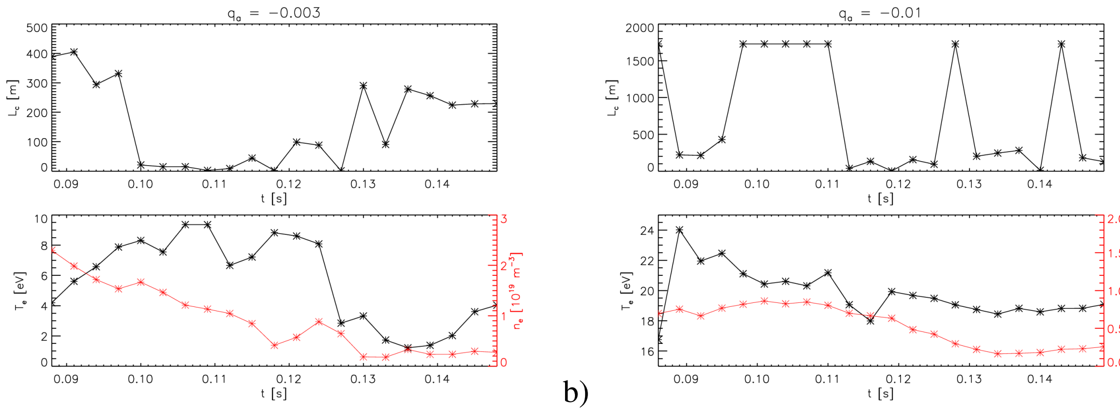

Figure 3: Upper panel: L_c computed by FLiT as a function of time for shallow (a) and deep (b) q_a value. Lower panel: T_e and n_e as function of time for $r_{probe} = 446\ mm$ at $q_a = -0.003$ and $r_{probe} = 442\ mm$ at $q_a = -0.01$.

due to anomalous transport driven by electrostatic turbulence [10]. Although we believe Eq.(1) to give a reliable description, the local modulation of transport properties might then be related to the modulation of fluctuations at small scale length and not just of the averaged quantities. In this contribution we focused on edge measurements of the electron density $n_e(r,t)$ and temperature $T_e(r,t)$ fields. In analogy with RMP experiments in tokamaks, these plasma parameters are locally modulated during the application of an external helical field. They are, indeed, found to be depending on the local rotating magnetic topology as described in terms of $L_c(r,t)$. The implications of these observations are still under investigation.

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