Comparison of edge island transport in tokamaks and RFPs

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In the RFP edge, measured transport and flows are strongly influenced by magnetic islands [1]. The edge ($r/a \gtrsim 0.8$) is characterized by resonances (islands) at the reversal surface $q = 0$, and consequently by weak chaos. These islands determine a differential radial diffusion of electrons and ions which is balanced by an ambipolar potential. A natural analogue of this phenomenology are the resonant magnetic perturbations (RMPs), applied in tokamaks to reduce ELM's. They impose a characteristic modulation to the edge electron density and temperature fields, which are in close correlation with the local magnetic vacuum topology [2]. In order to understand if a unified picture of the particle transport is possible, and there are any similarities between the phenomena observed in tokamak devices with RMP (such as the particle pump out), and those in the RFP (such as convective cells in the edge), transport simulations have been performed on TEXTOR with the Monte Carlo, Hamiltonian Guiding-Centre (GC) code ORBIT [3]. Results can be thus compared with RFX-mod [4].

The code ORBIT uses the Hamiltonian formalism to describe the motion of a test-particle in an electromagnetic field. The tearing perturbations, primarly orthogonal to the equilibrium magnetic field $\vec{B}$, are described as having the vector potential with gauge $\delta\vec{A} = \alpha\vec{B}$, or $\delta\vec{B} = \nabla\times\alpha\vec{B}$, where α is an arbitrary scalar function which contains information about all of the three components (radial, toroidal, poloidal) of the perturbation. The Fourier components of α are usually derived from the radial component of the perturbation, δB^r, through

$$\alpha_{m,n}(r) = \frac{\delta B^r}{mg/r + nI} \qquad (1)$$

where I and g are the equilibrium magnetic field components (poloidal and toroidal, covariant form). A detailed description of ORBIT code can be found in Ref. [5].

The magnetic equilibrium has been reconstructed in circular approximation and a proper form for the perturbations developed, on the basis of the analytical formulae used in TEXTOR [6]. For a toroidally symmetric equilibrium the Grad-Shafranov (GS) equation, written in magnetic flux coordinates has the form

$$\nabla \cdot \frac{\nabla \psi_p}{X^2} + p' + \frac{gg'}{X^2} = 0 \qquad (2)$$

where primes ($'$) indicate derivatives with respect to ψ_p, the poloidal flux. Expanding Eq. (2) at the second order in $\varepsilon = a/R$, the equilibrium surfaces consist of shifted circles and it can be shown that the equilibrium is defined by two functions, chosen among the pressure p, toroidal field g, and the safety factor q. Once two of them are defined, the third comes from the solution of (2). Magnetic perturbations are generated by the current distribution over the coils of the Dynamic Ergodic Divertor (DED). The DED configuration can be set to create the (m,n)=(3,1),(6,2),(12,4) operational modes. The resulting perturbation field can be described, in the assumption of full penetration (vacuum approximation), as

$$B_r(r,\theta,\phi) = \sum_{m,n} B_{mn}(r)\sin(-m\theta + n\varphi + \chi_{mn}) \qquad (3)$$

with

$$B_{mn}(r) = \iota_n B_c g_{mn} C_{mn} \left(\frac{r}{r_c}\right)^{|m|-1} \qquad \chi_{mn} = \frac{m_0 n}{4}(\pi - \theta_0) - \chi_n + \frac{\pi}{2}$$

where $B_c = \frac{m_0 \mu_0 I_d \cos\alpha_0}{\pi r_c}$, I_d is the amplitude of the current in the DED, g_{mn} is a function equal to 1 in the area covered by coils and *zero* elsewhere, C_{mn} is a correction factor due to non-ideal configuration, r_c =53.25 *cm* the DED radius, $\alpha_0 \simeq 4.6°$ the angle between current direction and toroidal axis, $\theta_0 = 169.35°$ the starting poloidal angle of the first coil, $m_0 \simeq 20$ and

$$\iota_n = \left[\frac{\sin(\pi/4)}{4\sin(\pi/16)}, \frac{1}{2\sin(\pi/8)}, \sqrt{2}\right] \qquad \chi_n = [3\pi/16, 3\pi/8, 5\pi/4]$$

The magnetic spectrum for a typical (m,n)=(12,4) configuration is shown in Fig. 1. B_r can be used in Eq. (1) to get the correct α's to insert in ORBIT.

To characterize the TEXTOR edge we analysed the parallel connection length, $L_\parallel(r,\theta) \simeq v_{th}\tau_{trav}$, of the topology, τ_{trav} being the electron travel time between the initial and final positions and v_{th} the thermal velocity. In ORBIT the collisions enter through a pitch-angle scattering operator, implemented by taking into account ion-ion, ion-electron, electron-electron, electron-ion encounters, using the Kuo-Boozer approach. The Poincaré plot of the magnetic field lines shows the expected topology at the edge of TEXTOR (Fig. 2): in the inner region ($\psi_p/\psi_{p,w} \simeq 0.89$) the last island chain, in the middle ($\psi_p/\psi_{p,w} \simeq 0.92$) the remnant islands, and in the outermost region ($\psi_p/\psi_{p,w} > 0.94$) the so-called laminar flux tubes embedded into "ergodic fingers" touching the wall, are found. Color codes indicate the characteristic length of thermal ions (Fig. 2(a)) and electrons (Fig. 2(b)). The ion $L_\parallel$ is rather uniform, with a slight poloidal asymmetry at $\theta > 0$ due to the well-known θ-pinch drift. The electrons, having a smaller larmor radius, follow closely the field lines and, as a consequence, their $L_{\parallel}$ is much larger than the ion one in the main island chain and in the O-point (OP) of the remnant islands where the electrons are trapped. Conversely, the electron $L_{\parallel}$ is smaller in the X-points (XP) of the remnant islands. Finally, it is also small ($L_{\parallel} \approx 0$) in between the main island chain and the remnant islands, and in corrispondence of the laminar flux tubes, where electrons rapidly bounce to the wall. The variation of the electron $L_{\parallel}$ entails a modulation of the radial electric field (Fig. 3), that can be estimated, neglecting the ion mobility ($\mu_i \ll \mu_e$), as $E^r = \frac{1}{n|\mu_e|}(\Gamma_e - \Gamma_i)$, where $\Gamma \propto \frac{1}{\tau_{trav}}$ is the particle flux, n the background density. E^r experiences very large positive values where the electron $L_{\parallel} \approx 0$. The ambipolar electric field in TEXTOR shows the same symmetry of the magnetic topology created by the $(m,n) = (12,4)$ configuration, confirming the results found in RFX-mod simulations [4], where the ambipolar potential has the symmetry of the main island $(m,n) = (0,1)$ in the multi-helicity configuration, as found in experiment for both $(0,1)$ and $(1,7)$ symmetries [1]. The electric field in TEXTOR is anyway ~ 1 order of magnitude larger than in RFX-mod. This is maybe due to the electron $L_{\parallel}$ difference (in RFX-mod ~ 6 times larger), being the edge of RFX-mod less chaotic than the TEXTOR one. This would explain also the fact that electron periods are larger in the XPs of the "remnant" islands in RFX [1], and in OPs in TEXTOR.

References

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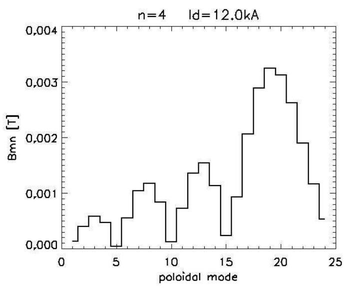
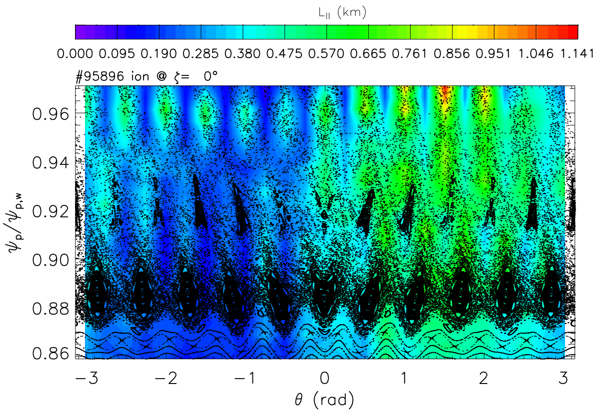
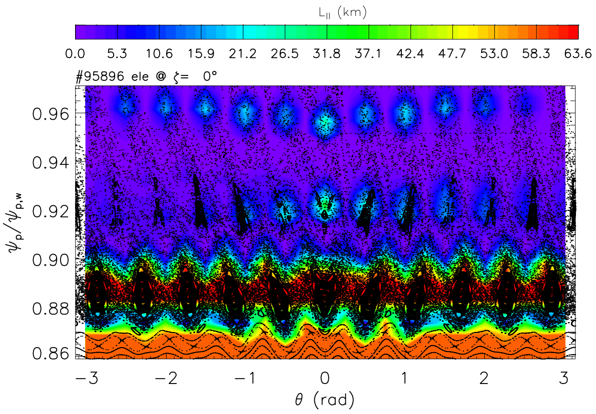


Figure 1: Spectrum of the modes for n =4.



(a) Ions $L_{\parallel}$



(b) Electrons $L_{\parallel}$

Figure 2: Poincaré plot at $\zeta = 0$. Color codes indicate the ions (a) and electrons (b) $L_{\parallel}$.

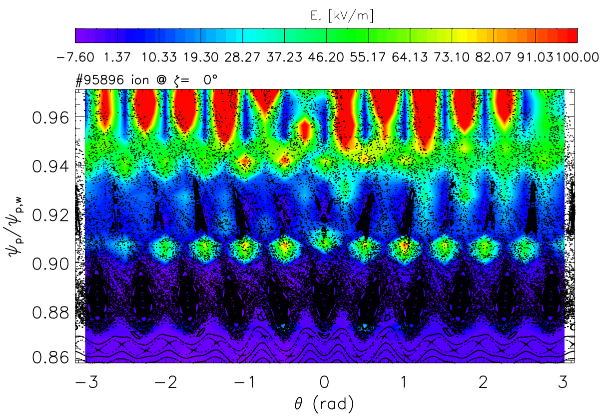


Figure 3: Map of the radial electric field.