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Implementation in the ORBIT code of radial perturbations in the RFX-mod toroidal geometry

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The RFX-mod experiment. The RFX-mod experiment [1] is a reversed field pinch configuration (RFP) provided of saddle coils which act as an active shell (*Virtual Shell* [2]) to reduce the magnetic perturbations and improve the magnetohydrodynamic (MHD) stability of the plasma. In fact, the RFP is characterized by a wide spectrum of resonant $m = 1$, $n < -2R_0/a$ tearing modes, where a and R_0 are the minor and major radius respectively. A passive ideal boundary, i.e an infinitely conducting shell, is able to maintain at a low amplitude level the tearing modes, but its finite penetration time for the radial magnetic field limits the plasma sustainment for long times compared to the shell time constant τ_s. Only an active control of the MHD perturbations can overcome these limitations and reduce the edge radial field on time scales longer than τ_s. Thus, considerable effort is being spent in optimizing the control algorithms and, to this end, a detailed knowledge of the relation between external magnetic measurement and the topology of the magnetic field, as modified by resonant plasma modes, is essential. The reconstruction of the magnetic field topology in RFX-mod is obtained by the guiding center code ORBIT [3]. It requires as inputs the equilibrium configuration of the magnetic field, usually computed by a $\mu\&p$ model, as described in [4], and the radial profiles of the eigenfunctions for the resonant tearing modes. In the following we shall consider discharges with $Ip \sim 800kA$, reversal parameter $F = < B(a) > / < B > = -0.1 \div 0$ and pinch parameter $B(a) / < B > \sim 1.5$. Up to now the instabilities eigenfunctions have been calculated with the hypothesis of a cylindrical geometry. In this paper we present the first results concerning the topology and the particle transport in RFX-mod implementing the correct toroidal eigenfunctions in the ORBIT code. These eigenfunctions are computed using sideband cleaned harmonics: in fact, a source of systematic error, due to the aliasing of the sidebands produced by the control coils, has been recently identified in RFX-mod and a correction algorithm developed. This systematic error also affected the real time control system, and appropriate corrections were also performed on the control system too [5]. In the following we shall refer to discharges where these corrections have been performed as *CMC* *shots* (Clean Mode Control) to discriminate them from the others where only the active coils are working (*VS shots*, Virtual Shell).

Modes eigenfunctions in toroidal geometry. The ORBIT code deals with Boozer coordinates [6], a particular case of straight field line coordinates with a Jacobian J proportional to $1/B^2$. All the quantities are functions of the poloidal and toroidal angles θ, ζ and of a flux variable such as the poloidal flux ψ_p. In the code all the lengths are normalized to the major radius and the magnetic fields to the field on axis; moreover masses and charges of the test particles are taken equal to 1 and also $\mu_0 = 1$. In this formalism the equilibrium magnetic field can be expressed in its covariant form as:

$$\mathbf{B}=g\nabla\zeta+I\nabla\theta+\delta\nabla\psi_p \qquad (1)$$

where the term with δ is related to the non-orthogonality of the coordinate system but it's very small if compared to I and g and can usually be

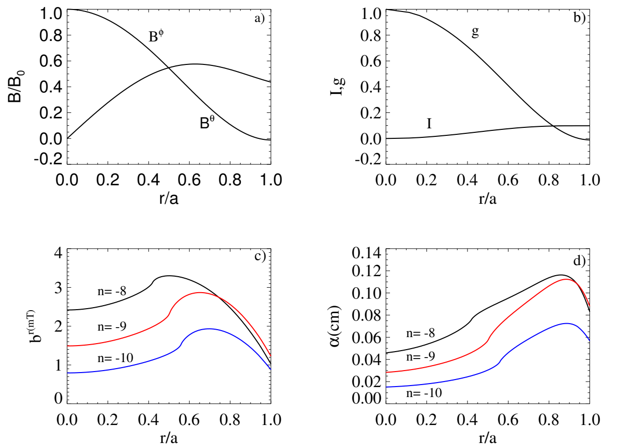

Figure 1 *(a) Equilibrium magnetic field in RFX-mod normalized to* B_0*. (b) Current profiles for RFX-mod. (c) Radial profiles for the eigenfunctions* $m = 1$ (n=-8,-9,-10) *(d) Radial profiles for* $\alpha(\psi_p)$ *relative to the same modes.*

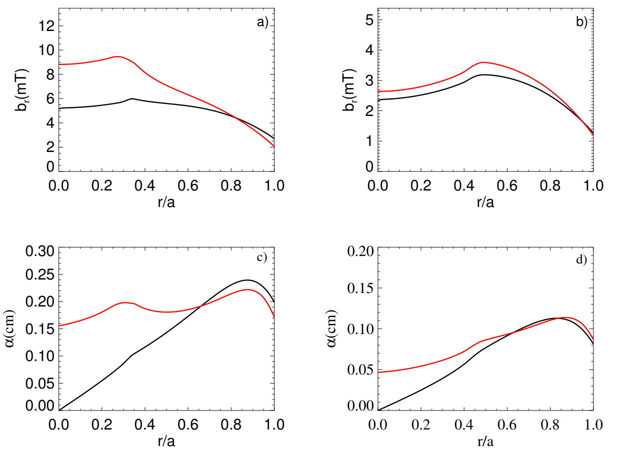

Figure 2 *(a) Radial* b^r *eigenfunction for the* $(1,-7)$ *mode in cylindrical (black) and toroidal (red) reconstruction. (b) The same as (a) for the mode* $(1,-8)$*. (c) Cylindrical (black) and toroidal (red) reconstruction of* α *for the* $(1,-8)$ *modes. (d) The same as (c) for the* $(1,-8)$ *mode.*

neglected; $g(\psi_p)$ is proportional to the poloidal current outside ψ_p and $I(\psi_p)$ to the toroidal current inside ψ_p. In fig. 1(a) the typical profiles of the equilibrium magnetic field are represented, while (b) displays the currents I,g. The radial perturbations in the code are implemented by computing the $\alpha(\psi_p)$ function which is related to the magnetic eigenfunctions $\boldsymbol{b}$ by the following relation:

$$\boldsymbol{b} = \nabla\times(\alpha\boldsymbol{B}) \qquad (2)$$

Up to now b^r and α were calculated by using the cylindrical approximation, following [4]. Now, starting from the computed toroidal functions of b^r we directly get $\alpha(\psi_p)$ by using formula 2. For the radial component of a perturbation with (m,n) helicity, and assuming: $\alpha = |\alpha(\psi p)|\, e^{i(n\zeta - m\theta)}$, we obtain:

$$b^r = \frac{R_0}{J}\left[\frac{\partial(\alpha g)}{\partial\theta} - \frac{\partial(\alpha I)}{\partial\zeta}\right] = \frac{R_0|\alpha|(mg+nI)}{J} e^{i(n\zeta - m\theta - \frac{\pi}{2})} \quad (3)$$

where $J = (I + gq)/B^2$ is the Jacobian and q is the usual safety factor. The toroidal eigenfunctions are computed by a standard procedure, described in [7] for the RFX-mod experiment; once these are known, by inverting eq. 3 it's possible to express α in terms of b^r. The absolute value of the $\alpha(\psi_p)$ profile is thus given by:

$$\alpha = \frac{J|b^r|}{R_0(gm+nI)} = \frac{(I+gq)}{R_0 B^2}\frac{|b^r|}{(gm+nI)} \quad (4)$$

Examples of the eigenfunctions for the $(m = 1, n = -8, -9, -10)$ modes are reported in fig.1 (c). The corresponding $\alpha(\psi_p)$ profiles, obtained by applying eq. 4, are in fig1(d). Note that α has the dimension of a length and is associated to the displacement of the plasma from the equilibrium due to the modes.

Magnetic field topology and QSH regimes. The toroidal $\alpha(\psi_p)$ profiles have been implemented in ORBIT in order to study the magnetic topology in several shots. In fig. 2(a)-(b) we have reported the averaged profiles of the modes $(m = 1, n = -7, -8)$ from a cylindrical (black) and toroidal (red) reconstruction, both for b^r and α in *CMC* shots. The mode values in the toroidal reconstruction for α and b^r are slightly greater than those cylindrical near the origin but have similar shapes. On the contrary, for the $m = 0$ modes, resonant near the edge where the toroidal magnetic field reverses its direction, the profiles are more different. This is clear in fig. 3 where a comparison between cylindrical and toroidal m=0 eigenfunctions is reported. Otherwise we expected a stronger effect on the $m = 0$ modes due to the toroidicity, in particular for the $m = 0, n > 6$ modes. In fact, the geometry introduces a toroidal coupling *(±1,0)* which, interacting with the tearing instability in the plasma (*m*

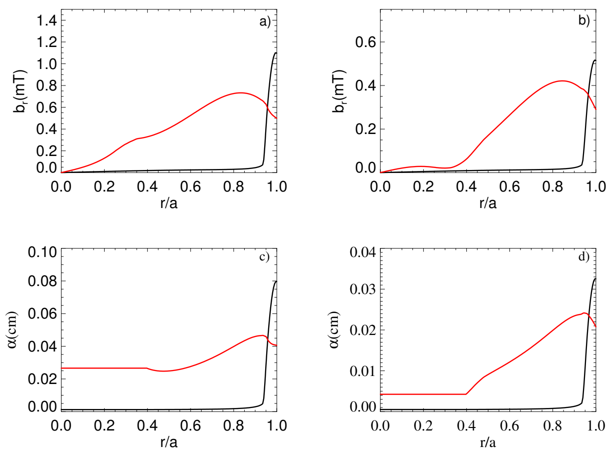

Figure 3. *(a) Radial b^r eigenfunction for the* (0,7) *mode in cylindrical (black) and toroidal (red) reconstruction. (b) The same as (a) for the mode* (0,8). *(c) Cylindrical (black) and toroidal (red) reconstruction of* α *for the* (0,7) *modes. (d) The same as (c) for the* (0,8) *mode.*

$= 1, n < -6$) generates additional components for the ($m = 0,2$ $n > 6$) modes. This may affect the particle transport near the edge and will be the object of future studies. The topology of the magnetic field is analyzed using the toroidal α eigenfunctions for several discharges, in particular when one mode is dominant respect to the others and a helical deformation of the plasma (Quasi Single Helicity, see [8]) is detected by the Soft X-Ray tomography [9]. In figure 4(a) a magnetic field Poincaré with a QSH $n = -7$ island is shown, reconstructed by the code ORBIT where formula 4 is implemented. The *conserved flux surfaces* are shown in red while *chaotic* magnetic field lines in black. Often, in the RFX-mod QSH discharges, *sticky areas* structures appear (orange in fig 4-(a)), i.e. magnetic field lines stay a long time close to the QSH island.

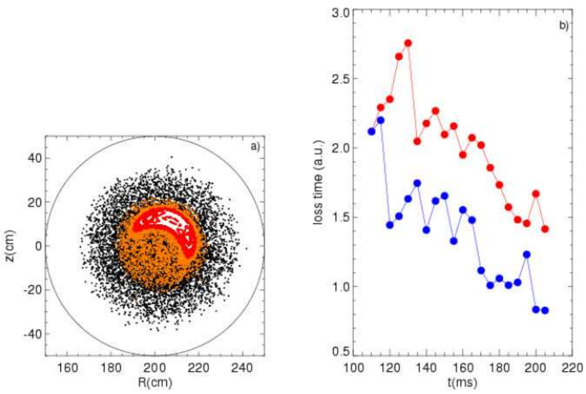

Figure 4 *(a) Quasi Single Helicity state. In red the helical conserved flux surfaces and in orange the partially chaotic magnetic field lines. (b) Comparison between the loss times in a CMC shot (red) and in a VS (blue) one.*

Finally, we report in fig. 4(b) a comparison of the confinement properties between a *CMC* discharge and a *VS* one. By the code ORBIT we compute, at several times during the discharge, the time (*loss time*) required for an ensemble of particles to escape a given region ($0.3<r/a<0.6$) where they were initially placed. Not only the real time correction of the sideband aliasing decreases the radial field at the wall, and consequently reduces plasma wall interaction, but the beneficial effect extends also inside the plasma, reducing the degree of magnetic chaos. More experiments are planned to support this observation with thermal measurements.

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