RFX-mod2: a reversed-field pinch device with edge transport optimization

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Introduction. The edge of magnetically confined hot plasmas in toroidal configurations is characterized by the presence of magnetic fluctuations with helicity $m/n$, with $m$ and $n$ the poloidal and toroidal mode numbers. In the reversed-field pinch device RFX-mod an almost-monochromatic spectrum develops in the whole plasma volume: this is the so-called quasi-single helicity plasma (QSH), characterized by enhanced confinement properties [1]. Edge measurements indicate the presence of a dominant mode with $m/n = 1/7$ and of a spectrum of nonlinearly interacting secondary modes [2], resulting in the possibility of constructive interference: a localized toroidal deformation of the edge radial magnetic field may thus be present where the modes are phase locked, with a position changing in time. Such localized deformation has negative effects on plasma-wall interaction (PWI) and on operations at high current.

The aim of this paper is to analyze the global PWI in QSH plasmas, both experimentally and numerically, for the RFX-mod and the upgraded RFX-mod2 device, soon starting operation [3]. This paper begins with the experimental characterization of the secondary modes locking in RFX-mod, and of its effect on PWI. Then, the features of the edge magnetic field topology will be described, together with a MHD description of secondary modes locking. Eventually, the positive effect of secondary modes mitigation expected in RFX-mod2 will be discussed.

The local radial magnetic deformation $\Delta$ (a.k.a. shift) of a given $m/n$ mode is related to its perturbed radial field $b_{r,m/n}$ through [4]:

$$\Delta_{m/n}(t, \theta, \phi) = \frac{-iab_{r,m/n}(t,a)e^{i(m\theta-n\phi+\phi_m(t,a))}}{(m-nq(t,a))B_{0\theta}(t,a)}.$$ (1)

This formula is written considering a cylindrical geometry $(r, \theta, \phi)$. $q(a)$ is the safety factor at the plasma edge $a$ and $B_{0\theta}$ is the equilibrium poloidal field. The $m=1$ secondary modes shift is defined as $\Delta_{sec} = \sum_{n=8}^{n=23} \Delta_{1/n}$ c.c., and the dominant mode shift as $\Delta_{1/7}$. Another useful parameter is the ratio $S_k(t) = \max_{\theta, \phi} (\Delta_{sec}(t, \theta, \phi))/\max_{\theta, \phi} (\Delta_{1/7}(t, \theta, \phi))$: it measures the disturbance of the helix associated with the dominant mode caused by secondary perturbations. Such parameters, when evaluated at the edge $r = a$, contain a 2D information about plasma edge.

Experimental findings. Thanks to a full coverage of edge diagnostics along the poloidal and toroidal angles, it is possible to reveal the 3D structure of the PWI and to correlate its topology with the magnetic deformation due to the dominant $\Delta_{1/7}$ and secondary modes $\Delta_{sec}$. All
the measurements indicate that an interferential pattern created by secondary modes causes a
toroidally localized deformation $\Delta_{\text{sec}}$, whose toroidal position changes in time.

Fig.1i shows the effect of the presence of a phase locking on PWI, considering two different
frames taken from a CCD camera looking at the CI line at 970nm: panel a) shows the situation
away from the localized toroidal deformation, while panel c) exhibits strong local emission of
CI, in particular two “stripes” toroidally localized. The strong local emission of panel c) is well
correlated with the two peaks of $\Delta_{\text{sec}}$ observed in panel d) around $\phi \sim 0$, while the smooth CI
emission observed in panel a) is the due to the fact that phase locking, at this time, is located
at 100°, outside the CCD camera field of view (see panel b). In Fig.1ii the temporal behaviour
of the maximum $\Delta_{\text{sec}}$ and $\Delta_{1/7}$ (black and red lines in panel a) is shown: the shaded regions
correspond to an increase of wall emission, which is well correlated with the condition $S_k \gtrsim 1$.
Further experimental evidences are shown in [7] and describe the PWI shape as given by a helix
rotating at few tens of Hz, distorted poloidally and with a localized toroidal deformation. In the
next paragraph the effect of such deformation on the magnetic topology is described.

**Connection length structures** are evaluated computing the average length travelled by a bundle
of 1000 magnetic field lines from an initial condition in the plane $(r,0,\phi)$ to the wall, namely
$L_{cw}$. The calculation is performed with the ORBIT code, considering modes with $m = 0,1$ and
$n = 1 : 24$ coming from the solution of ideal MHD Newcomb’s equation [9]. The reference shot
used is #37537, $I_p \sim 1.5$MA, $t = 130$ms where $S_k = 0.51$. The results are shown in Fig.2i. The
toroidal shape of $L_{cw}(\phi)$ (panel a) reproduces the $n = 7$ dominant mode topology, but with a
strong decrease in the region around $\phi = 120^\circ$, corresponding to the region where two maxima
of $\Delta_{\text{sec}}$ are observed (panel b). The two minima of $L_{cw}$ in the locking region ($L_{cw,\text{hole}}$, shaded
region in Fig.2i) can be associated quite well to the couple of stripes shown by the visible
camera in Fig.1i: a similar phenomenon is observed in the X-point region of tokamaks when
RMPs are applied and it is described as “homoclinic lobes” [5]. To assess the role of secondary
perturbations on the edge topology, a scan of $S_k$ is done by rescaling the amplitude of secondary
modes fixing their phase and the dominant mode. The most interesting observation is an order-
of-magnitude increase of $L_{cw}$ when $S_k \lesssim 0.3$, i.e. decreasing secondary modes of about a factor
of 2 (the same decrease foreseen in RFX-mod2, see the final remarks). One also notices a more
regular behaviour of the mean value of connection length in the locking region $L_{cw,\text{hole}}$.

**3D nonlinear viscoresistive MHD modelling** gives a description of mode locking similar to
the one coming from the experimental measurements previously described. With respect to
the MHD simulation described in [7], more realistic boundary conditions take into account a
thin resistive wall with resistive diffusion time $\tau_W$ at $r = a$, and a vacuum region surrounded
by an ideal wall at \( r = b \), as described in [6]. A simulation with inversed normalized resistivity \( S = 10^6 \), inverse normalized viscosity \( M = 10^4 >, b/a = 1.2, \tau_W/\tau_A = 10^4 \) is analyzed. In panel a) of Fig.2ii a part of the temporal dynamics of the dominant \( m = 1, n = 7 \) MHD mode and of \( m = 1 \) secondaries is shown (the complete simulation can be found in [6]). During this snapshot a QSH states with \( n = 7 \) spontaneously appear, interrupted by relaxation events at around \( t \sim 0.148 \tau_R \) and \( t \sim 0.154 \tau_R \). We evaluate \( S_k \) (in panel b) and the shifts \( \Delta_{1/7}, \Delta_{sec} \) at \( r = a \) using \( a = 0.459m \) and \( I_P = 1.5MA \) to normalize the magnetic field. Despite the presence of a weak QSH state (red mark in panel b)) an interference pattern due to secondary modes is present at \( \phi \sim 180^\circ \) (panel d). Panel c) instead shows a case with higher secondary shift, corresponding to the first relaxation event. A more quantitative agreement with respect to mean \( S_k \) values between numerical simulations and experiments could be achieved by performing simulations at a higher and more realistic value of inverse resistivity (in high current experiments at RFX-mod it is estimated \( S \propto T^{3/2} \sim 5 \cdot 10^7 \)). Higher \( S \) produces a general decrease of secondary modes’ intensity, and thus a reduction of \( S_k \) to values similar to the ones in Fig.1ii. Another case from MHD simulations with ideal magnetic boundary conditions is described in [7].

Considerations about RFX-mod2, and final remarks. The major upgrade foreseen on the RFX-mod machine is the removal of the vacuum vessel facing the plasma. As a result, the distance of the plasma from the stabilizing shell will be reduced, decreasing the intensity of secondary modes [8]. A twofold decrease of the magnetic deformation at the edge is expected. As a preliminary assessment of the resulting topology, the RFXlocking code [9] has been applied in two cases mimicking the two different front-end layouts (more details in [7]). The main prediction from the topological analysis is that the decrease of the plasma deformation should allow a clear increase of the connection length to the wall and the disappearance of the residual “hole” in the locking region, a feature expected to mitigate PWI. This opens the possibility of an edge transport in principle only affected by error fields at the gaps.

References

(i) Two CCD time frames during QSH states, with a field of view centered at $\phi = 0^\circ$: in panel a) without presence of phase locking in the field of view and panel (c) with the locking. The corresponding toroidal amplitude of $\Delta_{1/7}$ (red line) and $\Delta_{sec}$ (black line) are shown respectively in panels b) and d).

(ii) Time behavior of the maximum of interferential pattern in panel a). $\text{max}_{\theta,\phi}(\Delta_{sec})$ (black line) compared with $\text{max}_{\theta,\phi}(\Delta_{1/7})$ (red line); their ratio $S_k(t)$ is shown in panel b). Blue shaded areas correspond to time windows with increased wall emission in QSH state ($S_k > 0.7$), while red shaded area correspond to MH states.

Figure 1: Experimental results.

(i) Toroidal behavior of the connection length to the wall $L_{cw}$, simulation on the equatorial plane ($\theta = 0^\circ$) with $S_k \sim 0.50$. Panel (b) behavior of $\Delta_{1/7}$ (red) and of $\Delta_{sec}$. Panel (c) Scaling of $L_{cw}$ simulation with $S_k$: the black line is the average value along the toroidal direction, the red line is the value in the locking region, the blue line is the Kolmogorov length. $\langle L_{cw} \rangle$ presents a threshold-like behavior at $S_k \sim 0.3$.

(ii) Evolution of a 3D nonlinear simulation of the RFP configuration (better described in [6]); a) single MHD cycle: the growth of dominant mode is disturbed by relaxation events; (b) time evolution of $S_k$ during the MHD cycle, two different snapshots are identified (vertical lines); panels (c) and (d) toroidal behavior of the displacements $\Delta$, corresponding to the two snapshots of panel (b) with $S_k > 2$ and $S_k < 2$.

Figure 2: Numerical results.