34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-1.130 (2007)

Imaging of core MHD activity in RFX-mod

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In the Reversed Field Pinch (RFP) toroidal configuration for plasma confinement, the magnetohydrodynamic (MHD) modes (characterized by the poloidal, *m,* and the toroidal, *n,* mode numbers) drive a large part of the toroidal magnetic field through a self-organized mechanism called "dynamo". The dynamo can be produced by only one MHD mode ($m=1$, $n_0 \approx -2R_0/a$, where R_0 and a are the major and minor radii of the torus, respectively). In this regime, called Single Helicity (SH), the whole magnetic field has a helical symmetry. Experimentally this state is not fully achieved, since a residual level of low-amplitude secondary $m=1$ modes (with $n<n_0$) determines a perturbation of the helical symmetry (through the dependence on the poloidal angle θ), leading to a hybrid state called Quasi Single Helicity (QSH). In QSH, the helical deformation survives as a localized island in the core, which is heated, and surrounded by residual chaos generated by the non-linear interaction with the secondary modes. The helical symmetry of QSH can be further perturbed if the secondary mode amplitude is increased, leading to the multiple helicity (MH), where magnetic chaos covers most of the plasma volume, and the island disappears. This leads to increased particle and energy losses, except for the edge, where residual conserved magnetic flux surfaces are present [1].

In this paper we present a complete characterization of QSH islands and their dynamics from the thermal and magnetic point of view, in the RFX-mod RFP experiment [2]. In RFX-mod, a very effective technique for producing strong QSH states is represented by the Oscillating Poloidal Current Drive (OPCD) [3]: the reduction of the global magnetic fluctuation level induced by the OPCD cycle is regularly associated to the formation of a QSH, as well as to a global increase of the electron temperature and to a reduction of the electrons energy transport. Another technique to achieve the QSH regime is based on the MHD active control system implemented on RFX-mod and which can affect the magnetic boundary condition in the Virtual Shell operation (VS) [4]: saddle coils can be used to produce helical fields, following a reference input, thus leading to QSH states. This technique can be effectively studied by a non-invasive diagnostic, the soft X-ray (SXR) tomography installed on the RFX-mod device [5]. This diagnostic permits the 2-D map reconstructions of the plasma radiation emissivity with high temporal and spatial resolution, allowing the characterization of the

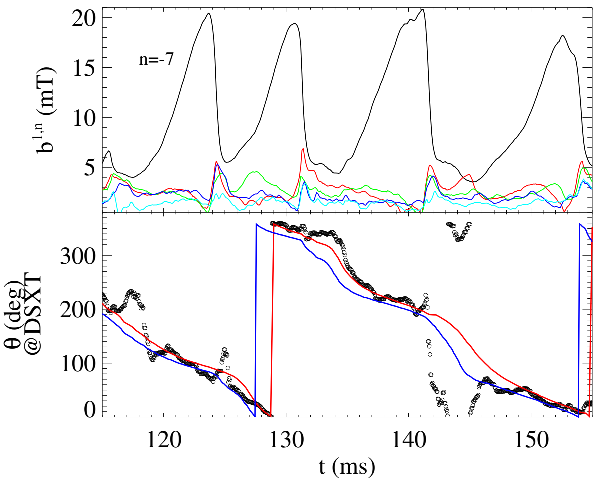

Fig.1. *(a) Temporal evolution of the magnetic perturbation $b^{1,n}$, for $-11 \leq n \leq -7$. (b) The magnetic phase of the dominant $b^{1,-7}$ at the tomographic section, for magnetic measurements affected by aliasing (blue line) and after correction (red line). The poloidal position of the SXR centre of mass is superimposed (empty circles).*

MHD instabilities and of their dynamic evolution. A local increase of the SXR measurements (*brightness*) is observed during QSH, both in VS and OPCD operational conditions, associated to more emissive localized SXR structures emerging in the plasma core in correspondence of the mode dominating the magnetic spectrum, and at the radial position corresponding to its resonant surface. But accurate comparisons between the poloidal position of the SXR O-point (defined as the center of mass of the SXR plasma emissivity) with the position of the island from magnetic measurements highlighted a non-negligible systematic mismatch, larger up to 30-40 degrees. This mismatch was identified during QSH appearing spontaneously but in particular was evident in QSH plasmas induced by the MHD active coil system. The high reliability of the information from the SXR reconstructions suggested for investigating deeply the reason of this mismatch which was identified in a systematic error in magnetic measurements due to the aliasing of the sidebands generated by the saddle coils [6]. An example of the differences between the SXR centre of mass (empty circles) and the magnetic measurements (blue line) is represented in Fig.1(b), while the corresponding temporal evolution of the internal resonant MHD instabilities ($m=1, 7 \leq |n| \leq 11$) are displayed in Fig.1(a). The magnetic measurements cleaned from the aliasing effect are superimposed with a red line: a very good agreement for the *(m=1,n=-7)* phase with the poloidal position of the SXR structure is found when the QSH regime is robust; when all of the perturbations have similar amplitudes, the SXR centre of mass does not agree perfectly with the magnetic phase, even if an asymmetry in the plasma emissivity seems to remain. The corrections of the Fourier aliasing have also been implemented in the real time algorithms and have led to the concept of Clean Mode Control (CMC) operation [6,7]. Combining the high spatial resolution and the temporal accuracy of the tomographic diagnostic, a detailed characterization of the SXR structure during the dynamic evolution of the dominant mode in the plasma core can be performed. The truncated Cormack Fourier-Bessel algorithms used for the plasma emissivity

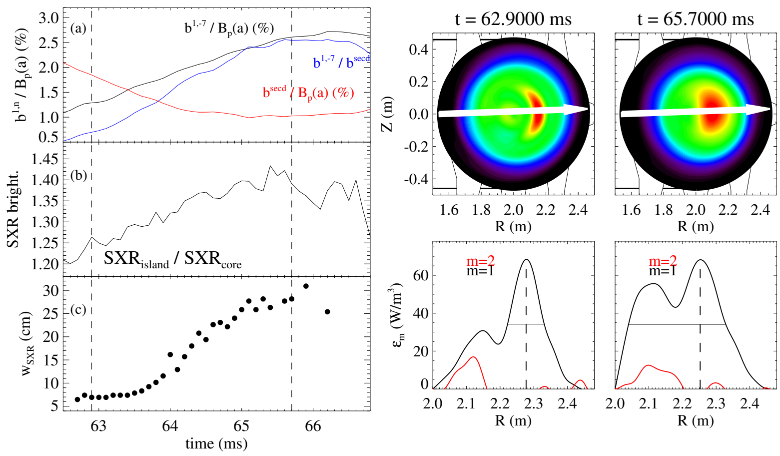

Fig.2. *(a) Temporal evolution of the dominant magnetic $b^{1,-7}$ (black line) and secondary modes $b^{1,n}$ in a OPCD QSH cycle (red line), superimposed to the ratio $b^{1,-7}/ b^{1,n}$ (blue line). (b) Temporal evolution of the ratio between the SXR brightness along a line of sight looking at the island O-point and at the plasma core. (c) Temporal evolution of the width w_{SXR} of the SXR reconstructed island. Two examples of tomographic reconstructions for the times indicated by the vertical dashed lines of the left panel are reported in the right panel, together with the m=1, m=2 Fourier reconstructed components along the island O-point direction, identified by the white arrows.*

reconstructions allow for defining the radial width (w_{SXR}) of the SXR islands as the FWHM of the *m=1* component of the truncated Fourier series. Even if the SXR reconstructions are performed with *m* up to 2, for the w_{SXR} estimation the *m*=2 component has not been considered for simplicity being less than 10% with respect to the *m*=1 component. In the right panel of Fig.2, the SXR tomographic reconstructions at different times are displayed, and the corresponding radial component *m=1* (black line) and *m=2* (red line) of the truncated Fourier series along the white arrows through the SXR island O-point are illustrated. In a single QSH cycle (during OPCD), the width w_{SXR} increases as a function of the dominant mode amplitude, and inversely with respect to the secondary modes (see Fig.2(a)), and the ratio between the SXR brightness along a line of sight looking at the island O-point and at the plasma core reflects the evolution of the magnetic $b^{1,-7}/ b^{1,n}$, being $b^{1,n}=sqrt(\Sigma_{n\neq-7}\, b^{1,n})$ (see Fig.2(b)). This means that the evolution of the SXR island is linked both to the dominant ($b^{1,-7}$) and to the secondary modes ($b^{1,n}$): it appears in the plasma column when the $b^{1,-7}$ is sufficiently robust with respect to the $b^{1,n}$, and can grow in the radial direction because of its reduced overlapping with the secondary islands due to their small amplitudes. In this respect, there are evidences that suggest a role of the secondary modes in increasing the chaos in the region of the X-point [8]. In Fig.3(a), the w_{SXR} evolution for the QSH cycle of Fig.2 is displayed as

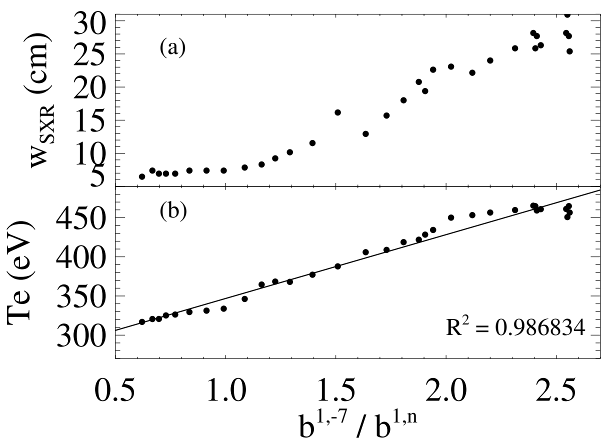

Fig.3. *(a) w_{sxr} and (b) Te as functions of the ratio between the dominant mode $b^{1,-7}$ and the secondary ones ($b^{1,n}$).*