

## **Tomographic imaging of RFX plasmas in various confinement regimes.**

A.Murari, P.Franz, L.Marrelli, G.Spizzo, D.Terranova, L.Zabeo,  
R.Bilato, P.Martin, S.Martini, P.Zanca

*Consorzio RFX, Corso Stati Uniti,4 - 35127 Padova, Italy*

### **1. Introduction**

The Reversed Field Pinch (RFP) is a self-organising quasi-minimum energy state whose dynamics is governed by a magnetic field regeneration mechanism, called dynamo [1] in analogy to other physical systems. The most specific characteristic of the RFP is the reversal of the toroidal component of the magnetic field at the edge with respect to the direction on axis. This configuration is partially generated by the plasma itself and the resulting safety factor profile renders it unstable to helical modes of the form  $B_{m,n}(r,\theta,\varphi) = b_{m,n}(r)\exp[i(m\theta+n\varphi)]$ , which can give rise to different quasi relaxed states, characterised by different topologies of the magnetic fields. The purpose of this paper is to present some experimental investigations of the RFP plasmas' internal structure obtained by means of Soft X Ray (SXR) Emission tomography. This diagnostic is a non-invasive method that permits the reconstruction, with good spatial accuracy and high time resolution, of the plasma radiation emissivity  $\varepsilon$  (defined as the power emitted per unit volume). If some basic hypothesis on the plasma purity are satisfied, the iso-emissivity curves are a good approximation of the magnetic surfaces, providing valuable information on the field topology and the magnetohydrodynamic (MHD) activity.

In RFX [2], a large reversed field pinch (RFP) experiment with circular cross section (major radius  $R_0=2$  m, minor radius  $a=0.46$  m, target plasma current=2 MA), an integrated SXR tomographic system has been installed [3]. The diagnostic consists of four linear translators, which allow the insertion of four instrumented heads near to the plasma edge, for a total of 78 lines of sight and impact parameter  $p$  exceeding 0.9.

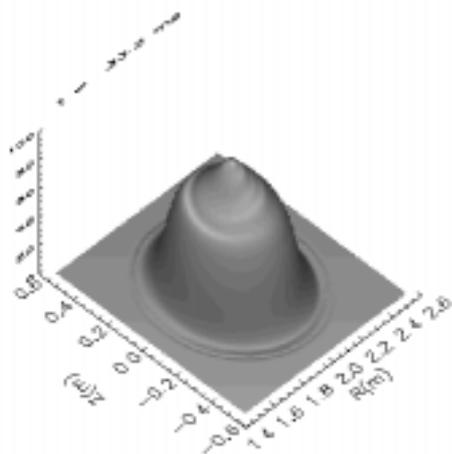
The paper is organised as follows: in the next section, after a short description of the various tomographic methods adopted in RFX, some reconstructions are shown, with particular attention to the comparison between various confinement regimes and the relationship between the topology of the SXR emission and that of the magnetic fields. The thermal properties of a particular plasma state (QSH) and future prospects are the subject of the last section.

### **2. SXR emissivity and magnetic fields topology in Multiple and Single Helicity states.**

To reconstruct SXR emissivity in RFX, three different algorithms have been compared: the Cormack technique, a maximum entropy constrained finite element algorithm and a hybrid method. The first one is based on the Cormack [4] series expansion, where the choice of the number of coefficients has been optimised by means of a generalised cross validation approach. A maximum entropy constrained finite element method [5] has also been considered, which better exploits the non uniform spatial resolution of the diagnostic and allows, in principle, to obtain more accurate spatial information about emissivity localised features. Finally, the preceding techniques have been merged in a hybrid algorithm: the plasma is subdivided in concentric pixels, over which the emissivity is expanded in Fourier harmonics. A comparison of the reconstructions, obtained with the three aforementioned methods, has given reasonable

agreement, increasing the confidence in the quality of the results. Moreover, this also allows to use the first method, which is based on the Bessel-Fourier series expansion [6] and is the most favourable in terms of computational requirements; for this reason, all the results mentioned in this paper have been obtained with this reconstruction technique.

In RFX, during standard operation, the core of the plasma is believed to be

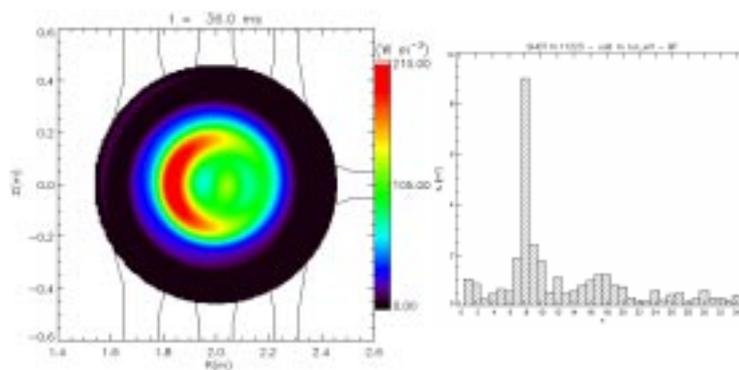


**Fig.1** Typical bell-shaped emissivity during RFX standard operation (MH state).

quite stochastic, due to the simultaneous presence of several instabilities, as derived by the results of the external magnetic measurements. Density and temperature profiles, measured with interferometry and Thomson scattering respectively, are indeed relatively flat in the central region, whereas most of the gradients are concentrated at the edge. In this plasma state, called Multiple Helicity (MH), no macroscopic features are normally detected in the SXR data and the emissivity reconstructions have therefore the typical bell-shaped form of the kind shown in fig.1.

A different behaviour is observed when the plasma reaches a Quasi Single Helicity state (QSH). In fact, as discussed in [7], RFX plasmas can exist in an alternative quasi relaxed state, in which one single mode is largely dominant. When this QSH state is attained, a clear  $m=1$  structure is typically present in the brightness profile which, once inverted, corresponds to a macroscopic  $m=1$  island in the emissivity, as shown in fig.2. The presence of a dominating  $m=1$  mode is also confirmed by the Fourier transform of the signals obtained by the pick-up coils, which for the QSH states give the toroidal spectrum also reported in fig.2. From this kind of spectrum it can be deduced that the global structure, which characterises the QSH state, normally appears as an  $m=1$   $n=7$  or 8 mode in the magnetic measurements (the case shown in fig. 1 is characterised by a toroidal number  $n=8$ ).

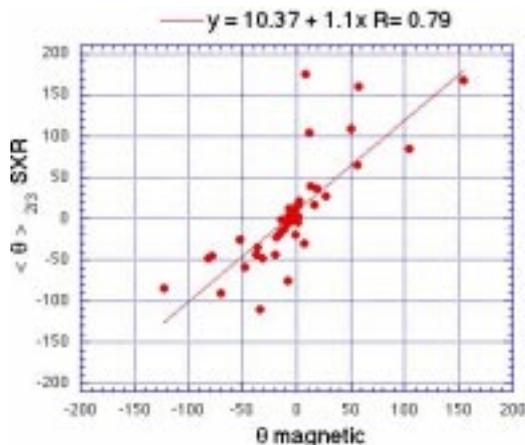
It is worth pointing out that both the time evolution and the spatial localisation of the  $m=1$  features detected by the SXR tomography are in agreement with the reconstructions of the magnetic structures determined from the pick up coils. Indeed, when the QSH state is attained transiently, as for example during operation with PPCD [8], the evolution of the magnetic and SXR measurements provide coherent results, showing simultaneous growth and decay of the  $m=1$  structures. With regard to their spatial location, it should be mentioned that the dominant mode of the QSH state determines a non-axisymmetric distortion of the plasma column, which can be reconstructed from the external magnetic measurements [9]. The poloidal position of the SXR features correlates quite well with



**Fig.2** Contour plot of the emissivity and the magnetic toroidal spectrum for a QSH state.

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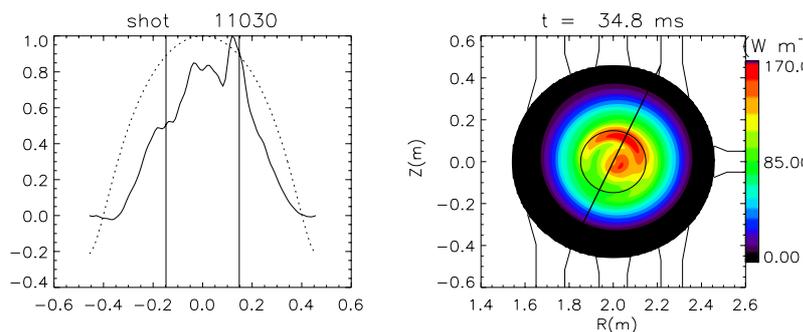
the results of these magnetic reconstructions. This is shown in fig.3, where the relationship between the poloidal angle of the SXR data ( $\theta$ -SXR) and that of the magnetic measurements ( $\theta$ -magnetic) is shown. In more detail, the  $\theta$ -SXR is obtained from the  $m=1$  components of the brightness, averaged between 1/3 and 2/3 of the normalised radius (which is the radial position where the structure is normally detected). On the other hand, the  $\theta$ -magnetic is the poloidal position of the plasma column maximum displacement at the tomography toroidal location. This plot indicates that the  $m=1$  region of increased emissivity can be located at different poloidal positions in the cross section of the tomographic diagnostic and that its poloidal angle is strongly correlated with that of the plasma column's maximum displacement determined by the magnetic measurements.



**Fig.3** Poloidal angle of the SXR  $m=1$  structure plotted against the poloidal phase of the plasma column magnetic displacement.

To summarise, it can be stated that the tomographic reconstruction of the SXR emission in RFX has proved to give results which are in good agreement with the field topology expected on the basis of the magnetic measurements. It seems therefore reasonable to assume that the main emissivity features detected in the QSH states are indicative of the existence of magnetic islands. In this respect, it is interesting to notice that the radial position of the SXR feature can be quite accurately predicted on the basis of the expected safety factor profile, assuming that the structure detected by the tomography coincides with a magnetic island. If the  $q$  profile is indeed deduced from the  $\mu$ & $p$  model [1], which

allows the determination of the current density profile on the basis of external measurements, the magnetic island, whose toroidal  $m$  and poloidal  $n$  numbers are derived from the pick-up coils, is predicted to be localised at the radial position at which the SXR structure is effectively detected (see fig.4). Moreover, the higher the toroidal  $n$  number of the mode dominating the QSH spectrum, the more external is the position of the SXR island. On the other hand, since at the moment no direct measurement of the safety factor is available in RFX, this last result should be treated with great care and simply considered as additional evidence of the agreement between tomographic and magnetic measurements.



**Fig.4** SXR emissivity for a QSH (continuous line), safety factor profile (dotted line) and predicted radius of the island.

### 3. Thermal properties of the SXR features and conclusions.

The relevance of the QSH, both for the dynamo studies and for the control of the RFP configuration, has stimulated further study of the characteristics of this plasma

state, with particular regard to its thermal properties. First of all, it should be mentioned that these  $m=1$  structures, present in the SXR data, seem to be due to a local increase of the electron temperature, with respect to the remainder of the plasma core. A fit of the SXR data and a comparison with the Te results obtained with a separate diagnostic, based on the double foil method, indicate that the temperature inside the structure is about 30 % higher than in the surrounding plasma. These values have also been confirmed by some temperature profiles measured with a 20 point Thomson Scattering<sup>[10]</sup>.

Further investigation has also been dedicated to the behaviour of the SXR fluctuations inside the region of enhanced emissivity. It turns out that the viewing chords, which cross the  $m=1$  feature, show a higher level of fluctuations (rms), up to one order of magnitude, when the brightness is filtered in the range between 300 Hz and 3 kHz (this frequency interval has been carefully chosen to include practically all the power in the fluctuations and to exclude slow global variations of the plasma). This result has been confirmed by a Singular-Spectrum analysis <sup>[11]</sup>, see fig. 5, which provides an alternative discrimination method between global trends and actual fluctuations. The physical phenomena, determining these higher frequency components of the SXR signals, are under study.

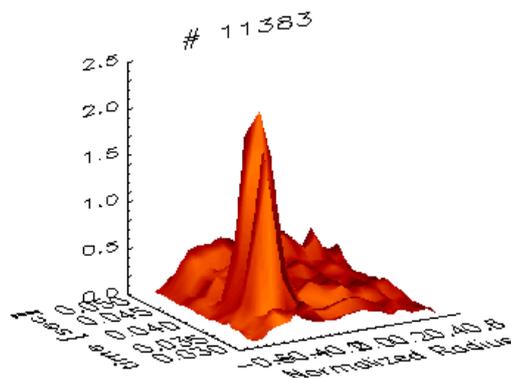


Fig.5 Radial profile of SXR fluctuations for a QSH state.

In conclusion, it can be stated that the internal topology of the magnetic fields, as derived from the SXR emissivity, is consistent with the results based on the external magnetic measurements for both QSH and MH states. The SXR tomography can therefore give useful information about the magnetic and thermal evolution of the RFP configuration in all the experimentally accessible confinement regimes.

As far as future developments are concerned, to improve the thermal characterization of these structures and to improve the understanding and control of the bifurcation leading to the QSH states, further investigations are planned in mainly three directions; (a) a space and time resolved analysis of the electron temperature profiles and fluctuations inside the islands; (b) the measurement of the internal magnetic fields in order to obtain a better estimate of safety factor profile before and during the formation of the QSH states and (c) a thorough investigation of the ion fluid behaviour during the QSH state.

## References

- [<sup>1</sup>] S. Ortolani, D.D. Schnack, *Magnetohydrodynamics of plasma relaxation*, World Scientific, Singapore 1993.
- [<sup>2</sup>] L. Fellin et al., *Fusion Engineering and Design*, V25 (1995), January II 1995
- [<sup>3</sup>] P.Martin, A.Murari et al., *Rev. Sci. Instr.* **68** (2) (1997), 1256.
- [<sup>4</sup>] A. M. Cormack, *J. Appl. Phys.* **34** (1963), 2722
- [<sup>5</sup>] S. Gull and G. Danniell, *Nature* **272** (1978), 686
- [<sup>6</sup>] L. Wang and S. Granetz, *Rev. Sci. Instruments* **62** (1991), 842
- [<sup>7</sup>] P. Martin, *Plasma Phys. Controlled Fusion*, **41** (3A) (1999), A247
- [<sup>8</sup>] Sarff J. S. et al., *Phys. Rev. Lett.* **72** (1994), 3670
- [<sup>9</sup>] P. Zanca and S. Martini, *Plasma Phys. Controlled Fusion*, **41** (1999), A315
- [<sup>10</sup>] R.Pasqualotto et al., *Energy transport in RFP enhanced confinement regimes* this conference
- [<sup>11</sup>] R.Vautard et al., *Physica D* **58** (1992), 95-126