

Two-dimensional time resolved measurements of the electron temperature in MST

P. Franz

Consorzio RFX, Euratom-ENEA Association, 35127 Padova, Italy

F. Bonomo

*Consorzio RFX, Euratom-ENEA Association, 35127 Padova, Italy
and Dipartimento di Fisica, Università di Padova, 35127 Padova, Italy*

L. Marrelli

Consorzio RFX, Euratom-ENEA Association, 35127 Padova, Italy

P. Martin

*Consorzio RFX, Euratom-ENEA Association, 35127 Padova, Italy
and Dipartimento di Fisica, Università di Padova, 35127 Padova, Italy*

P. Piovesan and G. Spizzo

Consorzio RFX, Euratom-ENEA Association, 35127 Padova, Italy

B. E. Chapman

Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706

D. Craig and D. J. Den Hartog

*Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706
and Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas,
University of Wisconsin-Madison, Wisconsin 53706*

J. A. Goetz and R. O'Connell

Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706

S. C. Prager

*Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706
and Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas,
University of Wisconsin-Madison, Wisconsin 53706*

M. Reyfman

Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706

J. S. Sarff

*Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706
and Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas,
University of Wisconsin-Madison, Wisconsin 53706*

(Received 7 May 2006; presented on 10 May 2006; accepted 19 June 2006;
published online 3 October 2006)

Two-dimensional (2D) time resolved images of the electron temperature profile in the core of the MST reversed field pinch plasma are presented. The measurements have been obtained with a soft x-ray (SXR) tomographic diagnostic comprised of four cameras, each with a multichannel photodiode array, viewing the plasma at different poloidal angles, with a total of 74 channels. The 2D electron temperature profile is estimated by simultaneously measuring the SXR emissivity through different beryllium foils, using the standard double-filter technique. With these methods, fast temperature variation in the core of the plasma (up to 100 kHz) can be analyzed. © 2006 American Institute of Physics. [DOI: [10.1063/1.2229192](https://doi.org/10.1063/1.2229192)]

I. INTRODUCTION

In this article, the initial results of the two-dimensional electron temperature, T_e , profile measurements, performed in the Madison Symmetric Torus¹ (MST) reversed field pinch (RFP), will be shown. The profiles have been obtained using the soft x-ray (SXR) spatial-resolved measurements of the SXR tomography² installed in MST.

This diagnostic is composed of four units, SXR1, SXR2,

SXR3, and SXR4, all installed on 1.5 in. portholes at the same toroidal location. Each instrument includes a photo-camera (which contains the SXR detectors) and the mechanical support (used to place the camera in its operating position). Three of them, SXR1, SXR3, and SXR4, are mounted on manipulators, which enables one to insert, extract, or remove the diagnostic without breaking MST vacuum; SXR2 is more compact and the photocamera is in a fixed position. All the SXR cameras are of the same design: an array of 20

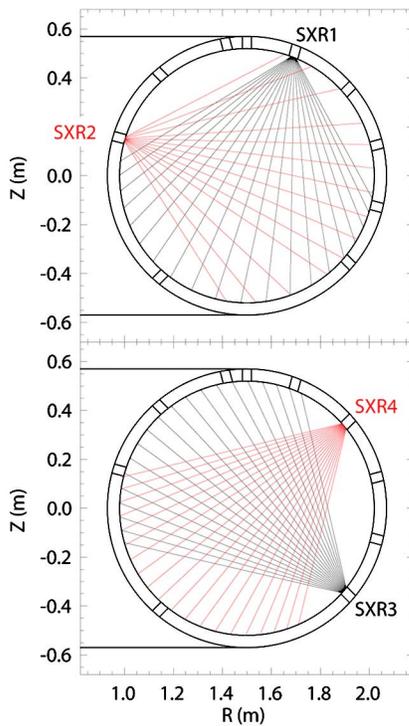


FIG. 1. (Color online) Lines of sight of SXR1, SXR2, SXR3, and SXR4 photocameras.

silicon photodiodes (the AXUV-20ELM manufactured by IRD) is installed inside, a pinhole (1×4 mm) defines the geometry of the lines of sight, and a beryllium foil, placed between the pinhole and photodiodes, is used to define the desired SXR energy range and to block visible light. The total number of lines of sight is 74: Fig. 1 shows the present geometry of the SXR tomography diagnostic.

Instead of using the same thickness of Be foil for all the SXR probes (as has been done in the past), which allows only for tomographic reconstructions of the SXR emissivity³ (radiation power per unit volume), different foils have been installed in the diagnostic to provide information on the electron temperature. The continuum of SXR radiation depends on the electron temperature and density, and on the impurity content of the plasma. The dependence on T_e can be highlighted if the SXR emission is observed in different energy ranges, by opportunely selecting the Be filters. The density term does not enter into play if the ratio of SXR measurements is taken. In addition, the contribution of impurity radiation lines can be greatly reduced if the filter thickness is large enough.

Two diagnostic configurations have been explored: the “multicolor” tomography, with different foils on all four cameras, and “two-color” tomography, with a given Be thickness used in a pair of probes and another thickness in the remaining pair. In both cases T_e is calculated by taking the ratio of two SXR emissivity distributions measured with different Be foils and is the application of a standard method based on the filter absorption technique (also referred to as the “double-foil” method), used, for example, for core electron temperature measurements^{4–6} in the RFX device. In the multicolor configuration the SXR emissivity distributions

are obtained through a simulation of the experimental data, while the two-color configuration utilizes tomographic algorithms.

These techniques have been applied to determine T_e in the plasma core during the application of pulsed parallel current drive (PPCD).^{7,8}

This article has been organized as follows: Section II will first illustrate the double-foil technique used for T_e calculations. The application of this technique will be described in Sec. III for the “multicolor” results and in Sec. IV for the “two-color” initial data. The discussions are presented in Sec. V.

II. DOUBLE-FOIL TECHNIQUE

It can be shown that the ratio R of two SXR intensities measured by two detectors viewing the same region of plasma (for example, with two overlapped lines of sight) through two different thicknesses of material filters is a function of the electron temperature and can provide a relatively crude measure of the highest temperature along the line of sight. This method has been substantially refined on MST to take advantage of the SXR emissivity distributions available through tomographic reconstruction. In the usual two-foil technique, the ratio of line integrated measurements of emissivity (brightness) is considered, and this leads to a systematic error in the T_e calculations due to the uncertainties in the electron density and temperature profiles. This error disappears if the ratio of two SXR emissivity distributions is taken.

The SXR radiation emissivity ε and the brightness $f(L)$ (along the line of sight L) have been calculated using a detailed model⁹

$$\varepsilon = K \int_E dEA(E)T(E, \text{Be}) \left\{ \frac{n_e^2(r)}{\sqrt{T_e(r)}} \exp \left[-\frac{E}{T_e(r)} \right] \right\}, \quad (1)$$

$$f(L) = \int_L dl \varepsilon. \quad (2)$$

In this case only the emission due to the continuum is modeled. In formula (1) the term between the curly brackets is the bremsstrahlung emission, A is the absorption function of the silicon detector, and T is the transmission function of a beryllium filter of thickness Be. The simulated emission lies on a set of circular surfaces, shifted horizontally by a quantity varying between the shift of the magnetic axis and the Shafranov shift of the last closed flux surface of the plasma. The radial profiles of the electron density and temperature are fitted as $n_e = n_{e0}(1-r^\gamma)$ and $T_e = T_{e0}(1-r^\alpha)^\beta$. One or more structures in the profiles (that is, locally large or small n_e or T_e), as the ones found in quasisingle helicity (QSH) states,^{3,9,10} can be added in the model to better reproduce the experimental data. The main difficulty usually encountered with this technique is the spectral distortion caused by line emission as well as by the recombination radiation. These two contributions are not directly modeled but are included only through the constant K . To overcome this limit, the thickness of the foils must be precisely selected in order to detect only the continuum part of the SXR spectrum. Using

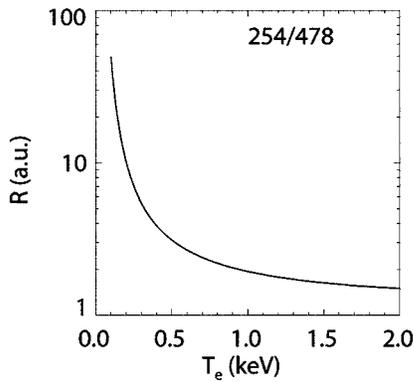


FIG. 2. Ratio R , as a function of the temperature T_e , of the emissivity distributions ε with the pair of beryllium foils 254 and 478 μm .

filters thick enough (for MST plasmas thicker than 250–300 μm) the radiation line contribution can be assumed small.

When a pair of filters, Be_1 and Be_2 , is selected, the SXR emissivity can be simulated and an interpolation formula which relates the ratio R to the temperature T_e can be provided. R can be calculated as $f(L, \text{Be}_1)/f(L, \text{Be}_2)$ along a given line of sight—this is the standard two-foil technique, or, as in the present case, as $\varepsilon(\text{Be}_1)/\varepsilon(\text{Be}_2)$. An example of the ratio, as a function of the temperature T_e , of the emissivity distributions ε with the pair 254 and 478 μm of beryllium foils is shown in Fig. 2. This curve is well interpolated by the formula

$$T_e = \exp(8.540 - 3.161 \times \ln R + 1.257 \times \ln^2 R - 0.263 \times \ln^3 R + 0.021 \times \ln^4 R). \quad (3)$$

It is easy to show that in order to increase the resolution in the T_e estimates one of the two foils should be at least two or three times thicker than the other.

III. MULTICOLOR MEASUREMENTS

The multicolor tomography was tried first to estimate the electron temperature in the core of the MST plasma. This was done also to check if the SXR flux during PPCD experiments was enough for this kind of measurement. In this configuration, four different thicknesses of Be foils have been used in the photometers. In particular, two sets of filters have been selected: (80, 15, 140, and 478 μm) for SXR1, SXR2, SXR3, and SXR4, respectively, and (140, 15, 254, and 478 μm). The thickness of the foils has been measured with a precision of $\pm 1 \mu\text{m}$ to minimize the propagated error on the temperature estimates. As previously stated, one important issue in this selection was the reduction as much as possible the impurity line radiation, mainly due to aluminum, in the measurements; these lines have energy of about 2 keV. The second set of filters was chosen in order to further decrease the Al contribution in the data. This contribution is surely significant in the 15 and 80 μm signals, but is greatly reduced in the 140 and 254 μm and almost entirely avoided in the 478 μm measurements. One additional interesting application of the multicolor tomography could be, thus, the qualitative estimate of the Al content in the plasma, obtained by comparison of the SXR profiles resolved with the differ-

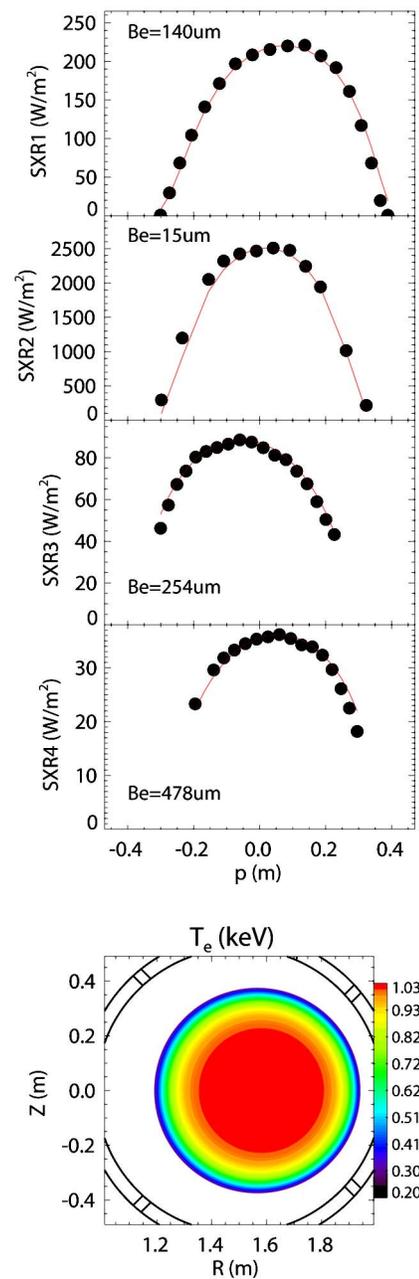


FIG. 3. (Color online) An example of multicolor measurements (black circles). The lines shows the best simulated values for that particular shot. The contour plot of the T_e calculated from the SXR profiles is also shown.

ent Be filters. An example of multicolor measurements is shown in Fig. 3 (black circles) for a high current (550 kA) PPCD plasma. All four SXR profiles have been measured, and this proved that the PPCD experiment was the optimum condition for this kind of measurements. Without the PPCD, or at lower plasma current, the emitted SXR flux was reduced to a level where the cameras with thicker foils could not measure any significant profile.

For each selected time, the signals (brightness) measured with the four photometers have been simulated using the SXR model, and the density and temperature profile have iteratively evolved, together with the shifted emissivity surfaces, so as to reproduce as well as possible the experimental data. As an example, the lines in Fig. 3 show the best simu-

lated values for that particular shot. Once the best parameters of the SXR model have been found, an estimate (or indirect reconstruction) of the SXR emissivity measured by each camera could be obtained calculating the integral (1). In our particular case the SXR emissivity distributions ε with 254 and 478 μm foils have been considered and the ratio $R = \varepsilon(254 \mu\text{m})/\varepsilon(478 \mu\text{m})$ has been calculated. Since, as shown in Sec. II, R is a function of the temperature, each point of this two-dimensional (2D) distribution could give an estimate of the temperature through the formula (3). The resulting 2D T_e profile is shown in Fig. 3. The on-axis temperature is about 1 keV, comparable with the Thomson scattering T_e measurements obtained in similar plasmas.^{7,11}

IV. TWO-COLOR MEASUREMENTS

The results shown in the previous section validate the multicolor tomography but also indicates a strong limit in the method. In fact, for each time, all the SXR radial profiles must be simulated and from that simulation the reconstructed emissivity distributions can be obtained and then the ratio R can be calculated, which eventually gives the 2D T_e reconstruction. Each parameter in the model should be iteratively evolved until the differences between the simulated values and the experimental measurements are minimized. This is a time consuming process.

The next step has been, to overcome these limits, the replacement of the Be foils for all the photocameras and the installation of only two suitably selected filters, one in the SXR1 and SXR2 cameras and the other in SXR3 and SXR4. Figure 1 shows that the angular distance between SXR1 and SXR2 is 90°, and the same is true for SXR3 and SXR4. Each pair of probes can then be used to reconstruct the SXR emissivity through tomographic inversion, which is much faster than the profile simulations. The two ε distributions will be referred to the two different selected filters. Using two probes in the tomographic inversion, instead of four (as in the case where the diagnostic is equipped with the same Be foil for all photocameras), would provide less resolved reconstructions, but provide one with the ability to track fast changes in electron temperature in the core of the plasma.

Taking the ratio of these two reconstructions and using the relation between R and the electron temperature, a 2D estimate of T_e can be obtained. Again, the two Be foils have been selected with thickness greater than 300 μm in order to avoid the radiation lines emitted by impurities; in particular, SXR1 and SXR2 have a 303 μm foil, Whereas SXR3 and SXR4 have a 761 μm foil. The interpolation formula of $R(T_e)$, for these filters, is now

$$T_e = \exp(8.911 - 2.649 \times \ln R + 0.885 \times \ln^2 R - 0.156 \times \ln^3 R + 0.011 \times \ln^4 R). \quad (4)$$

Figure 4 shows the reconstructed emissivities $\varepsilon(303 \mu\text{m})$ and $\varepsilon(761 \mu\text{m})$, together with the T_e contour plot and radial profile. This example is a 550 kA PPCD shot. The SXR and T_e profiles indicate that the plasma is shifted towards the outboard side of the vessel more than in standard discharges and that the application of PPCD can distort the plasma shape and make it poloidally asymmetric. The reconstructed

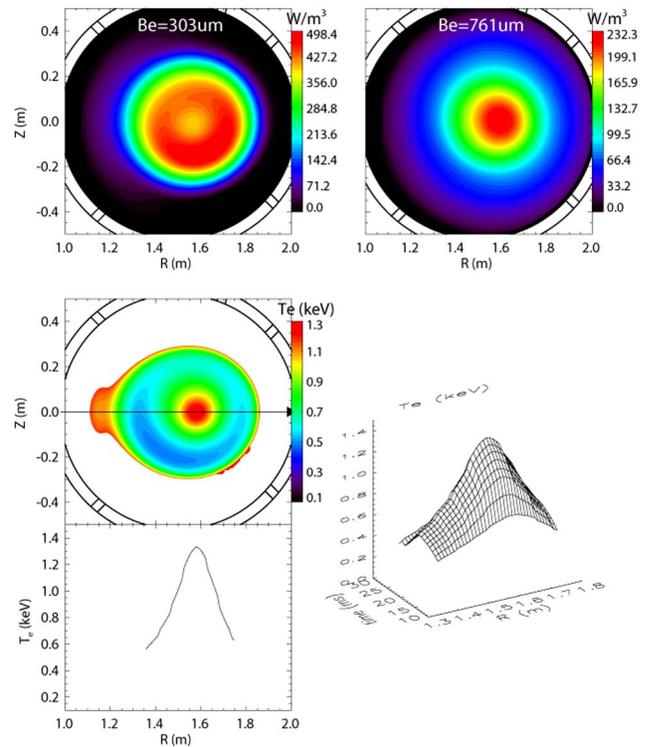


FIG. 4. (Color online) The reconstructed emissivity distributions $\varepsilon(303 \mu\text{m})$ and $\varepsilon(761 \mu\text{m})$, together with the T_e contour plot and radial profile for a given time. The 2D reconstruction of T_e is also shown.

2D temperature, also in the figure, shows that the T_e remains above 1 keV for several milliseconds, with a maximum value of 1.3 keV.

V. DISCUSSIONS

The SXR tomography, both in the “multicolor” and the “two-color” configurations, can be successfully used to reconstruct the T_e profiles. In particular, the two-color measurements are more reliable and the calculations are faster, making it better adapted for the analysis of the time evolution of the temperature. The two-color method could also be used to study T_e for the rotating coherent structures,^{3,12} that is, locally enhanced SXR emissivity regions, which appear in the core of the plasma as a result of PPCD. During these experiments, all tearing mode amplitudes can be reduced and the overlap of the associated islands decreases to such an extent that magnetic flux surfaces are at least partly restored and multiple, discrete islands can form. In some PPCD plasmas, however, the mode resonant nearest the magnetic axis remains relatively large, resulting in a single island in the plasma core. In this case the spectrum of $m=1$ modes condenses spontaneously to one dominant mode with a well defined toroidal number n (QSH state^{10,13}). The increased SXR emissivity in the islands is believed to be a local increase of the electron temperature, and the measurements described in this article will allow a better imaging of the helical structure.

ACKNOWLEDGMENT

This work was supported by the European Communities under the Contract of Association between EURATOM/ENEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

- ¹R. N. Dexter D. W. Kerst, T. W. Lovell, S. C. Prager, and J. C. Sprott, *Fusion Technol.* **19**, 131 (1991).
²P. Franz, F. Bonomo, G. Gadani, L. Marrelli, P. Martin, P. Piovesan, G. Spizzo, B. E. Chapman, and M. Reyfman, *Rev. Sci. Instrum.* **75**, 4013 (2004).
³P. Franz *et al.*, *Phys. Plasmas* **13**, 012510 (2006).
⁴P. Martin, A. Murari, and L. Marrelli, *Plasma Phys. Controlled Fusion* **38**,

- 1023 (1996).
⁵A. Murari *et al.*, *Rev. Sci. Instrum.* **70**, 581 (1999).
⁶R. Bartiromo *et al.*, *Plasma Phys. Controlled Fusion* **42**, 881 (2000).
⁷B. E. Chapman *et al.*, *Phys. Plasmas* **9**, 2061 (2002).
⁸R. Bartiromo, P. Martin, S. Martini, T. Bolzonella, A. Canton, P. Innocente, L. Marrelli, A. Murari, and R. Pasqualotto, *Phys. Rev. Lett.* **82**, 1462 (1999).
⁹P. Franz, L. Marrelli, A. Murari, G. Spizzo, and P. Martin, *Nucl. Fusion* **41**, 695 (2001).
¹⁰P. Martin *et al.*, *Nucl. Fusion* **43**, 1855 (2003).
¹¹J. S. Sarff *et al.*, *Nucl. Fusion* **43**, 1684 (2003).
¹²P. Franz, L. Marrelli, P. Piovesan, B. E. Chapman, P. Martin, I. Predebon, G. Spizzo, R. B. White, and C. Xiao, *Phys. Rev. Lett.* **92**, 125001 (2004).
¹³L. Marrelli *et al.*, *Phys. Plasmas* **9**, 2868 (2002).