Improvements in SXR and Te measurements in the Madison Symmetric Torus

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Introduction The analysis of the data from the recently installed soft x-ray (SXR) tomography [1,2] in the Madison Symmetric Torus (MST) [3] has revealed several effects which were not accounted for in past diagnostics. For example, the purity of the beryllium foils (used to block visible light and to select the SXR energy range) can produce significant changes in the data. In addition, the detailed geometry of the SXR detectors (silicon photodiodes) must be taken into account, including any difference in material composition (front windows etc.) to avoid wrong interpretation of the data. All these effects have been studied and will be presented in this work. Modifications of the diagnostic have been implemented in order to reduce the impact of these features on the measurements. This has led to improved measurements and a validation of the results from the SXR tomography. Time resolved electron temperature Te (obtained from the tomography SXR measurements through the double-foil technique) has been analyzed and compared to measurements from Thomson Scattering.

The diagnostic The SXR tomography is comprised of four probes separated poloidally at a single toroidal location. Each probe contains two columns of 10 diodes, where each column has its own filter and pinhole, and the cones-of-sight for the two columns overlap in the plasma (see Fig. 1 for the geometry of the lines of sight). As a result, each pair of diodes can be considered as viewing the same plasma volume. Two thicknesses of beryllium foils have been selected and installed in all probes, 421 and 857 μm. Two diodes looking at the same plasma through different filters sample different components of the energy distribution, and their measured brightness is used to directly calculate electron temperature. The ratio of the two measurements approximately gives the hottest Te along each line-of-sight (this is called the double-foil technique). Additionally, two tomographic reconstructions of the SXR emissivity in the plasma cross-section can be simultaneously obtained, one using 40 diodes with the first set of filter thickness and the other using the remaining 40 detectors. These two emissivity distributions can be also combined together to have a 2-D map of the electron temperature using the same technique as with the brightnesses.

Differences in the Brightness Profiles A systematic difference in core brightness profiles between the probes has been observed since the beginning of operation of the SXR tomography. Fig. 1 shows the brightness profiles of the four probes (labelled SXR-A,B,C and D) for a MST shot at a given time, a different color for each probe. The thin filter (thickness of 421 μm) top peaks at about 10 W/m^2 for SXR-C,D compared to about 12 W/m^2 for SXR-A,B. The thick filter (857 μm) profiles show smaller discrepancy. The peak signals correspond to the core brightnesses measured by the probes, and in principle they should be the same even if the plasma is sampled at different angles. This 10-15% difference between probes triggered a series of studies to find out what was causing this discrepancy. First, the electronics (cables, amplifiers etc.)

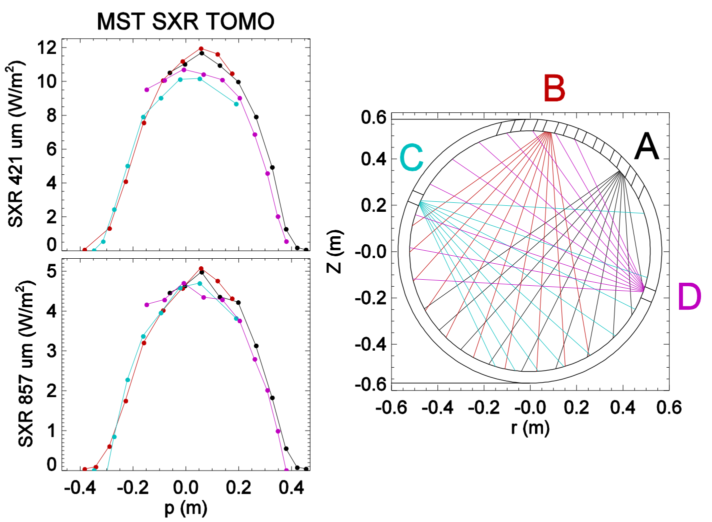

Fig. 1 Brightness profiles of the four SXR probes. Top left: 421 μm, bottom left: 857 μm. Right: lines of sight.

and the machine view were checked, but no problems were found. Then the geometric properties of the four probes were measured and compared with the original drawings (including the absolute location of the probes with respect to the plasma). Also in this case there were no indications of mistakes or errors in the fabrication process. Only two components remained to be analyzed: the diodes and the beryllium foils.

Effect of Silicon Thickness and Aluminum frame of the Diodes Due to the location of the photodiodes and of the pinholes (the opening through which the plasma is observed) in the probe, the resulting lines of sight are in general not normally incident with respect to the surface of the diode. Therefore, the effective thickness of the Si is not the same for all diodes, changing the cut-off energy of the detector for each line: the larger the angle, the thicker the silicon, resulting in a higher cut-off energy and thus a larger response of the diode. This effect has been studied to understand how it affects profile shape. Fig. 2 (left) shows the simulated brightness profiles for two probes (SXR-B and SXR-D) assuming a fixed Si thickness (black) versus an effective thickness that varies with angle of incidence (red). A SXR model (described in [4]) has been used to simulate the tomography measurements. Fig. 2 (right) shows the percent difference in brightness signal for each chord of the array due to the Si effect for thin (top) and thick (bottom) Be filters. The simulation indicates that for Te=1.5-2.0keV (typical Te at MST for improved confinement plasmas) the edge lines of sight (most extreme Si thickness) under-estimate the signal by 4-5% for thin foils and 5-6% for thick foils if the variation in Si thickness with angle of incidence is not accounted for. The thick filter signal is more impacted than the thin filter because its measurement is comprised of proportionally more high-energy x-rays compared with the thin filter. Core-viewing diodes, with an impact parameter p=0, show an underestimate of 1-2% because they are not normally incident in SXR-A,B. Thus, accounting for the effective Si thickness reduces but does not eliminate the discrepancy in peak brightness between probes. Another feature that has been considered was the presence of a 1 μm thick aluminum frame covering about 20% of the active area of the photodiode [5]. This results in a distorted x-ray spectrum measured by the photodiode due to the rapidly changing transmission function of the Al in the soft x-ray range (1-10 keV), because the aluminum frame around the edges of the photodiode blocks x-rays at lower energies, while sufficiently high x-rays can pass through the aluminum layer and be detected in the silicon layer. However, the impact of this frame on the SXR brightness is also small, decreasing the signals by 1-2%. Moreover, this is a systematic effect on absolute brightness but does not differ between probes.

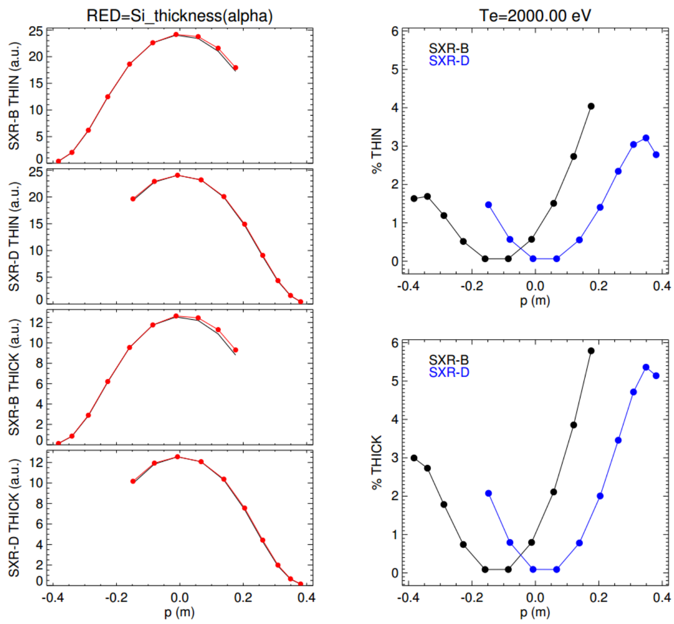

Fig. 2 Left - Simulated brightness assuming uniform Si thickness (black) or accounting for effective thickness due to angle of incidence (red) for a 2.0keV plasma.
Right – Percent change in measurement accounting for effective silicon thickness compared to assuming uniform thickness across all diodes, for SXR-B (black) and SXR-D (blue) geometries.

Impact of Be Foil Purity Each Be filter is assembled by stacking a series of thin foils. The thin filters (421 μm) are stacks of 5 individual Be foils, while the thick filters (857 μm) are stacks of 9 individual Be foils. Most of the Be foils are 80-90 μm thick. In the initial implementation of the diagnostic, two of the probes (SXR-A and B) used 2 thinner (40 μm) foils instead of one 80 μm foil in order for the stacks to all become equal in total thickness. SXR-C and D have no such thinner foils. The 80 μm and the 40 μm foils came from different material batches (same company) and have a Be purity of 99.8% and 99.9% respectively. In particular, a 0.1% zirconium content was listed in the specification for the 80 μm foils, while for the 40 μm foils there were no traces of Zr. The effect of zirconium on material density is nearly-negligible, but the photo-absorption cross-section at about 3 keV (1800 cm^2/g) is 90 times larger than Be (21 cm^2/g) and so it in fact has a measurable effect.

The SXR model has been updated to include the effect of impurities in the filters. The photo-absorption coefficients for Be and Zr have been modelled using the Lawrence Berkeley National Laboratory X-ray database [6]. The impact of Zr on total filter transmission is shown in Fig. 3. The impact of that small amount of Zr in the transmission is not negligible; the cut-off energy of the filter (energy corresponding to a transmission of 10%) changes from about 2.7 to 3.3 keV, and it must be included in the analysis. A more detailed study has been performed and all impurities listed in the filter specification (in particular heavy elements like tungsten and iron) have been included. Fig. 4 shows the transmission function for a Be foil of 421 μm with all the impurities: the curve is even more shifted towards higher energies if compared with the black line in Fig. 3 (the cut-off energy increases at about 3.7 keV).

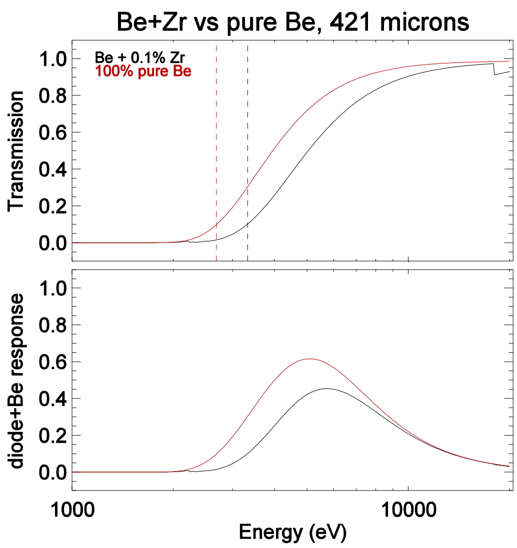

Fig. 3 Top - Transmission function of a 421 μm 100% pure Be foil (red) and of a Be plus 0.1% of Zr (black). The dashed lines show the cut-off energy at a transmission of 10%. Bottom – Diode and filter total response of the same type of foils.

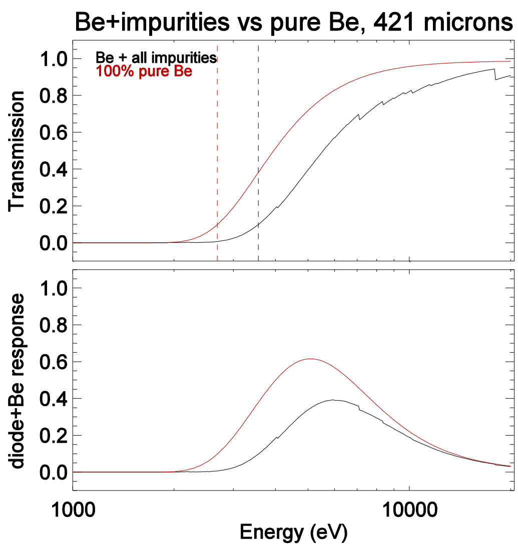

Fig. 4 Top - Transmission function of a 421 μm 100% pure Be foil (red) and of a Be plus all measured impurities (black). Bottom – Diode and filter total response of the same type of foils.

The SXR tomography diagnostic has been modified by replacing all 99.9% Be foils with thicker 99.8% foils to make total filter composition consistent for all probes, both for 421 and 857 μm. This modification led to a dramatic improvement in the agreement between the SXR probes, and the probe-to-probe variation in peak brightness decreased from the initial 10-15% to less than 5%. This residual difference might be assumed as the combination of the effect of a larger effective thickness of Silicon in the core-viewing diodes of the probes and uncertainty due to the Be thickness (± 2%).

Effect on Te calculations From the previous analysis it has been shown that the discrepancy in brightness between the SXR probes was due to a difference in beryllium purity between the foils. The next step, after the modification of the diagnostic to install all Be foils of the same purity, has been the study of the effect of the impurities in the Be and Si effective thickness on the temperature calculations from the ratio of brightnesses. The SXR model has been used to find, for each pair of diodes, the theoretical curves Te(R) that give the temperature as a function of the ratio of the signals along the same line of sight but through two different filter thicknesses. Both the Be purity and the effective thickness of the silicon detectors have been included in the model. In particular, it was assumed that zirconium was the main impurity, leaving all the others out of the calculations. Then, the calculated curves have been applied to the data of an example shot and the temperatures have been found for all lines of sight. The radial profiles of the SXR Te have been compared with the measurements of the Thomson Scattering [7], which gives the Te profile along 30 points every 0.5 ms. A systematic mismatch in the two temperatures has been observed, with the SXR Te 200-300 eV (for a peak core Te of about 1.5 keV) larger than the Thomson data. This is shown in Fig. 5, where the core Te from SXR (in red) and Thomson are plotted as a function of time (each point is the average of 3-4 spatial points measured along core-viewing lines of sight). In this case the quoted 0.1% Zr content (1000 ppm) was introduced in the SXR model.

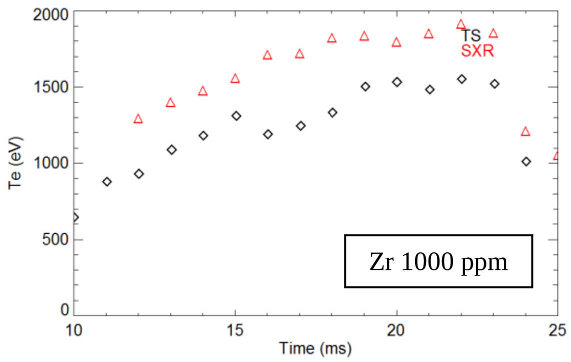

Fig. 5 Black diamonds: Thomson Scattering core temperatures. Red triangles: Te from SXR data. Time evolution of Te for a given shot assuming a Zr content as listed in the foil specification of 0.1%, or 1000 ppm (parts per million).

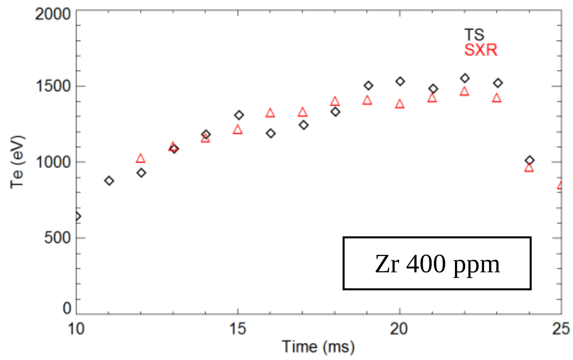

Fig. 6 Black diamonds: Thomson Scattering core temperatures. Red triangles: Te from SXR data. Time evolution of Te for the same shot of Fig. 5 but changing the Zr content to match the Thomson data. In this case a content of 400 ppm has been used.

The Zr content was then artificially varied to quantify the sensitivity of the SXR Te measurements on this parameter, and it was found that a Zr amount of 400 ppm reduced the mismatch between the two temperatures to less than 100 eV. This is shown in Fig. 6 for the same shot of Fig. 5. The ΔTe is almost constant in time, with the Te ranging between 600 and 1500 eV, indicating that the new Zr content is consistent within a wide range of temperatures. Thus, a careful material analysis is needed to precisely simulate the measurements. A future simulation will include all impurities as listed in the Be foil specification for a detailed and complete analysis of the impact of the Be purity in Te calculations.

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