Energy-Resolved Soft X-ray Camera on TCV: First Measurements of Electron Temperature

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Introduction

Kinetic parameters of electrons and ions are key parameters in tokamak performance and transport analysis. On the TCV tokamak, core T_e is routinely measured using Thomson scattering (TS), but this is limited to 60 Hz and a single vertical line-of-sight [1]. This limits the analysis of fast transient events, and motivates the development of complementary diagnostics.

A new energy-resolved soft X-ray (SXR) system has been deployed on TCV. This contribution describes this diagnostic and its use for time-resolved electron temperature estimation via x-ray emission. The results demonstrate the system's potential for 2D temperature tracking on TCV.

Diagnostic Overview

X-ray detection uses a PILATUS3 photon-counting unit mounted in a pinhole camera configuration (Fig. 1). The detector is mounted on a vertical port and views the plasma through a 50 μm beryllium window with acquiring at 500 Hz and achieves sub-centimeter spatial resolution. The PILATUS3 detector houses $\approx 10^5$ pixels, with each functioning as an independent photon counter with a user-defined lower energy threshold E_{th} that can be set approximately from 2 to 20 keV using a pulse-height thresholding: each photon is either counted or ignored depending on whether its energy exceeds E_{th}. This configuration allows for energy-resolved measurements by setting pixels observing the same plasma at multiple thresholds as shown in Fig. 1(b). Details on the system calibration and detector modeling are provided in [3, 4]. Here, we limit the threshold energy to the range 6.5-10.5 keV due to the available energy calibration of the unit.
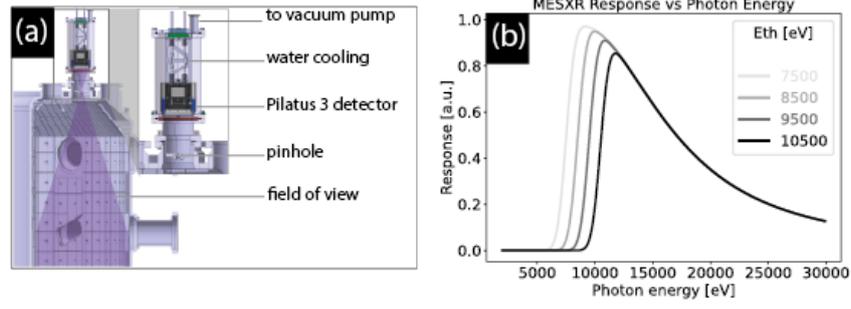
Figure 1: Left: Schematic of the SXR diagnostic on TCV. Right: Simulated pixel response for various energy thresholds.

Electron Temperature Estimation from x-ray

Plasma x-ray emission provides a continuous spectrum whose shape depends on the local T_e [2]. Under the assumption of a Maxwellian distribution and in the absence of high-z impurities, the SXR spectral emissivity $\varepsilon(E)$ depends on T_e as:

$$\varepsilon(E) \propto \frac{1}{\sqrt{T_e}} \exp\left(-\frac{E}{T_e}\right)$$

where n_e is the electron density, and Z_{eff} the effective ion charge. The exponential dependence on energy permits T_e inference from the ratio of brightness recorded above two thresholds. This method estimates T_e from the ratio of emissivities above at least two thresholds:

$$\frac{g_1^*}{g_2^*} = \frac{\int_0^\infty p_1(E)\,\varepsilon(E)\,dE}{\int_0^\infty p_2(E)\,\varepsilon(E)\,dE}$$

Here, g_1^* and g_2^* are the emissivities convolved with the spectral response of the detector using two lower energy thresholds, and $p_1(E)$, $p_2(E)$ are the detector response functions as shown in Fig. 1(b).

Figure 2(a) shows theoretical mappings between T_e and brightness ratios for selected threshold pairs, with a reference threshold $E_{th,ref} = 6.5$ keV , derived from synthetic spectra and detector response modeling. These curves exhibit decreasing sensitivity at higher T_e, due to the flattening of the exponential tail.

For the initial analysis, we compute line-integrated brightness ratios along selected chords, without emissivity inversion. This approach minimizes uncertainties by any geometric assumptions and inversion regularization, while providing a first-order estimate of T_e.
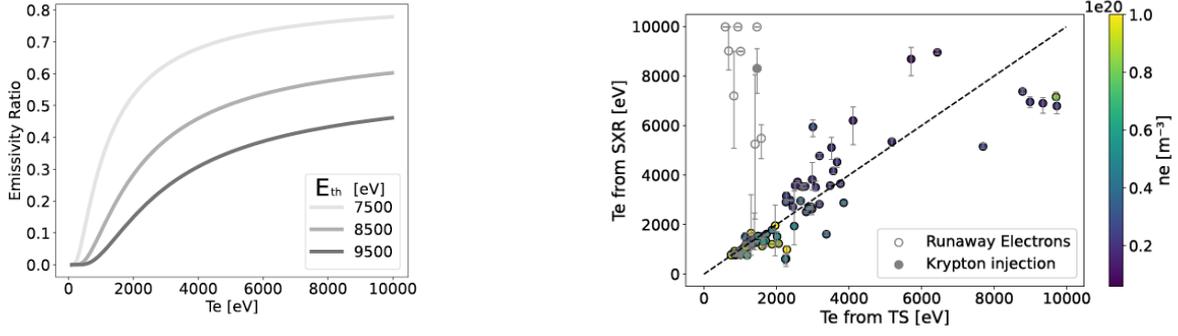
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Figure 2: (a) Mapping between SXR brightness ratio and T_e for various threshold pairs. (b) T_e from SXR brightness ratios vs. Thomson scattering on a central chord.

Experimental Results

Comparison with Thomson Scattering

Figure 2(b) compares systematic T_e estimates obtained from SXR brightness ratios with TS measurements for a set of discharges at time t = 1.0 s. The data corresponds to the central viewing chord. Good agreement is observed where $T_e < 4$ keV, where the brightness ratio method retains adequate sensitivity.

At higher temperatures, discrepancies appear. A possible explanation is the reduced slope of the mapping function in Fig. 2(a), leading to increased uncertainty as any error on the emissivity ratio translates into larger errors in the T_e estimates. In some cases, errors are due to the presence of high-Z impurities or the presence of runaway electrons.

Reconstruction of Radial Profiles

To assess the system's ability to provide reliable T_e spatial profiles, we performed an emissivity profile reconstruction by inverting brightness profiles, obtained from the Pilatus using the energy thresholds in Fig. 2(a), using the ToFu inversion code [5]. TCV discharge 85484, an L-mode plasma with core $T_e = 1500$ eV and $n_e = 4 \times 10^{19}$ m^{-3}, was chosen. The profile inversion relies on the magnetic equilibrium geometry and is followed by T_e extraction from the local emissivity. This procedure allows comparison with TS profiles across the plasma radius and shows that T_e profile agrees well with TS at $\rho < 0.6$ beyond which the signal level is too low for reliable T_e determination.
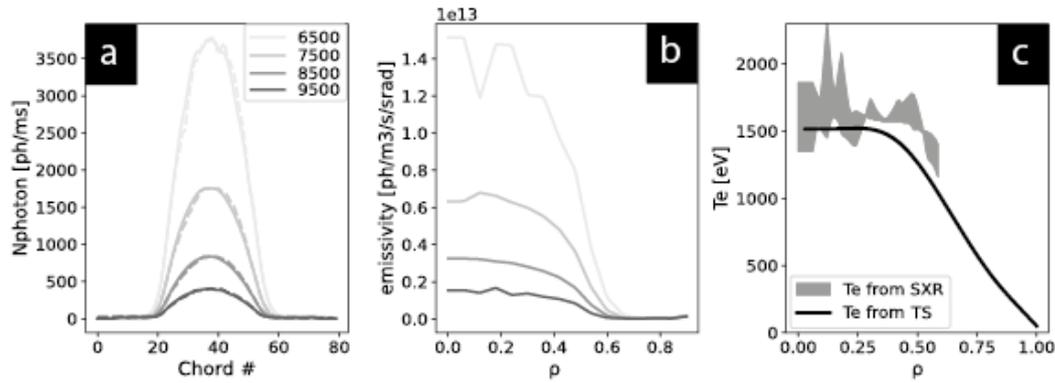
Figure 3: (a) Brightness profiles at different thresholds. (b) Corresponding inverted emissivity profiles. (c) Reconstructed T_e vs. TS.

Discussion and Outlook

This first deployment of an energy-resolved SXR camera on TCV demonstrates the feasibility of electron temperature estimation from soft x-ray measurements using the Pilatus detector. The results show encouraging agreement with TS and validate the underlying assumptions over a significant portion of the plasma radius.

Although the 500 Hz frame rate is insufficient to resolve rapid MHD phenomena such as sawteeth or ELMs on TCV, the system provides flexibility and easy installation. Future work will include:

- Improving inversion techniques for systematic T_e profile computation.
- Extending energy threshold calibration to lower energy ranges (2-6 keV) for better signal-to-noise ratio and studying impurities transport.
- Applying the results to impurity transport studies

References

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