Spectrally adaptable Soft X-ray imaging on Tore Supra: preliminary results and simulations

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State of the art

Due to its dependence on electron temperature and density (T_e and n_e respectively) and on impurity distributions, Tokamak Soft X-ray (SXR) radiation conveys a lot of information on MagnetoHydroDynamics (MHD) and impurities. Furthermore, the measurement technique is entirely passive (no radiation is emitted by the diagnostics into the plasma). However, usual Silicon-based detectors (semiconductors) only give access to measurements integrated both spatially (along their lines of sight) and spectrally (≈ [2 keV; 20 keV]). On Tore Supra, spatial localisation is achieved by tomographic inversion using a standard SXR diagnostic (SSXRD) [1-3], recently optimized [1] and comprised of 82 Si diodes placed in a poloidal cross section (see figure 1 (a)). The inversion technique is based on the Minimum Fisher Information (MFI) algorithm [4]. Further details on the inversion techniques can be found in [5].

In an effort to better analyse MHD phenomena and impurity distributions via SXR, a series of improvements have recently been implemented and tested on Tore Supra. Ultimately, they aim at achieving better – and potentially 3D - spatial resolution and accessing spectral information. This paper focuses on the first steps made towards these goals: the successful installation and characterisation on Tore Supra of a new SXR camera and the analysis of a tungsten injection on Tore Supra that highlights the two diagnostics' complementarity.

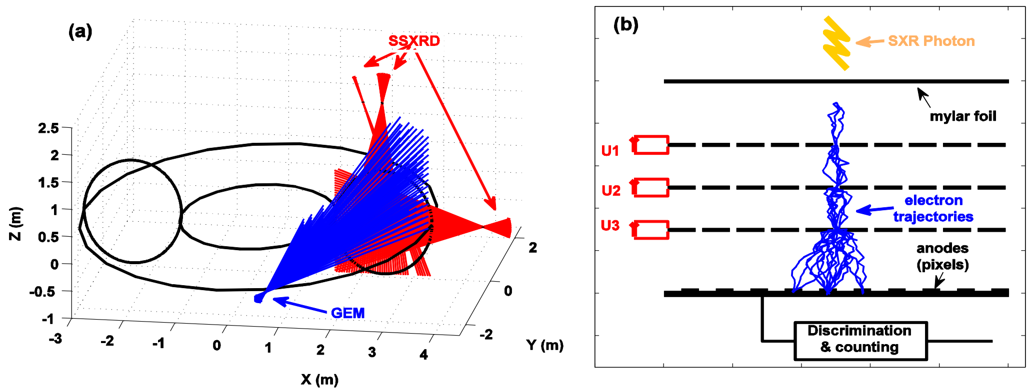

Fig. 1: (a) Geometry of SSXRD and the GEM's lines of sight in a 3D Tore Supra geometry (b) Schematic diagram of the prototypal GEM used on TS

Experimental setup and first GEM results on Tore Supra

A new SXR pinhole camera based on a triple Gas Electron Multiplier (GEM) [6-10] with a toroidal view of the plasma has been installed and characterized on actual TS pulses. It is a box filled with a flowing gas adapted to photoionisation by SXR (Ar 45%, CO_2 15% CF_4 40 %) and closed by a 10 cm x 10 cm Mylar foil. As depicted on figure 1 (b), photoelectrons are produced in the first chamber and drift towards the first micrometrically perforated copper-clad Kapton foil where electron avalanching amplifies the signal. The detector gain is monitored in real time and depends on the high voltage used for avalanching. A similar process occurs two other times and the resulting charge is then collected on 128 anodes (pixels). A lower threshold is then applied to the electronic signal to limit the energy interval on which SXR radiation is integrated. It can also be changed in real time and makes the GEM a spectrally adaptable SXR camera, and a potentially energy-resolved SXR camera provided some near-future developments are successfully implemented.

This new - and prototypal - SXR diagnostic can be considered both as a complement (it gives additional information on the spatial distribution and energy band selection) and as a technical first step towards more ambitious diagnostics (with finer spatial and spectral resolution). Also promising is the recently demonstrated capability of the GEM to measure SXR in neutron and gamma-rich environments [11]. However, its two operating parameters (the gain and the lower threshold) have to be experimentally tuned in order to get an optimal signal/noise ratio. Indeed, if the threshold is too low, the electronics artificially cut the signal, and if it is too high, the energy interval is so narrow the signal becomes meaningless. Since experimental noise is approximately uniform over the domain of possible values for both parameters, figure 2 (a) can be interpreted as a map of the signal/noise ratio on this domain. An optimal area was identified. This map was derived from a series of long and stationary TS pulses.

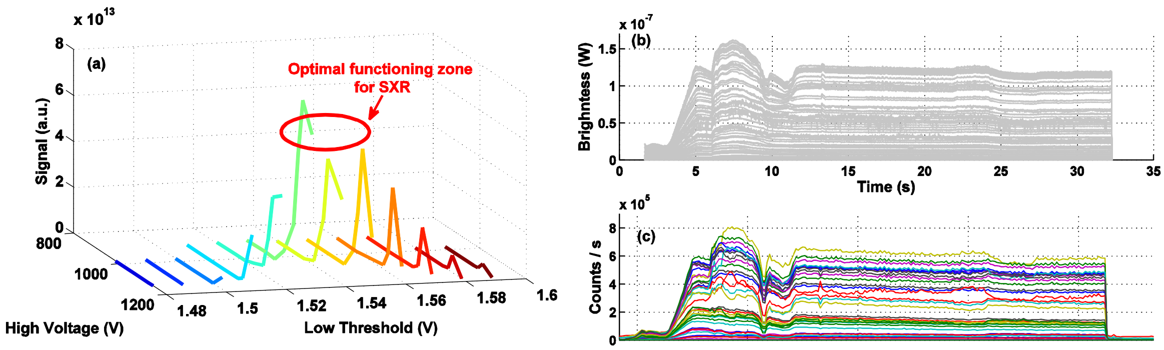

Fig. 2: (a) Map of the signal to noise ratio of the GEM as a function of its two operating parameters (the gain and the low threshold). An optimum functioning zone was experimentally identified. Also given is a comparison of the time traces of SSXRD (b) and the optimized GEM (c) for TS # 47972.

Figures 2 (b) and (c) show that, for TS # 47972, the use of the GEM in its optimal operating zone gives time traces that are very consistent (in shape) with the SSXRD time traces in spite of different lines of sight and the fact the GEM is not absolutely calibrated.

Application to a tungsten injection and analysis using a synthetic diagnostic

The complementarity of the GEM with SSXRD is best seen on pulses with tungsten injections like TS # 48174. As seen on figure 3, opposite evolutions occur during the laser blow-off injection. No additional heating is used and the current is stationary at 1 MA.

Under the usual assumption that the background plasma is unaffected by the injection, figure 3 (d) shows that the peaking of the emissivity profile goes along with a slight decrease of emissivity (and of T_e) in the outer plasma (associated to peripheral lines of sight with slightly decreasing time traces, red on figure 3 (a bis)). A first and simple approach consists in assuming that the GEM and SSXRD have equal spectral responses and in assessing geometrical differences. Indeed, the solid angles subtended by the GEM pixels include significant volumes from the outer, less radiative, region of the plasma.

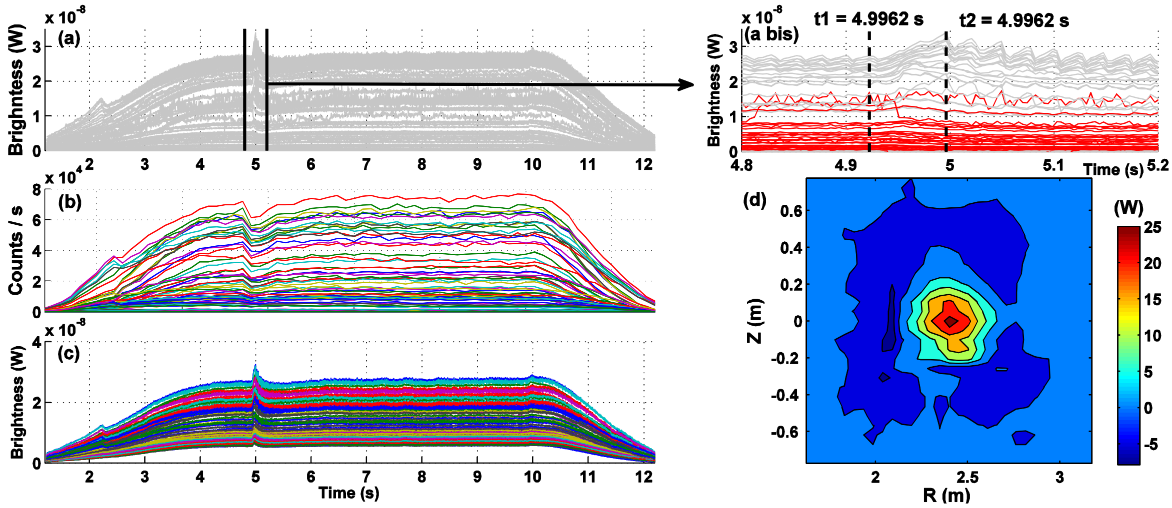

Fig. 3: (a) SSXRD and (b) GEM experimental time traces for TS # 48174, ohmic pulse, 1 MA current (a bis) zoom on the injection, red time traces have smaller values at t2 = 4.9225s than at t1 = 4.9962s (c) Synthetic GEM time traces: SSXRD tomographic inversions are expanded toroidally to assess what the GEM would see if it had the same spectral response as SSXRD. (d) Background-subtracted tomographic inversion (t2-t1).

In this context, a 3D Tokamak geometry was modelled (using Tore Supra geometry) with a 3D mesh in cylindrical coordinates. The solid angles of each SSXRD and GEM detectors were computed in 3D (taking into account their poloidal and toroidal expansion and associated pinholes). The poloidal cross-section of the 3D cylindrical mesh was made to match the 2D poloidal grid used for the tomographic inversion, for consistency. The tomographic inversions derived from SSXRD measurements at each time step were then expanded assuming a toroidally invariant emissivity field, and the associated virtual GEM time traces deduced (see figure 3 (c)). In spite of our initial guess, it appears on figure 3 (c) that no clear geometrical effect can explain the differences between figures 3 (a) and (b) if the GEM and SSXRD had identical spectral responses. A more in-depth analysis will then have to be carried out, involving both an evaluation of the GEM spectral response and an assessment of whether the SXR emissivity field really is toroidally invariant.

Such a geometry-oriented synthetic tool is useful both for diagnostics conception and design studies and for experimental pulse analysis. However, it would be advantageously complemented by a simulation tool that would give more detailed information on the impurity distributions using experimental T_e, n_e and SXR profiles as inputs. A simplified SXR simulation tool was developed [12] in order to quickly estimate the total density profile of a dominant and previously identified impurity using local ionization equilibrium and SXR tomography, under quasi-stationary conditions. In order to assess the validity of such a simplified approach, tests were run on TS # 40801, during which a Ni injection had been previously thoroughly studied using the transport code ITC [13]. The preliminary results are encouraging [12], but the domain of validity of such a simplified approach (use of a local ionisation equilibrium) still has to be further investigated [12,14].

Conclusion

A new, GEM-based and potentially energy-resolved SXR camera with a toroidal view of the plasma was successfully installed and characterised on Tore Supra. It comes as a useful complement to a recently optimized Si diode-based poloidal SXR tomography. Preliminary results show both good agreement and interesting differences that the geometry alone cannot account for. This was shown using new synthetic tools that, together with a fast SXR simulation tool, are milestones on the way towards an integrated SXR synthetic diagnostic.

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