Soft X-ray tomography in support of impurity control in tokamaks

J Mlynar¹, D Mazon², M Imrisek¹, V Loffelmann¹, P Malard², T Odstrcil¹, M Tomes¹, D Vezinet³ and V Weinzettl¹

¹Institute of Plasma Physics AS CR, v.v.i., Za Slovankou 3, 182 00 Praha 8, Czech Republic
²IRFM, CEA Cadarache, 13108 Saint Paul lez Durance cedex, France
³Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany

E-mail: mlynar@ipp.cas.cz

Abstract. This contribution reviews an important example of current developments in diagnostic systems and data analysis tools aimed at improved understanding and control of transport processes in magnetically confined high temperature plasmas. The choice of tungsten for the plasma facing components of ITER and probably also DEMO means that impurity control in fusion plasmas is now a crucial challenge. Soft X-ray (SXR) diagnostic systems serve as a key sensor for experimental studies of plasma impurity transport with a clear prospective of its control via actuators based mainly on plasma heating systems. The SXR diagnostic systems typically feature high temporal resolution but limited spatial resolution due to access restrictions. In order to reconstruct the spatial distribution of the SXR radiation from line integrated measurements, appropriate tomographic methods have been developed and validated, while novel numerical methods relevant for real-time control have been proposed. Furthermore, in order to identify the main contributors to the SXR plasma radiation, at least partial control over the spectral sensitivity range of the detectors would be beneficial, which motivates for developments of novel SXR diagnostic methods. Last, but not least, semiconductor photosensitive elements cannot survive in harsh conditions of future fusion reactors due to radiation damage, which calls for development of radiation hard SXR detectors. Present research in this field is exemplified on recent results from tokamaks COMPASS, TORE SUPRA and the Joint European Torus JET. Further planning is outlined.

1. Introduction
Fusion research has been pursued with the aim of achieving conditions required for useful production of energy by nuclear fusion in high temperature plasmas. These conditions are very severe even for the most reactive fusion fuel, i.e. the mix of hydrogen isotopes deuterium and tritium [1]. In the case of the magnetic confinement fusion (MCF) it is paramount to increase the energy confinement time, see e.g. [2]. This parameter is defined as follows:

$$\tau_E = \frac{W_P}{P_L}$$

(1)
where \( W_F \) is thermal energy and \( F_L \) total power losses of plasma in a thermal equilibrium. It is presently the tokamak configuration that comes with the best performance in terms of energy confinement time. As a result, the ITER machine is a tokamak [3].

Most of the power losses in high-temperature hydrogen plasmas are due to the turbulent thermal convection, radiation losses prove to be much lower. However, the radiation losses may increase significantly due to the presence of heavy plasma impurities. First, intensity of bremsstrahlung (i.e. the free-free collisions between electrons and ions) rise with square of the ion charge number, and second, more importantly, impurities with high proton number \( Z \) will not get fully stripped, i.e. completely ionised to bare nuclei even in thermonuclear conditions, at temperatures around 150 million kelvin (approx. 15 keV). Therefore, with heavy impurities the recombination (the free-bound) and line (deexcitation, bound-bound) radiation sharply increases in intensity and exceeds the bremsstrahlung, see figure 1 (notice the logarithmic scales). This figure allows comparing intensities of hydrogen plasma bremsstrahlung with total radiation of tungsten impurity. The figure clearly demonstrates that for the plasma core the radiation of tungsten (in particular, its line radiation) presents the key contributor to total radiation losses even at concentration of tungsten in the order of \( 10^{-5} \) relative to the plasma density, see also section 4. As a consequence, heavy plasma impurities can cause considerable decrease of the energy confinement time (1) and prevent thermonuclear burn.

The intensity and spectral properties of radiation losses from plasmas strongly depend on plasma temperature. In MCF experiments, plasma temperatures correspond to mean thermal energy of the plasma particles in the order of keV, which means that their radiation due to bremsstrahlung and atomic processes falls into the soft x-ray (SXR) frequency range. Tungsten with its proton number 74 deserves special attention here: Due to its high melting temperature and low sputtering it has been proposed as one of the materials for plasma facing components in ITER as well as in other tokamaks. The risk of the tungsten influx into the plasma core is therefore imminent and calls for dedicated studies. The fractional abundance of tungsten ionic charges for temperatures 1 keV - 10 keV is shown in figure 2, which is derived from the OPEN-ADAS database [4]. This figure demonstrates that even at the peak thermonuclear temperatures the tungsten charge is not higher than 57; therefore, its ions are a major contributor to the losses caused by radiation in the SXR region, and subsequently a serious concern to the energy confinement of fusion plasmas.

![Figure 1. SXR radiation level from a high-temperature pure hydrogen plasma in comparison to total radiation of tungsten impurity as a function of the tungsten concentration at ion temperature 1 keV (full line) and 10 keV (dashed line)](image)
In the following section, principles of diagnostic methods for the SXR radiation of the MCF plasma core is briefly reviewed, including the novel Gas Electron Multiplier (GEM) detector [5]. In section 3, tomography reconstruction based on regularisation of the inversion task is presented and Singular Value Decomposition of the temporal evolution of the reconstructed emissivity exemplified on recent COMPASS results. In section 4, the present works aimed at use of SXR data for impurity control in real time are detailed, including SXR tomography reconstructions recently published by JET and by TORE SUPRA. In the conclusions, further planning in the framework of the co-ordinated fusion research is discussed.

2. SXR diagnostic methods
Spatial distribution of the SXR emission from MCF plasmas can be determined from a set of line-integrated measurements by detectors sensitive to SXR radiation. A typical diagnostic setup consists of a pinhole camera with a linear array of the SXR detectors. At present, semiconductor photosensitive elements are widely used for the SXR detection [6]. Recently, 2D pinhole cameras consisting of a matrix set of SXR detectors have been also proposed [7]. In order to limit the range of spectral sensitivity to the SXR region only, the pinhole is often combined with a spectral filter, usually in the form of a thin beryllium foil (tens to hundreds of micrometers thick), which is not transparent to ultraviolet and longer wavelength radiation. Notice that without this filter, the SXR intensity would be too low to contribute discernibly to the total observed intensity of plasma radiation. The filter limits the detected spectral region to photon energies higher than approx. 100 eV – 1 keV, while the high energy end is given by thickness of the sensitive region of the semiconductor photodiodes and can reach approximately 10 keV – 100 keV. The detectors can be absolutely calibrated in W/m² which corresponds to line integrated plasma power loss in the detector’s spectral range. To improve sensitivity, stability and radiation resilience of the detectors, individual silicon barrier diodes, see e.g. [8], can be used instead of a the cost-effective set-up based on a photosensitive chip [6].

The semiconductor detectors - albeit radiation hardened - would not withstand conditions of the future fusion reactors including ITER due to the damage made by ionising radiation in the depleted area of the semiconductor. Therefore, a different principle of detection of the SXR radiation has been searched in order to design a reactor-relevant SXR diagnostic system, including e.g. diamond detectors or vacuum photodiodes. In the targeted spectral region, the Gas Electron Multiplier (GEM) represents a very promising candidate for a radiation resilient compact SXR detector with a good temporal and spatial resolution. GEM, which had been originally developed for particle physics research [5], [9], relies on conversion of the SXR photons to photoelectrons in a gas, followed by multiplication of the

Figure 2. Fractional abundances of tungsten ions as a function of plasma temperature.
photoelectrons in a high electric potential in a grid made of a thin Kapton foil, see figure 3a. The photoelectrons are eventually collected at a pixelated anode, see figure 3b. The GEM detector works in a photon counting mode, with variable gain and, importantly, a tunable spectral response. The detector was successfully tested on TORE SUPRA [10], [11] where it is also foreseen as the principal diagnostics for the spatially resolved SXR studies in the future WEST configuration.

![Figure 3a](image1.png) ![Figure 3b](image2.png)

**Figure 3.** Principle of the Gas electron multiplier (GEM) detector of the SXR radiation: (a) detail of the Kapton foil with electron multiplication in the thin but intensive electric field (b) general scheme showing SXR photon, photoelectron, its multiplication in the grid made from the Kapton foil, and photon counting on the matrix anode. In practice, ‘triple GEM’ is used with three Kapton foils between the cathode and the anode. [10]

3. Tomography

Tomographic inversion is very often applied in the SXR data analyses in order to derive spatial distribution of SXR plasma emissivity from the measured line integrated data, i.e. from the plasma projections. The link between measured projections $f_i$ and unknown distribution of the sources $g_j$ is given by a set of linear equations

$$ f_i = \sum_j T_{ij} g_j, $$

where the contribution matrix $T_{ij}$ specifies contribution of the $j$-th source of radiation to the $i$-th projection of plasma. It is obvious that this set of equations must be inverted to find the unknown $g_j$ values, see figure 4. Inversion presents an ill-conditioned problem, so that existence and uniqueness of solution cannot be expected and minor errors in data can cause substantial errors in the resulting distribution of sources, called artefacts. In order to find a unique and dependable solution of an ill-conditioned problem, a suitable regularisation method has to be applied. A regularisation method usually relies in implementation of realistic constraints, in the case of plasma tomography e.g. smoothness of the distribution of the SXR radiation and its non-negativity.
Plasma tomography in MCF is not only ill-conditioned, but also as a general rule underdetermined, as the spatial resolution of the SXR diagnostics is sparse. In particular, plasma projections can only be measured from a very limited set of angular positions due to constraints presented by magnetic coils, vacuum vessel and the in-vessel components. Several dedicated methods for MCF plasma tomography have been developed [12], [13]. In our experience, Minimum Fisher Regularisation (MFR) [14] algorithm based on Tikhonov regularisation constrained by minimisation of the Fisher information in the resulting image provides a robust and reliable solution [15].

In MFR, a reconstruction matrix $M_{ij}$ is found that gives a unique smooth solution for the 2D plasma emissivity on a discrete rectangular mesh of $R$ pixels (see figure 4) as follows:

$$g_j = \sum_i R_{ji} M_{ij} f_i .$$

(3)

The matrix $M_{ij}$ is found by Tikhonov regularisation which efficiently minimises $\Lambda_{MF} = \frac{1}{2} \chi^2 + \lambda \Omega$ where $\chi^2$ is the goodness-of-fit parameter, $\lambda$ is a regularisation (smoothing) parameter and $\Omega$ the objective functional [12]. In the MCF, the role of the objective functional is consigned to the Fisher information $I_F$ defined by:

$$I_F = \int \frac{(\nabla g)^2}{g} dS$$

(4)

Due to the discrete character of eqs. (2) and (3) the $I_F$ value has to be computed by advanced numerical methods. Besides, the Fisher information has to be implemented into the linear regularisation as an iterative process due to its nonlinear character [14]. Notice that in Tikhonov regularisation the smoothness of the resulting emissivity distribution can be controlled implicitly via expected data errorbars, i.e. through the goodness-of-fit $\chi^2$.

As a significant novel physical constraint, anisotropic smoothness of the reconstruction with respect to the magnetic flux has been introduced in MFR via numerical differentiation matrices acting parallel and perpendicular to the magnetic flux, respectively. In this coordinate basis, preferential
smoothness along the magnetic flux surfaces can be enforced, allowing for steeper gradients in the cross-field profile of plasma emissivity, for details see [15]. This new constraint reflects the fact that the plasma temperature and density gradients increase in the direction perpendicular to the field, and remain close to zero along magnetic field lines.

**Figure 5.** Singular value decomposition of a sawtooth event in the COMPASS discharge #6071. The thick black line in the topos image corresponds to the cross-section of the tokamak vacuum vessel.

Temporal evolution of plasma emissivity can be eventually decomposed into spatial and temporal eigenvectors - topos $v_i$ and chronos $u_i$ - by Singular Value Decomposition (SVD), see [14]:

$$ g(r,t) = \sum_i s_i v_i(r)u_i(t). $$  \hspace{1cm} (5)

The SVD helps to visualise the main processes and to filter out the noise. Performance of the SVD procedure is demonstrated in figure 5, which results from the MFR analyses of recent SXR measurements on the COMPASS tokamak. The SXR data have been collected from two pinhole detectors [6], each with a sufficient signal from the plasma core in about 12 lines of sight. In the figure, four eigenvectors showing SXR plasma emissivity (topos) with evolution of their amplitude (chronos) are presented, based on SVD from 114 timeframes of the tomographic reconstructions. The first and the second eigenvectors clearly display the effect of a sawtooth instability on the SXR emissivity – after the crash, the steep radiation peak in the plasma centre decreases in intensity, while the SXR intensity around the peak increases (notice that the second chronos has a negative amplitude). The third and the fourth eigenvectors visualise a rotating mode (notice the mutual phase shift in chronos), which increase in amplitude just before the sawtooth crash. Higher eigenvectors are not shown as they contain data noise.

Most of the present plasma tomography algorithms are computationally rather heavy and require input from processed data of other diagnostic systems, e.g. position and shape of magnetic field configuration. Although this is fully acceptable for the post-discharge data analyses, it disqualifies
tomography from the list of prospective tools for the real-time control (RTC) of the tokamak discharge. Therefore, a new simplified version of real-time relevant MFR has been developed recently on the COMPASS tokamak [16]. The main novel idea relies in avoiding iterative processes and instead assuming smooth temporal evolution of data. The first applications of this new MFR version demonstrated good stability of the algorithm and a low level of artefacts. However, even in this version the computation load reaches present limits on the allowed delay time for the RTC. Therefore, further evolution of linear inversion methods is fostered on COMPASS together with developments of simplified rapid algorithms for non-inversion analyses of SXR data to directly calculate some basic parameters (e.g. plasma position) for the prospective RTC applications [17].

4. Impurity control: the way forward

In the SXR diagnostic applications focused on impurity studies, the information of key interest is the evolution of density distribution of the radiating species $n_S$. The SXR tomography reconstructs the evolution of plasma emissivity

$$ g = n_s \sum n_S L_S, $$

where the radiation cooling factor $L_S$ – actually only its filtered part, corresponding to the detector spectral sensitivity range [18] – is a function of plasma temperature and impurity transport. Therefore, in order to derive impurity density from the SXR emissivity, plasma density $n_s$, temperature $T_S$, and impurity transport properties of individual species must be accounted for. In the foreseeable future, this would not be feasible within the available delay times of the real-time control, in particular due to the complexity of the transport models. In other words, for a real-time relevant diagnostic system it is desirable to avoid SXR spectral intervals with radiation of ionic states for which transport plays a significant role.

Recent studies have shown that in SXR radiation of tokamak plasmas at high temperatures, transport plays little role for low Z impurities (which become fully stripped rapidly) and heavy Z impurities (which have very fast ionisation-recombination characteristic time scales [19]). The challenge thus remains with the intermediate Z impurities. A detailed study was published recently [18] where it is shown that the dependence of the filtered cooling factor on transport can be neglected provided that the spectral sensitivity of the SXR detector is limited to certain range of energies. However, it is far from obvious to find a suitable detection method for this task. Dedicated experiments with the GEM camera are currently planned to validate the possibility of controlling the GEM spectral sensitivity region just to the required range of energies. With this spectral filtering, the cooling factor would be dependent on local plasma temperature and density only. Consequently, a system for real-time control of impurity species could promptly derive evolution of the distribution of species $n_S$ from real-time data on plasma density, plasma temperature and real-time SXR tomography. This is currently considered as a potentially feasible process.

At present, considerable efforts have been invested into analysing the special case of tungsten, a very heavy impurity with high probability of incident influx to the MCF plasma (‘tungsten event’) due to erosion of the plasma facing material. For heavy impurities, transport effects on the SXR radiation are negligible [18], [19]. However, it still proves rather demanding to derive tungsten density distribution from the SXR data due to systematic errors in diagnostic systems on one side (in particular, with respect to the SXR spectral sensitivity, or with mapping of the temperature profile) and in the atomic data on the other side. The contribution of line radiation to the overall intensity of radiation by tungsten can be computed with application of the photon emissivity coefficients provided e.g. by OPEN-ADAS [4] on the results of the ionization balance corresponding to the measured temperature profile. In tokamaks, the simplified calculation of this balance can be based on the collisional radiative steady state model, for details see [20], [21].
SXR radiation due to tungsten impurity has been systematically studied in particular at JET where the ITER-like wall with tungsten divertor has been used since 2011. The diagnostic system for analyses of spatial distribution of the SXR radiation is challenging at JET for three reasons, see [22]: first, the pinhole cameras have different spectral sensitivities due to different thicknesses of Be foils, second, the cameras are located at different toroidal positions and third, the horizontal camera is tilted in toroidal direction. In spite of these difficulties, useful results have been achieved with the MFR algorithm [15], [22]. Recent results - which proved to be in good agreement with transport modelling, see [23], are exemplified in figure 6. In this figure, the radiation asymmetry at 5.6 s is due to centrifugal forces on tungsten in a toroidally rotating plasma. At a later time, at 7.5 s most of the tungsten impurity becomes accumulated in the plasma centre. Other JET works demonstrate that radiofrequency heating can be used to prevent this accumulation, e.g. [24].

Figure 6. Tomographic reconstruction of the poloidal cross-section of the SXR emissivity during a tungsten event in JET discharge #82722 at two different times: (a) at 5.6 s, (b) at 7.5 s. [23]

Figure 7. SXR tomography at TORE SUPRA. Left: experimental set-up with three pinhole cameras. Right: Cross-section of the SXR emissivity in the tungsten ablation experiment with LHCD in discharge #47757 shortly before tungsten radiation peaks in the plasma centre. Notice the asymmetry is opposite to the asymmetry due to centrifugal forces in figure 6. [27]
Even if a prompt and reliable sensor of behaviour of impurities existed, RTC would still require a process model and an efficient actuator to control plasma impurities – above all, to prevent influx of heavy impurities into the plasma core. It is beyond the framework of this contribution to discuss the challenge of developing actuators for the impurity control, see refs. [24] – [26]. Let us briefly summarise here that in general, plasma heating systems have proved to influence impurity transport in MCF plasmas. Ion cyclotron resonant heating (ICRH) has been routinely used to prevent impurity concentration in the plasma core, see e.g. [25]. In the basic interpretation, increased electron temperature exerts higher pressure on ions with multiple charge and results in a negative pinch [26], however, quantitative understanding is still incomplete so that the present use of ICRH in the impurity control is largely empirical. A clear effect of Lower Hybrid Resonant Heating on impurity radiation was also observed, see figure 7. Understanding this result proves even more challenging [27]. To conclude, an in-depth investigation of the prospective actuators and further development of the process model is required before the impurity control can make a standard part of the RTC system. Dedicated experimental campaigns will be pursued at major facilities, including ASDEX Upgrade and JET in order to benchmark simulations and increase our understanding of the impurity transport.

5. Conclusions
SXR diagnostic with spatial and temporal resolution proves to be information rich, however analysis and interpretation of the information is not straightforward and can be computationally heavy for multiple reasons. Among others, tomographic inversion to retrieve distribution of radiation sources from plasma projection is an ill-conditioned task. Next, SXR intensity can be dominated by impurity radiation, which in turn can be dependent on plasma transport properties.

On the other hand, the SXR diagnostic systems have unique capability of diagnosing heavy impurities in the MCF plasmas with valuable (albeit limited) spatial and high temporal resolution. Therefore, SXR diagnostics present a candidate sensor for future real-time impurity control systems. With respect to this prospective, new simplified methods of SXR data analyses are under development at COMPASS tokamak, where engineering feasibility studies of SXR implementation into RTC are foreseen. In parallel, novel diagnostic methods with controllable spectral range and a high radiation resistivity are under development in CEA France in a framework of a broad international collaboration. While the TORE SUPRA tokamak is being refurbished to the WEST configuration with a tungsten divertor, the GEM detector shall be tested in Germany at ASDEX-Upgrade, a tokamak with the plasma facing wall made of tungsten. Further development of the atomic database will be also significant in this respect. It is foreseen that results from (i) real-time relevant data analyses, (ii) novel diagnostic system based on GEM and (iii) tungsten plasma facing components shall be merged in the future operations of the WEST configuration of TORE SUPRA. The Joint European Torus JET presents another essential facility for the tungsten impurity studies preceding the ITER operation, due to the ITER-like wall, high energy confinement and tritium capability of JET.

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