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A simplified automatic method to infer information about impurity content and spatial distribution in tokamak plasmas

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Introduction

The impurities content and their spatial distribution, in a Tokamak plasma, is an important issue. Until now these evaluations are performed by means of time consuming post process simulations with impurity transport codes, constrained with measurements of X-ray, VUV, visible spectroscopy, bolometry and energy integrated SXR Tomography [1],[2]. Our objective is the development of a technique to assess coarsely the absolute amount of the dominant impurities present in the plasma as well as their spatial distribution. This technique, once well tested and validated, will be applied for an automatic evaluation of the impurity content, to be ultimately used in a real time feedback control loop. The proposed method uses the Soft X-ray (SXR) emissivity profile reconstructed by the tomography cameras, in different energy bands. The preliminary results are very encouraging, in the perspective of developing an automatic treatment for impurity estimation, once energy resolved tomography is available.

Simulation of energy resolved SXR emissivity

To simulate the SXR spectral emissivity, the relative abundances of various ionization states of a given impurity must be known as a function of plasma parameters. These can be obtained by solving the Ionization Equilibrium (IE) equations (1) whose source term Q^Z_i is given by the ionisation and recombination processes (2):

1) $$\frac{\partial N_i^z}{\partial t} + div\,(\Gamma_i^z) = Q_i^z$$

2) $$Q_i^z = N_e (N_{i-1}^z S_{i-1}^z + N_{i+1}^z \alpha_{i+1}^z - N_i^z \alpha_i^z - N_i^z S_i^z)$$

3) $$\frac{\partial N^z}{\partial t} + div\,(\Gamma^z) = Q^z$$

4) $$N_i^z = f_i^z \, N^z$$

where N^Z_i is the ionisation state densities of impurity of atomic number Z in the ionization level i, while $S^Z_i(T_e)$ and $\alpha^Z_i(T_e)$ are the total ionization rate and the total recombination rate for the ionization state Z_i, respectively. The equation 1, solved in the stationary condition and once the transport is neglected, provides the population densities in the Coronal Equilibrium.

When normalized to the total impurity density, the solutions of eq.1 are expressed as fractional abundances, then f^Z_i is the percentage density of impurity Z in the state i. The f^Z_i are calculated, for each impurity Z, once forever, as function of the electron temperature since the ionization and recombination rates depend on the electron temperature only. The effect of transport is retained only in the equation 3, providing the total impurity radial distribution N^Z. This is justified by the fact that the SXR emissions are less sensitive to the transport effects on the single ion species because they represent a sum over many emissions and many charge states. From an operative point of view, N^Z is the real unknown variable to be derived. Starting from a guess of N^Z and using the already calculated f^Z_i functions it is possible to derive the density of each charge state N^Z_i (4). Finally a simulation code calculates all the soft X-ray emissions (continous, recombinations and line transitions) of each charge state N^Z_i, for all the impurities Z present in the plasma. The unknown profile N^Z is then adapted iteratively, looking for a best fit between the calculated and measured total SXR emissivity profile. With a single impurity present into the plasma, the technique is rather straightforward [3], while with many contaminating impurities there are many unknown functions N^Z and only one experimental constraint. We have investigated the possibility of solving this problem by using different SXR profiles, integrated on different energy bands, suitably chosen to be dominated by one impurity at a time, at least in a given radial region, i.e. in a given temperature range.

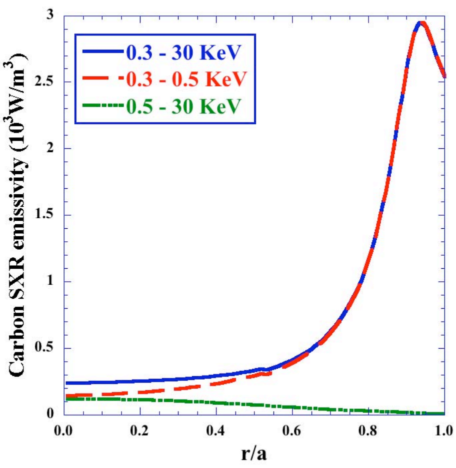

Figure 1: simulated SXR emissivity as due only to Carbon (T_e=2KeV,n_e=3.0 $10^{19}m^{-3}$)

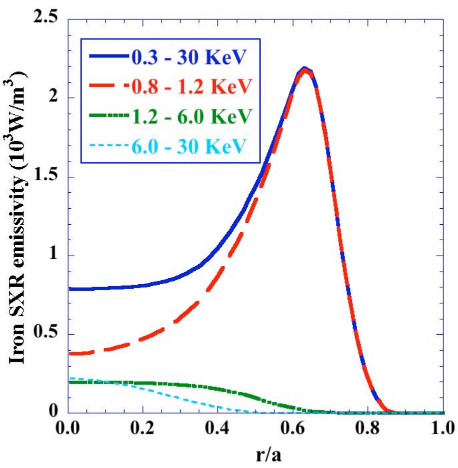

Figure 2: simulated SXR emissivity as due only to Iron (T_e=2KeV,n_e=3.0 $10^{19}m^{-3}$)

Significative simulations are presented hereafter demonstrating that a combination of spatial and energy resolution of the SXR emissivity allows the discrimination of the dominant impurities, providing the basis for a future technique for an automatic recognition of these impurities. We consider in the simulations C and O, as light, and Fe as medium Z contaminating impurities. We take the electron density, $n_e(r)$, and temperature, Te(r), profiles for two different values of the central electron temperature: 2 and 5 keV and a central electron density of $310^{19}m^{-3}$, from Tore Supra (TS) discharges. In fig. 1 the plasma SXR emissivity, for the 2 keV plasma is simulated as due only to carbon with a central concentration 1% of electron density. The emissivity is integrated in energy between 0.3 and 30 keV (continuous line) and in two separate bands: 0.3-0.5 keV (K emissions) and 0.5-30 KeV (continuous contribution). The difference is remarkable, the K emissions being extremely strong and radially localized at the edge. In Fig. 2 the same simulation has been done for iron impurity and with a central concentration of 0.1%. In this case, three energy bands have been chosen: 0.8-1.2 keV dominated by the L-shell, 1.2-6.0 KeV dominated by the continuum and 6.0-30 dominated by the K shell. The pattern of the SXR emissivity changes dramatically depending on the energy band. Combining together C and Fe in the same plasma (Fig3), we have a confirmation that, by suitably choosing the energy bands, we can identify radial regions where the SXR profiles are dominated only by single impurities. At much higher temperature, 5 keV for example, the pattern, integrated in energy, is completely changed (Fig.4), but the SXR profiles in the bands are still representative of one impurity at time.

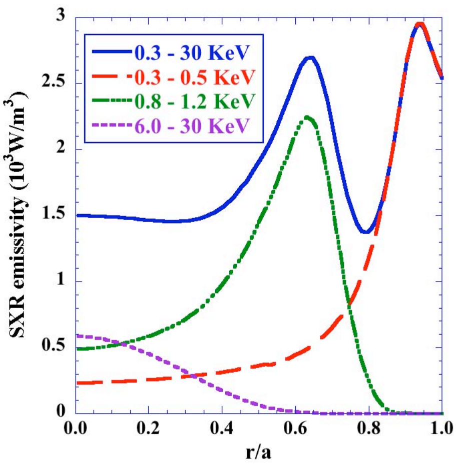

Figure 3: C and Fe simulated SXR emissivity, 2KeV the central electron temperature, n_e=3.0 $10^{19}m^{-3}$

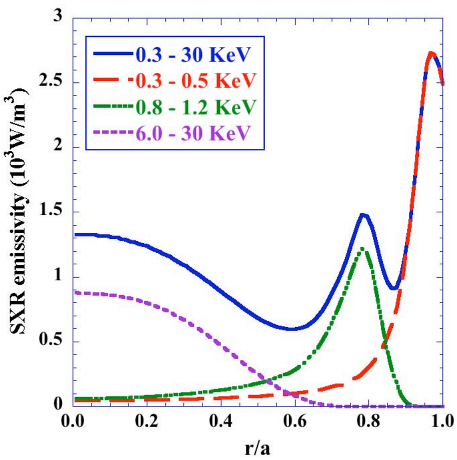

Figure 4: C and Fe simulated SXR emissivity, 5KeV the central electron temperature. n_e=$3.010^{19}m^{-3}$

Comparisons with discharges at Tore Supra

The previous simulations demonstrate that it is possible to infer information on the impurities having an energy resolved tomography and if the energy domain is extended downward, to 0.3 keV, to include K- emission of light impurities or L-shell of metals (Ni, Cr, Fe, Cu) or M-shell of heavy impurities (like Mo). It means to extend the measured SXR emissivity radially up to the edge. Present day unfortunately few tomography diagnostics have an energy resolution and a lower threshold in energy of the order of a few keV [4], loosing therefore the sensitivity to the different impurities and limiting themselves to the sole core. The soft X ray emissions of two TS plasma discharges [5], [6] is simulated in fig. 5 with only light impurities (central concentration of 1% for C and 0.1% for O are guessed) and in fig. 6 dominated by iron (central density of 1% of C, 0.1% of O and 0.1% of Fe are guessed). Both cases have a 100 μm Be filter, implying an energy cutoff at 3-5 keV. Despite the fact that the two discharges have different dominant impurities (C in the first and Fe in the second), the measured SXR profiles, once integrated in energy with the low energy spectrum cutoff, show exactly the same profiles (fig. 7) when normalized, thus confirming the need of a lower energy cutoff and different energy bands of integration. In this case we were obliged to derive the relative abundances of these impurities from the VUV spectra, while the absolute amount were obtained simulating the measured SXR emissivity.

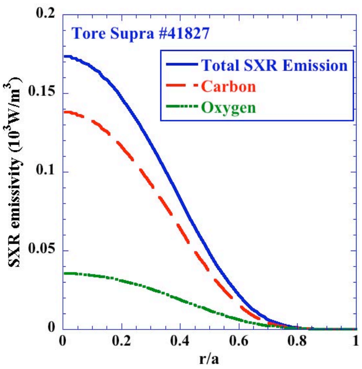

Figure 5: Tore Supra shot 41827 simulated SXR emissivity: only light impurities in the plasma

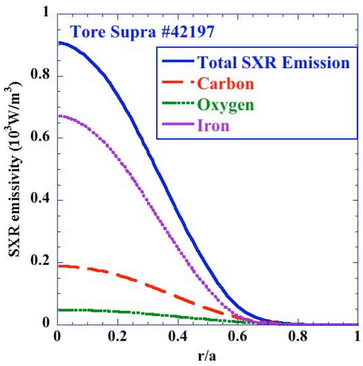

Figure 6: Tore Supra shot 42197 simulated SXR profiles: Fe, C and O in the plasma

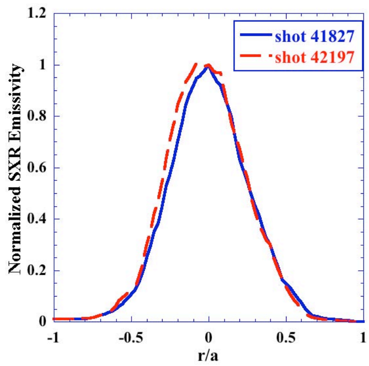

Figure 7: Tore Supra shots 41827 and 42197: reconstructed and normalized measured SXR emission profiles

Conclusions and perspectives

Energy resolved tomography coupled with ad hoc calculations of SXR emissivity, could provide a coarse estimation of the absolute amounts of the impurities and even of their radial distributions. VUV spectroscopy could help in the identification of the dominant impurities. Since the core of the simulation code of SXR emissivity is based on that carried out by Mario Mattioli, we would like to express our warmest acknowledgements to his memory.

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