SXR tomography of tungsten radiation patterns with and without MHD

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Introduction

The soft X-ray (SXR) radiation in combination with tomographic reconstruction allows to monitor the local plasma emissivity and the impurity content in the plasma core with good temporal and spatial resolution. This is particularly important in the ASDEX Upgrade tokamak (AUG), where the core SXR radiation is dominated by tungsten (W) ions released from the first wall. A specific feature of the W SXR radiation are the large gradients caused by neoclassical impurity transport and steep dependence of the W radiation on the electron temperature.

AUG is equipped with seven cameras, providing in total of 224 lines of sight (LoS) and allow for a spatial resolution of 2 cm horizontally and 4 cm vertically (see Fig. 1). The cameras H and J at the low field side have three heads with separated diode arrays and the top camera K has two heads. Plasma radiation with energy below $\sim$1.8 keV is absorbed in a bended 75 μm thick Be filter. Signal to noise ratio in H-mode discharges is up to 100 for cameras H-K and lower, about 20, for G, L and M cameras observing plasma through the gaps in limiter/divertor.

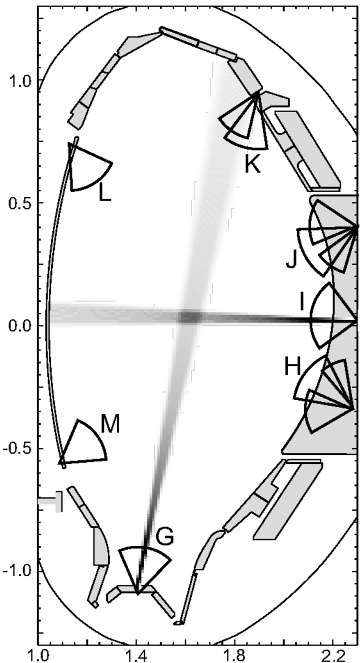

Figure 1: The poloidal cross-section of the SXR diagnostic setup in AUG. An example for real profiles of lines of sight (LoS) is shown for one horizontal and one vertical LoS.

Algorithms accurate and flexible tomography are required for a reliable reconstruction of the radiation contours. The standard methods like Cormack-Bessel or Tikhonov-Phillips method regularized by second order derivatives are not able to provide the required accuracy due to significant ringing artifacts, negative emissivity regions and underestimation of peaks. Therefore, we propose a new nonlinear regularization method and we will demonstrate its superiority to the Minimum Fisher Regularization (MFR) [1].

Tomographic inversion of SXR measurements

The investigated algorithm belongs to the class of pixel based methods where the unknown emissivity profile is discretized into N rectangular pixels g_i and consequently the response of j-th detector f_j on i-th pixel g_i is described by the contribution matrix $\mathbb{T}_{ij}$. This task leads to a system of linear equations which is singular or ill-posed. A common method to find a unique solution is the Philips-Tikhonov regularization that minimizes the misfit together with a regularization functional $O(g)$, i.e $\min_g \left(\|\mathbb{T}g - f\|^2 + \lambda O(g)\right)$. The equation is solved by SVD of integrated projection matrix [2]. The solution is obtained in the form $g = \mathbb{V}\mathbb{D}^{-1}\mathbb{W}(\lambda)\mathbb{U}^T f$, where the matrix $\mathbb{U}$ is mapping the measurements to a sparse representation. The inverse of $\mathbb{D}$ is a diagonal matrix amplifying small features suppressed by the line integration and columns of $\mathbb{V}$ are the basis vectors in the reconstruction space. Finally, $\mathbb{W}$ is a filtering matrix suppressing the noise dominated dimension defined as $W_{ii} = (1 + \lambda/D_{ii}^2)^{-1}$. Optimal value of λ parameters was selected by cross-validation PRESS method [6]

Nonlinear regularization functional

A remarkable improvement of the SXR emissivity reconstruction can be achieved if the regularization is based on MFR. The key of its effectiveness is a nonlinear adaptation of the reconstruction basis $\mathbb{V}$ to the observed solution. The emissivity profile g is consequently represented by a lower number of basis vectors. The compression of an energy spectrum $(U^T f)^2$ between the first and the last iteration of MFR is shown in Fig. 2. The number of basis vectors was reduced from ~140 to ~30 leading to a factor of 5 noise sensitivity reduction.

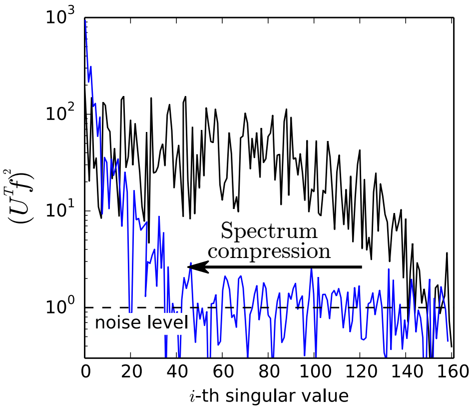

Figure 2: Compression of the energy spectrum during nonlinear iterations. First iteration is in black, last in blue.

Motivated by a frequent observation of exponentially peaking SXR radiation profiles, we propose a new regularization functional that results in minimal variation of the normalized gradient of emissivity: $O(g) = \sum_{i,j=1}^{2} \int \left(\frac{\partial^2 \ln(g)}{\partial x_i \partial x_j}\right)^2 dS$. We will call this method Minimum Normalized Gradient Regularization (MNGR). The discretization scheme is implemented analogously to MFR i.e. $O(g) = \sum_{i,j=1}^{2} g^T D_i^T W D_j D_i^T W D_j g$, where $\mathbb{W}_{ii} = 1/g_i$ and D_i is a finite difference operator.

The new isotropic MNGR method was compared with anisotropic (i.e. smoothing along magnetic surfaces [3]) and isotropic MFR on four different artificial profiles called *phantoms*. The first profile called "Gaussian" is a moderately peaked profile defined by $\exp(-\rho^2/2)$. The second "Peaked" profile is defined as sum of this Gaussian (simulating the bremsstrahlung) and a peaked function $(\rho^2 + 0.02)^{-2}$. The third phantom "snake", representing impurity accumulation in the O-point of the mode, is obtained by displacing the peak in the previous profile radially and adding rotation in poloidal direction. And finally the "Hollow" phantom simulating hollow profile observed in discharges with ECRH heating and saturated 1/1 mode. The comparison is shown in the following table:

	Gaussian	Peaked	Snake	Hollow
Anisotropic MFR	**1.4%**	8.5%	17%	**2.8%**
Isotropic MFR	3.0%	19%	15%	7.5%
Isotropic MNGR	4.3%	**6.7%**	**9%**	5.3%

Table 1: Relative differences ($\|g - g_0\|_2 / \|g_0\|_2$) of the reconstructed profile with respect to phantoms

These comparisons clearly show the advantage of the anisotropic MFR for profiles with a high level of poloidal symmetry. However if this assumption is not correct, like in the case of a snake mode, or snake-like sawtooth crash, the MNGR method is clearly better. Also for strongly peaked profiles the MNGR method performs slightly better than anisotropic MFR. The reconstruction quality is illustrated by Fig. 3 for a peaked profile. Isotropic MFR shows significant artifacts along the LoS, but contours of anisotropic MFR and new MNGR are almost indistinguishable despite no a priori knowledge about the magnetic equilibrium in MNGR is used.

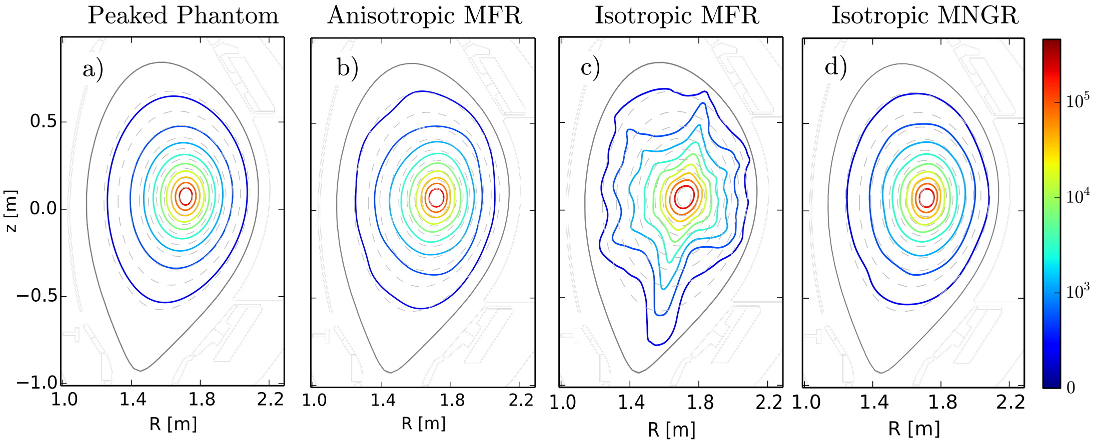

Figure 3: a) a significantly peaked artificial profile simulating real AUG profiles with 1% additional noise was reconstructed with the b) anisotropic MFR, c) isotropic MFR and d) new isotropic MNGR method. Contours are shown in a nonlinear scale.

Multichannel harmonics filtering of SXR data

An issue closely related to the tomography of magneto-hydrodynamic (MHD) modes and the subsequent computation of 2D tungsten density profiles [4] is the treatment of noise in the signal. A common technique is based on bi-orthogonal filtering of the input data [5] or reconstructed profiles [1]. The first approach enhances the most significant spatial-temporal coherence but due to latter amplification in tomography small but important features will be lost. The post-processing approach is also not optimal because of an irreversible loss of reconstruction details caused by spatial filtering in the tomography algorithm applied on noisy data. We propose an alternative method for the filtering of quasi-stationary signals. A scheme of the filter is shown in the Fig. 4.

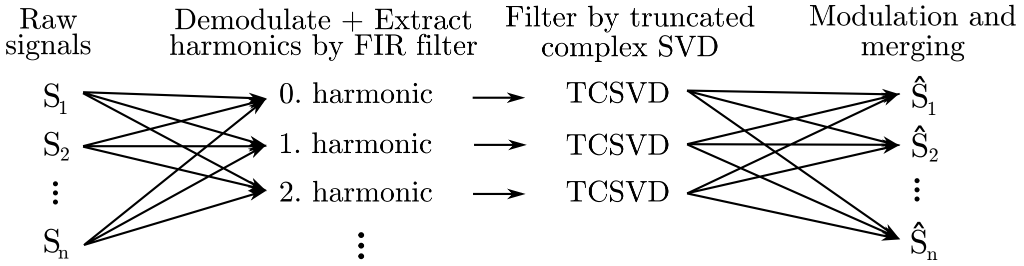

Figure 4: A diagram of the multichannel filter algorithm architecture

At first, the signals are demodulated by a complex exponential modulated on M-order of the fundamental frequency of the selected MHD mode. Further, the harmonic modes are extracted by the finite impulse response (FIR) filter designed using the Hamming window. The order of the filter enables the control of the bandwidth and the temporal resolution. This procedure results in slowly evolving complex signals describing phase and amplitude of the harmonics. This set of signals can be very effectively filtered by the truncated complex SVD (TCSVD) to suppress uncorrelated variation of the signals. Each channel is weighted according to its uncertainty in order to reduce influence of damaged or very noisy channels. Finally, the harmonics are modulated back and merged into the filtered signal. The obtained signals are virtually noiseless and therefore only a low spatial filtering will by introduced later by the tomography. Moreover, if multiple MHD modes with non-overlapping harmonics occur this method allows to isolate and reconstruct them separately.

Conclusions

We have introduced a novel non-linear regularization method for tomography allowing to reconstruct a peaked radiation profiles. A comparison with a standard MFR method is showing significant improvement with respect to isotropic regularized version mainly due to reduction of the artifacts in the profiles with high poloidal asymmetries.

Moreover a very efficient method for the filtering of quasi-stationary signals from SXR was presented. Thanks to these methods, it is possible to recover more details of the MHD modes that are necessary for instance in the case of 2D W density profiles reconstructions [4] or reconstructions of a very weak modes which would be lost in noise.

Acknowledgment

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