Optimization of Lines of Sight for Tomographic Reconstruction of the Bolometer Diagnostic at the W7-X Stellarator

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1. Introduction

The bolometer system at the stellarator W7-X consists of 11 bolometer cameras in total. They are distributed at three toroidal positions aiming at determining the radiative power loss from different poloidal cross sections and subsequently the global power loss. In the first operation phase (OP1) beginning in 2015 the plasma emission will only be measured in a triangular cross section. Later further systems will be added in a bean-shaped cross section as well as in in-between regions. This paper focuses on the bolometer system viewing the triangular plasma cross section, which consists of five bolometer cameras. They will be gradually installed in five ports, as schematically shown in Fig.1, in order to view the same plasma from different poloidal directions and therefore to perform tomographic reconstructions. Of these one horizontal camera (HBC) and one quasi-vertical camera (VBC) have already been designed and are presently being manufactured. The other 3 cameras are foreseen for installation after OP1. The design was optimized with respect to the distribution of the lines of sight (LoS) and other aspects concerning spatial resolution as well as signal-to-noise ratio. The detailed design of the first two W7-X steady-state operations compatible cameras has been reported on in ref. [1]. It is attempted to use the line-integrated measurements from the HBC (32 channels) and in combination with those from the VBC (2x24channels) to perform tomographic reconstructions in OP1. Using a newly developed algorithm based on minimum Fisher regularization (MFR), the reconstruction quality has been investigated for sparse and improved LoS coverage as well as for a case with LoS misalignment.

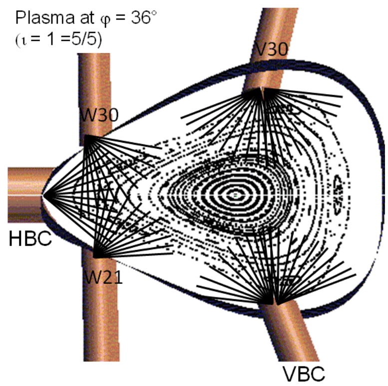

Fig.1 The five bolometer cameras for measuring the plasma radiation in the triangular cross section.

2. On the algorithm to solve the tomographic reconstruction

The principle of the MFR-method involved in the algorithm is described in ref. [2]. For dealing with the reconstruction of the plasma at W7-X some new ideas are implemented: a) The whole plasma region to be studied is divided into fan-shaped grids, instead of the usual square shaped ones, as the former meet the plasma geometry better. The grids in the core are based on the closed magnetic flux surfaces, whereas those at the edge, i.e outside the last closed flux surface (LCFS) are obtained through linear extrapolation (see Fig.2 left). For achieving the desired spatial resolution of ~5cm, the total grid point number is chosen as n_r=16 and n_θ=70 in the minor-radius and the poloidal direction, respectively. b) The geometric matrix *T,* representing the contributions of the grid points to the bolometer signals P_l , i.e. $P_l = T \cdot g$, are calculated with a higher accuracy through partitioning the aperture and the detector area into segments and additionally taking the toroidal variation of the flux surfaces into account. The information available from the line-integrals (n_l=80 at OP1) is much less than the number of unknown emissivities $g(i)$ ($i=1,\ldots, n_p$ with n_p=1120). This highly underdetermined problem is solved by minimisation of the following regularization function $\Phi=\frac{1}{2}\chi^2+\lambda\cdot I_F$, with $\chi^2 = \frac{1}{n_l}\sum_l \frac{(\sum_i T(i,l) * g(i) - P_l)^2}{\sigma(l)^2}$ being the goodness-of-fit of the measured signals, σ the measurement errors and $I_F = \sum_{i=0}^{n_p-1} \frac{(\nabla_r g(i))^2 + (K_{ani} \cdot \nabla_\theta g(i))^2}{g(i)}$ the Fisher information in flux surface coordinates. A smooth profile is obtained by optimizing λ until χ^2 ~1 is reached. A weighting factor K_{ani} is introduced in I_F to allow for anisotropic smoothness, which is inspired by the literature [3, 4, and 5]. For K_{ani} >1, the smoothness on the flux surfaces increases.

The numerical algorithm was implemented in IDL and has been tested using a known phantom distribution. A simply peaked emissivity profile *f(r),* depending only on the minor radius, is selected to create the discrete grid emissivity pattern (phantom). The artificial signals for the 80 channels of the HBC and VBC were calculated using the matrix *T* for the designed camera geometries. A relative error of 3% is assumed. Non-negativity constrains are used during the

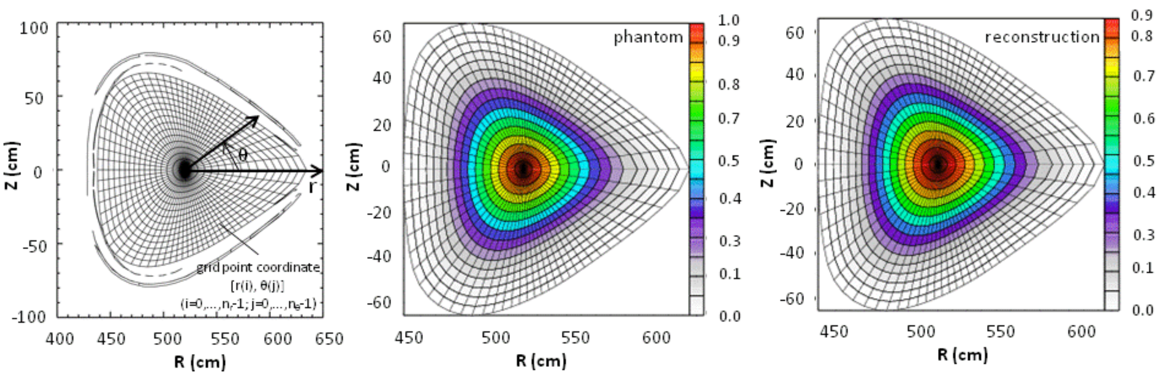

Fig.2 (Left) Fan-shaped grid made based on the magnetic flux surfaces of the 'standard' magnetic field configuration. (Mid and right) A centrally peaked phantom and the tomographic reconstruction using the MFR-algorithm.

iterations. 'Over-smoothing' of the peak as well as poor fitting of the channels viewing the peak has been observed. By increasing the weight of these channels in the χ^2 optimization this effect could be somewhat suppressed. In order to quantitatively qualify the reconstruction g_{rec}, the mean square deviation defined as $MSD=\sqrt{\sum_j (g_{rec,j}-g_{phan\,j})^2} / \sqrt{\sum_j (g_{phan\,j})^2}$ was introduced. For k_{ani}=1, a *MSD* of 9 % is obtained; using k_{ani}=1.2-2, the *MSD* reduces to 6% and keeps almost unchanged; further increasing k_{ani} results in poorer reconstructions. The results (for k_{ani}=1.5), together with the input phantom, are shown in Fig.1 (mid and right). Keeping these conditions a hollow profile can be reconstructed with a *MSD* of 3%. These tests indicate the feasibility of the developed MFR-algorithm for performing reconstructions.

3. Challenges of the tomographic reconstruction of the plasma radiation at W7-X

The plasma radiation profile at W7-X is more complicated due to the 3D magnetic field topology, especially at the edge. Around the magnetic island chains strong local emissivities are expected based on the simulation of the edge plasma radiation at W7-X and the experience gathered on W7-AS [6]. Taking the 'standard' magnetic field configuration (ɫ=1) as an example, it is assumed that close to the five islands five strongly emitting areas are located, each of which are five times brighter than the emission from near the core plasma axis. This is based on the fact that the low-Z

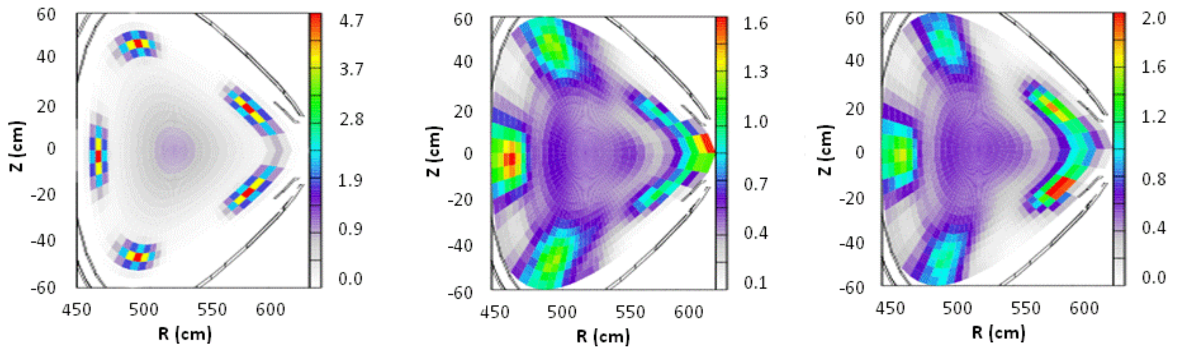

Fig.3 (Left) A phantom with five 'hot-spots' close to the island chain imitating the plasma radiation at W7-X. (Mid) The reconstruction using MFR-algorithm based on 80 line integrals (OP1). (Right) The reconstruction with 144 line integrals and improved coverage showing enhanced accuracy.

impurities, like C-ions, have higher fractional abundances and also larger radiative loss coefficients at the edge (Te~100eV). In the core the peaked emissivity profile mentioned above is still used. The projected 2D-phantom used to simulate the line-integrals of the 80 camera channels is shown in Fig.3 (left). A relative error of 3% is assumed for all signals. The achieved reconstruction is shown in Fig.3 (mid). The structure of the five bright areas at the edge as well as the peakedness at the core got somewhat washed out in comparison to the input phantom. The

MSD reaches a value of 94%. A further reconstruction test was performed assuming all 5 cameras to be installed, i.e. using a higher LoS coverage by adding further virtual channels: 40 channels for camera-V30 and 12 channels for each of camera-W30 and -W21 (see Fig.1). The reconstruction using these 144 simulated signals shows indeed an improved accuracy, which is reflected by the better resolved bright areas as show in Fig.3 (right). The *MSD* is reduced to 76%.

The effect of LoS-misalignments on the tomographic reconstructions In the above described reconstructions design values for the camera geometries were used in the calculations. They may, however, deviate from the as-installed ones to some extent, leading to geometric errors. Additional misalignments might be induced by possible displacements of the system arising from mechanical forces during plasma vessel (PV) pump-out and from thermal expansion of the PV particularly during long pulse experiments. In sensitivity studies of the tomographic reconstruction with respect to LoS geometric errors, the channels viewing the bright areas were more sensitive to misalignments. An angular error of ±0.5° in addition to a displacement of ±5mm, did not result in any significant effect in the reconstructions, the reason being that the assumed signal error due to the misalignment was comparable to the assumed measurement error. In order to avoid unexpected large geometric errors, a spatial calibration of the LoS is foreseen: The detector positions relative to the aperture will first be measured in the laboratory after assembly. Then, after the final installation on W7-X, the aperture position as well as its normal will be measured in the machine coordinate system. From this the final coordinates of the detectors can then be derived. In addition the expected LoS distribution will be measured using a moveable high power light source mounted inside the torus. The camera movements during the PV pump-out and thermal PV expansion during long pulse operation will be monitored by fixing 2 lasers to the camera support structure and following their spot-movements on a CMOS camera chip.

Remarks The accuracy of the tomographic reconstruction depends on the measurement accuracy, the geometric accuracy and the coverage quality by the LoS. Further improvements of the results are possible through implementing further constrains, e.g. for the system in OP1.

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