Development of a set of synthetic diagnostics for the WEST tokamak to confront 2D transport simulations and experimental data

Ivan Kudashev, Anna Medvedeva, Nicolas Fedorszak, David Zarzoso, Manuel Scotto d' Abusco, Vladislav Neverov, Pascal Devynck, Eric Serre

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I. Kudashev,[a,1] **A. Medvedeva,**[a] **N. Fedorszak,** [b] **D. Zarzoso,** [a] **M. S. d' Abusco,** [a] **V. Neverov,** [c] **P. Devynck,** [b] **E. Serre** [a]

[a] *Aix-Marseille Université, CNRS, Centrale Marseille, M2P2 UMR 7340, Marseille, France*
[b] *IRFM, CEA Cadarache, 13108 Saint Paul-lez-Durance, France*
[c] *National Research Centre "Kurchatov Institute", Moscow, Russian Federation*

E-mail: ivan.kudashev@univ-amu.fr

Abstract: Significant scientific effort has been focused on optimizing the scenarios and plasma parameters for tokamak operations. The lack of comprehensive understanding of underlying physical processes leads to simplifications used both in plasma simulation codes and for diagnostics, which is also complicated by the harsh plasma environment. One of the main tools to couple, check and verify these assumptions are the synthetic diagnostics. In this work we demonstrate current results of the development of the set of synthetic diagnostics for the WEST tokamak to couple experimental data with the SolEdge3X-HDG 2D transport code.

Keywords: Plasma diagnostics - interferometry, spectroscopy and imaging, Plasma diagnostics - charged-particle spectroscopy

[1]Corresponding author.

Contents

1 Introduction

In order to improve and optimize tokamak performance, considerable scientific efforts have been put into experimental and theoretical investigation of handling power and particle exhaust. However, the harsh plasma environment complicates direct measurements and the interpretation of experimental data remain challenging. Synthetic diagnostics might be very helpful in these circumstances allowing confrontation between transport codes and the full set of plasma diagnostics.

In this work we demonstrate current results in the development of the set of synthetic diagnostics for the WEST tokamak coupled with the SolEdge3X-HDG 2D transport code [1]. The numerical models of the diagnostics exploit Cherab [2] and Raysect [3] Python libraries.

First results of this study, concerning horizontal bolometer system and synthetic visible camera are shown in [4]. Here we focus more on the possibilities of the upcoming implementation of the vertical bolometer systems. We evaluate influence of the reflections on the recorded signal using wavelength resolved reflection models of plasma facing components (PFCs) and deuterium line radiation in the range of bolometer detection. More detection channels also give an opportunity to perform tomographic inversions of the detected radiation. We have performed first studies on using conventional tomographic tool, non-negative least square (NNLS) solver, and an artificial intelligence (AI) supplied one, variational autoencoder (VAE) and deep neural network (DNN).

2 Bolometer digital twin

2.1 Synthetic diagnostics and simulation parameters

A digital twin of bolometer systems of the WEST tokamak has been developed, which couples 2D plasma simulations using SolEdge3X-HDG code with the experimental data with the help of Cherab and Raysect libraries. Deuterium 2D transport simulation of the entire WEST discharge # 54487 was employed as a simulated plasma background, details of which can be found in [6]. Plasma radiation was calculated based on profiles $n_e, n_{D^+}, n_{D^0}, T_i, T_e$. To evaluate reflections influence deuterium Lyman lines $(\alpha, \beta, \gamma, \epsilon)$ has been taken into account using corresponding

photon emission coefficients from OpenADAS [7]. Fully absorbing and glossy tungsten models of the WEST PFCs has been compared as the most extreme cases. Refractive index and extinction coefficient were taken from [8].

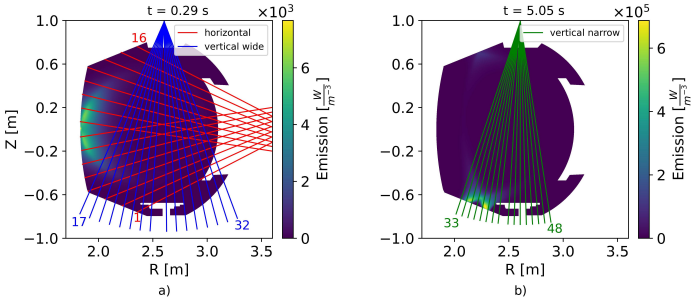

Figure 1. a) Radiation profile at the limiter stage of the discharge with horizontal and vertical wide bolometer LOSs; b) radiation profile at flat-top stage with vertical narrow bolometer LOSs

To create a training dataset of 64×64 pixel images of radiation for AI supported tomography inversion TotalRadiatedPower model from Cherab has been employed, based on approximately 400 snapshots of the discharge under consideration. This model takes into account total continuum recombination, line recombination and excitation and bremsstrahlung emission based on OpenADAS [7]. Pure deuterium plasma and fully absorbing PFC have been used. For these parameters difference between TotalRadiatedPower and sum of chosen Lyman series lines of deuterium radiation was lower than few percents for considered discharge.

Lines of sights of bolometer systems with radiation profiles for limiter and flat-top discharge are shown in the figure 1. Details of the horizontal system are described in [4, 5]. Parameters of the foils of the horizontal cameras are similar, but 16 foils per each. Centers of the rectangular slits are located at (R, Z, ϕ) = (2.61 m, 0.99 m, 279.3°), (2.61 m, 0.99 m, 280.1°) with their size of 4.3×6.1 mm, 13×6.1 mm, distance between slit and foils of 10.2, 16.7 cm correspondingly for "wide" and "narrow" vertical systems and distance between foils approximately 5 mm.

2.2 Influence of wavelength resolved optic PFC model on bolometer signals

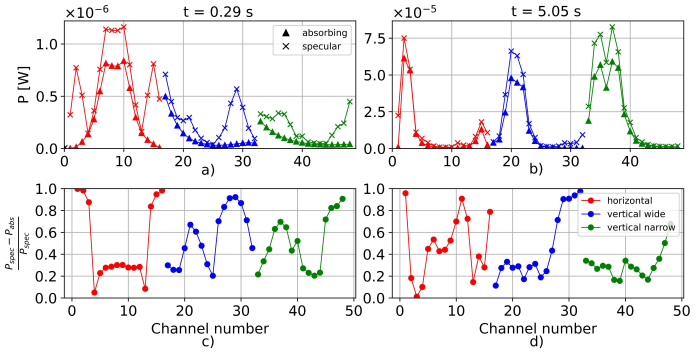

Figure 2. Simulated bolometer signals (a, b) for absorbing (triangles) and specular tungsten (crosses) models and their relative difference (c, d) for limiter (a, c) and flat-top (b, d) phases of the discharge

We calculated bolometer signals for limiter and flat-top phases from figure 1 for absorbing and specular tungsten models. According to figure 2 the reflected light can contribute up to almost 100% of detected power. This difference is most noticeable for channels which do not cross the most radiating parts of the plasma but collect light due to reflections. These channels should be properly considered while interpreting experimental data. However, this extreme case of specular tungsten may be far from real surfaces which should be more diffusive. Nevertheless it is shown that reflections can play a significant role for bolometers in WEST tokamak.

2.3 Bolometer signal tomographic inversions

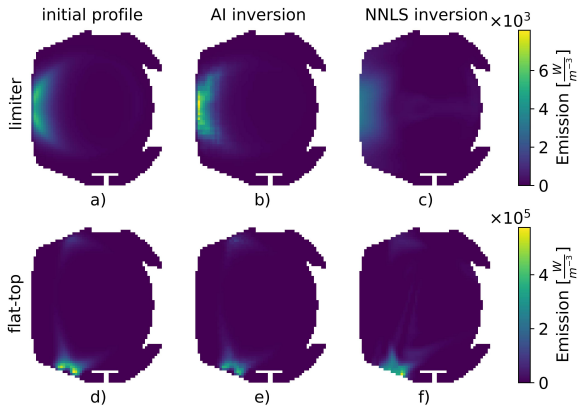

Figure 3. Tomographic inversions using AI (b, e) and NNLS method (c, f) of the initial profiles (a,d) for limiter (a, b, c) and flat-top (d, e, f) phases of the discharge

Using the synthetic diagnostic coupled with 2D plasma simulation we can investigate the possibilities of the tomographic inversions of the bolometer signals without having experimental data yet. We can provide radiation profiles such as in figure 1 and then obtain simulated bolometer signals. Inverting them, we can restore 2D profiles of radiation and compare with the initial one.

We used two methods of inversions. First, using Cherab methods for NNLS (non-negative least square solver) with ADMT (Anisotropic Diffusion Model Tomography) regularisation operator [9], implying the assumption that radiation should vary less along magnetic flux surfaces than across. For the second one we employed AI libraries Keras [10] and TensorFlow [11] to build Variational Autoencoder (VAE) which reproduces initial 2D profiles passing through a bottleneck of latent space, which is reduced information of the dataset profiles. VAE consisted of convolutional part of 3 convolutional layers with MaxPooling and of deconvolutional part of 3 convolutional layers with UpSampling. Then a DNN with two dense layers was trained to connect 48 bolometer signals with 16 values in the latent space of VAE. Radiation profiles and detected bolometer signals in training dataset were normalized to values in the range from 0 to 1, using logarithmic scale in the range of lowest and highest expected signals to be detected. After training bolometer signals can be passed through deep neural network (DNN) and decoder part of VAE to obtain 2D profiles of radiation.

According to figure 3 we can see that AI supported tomography gives slightly better results compared with NNLS which has some artifacts, caused by the use of sensitivity matrices. However, the AI tool might be overtrained on a given dataset and further studies with higher variety of phantoms for various magnetic profiles and sources of radiation should be done.

3 Conclusions

In this contribution we present the progress in the development of a set of synthetic diagnostics for the WEST tokamak. Taking into account wavelength resolved plasma emission as well as applying a PFCs surface model we showed that for deuterium plasmas reflections might contribute up to 100% of detected power, especially for the outer channels of the vertical bolometers. Expanding our digital twin with vertical bolometer cameras allowed to perform tomography using VAE and DNN and NNLS method. The inversions of a promising quality are achieved and further investigation on different tomography methods, employing more variable sets of the phantoms of radiation, should be performed.

Acknowledgments

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