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Initial design of a real-time and an intershot bolometric data exploitation strategy for DTT

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Abstract: One of the milestones to be achieved in the design of the bolometric diagnostics for the new Italian Divertor Tokamak Test (DTT) project is the estimation of the radiated power at the start of operation, i.e. the so-called first plasma, in order to perform various tasks ranging from scientific analysis and planning of the discharges to the feedback protection of the machine. In fact, real-time (RT) feedback control of the radiation pattern for prevention is both a delicate and important matter, for example in terms of mitigating and avoiding disruptions. It would therefore be desirable to monitor not only the total power emitted, but also the one emitted by the different regions of the plasma. This paper then focuses on showing the initial design of the main strategy for estimating the plasma radiation in two different situations: for RT control and for an inter-shot analysis. The first approach for RT then, is based on the estimation of the radiated power inside the first wall using specific lines of sight (LoS). Such estimates have been compared with those obtained from slower tomographic reconstructions of synthetic emissivity profiles (*phantoms*). Furthermore, a first design of the Region Of Interest

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(ROI) for a fast implementation of an already established macro-estimation of the radiated power in different locations of the main chamber is provided and the overall method is adapted for DTT. Regarding the design of the inter-shot data exploitation then, since tomographic reconstructions will most likely be available during an inter-shot basis, it is planned to provide a more accurate estimate of the radiated power from different locations of the device for a better design and tuning of the discharges. In order to achieve such a long-term goal, an initial strategy for adapting a maximum likelihood based algorithm for inter-shot analysis is described.

KEYWORDS: Data processing methods; Nuclear instruments and methods for hot plasma diagnostics; Plasma diagnostics - interferometry, spectroscopy and imaging

Contents

1 Introduction

The possibility of defining a diagnostic layout, such as the bolometry for the Divertor Tokamak Test Facility (DTT) [1, 2] under construction at the ENEA Research Centre in Frascati, is an interesting opportunity to define in perspective both the scientific exploitation of the data collected and their use as feedback and feedforward control of a plasma discharge in real time (RT). Bolometric data have traditionally been used to obtain both rapid estimates of the power emitted by the plasma in RT and, at a later stage, tomograms, i.e. reliable estimates of the emissivity profiles, in this case after the application of an inversion algorithm [3]. Depending on the temporal resolution, robustness, and sensitivity of the detector type, bolometers or semiconductor detectors can be used for different applications. Metal foil bolometers are robust, reliable and with a temporal resolution of a few milliseconds. Silicon Absolute eXtended UltraViolet (AXUV) diodes can achieve even a few microseconds, but they show a spectrally dependent degradation of their responsivity rather quickly during operations [4]. A wide range of studies can therefore be conducted in principle, including power balance, transport, modelling, and specific analyses of magneto-hydrodynamic (MHD) instabilities. At this stage, metal foil bolometers are considered for the so-called “first plasma” of DTT. Each bolometer defines a line of sight (LoS) and its measured brightness behaviour over time, as well as that measured by fast photo-diodes, is becoming increasingly important as an indicator of phenomena that can profoundly affect the plasma evolution, even leading to the so-called disruptions [5]. Disruptions are abrupt events leading to a rapid loss of plasma confinement with a consequent release of large thermal and particle loads on the plasma-facing components while, at the same time, inducing huge mechanical stresses on the vacuum vessel (VV) [6, 7]. It is therefore desirable to consider the long-term goal of using such data in RT already during the design phase of the bolometric layout. The development just described can then be completed with a preliminary study of inter-shot data analysis for scientific exploitation and experimental support.

Section 2 shows how the synthetic diagnostic for bolometric DTT [8] data can be used to estimate the radiated power in RT and how such data can be used for RT control. The section proceeds with the initial design of the inter-shot analysis for supporting experiments, before landing on the conclusions.

2 Real time and inter-shot preliminary exploitation strategy

This section is dedicated to the description of the initial strategy for the RT exploitation of bolometric data. The bolometric layout considered in this paper has already been shown to be able to retrieve emissivity profiles while minimizing the risk or producing artefacts [8]. Such a layout, reported in

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figure 1a, has been designed for the first plasma of the DTT and has 120 LoS with respect to the 216 of the extended one [9]. The radiated power can be obtained directly from the synthetic brightness of the bolometers in P1, P2 and P3 (averaging P3T and P3B), or by averaging their estimates. Of course, the radiated power can also be estimated by applying an inversion algorithm, such as the Maximum Likelihood (ML) algorithm [10], but this approach is slower. It is therefore more suitable for an inter-shot analysis. Synthetic emissivity profiles, *phantoms*, that have been used in this article are shown in figure 1b-e. Figure 1b illustrates an inner detached plasma with a stable X-point radiator and a close to the edge impurity accumulation. Figure 1c includes a core accumulation also. Then, symmetric emissivity profiles in the divertor are illustrated in figure 1d and figure 1e. Finally, figure 1f represents either a successful impurity screening case or a fast rotating mode. Table 1 reports the radiated power estimates of the phantoms, obtained by directly considering the emissivity profiles as known, and those derived by using the brightness of the LoS instead. The former estimate can be derived by summing the emissivity profile within each of the N pixels (33800) with area $A_{\text{vox}}^{\text{pol}} \simeq 1.56\,\text{cm}^2$, of a poloidal plane and then assuming the toroidal symmetry of such profiles to be valid:

$$P_{\text{rad}}^{\text{phantom}} = 2\pi R_0 A_{\text{vox}}^{\text{pol}} \sum\nolimits_i^N \varepsilon_i \tag{2.1}$$

Where R_0 stands for the major radius of the torus and ε_i stands for the emissivity inside the i-th voxel. Considering the brightness I_{jq} of each "j"-LoS belonging to the bolometer array "$q'' := \{P1, P2, P3B \cup P3T\}$, its length inside the plasma L_{jq} and its poloidal area S_q^j, then, by using the Einstein convention for each array, the radiated power can be estimated as:

$$P_q^{\text{brightness}} = 2\pi R_0 S_q^j \left(\frac{I_{jq}}{L_{jq}}\right) c_q \tag{2.2}$$

Details regarding the derivation behind the contribution of each voxel can for DTT synthetic diagnostic can be found in [8].

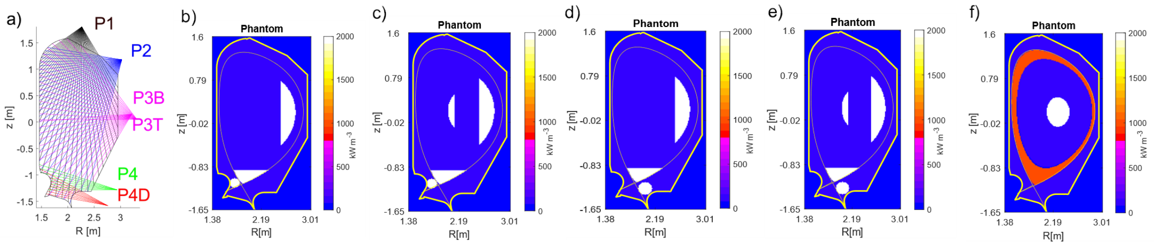

Figure 1. a) Bolometric layout considered for the first plasma of DTT [8]; b),c),d) e) f) synthetic emissivity profiles, i.e. phantoms as in [8], used for the analysis in this article. Reproduced from [8]. CC BY 4.0.

In the previous expression, c_q represents a correction coefficient. It is an average value of all the discrepancies obtained, i.e $\delta = (P_{\text{rad}}^{\text{brightness}} / P_{\text{rad}}^{\text{phantom}} - 1)$, for different phantoms and for each set of bolometers considered. The need for such a parameter is most likely due to the approximation made to model truncated pyramidal LoS composed of parallelepipeds in terms of line integrals [8]. Further tests are expected also to fine-tune such a parameter, but as table 1 shows, the results are already satisfactory. In fact, the final discrepancy, especially when averaging the estimates from different arrays, does not exceed a ~3% between the expected $\left(P_{\text{rad}}^{\text{phantom}}\right)$ and the estimated radiated powers $\left(P_{\text{rad}}^{\text{brightness}}\right)$.

Table 1. Estimates of the reference radiated powers obtained from the phantoms in figure 1b–e by using eq. (2.1) and from the synthetic brightness of the three different arrays of bolometers ($P1$, $P2$, $(P3B + P3T)/2$) using eq. (2.2) have been reported. For each evaluation, the discrepancy "δ" with respect to the value used for reference has been reported.

Phantom		**Array P1**		**Array P2**		**Array P3**		**P1 and P2**		**P1,P2 and P3**	
P_{rad} $[MW]$		P_{rad} $[MW]$	$\delta_{\%}$	P_{rad} $[MW]$	$\delta_{\%}$	P_{rad} $[MW]$	$\delta_{\%}$	P_{rad} $[MW]$	$\delta_{\%}$	P_{rad} $[MW]$	$\delta_{\%}$
Figure 1b	13.44	12.91	−3.92	13.69	1.86	14.12	5.06	13.30	−1.04	13.57	0.97
Figure 1c	14.63	14.50	−0.86	14.96	2.26	15.17	3.69	14.73	0.70	14.87	1.70
Figure 1d	13.93	13.30	−4.55	14.01	0.54	14.47	3.87	13.65	−2.01	13.92	0.047
Figure 1e	15.03	14.68	−2.35	15.10	0.48	15.35	2.16	14.89	−0.94	15.04	0.097
Figure 1f	16.72	18.68	11.71	15.86	−5.15	14.34	−14.25	17.27	3.28	16.29	−2.56

Another operational consideration is the definition of ROIs for feedback and possibly feedforward control of the discharge, since radiation patterns have recently been explicitly linked to disruptive events [6]. By assuming a uniform radiated power in selected areas, i.e $P_{\text{ROI}1,\ldots,8}$, a fast but approximate method can be used [11]. Here it has been adapted for DTT. At this preliminary stage, 8 ROIs were defined, as shown in figure 2a,b.

The sets are considered by summing the synthetic brightness of specific LoS for each array of bolometers to group the LoS into eight sets, e.g. $V_1 = \text{ROI}_1 + \text{ROI}_4$ as shown in figure 1a. Then, weights for each ROI can be considered. The ratio between the area of the ROI itself and that of the whole set can be a valid choice, but in principle other choices of weights for tuning can be applied.

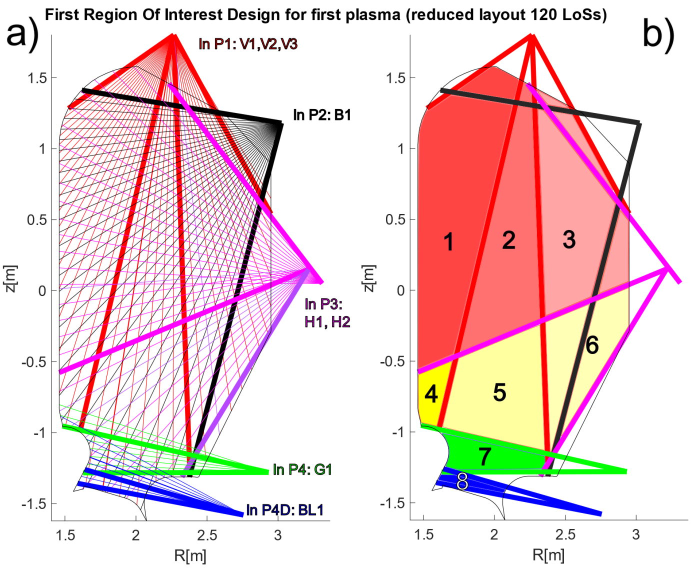

Figure 2. a) LoS layout divided into eight sets of measurements: V1,V2,V3 (from P1), B1 (from P2), H1, H2 (from P3), G1 from P4 and BL1 P4D; b) The eight ROIs have been numbered. Each ROI is highlighted by a coloured area and divided by thick lines. Reproduced from [8]. CC BY 4.0.

A closed system of eight equations can then be written and summarized in a vector format, as in eq. (2.3) where the matrix $\mathbb{G}$ contains the geometrical weights described above.

Using a non-negative least-squares fit, the radiated power $P_{\mathrm{ROI}1,\ldots,8}$ in each region can then be estimated in RT. In principle, it would be possible to consider the brightness of individual LoSs directly to monitor the "trajectory" of anomalous features, such as Multifaceted Asymmetric Radiation From the Edge (MARFE), but ROIs are expected to smooth more isolated spikes, in order to minimize the risk of feeding the RT network with false alarms.

$$\begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ H_1 \\ H_2 \\ G_1 \\ BL_1 \\ B1 \end{pmatrix} = \mathbb{G} \begin{pmatrix} P_{\mathrm{ROI1}} \\ P_{\mathrm{ROI2}} \\ P_{\mathrm{ROI3}} \\ P_{\mathrm{ROI4}} \\ P_{\mathrm{ROI5}} \\ P_{\mathrm{ROI6}} \\ P_{\mathrm{ROI7}} \\ P_{\mathrm{ROI8}} \end{pmatrix} \Rightarrow \begin{cases} V_1 = 2\pi R_0 \sum_q^{\#\, L.I. \in V1} S_q \left(\frac{I_q}{L_q}\right) = \frac{S_{\mathrm{ROI1}}}{S_{V1}} P_{\mathrm{ROI1}} + \frac{S_{\mathrm{ROI4}}}{S_{V1}} P_{\mathrm{ROI4}} \\ \ldots \\ B_1 = 2\pi R_0 \sum_q^{\# L.I. \in B1} S_q \left(\frac{I_q}{L_q}\right) = \sum_r^8 \frac{S_{\mathrm{ROI}\ r}}{S_{B1}} P_{\mathrm{ROI}\ r} \end{cases} \tag{2.3}$$

However, the above ROIs layout and associated weights need to be tested on synthetic set of phantoms mimicking a plasma evolution as shown in [6] for example. Regarding the possible actuators to be triggered by a RT network, it has been described in [6] how the early detection of an unstable X-point radiator leading to peripheral MARFEs can be used as a precursor to trigger avoidance schemes, involving actuators then, for a class of disruptions commonly known as "density limit" disruptions on AUG. This includes the use of external heating, such as ECRH, fuelling schemes and reshaping, such as the reduction of the upper triangularity [6].

Another advantage of this approach is that it can be used, in principle, to feed the tomographic code for inter-shot analysis with first, not uniform initial estimates. To conclude this section in fact, the tomographic code currently adapted to DTT, which is based on a maximum likelihood approach [8], is expected to be optimized for at least an inter-shot application. The conceptual design of such an algorithm has been graphically depicted in figure 3, considering the Fortran and Python programming languages as the best options at this stage.

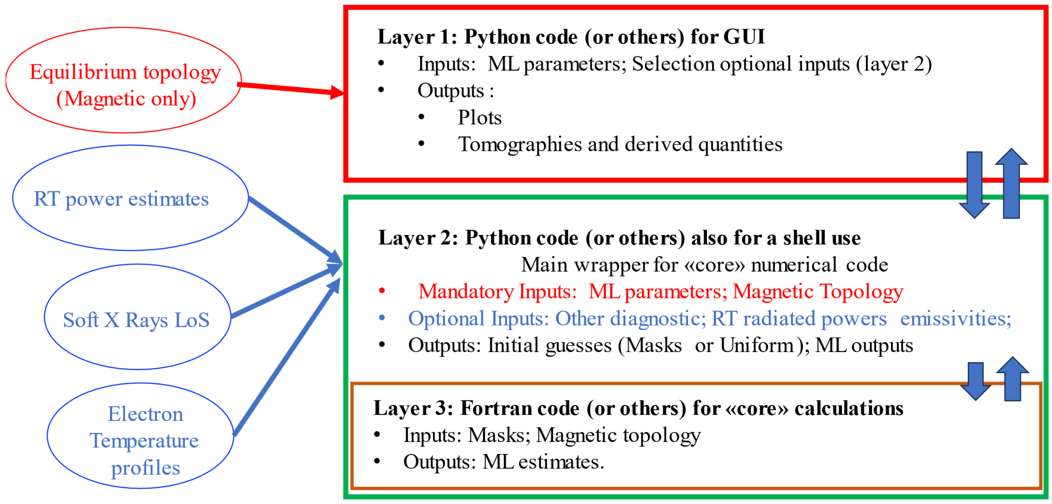

Figure 3. Graphical representation of the structure of the inter-shot tomography code under development.

A Fortran code performs the core computations (Layer 3), while two Python wrappers are used on top of each other. The first wrapper (Layer 2) will handle the input and output of the Fortran code, while the other (Layer 1) will handle the plotting and display of the output from the inner layers. In particular, the Layer 3 will provide matrices (tomograms) and vectors (derived quantities, such as radiation density profiles) as outputs [10]. Mandatory inputs to this layer are the poloidal flux (magnetic topology) and the ML code settings. Optional inputs are instead initial estimates, *masks* [12], which are planned to be provided by the wrapper Layer 2. To build such masks, i.e. the optional initial estimates for the iterative procedure performed in Layer 3, the Layer 2 would benefit from the RT estimates in eq. (2.3) to properly fill the initial matrix. In principle, other measurements could be used, mainly soft X-ray (SXR) and electron temperature profiles, to confirm asymmetries for example. Such an approach aims to provide *de facto* further constraints on the ill-posed tomographic problem. Finally, a top layer (Layer 1) wrapper in Python will be dedicated to displaying plots and various outputs from the inner layers.

3 Conclusions

This paper describes the preliminary strategies for Real Time (RT) and inter-shot analysis of bolometer data for DTT, which could be further adapted in the future development of the diagnostic. The former aspect has been studied both in terms of estimating the radiated power directly from the synthetic brightness and by defining a first set of Region Of Interests (ROIs) to be further studied on phantoms for operational purposes. The tests performed on synthetic data to verify the ability of the synthetic diagnostic to estimate the total radiated power have given satisfactory preliminary results, with discrepancies between expected and brightness derived quantities within the $\sim 3\%$ range. Furthermore, taking into account the preliminary definition of ROIs for operational purposes, the analysis confirmed the importance of considering such a long-term goal in the design phase of the diagnostic layout in order to optimize the poloidal coverage. Refinements could then be expected, as other DTT-relevant scenarios (such as the Negative Triangularity one) and a different coverage of the LoS layout, currently optimized for the Single Null scenario, should also be considered. Another use of the ROIs lies in their use for inter-shot analysis as masks, i.e first guesses of more accurate tomographic codes, such as the Maximum Likelihood one, which has already implemented and included in the bulk of the synthetic bolometric diagnostic for DTT.

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