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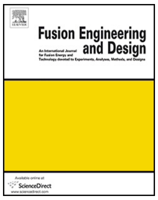

Plasma diagnostics at Aditya Tokamak by two views visible light tomography

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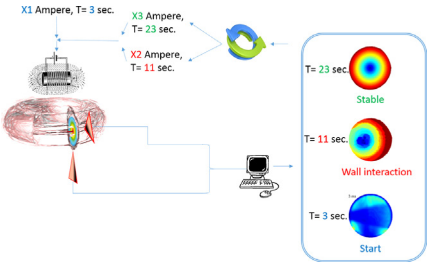
HIGHLIGHTS

- Improved algorithm works equally well for central as well as for peripherical plasma regions.
- Entropy optimized smoothening parameters eliminate user dependencies.
- Real time fusion grade plasma diagnostics images.

GRAPHICAL ABSTRACT



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ABSTRACT

This visible light computerized tomography exercise is a part of a project to establish an auxiliary imaging method to assist other imaging facilities at the Institute of Plasma Research (IPR), India. Space constraints around Aditya Tokamak allow only two orthogonal ports. Each port has one detector array (64 sensors) sensitive to the visual spectrum emitted by H_α emission. The objective here is to report the developments on limited view tomography for hot plasma imaging. Spatially filtered entropy maximization algorithm with non-uniform discretization grids is employed. Estimation of unique kernel smoothening parameters (mask size and exponent factor) depends on entropy function and projection data. It removes requirement of any arbitrary/user-based decision for choosing a regularization factor thus minimizes the chance for biasedness or errors. Synthetic projection data is used to analyse the performance of this modification. The error band in the process of recovery remains under acceptable level (less than 15%) irrespective of the origin of the emissions from the core. Reconstructed hot plasma images/profiles from Aditya Tokamak are shown. These profiles may improve the current understanding about (a) plasma–wall interaction or edge plasma turbulence, (b) control and generation of plasma and (c) correlations between theoretical and engineering advancements in Tokamak reactors.

1. Introduction

Tokamak has become a standard design to contain/generate/withhold the fusion grade plasma for economically useful duration. Magnetic field, around the toroidal and poloidal axes, is a major controlling factor that governs the plasma profile. Imaging techniques, based on spectroscopy, computerized tomography (CT) and Thompson scattering can be useful to understand the relation between various micro and macro level phenomenon [1–4]. Correlations between theoretical estimations and measured parameters can be obtained via characterizing the radiation spectrum [4–6].

Surrounding parameters of plasma core (e.g., very high temperature, density ratio, etc.) permit only in vivo methods. Analysis

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involving wide energy spectrum is employed to improve the current understanding of plasma physics [7–10]. External design parameters, for example number of views/ports, allow limited options to place the detector setup that is sensitive for a particular modality. Space constraints thus force to distribute/prioritize available locations/ports according to suitability of experiments for which the Tokamak has been designed.

Visible light computerized tomography (VLT) is one of the non-invasive imaging technique that supports selective optical interference filtering to obtain element specific e.g., H_α emission profiles [11–13]. Several works using VLT for plasma imaging in laboratory and real world environments, e.g., hot plasma in Tokamak, are reported [8,14–18]. Visible light tomography also compliments other modalities, such as X-ray tomographic imaging, particularly for low emission regions, at the edges [9].

This work reports tomographic imaging profiles of H_α emission measured from boundary/edges of the Aditya Tokamak developed at Institute of Plasma Research (IPR, India). We attempt to establish an auxiliary imaging method with this exercise to assist imaging facilities based on alternative spectra, e.g., X-ray imaging [13,19].

Several geometrical constraints imposed by the port size and presence of other diagnostic techniques permitted to create only two ports. This limited view and limited detector condition provides sparse data to analyse within the realm of limited data/view tomography problems [20,21]. Abel transformation (for asymmetrical geometries/profiles) has been refined as a possible solution technique specifically for plasma profile reconstruction [8,22,23]. Singular value decomposition methods and algebraic reconstruction techniques are other possible options [24]. Entropy maximization (MaxenT) is employed in this work [21,25–31] as this objective function provides a unique unbiased solution for a given under-determined system of equations. The formulation is convoluted by an entropy controlled/optimized spatial filtering step within each iteration [29].

Smoothing in previous works is accomplished with preferred square mask sizes of 2×2 pixels or 3×3 pixels. Edge length of a single pixel corresponding to our case would be $500/64 = 7.8$ mm. Kernel smoothening technique herein computes the entropy optimized mask size and filtering exponent, each depending on the measured tomographic projection data.

It is shown earlier, that reliable reconstruction is possible even with two views, if prior information is available [31,32]. The most probable photonic emission in visible range spectrum, for optically thin plasmas, would emerge only from the outer layer/edge of the Tokamak [18,33]. Non-uniform adaptive meshes permit modelling that is independent of the region but depends only on data [21,28,29].

We examine the feasibility of the analysis combining adaptive grid, optimal spatial filtering and entropy optimized solution technique via numerical simulations w.r.t. visible light tomography. Root mean square error, RMSE (Eq. (8)) is employed to quantify error on reconstruction [34]. Comparison of line integrals, before and after reconstructions, is also performed to adjudicate the efficacy of the proposed solution method for real data.

The goal is to test the established VLT facility at IPR, India and report the reconstructed time dependent plasma profiles.

Next part describes the geometry of setup. Section 3 provides details of reconstruction algorithm. Sections 4 and 5 contain performance characterizations via numerical simulations and real data measurements.

2. Data collection geometry

Specifications for Aditya Tokamak are available elsewhere [19]. The VLT setup (detector arrays and electronics) with standard assemblies is positioned just outside the vacuum vessel of the Aditya Tokamak [18]. Fig. 1 illustrates the setup geometry. The layout for data collection is detailed in Section 5.

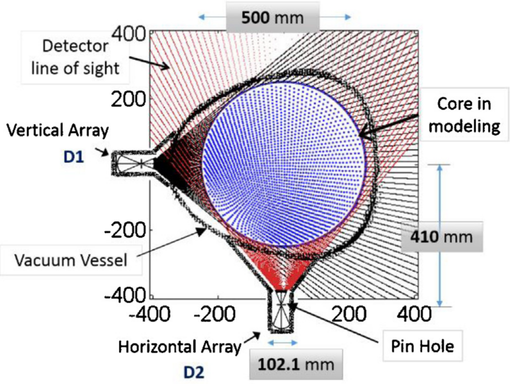

Fig. 1. Data collection geometry at Aditya Tokamak.

The setup comprises of two 64 element linear photo-diode arrays (Hamamatsu model S6494, driver circuit C6495) installed at orthogonal positions in one poloidal plane [35]. Detectors are placed at 410 mm from the centre of the core. Collimation (pin hole arrangement) is achieved such that the detector line of sight spans the circular shaped plasma core (Fig. 1) with a fan angle of 79°. Circular core is modelled with diameter of 500 mm [19].

3. Modelling

Projection data from the plasma diagnostic is composed of a local intensity values that can be integrated along the detector line of sight [36]. Light radiation gathered from an optically thin plasma is a consequence of the summation of independent emissions along the ray at different intervals [33]. This notion permits extraction of radial distribution of plasma from the projection data of visible radiation. Modelling is thus performed similar to the transmission phenomenon [25].

It is inferred that distribution of information is non-uniform and comparatively denser near to the detectors due to fan-beam geometry. It has become a custom to avoid more than one line of sight per pixel to maintain the consistency in the system of equations. This modelling criterion also facilitates grid resolution, thus directs to maintain the Shannon sampling limit. The degree of ill-posedness which is the difference between number of equations ($64 \times 2 = 128$) and number of variables ($64 \times 64 = 4096$) is significant here [37]. Presence of inactive pixels is found (Fig. 2) with implementation of this standard.

Iterative reconstruction methods fail to update these pixels, leading to inaccurate depiction [21], as illustrated in Fig. 2 using a cyber phantom with unit distribution. This fact motivates to choose non-uniform discretization strategy with expectation of improved reconstructions. Non-uniform/adaptive restructuring of reconstruction grid resolves all these issues by adjusting number and location of nodes as per the projection data itself [21]. It reduces the condition number of the weight coefficient matrix and alleviates the ill-posedness thus providing a stable solution against noise [28,29]. Delaunay triangulation is employed to discretize the image space and the associated finite element method is used due to its flexible formulation.

Kernel smoothening (spatial smearing) is preferred to mollify the ill effects of non-uniform spread of information during the regression/curve fitting problems [29,36–41]. The operation also assuages noisy artefacts. A generalized function, similar to Nadaraya–Watson estimator, is used to estimate the smearing parameters (circular mask radius R and exponent γ) [29,42].