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Tomographic reconstruction for a tangentially viewing visible light imaging diagnostic on EAST

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ABSTRACT

A two-dimensional tomographic reconstruction method based on the Phillips-Tikhonov regularization is proposed in this study, for a tangentially viewing visible light imaging diagnostic on EAST. Phantom tests are demonstrated to evaluate the performance of this method. The purpose of this method is to reconstruct the local emission from experimental images in various parts of the visible spectrum, which can be employed to reflect spatial distributions of certain particles (Li-II in this study) in plasmas. As a potential application of the Li-II distribution, the measurement of plasma boundary displacements in the presence of resonant magnetic perturbations is tried. Though the result of this attempt is limited by the computational precision and conditions of diagnostic system at present, it provides valuable references for further works.

1. Introduction

The tangentially viewing visible light imaging system, as a kind of regular diagnostic applied on magnetic confinement fusion devices including the Experimental Advanced Superconducting Tokamak (EAST) [1], can be employed to evaluate shapes of plasmas and status of discharges by recording the plasma emission in the range of the visible spectrum [2]. On the other hand, this system can also monitor the operating state of some components of the fusion device, such as the first wall, antennae, divertor, and so on. Using visible light imaging system, lobes have been observed in resonant magnetic perturbation (RMP) experiments on MAST [3]. As the images recorded by the tangentially viewing visible light camera are line-integrated (i.e., projected), it is necessary to perform a reconstruction in order to resolve the local emission of visible light in plasmas. The purpose of the visible light tomography is to reconstruct the local emission in various parts of the visible spectrum, which can be employed to reflect the spatial distributions of certain particles in plasmas. In addition, the visible light tomography can also be employed to investigate the spatial-temporal behavior of macroscopic instabilities and small-scale fluctuations [4].

The operation in H-mode is accompanied by edge localized modes (ELMs), resulting in excessive transient heat loads on the divertor target, while there is no material that can withstand such a high heat flux [5]. RMPs are extensively used to avoid the above challenges by mitigating or suppressing ELMs, whose effectiveness has been proved on almost all of the major fusion devices [6–9]. On the base of both experimental observations and modeling results, it has been indicated that the deformation of plasma boundary can emerge owing to the magnetic perturbation field [10]. The general method to determine the position of the last closed flux surface (LCFS) is the equilibrium reconstruction by EFIT [11], while its accuracy is affected by the uncertainty of magnetic measurements and input assumptions when the equilibrium is reconstructed. In addition, three-dimensional (3D) perturbation fields are not considered in EFIT, which makes it unable to reconstruct the equilibrium when RMPs are applied. Furthermore, influenced by cruel conditions in future fusion reactors including the international thermonuclear experimental reactor (ITER), magnetic probe measurements will be constrained. Various diagnostics have been employed to measure plasma boundary displacements, such as the imaging beam emission spectroscopy on DIII-D [12], high-resolution Thomson scattering and edge charge exchange diagnostic on JET [13], and multi-energy soft-X-ray diagnostic on NSTX [14].

The lithium (Li) evaporation and real-time Li aerosol injection, which are unique technological methods employed on EAST, are used to suppress ELMs [15]. Owing to the excitation of Li around the plasma boundary, the Li-II spectrum obtained by the visible light system can reveal the Li-II distribution. Further, relative shifts of the peak values in the Li-II profile reflect the plasma boundary displacements. Therefore, it is possible to characterize the displacements by analyzing the Li-II spectrum. As the range of visible spectrum is broad, the green

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component of visible spectrum employed in this study consists of not only the Li-II spectrum. This will affect the accuracy and contrast ratio of results under current experimental conditions. Filters will be employed to reduce this negative influence in the future. The one-dimensional (1D) Abel transform has been employed to reconstruct the Li-II distribution using the visible imaging diagnostic on EAST [16]. However, only displacements of certain points locating at the same Z position where the camera is fixed can be measured.

In this study, a novel method based on the two-dimensional (2D) tomographic reconstruction is proposed, using the tangentially viewing visible light imaging diagnostic on EAST. It can be employed to reconstruct the Li-II emission profile in a complete poloidal cross section, rather than for certain points in the case of using 1D Abel transform. The measurement of plasma boundary displacements in the presence of RMPs is tried as a potential application case of Li-II distribution, though the result shows that current computational and experimental conditions are not mature and more subsequent works are needed.

This paper is organized as follows. In Section 2, the algorithm of the 2D tomographic reconstruction is introduced and phantom tests are performed to evaluate the effectiveness of this algorithm. The experimental setup is briefly described in Section 3. Then, the results of data analysis are presented in Section 4. The summary and discussion of this study are provided in Section 5.

2. Algorithm and phantom test

2.1. Algorithm of the 2D tomographic reconstruction

One tangentially viewing visible light system cannot provide sufficient information to reconstruct a 3D distribution. Assuming that the plasma emission is toroidally symmetric in a tokamak [17], lines of sight can be projected onto one poloidal cross section. A previous report showed that the plasma boundary displacements caused by RMPs are measured up to ± 5% of the minor radius [18]. As for EAST, the minor radius is 0.45 m, and the major radius is 1.88 m. The perimeter of the central axis in the toroidal direction is calculated exceeding 11.8 m. Plasma boundary displacements caused by RMPs in the poloidal direction are estimated up to 2–3 cm, which are much smaller than the characteristic scale of EAST in the toroidal direction. Therefore, the assumption of toroidal symmetry is still valid in the presence of RMPs. Then, the 3D tomographic issue can be simplified to be a 2D issue. As an example, the one-column sight-line projections of the tangentially viewing visible light imaging system onto a poloidal cross section on EAST are shown in Fig. 1. The curved lines represent the projections of sight lines in the central column.

In general, the Radon transform can be expressed as [19]:

$$p_i = \int \int K_i(x, y) e(x, y) dxdy, \tag{1}$$

where $e(x, y)$ denotes the 2D emission profile, p_i denotes the i^{th} line-integrated measured value of the camera, and $K_i(x, y)$ represents the geometry. The tomographic reconstruction is the solving of $e(x, y)$ from Eq. (1). The discrete linear algebra form of Eq. (1) is:

$$P = KE, \tag{2}$$

where $K(M \times N)$ is called geometric matrix or weight matrix. K_{ij} is the geometric weight relating the contribution of j^{th} node of the grid in the poloidal projection cross section to the i^{th} line-integrated projection. M is the total number of lines of sight, and N is the total number of nodes of the grid. As shown in Fig. 1, the length of each projected line in one node of the grid reflects the contribution weight mentioned above. So, the geometric matrix can be calculated by counting the length of the i^{th} line of sight projected onto the j^{th} node of the grid.

As solving Eq. (2) is a highly ill-posed problem owing to the non-unique and unstable solution [20], it is necessary to perform smoothing or regularization procedures. In this study, the Phillips–Tikhonov regularization [21] is employed. The regularization method in this study applied to the solution of Eq. (2) is equivalent to minimizing the quantity Q:

$$Q = \alpha |LE|^2 + \frac{|P - KE|^2}{M}, \tag{3}$$

where α is the regularization parameter that controls the smoothness of the solution, and $L(N \times N)$ is the discrete Laplacian matrix that can be expressed as: $L = \nabla_R^T \nabla_R + \nabla_Z^T \nabla_Z$ in the two-dimensional (R, Z) rectangular coordinate. As for a discrete function f, its second order difference form can be expressed as:

$$\begin{aligned} Lf(m, n) = \Delta f(m, n) = \nabla^2 f(m, n) = [f(m+1, n) - f(m, n)] \\ + [f(m-1, n) - f(m, n)] + [f(m, n+1) - f(m, n)] \\ + [f(m, n-1) - f(m, n)] = f(m+1, n) + f(m-1, n) \\ + f(m, n+1) + f(m, n-1) - 4f(m, n). \end{aligned} \tag{4}$$

So, the Laplacian matrix L can be expressed as:

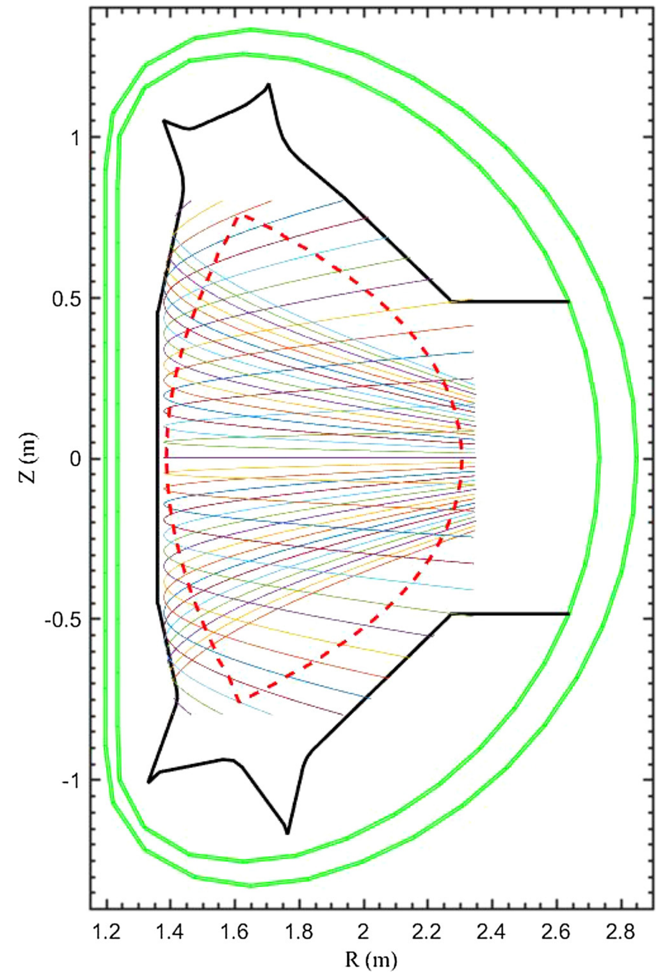

Fig. 1. One-column sight-line projections of the tangentially viewing visible light imaging system onto a poloidal cross section on EAST. The green thick solid line and black solid line outline the shell and first wall of the EAST, respectively. The red dashed line outlines the LCFS for the discharge #41079 at t = 6s. The curved lines represent the projections of sight lines in the central column.