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Tomographic reconstruction of two-dimensional radiated power distribution during impurity injection in KSTAR plasmas using an infrared imaging video bolometer

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ABSTRACT

Based on the two-dimensional radiation images obtained by an infrared imaging video bolometer (IRVB) with tangential view, the two dimensional radiation profiles of plasmas in KSTAR were reconstructed. The IRVB installed on KSTAR has a tangential view of the plasma, and thus tomographic reconstruction of the raw images of radiation profiles was performed to remove the chord-integration effect by using a tomographic reconstruction code based on the Phillips-Tikhonov algorithm. Phantom reconstruction tests with various synthetic images were carried out to validate the accuracy of the reconstruction results. It is found that hollow radiation phantoms with strong divertor radiation were reconstructed with high accuracy. Furthermore, the effects of the number of channels of the IR camera, and the number of pixels of the plasma and of the IRVB on reconstruction performance are studied with phantom tests. Two-dimensionally reconstructed images of KSTAR plasmas demonstrated that radiation loss at the plasma edge and near the divertor region increased significantly after gaseous impurity injection. The total radiated power was up to 1.2 MW at the disruption, which was 40% of the NBI power. After argon and krypton gas injection, total radiated power was increased by 325 kW and 180 kW, respectively.

1. Introduction

Plasma radiation is a key parameter in the study of power balance [1], edge plasma physics, and impurity transport in fusion plasmas. While plasma core radiation must be kept low since plasma confinement can be significantly degraded by radiation losses, radiation in the plasma edge is considered as a good indicator of the mitigation of the heat load to the divertor [2–4]. In addition, Radiated power is critical information for ELMs [5,6], disruptions [7] and impurity transport studies [8,9]. Therefore, accurately measured two-dimensional (2-D) radiation profiles from the core plasma to the divertor are very important for the steady state operation of fusion devices.

In order to measure radiated power from fusion plasmas, foil bolometry has been commonly used due to its flat sensitivity in the wavelength range. Conventional resistive bolometer arrays utilize the temperature dependence of the electrical resistance of a metal grid thermally connected to the foil [10]. Another type of foil bolometry is the infrared imaging video bolometer (IRVB), which is equipped with an IR camera to measure directly the foil temperature. One of the advantages of IRVBs is its stability against electromagnetic noise compared with resistive bolometers. Also, an IRVB can observe the whole poloidal cross section of the plasma with one tangentially viewing array, while multiple resistive bolometer arrays in different poloidal location are necessary for the same purpose. In addition, an IRVB requires fewer in-vessel

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components, so that maintenance during plasma operation is easier than with the resistive bolometer. Recently, IRVBs have been successfully operated in a number of fusion devices [11–14].

Since the incident power on the IRVB foil is the sum of the local emission along the line of sight, radiation profiles cannot be resolved directly from the raw data of the IRVB. Therefore, tomographic reconstruction for removing the chord-integration effect is essential to obtain accurate 2-D images of radiated power. Tomography has been used for 2-D reconstruction of AXUV [15–17] and resistive bolometer measurements [18–20]. For an IRVB, this technique was firstly applied for measurement in JT-60U [21]. In this study, a tomographic reconstruction code for the KSTAR IRVB is developed using the Phillips-Tikhonov (P-T) method. Tomography performance and signal to noise (SNR) ratio dependence on IRVB hardware specification are studied. The stability of the reconstruction solution against detection noise is also investigated. Equipped with the IRVB hardware and the tomographic reconstruction code, the behavior of the 2-D radiation profiles during gaseous impurity injection in H-mode discharges are analyzed.

This paper is organized as follows. Section 2 describes the details of the KSTAR IRVB system. The description of the tomography algorithm and phantom test results of the IRVB set up are given in Section 3. Section 4 shows the experimental results from a gas injection experiment, which is followed by conclusions in Section 5.

2. IRVB hardware on KSTAR

Fig. 1 illustrates a schematic of the IRVB diagnostic system installed on a mid-plane port of the D-port cassette of the KSTAR vacuum vessel. The entire system is 3.5 m long and 1.2 m high. The FLIR Phoenix IR camera and IR optical system originally was installed on JT-60U [22] and then moved to KSTAR. Currently, the same optical system as the JT-60U is used, while the vacuum window and IR camera were replaced. Plasma radiation passes through a pinhole of 5 mm in diameter and heats a metal foil. A 2 μm thick 70 mm × 90 mm platinum foil is used to absorb photons with energies up to 7.5 keV. The distance between the foil and the aperture is 7.65 cm. The heated foil emits thermal radiation in the

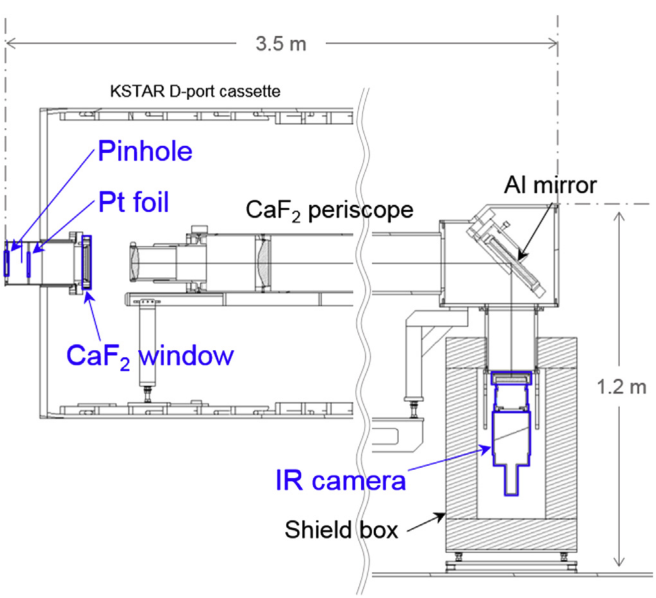

Fig. 1. A schematic illustration of the KSTAR IRVB diagnostics. In-vessel components are a pinhole and a platinum foil. Ex-vessel components are a periscope lens system, an IR camera, and a shield box.

infrared (IR) range, which is enhanced by graphite coating on both sides of the foil. The heat diffusivity and the thickness of the foil were calibrated using a MIKRON M315 blackbody radiation source [23]. Foil temperature with plasma radiation is up to 40–50 °C while the temperature of the calibration source is up to 100 °C, so the whole foil radiation caused by plasma can be measured during experiment. The IR radiation from the foil is delivered through a 100 mm diameter, 4 mm thick CaF_2 vacuum window to a periscope lens system. Inside the periscope lens system, four CaF_2 lenses are used to transmit IR radiation. The first one has a diameter of 100 mm and the rest have diameters of 150 mm. An aluminium mirror is placed at the end of optical axis to reflect IR radiation into IR camera, which is used as a detector. FLIR Phoenix camera from JT-60U was replaced by FLIR SC7600 camera in 2016. The effects of IR camera replacement on tomography accuracy and signal to noise ratio are discussed in Section 3. The IR cameras are covered with three layers of shields. The innermost is 15 mm thick lead which blocks the secondary gamma rays. The second layer is 20 mm thick soft iron blocking the magnetic field. The outermost layer is a boron-doped polyethylene that blocks the neutron.

Fig. 2(a) illustrates the field of view of the IRVB on KSTAR where blue dashed lines indicate the lines of sight of the IRVB. The whole poloidal cross-section of the KSTAR is within the viewing range, which enables the calculation of the total radiated power emitted from the plasma. Fig. 2(b) shows an aperture and foil of the IRVB. We define here bolometer pixels as the grid on the foil whose size is determined by a certain aperture size and an IR camera. Plasma pixels denote the grid on the target poloidal plane, which is parallel to the foil.

3. Tomography algorithm for KSTAR IRVB

A tomographic reconstruction code for the KSTAR IRVB was developed based on the Phillips-Tikhonov (P-T) algorithm, which is known for its higher reconstruction accuracy compared to other algorithms [24]. The line-integrated data $\vec{f}$ measured by a detector is the product of a response (geometry) matrix $\overleftrightarrow{W}$ and local emissivity vector $\vec{g}$, i.e. $\vec{f} = \overleftrightarrow{W} \cdot \vec{g}$. The signal from the ith channel is expressed as a weighted sum $f_i = \sum_{j=1}^{N_{pl}} w_{ij} g_j$ where N_{pl} is the number of plasma pixels. The length of the intersection between the ith sight line and jth plasma pixel is defined as w_{ij}. To solve an ill-posed problem, the P-T method minimizes the following functional

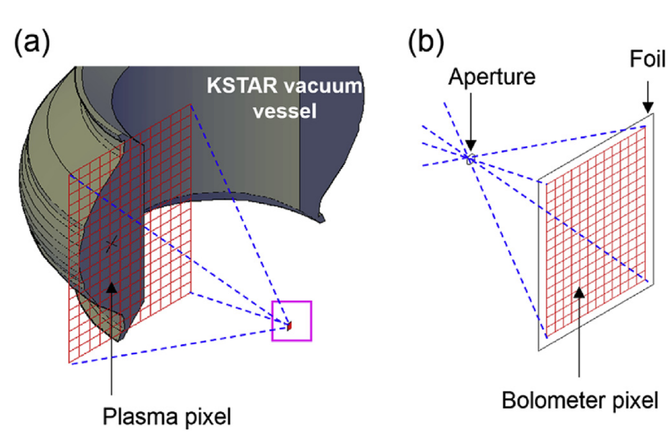

Fig. 2. Schematic diagram of (a) field of view of the KSTAR IRVB, and (b) pinhole and foil. Bolometer pixels are shown on the foil.