Modification of Tomography Technique for Two-Dimensional Spectroscopic Measurement in JT-60U Divertor Plasmas

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Tomography techniques using the two measurement arrays were investigated. To evaluate test reconstruction methods with three combinations of calculation grid and observation view lines, a model distribution was reconstructed. The two-dimensional distribution generated on a calculation grid arranged parallel to the actual apparatus view lines was in better agreement with the model distribution than the distribution generated on a square grid. This parallel grid was applied to the reconstruction of the deuterium Balmer-series lines in the JT-60U detached divertor plasmas.

Keywords: tomography, detachment, two-dimensional distribution, deuterium Balmer-series lines, divertor plasma

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1. Introduction

Understanding of fuel particle transport in divertor plasmas is important for controlling heat and particles in tokamak fusion reactors. Detached divertor plasmas have attractive properties to reduce energy and ion flux onto the divertor tiles [1]. In detached divertor plasmas, ionization of D_2 molecules and D atoms and recombination of the D^+ ions occur contiguously [2, 3]. Two-dimensional spectroscopic measurement of deuterium emission allows determination of the spatial distribution of the ionizing and recombining plasmas. Two-dimensional distributions of the deuterium Balmer-series line intensities were reconstructed with tomography techniques to obtain the spatial distribution of the ionizing and recombining plasma in the JT-60U detached divertor plasma [4].

Since an algorithm is simple and an array-handling is convenient, tomography technique with a square or rectangle grid have been used for divertor plasma analyses [5, 6]. Also for core plasma analyses, a square grid has been used for its simplicity [7]. The reconstruction with a concentric grid in RFX was developed and successful result was obtained [8]. In this study, we investigate the tomography technique for the divertor plasma analysis. Reconstructed results with three combinations of a calculation grid and view lines are compared for a model distribution of the deuterium emission. False geometric patterns appear in the two-dimensional distributions calculated with the square grid both for the algebraic reconstruction technique [9] and the maximum entropy method [10]. Failures of tomography techniques hinder the physical understanding and the improvement of tomography techniques is required. The new grid arranged parallel to the view lines is proposed for the improvement.

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2. Tomography Technique

The algebraic reconstruction technique (ART) is used in the present analysis because this is the simplest of computer tomography methods. This method generates a two-dimensional distribution which reproduces the measured line-integrated intensity, without considering of measurement error. The ART can reconstruct the spatial distribution even though the information is inadequate, though it takes no measures to avoid the deformation of the distribution or a false geometric pattern.

As shown in Fig. 1, the experimental view lines of the two-dimensional spectroscopic system for this study comprise 92 channels (vertically 60 channels, horizontally 32 channels) with a spatial resolution of about 1 cm. The first through the 17th of the horizontal view channels are interrupted by the divertor dome top. Three combinations of the calculation grid and view lines were used, as shown in Fig. 2; (a) a combination of the square grid and view lines arranged parallel to the grid (S-P combination), (b) a combination of the square grid and the experimental view lines (S-E combination), and (c) a combination of the grid arranged parallel to the view lines and the experimental view lines (P-E combination). The S-P and the S-E combination have 45×56 calculation cells with 1 cm spatial resolution, and the P-E combination has 53×32 cells with about 1 cm spatial resolution.

The values in cells are allocated in the inner divertor region where the horizontal view lines are interrupted by the divertor dome top were calculated. The spatial distri-

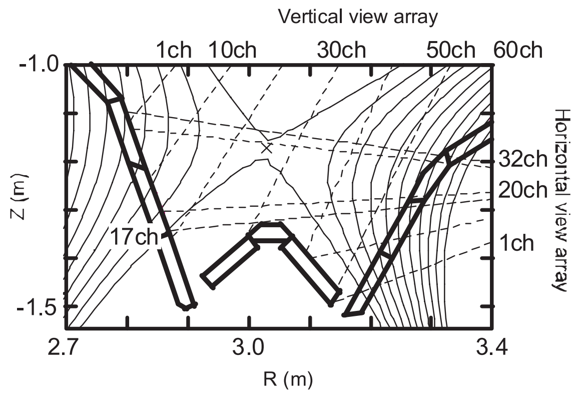

Fig. 1 The view channels in the JT-60U divertor region.

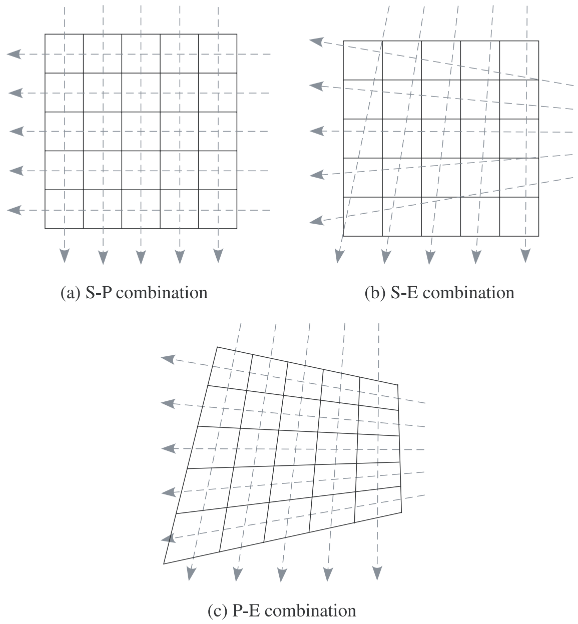

Fig. 2 The combination of the calculation grid and the view lines, (a) the square grid and view lines arranged parallel to the grid, (b) the square grid and the experimental view lines, (c) the grid arranged parallel to the view lines and the experimental view lines.

bution in this area was reconstructed with only the information of vertical view lines. Because the number of vertical view lines which pass through each cell are different with the S-E combination (one line passes in most cells and two lines pass in some cells), a false distribution was reconstructed. Each cell of the S-P and P-E combination has only one vertical view line, and consistent distribution among the vertical view lines is obtained.

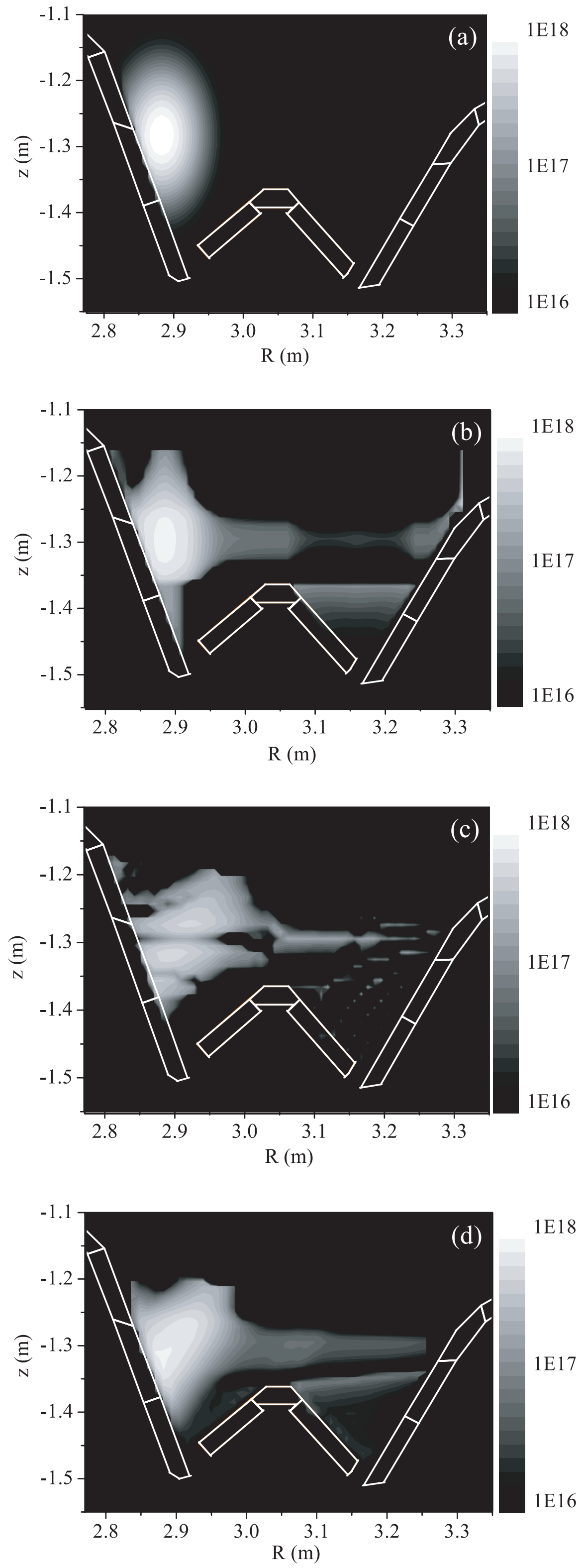

Fig. 3 The results of the test reconstruction. (a) a model data, (b) with the S-P combination, (c) with the S-E combination, and (d) with the P-E combination.

3. Comparison of Three Combinations of Grid and View Lines

A model distribution shown in Fig. 3 (a), was used in the present reconstruction test. In the JT-60U inner detached divertor plasmas, a typical distribution of the deuterium emission is like this model. It was a Gaussian distribution with a peak intensity of 1.0×10^{18}, with a full width at half maximum (FWHM) of 4 cm in the z-direction and an FWHM of 2 cm in the R-direction on a background of 1.0×10^{16} in the divertor region. The peak intensity and the calculation error χ^2 defined in Eq. (1) were used for the comparison of the accuracy of the distributions calculated with the three combinations:

$$\chi^2 = \sum_m \frac{\left(E_m^{\mathrm{cal}} - E_m^{\mathrm{model}}\right)^2}{E_m^{\mathrm{cal}}}, \qquad (1)$$

where m, E_m^{cal}, and E_m^{model} are the cell number, the intensity of the model distribution at the m-th cell, and the intensity of the reconstructed distribution at the m-th cell, respectively. The convergence condition of the ART is

$$\sqrt{\frac{\sum_k \left(S_k^{\mathrm{exp}} - S_k^{\mathrm{cal}}\right)^2}{\sum_k S_k^{\mathrm{exp}2}}} < 0.001, \qquad (2)$$

where k, S_k^{exp} and S_k^{cal} are the view line number, the measured intensity at the k-th view line, and the line-integrated intensity of the calculated distribution at the k-th view line, respectively.

The reconstructed results for the S-P combination are shown in Fig. 3 (b), for the S-E in Fig. 3 (c), and for the P-E in Fig. 3 (d). Though the two-dimensional distribution with the S-P combination spreads like a crisscross due to the deformation caused by two-array tomography [11], it shows good agreement with the model distribution. A false geometric pattern clearly appears in the two-dimensional distribution with the S-E combination. The stronger distribution in the inner divertor region is divided into more than four areas and strong emission spots are seen in the outer divertor region. Since the distribution with the S-E combination is very different from the model distribution, this combination is inappropriate for the reconstruction of divertor plasmas.

The two-dimensional distribution with the S-P combination is in better agreement with the model distribution than the distribution with the S-E combination, indicating that the view lines should be arranged parallel to the grid as in Fig. 2 (a). However, this arrangement is difficult in fusion reactors for a number of reasons, such as restriction in the number of observation ports. A calculation grid arranged parallel to the apparatus view lines is introduced here as an alternate combination. In the two-dimensional distribution with the P-E combination (Fig. 3 (d)), the geometric pattern disappears. Though the distribution is tilted toward the inner divertor plates and some image deformation remains, the two-dimensional distribution with the P-E combination is better than the distribution with the S-E combination.

The peak intensity and χ^2 of the three combinations are summarized in Table 1. The S-P combination is the best because the peak intensity is close to that of the model distribution and the χ^2 is the smallest of the three combinations. However, as already mentioned, the S-P combination is difficult to be achieved for the plasma measurement. Comparing of the peak intensity and χ^2, the P-E combination is better than the S-E combination. The application of the P-E combination to the tomography of the deuterium Balmer-series lines thus should be highly advantageous.

Table 1 Comparison of peak intensity and error of three combinations.

	Peak intensity	χ^2
Model distribution	1.0×10^{18}	---
S-P combination	6.9×10^{17}	5.8×10^{19}
S-E combination	4.4×10^{17}	2.4×10^{20}
P-E combination	6.5×10^{17}	1.9×10^{20}

The reason why the reconstructed two-dimensional distribution with the grid arranged parallel to the view lines becomes better than that with the square grid is not clarified at present. We presume two reasons; (1) the spectroscopic system has only two detector arrays, (2) the observed target is divertor plasmas. Failures of tomography techniques, such as a deformation of distributions or an appearance of geometric patterns, are considered to be mitigated as detector arrays are increased. Failures can affect strongly on two-dimensional distributions because the number of detector arrays of the spectroscopic system is minimal. In the divertor region, the cross-section shape of plasma is complex and the plasma parameters are asymmetric. Clarification of the reason of better reconstruction and further improvement are the future work.

4. Application of Improved Tomography Technique for JT-60U Divertor Plasma

The deuterium Balmer-series lines of an L-mode discharge in the JT-60U detached divertor plasma were measured by a wide-spectral-band spectrometer with a CCD detector. The plasma current, the toroidal magnetic field, the neutral beam heating power, the electron density of the main plasma, and the electron density normalized to the Greenwald density limit were 1.0 MA, 3.6 T, 4.4 MW, $1.4 \times 10^{19}\,\mathrm{m}^{-3}$, and 64 %, respectively. The two-dimensional distribution of the D_β (transition; n = 2-4, wavelength; λ = 486.1 nm) emission with the S-E combination is shown in Fig. 4 (a) and that with the P-E is shown in Fig. 4 (b).

The distribution of the D_β emission with the S-E combination has a false geometric pattern and must be considered unacceptably inaccurate. On the other hand, this geometric pattern disappears in the distribution of the D_β emission with the P-E combination. The D_β emission is strong above the inner strike point and near the outer strike point. The emissive region in the inner divertor area is distributed along the magnetic field lines naturally. The D_β distribution with the P-E combination is better than that with the S-E combination.

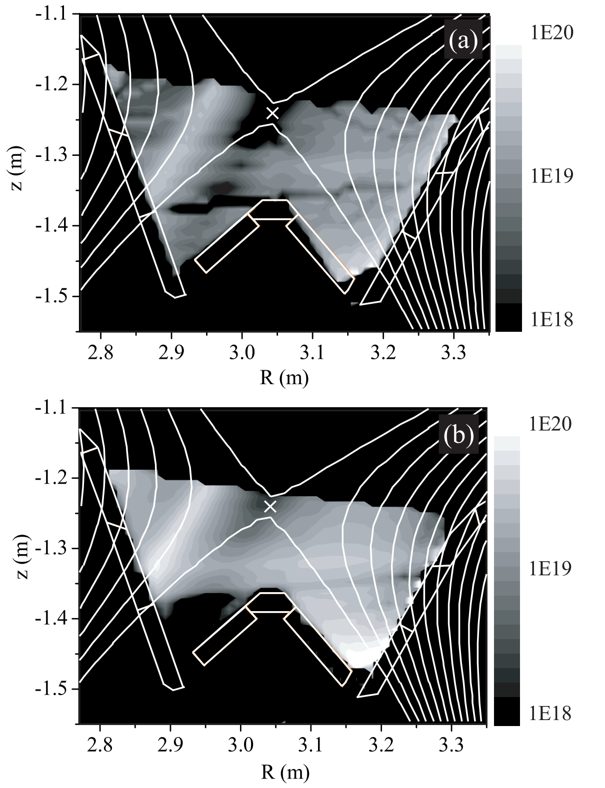

Fig. 4 The two-dimensional distribution of the D_β emission in the detached divertor plasma. (a) with the S-E combination, (b) with the P-E combination.

5. Summary

Tomography techniques have been introduced for the study of the JT-60U detached divertor plasmas. Since the two-dimensional spectroscopic system for JT-60U divertor plasmas has only two measurement arrays, false geometric pattern can appear in the reconstructed spatial distribution. These geometric patterns are investigated for a model distribution of deuterium Balmer-series line emission. The algebraic reconstruction technique is used because of its simplicity. Three combinations of a calculation grid and view lines are used for reconstruction testing. A false geometric pattern appears in the two-dimensional distribution with the combination of the square grid and the apparatus view lines, but it disappears in the distribution with the new grid arranged parallel to these view lines. With the use of this new grid, we can obtain a higher-accuracy spatial distribution.

The combination of the apparatus view lines and a grid arranged parallel to the view lines is employed in the reconstruction of the deuterium Balmer-series lines in the JT-60U detached divertor plasmas. An improved two-dimensional distribution of the D_β emission is obtained. The D_β emission is stronger above the inner strike point and near the outer strike point. Since the two-array tomography technique is thus improved, the study of the ionizing and recombining process is facilitated. We plan to study the ion source, ion sink, and the process of the energy loss in divertor plasmas with this technique.

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