Field of View Optimization for IR Imaging Video Bolometers in LHD*)

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An IR imaging video bolometer (IRVB) is a measurement instrument for plasma radiation with the pinhole projection principle. The IRVB has an advantage of having a large number of detector channels. The advantage is necessary for three dimensional observation of plasma radiation with tomography techniques. The observation also requires the calculation of geometry matrices and optimization of the fields of view for the IRVB to reconstruct accurate plasma radiation distributions. In this study, fields of view for four IRVBs which were installed in LHD have been optimized by changing the aperture positions to minimize the total number of non-visible plasma-voxels in the LHD plasma. The best fields of view were chosen with the geometry matrix which is calculated as a projection matrix of the plasma radiation to the bolometer foil with an assumption of helically symmetry. There were 169 non-visible plasma-voxels which could not be measured by any of the IRVB channels in the setting before optimization. The number could be decreased to 0 by this optimization. By improving the fields of view, the three dimensional plasma radiation distributions will be reconstructed with higher accuracy.

Keywords: IRVB, optimization, field of view

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1. Introduction

Radiation is one of the major channels for power loss from fusion devices. Measurement of the radiation from plasma is necessary to understand power balance in fusion devices. In LHD, a helically periodic symmetry for the plasma radiation can be assumed by which the plasma repeats itself every 18 degree toroidally [1]. However, the radiation structure with in the plasma period has not been investigated. It is necessary to measure the radiation structure.

While inside of the last closed flux surface (LCFS) plasma parameter may be assumed to be constant on a flux surface therefore a one dimensional measurement is effective to understand plasma phenomena on a flux surface based coordinate system. In the ergodic edge region beyond the LCFS on helical devices such as LHD [2], the magnetic field and the plasma parameters are completely three dimensional but have helical symmetry. In other words the plasma can be assumed to repeat itself every half field period (18 degrees toroidally), but within that half field period the plasma is three dimensional in the ergodic edge region. Recently tokamak devices also have an ergodic edge region using supplementary perturbation coils to control edge localized modes. The radiation mainly occurs in the ergodic edge region, therefore three dimensional measurements are necessary to understand radiation phenomena [3].

An IR imaging video bolometer (IRVB) [4] is a measurement instrument for plasma radiation. It is useful for the measurement of both radiation intensity and spatial distribution. IRVBs have been used in LHD [5] and JT-60U [6] with a bolometer foil. The IRVB has the advantage of having a large number of channels in a 2D array. The advantage is necessary for three dimensional observation of plasma radiation which is planned in LHD using four installed IRVBs and a tomography technique. The IRVBs are installed at the 6-T, 6.5-U, 6.5L and 10-O ports in LHD. Figure 1 shows the installation locations for the IRVBs.

In IRVB observation, plasma radiation enters through an aperture and is absorbed by the bolometer foil. The

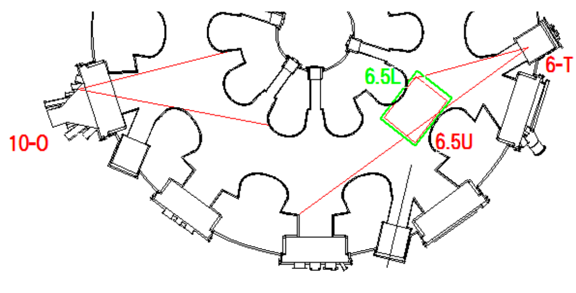

Fig. 1 Top view of LHD showing installation locations for IRVBs.

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radiation power which is absorbed by the foil is given in terms of the 2D temperature distribution on the foil with the same principle as a pin-hole camera. The 2D temperature distribution is measured by an IR camera to calculate the plasma radiation.

The radiation power at the foil is calculated by solving the thermal diffusion equation on the foil and is related to the plasma radiation by the following equation.

$$P_{\mathrm{rad},j} = \sum_{k=1} h_{j,k} S_k. \tag{1}$$

Where $P_{\mathrm{rad},j}$ is the incident radiation power density on the j-th detector channel, S_k the radiation intensity from the plasma-voxel defined in the observation region, $h_{j,k}$ the element of the geometry matrix as a projection matrix to the bolometer foil from the plasma-voxel, k the index of the plasma-voxel and j the index of the detector channel. The plasma radiation distribution can be reconstructed from the IRVB output using a tomography technique to invert the geometry matrix. Therefore the geometry matrix should be calculated to obtain the radiation distribution.

The geometry matrices are also used to optimize the fields of view of the IRVBs. The tomography technique requires information from all plasma elements to reconstruct the 3D plasma radiation distribution with high accuracy from the 2D output of the IRVBs. With the previous fields of view of the IRVBs on LHD, many plasma-voxels could not be measured by any IRVBs. Fields of view should be optimized to minimize the number of these non-visible elements. In LHD, changing the field of view is limited by the first wall, port position for installation of the IRVBs and other structures.

In this study, the calculation procedure for the geometry matrix was developed and optimization of the field of view for the installed IRVBs was carried out using the geometry matrices.

2. Geomatrix Calculation

Figure 2 shows the flowchart of the geometry matrix calculations. The LHD plasma is divided in cylindrical coordinate into plasma-voxels which measure 5 cm vertically, 5 cm major radially and 1 degree toroidally as plasma elements for this geometry matrix calculation. An assumption of helically periodic symmetry for the plasma radiation is made by which the plasma repeats itself every 18 degree toroidally.

In the present IRVB installations on LHD, the FOV(field of view) of the each detector go through square apertures with 4 mm or 8 mm sides. The geometry matrix for each field of view was calculated by tracing the FOV of the each detector in camera based coordinate until they hit the first wall. The FOVs of the each detector after passing through the aperture are divided into FOV-voxels by 1 cm steps in the direction of movement until they hit the wall. The FOVs of the each detector also broaden as they extend. When the width of the FOV-voxel becomes larger

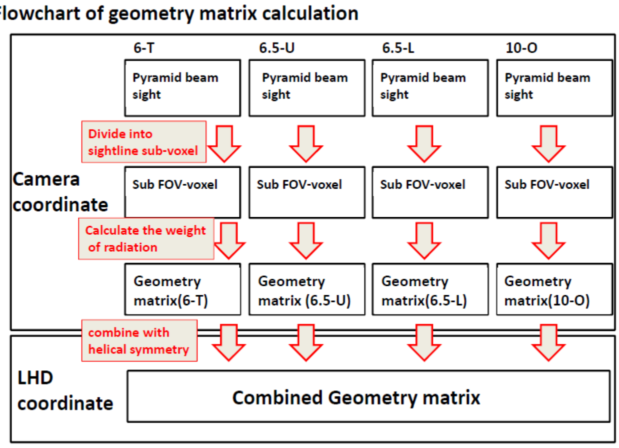

Fig. 2 Flowchart of geometry matrix calculation.

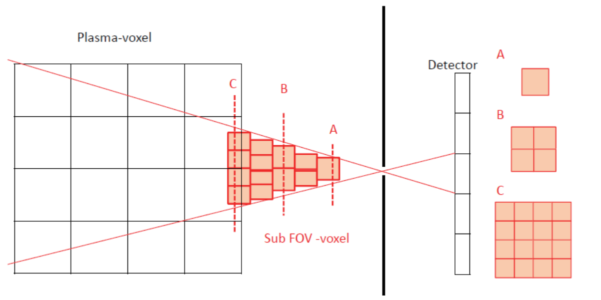

Fig. 3 Scheme for generating the sub FOV-voxel and calculating the weight of the radiation from the plasma-voxel on the detector. Red rectangle elements: sub FOV-voxel, red line: FOV of a detector, fh the plasma voxels.

than 1cm, the FOV-voxel is divided into sub FOV-voxels by four (2 × 2) in the directions perpendicular to the FOV direction. Figure 3 shows the sub FOV-voxel of a detector. As a geometry matrix calculation, the influence of each plasma-voxel on each detector was calculated using these sub FOV-voxels which are in the plasma-voxel, j, by the following equation.

$$h_{j,k} = \sum_{i=1} \frac{V_{i,j,k}\Omega_{i,j,k}}{4\pi}. \tag{2}$$

Where $h_{j,k}$ is the weight of the radiation from the kth plasma-voxel on the j-th detector, $V_{i,j,k}$ the volume of the sub FOV-voxel, $\Omega_{i,j,k}$ the solid angle of the detector with respect to the sub FOV-voxel, and i the index of the sub FOV-voxel. The geometry matrices have been calculated for the four installed IRVBs. The four geometry matrices have been combined in LHD coordinates with the assumption of helical symmetry.

The geometry matrix provides two pieces of information. One of these is the influence of each plasma-voxel on each detector of the four IRVBs as a projection matrix which can be used with the tomography technique. The other is the total number of non-visible plasma-voxels. In the geometry matrix,

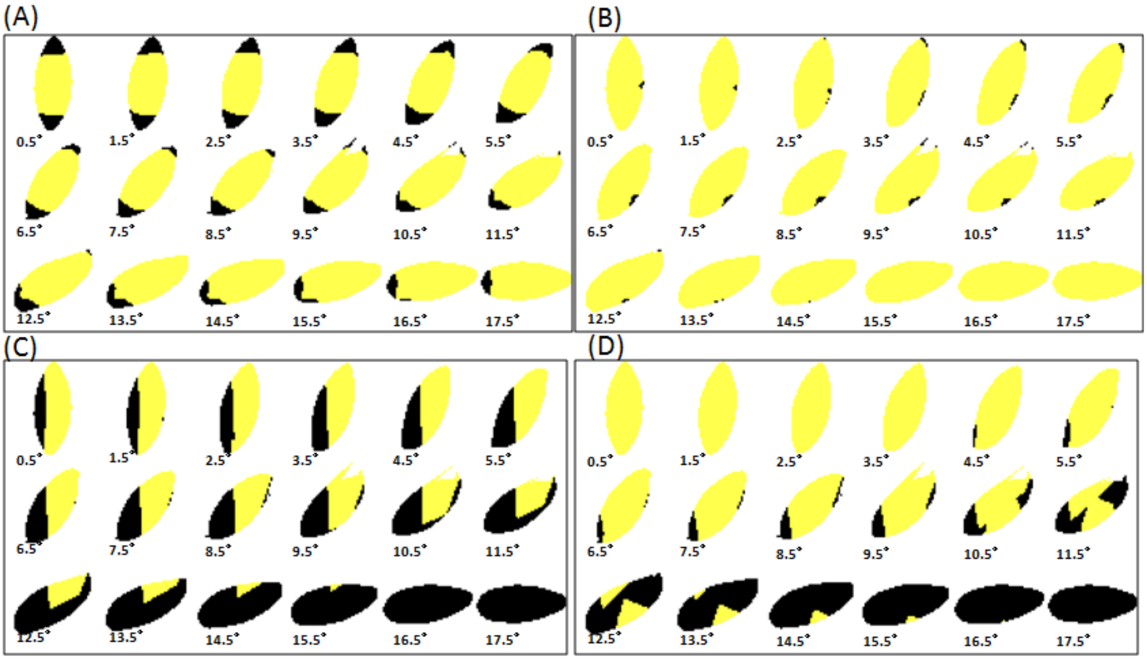

Fig. 4 Non-visible plasma-voxel (Black) and visible plasma-voxel (yellow) in the optimized fields of view at every one degrees of toroidal angle (0.5-17.5 degrees). (A): 6-T port, (B) 10-O port, (C) 6.5-U port, (D) 6.5-L port.

$$h_k = \sum_j h_{j,k} = 0, \quad (3)$$

indicates that the plasma-voxel could not be measured by any IRVBs.

The geometry matrices have been calculated changing the aperture positions. The aperture positions which provide the best fields of view are chosen to minimize the total number of non-visible plasma-voxels in the combined geometry matrix.

3. Results of Optimization

The optimized geometry matrices for four installed IRVBs were calculated. Figure 4 shows the total number of non-visible plasma-voxels in each geometry matrix at each one degree of toroidal angle. A mask of the radiation region which is obtained from the EMC3-EIRENE [7] code was applied. The geometry matrices have been combined with the assumption of helical symmetry. Figure 5 shows the total number of non-visible plasma-voxels in the combined geometry matrix as a result of the optimization. There were 169 non-visible plasma-voxels in the previous setting, this number has be decreased to 0 with optimized geometry matrices.

By this optimization, the three dimensional plasma radiation distributions will be reconstructed with higher accuracy.

4. Summary

The geometry matrix for each installed IRVB in LHD has been calculated as a projection matrix of the IRVB detector with respect to the plasma radiation region. The fields of view for the IRVBs have been optimized using the geometry matrix to measure all the plasma-voxels. The total number of non-visible plasma-voxels could be decreased to 0 from 169 by this optimization. All non-visible plasma-voxels were eliminated.

We plan to move the bolometer foil for the 6.5-U IRVB closer to the plasma to extend the field of view. The field of view for this setting will also eliminate all non-visible plasma-voxels. We expect to be able to apply the calculation and the optimization scheme to other devices and reconstruct more accurate 3D plasma radiation using the tomography technique through this field of view improvement.

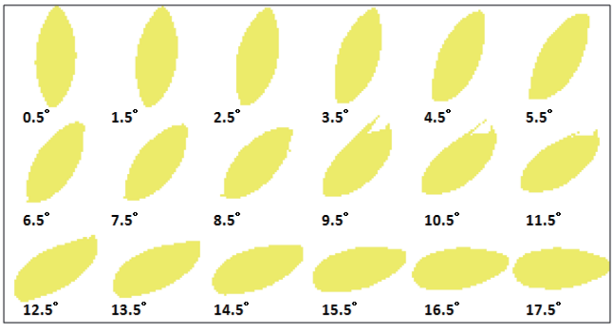

Fig. 5 Non-visible plasma-voxel (Black) and visible plasma-voxel (yellow) in the combined fields of view (after optimization) at every 1 toroidal degree (0.5-17.5 degree).

Acknowledgements

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