

Calculation of Geometry Matrices for IRVBs for Application to 3D Tomography of Radiative Phenomena in LHD^{*})

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InfraRed imaging Video Bolometers (IRVBs) can provide hundreds of channels of bolometric data forming an image of the plasma radiation [B.J. Peterson, Rev. Sci. Instrum. **71**, 3696 (2000)]. By calculating the geometry matrix (or response matrix) of the detector field of view (FoV) with respect to a predefined three dimensional (3D) plasma grid of plasma voxels these geometry matrices can be used for 3D tomography of the plasma radiation. This is done by assuming that the plasma reproduces itself every half field period. Then by combining the FOV of 3 IRVBs with different views of the plasma (top, tangential, semi-tangential), one large geometry matrix can be derived relating 1968 IRVB channels to 13,161 plasma voxels. Results indicate that FoVs should be modified or supplemented to view plasma voxels near the helical divertor xpoints of the diagonal cross-sections ($5^\circ < \phi < 13^\circ$) which are in the shadows of the helical coils.

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1. Introduction

Bolometry in magnetic fusion devices involves the measurement of the total radiated power loss from the plasma. In traditional tokamaks a two-dimensional (2D) approach usually has been taken by assuming axis-symmetry (radiation is independent of the toroidal angle, ϕ), and therefore 2D (major radial, R , and vertical, Z , dimensions) tomography was sufficient to describe the variation of radiation from the plasma. However, in helical devices in which the magnetic field is fully three-dimensional (3D) and also in recent tokamaks, which have applied a magnetic perturbation breaking the axis-symmetry, a 3D approach is called for. In the Large Helical Device (LHD) in particular the core plasma inside of the last closed flux surface may be responsive to a one dimensional (1D) treatment by assuming radiation is constant on a magnetic flux surface. However, in the natural ergodic edge region, which exists outside of the last closed flux surface in LHD, a fully three dimensional approach is necessary.

Ideally, for a correct tomographic inversion, each part of the target plasma volume should be viewed from every angle. This would necessitate an extreme number of detectors, while the number and direction of available sightlines is limited by the location of detectors and ports and other practical constraints. This problem can be remedied to some extent in two ways. The first is by the application

of Infrared Imaging Video Bolometers (IRVBs) [1] which greatly increases the number of channels available in an image of the plasma radiation. The second which applies to LHD and other helical devices is the assumption of periodic helical symmetry which mathematically can be expressed as

$$S(R, \phi, Z) = S(R, \pi/5 - \phi, -Z) \quad (1)$$

where S is the local radiated power density in W/m^3 , R is the major radial dimension, ϕ is the toroidal angle and Z is the vertical dimension. This implies that the radiation pattern repeats itself every half field period (18 degrees in LHD) and can be assumed including the ergodic region as long as no symmetry breaking sources are incurred such as magnetic islands or localized heating or fueling. This assumption effectively multiplies the number of sightlines by the number of half field periods through which each sightline passes and also switches the vertical direction of the sightline every other half field period.

In order to obtain S from the individual IRVB channel radiated power signals, P , the plasma volume must be divided up into volume elements, or voxels, and an equation relating P and S must be written as

$$P_i = \sum_j \frac{\Omega_{ij}}{4\pi} V_{ij} S_j = \sum_j T_{ij} S_j \quad (2)$$

where i is the channel index, j is the voxel index, Ω_{ij} is the solid angle of the i th detector from the j th voxel and V_{ij} is the intersecting volume of the field of view of the

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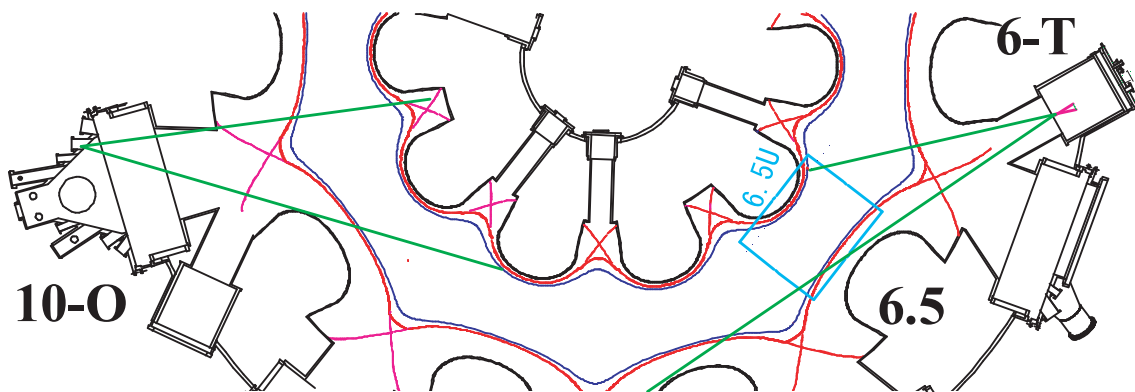


Fig. 1 Top view of LHD showing toroidal locations of IRVB FoVs (green for 6-T and 10-O and light blue for 6.5-U).

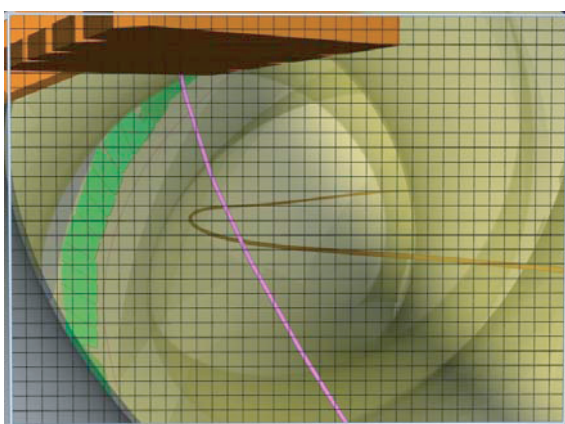


Fig. 2 Tangential FoV of IRVB at Port 6-T with 24×32 channels.

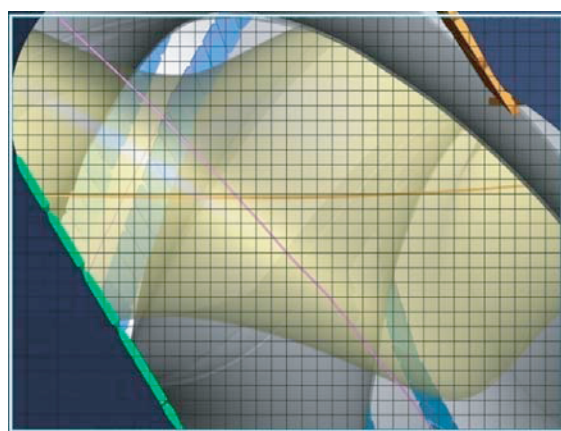


Fig. 3 Semi-tangential FoV of IRVB at Port 10-O with 24×32 channels.

i th detector with the j th plasma voxel. T_{ij} is the two dimensional geometry (or response) matrix which relates the detector signal to the local plasma radiation. By inverting this matrix and multiplying it by P_i one can obtain the local radiated power, S_j .

2. Imaging Bolometers on LHD

Three IRVBs are currently installed on LHD. One has a tangential view from Port 6-T, the second has a semi-toroidal view from Port 10-O [2] and the third has a top view from Port 6.5-U. The toroidal locations of the three imaging bolometers are shown in the top view of LHD in Fig. 1. The computer aided drawings (CAD) of the fields of view (FoVs) showing the individual channels are shown in Figs. 2-4. The total number of channels is 1968.

3. Definition of the Plasma Voxels and Calculation of the Geometry Matrices

The plasma is divided up into a 3D grid using cylindrical coordinates (R, ϕ, Z). The grid size in each dimension is $\Delta R = 5$ cm, $\Delta \phi = 1^\circ$ and $\Delta Z = 5$ cm. The extent of the

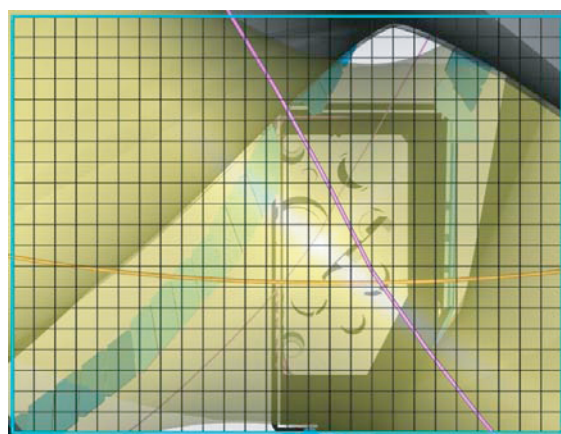


Fig. 4 Vertical FoV of IRVB at Port 6.5-U with 18×24 channels.

grid in each dimension is $2.5 \text{ m} < R < 5.0 \text{ m}$, $0^\circ < \phi < 18^\circ$ and $-1.3 \text{ m} < Z < 1.3 \text{ m}$. Therefore the number of grid elements is $50 \times 18 \times 52$, respectively for a total of 46,800 plasma grid elements. This includes the plasma core and ergodic edge region, but does not include the divertor leg region.

The calculation of the geometry matrix is then made in the following manner. First the toroidal extent of the geometry matrix is extended to be $0^\circ < \phi < 18^\circ$ to include all of the fields of view. In LHD ϕ is defined as 0° at the vertically elongated cross-section located at Port 10.5 and increases in the counter-clockwise direction as viewed from the top of the machine. Then a geometry matrix, T , is defined for each IRVB having 4 dimensions (i, R, ϕ, Z) where the R, ϕ, Z indices combine to make the j th voxel index in Eq. 2. Each channel's FoV is defined by the pyramid which has its apex at the center of the channel on the IRVB foil and the 4 legs of the pyramid are defined by the lines which start at the apex and pass through each of the four corners of the aperture. The aperture plates and detector foils are parallel to each other in the case of each IRVB. In order to integrate through the FoV, the calculation is incremented in 1 cm steps in the direction normal to the foil. Then the FoV is subdivided into 6 sided voxels defined by these planes parallel to the foil and the four legs of the FoV pyramid. As the FoV expands, moving further away from the aperture, the FoV is subdivided by subdividing the aperture to make sure that the largest dimension of each FoV subvoxel is less than 1 cm. This insures the accuracy of the geometry matrix calculation. The volume of the FoV subvoxel, V , is calculated and multiplied by the solid angle of the channel, Ω , divided by 4π to give the geometry matrix element, T_{sv} , for each subvoxel. Then the coordinates for each element are calculated and also the relative location of the first wall is determined. If the location of the FoV subvoxel is within the vacuum vessel (not

intersecting the first wall) then T_{sv} is added to the appropriate element of the geometry matrix, T , according to its location. If the location of the subvoxel has intersected the first wall then it is not added to T and the T_{sv} of all subsequent FoV subvoxels are also neglected. This is justified since the reflectivity of the stainless steel wall is negligible for UV and x-ray wavelengths which dominate the radiation in LHD [3]. This is repeated for each channel of each IRVB giving one geometry matrix for each IRVB.

Then by applying the symmetry of Eq. 1 the geometry matrices of the three IRVBs are combined and reduced to one half field period in one 4 dimensional geometry matrix which has the dimensions $1968 \times 50 \times 18 \times 52$. Using the results of the EMC3-Eireine code [4, 5] to predict the 3D radiation distribution those plasma voxels at the edge which have zero radiated power are eliminated from the geometry matrix. This reduces the number of plasma voxels from 46,800 to 13,161.

4. Number of IRVB Channels Viewing Each Plasma Voxel and Discussion

In Fig. 5 the number of channels viewing each plasma voxel is shown for each toroidal angle. The maximum number of channels viewing each plasma voxel is 113 and the minimum is 0. Plasma voxels on the edge which are predicted by the EMC3-EIRENE code to have zero radiation are shown in white. The total number of channels per plasma voxel is 575,975. In Fig. 6, in order to show

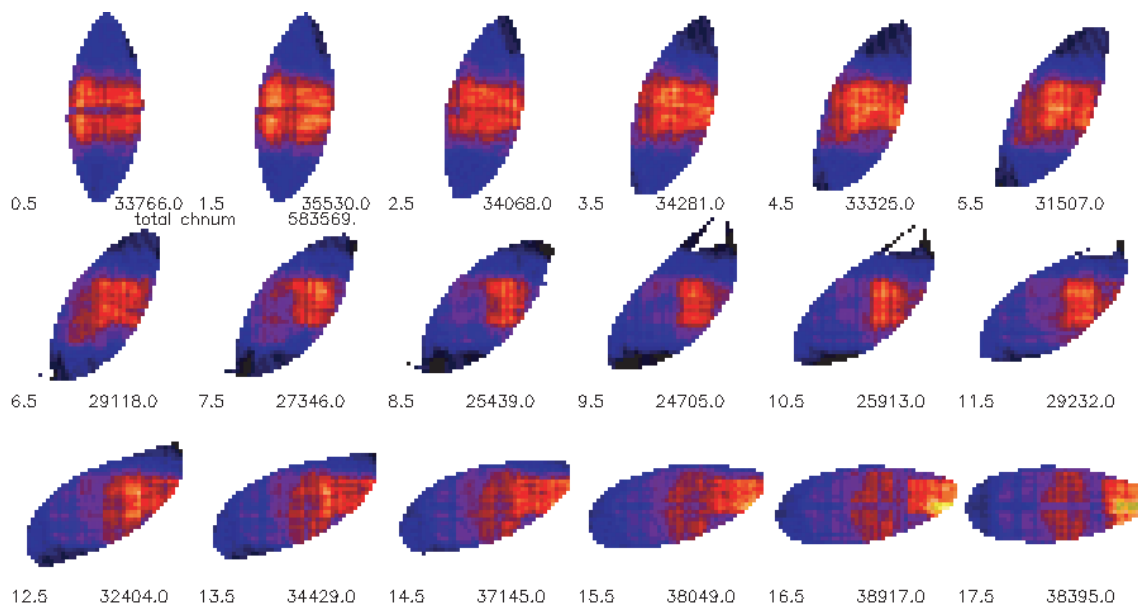


Fig. 5 Total number of IRVB channels viewing each plasma voxel. Each of the 18 subfigures shows the 50 (horizontal - R) \times 52 (vertical - Z) grid cross-section at one toroidal angle, which is indicated in the lower left hand corner of each subfigure. The color code has a minimum of 0 (black) and a maximum of 113 (green). The summation of the number of IRVB channels viewing each plasma voxel over the entire cross-section is given in the lower right corner of each subfigure. Plasma Voxels where the EMC3-EIRENE code predicts zero plasma radiation are indicated in white.

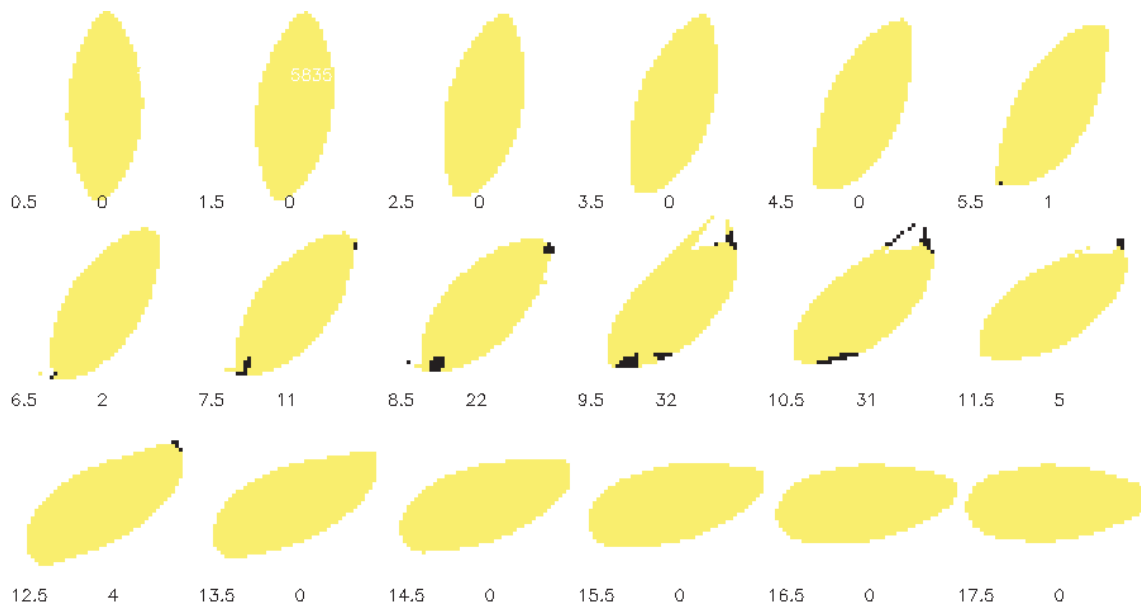


Fig. 6 The number of IRVB channels viewing each plasma voxel. Each of the 18 subfigures shows the 50 (horizontal - R) \times 52 (vertical - Z) grid cross-section at one toroidal angle, which is indicated in the lower left hand corner of each subfigure. The color code is zero IRVB channels (black) and one or more IRVB channels (yellow). The number of plasma voxels which are viewed by zero IRVB channels in each cross-section is given in the lower right corner of each subfigure. Plasma Voxels where the EMC3-EIRENE code predicts zero plasma radiation are indicated in white.

more clearly which plasma voxels are not viewed by any of the IRVBs, those voxels are shown in black while plasma voxels that are viewed by one or more IRVB channels are shown in yellow and those predicted by the EMC3-EIRENE code to have zero radiation are shown in white.

Black pixels in the diagonal crosssections $5^\circ < \phi < 13^\circ$ of Fig. 6 indicate that some plasma voxels near the helical divertor x-points are not seen by the IRVBs due to shadowing by the helical coils. This should be corrected by modifying existing IRVB FoVs or adding IRVBs to cover these areas of the plasma. For example by tilting the field of view of the IRVB at 6.5-U to look more in the tangential direction and moving the foil and pinhole closer to the plasma these shadowed regions should be visible. Also

the addition of an IRVB at an outer port should help to see these shadowed regions. Detailed work in optimizing these fields of view using the tools described in this paper is left to the future.

Acknowledgement

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