Development of Imaging Bolometers for 3-D Tomography of Radiation from LHD

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Imaging bolometers are a powerful tool for diagnosing plasma radiation in a reactor relevant environment. In a tokamak, an imaging bolometer with a tangential view has demonstrated the ability to provide two-dimensional poloidal profiles of radiation through tomographic inversion under the assumption of toroidal symmetry. In helical devices the imaging bolometers have shown their usefulness in the interpretation of 3-dimensionl radiation structures. In the Large Helical Device, modeling of transport in the stochasitic edge region predicts a very three-dimensional structure in the flow velocities and in the associated accumulation of carbon impurity ions. In this paper we make a proposal for the diagnosis of these three-dimensional radiation structures. This is to be done through the measurement of the radiation using multiple imaging bolometers and the tomographic inversion of their signals to produce a three-dimensional image of the plasma radiation for comparison with the three-dimensional structure of the carbon radiation from the transport model. We present and discuss the recent results of this ongoing research including imaging bolometer development, possible symmetry assumptions and prospective research targets.

Keywords: bolometer, imaging, three dimensional, tomography, helical, infrared

1. Inroduction

Bolometers play an important role in fusion devices in the diagnosis of radiative losses from the plasma [1]. The conventional bolometer detector is a gold or platinum resistive bolometer which consists of a thin radiation absorbing foil backed by an insulating layer of either kapton or mica which is in turn backed by a resistive grid of the same material as the absorbing layer [2]. The change in temperature of the foil due to the absorption of radiation is sensed by the change in the resistance of the grid as it heats up.

These resistive bolometers have several drawbacks, especially regarding application to a radiation rich, steady state fusion reactor including: signal drift, restrictions on absorber thickness, the risk of numerous wire vacuum feedthroughs, radiation induced electronic noise and the lack of neutron resistant materials. Therefore, research and development has been carried out on an alternative detector known as the InfraRed imaging Video Bolometer (IRVB) which addresses these concerns through the application of infrared technology to measure the temperature of a thin absorber foil [3,4].

The use of infrared imaging of the absorber foil advances bolometer diagnostics from the conventional one dimensional arrays of resistive bolometers to two dimensional images of the plasma radiation from imaging bolometers. These imaging bolometers have been used in LHD to investigate radiative phenomena [5] and a single imaging bolometer on the JT-60U tokamak has provided two-dimensional radiation profiles through tomographic inversion under the assumption of toroidal symmetry [6].

Helical devices differ from tokamaks in their three dimensional nature, compared to the two dimensional

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nature of tokamaks resulting from their toroidal symmetry. Therefore, while a single imaging bolometer can provide the two dimensional (minor radial and poloidal) radiation profiles needed to fully diagnose the radiation from a tokamak plasma, in helical devices multiple imaging bolometers can be used to perform the three dimensional tomography necessary to fully diagnose the radiation. This is analagous to multiple one dimensional arrays of resistive bolometers being used to perform two-dimensional tomography in a tokamak. In this paper we discuss preparations for such three dimensional tomography of radiation on the Large Helical Device (LHD), including imaging bolometer development on LHD, symmetry assumptions and prospective subjects of research.

2. Imaging bolometer development on LHD

In addition to IR camera development by industry, imaging bolometer detectors are advancing through our research into absorbing foil materials, suitable IR optics, camera shielding materials and calibration techniques. This work has been summarized recently [7,8]. A typical IRVB system consists of a foil mounted in a frame in a pinhole camera in the vacuum vessel, a vacuum IR window an IR optical system consisting of lenses and mirrors and the IR camera. In LHD two types of cameras are currently being used. The first is an FLIR SC500 long wave (7.5 - 13 μm) camera with 320 x 240 pixels and a frame rate of 60 Hz. The second is an Indigo Phoenix mid wave (3 - 5 μm) camera with 320 x 256 pixels and a frame rate of 345 Hz. Foils have been installed at four locations in LHD as shown in Figure 1. Currently an SC500 camera is operating at the 6.5-U port IRVB and a Phoenix camera is operating on the 6-T port IRVB. We plan to install another SC500 camera at port 1-O in the next year. In the future we plan to move another Phoenix camera from JT-60U to LHD port 6.5-L in time for the DD experiments planned for LHD. This system includes a neutron/gamma/magnetic shield, a 3.7 meter IR periscope with 4 CaF_2 lenses, an Al mirror and a sapphire vacuum window with a 5 micron thick Ta foil and is shown in Figure 2. The other foils installed on LHD are 1 micron Au or Al. Other possible IRVB installations would include moving the SC500 camera from 6.5-U port to the 8-O port and replacing it with an Omega IR camera with a periscope. Another possible installation would be with a second Omega IR camera at the 8-I port. This would give a total of 6 IRVBs with over 1000 channels. Except for the IRVB moved from JT-60U to Port 6.5-L, all the other IR cameras would need to have shielding against neutrons and gammas added before the first DD campaign on LHD.

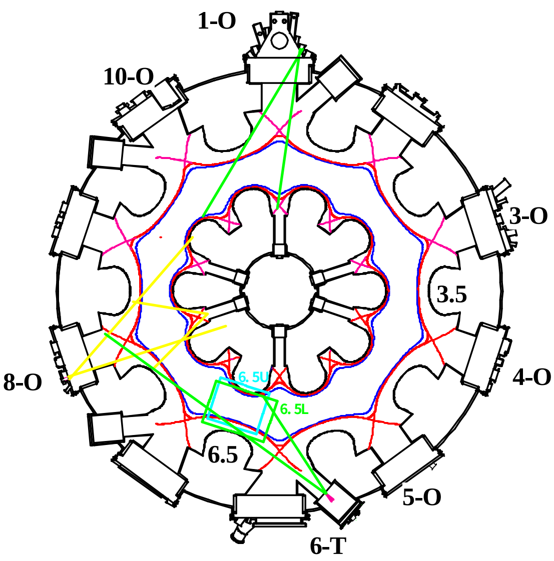

Fig.1 Top view of LHD vacuum vessel (black) showing existing (cyan and green) and prospective (yellow) IRVB foils.

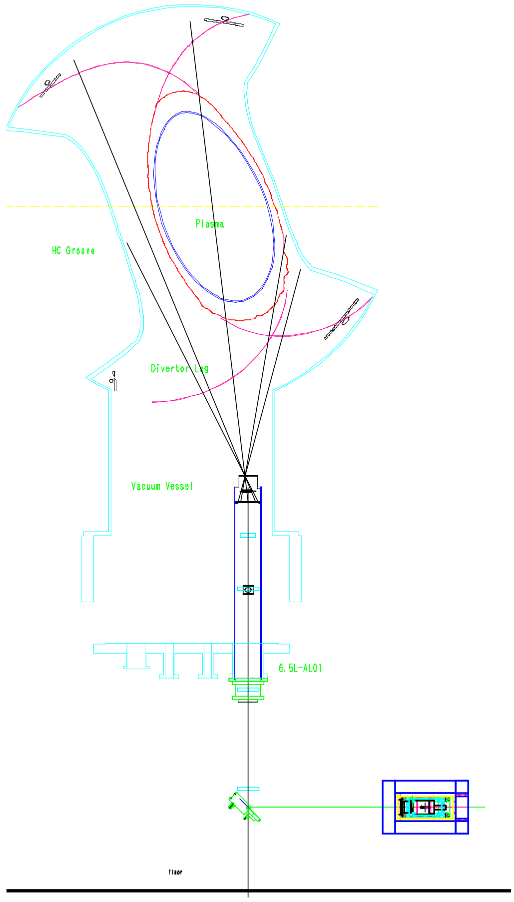

Fig.2 Side view of LHD Port 6.5-L showing position of foil, lenses, vacuum window, mirror, and IR camera in shield.

3. Plans for three dimensional tomography on LHD

In general, in order to carry out computed tomography the target volume is divided into cells with the centers of each cell representing the points at which one would like to know the measured quantity. The number and spacing of the cells determine the spatial resolution. In general for a well defined solution to the tomographic inversion the number of cells should not exceed the number of channels and each cell should be viewed by as many detectors from as many angles as possible. In order to reduce the number of unique cells and/or improve the spatial resolution certain assumptions regarding symmetry can be invoked. For instance in a tokamak by assuming toroidal symmetry, one of three spatial dimensions can be ignored greatly simplifying the problem.

In the same way in a helical device several different assumptions may be made to reduce the number of unique cells and simplify the tomographic inversion. For example let us start by dividing each half field period (18 degrees toroidally) into 10 radial sectors (8 inside the last closed flux surface (LCFS) and 2 in the ergodic region), 6 toroidal sectors and 8 poloidal sectors for a total of 480 cells/ half field period or 9600 cells throughout the entire toroidal volume. Since we do not have enough IRVBs to see every part of the plasma, we must make symmetry assumptions to reduce this number of cells.

The first assumption that can be made is what is called helical symmetry. If zero toroidal angle is defined to be at either the horizontally or the vertically elongated crossection, then this can be expressed as $S(r, \theta, \phi) = S(r, -\theta, -\phi)$ in toroidal coordinates minor radius, r, poloidal angle, θ, and toroidal angle, ϕ, where S is the local plasma emissivity. This essentially means that the plasma reproduces itself every half field period or 18 degrees toroidally in LHD. This reduces the number of unique cells to 480 in the previously given example.

Another assumption which is less strict is called toroidally periodic symmetry. This can be expressed as $S(r, \theta, \phi) = S(r, \theta, \phi+2\pi/m)$, where m is the number of toroidal field periods, or 10 in the case of LHD. This means that the plasma reproduces itself every field period or 36 degrees toroidally in LHD. This would result in 960 unique cells in our example.

Another much more simplifying assumption is called flux surface symmetry which requires that the radiation is constant on the flux surface. In the region of well formed flux surfaces inside the LCFS this removes the two coordinates of poloidal and toroidal angle from consideration, leaving only the minor radius. In our example this would reduce the number of cells inside the LCFS to 8 from 384, while the ergodic region where such symmetry can usually not be assumed would be divided into 96 or 192 depending on if helical symmetry or toroidally periodic symmetry where chosen, respectively. The choice of which of these symmetries to assume depends on the characteristics of the phenomena to be studied as is discussed next.

4. Physical targets of three dimensional tomography in LHD

Several phenomena which have appeared in LHD present excellent subjects for the application of three-dimensional tomography. The first of these is asymmetric radiative collapse, which occurs at the radiative density limit in LHD [9]. This has been observed by two IRVBs and diode arrays at two toroidal locations to be roughly toroidally symmetric. With three-dimensional tomography the degree of toroidal symmetry could be evaluated and the evolution of this phenomena's three-dimensional structure could be studied in detail. In this case toroidally periodic symmetry would be the appropriate assumption since the toroidal symmetry breaks the helical symmetry and the asymmetry is observed inside the LCFS.

A second interesting phenomena is the change in radiation structure predicted by the EMC3/EIRENE edge transport code in the ergodic region as the density increases. In the horizontally elongated cross-sections shown in Figure 3, the carbon radiation is localized polodally and radially at the inboard x-point at low density and moves inward towards the LCFS as density increases. With three-dimensional tomography this structure and its density dependence could be experimentally confirmed. The appropriate symmetry assumption for this study would be helical symmetry in the ergodic edge and flux surface symmetry inside the LCFS.

A third phenomenon of interest might be the serpens mode that has been observed under partially detached plasmas in LHD. This phenomenon has been described as a rotating belt of cold dense radiating plasma beneath the LCFS [10]. Since it rotates poloidally and toroidally none of the assumptions above may be applicable, but by observation with the multiple imaging bolometers this rotation could be observed in detail and confirmed.

4. Summary

Developemnt of imaging bolometers for LHD has been reviewed with a view towards the development of three-dimensional tomography of radiation. The present status of imaging bolometers on LHD and future plans have been presented. Possible simplifying symmetry assumptions have been reviewed and explained. Prospective subjects of study for three-dimensioanal tomography have been presented from phenomena previously observed on LHD. However, much work remains in order to realize this plan.

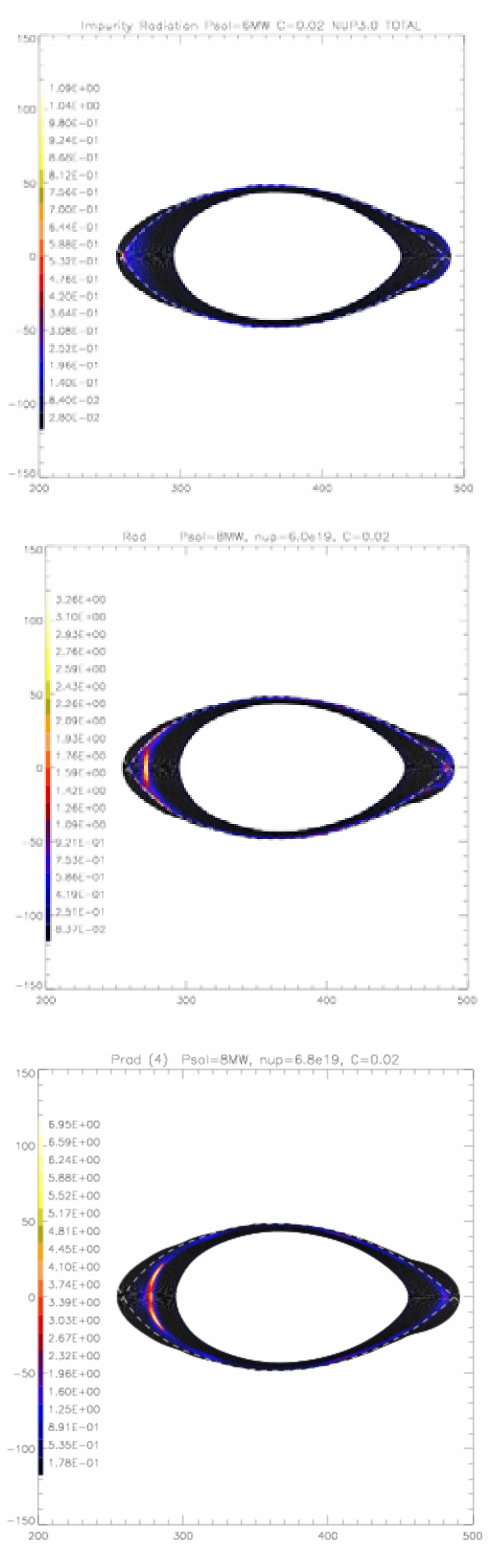

Fig.3 Two-dimesional profiles of carbon radiation intensity from the ergoic edge of LHD calculated by the EMC3/EIRENE code for n_{LCFS} = (a) 3 x $10^{19}/m^3$, (b) 6 x $10^{19}/m^3$ and (c) 6.8 x $10^{19}/m^3$.

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