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Bolometric images of the three-dimensional structure of asymmetric radiative collapse in LHD

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Abstract

The infrared (IR) imaging bolometer has the merit of being able to measure wide two-dimensional images of the plasma radiation. Two IR imaging video bolometers (IRVB, one type of IR imaging bolometer system) were installed on the large helical device (LHD). Using these IRVBs, the asymmetric radiation collapse that is similar to the multifaceted asymmetric radiation from the edge was measured in LHD. From the results of the asymmetric collapse study in LHD, the high radiation region is localized on the inboard side and under the midplane on the vacuum vessel, but this region is not the nearest point from the plasma to the first wall. From other reports on LHD, it is written that the wall recycling is not a trigger for the asymmetric radiation onset, which is confirmed by this new result.

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Keywords: Radiation collapse; MARFE; Wall recycling

1. Introduction

Multifaceted radiation from the edge (MARFE) that involves a strong radiation region at the inboard side with a high density and a low temperature has been observed in many tokamaks. Typical characteristics were shown by the results of many devices [1–5]. These characteristics are described in Ref. [2] as follows; (1) a toroidally symmetric, poloidally localized, strongly radiating region, (2) high electron density, and low electron temperature in the MARFE and (3) a thermal instability in a high radiation region. The location of the strong radiation tube with the MARFE is inside the last closed flux surface, around the horizontal minor radius of $\rho = 0.5$–0.8.

In helical devices, an asymmetric radiation collapse similar to the MARFE has already been observed in the large helical device (LHD) [6–8]. This type of asymmetric radiation structure is commonly observed when the plasma reaches the density limit in LHD. Previous observations of this phenomenon using various diagnostics at different toroidal cross-sections have indicated that it may be axisymmetric as in a tokamak, but the actual structure of LHD has a non-axisymmetric magnetic field and vacuum vessel. Fig. 1(a) shows the computer aided drawing (CAD) of the midplane of two LHD field periods. Due to the two helical coils, the plasma shape rotates through 10 field periods in the full torus as shown in Fig. 1(a). In LHD, the behavior of the asymmetric radiation collapse previously was observed by resistive bolometers [6] only at two toroidal angles, at the vertically elongated cross-section and at the horizontally elongated cross-section. Therefore, the continuous toroidal structure of the collapse in the LHD plasma was not understood. For example, at the vertically elongated cross-section inboard asymmetries in density and radiated power have been observed that are similar to the results in tokamaks. At the horizontally elongated cross-section an up/down symmetric radiation

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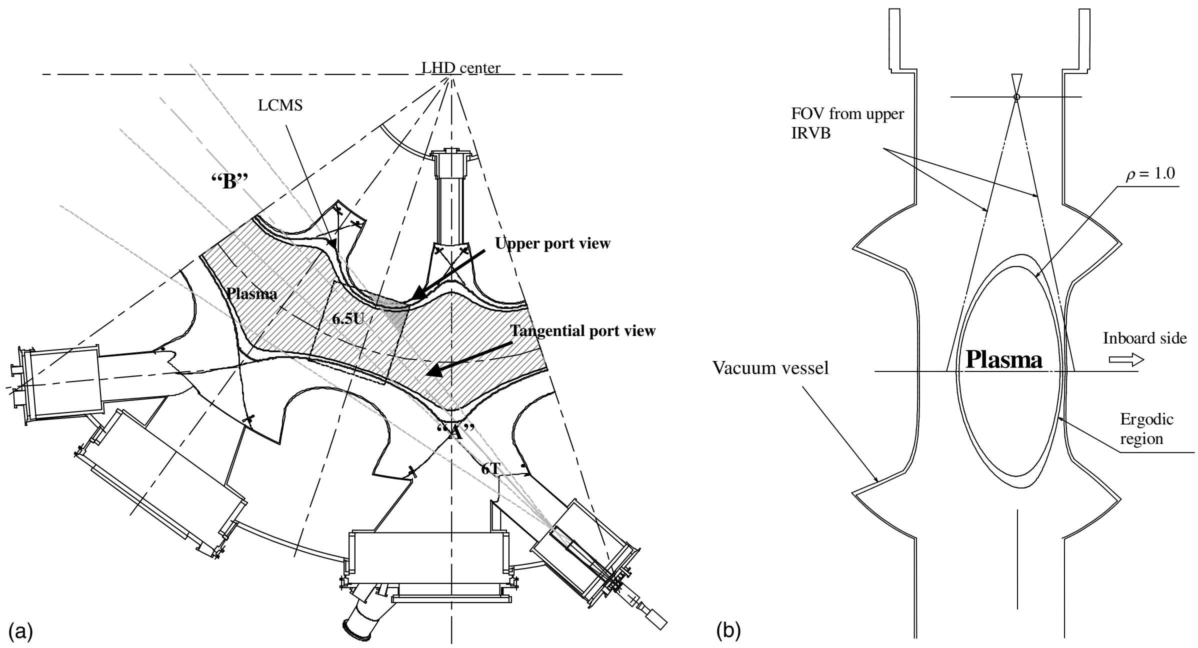

Fig. 1. (a) Each field of view on the midplane of two IRVBs on LHD. The upper port IRVB is installed around a vertically elongated cross-section and is shown as a square. The tangential one covers most of the FOV of the upper port. (b) The CAD of the vertically elongated cross-section on LHD. One of the channel rows from the upper IRVB observes this cross-section.

profile has been observed and an asymmetric temperature profile with lower temperature on the inboard side indicating stronger radiation on the inboard side has been seen.

However, experimental measurements of the plasma radiation for the full toroidal extent on LHD have not been made, since such measurement is difficult using only the existing diagnostics such as resistive bolometers. In this paper, the radiation structure is presented during asymmetric collapse as measured using two infrared (IR) imaging bolometers with wide fields of view (FOV).

2. Setup

The LHD is a large-scale superconducting heliotron system with a set of $l/m = 2/10$ helical coils. Since the first experimental campaign in 1998 it has been operated with $R/a = 3.6$–$3.9/0.6$ m, $B_t = 1.5$–2.9 T. Electron cyclotron heating is used for the plasma production and two or three negative-ion-based neutral beam injectors (NBI) are used to heat the plasma. For the diagnosis of the total plasma radiation, several bolometry systems are used. Resistive bolometers [9] are the main diagnostics for measuring the plasma radiation in LHD and IR imaging bolometers [10,11] and absolute extreme ultraviolet diode detectors [12] also are used.

The IR imaging bolometer is a two-dimensional diagnostic system for measuring the plasma radiation. The plasma radiation is absorbed by a metal foil in the vacuum vessel and the resulting temperature rise on the foil is measured by an IR camera from outside the vacuum vessel. For the metal foil, gold of 1 μm thickness is used and this foil was sandwiched by two identical copper mask frames. In particular, the type using a large foil area facing the plasma is called the IR imaging video bolometer (IRVB) [10,11]. Two IRVBs were installed in LHD for the LHD fifth campaign (2001–2002). One observed the plasma tangentially and the other from an upper port. Fig. 1 shows the FOV at the LHD midplane of each IRVB. The FOV of the upper IRVB (shown as a square) is almost covered by the FOV of the tangential IRVB. Only a triangular shaped region on the right side of the FOV of the upper IRVB is not covered by the FOV of the tangential IRVB. The resistive bolometers view the plasma from the lower port and their FOV is the same as that of the center row of channels of the upper IRVB, which is near the vertically elongated cross-section shown in Fig. 1(b).

For each IRVB system, the foil area is divided up numerically into a grid of bolometer channels. The tangential IRVB has 17 (horizontal) $\times$ 12 (vertical) bolometer channels. In a similar way, the upper IRVB is divided into 9 (horizontal) $\times$ 9 (vertical) bolometer channels. The frame rates of both IRVB systems are different since they depend on the frame rates of the IR cameras, i.e., the tangential IRVB with 15 Hz and the upper IRVB with 60 Hz.

With the development of the IRVB in LHD, many spatial channels were installed around the vertically elongated cross-section. Using the line of sight of each channel from the tangential IRVB and the upper port IRVB, the three-dimensional position of the radiation source in the LHD plasma could be determined.

3. Experimental results

Fig. 2 shows a discharge summary for LHD shot #28961. Two neutral beams were injected during the interval 0.30–2.30 s and the electron density was increased by hydrogen gas puffing as shown in Fig. 2(b). After 2.0 s a thermal instability develops leading to a sharp drop in the stored energy (Fig. 2(a)) and rapid increases in the total radiated power (Fig. 2(b)) and spectroscopic signals from CIII to OV (Fig. 2(d)) leading to the plasma termination at about 2.10 s by radiative collapse.

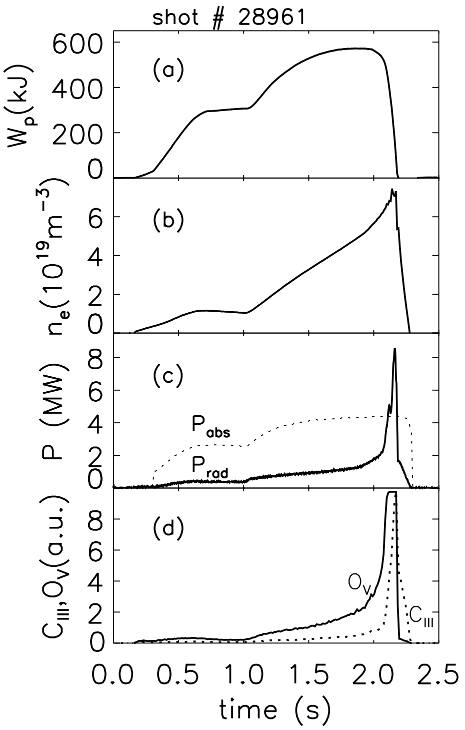

Fig. 2. Discharge summary for LHD shot #28961 with (a) stored energy from diamagnetic measurements and NBI (#2 and #3) timing, (b) line-averaged electron density, (c) total plasma radiated power from resistive bolometers and (d) spectroscopic signals from CIII to OV.

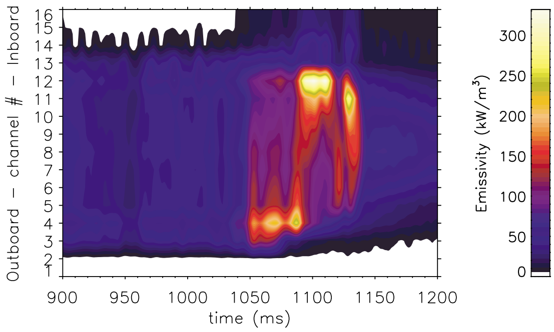

Fig. 3. The contour plot of the radiation emissivity profiles from the 6.5 lower port arrays. At 2.16 s, the strong radiation was located at the inboard side.

Fig. 3 shows the contour plot of the radiative emissivity during the period 1.6–2.2 s as a function of ρ using data from the two arrays of resistive bolometers at the vertically elongated cross-section from the lower port. Loading more closely at the radiative collapse, the radiative power rises up with increasing line-averaged electron density as shown in Fig. 2, after 2.1 s strong radiation appeared on the inboard side ($\rho = -1.0$) and soon thereafter the total radiation and the electron density decreased. Using the resistive bolometer data, the timing of the highest radiated power is taken as 2.16 s. In order to take advantage of the three-dimensional radiation diagnostic system, this discharge was observed by two IRVBs.

Fig. 4(a) and (b) show the tracings of magnetic field lines launched at the last closed magnetic surface ($\rho = 1.0$). Each blue point indicates a magnetic field line and shown in the boxes are the FOVs of the IRVBs from the tangential port (Fig. 4(a)) and from the upper port (Fig. 4(b)). The structures shown are similar to those of a hollow profile of the plasma radiation, these images of the IRVBs are shown in Fig. 4(c) from the tangential port and (d) from the upper port at 2.00 s when the radiation profile is hollow and symmetric as seen in the resistive bolometer data in Fig. 3. Fig. 4(e) and (f) shows the images of the IRVB during the radiation collapse at 2.16 s that are measured from the tangential port (e) and from the upper port (f). The units of intensity are arbitrary due to the lack of an absolute calibration, and therefore only relative signal levels for the same system, i.e., between (c) and (e), and between (d) and (f), can be compared. Before the radiation collapse, hollow profiles are measured by various bolometers, the results of the resistive bolometers are shown in Fig. 3. Images of the tangential and upper IRVBs at 2.09 s are shown in Fig. 4(c), (d), respectively. For a typical hollow radiation power profile, the image of the tangential IRVB shows the helical structure as shown in Fig. 4(c). This radiation is from the thick ergodic region which surrounds the

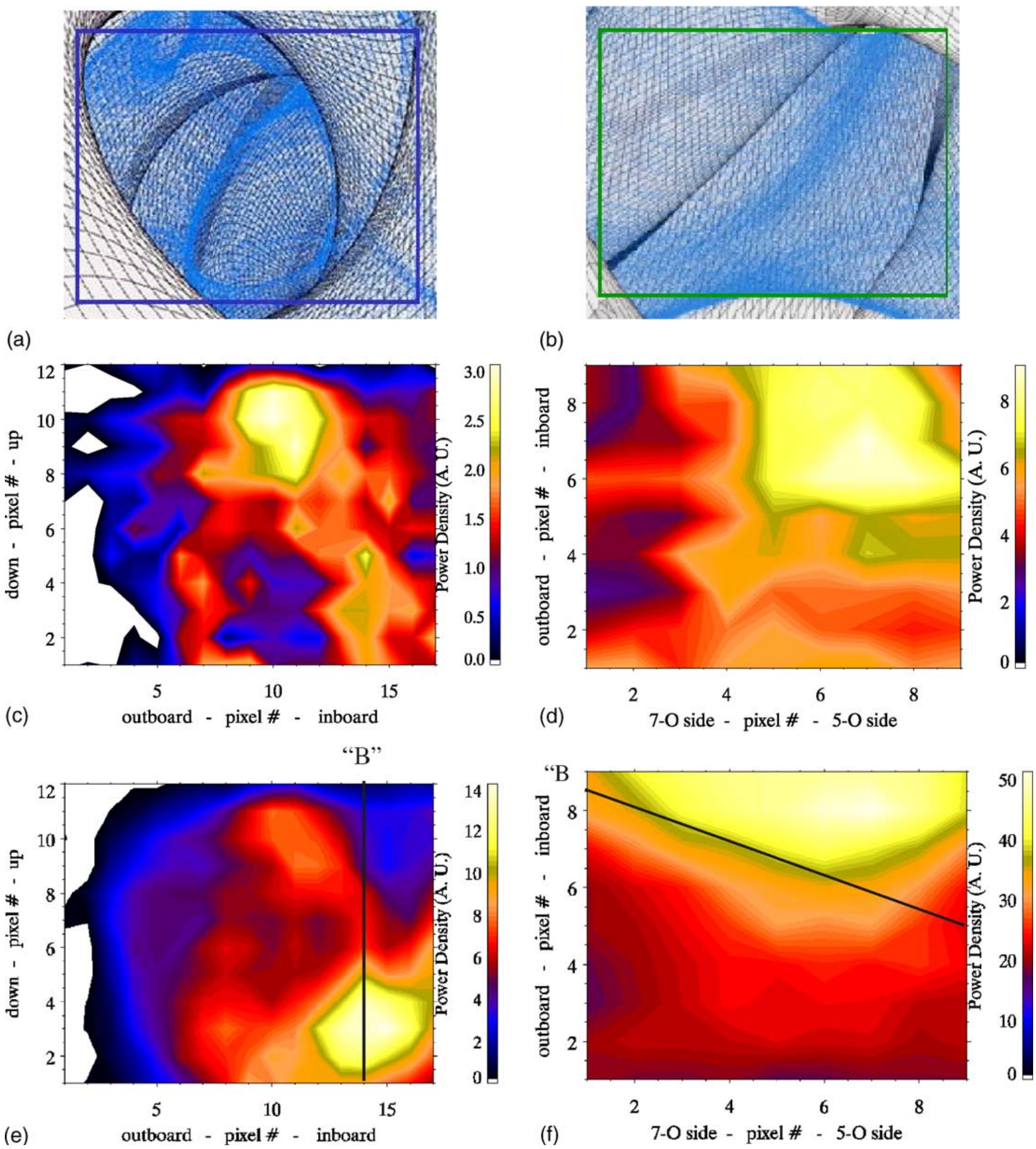

Fig. 4. (a, b) Each blue point indicates a magnetic field line launched in the region around the last closed magnetic surface ($\rho = 1$). The FOVs are shown as boxes. (c–f) Images of the IRVB before the radiation collapse and during the collapse. The relationship of each frame is that (c) and (d), (e) and (f) are at the same timing. (a), (c) and (e) are from the tangential port. (b), (d) and (f) are from the upper port with the upper side showing the inboard side on LHD.

LCMS. At the same time the image from the upper IRVB shows a widely high radiating region in Fig. 4(d). When the electron density approaches the density limit by gas puffing, the total radiation power suddenly rises up, and finally the plasma collapses. This phenomenon of the radiation collapse was observed during a time period of only 0.1–0.2 s. At this time of the peak radiation, the image of the tangential IRVB was measured as shown in Fig. 4(e). This type of result already has been reported in Ref. [6], with the data of the resistive bolometers and the CAD data.

From these data the high radiation region in the lower right side in Fig. 4(e) was estimated as the localized high radiation region. In this shot, #28961, the other IRVB from the upper port was working, and its image as shown in Fig. 4(f) was measured at just the same time as the collapse at 2.16 s. In this figure, the upper side is the inboard side on LHD, at which the strong radiation region was localized. The highest radiation level shown by yellow is about 50, which is 10 times higher than the peak level in Fig. 4(d). The area of the FOV on the midplane from the upper port is about 1.1 m $\times$ 1.1 m which is about a half field period of the LHD plasma (toroidal angle is 18°). Inside this FOV, the high radiation region at the inboard side is continuous. Basically the image of the upper IRVB during the hollow profile period shows an inboard-dominated asymmetry as shown in Fig. 4(d) due to the helical structure, which can be seen to some extent in the corresponding magnetic field plot in Fig. 4(b). On the other hand, the frame in Fig. 4(f) during the asymmetric phase shows a six times stronger signal along the inboard edge. For the tangential IRVB, the FOV of the cross-section of the vertical column of channels containing the channel with the strongest radiation is shown in Fig. 5, which corresponds to the line 'B' drawn in Figs. 1 and 4(e) and (f). Considering the result from the upper IRVB, the strong radiation region was estimated to be near the inboard area of the tangential FOV.

Considering the tangential IRVB, the channel with the strongest radiation is shown with hatching on Fig. 5. The portion of this sight line that passes through the FOV of the upper IRVB is located under the horizontal midplane. This cross-section corresponds roughly to the bright inboard region of the top viewing IRVB shown in Fig. 4(f).

We cannot exclude (based on the imaging bolometer data) the possibility that the radiation peak is coming from the near field region of the tangential IRVB system indicated by the letter 'A' in Figs. 1 and 5. But since the electron temperature profiles show a lower temperature on the inboard side at the horizontally elongated cross-section (which corresponds to the toroidal location of letter 'A') during similar discharges, the high radiation region is thought to be on the inboard side at this toroidal location also. Information about the vertical position of the localized radiation at the vertically elongated cross-section is not possible from the data of the resistive bolometer arrays therefore these IRVB images provide new information in this paper.

4. Discussion and summary

For the plasma discharge in LHD shot #28961 in 2001, the asymmetric radiation collapse was observed. In this discharge, the LHD plasma during the radiation collapse is seen to have a strong radiation source at the inboard side and this radiation source region extends widely along the toroidal direction of the vertically elongated cross-section at the inboard side. Using two IRVBs this position is identified as under the midplane along the inboard side around the vertically elongated

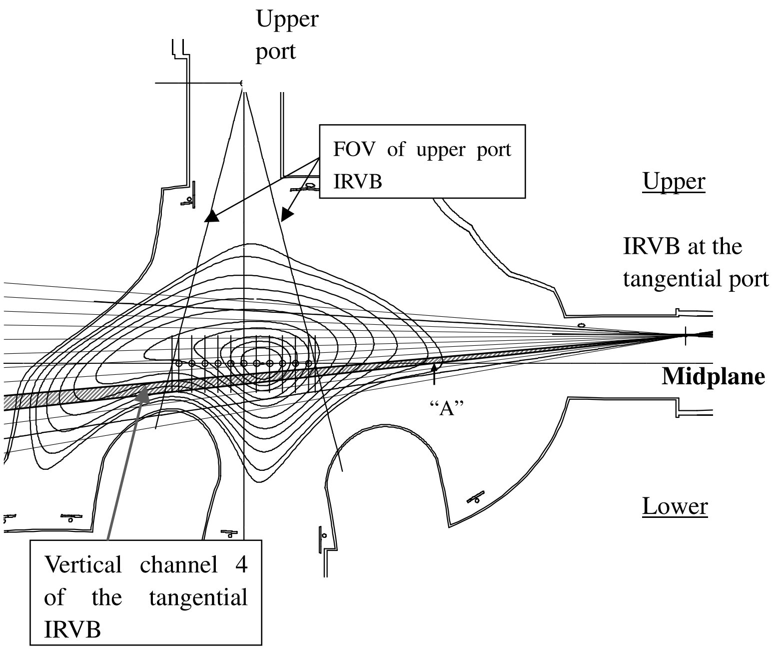

Fig. 5. The vertical cross-section of the tangential IRVB FOV at the cross-section of the vertical channel column containing the channel with the strongest radiation on LHD. This cross-section corresponds to line 'B' in Figs. 1 and 4(e) and (f). The channel with the highest radiation is shown by hatching and the portion of this sight line that passes through the FOV of the upper IRVB is located under the horizontal midplane.

cross-section. This information could not be measured by the other types of bolometers, and is new information from the IR bolometer system.

Some characteristics of this phenomenon, with the localized high radiation region at the inboard side of the radial cross-section, extending widely along the toroidal direction, are similar to those of MARFE in tokamaks. MARFE was observed near the electron density limit of the plasma, leading to disruption in tokamaks. Asymmetric radiation collapse in LHD also occurs in a similar density region near the density limit. Therefore comparison of MARFE in tokamaks to asymmetric radiation collapse in LHD can lead to a better understanding of the processes of both phenomena.

This position was not the nearest point from the plasma to the first wall. In addition, the high radiation region extended widely in the toroidal direction. Regarding the effect of wall recycling on the asymmetric collapse, it was reported that this is not a trigger to the asymmetry onset, but may be contributing to the acceleration of the phenomenon [7]. The new result about the position of the asymmetric radiation is consistent with this interpretation that recycling is a non-trigger for the onset of the asymmetric phase.

Regarding the effect of the magnetic geometry, the localized radiation appeared only at one side of the midplane, at the mirror position with respect to the midplane, at the upper side having the same length from the plasma to the first wall, this high radiation was not measured. In addition, the effect of magnetic geometry on MARFE in tokamaks has been recently proposed theoretically [4] which considered the poloidal variation of the distance between neighboring magnetic surfaces, but at present this has not been considered in LHD. We should closely investigate the differences between MARFE in tokamaks and asymmetric radiative collapse in LHD, especially taking into account the differences in the magnetic geometries. Therefore in the future we plan to investigate asymmetric radiative collapse in LHD under a variety of magnetic geometries. In addition, the study of the radiation behavior in the edge plasma with plasma wall interaction is important, and the IRVB system has been shown to be a useful diagnostic in these studies also [13].

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