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Observation of Highly Asymmetric Radiative Collapse of NBI Heated Plasma in LHD

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Abstract

During discharges in the Large Helical Device (LHD), the plasma radiated power has been measured by several bolometry systems mounted on different ports of the machine. The spatial structure of the radiation during the period prior to the termination of Neutral Beam Injected (NBI) heated plasmas was also investigated using multi-channel bolometric diagnostics. During discharges with strongly radiative collapse (RC) a highly asymmetric radiation profile which is stronger on the inboard side was observed beginning about 50 ms prior to the quench of the plasma. This asymmetry is spatially and temporally well correlated with the degradation of signal from the multi-chord interferometer, which presumably results from beam deflection due to large density gradients. Moreover, there is evidence that in LHD this poloidally asymmetric radiation distribution during RC may be toroidally symmetric. These results indicate that a phenomenon similar to Multifaceted Asymmetric Radiation from the Edge (MARFE), which has been observed widely in tokamaks, also exists in LHD.

Keywords:

bolometer, plasma radiated power, radiative collapse, MARFE, asymmetric radiation

1. Introduction

The study of density limit has always been an important issue in both tokamaks and heliotron/stellarator devices for achieving thermonuclear fusion conditions [1-3]. In helical devices, the radiation-induced density limit has particular importance since it is a main cause leading to collapse of the plasma when the radiated power increased with density exceeds the deposited power [3,4]. This type of density limit is thought to be related to the onset of an edge thermal instability arising from the increase of impurity radiation with reduced temperature [5-7]. In tokamaks, radiative collapse (RC) may result in a cooling of the plasma boundary. Additionally, a poloidally symmetric radiating belt is generally established in such RC discharges [1,8,9]. Meanwhile, another specific edge phenomenon, MARFE (multifaceted asymmetric radiation from the edge), which is a zone of high radiation located at the inner side of the torus, has been observed frequently in tokamaks [1,8,10-12]. These MARFEs are poloidally asymmetric but toroidally symmetric radiation distributions. Physics of density limit in the context of MARFE formation has been theoretically studied intensively [13-17]. It is suggested that the MARFEs might be caused by a poloidally asymmetric radial heat and particle flow and affected by the poloidally asymmetric recycling properties as well [1,18]. In toroidal helical plasma, much attention has been paid recently to the radiation-induced density limit

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phenomenon [2-4,19-24]. However, the experimental results of the radiation structure have rarely been reported in helical devices. In this paper, we provide some new evidence of the radiation distribution during radiative collapse in LHD and relate asymmetric radiative collapse to the MARFE phenomenon.

2. Experimental Setup

The Large Helical Device (LHD) is a large-scale superconducting heliotron system with a set of $l/m = 2/10$ helical coils. During the 1998 experimental campaign it was operated with R/a = 3.6~3.9/0.6 m, B_t = 1.5~2.75 T, n_e = 0.6~7.0 × 10^{19}/m^3, T_e = 0.5~2 keV and T_i = 0.5~2 keV [25]. For the diagnosis of the total plasma radiation, several resistive metal film bolometry systems were installed in different ports. Among them, one bolometer array consisting of 20 channels were installed prior to the 1998 experimental campaign at a bottom port with 14 of them viewing the vertically elongated poloidal cross-section of the core plasma and the lower divertor legs [24]. At an outer mid-plane port, another 16-channel bolometer array was mounted prior to the 1999 campaign viewing the horizontally elongated cross-section of the plasma. The temporal resolution of the bolometers is 5 ms.

3. Asymmetric Radiative Collapse Observed in NBI Heated Plasmas

In LHD, the discharges are usually terminated in two ways: (1) thermal decay (TD) after the termination of NBI and (2) radiative collapse (RC) during the NBI. It was found that the plasma radiation was usually inboard/outboard symmetric during thermal decay and asymmetric during radiative collapse. These patterns occurred independent of the wall conditioning such as glow discharge or Ti-gettering.

In Fig. 1, typical waveforms of the so-called radiative collapse (RC), are displayed. From Fig. 1(b), it can be seen that the electron density ne keeps increasing with the gas puffing for the duration of the discharge. Because the impurity radiation power, P_I, is determined by n_e, impurity density, n_I, and the radiative cooling rate, $L(T_e)$, i.e., $P_I = n_e n_I L(T_e)$, an increase of n_e will enhance P_I for each of the impurities and hence the total radiated power, P_{rad}. The gradual linear increase of P_{rad} and P_I from O_V, C_{III} and H_α can be seen in Figs. 1(c) and (d) before 0.86 s, at which time W_p begins to decrease rapidly. The drop of W_p occurs when the continuously increasing P_{rad} exceeds the net absorbed power (NBI deposited power minus other power losses which are not shown in the figure). At the same time, the increase of P_{rad} cools the plasma boundary. For the intrinsic low-Z impurities of O and C in the edge area, a reduction of the local temperature leads to an increase of $L(T_e)$ and thus P_I and P_{rad}, which may further reduce the temperature. This is the so-called thermal or radiative instability [5-7]. In the present discharge, the trigger of this thermal instability is marked by the sharp jumps in O_V and C_{III} signals at about 0.86 s. The enhanced impurity radiation results in a substantial increase of P_{rad}, as seen in Fig. 1(c). The instability proceeds with a further steeper drop of W_p and T_e and the increase of P_I and P_{rad} before the switch off of NBI.

The sharp increase in the radiation prior to the end of the discharge motivates us to further investigate the radiation distribution features. Fig. 2 displays the late-period time evolution of the chord-integrated radiation

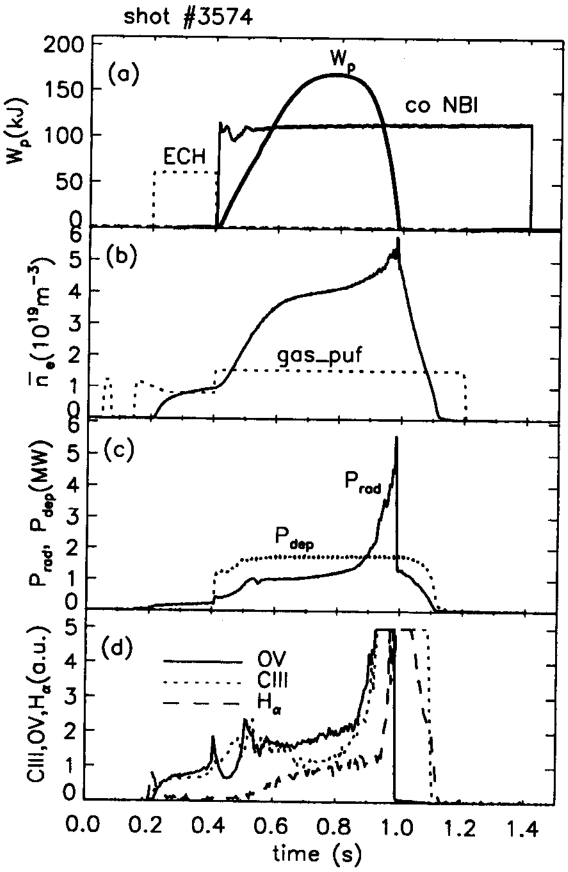

Fig. 1 Typical waveforms of a radiative collapse (RC) discharge (shot # 3574) (a) total plasma stored energy and ECH and NBI timing, (b) line-averaged density and gas-puff timing, (c) total radiated power and deposited NBI power and (d) spectroscopy signals from O_V, C_{III} and H_α.

brightness for the same RC discharge as shown in Fig. 1. From Fig. 2, we can see that prior to the loss of power balance (when P_{rad} becomes greater than the beam deposited power, P_{dep}, after t = 0.86 s as seen in Fig. 1(c)), the radiation profile is rather symmetric. However, with the trigger of the thermal instability, the radiation gradually becomes asymmetric beginning at about 0.94 s at which time the increase of radiation on the inboard side is much more drastic than that on the outboard side. This fact indicates that the radiation during RC discharges in LHD is poloidally asymmetric prior to the final collapse, similar to the MARFEs observed in tokamaks.

To further confirm whether this highly asymmetric radiation in RC is located within a region with extremely low temperature and high density as seen in tokamaks [8], a comparision has been made between the density signals measured by multi-chord FIR interferometer (λ = 119 μm) and the bolometer array signals both viewing verticaly elongated cross-sections from bottom ports which are separated in toroidal angle by approximately 72 degrees. In Fig. 2 the time of the loss of the density signals obtained from each vertical FIR channel at different major radial locations is also shown. A good spatial and temporal correlation can be observed between the highly asymmetric radiation and the peaks and periods of degradation of the density signal the latter which are thought to arise from the beam deflection due to large density gradients. This

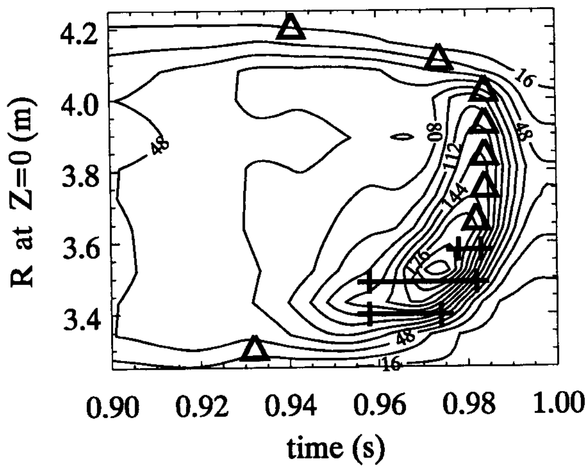

Fig. 2 Comparison between the contour plot of the bolometer-array-measured brightness for the shot shown in Fig. 1 and the time of the peaks (triangle) and period of signal degradation (++) in the FIR interferometer channels at various major radial positions.

result verifies that the intensive radiation regions correspond to regions of high density. This is the same phenomenon that has been observed during MARFE in tokamaks [8,11].

4. Toroidal Radiation Distribution

In tokamaks, the poloidally asymmetric MARFE has often been observed as a toroidally symmetric phenomena. Since the magnetic field configuration in helical device differs much from that in tokamak (i.e., non-axisymmetric), it is of great interest to investigate the radiation structure at different toroidal angles in LHD. Another bolometer array views a horizontally elongated cross-section which is separated by a toroidal angle $\phi \sim 54°$ from the previously described bolometer arrays viewing the vertically elongated cross-section. The sightlines of the two arrays allow them to simultaneously view the radiation from the inboard and outboard sides on on the vertically elongated cross-section and from the upper and lower sides on the horizontally elongated cross-section. The measurements of the time evolution of the radiation profile for an RC shot on these two ports are shown in Fig. 3. From Fig. 3(a), a clearly poloidally asymmetric radiation distribution, which is similar to that shown in Fig. 2, can be observed between the in-outboard sides at the vertically elongated cross-section. However, in Fig. 3(b) the radiation at the horizontally elongated cross-section exhibits a quite symmetric structure between the upper (detected by channels 9–15) and lower (detected by channels 2–8) sides. This result indicates that the poloidally asymmetric radiation in LHD may also be toroidally symmetric similar to a MARFE in a tokamak, even though LHD doesn't possess an axisymmetric magnetic configuration. However, we cannot definitely conclude that the poloidal asymmetry is axisymmetric as the array at the horizontally elongated port does not give us any information on the major radial profile of the radiation (whether it peaks in the center, on the inboard or outboard sides).

5. Conclusions and Discussion

We have reported on radiative collapse (RC), which occurs prior to the NBI termination as a result of the density exceeding the density limit when the radiated power exceeds the NBI deposited power. In the case of the thermal decay which occurs after the turn-off of the NBI heating the radiation profile is usually inboard-outboard symmetric while in the case of the radiative collapse it is usually asymmetric being

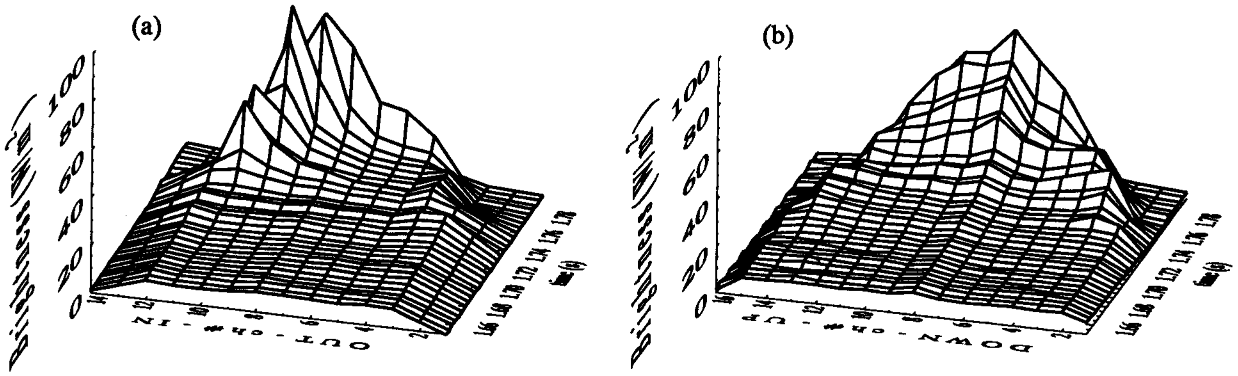

Fig. 3 Time evolution of the radiation brightness profile for an RC shot (shot # 10272) measured at (a) a vertically elongated cross-section and (b) a horizontally elongated cross-section.

stronger on the inboard side. In addition to this poloidally asymmetric radiation pattern the RC phenomenon is similar to MARFE in tokamaks in that a degradation of the interferometer signal due to steep density gradients is observed which coincides spatially and temporally with the asymmetry in the bolometer signal. Data from another bolometer array mounted at an outer port indicates that this asymmetry may be axisymmetric like a MARFE in a tokamak, however the definite determination of this is left to future measurements of the two- and three-dimensional radiation distribution using tomographic analysis of data from multiple bolometer arrays.

While asymmetric radiative collapse has many properties in common with MARFE, to this point it has only been observed in LHD as a transient phenomenon at the termination of the discharge, while MARFE in tokamaks has been observed to persist for several hundreds of milliseconds and does not necessarily lead to the termination of the discharge. We plan to study this phenomenon in more depth in the future, looking more carefully at how it affects the density limit in LHD and is related to the impurity content and power balance. In addition, as mentioned above we plan to look at the two- and three-dimensional structure of this phenomnenon to determine if it is axisymmetric like MARFE in a tokamak even though LHD has a three-dimensional vacuum vessel and magnetic field.

Acknowledgements

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