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Preliminary observations of hot spot for HT-7 long pulse discharges

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Abstract

Hot spot has been widely observed during long pulse discharge operation of tokamak devices. On HT-7, with the constant improvements on the plasma facing materials, in-vessel structure and plasma control technique in recent five years, the maximum pulse length has been extended to about 5 min. At the same time, it is more and more frequent to observe hot spot during HT-7 long pulse discharges. In addition, it has caused serious damages to the inner structure. Since one of the main missions of the HT-7 is the physics study of the steady state operation, hot spot becomes important not only because it is a research topic under this condition, but also because it should be understood to be avoided for extending the pulse duration. This paper introduces the preliminary observations of two typical kinds of hot spot in HT-7 by using visible camera, infra-red (IR) camera, etc.

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1. Introduction

Hot spot formation is an important plasma wall interaction (PSI) phenomenon for long pulse plasma discharges. It would lead to high or low Z impurity influx into plasma. Either could make steady state impossible. Moreover, it could cause damages to the inner structure of the device. Since the next step device will be working in the steady state, this topic has been studied in many devices, including, JT-60U [1], LHD [2], Tore Supra [3], TRIAM-1M [4], TEXTOR [5], etc.

HT-7 is a superconducting limiter tokamak. Long pulse discharge has been one of its primary topics. Through these years, various inner structure modifications have been conducted [6]. Doped graphite limiters have been installed to cover more area, and water cooling system has been equipped. In this way, the heat load on the wall is soothed and plasma discharges with the maximum duration of about 5 min have been obtained. For long pulse discharges, there are different factors limiting the plasma duration. It is observed for many times that towards the end of the discharges, carbon influx is related to the uncontrollable density rise [7]. Under

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this condition, the coupling of the 2.45 GHz lower hybrid wave (LHW) with the plasma becomes worse because the reflected wave power is observed to be higher with the same input power. Consequently plasma could not be maintained at the previous parameters (density, current) and terminates soon. There is another kind of circumstance during which high *Z* impurities terminate the discharges. In this case, big increase of metal influx is observed before the abrupt quench of the plasma.

Most of the times, hot spots are observed during these two kinds of discharges. In the following section, hot spots' damages on the inner structure are shown. In Section 3, the diagnostics used for hot spot observation are introduced. After the discussion of some preliminary experiments about hot spot on HT-7, summary is given at the end.

2. Damages on the inner structure

For HT-7, the major radius is 1.22 m, and the minor radius is 0.27 m. Fig. 1 shows the inner structure of HT-7. The plasma is limited by a few limiters from different directions. Most of the high field side is covered by a band of belt limiter (BL), about 0.12 m in width. On the low field side, poloidal limiter (PL) is installed up-down symmetrically covering about 1/3 of the circumference of the cross section. There are two PLs located 180° away from each other toroidally. Above and below the plasma, toroidal limiters (TL) form a band 0.15 m in width

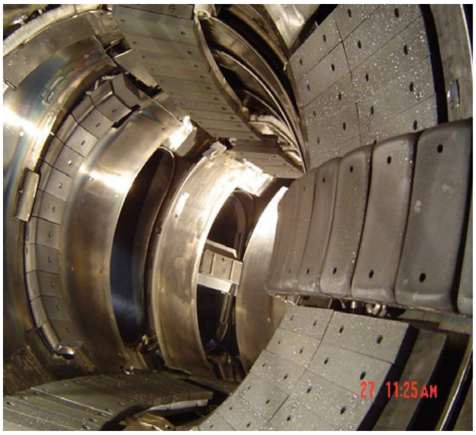

Fig. 1. This photo shows the relative position of limiters inside HT-7 chamber. The circular belts on the top and at the bottom of the photo are the upper and bottom TL. The extruded part to the left between the upper TL and bottom TL is one of the PL. The horizontal array of a few tiles in the middle of the right hand side is the BL (It should be pointed out that part of the TL was removed for the present situation.).

and basically cover the 1st and the 3rd quarter of the toroidal circumference continuously. The TLs are symmetric poloidally. The BL, PL and TL form the main limiters of HT-7. Besides, there are some protection boards for rf antenna located less than 10 mm away from the plasma.

All these limiters use doped graphite with SiC coating as the plasma facing material. The total area of the graphite tiles facing plasma is about 1.6 m^2. For long pulse discharges, active cooling is used. The tiles are bolted to the heat sinks, and water flows through the heat sinks to remove the heat.

During the venting of the HT-7 tokamak device, obvious damages are observed on the inner structure. Coincidently, there are a few positions matching to that of the hot spots observed during the discharges very well. One position is within the same cross-section as one of the PL and at the top of the vacuum chamber (Fig. 2). This position was formerly covered by the limiter. In 2004, the limiter at this part was removed. Since it is as far as 3 cm away from the last closed flux surface, it was not realized that there was possibility of PSI. This area was just covered by about 1 mm thick stainless steel (SS) patch to fix the passing thermal coupler (TC). However, during experimental run, fierce PSI was observed in this area by visible camera, frequently in disrupted plasma discharges. During the following venting period, it was found that an area of the SS patch (about 50–100 mm in diameter) was almost completely gone. The TC was melt broken in half. What was worse, the 5 mm thick SS board beneath was melted and leak was formed on the vacuum vessel. This hot spot could be related to the quench of the discharges caused by abrupt metal impurity influx.

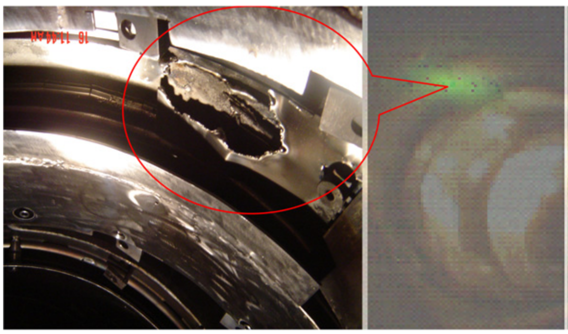

Fig. 2. The left photo was taken during venting period, showing the melt area on the top of the vacuum chamber. The right was taken by visible camera, showing strong PSI before disruption in the corresponding position during plasma discharge.

There is another seriously damaged area on the BL. That is located about 180° away from the LHW antenna toroidally. There are 12 tiles on this part of the BL. The tiles are numbered from 1 to 12 clockwise on the planform. For many long pulse discharges, strong PSI is often observed on the tile numbered 12, which is located at one end of this part of BL. During the venting period, it is found at the edge of this tile that area of several square cm lose the SiC coating completely and the substrate graphite be eroded by a few mm. It is believed that this hot spot be related with the discharge quenches caused by low *Z* impurity influx. Without SiC coating, the chemical sputtering on this tile could be more serious and C influx would be greatly enhanced at high temperature (the maximum measured bulk temperature of this tile is higher than 1400 K) due to various mechanism, e.g. radiation enhanced sublimation. For recent 2 years, long pulse operation was carried out mainly. Each time before the campaign, this number 12 tile has to be changed due to the damage.

3. Diagnostics

To keep trace of the hot spots during plasma discharges, TC, visible cameras and IR camera are installed. The bulk temperature of the tiles is measured by type K TC with the highest capacity up to 1400 °C. They have been installed at about 60 positions, mainly mounted at the back of tiles, 2–5 mm beneath the plasma facing surface. Though the initial temperature of the tiles is mainly at room temperature, most tiles are heated to 300 °C towards the end of the discharges, while the maximum temperature in some tiles could surpass 1000 °C. Visible cameras are used to monitor the PSI inside the vacuum chamber with the capacity of taking 60 frames per second (commonly at 30 fps). One IR camera is used to measure the surface temperature of the graphite tiles on the BL at the frequency of about 50 fps. Presently, these diagnostics are the main tools for hot spot observation on HT-7.

4. Discussion

It is found that the generation of hot spots in both positions is closely related to the LHW. There are two reasons. Firstly, LHW could drive plasma for much longer duration (maximum duration is about 5 min). Otherwise, the maximum plasma pulse is about a couple of seconds. For this kind of short discharges, the auxiliary heating power on HT-7 is not enough to generate hot spot. Secondly, LHW could generate large amount of energetic particles, which are probably the main causes for the hot spots.

For the first position discussed in Section 3 (case A), it is observed that the temperature starts to rise soon after LHW is applied. For the 2nd position (case B), which is within the coverage of the IR camera, a few 10 s discharges are carried out for the experiment. Fig. 3 shows an example. It is arranged that the power of the LHW be switched off at about 8.9 s. It could be seen that plasma remains for another half a second before termination. Soon after the application of LHW, the visible camera observes a very bright spot at the edge of that tile. The IR camera shows that the surface temperature (T_{surf}) reaches about 500 °C. Then the T_{surf} decreases by about 100 °C for a few seconds possibly due to the cooling by the heat sink, and keeps increasing until the termination of the LHW. Though the horizontal or the vertical position of the plasma remains unchanged after the LHW is turned off, it is observed on the visible camera that

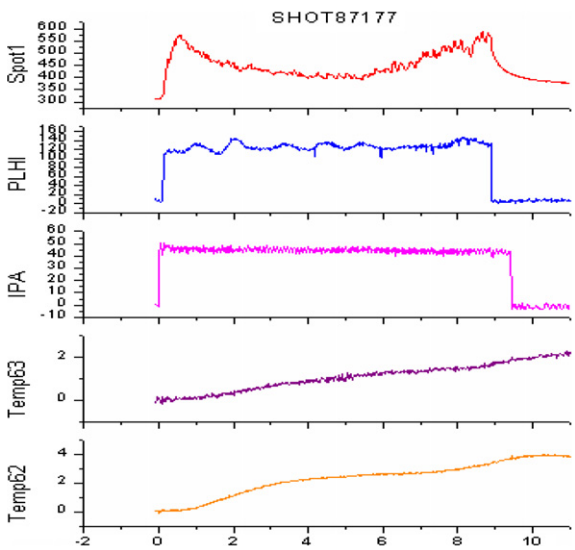

Fig. 3. LHW effect on the hot spot. (Waveforms from top to the bottom are surface temperature of the hot spot measured by IR camera, power of LHW, plasma current and bulk temperature of the tile at different depths measured by TC.) It should be pointed out that the surface temperature responds to the LHW very quickly, while the slow response of the bulk temperature evolution reflects that the thermal conduction between the heat sink and the tile is not good.

the bright spot disappears very soon, and IR camera shows that T_{surf} decays exponentially. This evolution shows that hot spot corresponds well to the energetic particles generated by the LHW.

Discharges with the same duration but different plasma current, thus different $q(a)$ have been carried out successively with the hope that the change of the $q(a)$ could change the energetic particle deposition on the limiter and mitigate the mechanism for hot spot formation. The safety factor is scanned from 11 to 5.5. However, no obvious change has been observed.

More efforts are made on avoiding the hot spot formation. For case A, a few references (e.g. Ref. [3]) describes a probable mechanism that fast electrons accelerated by the LHW firstly are trapped due to the ripple effect, and then pushed toward the top of the vessel by the curvature and gradient drifts. On HT-7, the area is now covered by a piece of graphite board. The damage to the area is greatly mitigated. Though the quick rise of the temperature in this area was still monitored during the long pulse discharges, and damage on the protective board was still visible during the venting check, there was less frequency of discharge quenches related with the high Z impurities. Water-cooling system is under consideration for better removal of the power.

For case B, it is observed that the surface and bulk temperature of the graphite tiles is very sensitive to the displacements. With a fixed position throughout the discharge, temperature of the tile contacting with the plasma could easily exceed 1000 °C, and sometimes the TC is damaged. Sweeping displacements during a discharge is effective for avoiding hot spot.

The modification on the dimensions of the tiles is proved to be useful as well. In the latest campaign, the tile in case B was changed to that with a tilted edge facing plasma to avoid the concentration of heat flux. Though the erosion was still obvious during the venting check, the PSI on this tile was observed to be mitigated during discharge.

5. Summary

Hot spot has been observed in HT-7 to cause serious damage to the inner structure. It could be an important reason for the impurities generation, which prevent from achieving longer pulse. With the help of visible camera, TC and IR camera, some characteristics of hot spots on HT-7 have been observed. An SS region in the shadow area at the top of the cross section of the vacuum vessel could be the source for the high Z impurities. While an eroded area on a poloidal limiter could be one of the sources for the C influx. It is found that the hot spot on the belt limiter tile is closely related with the energetic particles generated by the LHW. It is concluded from the HT-7 campaign that methods including installing protective graphite boards, active control of plasma displacements and modification of tile shape are helpful.

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