Production of Hot Spot on a Vertically Installed Divertor Plate by ICRF Heating in the Large Helical Device

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Abstract—**Plasma-wall interaction in long-pulse plasma discharges is an important issue for optimizing the first wall materials and divertor configurations for future nuclear fusion reactors. A visible charge coupled device (CCD) camera observed a hot spot on a vertically installed divertor plate in a long pulse discharge heated by ion cyclotron range of frequency (ICRF) in the large helical device (LHD). Two bright thin lines also appeared on a divertor leg. The analyses of the three-dimensional trajectory of protons accelerated by ICRF waves on two ion cyclotron resonance (ICR) layers in the plasma periphery can explain the observation of the CCD camera.**

Index Terms—**Charge coupled device (CCD), divertor plate, hot spot, ion cyclotron range of frequency (ICRF) heating, large helical device (LHD).**

THE large helical device (LHD) is the largest super-conducting heliotron-type device, with major radius $R = 3.9$ m, minor radius $a \sim 0.6$ m, and toroidal magnetic field $B = 2.9$ T [1]. LHD has fully superconducting magnetic coils, which produces magnetic configurations for plasma confinement in steady state without the toroidal plasma current. Therefore, LHD has an advantage for long pulse plasma discharge experiments over other plasma confinement devices.

One of the critical issues for nuclear fusion reactors is plasma-wall interactions in long pulse discharges in which the plasma can be contaminated by impurities, and it can cause unfavorable gas fueling which disturbs control of the plasma density and temperature. In LHD, toroidally twisted circular shaped plasmas are produced with four divertor legs and ergodic layer around the main plasma. The vacuum vessel is covered with stainless armor tiles and carbon divertor plates installed at the strike points of the divertor legs. The backside of the divertor plates are mechanically attached to cupper plates directly connected with water cooling pipes. Five kinds of vacuum ports (lower, upper, inner, outer, and tangential ports) are equipped in the vacuum vessel for plasma diagnostic systems. There are twenty divertor plates which are vertically installed in every lower and upper port for protection of the cooling pipe at the edge of the ports with keeping the field of view from the plasma diagnostic systems. Divertor plates and the divertor legs near a lower port were observed with a visible charge coupled device (CCD) camera mounted on an outer port. Thermocouples are embedded in some divertor plates for measuring toroidal and poloidal distribution of the heat load [2].

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Long–pulse discharge experiments were carried out by ICRF heating in a magnetic configuration where the radial position of the magnetic axis $R_{\rm ax} = 3.60$ m. The ion cyclotron range of frequency (ICRF) antennas are supported from the upper and lower ports which are next to the port where CCD camera is installed. A minority heating method was employed in helium plasmas as the majority ions and protons as the minority ions. Two ion cyclotron resonance (ICR) layers were located at the saddle point of the mod-B surface for optimizing the heating efficiency. The ratio of the density of the minority ions to the electron density $n_{\rm H}/n_{\rm e}$ was controlled to 5%–10% by monitoring the ratio of the intensity of visible line emission from neutral hydrogen and helium atoms [3]. The CCD camera observed a hot spot on a vertically installed divertor plate. Two bright thin lines on the divertor leg were also observed during the ICRF heating, as shown in Fig. 1(a). The brightness of the hot spot on the divertor plate increases with duration of ICRF heating. Measured temperature of the some divertor plates was in the range from 450 to 700 K, which did not saturate during the plasma discharge.

These observations are investigated from the view point of the trajectories of protons accelerated by ICRF waves. Fig. 1(b) and (c) illustrates the proton trajectories traced from the start points on the two ICR layers in front of the lower and upper ICRF antennas (blue and red points, respectively). The magnetic field lines traced from the just outside of the main plasma (green points) are plotted, and a typical trajectory from the lower ICR layer is also shown (black line). Without ICRF heating, the visible emission on the right divertor leg (behind a port edge) is always observed in the magnetic configuration ($R_{\rm ax} = 3.60$ m). It is consistent with the image of the magnetic field line traces (green plots), which means the presence of the plasma flow along the magnetic field lines from the main plasma. Impurities and neutral particles recycled on the divertor plates interact with the plasma flow, enhancing the intensity of the visible emission on the divertor leg. When the ICRF heating was turned on, the two bright thin lines appeared on another divertor leg. It can be explained by the trajectories of the protons from the two ICR layers. A magnification of the strike points of accelerated protons on the vertically installed divertor plate is depicted in Fig. 1(d). The distribution of the strike points agrees with the position of the hot spot (See the adjacent picture). The toroidal and poloidal distribution of the divertor plate temperature is qualitatively consistent with that of the strike points of the accelerated protons. The trajectory analyses indicate that the hot spot was caused by local heating of the divertor plate due to interactions with the accelerated protons by ICRF waves.

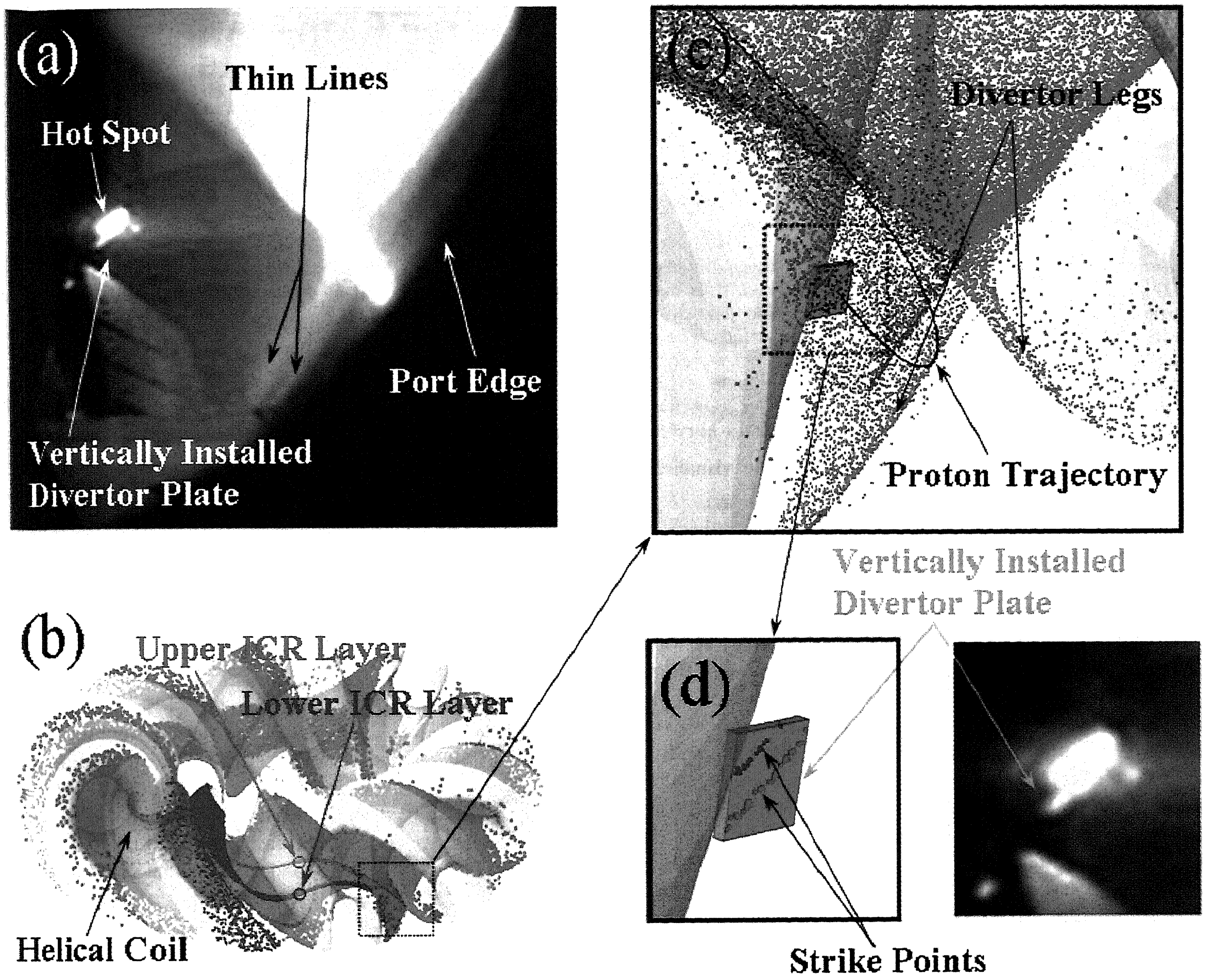

Fig. 1. (a) Hot spot on a vertically installed divertor plate during a long pulse discharge by ICRF heating. (b) Calculation of three-dimensional trajectories of protons accelerated by ICRF waves on two ion cyclotron resonance layers (red and blue plots) with magnetic field lines (green plots). (c) Enlarged view of the trajectories near the divertor plate with a typical trajectory of an accelerated proton (black line) and (d) the distribution of the strike points of the protons on the divertor plate.

In conclusion, images of divertor plates and divertor legs near a lower port in a long pulse discharge by ICRF heating give useful information on the plasma-wall interactions between the accelerated protons and the divertor plates. Optimization of ICRF heating schemes is one of the candidates for sustaining steady state plasmas without serious damages of divertor plates, impurity contamination and unfavorable gas fueling in LHD plasmas.

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