Analyses of Visible Images of the Plasma Periphery Observed with Tangentially Viewing CCD Cameras in the Large Helical Device

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Magnetic field produced by helical and poloidal coils in LHD forms a complicated structure of the magnetic field lines in the plasma periphery (ergodic layer and divertor legs), which can change the radial position of the magnetic axis, the shape and size of magnetic surfaces and the location of the strike points, etc. CCD cameras have observed complicated structure of the visible emission depending on the magnetic configurations. The dependence of the images of visible emission on three magnetic parameters which specify magnetic configurations (the position of the magnetic axis, coil pitch parameter, quadruple magnetic components) is investigated by tracing magnetic field lines. The images of the three-dimensional plots of the magnetic field lines quite agree with the observations in various magnetic configurations. Safe operational range of the three magnetic parameters from the viewpoint of minimizing the direct heat load onto the vacuum vessel is found by calculating the distributions of strike points.

Keywords: visible image, plasma periphery, CCD camera, Large Helical Device, magnetic field line, strike point, magnetic axis, coil pitch parameter, quadrupole magnetic component

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1. Introduction

Large Helical Device (LHD) is the largest super-conducting helical machine. The super-conducting coils consist of three pairs of poloidal coils and two twisted helical coils which have three independent conducting layers for changing the radial profile of rotational transform (coil pitch parameter γ). The magnetic field produced by the poloidal coils can control the position (magnetic axis R_{ax}) and shape of the plasmas (quadruple magnetic components B_q). The two super-conducting coils form complicated magnetic field line structures (ergodic layer) with four divertor legs in the plasma periphery. Open magnetic field lines are created in the peripheral region outside of the last closed magnetic flux surface (LCFS). The magnetic field lines along the divertor legs directly connect to divertor plates (graphite) or the vacuum vessel (stainless steel) at strike points.

Tangentially viewing CCD cameras have routinely monitored the images of visible emission. Complicated structure of the images depending on the magnetic configurations has been observed, providing experimental information about the location and distribution of the strike points, the structure of the peripheral plasma, atomic and molecular processes.

In this paper, the observed images are analyzed from the viewpoint of the three-dimensional structure of magnetic field lines in the plasma periphery. The dependence of the images on the three magnetic parameters (R_{ax}, γ and B_q) is investigated by comparing the observations and calculations. The range of the three magnetic parameters for safe plasma discharge operations is proposed by calculating the distribution of the strike points onto the divertor plates and the vacuum vessel.

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2. Observed Visible Images with Tangentially Viewing CCD Cameras

Two tangentially viewing visible CCD cameras have routinely monitored LHD plasmas. One camera is installed at a tangential port (6-T) for monitoring the behavior of the whole plasma. Another camera is located at an outer port (3-O), which can monitor the peripheral plasmas and the plasma-wall interactions on the divertor plates installed around a lower port (2.5-L). The experimental setup and the position of the cameras are described in Figure 5 in the reference paper [1].

The complicated structure of visible emission which depends on the magnetic configurations has been observed. Low electron temperature plasmas ($T_e <$ several tenth eV) emit visible light by atomic and molecular processes, which means that the observed images are formed by the line integrated intensity of the emission in the plasma periphery (low electron temperature region).

The dependences of the images on the three magnetic parameters are given in Figure 1 (a), 2 (a) and 3 (a), respectively, showing change of the emission profile. The emission area observed from the tangential port moves to out-

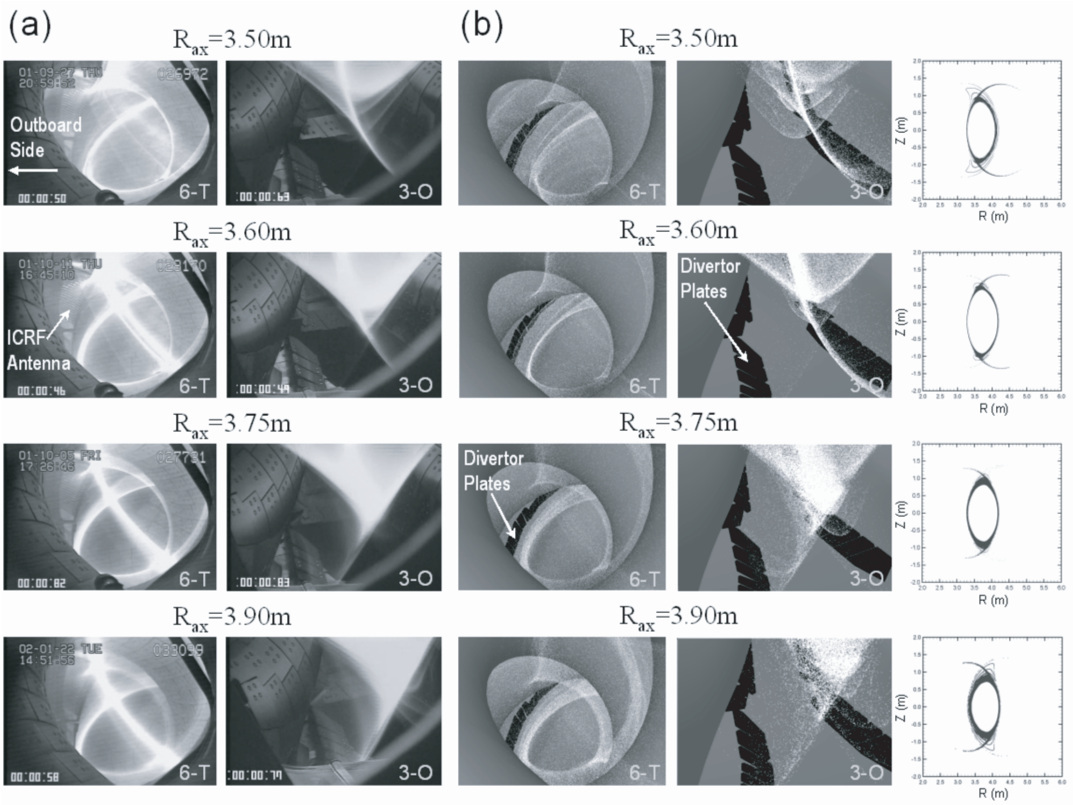

Fig. 1 (a) Observed images of the visible emission profile, (b) calculated images of the plots of magnetic field lines with the Poincare plots in the plasma periphery (R_{ax}-dependence).

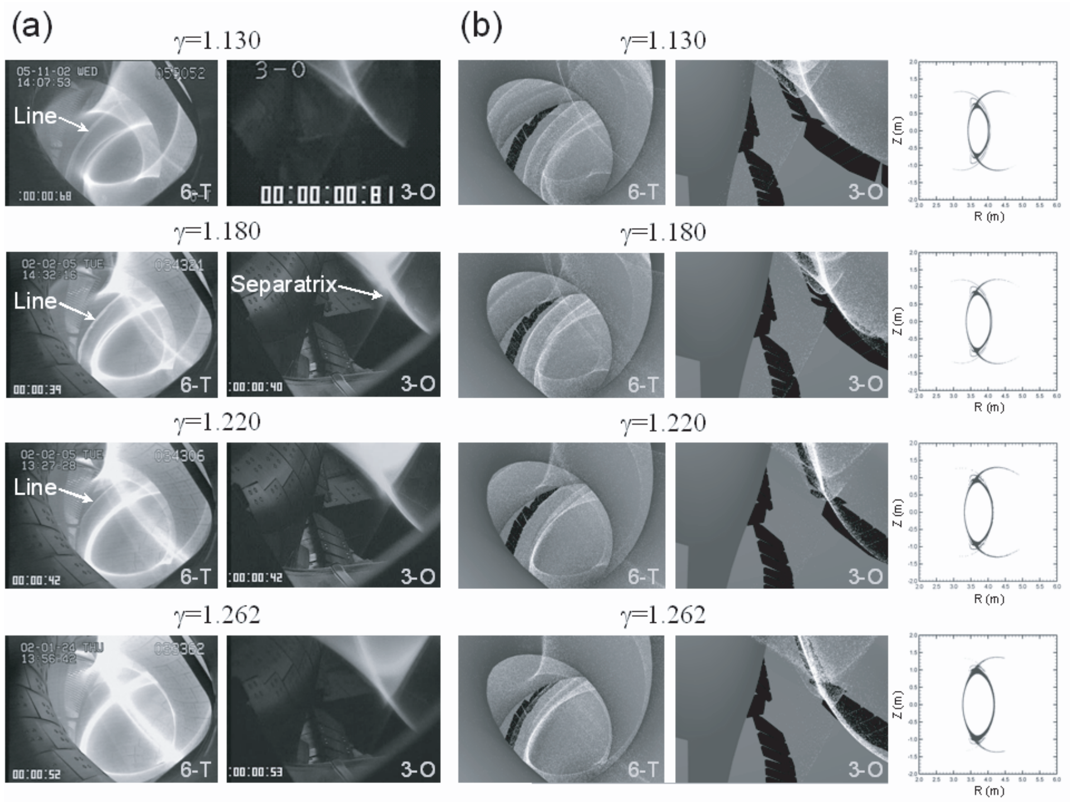

Fig. 2 (a) Observed images of the visible emission profile, (b) calculated images of the plots of magnetic field lines with the Poincare plots in the plasma periphery (γ-dependence).

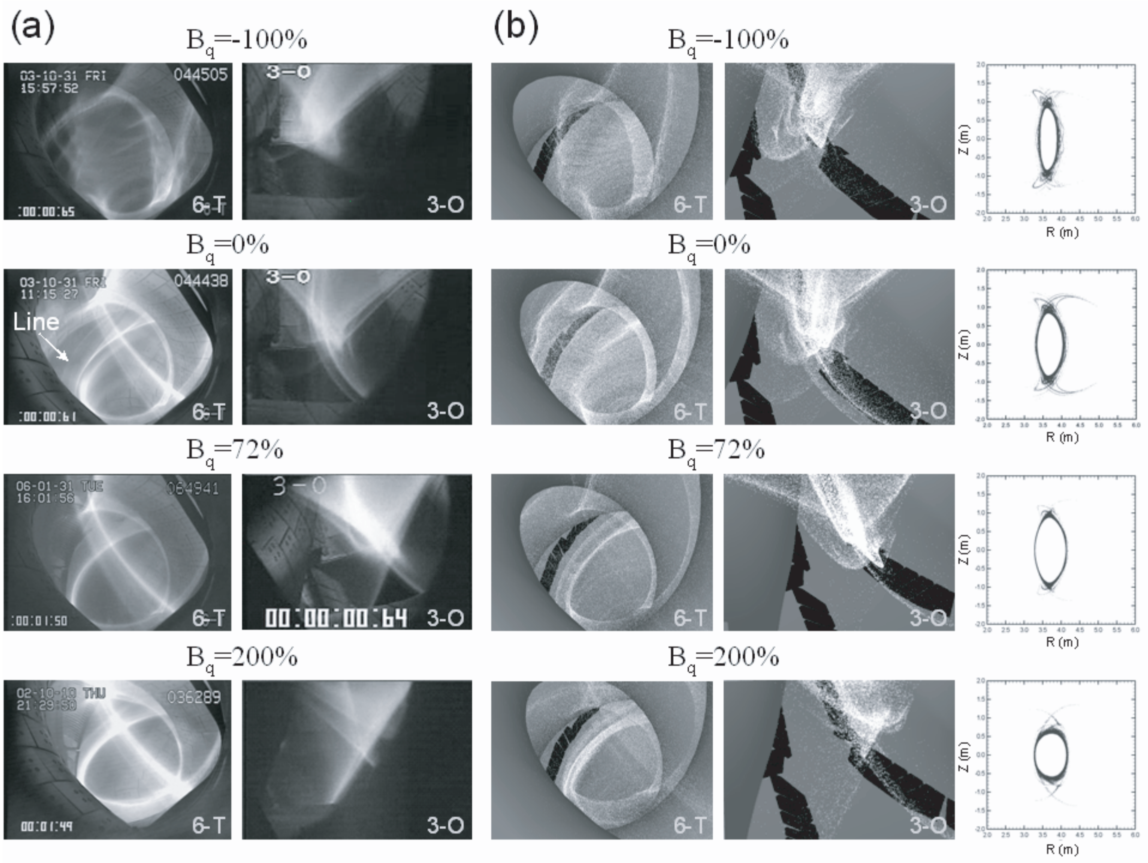

Fig. 3 (a) Observed images of the visible emission profile, (b) calculated images of the plots of magnetic field lines with the Poincare plots in the plasma periphery (B_q-dependence).

side in the major radius (to left side) with the magnetic axis (R_{ax}). The emission area expands with the coil pitch parameter (γ). The shape of the emission profile expands vertically (horizontally) for the low (high) quadrupole magnetic components (B_q). The camera installed in the outer port observed transition of the emission area on the lower divertor legs from the right side ($R_{ax} = 3.50$ m) to the left side (3.90 m) with the magnetic axis. It also observed that the vertical position of the separatrix (cross point of the divertor legs) goes down with the coil pitch parameter.

3. Three Dimensional Structure of Magnetic Field Lines in the Plasma Periphery

Low electron temperatures in the plasma periphery are experimentally observed by Thomson scattering, Langmuir probes and spectroscopy. The intensity of the visible emission increases with the plasma density. The structure of the density profile in the plasma periphery basically corresponds to that of the magnetic field lines because of fast plasma diffusion along the field lines.

In order to interpret the observed images, magnetic field lines outside the LCFS are plotted three-dimensionally by tracing the magnetic field lines. The initial points for the traces are uniformly distributed in poloidal and toroidal planes. The points are moved from inner to outer side in the minor radius. The magnetic field lines of which path length is below about 0.7 and over 20 torus circulations are ignored in the calculation. The geometrical data of the vacuum vessel and the divertor plates are included for determining the position and the distribution of the strike points.

The calculated images of the magnetic field lines looked from the position of the cameras in various magnetic configurations are illustrated in Figure 1 (b), 2 (b) and 3 (b). The Poincaré plots in the plasma periphery at a toroidal position where the LCFS is vertically elongated are also shown. The calculations agree with the observations in all configurations. The dependence of the images on the three magnetic parameters (R_{ax}, γ and B_q) is consistent with the observations. The reason why the transition of the emission area on the lower divertor legs depending on the magnetic axis is that magnetic field line structure in the outboard region where the shape of the plasma is horizontally elongated is changed with the magnetic axis position. These magnetic field lines directly connect to the lower divertor legs. The vertical movement of the position of the lower separatrix is ascribed to the change of the magnetic field produced by each conducting layer of the helical coils (finite volume effect of the coils).

4. Distributions of the Strike Points in Various Magnetic Configurations

Magnetic field line traces to the divertor plates or the vacuum vessel can calculate the poloidal and toroidal distribution of the strike points. The presence of the plasma along the magnetic field lines on the divertor legs has been confirmed by the consistency between the observed images and the calculated ones as described in the previous section. Figure 4 (a), (b) and (c) are the images of the vacuum vessel (one toroidal pitch angle) with the divertor plates (showed as black plates) for indicating the distribution of the strike points (white points). The strike points for low γ (< 1.22) significantly deviate from the position of the divertor plates. By the images of the distribution of the strike points looked from the tangential port (6-T), we have recognized that the line structure of visible emission close to an ICRF antenna in low γ cases originates from the plasma wall interactions at the strike points at the sidewall of a helical coil.

Figure 5 (a), (b) and (c) indicate the ratios of the number of the strike points locating on the divertor plates on the total number of the strike points. More than 80 % of the strike points locate on the divertor plates for all magnetic axes ($3.50\,\mathrm{m} < R_{ax} < 4.05\,\mathrm{m}$). The ratio drastically decreases for low γ (< 1.22). The B_q dependence shows that the ratios is less than 60 % except for around $B_q = 100\,\%$.

The calculations indicate that high heating power or long pulse operation in low γ cases should be restricted for minimizing the direct heat load onto the vacuum vessel. Magnetic field configurations for distorting the plasma shape ($B_q < 50\,\%$ or $> 150\,\%$) should not be employed for the operations. Installation of additional divertor plates will accept broader range of the magnetic configurations with high heating power. The analyses of the distribution of the strike points propose the safe operational range of the magnetic configurations from the viewpoint for minimizing direct heat load onto the vacuum vessel.

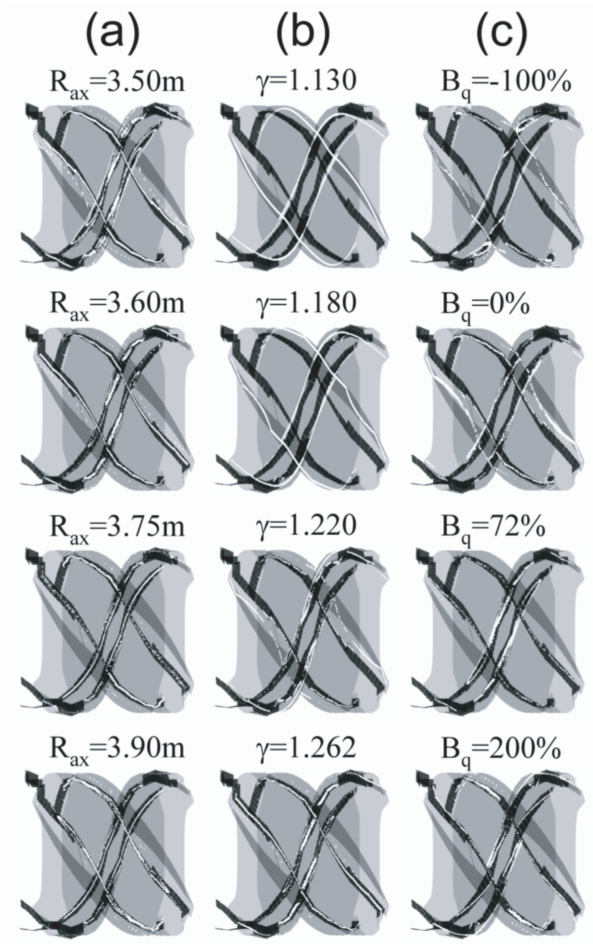

Fig. 4 Three dimensional plots of the strike points, depending on R_{ax} (a), γ (b), and B_q (c).

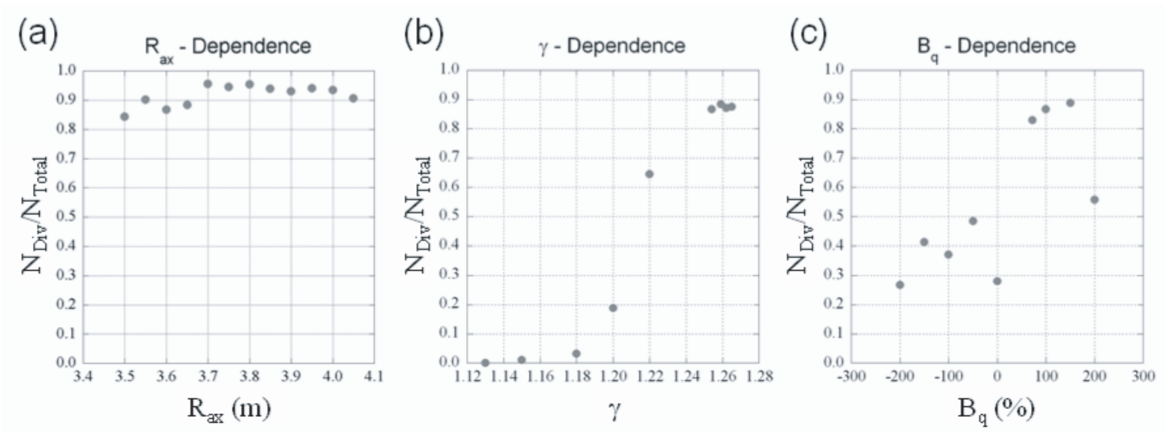

Fig. 5 The ratios of the number of strike points locating on the divertor plates on the total number of the strike points, depending on magnetic parameters R_{ax} (a), γ (b), and B_q (c).

5. Summary

Tangentially viewing CCD cameras have observed complicated structures of visible emission. Three-dimensional plots of magnetic field lines show that the images are explained by the magnetic field line structures in the plasma periphery. The dependence of the visible images on the three magnetic parameters (R_{ax}, γ and B_q) is also consistent with that of the calculations. The calculated position and distribution of the strike points in various magnetic configurations reveal the range of safe magnetic configurations for high heating power or long pulse discharges in LHD.

[1] M. Shoji *et al.*, J. Nucl. Mater. **337-339**, 186 (2005).