Change of Edge Plasma Distribution during a Discharge in Heliotron J

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In order to monitor the diverted plasma flux distribution for various field configurations in Heliotron J, a new edge-plasma monitor system was installed. During a single discharge, a high-speed video camera (250-500 fps) records a stack of two-dimensional images of visible light emission (mainly from recycling neutrals) near a movable carbon target, which is inserted to the peripheral region of the core plasma. A spontaneous shift of the brightest spot of the light emission along the target was clearly observed. This shift is qualitatively consistent with a poloidal shift of the diverted plasma position which was observed in the diverted plasma flux measurement with a Langmuir probe-array near the wall at a different toroidal position. These findings indicate the global shift of the edge plasma position during a discharge. The most plausible mechanism for the observed shift is the change of the edge field topology caused by a non-inductive plasma current of a few kA.

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1. Introduction

In a toroidal plasma confinement device with a low magnetic shear, the core plasma confinement is very sensitive to the value of the rotational transform $\iota/2\pi$ as experimentally demonstrated in W7-AS [1] and Heliotron J [2]. In addition, the $\iota/2\pi$-value on the last closed flux surface (LCFS) is closely related with the edge field topology, which is to be used for a "built-in" divertor in helical systems. Although no net plasma current is necessary in helical systems, the finite-β effect (Shafranov shift, bootstrap current) and/or non-inductive net plasma current I_p, which can be driven through plasma heating schemes, modifies the rotational transform and its radial profile. This modification of the rotational transform will also change the edge field topology and then affect the divertor plasma distribution. Therefore, especially in helical systems, it is important to experimentally and theoretically study the dynamics of the divertor plasma distribution caused by the plasma discharge and its controllability.

Heliotron J [3, 4] is a low-magnetic-shear helical-axis heliotron device with an $L = 1/M = 4$ helical coil ($R_0 = 1.2\,\mathrm{m}$, $B_0 \leq 1.5\,\mathrm{T}$), where L is the pole number of the helical coil and M is the pitch number of the field along the toroidal direction. In the standard configuration of Heliotron J (the edge rotational transform $\iota(\mathrm{a})/2\pi \approx 0.56$) the last closed flux surface is surrounded by "ergodic" field lines and some parts of the "whisker" field lines outside the LCFS cross the vacuum chamber, forming "divertor traces" on the wall [5]. When the edge rotational transform is set near a rational, 4/7 ($\approx$0.571), closed or non-closed magnetic islands of $n = 4/m = 7$ around LCFS cause to modify the divertor field topology.

Figure 1 shows a schematic view of Heliotron J with the positions of heating equipments and diagnostics relating to this paper. In the previous Heliotron J experiments in the standard configuration, the plasma flux coming to the wall along the divertor flux bundle has been monitored with poloidal arrays of Langmuir probes (divertor probe array, DPA,) [6]. These Langmuir probe arrays are installed near the wall at two toroidal sections ($\phi = 67.5°$ and $112.5°$ sections) as shown in Fig. 2, where the field topology is up-down symmetric each other. Since the arrays are designed for the field topology of the standard configuration of Heliotron J, however, the position of the array might not be the best one for other configurations. Moreover, increasing of in-vessel equipments such as NBI beam-dumps, ICRF antenna and armor tiles protecting some in-vessel diagnostics might make their shadows on the probe arrays depend-

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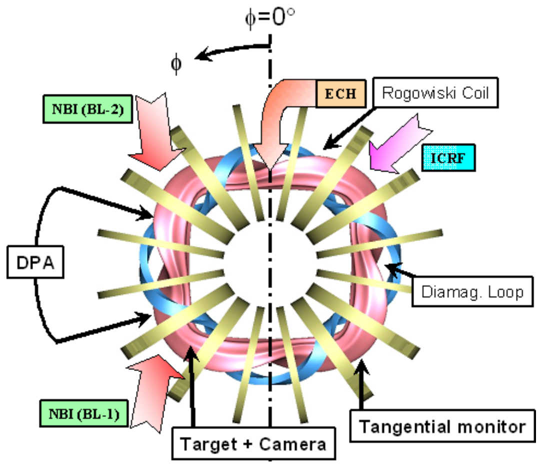

Fig. 1 Schematic view of the Heliotron J experimental setup.

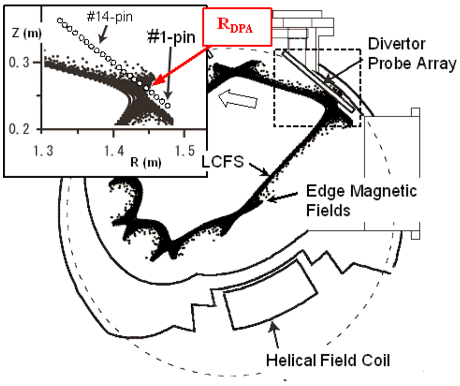

Fig. 2 Schematic view of the divertor probe array at ϕ = 67.5° with a Poincaré plot of the edge field lines. The inset shows the probe-pin positions.

ing on the examined field configuration. To compensate these disadvantages of the existing divertor probe measurement, we have installed a new edge-plasma monitor system which can work effectively in various configurations of Heliotron J. This paper reports the observation of the diverted plasma position and its spontaneous shift during a discharge by using this new system. The detailed discussion on the mechanisms of the observed shift is beyond the scope of this paper and it will be discussed elsewhere.

2. A New Edge-Plasma Monitor System with a High-Speed Video Camera

A combination of a small target and a high-speed video camera is a very powerful tool to visualize the edge plasma behavior and/or the plasma-wall interactions with high spatial and time resolutions. In the Heliotron J experiments, we have used this method to investigate coherent oscillations or turbulence in edge plasmas [7]. Based on this experience, a new two-dimensional measurement of

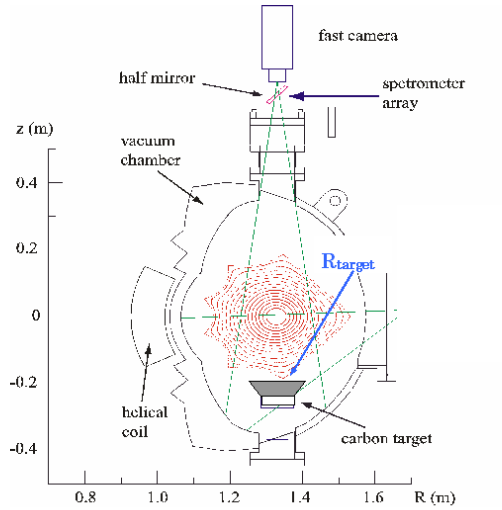

Fig. 3 Schematic view of the rail-limiter type carbon target and the fast-camera image monitoring system.

the visible light image near a movable rail-limiter type carbon target is applied to monitor the diverted plasma flux position in the device.

Figure 3 schematically shows the setup of the system equipped at the toroidal section of ϕ = 157.5°. In this monitor system, a rail-limiter type carbon target (16 cm in length along the major radius direction R) is inserted to the peripheral region of Heliotron J plasma from the bottom of the torus. A high-speed eight-bit digital video camera is set at the opposite port and monitor two-dimensional images of visible light emission near the target. The target position can be set at a proper position for each discharge condition to contact with a part of the "whisker" field lines outside LCFS. Since the previous image measurements using a cannon-ball type target [7] indicate that the brightness of the image near the target is well correlated to the profile of the plasma flux coming to the target, we consider the observed image with this rail-type target has profile information of the incoming plasma flux also in this experiment. The frame speed of the camera system is 500 fps (or 250 fps if necessary to monitor a wider area) and the numbers of pixel in a frame is 480 (for 250 fps) or 240 (for 500 fps) × 512 pixels. Depending on the brightness of the image, an exposure was set to 1/500 or 1/1000 of a second. In the present camera setting, one pixel of the image data corresponds to about 1 mm. The digital data of the image are stored as an AVI-format file automatically for every discharge. In order to discuss the shift of the diverted plasma position, we focus on the peak position of the brightness profile, R_{target}, along the leading-edge of the target in this paper.

3. Experiments

The details of Heliotron J are described in Refs. [3] and [4]. For ECH-only discharges, the plasma production and heating is performed by using the 70-GHz, 0.4-MW

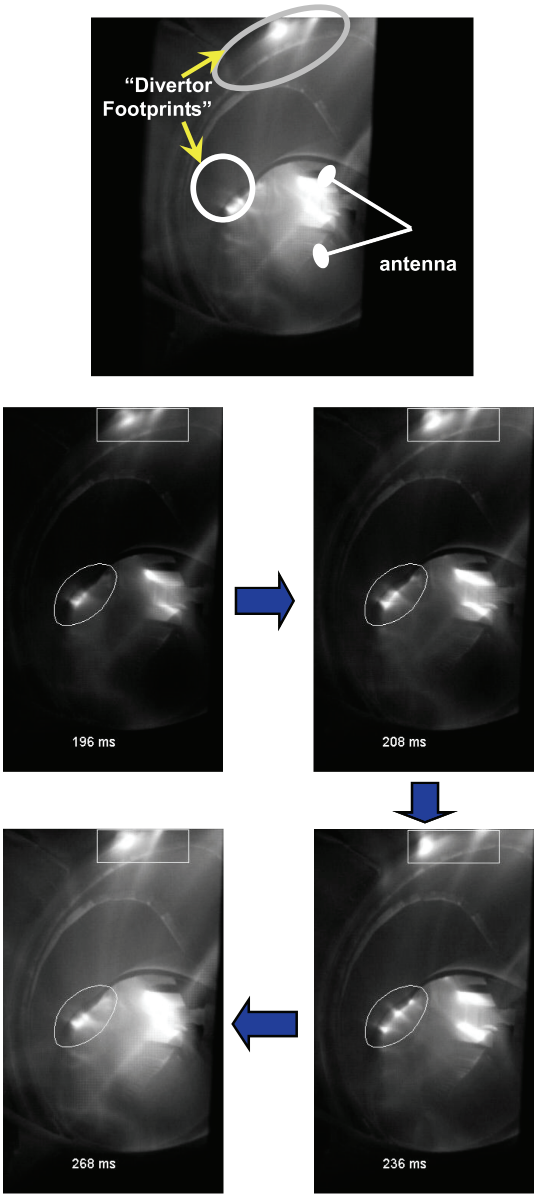

Fig. 4 Snapshots of the tangential view of plasma. (#23635)

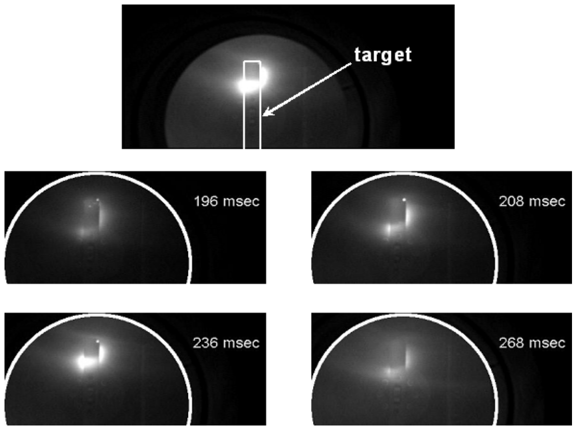

Fig. 5 Snapshots of the target image. The bright area corresponds to the hitting point of the diverted plasma. The white circle indicates the edge of the viewing port. (#23635)

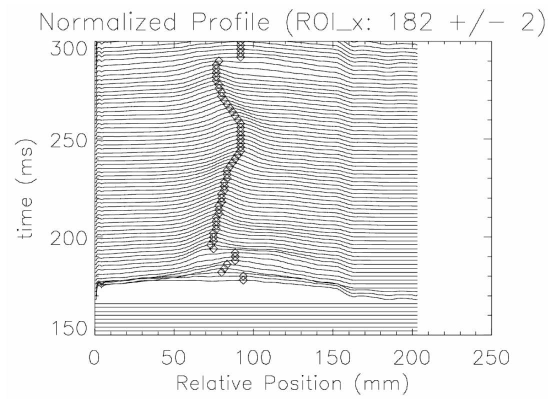

Fig. 6 The normalized profile of the brightness along the leading-edge for each time slice of the target image. (#23635)

second harmonic X-mode ECH launching from a top port located in a straight section of Heliotron J [8]. The toroidal angle of this section is defined as $\phi = 0.0^\circ$ in this paper. For NBI experiments, the hydrogen beam ($E_{NBI} \sim 28$ kV, $P_{NBI} \sim 0.5$ MW) [9] is tangentially injected into a deuterium target plasma generated by ECH. Selecting one of two beam-lines of NBI, co- or counter-injection experiments can be performed.

The plasma is routinely monitored by using a video camera tangentially viewing from a view-port at $\phi = 202.5^\circ$ (see Fig. 1). In some discharge conditions, we can clearly observe bright images of edge plasma structure and/or divertor footprints on the vacuum camber with this tangential plasma monitor. Figure 4 shows snapshots of the tangential image at four different timings from a discharge (shot number #23635) maintained by NBI-only (co-injection) in a slightly inward-shifted ($<R_0> \sim 1.12$ m) configuration, where some of the whisker field lines cross the wall making footprints on the inboard-side and upper-side of the vacuum chamber (encircled area in the right and upper sides of the figure). Although these snapshots well indicate spontaneous movement of the footprint positions during a discharge, the quantitative estimation of the amount of its shift is not easy because of the tangential view.

Figure 5 shows snapshots of the target image obtained the new monitor system from the same discharge and at the same timings as those in Fig. 4. Here, the target was set at 0.195 m below the equatorial plane ($Z = -0.195$ m). It is shown the position of the bright area changes up and down in the figure for different timings. Here, the top side of each image frame corresponds to the direction of the major axis of the torus. Due to the helical-axis configuration, the plasma column is inclined in this toroidal section and the leading-edge corresponds to the left side of the target. Figure 6 shows the profile of the brightness along the leading-edge for each time slice of the image stack, where the pro-

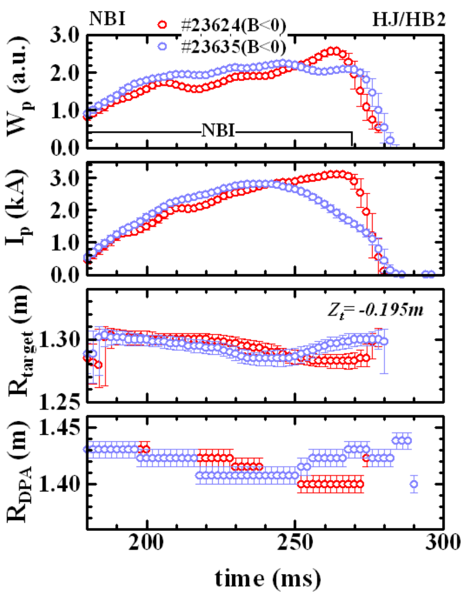

Fig. 7 Time traces of W_p, I_p, R_{target} and R_{DPA} for two NBI-only shots.

file is normalized by the peak intensity in each frame. The horizontal axis in Fig. 6 is the relative distance X along the target. The small circles indicate the peak positions of the normalized intensity, R_{target} in this X-coordinate. This figure clearly shows that the X-value of the peak position increases and decreases back to the original position as a function of time.

4. Discussions

Figure 7 shows the time traces of the stored energy W_p, plasma current I_p, the peak position of the brightness along the leading edge of the target $R_{tareget}$ and the peak position of the ion-saturation current profile R_{DPA} on the divertor probe array at $\phi = 67.5°$, which is the probe-pin position corresponding to the peak position of the ion-saturation current profile at each timing, where both values of R_{target} and R_{DPA} are converted to those in the R (major radius) coordinate. The plasma current is driven by the plasma pressure (bootstrap current) and NBI (Ohkawa current) in this case. Here, we define the direction of the "positive" toroidal current as the direction where the plasma current increases the poloidal field by the coil system. This figure shows the temporal inward shifts of R_{target} and R_{DPA} are well correlated to the change of W_p and/or I_p.

In the shot #23624, W_p and I_p were kept increasing until almost the end of discharge, but in #23635, I_p started to decrease at $t \sim 240$ ms while W_p did not decrease and was kept almost the same value until the end of the NBI pulse. (This difference in W_p and I_p might be attributed to the decrease of plasma temperature due to the increase of radiation-loss for #23635.) As shown in the figure, for #23635 discharge, the inward shifts of R_{target} and R_{DPA} were observed until $t \sim 240$ ms. For $t > 240$ ms, they started to going back to the values at the initial phase of the discharge. This indicates that the shifts of R_{target} and R_{DPA} are more closely related to the change of plasma current. These observations by using different methods at different toroidal and poloidal positions suggest the observed shift of the edge-plasma position is not a local event but a global change of the edge plasma distribution during a discharge. Since a positive plasma current increases the rotational transform from the value for the vacuum condition ($\iota(a)/2\pi \approx 0.56$), this experiment suggests that the deformation of the field topology could be remarkable due to the resonant effect near a rational 4/7 (= 0.571...) even for a small amount of the plasma current ($I_p < 3$ kA in this case). To clarify this point, it is necessary to check the change of edge plasma distribution during discharges with negative plasma currents.

5. Summary

A new two-dimensional imaging system for monitoring the edge plasma distribution is installed in Heliotron J. The system consists of a high-speed video camera and a rail-limiter type carbon target which is adjustable the position to touch a part of the whisker filed lines outside the LCFS. By using this system, a spontaneous shift of diverted plasma position during a discharge was observed in Heliotron J. For discharges with a small non-inductive plasma current ($I_p < 3$ kA) and the plasma stored energy ($W_p < 3$ kJ), the observed shift along the target was an order of a few cm. The observed shift seems to be related to I_p more closely than W_p. The most plausible mechanism for the observed shift is the change of the edge field topology caused by I_p.

Acknowledgments

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