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Experimental study of edge plasma structure in various discharges on compact helical system

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Abstract

Precise measurements of edge density profiles in various discharges have been performed successfully in the compact helical system (CHS) with a thermal neutral lithium beam probe. During high beta discharges, an outward shift of the plasma edge boundary was observed with an increase in the beta value, which was found to agree qualitatively with theoretical calculations. Experiments with different magnetic field configurations, i.e., with limiter, divertor and with an $m/n = 1/1$ island, were also performed. Clear difference in the edge density profiles among the configurations and a large change of plasma parameters in the configuration with the $m/n = 1/1$ island were observed.

Keywords: Boundary plasma; Plasma density diagnostic; Limiter; Stochastic boundary

1. Introduction

In toroidal magnetic confinement systems such as tokamaks and helical devices, the edge plasma or its performance has been considered to be very important since it plays an important role in the overall plasma confinement, and determines the heat and particle fluxes to the limiters or divertor plates [1]. Therefore it is crucially important to study the edge plasma behavior in various discharges by measuring some plasma parameters, e.g., density, temperature and their fluctuations.

Precise measurements of the edge plasma behavior have been performed in the CHS heliotron/torsatron [2,3]. Because of its low aspect ratio of 5, a large Shafranov shift of the magnetic axis takes place, and the plasma boundary moves outward during the high beta discharges. The position of the plasma boundary at any beta value can be calculated theoretically, so that it is meaningful to compare experimental results with theoretical ones. Another interesting characteristic of CHS is its magnetic field structure in the edge region. In toroidal heliotron/torsatron configurations, the toroidal effect makes the separatrix surface fairly vague [4]. The closed surface region is surrounded by the stochastic structure and no clear separatrix exists. If the magnetic field structure in the edge region is changed for some reasons, it is quite important to know the changes of edge plasma parameters because useful information is needed for the control of the edge plasma. In this paper, we intend to investigate the edge plasma behavior related to the edge magnetic field structure, after describing results in high beta experiments.

2. Experimental setup

CHS is a heliotron/torsatron type device with poloidal/toroidal mode numbers of $\ell/m = 2/8$. The major radius R and averaged plasma minor radius a are 1 m and 0.2 m, respectively. The CHS was operated with a toroidal magnetic field B_t of 0.6–0.9 T and experiments were carried out on a hydrogen plasma, which was pro-

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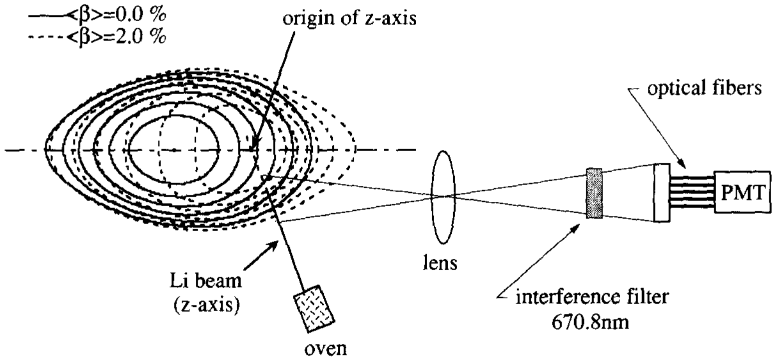

Fig. 1. Schematic drawing of the thermal neutral lithium beam probe. Magnetic surfaces with $\langle \beta_{\text{dia}} \rangle$ of 0% and 2.0% are also depicted.

duced initially by the ion Bernstein wave (IBW). Neutral beam (NBI), whose port-through power was up to 1.8 MW, was injected to sustain and heat the plasma. The averaged electron density $\bar{n}_e$ was $(2.0\text{–}6.5) \times 10^{19}$ m^{-3}.

For the edge plasma control, a movable limiter, whose head was shaped to the magnetic flux surface, was installed to scrape off the edge plasma. Eight pairs of circular coils were also installed above and below the CHS vacuum vessel for applying a resonant perturbation field to generate a magnetic island with poloidal/toroidal mode numbers of $m/n = 1/1$.

A thermal neutral lithium beam probe was used for edge plasma measurements. The beam probe can measure radial profiles of the electron density and its fluctuations simultaneously in one shot and has the advantage over a Langmuir probe of no direct disturbances and no contamination of the plasma. The thermal beam is produced with an oven which is located about 1.4 m apart from the equatorial plane. The beam is collimated with two apertures of 0.01 m in diameter, and injected into the plasma at the angle of 20° to the vertical line. The optical detection system has 10 channels for the profile measurement, and consists of a lens, an interference filter with a spectral bandwidth of 1 nm, optical fibers and photomultiplier tubes (PMT). The spatial resolution of each channel is 5 mm and the distance between adjacent channels is 6–7 mm on the z axis. Here, z is the distance between the measuring point and the midplane along the lithium beam (see Fig. 1).

The signals are digitized at 40 kHz with a transient recorder. We calculate the density profile using a reconstruction method which has been developed recently. This method takes into account the distribution of the beam velocity, and can reconstruct electron density profiles in the density range up to $\sim 1 \times 10^{19}$ m^{-3}.

3. Results and discussion

3.1. Edge plasma behavior during high beta discharge

A high beta experiment was performed using two tangentially-injected neutral beams with the strong gas puffing, and a volume-averaged beta value $\langle \beta_{\text{dia}} \rangle$ up to 2.1% was achieved in the reheat mode [5].

In Fig. 2(a), the temporal evolution of edge density profiles measured with a lithium beam probe is presented. According to the numerical calculation of magnetic field lines in the vacuum configuration, the last closed flux surface (LCFS) is located at $z \sim 0.12$ m, close to the position where the density profile at $\langle \beta_{\text{dia}} \rangle = 0.02\%$ changes its gradient. By comparing the profiles at $\langle \beta_{\text{dia}} \rangle = 0.8\%$ with that at 0.02%, it can be seen that the position where the density gradient becomes steep shifts outward more than 0.01 m from the position at $\langle \beta_{\text{dia}} \rangle = 0.02\%$, and keeps expanding up to $z \sim 0.143$ m at the increased beta value $\langle \beta_{\text{dia}} \rangle = 1.75\%$.

The outward shift Δz of the edge plasma boundary with the increase in $\langle \beta_{\text{dia}} \rangle$ was estimated by three-dimen-

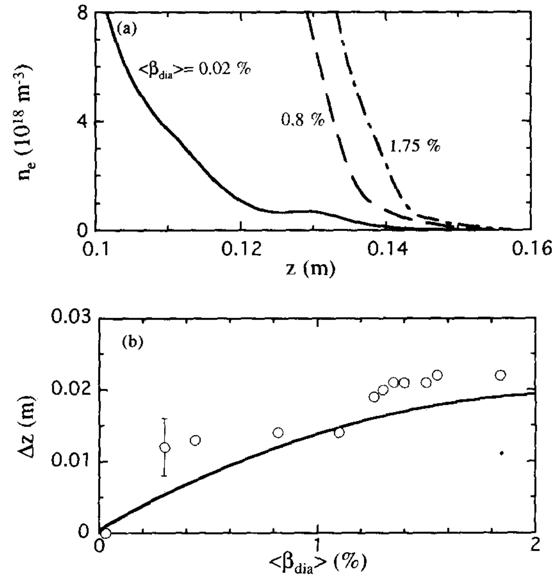

Fig. 2. (a) Edge density profiles during high beta discharge and (b) dependence of boundary shift Δz on $\langle \beta_{\text{dia}} \rangle$. The solid line and circles are for calculated and experimental results, respectively.

sional MHD equilibrium calculations (free-boundary VMEC code [6]), and it was compared with the experimental results. Since it is difficult to find the LCFS position in the experiment, we compared the calculated LCFS shift at finite beta from vacuum with the measured edge boundary shift from the lowest $\langle \beta_{\mathrm{dia}} \rangle$ of 0.02% ($\sim$ 0%). Here the edge boundary is defined to be the position where the density gradient becomes steep, and the edge boundary shift is assumed to be equal to the LCFS shift. Fig. 2(b) shows the $\langle \beta_{\mathrm{dia}} \rangle$ dependence of the shift Δz from vacuum. Open circles and the solid line represent experimental and calculated results, respectively. It is found that Δz's measured experimentally agree qualitatively with results by the VMEC calculation.

Another interesting characteristic is that, as $\langle \beta_{\mathrm{dia}} \rangle$ increases, the gradient of the density profile becomes steeper and the normalized density fluctuation $\tilde{n}_e/n_e$ becomes smaller, although the fluctuation amplitude (not normalized) sometimes increases when the edge density increases. Such tendency as observed in CHS is similar to that observed in the TEXTOR tokamak [1].

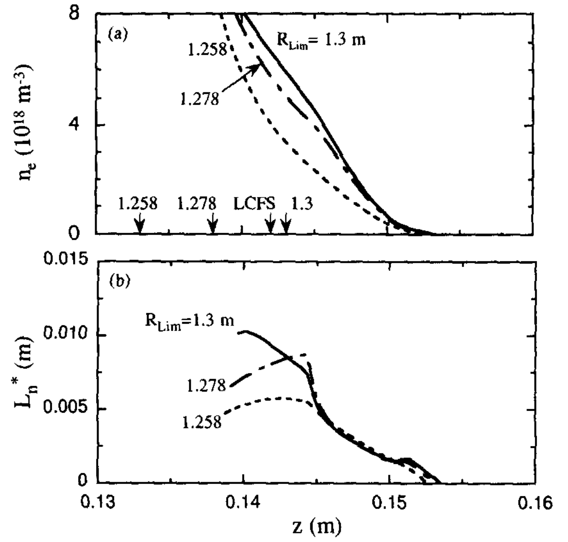

Fig. 3. (a) Edge density profiles and (b) density scale length profiles in the divertor and limiter configurations.

3.2. *Effect of magnetic field structure on edge plasma property*

For heliotron/torsatron type devices, a built-in divertor configuration exists [4]. Although a full divertor configuration can not be achieved in CHS because of the small size of the device, the difference between limiter and divertor configurations has been identified in the numerical calculation of magnetic field lines. In order to know the effect of the magnetic field structure on plasma especially in the edge region, a movable pump limiter, whose head was shaped to the magnetic flux surface, was installed to scrape off the edge plasma.

Fig. 3(a) shows the edge density profiles measured in divertor and limiter configurations, characterized by limiter positions from $R_{\mathrm{Lim}} = 1.3$ m (equivalent to $z = 0.143$ m) to $R_{\mathrm{Lim}} = 1.258$ m (equivalent to $z = 0.133$ m), where R_{Lim} is the limiter distance from the torus center. Positions of the limiter edge and LCFS without the limiter are also depicted on the z-axis in the figure. Note that the limiter was installed on the midplane and 135° apart, in the toroidal direction, from the position where the beam probe was installed. It was impossible to move out the limiter further than $R_{\mathrm{Lim}} = 1.3$ m. Moving the limiter to smaller R_{Lim}, the profile of the edge density shifts inward. In spite of moving the limiter more than 0.01 m on z-axis, the shift of the density profile appeared to be less than 0.005 m. In order to know the edge magnetic field structure, the connection length L_c was calculated for the vacuum configuration. From the calculation it was found that there exists a narrow region at $z \sim 0.14$ m where L_c is more than several hundred meter, even if the limiter is moved to $R_{\mathrm{Lim}} = 1.258$ m ($z = 0.133$ m). This is considered to be one of the reasons why the changes of density profile do not reflect the limiter position so much.

For getting more information from the density profiles, the density scale length L_n^* $(= n_e(\mathrm{d}n_e/\mathrm{d}z)^{-1})$ was calculated, and profiles of L_n^* are presented in Fig. 3(b). It is found that the limiter configuration makes L_n^* short. In the scrape off layer, it is known that L_n^* is a function of L_c according to $L_n^* \sim (DL_c/c_s)^{1/2}$, where c_s and D are the ion sound speed and the radial diffusion coefficient, respectively [7]. In the limiter configuration, e.g., $R_{\mathrm{lim}} = 1.258$ m ($z = 0.133$ m), L_c is smaller than that in the divertor configuration in almost the whole region, except for the peculiar region at $z \sim 0.14$ m which we discussed before. The result of L_c calculation is consistent with the experimental result.

To get more information about the relationship between the magnetic field configuration in the edge region and the plasma behavior, we generate a magnetic island with poloidal/toroidal mode numbers of $m/n = 1/1$, by applying a resonant perturbation field. The magnetic configuration with the island in the poloidal plane at the beam probe is presented in Fig. 4. This configuration is similar to the new boundary control scheme called SHC boundary which was proposed recently and expected to achieve the H-mode and radiative cooling simultaneously [8], although the device size of CHS is not enough to examine the function of the SHC boundary. The ratio of perturbation field to toroidal field was about 0.1%, and the width of the island was about 0.05 m. Little shift of the edge boundary takes place by applying the perturbation field.

Fig. 5 shows the time evolution of the line averaged

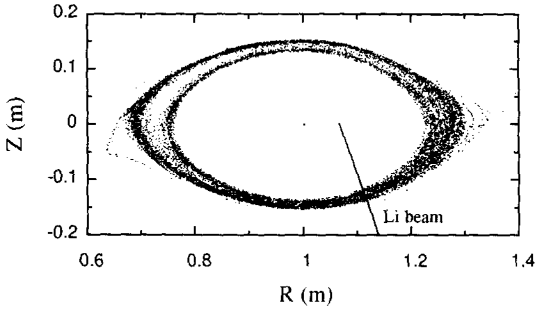

Fig. 4. Magnetic configuration with the 1/1 island in the poloidal plane at Li beam probe.

density $\bar{n}_e$ and the plasma stored energy $W_{\rm dia}$ with and without the perturbation field $\tilde{B}$, together with the time sequence of gas puffing, IBW and NBI. With the existence of the island, it is clearly found that the achieved plasma density is almost half of that without $\tilde{B}$, although the gas puffing rate was the same in both cases. The stored energy is also decreased by applying $\tilde{B}$, but the decreasing rate of $W_{\rm dia}$ is smaller than that of $\bar{n}_e$. This result suggests an increase in the temperature. In fact, other diagnostics (Thomson scattering and Langmuir probe) show the rise in the temperature.

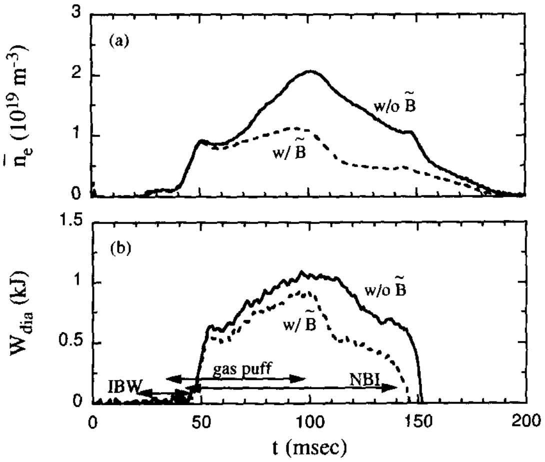

Fig. 5. (a) Time evolution of the line averaged density $\bar{n}_e$ and (b) the plasma stored energy $W_{\rm dia}$ with and without the perturbation field $\tilde{B}$, together with the time sequence of gas puffing, IBW and NBI.

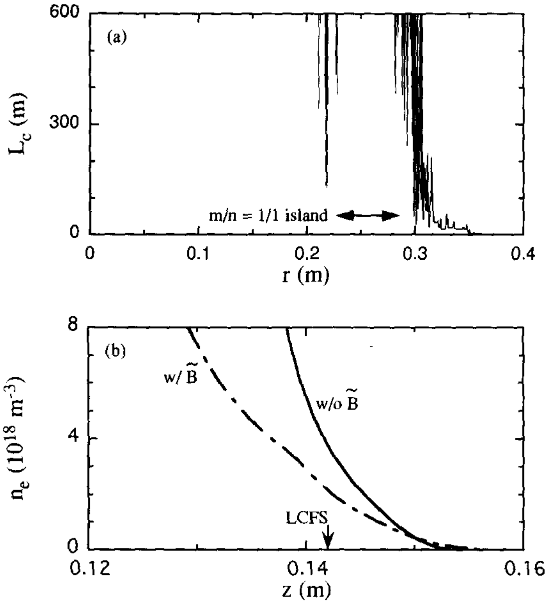

Fig. 6. (a) Connection length L_c with an $m/n = 1/1$ island and (b) edge density profiles with and without the island.

The reduction of the density is considered to be caused by the island. In Fig. 6(a), the profile of the connection length L_c across the O-point of the island is shown. The abscissa is the minor radius. It is found that an ergodic structure is surrounding the closed region and there is a very narrow region, where L_c is short, at the inboard side of the island ($r \sim 0.22$ m). Particles diffusing from the core plasma will soon be removed to the wall, if they come into the region of the island separatrix. Edge density profiles with and without $\tilde{B}$ are presented in Fig. 6(b), together with the LCFS position. When $\tilde{B}$, is applied, the edge density is decreased and the gradient of the profile becomes gentle. No pedestal structure can be seen in the profile with $\tilde{B}$, in spite of the existence of the island. This is due to the observing geometry, as shown in Fig. 4, the beam is injected near the X-point where the island width is small The large diffusion coefficient D in the edge region may also be another reason.

In this experiment, although the L–H transition or other confinement improvement could not be achieved, we could change the global plasma parameter by controlling the edge plasma.

4. Summary

The edge plasma behavior in various discharges was investigated in CHS with a thermal neutral lithium beam probe. An outward shift of the plasma edge boundary more than 0.02 m was observed in the high beta discharge, which was found to agree qualitatively with theoretical calculations with the VMEC code.

In the limiter experiment, it was found that the edge density profiles do not always reflect the limiter position, but may reflect the edge magnetic field structure. For another examination of the edge plasma control, the divertor configuration with an $m/n = 1/1$ island was investigated. In this configuration, not only changes of the edge plasma parameters, but also large changes of the global plasma parameters were observed. This result suggests that this configuration will be useful for the edge plasma control.

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