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Ergodic edge region of large helical device

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Abstract

Ergodicity in various vacuum magnetic configurations in large helical device was quantitatively estimated, using the Kolmogorov length as a measure. It is found that the edge electron temperature profile changes its gradient at the position where the ergodicity begins to increase several cm outside the last closed flux surface (LCFS). In the profiles no distinguished change of plasma parameters was seen at the LCFS, which suggests the existence of a region just outside the LCFS where the confinement performance is relatively as good as that in the closed region. The radial electron heat conductivity was also estimated using a simple energy balance equation and it was confirmed that the conductivity is strongly affected by the ergodicity. Using the relationship between ergodicity and electron heat conductivity, a new practical definition of the LCFS based on the experiments is proposed.

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Keywords: Heliotron; Ergodicity; Kolmogorov length; Divertor; Edge plasma

1. Introduction

One of the features of the heliotron configuration is a thick open ergodic region surrounding closed magnetic surfaces [1]. It is known that the ergodic layer becomes thicker as the magnetic axis shifts outward by means of the vertical field control [2] or as the β value increases. However there has been little information for a heliotron system as to whether the ergodicity itself changes, depending on the magnetic configurations or the β value. Does a thicker ergodic region indicate high ergodicity? Or, can the thickness of the ergodic region be a measure of ergodicity?

From the viewpoint of energy transport in the edge region, it is also interesting to study the effect of ergodicity on heat and particle transport through the formation of density and temperature profiles. Although magnetic field lines in the ergodic region have radial deviation or diffusion, they are long enough to sustain plasmas with sufficient temperature and density. Actually the electron temperature and density just outside the last closed flux surface (LCFS) are relatively high and no clear change can be seen in those profiles. This kind of 'paradox' may come from the definition of the LCFS now in use.

In this paper ergodicity of the edge region in the large helical device (LHD) is estimated quantitatively for each vacuum magnetic field configuration and the relationship between ergodicity and the edge transport property is discussed mainly, leading to a proposal for a new practical LCFS definition. In Section 2, characteristics of the edge magnetic field structure of LHD are presented. After describing the numerical method and experimental conditions in Section 3, results and discussions are presented in Section 4, finally a summary is given in Section 5.

2. Edge magnetic field structure of LHD

The LHD is the largest superconducting heliotron device of which poloidal/toroidal period numbers are

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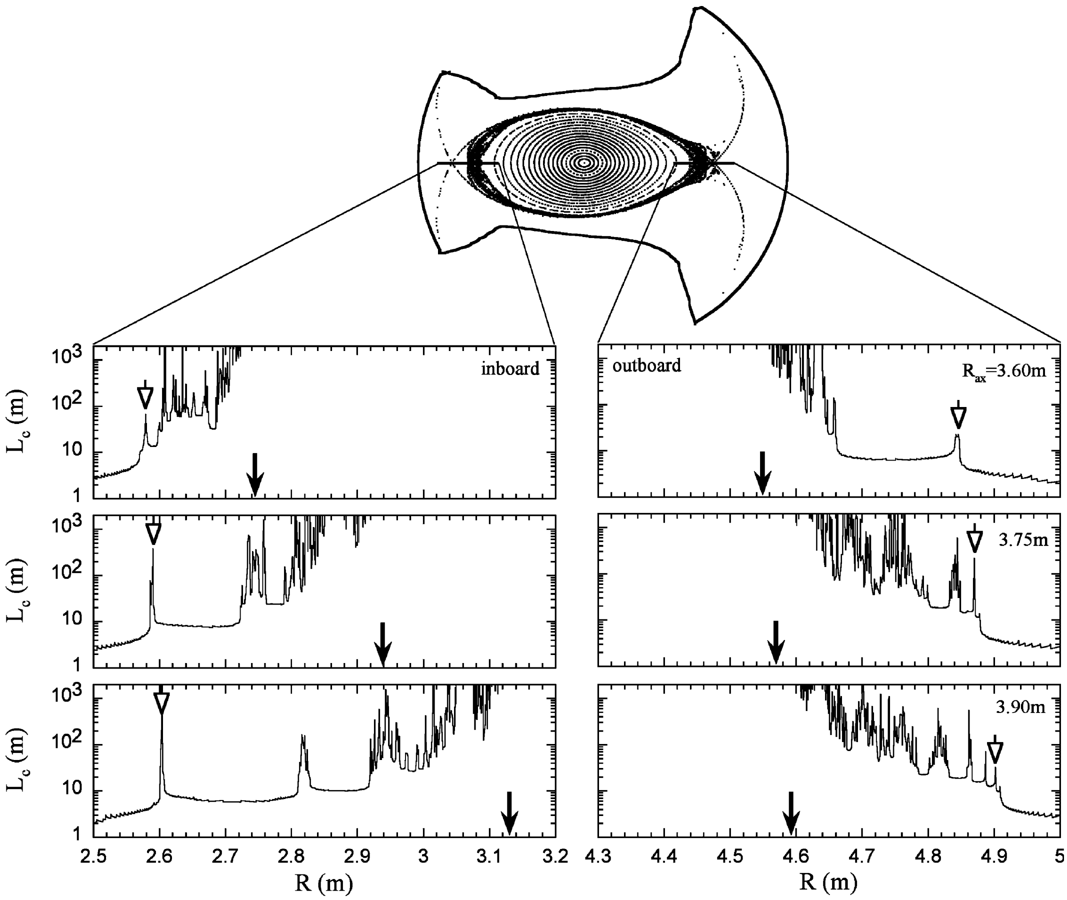

Fig. 1. Connection length L_c profiles on the midplane for different magnetic axis positions R_{ax} where flux surfaces are horizontally elongated (shown in the inset). Left and right columns are for the inboard and outboard sides of the torus, respectively. The LCFS and ergodic boundary are depicted with closed and open arrows, respectively.

2/10, major radius and averaged minor radius are 3.9 and 0.6 m, respectively [3]. Fig. 1 shows the connection length L_c profiles on the midplane for three different magnetic axis positions R_{ax} in vacuum, where the plasmas are horizontally elongated. Left and right columns are for inboard and outboard sides of the torus, respectively. Closed arrows in each figure indicate the LCFS positions defined as follows, i.e., the outermost flux surface on which the deviation of the magnetic field line is less than 4 mm while it travels about 1000 m along the torus. Outside the LCFS the ergodic region spreads, which is depicted by the number of L_c peaks.

The LCFS position on the inboard side shifts about 0.4 m in the range $3.6 < R_{ax} < 3.9$ m, while LCFS on the outboard side keeps its position within a few cm. The boundary of the ergodic region on both sides (open arrows) also shifts little. These results can be interpreted such that, in the LHD heliotron configuration, magnetic surfaces and the ergodic region are allowed to exist in the region where $R = 2.6 - 4.9$ m, as if there were limiters at $R \sim 2.6$ and 4.9 m [4]. In the outward shifted configuration, the virtual limiter on the outboard side scrapes closed surfaces off making the scrape off layer (SOL) ergodic. Consequently the confinement volume decreases and the ergodic SOL on the inboard side becomes thick. These 'limiters' are so rigid that plasmas cannot be attached to the wall even if the vertical field is fully controlled to push the plasma column in or back.

Outside of this ergodic region, there exist four intrinsic divertor legs between the X-points and the wall. Diffused particles from the core region escape, through the ergodic region, the X-point and finally the divertor leg, to the wall.

3. Numerical method and experimental conditions

In the ergodic region magnetic field lines present chaotic trajectories. A flux tube there deforms its shape and the circumference d of the tube increases exponentially [5], which is described as $d(l) = d_0 \exp(l/L_K)$ where d_0, l and L_K are initial value of the circumference, length of the flux tube and Kolmogorov length, respectively. Since L_K is the e-folding length of the exponential increase of the circumference, it can be a good measure of ergodicity [6]. In order to obtain L_K 100 field lines were traced for 50 toroidal turns, i.e. ~1200 m, from the circularly distributed starting points whose diameter was 1 mm on the poloidal plane. Then the circumference d of the flux tube was measured every toroidal turn, which resulted in the averaging effect over one toroidal turn in measuring d. If the field line hits the wall during the trace, the calculation was stopped at that point. Small bundles of starting points were distributed every 5 mm from just inside LCFS to the X point on the midplane at the poloidal cross section where plasmas are horizontally elongated. These bundles were exactly on the line of sight of the Thomson scattering. Fig. 2 shows an example of calculations in the configuration of $R_{ax} = 3.6$ m. For each radial position, the growth of the circumference d of the flux tube from the initial small circle is depicted as a function of flux tube length. In this configuration the LCFS is at $R = 4.548$ m. Fitting a straight line to $\ln(d)$, its slope provides the inverse Kolmogorov length L_K^{-1} which represents the ergodicity itself, i.e. large L_K^{-1} means large ergodicity. One can easily distinguish the ordered region, i.e., inside the island or LCFS, from the ergodic region, since flux tubes there do not grow exponentially, but linearly or flat (e.g. at $R = 4.555$ m).

Experiments in LHD were carried out with ECH initiated NBI plasma. The averaged electron density and temperature at the center were $\sim 2 \times 10^{19}$ m^{-3} and ~1 keV, respectively. The magnetic axis position R_{ax} was set from 3.6 to 3.9 m. Furthermore, in order to modify the edge magnetic field structure, a perturbation field was externally applied with small loop coils.

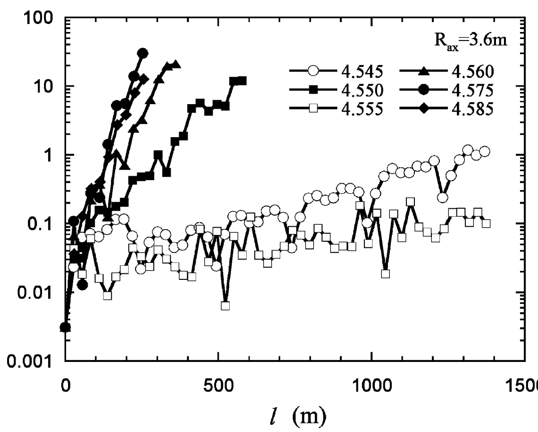

Fig. 2. Growth of the circumference d of the flux tube as a function of the flux tube length. Open circles at $R = 4.545$ m are inside the LCFS and open squares at $R = 4.555$ m are inside the island.

4. Results and discussions

Fig. 3 shows radial profiles of L_K^{-1} for different configurations corresponding to Fig. 1 (outboard). The LCFS positions are also depicted with solid lines. The scattering of L_K^{-1} results from the existence of small remnant islands or thin edge surface layers [1] where the ergodicity is partially small. It is found that L_K^{-1} is an increasing function of R and the gradient of the function is almost the same in each configuration. Therefore the thicker the ergodic region spreads out, the higher L_K^{-1} becomes at the periphery of the ergodic region. At this stage one may say that ergodicity in the thick ergodic region is high. Another important piece of information can be seen in the profiles in Fig. 3. L_K^{-1}'s start to increase abruptly several cm outside the LCFS positions (broken lines). Electron temperature T_e profiles (not shown) obtained with Thomson scattering also become gentle or flat several cm outside the LCFS positions, reflecting the L_K^{-1} profiles. This can be explained by quasi-closed flux surfaces just outside LCFS, which have enough quality to confine plasmas like perfect closed surfaces. The effective confinement boundary seems to exist at the position where L_K^{-1} starts to increase, rather than at the LCFS position. However once field lines start to diffuse

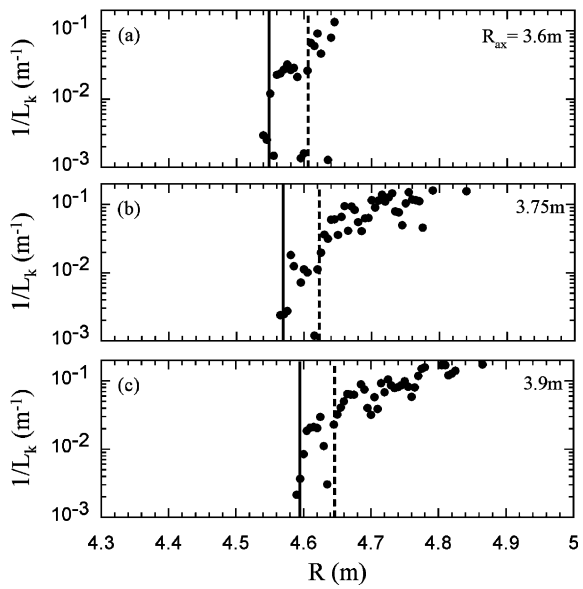

Fig. 3. Radial profiles of inverse Kolmogorov length L_K^{-1} for the same configurations as in Fig. 1. LCFS positions are depicted with solid lines while L_K^{-1} starts to increase at dashed lines.

as the result of ergodization, heat flux can easily propagate in the radial direction, which results in the flattening in the T_e profiles [7]. The ordinary parallel flow has a possibility to flatten the T_e profile, to be sure, not only in the simple tokamak SOL [8] but also in the complicated heliotron SOL. However its contribution to the T_e flattening is smaller than that by the field line ergodization because L_c in the heliotron SOL is much longer than that in the tokamak SOL. In short, the large L_K^{-1} flattens the T_e profile.

A favorable experimental result to show the relationship between the magnetic ergodicity and the temperature profile, as mentioned above, was obtained. In the experiment, the edge magnetic ergodicity was changed by the perturbation field externally applied with ten pair of small loop coils. Fig. 4 shows the radial profiles of (a) inverse Kolmogorov length L_K^{-1} and (b), (c) electron temperature T_e. Open and closed circles are for with and without perturbation field, respectively. It can be seen that ergodicity around the region where $R =$ 4.64–4.70 m is decreased by applying the perturbation field, hence the T_e profile there becomes steeper. Furthermore very small flattening in the T_e profile with the perturbation field can be seen, corresponding to the small increase in L_K^{-1} around the position where $R = 4.50$–4.54 m.

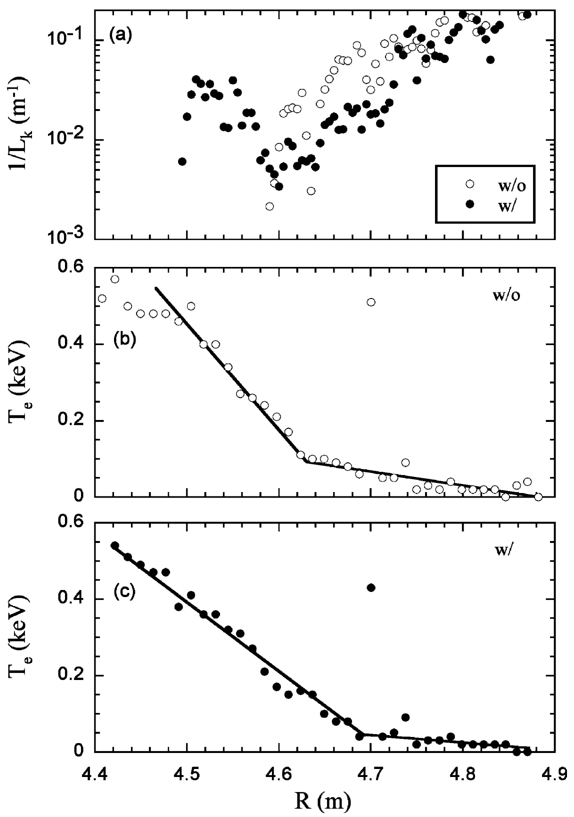

Fig. 4. Radial profiles of (a) inverse Kolmogorov length L_K^{-1} and (b), (c) electron temperature T_e. Open and closed circles are for with and without perturbation field, respectively.

Numerical and experimental results described above strongly suggest that the magnetic structure plays an important role in the profile formation in the edge region. Thus, in order to study the effect of ergodicity on the edge transport property, the relationship between L_K^{-1} and the radial effective electron heat conductivity $\chi_e^{\rm eff}$ was investigated quantitatively. For the $\chi_e^{\rm eff}$ extraction, a simple one-dimensional energy balance equation is applied to the edge region, as follows:

$$\frac{d}{dt}\left(\frac{3}{2}n_e kT_e\right) = P_{\rm abs} - P_{\rm loss} + \frac{1}{r}\frac{\partial}{\partial r} r\left(n_e\chi_e^{\rm eff}\frac{\partial kT_e}{\partial r} + D\frac{3}{2}kT_e\frac{\partial n_e}{\partial r}\right), \quad (1)$$

where no energy transfer between ion and electron, no energy loss by radiation or charge exchange processes, and no energy absorption are assumed in the steady state edge region. Neglecting the convective term in Eq. (1), the result was not so different from that obtained from substituting 0.1 m^2/s for the diffusion coefficient D, which has been found in another experiment. Fig. 5 shows the radial edge electron heat conductivity $\chi_e^{\rm eff}$ as a function of the inverse Kolmogorov length L_K^{-1}. Some data points with relatively large $\chi_e^{\rm eff}$ at $L_K^{-1} \sim 0$ (enclosed with an ellipse) are of small remnant islands in the ergodic sea. The islands are so small, compared to the spatial resolution of the diagnostics or the transport scale length in the ergodic region, that $\chi_e^{\rm eff}$ is observed to be as high as that of the ergodic region surrounding the islands. The important information presented in Fig. 5 is that $\chi_e^{\rm eff}$ does not change so much when L_K^{-1} is small,

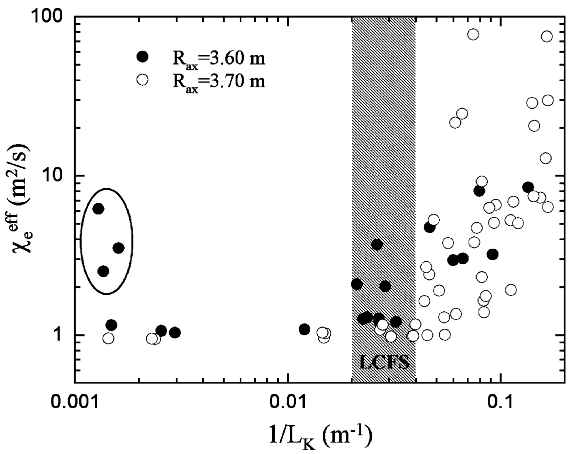

Fig. 5. Radial electron heat conductivity $\chi_e^{\rm eff}$ as a function of the inverse Kolmogorov length L_K^{-1}.

however it increases rapidly in the region where $L_K^{-1} \sim 0.2$–$0.4\ m^{-1}$, showing a threshold property. Utilizing these characteristics of the χ_e^{eff} behavior, it may be possible to define the practical LCFS at the position where $L_K^{-1} \sim 0.2$–$0.4\ m^{-1}$. It may be better to use this new LCFS definition based on the experiment, e.g., as the boundary condition in the equilibrium calculation. Further experiments are required in order to prove the validity of the new procedure.

5. Summary

Ergodicity in various vacuum magnetic configurations for LHD was quantitatively estimated by the measurement of Kolmogorov length. It is found to be about 30 m (for $R_{ax} = 3.6$ m)–10 m (for $R_{ax} = 3.9$ m), which is shorter than that in W7-X [6]. Existence of the high shear region in the heliotron configuration may be one of the reasons for this. Furthermore the condition $L_K < L_c$ is fulfilled everywhere in the edge region, which means that the LHD edge region is sufficiently ergodic to show its characteristics.

Estimation of the ergodicity under finite β conditions should be required for future experiments with higher heating power. A new edge analysis code coupled with the HINT code is being prepared.

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