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Relationship between Edge Magnetic Field Structure and Density/Temperature Profiles in LHD Heliotron

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1. Introduction

One of the features of the heliotron configuration is a thick open ergodic region surrounding closed magnetic surfaces [1], which is considered to play an important role in the core plasma confinement via the edge temperature/density profile control, needless to say the screening effect [2,3]. The ergodic layer becomes thicker as the magnetic axis shifts outward by means of the vertical field control or finite beta effect, showing the characteristic profiles of the electron temperature and density for each configuration. Although the fine structure of the ergodic layer and the dependence of its thickness on the magnetic axis position were studied in detail [4], ergodicity itself in each configuration has not been estimated quantitatively. Furthermore, taking account of the fact that magnetic field lines just outside the last closed flux surface (LCFS) are long enough to sustain plasmas with sufficient temperature and density, there has not been a appropriate criterion to determine the effective boundary position of the confinement region.

In this paper ergodicity in each vacuum magnetic field configuration for the Large Helical Device (LHD) [5] is estimated quantitatively and the relationship between edge ergodicity and temperature profiles is mainly discussed.

2. 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, 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. In order to obtain an L_K, 100 field lines were traced for 50 toroidal turns, i.e. ~ 1200m, from the circular starting points with 1mm in diameter on the poloidal cross section. 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. Small bundles of field lines for starting points were distributed on the midplane at the poloidal cross section where plasmas are horizontally elongated, and are exactly on the line of sight of the Thomson scattering. Field line tracing for the calculation of L_K and connection length L_c were performed by KMAG code.

Experiments in LHD were carried out with ECH initiated NBI plasma. The averaged electron density and temperature at the center were $\sim 2\times10^{19}\mathrm{m}^{-3}$ and ~1keV, respectively. The magnetic axis position R_{ax} was set from 3.6m to 3.9m. Furthermore, in order to change ergodicity, perturbation field externally applied by small coils was also employed in addition to the dipole field control.

3. Results

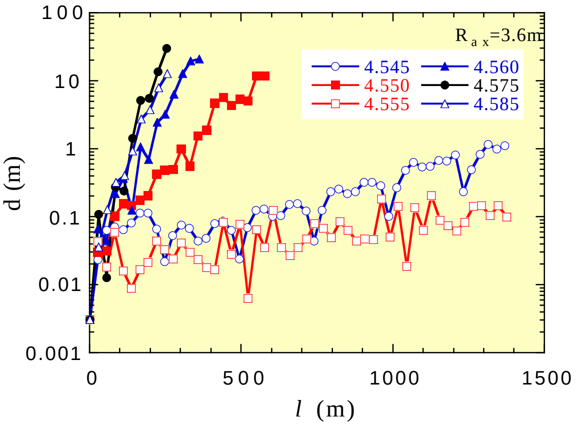

Fig.1. Circumference d of flux tubes as a function of flux tube length.

In order to obtain radial profiles of Kolmogorov length $L_K(R)$, calculations were performed every 5mm from just inside LCFS to near the X point. Figure 1 shows a example of calculations in the configuration of R_{ax}=3.6m. For each radial position, growth of circumference d of flux tube from the initial small circle is depicted as a function of flux tube length. Numbers in the legend of the figure are corresponding to radial positions of start points of the flux tubes. Note that LCFS is at R=4.548m in this configuration. 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., island or inside LCFS, from the ergodic region, since flux tubes there do not grow exponentially, but linearly or flat. Even a negative slope one can sometimes see in a magnetic island. From Fig.1, it is found that field lines outside LCFS are scattered and the growth rate of the circumference of the flux tube is indeed high, except for R=4.555m where a small magnetic island exists.

Utilizing the procedure explained above, some L_K profiles were obtained for different magnetic configurations, and compared with electron temperature and density profiles measured by the Thomson scattering method. In Fig.2 radial profiles of (top) connection length L_c, (mid) inverse Kolmogorov length L_K^{-1} and (bottom) electron temperature T_e on the outboard side of the torus are shown for different magnetic configurations. Left and right columns are for R_{ax}=3.6m and 3.7m, respectively. It is found that, from the L_K^{-1} profiles, ergodicity in R_{ax}=3.7m is larger than that of R_{ax}=3.6m's, in addition to thicker ergodic layer. At R~4.60m and ~ 4.63m, there are two dips in L_K^{-1} profile in the R_{ax}=3.6m configuration, indicating the existence of magnetic islands, which is advantage of L_K^{-1} profile to the L_c profile because we cannot distinguish the island from ergodic region in L_c profiles.

T_e profiles at the bottom of Fig.2 are measured by the Thomson scattering method with good time and spatial resolutions. Although the error bar for absolute T_e is large because of weak emission from edge plasmas, qualitative discussion about its profile may be possible. Furthermore the position uncertainty of each channel is within 20mm, which should be taken into account.

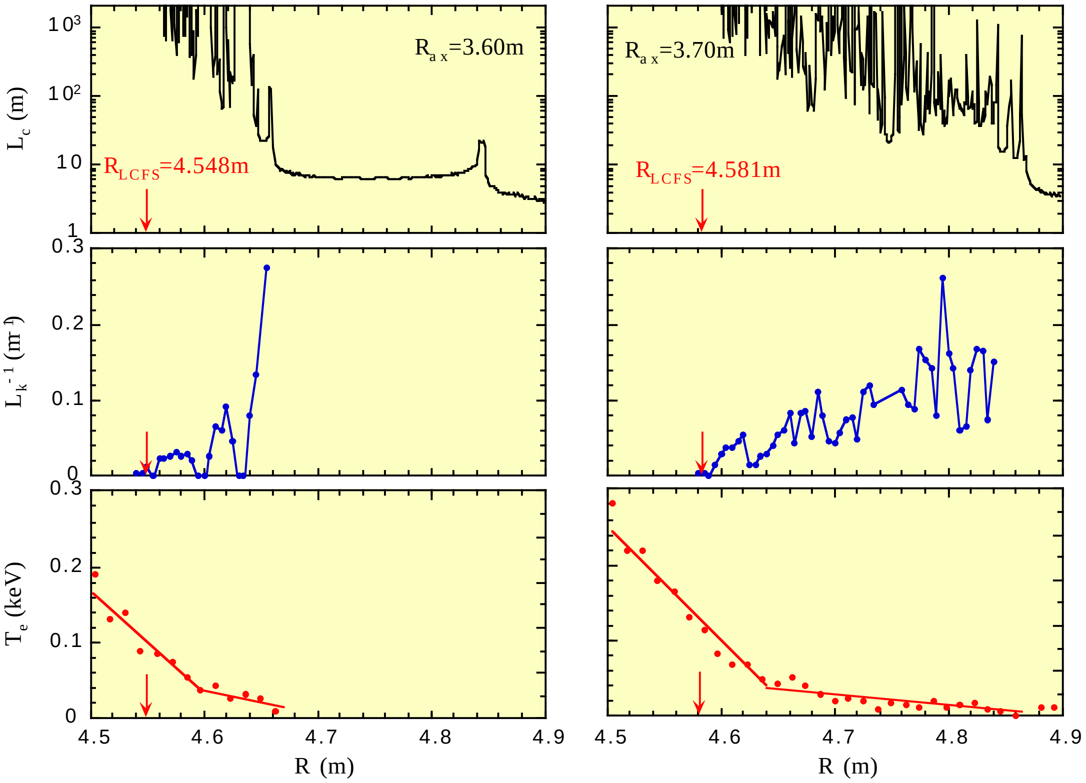

Fig.2. Radial profiles of (top) connection length L_c, (mid) inverse Kolmogorov length L_K^{-1} and (bottom) electron temperature T_e. Left and right columns are for R_{ax}=3.6m and 3.7m, respectively.

Considering the relationship between T_e profiles and the magnetic field structure in the edge region, it is found that the position where the gradient of the T_e profile changes is not corresponding to the LCFS position. This can be explained that there are quasi closed flux surfaces just outside LCFS, which have enough quality to confine plasmas as perfect closed surfaces. In order to confirm the position where field lines lose their ordered properties for “closed” surfaces, the position where L_K^{-1} begins to rise provides good information. Once field lines start to diffuse as the result of ergodization, heat flux can easily cross in the radial direction, which results in the flattening in T_e profiles [6]. We can see results of this process in Fig.2. Flattening in T_e profiles takes place where L_K^{-1} is large, and the folding point of T_e profiles, where transport properties are changed significantly, is almost corresponding to the position where ergodicity L_K^{-1} starts to rise suddenly.

For the active edge control there are ten pair of small coils in LHD. Utilizing these coils, a perturbation field was applied to increase ergodicity in the edge region. Experiments were carried out in the R_{ax}=3.9m configuration which has no resonant surfaces with an m/n=1/1 component. Figure 3 shows radial profiles of (a) inverse Kolmogorov length L_K^{-1} and (b) electron temperature T_e . Although the ergodic region broadens out a little, ergodicity itself does not change so much. Therefore very small flattening can be seen in T_e profiles. For both configurations folding points in T_e profiles are clearly corresponding to the position at R~4.7m where ergodicity L_K^{-1} starts to rise.

Discussion

In the LHD edge region Kolmogorov length L_K in the vacuum field is about from ~30m for R_{ax}=3.6m to ~10m for R_{ax}=3.9m, which is shorter than those in W7-X [7]. Existence of the high shear region in the heliotron configuration may be one of reasons of it. Furthermore, in LHD, the condition $L_K < L_c$ is always fulfilled everywhere, which means that the LHD edge region is sufficiently ergodic to show its characteristics.

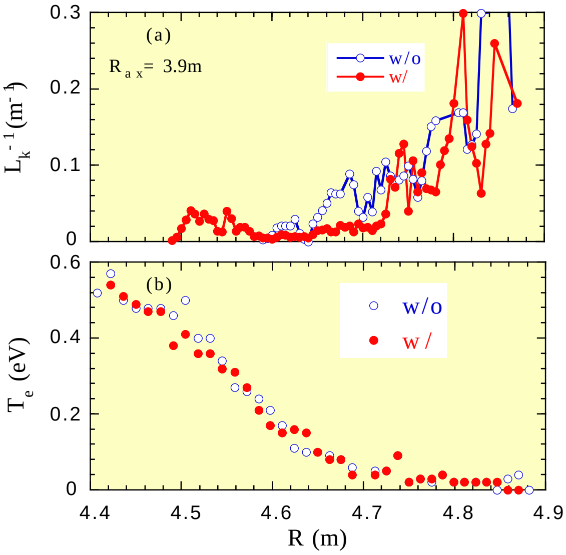

Fig. 3. Radial profiles of (a) inverse Kolmogorov length L_K^{-1} *and (b) electron temperature* T_e .

With regard to electron density profiles, they are more expanded than those of T_e. In order to discuss about both profiles at the same time, estimation of neutral source and so on should be carried out.

Summary

Ergodicity in various vacuum magnetic configuration for LHD was quantitatively estimated by measure of Kolmogorov length, which is found to be about 30-10m. In electron temperature profiles, there exist flattened regions where ergodicity of the magnetic structure is high enough.

Estimation of ergodicity under finite beta conditions should be required for future experiments with higher heating power. From the coming experimental campaign, LHD will equip some new edge diagnostics, so that more precise information will be provided.

References

[1] N. Ohyabu, et al., Nucl. Fusion **34** (1994) 387.
[2] S. Morita, et al., *26th EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14-18 June 1999 ECA Vol.23J (1999) 1321.*
[3] S. Masuzaki, et al., *26th EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14-18 June 1999 ECA Vol.23J (1999) 1345.*
[4] T. Morisaki, et al., Contrib. Plasma Phys. **40** (2000) 266.
[5] O. Motojima, et al., Phys. Plasmas **6** (1999) 1843.
[6] Ph. Ghendrih, et al., Plasma Phys. Control. Fusion **38** (1996) 1653.
[7] E. Strumberger Contrib. Plasma Phys. **38** (1998) 1/2. 106.