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Relationship between Magnetic Field Structure and Plasma Density Profile in LHD Edge Region

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Abstract

Magnetic field structure and edge plasma density profile in the large helical device are studied. Using a lithium beam probe, we obtained the edge density profiles, which show some relation with magnetic field topology there. We select Lyapunov exponents as a quantitative measure and study the magnetic field structure just outside of the last closed magnetic surface. It is shown that the position of small natural islands is one of key parameters which determines plasma density foot points.

Keywords:

Large Helical Device (LHD), Last closed flux surface (LCFS), Separatrix Layer, Li beam probe, Lyapunov exponent, magnetic island, connection length

1. Introduction

The last closed flux surface (LCFS), which define the boundary between nested magnetic surfaces and the so-called separatrix layer is one of the key parameters for the coil winding design of the helical experimental devices. Due to the complicated ergodic properties, however, its position is still unclear [1]. Moreover, this ergodicity is thought to change with the magnetic axis shift or the plasma beta effect. Though magnetohydrodynamic (MHD) equilibrium theory gives us a theoretical background on magnetic surfaces in the main plasma region, we have no measure to quantify the magnetic structure of the separatrix layer yet.

In the 6th experimental campaign, detailed electron density profiles of the large helical device (LHD) edge region are measured experimentally with a 20keV lithium beam probe (LiBP) [2]. Especially in low density plasma, density profiles are thought to show some properties of the vacuum magnetic field ergodicity. It will be fruitful to compare the edge density profile and magnetic field structure.

During the past decades, various methods such as connection length, Kolmogorov entropy, and so on have been proposed and tried to study the helical magnetic field ergodicity. In this paper, we calculate the Poincare map of vacuum field lines and their Lyapunov exponents for various LHD magnetic configuration [3]. Lyapunov exponents are the measure of the distance in the phase space between the reference orbit and the neighborhood point.

In the section **2**, the density profile measured with LiBP and its flattening are shown. In the section ***3***, we calculate the connection lengths and maximum Lyapunov exponents of the magnetic field lines. The section **4** is the conclusion on these profiles.

2. Experimental apparatus and density profile results

The LHD is the largest super conducting heliotron device of which poloidal/toroidal period numbers are 2/10, major radius and averaged minor radius are 3.9 and 0.6 [m], respectively [4]. By controlling the vertical field strength, the plasma column, i.e., the Magnetic axis position (R_{ax}) can be shifted.

Edge density profiles ware measured with a LiBP system. The details of its beam injector and its optical detector are reported in [5]. Its beam path does not lay on the poloidal cross section of LHD, so some modification of magnetic field line tracing code such as KMAGN [6] is needed in order to compare with density profile data. We also defined new coordinate (x) along the Li beam path to show the density profile obtained by LiBP. $x = 0$ [m] correspond to torus center (major radius $R = 3.9$ [m]), and density data for $x = 0.3 \sim 1.3$ [m] was obtained. One example of density profile is shown in the Fig. 1. Experiments ware carried out mainly with electron cyclotron heating (ECH) plasmas with the averaged electron density $0.2 \sim 2 \times 10^{19}$ [m^{-3}] and the central

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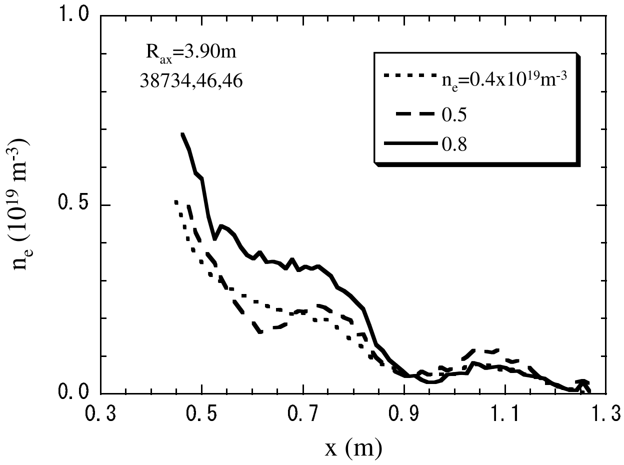

Fig. 1 Flattening in the edge density profile is seen at outside of the LCFS (x ~ 0.6 [m]) in the outward-shiftted magnetic axis configuration. Sub peak around x ~ 1.1 [m] is thought to correspond to the plasma at the divertor leg.

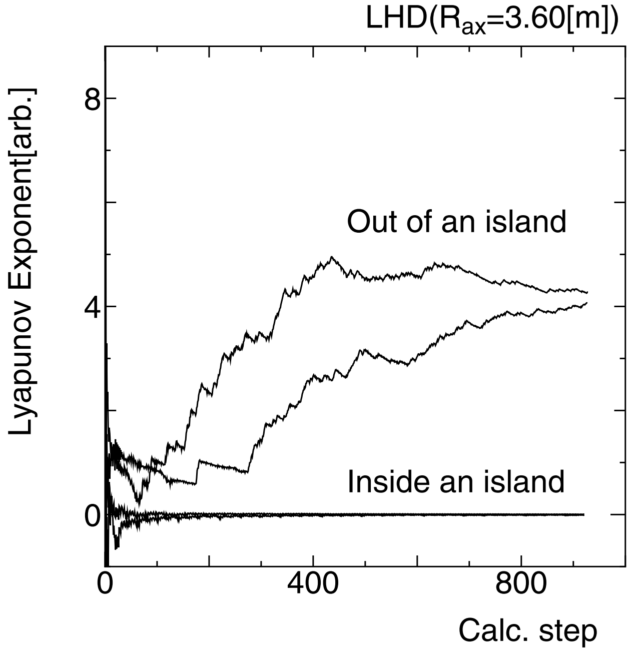

Fig. 2 Maximum Lyapunov exponents (λ_1) are converged after more than 500 step. Inside an island, λ_1 ~ 0. Data of "Inside an island " correspond to these of two field lines which start at x = 0.466 and 0.470 [m]. But, just out of this thin island (x = 0.464 and 0.472 [m]), λ_1 becomes very large.

temperature 1 ~ 3 [keV]. Toroidal magnetic field was ~ 1.5 [T]. Magnetic axis position is R_{ax} = 3.90 [m] and the the position of LCFS deduced from field line tracing calculation is x ~ 0.6 [m]. The foot point in density profile exist at x ~ 0.9 [m]. Even flattening in the edge density profile is seen at outside of the LCFS. This is why the definition of LCFS must be reconstructed. Sub peak around x ~ 1.1 [m] is thought to correspond to the plasma at the divertor leg.

3. Lyapunov exponent and connection length

Lyapunov exponents are One of most promising tools for detecting the onset of chaos of the reconstructed attractor. Though various algorithm to calculate the Lyapunov exponents have been proposed, Wolf's method [7], which counts the expansion of the distance between the reference orbits in the phase space and neighborhood point, is the most convenient to use. About 1,000 step data usually allow the maximum Lyapunov exponent (λ_1) to converge to a constant value.

In the Fig. 2, examples of the Wolf's algorithm calculation are shown for a few field lines with the different start points. Maximum Lyapunov exponents (λ_1) are converged after a few hundreds step. Inside an island, λ_1 ~ 0. Data of "Inside an island " correspond to these of two field lines which start at x = 0.466 and 0.470 [m]. But, just out of this thin island (x = 0.464 and 0.472 [m]), λ_1 becomes very large. On the Poincare map, it is difficult to distinguish this island, since it is masked by the scattering of stochastic field lines. So λ_1 is a nice measure to study magnetic structure in the separatrix layer.

In Fig. 3, the estimated λ_1 and connection length in R_{ax} = 3.90 [m] case are plotted as the function of x defined in the previous section along Li-beam path. The foot point of density profile seems to correspond to the the third peak of connection length (L_c) at x ~ 0.9 [m]. The first or second peak of L_c produce the so-called whisker structure of divertor leg. In these region (x > 0.7 [m]), we can get only a few Poincare plot data so that Lyapunov exponents can not be estimated. Near the LCFS (x ~ 0.6 [m]), however, L_c becomes too large

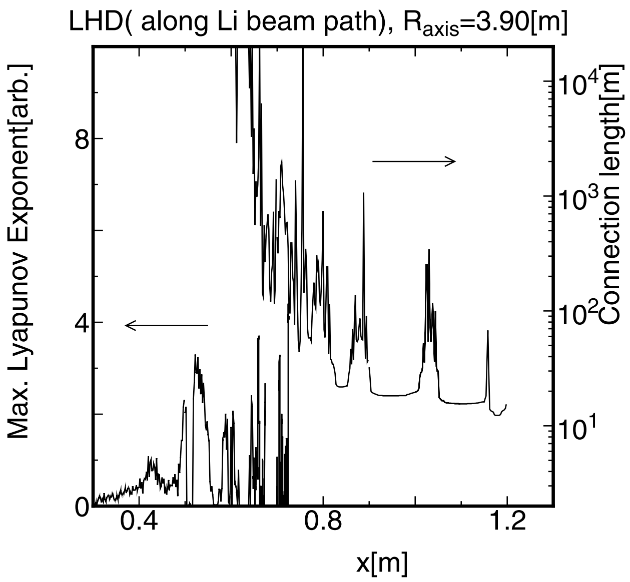

Fig. 3 In R_{ax} = 3.90 [m] case, the foot point (x ~ 0.9 [m]) of density profile seems to correspond to the the third peak of connection length (L_c). The first or second peak of L_c produce the so-called whisker structure of divertor leg. In these region (x > 0.7 [m]), we can get only a few Poincare plot data so that Lyapunov exponent can not be estimated.

to use for studying magnetic field structure. Lyapunov exponent (λ_1) is positive there and magnetic field lines are chaotic ("chaos sea"). But in some place, $\lambda_1 \sim 0$ and regular structure is formed. These correspond to natural magnetic islands.

By studying with the Lyapunov exponent profile more in detail, we can distinguish magnetic islands around $x = 0.51$, 0.57, 0.59, and 0.63 [m]. As for the last island, its width is relatively large (~ 0.02 [m]) and we can see also sub-islands around it in the enlarged Poincare map. This island must be the cause of the density flattening observed experimentally. If a large island exists, rapid motion along the field lines would also enhance the radial particle transport within this island width.

4. Conclusion

The edge plasma density in LHD was measured with LiBP. No change in its profile is seen at LCFS and flattening was observed in the separatrix layer.

The magnetic structure of LHD edge region was studied with the profile of Lyapunov exponent and connection length. As the distance from magnetic axis become larger, Lyapunov exponent increases rapidly near LCFS, When magnetic islands exist, however, Lyapunov exponent becomes zero around there. Lyapunov exponents is a more useful tool than the connection length or Poincare map to distinguish small elongated natural islands in the stochastic layer.

However, some field lines may stay at toroidally-departed place and not to come back to the neighborhood of start points. In this situation, which is the case of divertor legs (or the whisker region) of helical systems, we can neither draw the Poincare map nor calculate Lyapunov exponents. So connection length of field line become a useful tool to study the ergodicity in the divertor legs.

In LHD, local island divertor (LID) experiments are proceeding to control the edge ergodicity of magnetic configuration. The comparison of Lyapunov experiment/ connection length and density profile in this case will be reported elsewhere.

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