Effects of the stochasticity on transport properties in high-β LHD

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Effects of the stochasticity of magnetic field lines on transport properties are investigated. In a high-β LHD plasma, the structure of field lines in the edge region becomes stochastic by finite-β effects but the finite pressure gradient exists in the region. The radial diffusion coefficient and the Kolmogorov length of stochastic field lines are estimated. In the edge region, the radial diffusivity of stochastic field lines becomes large and the Kolmogorov length becomes short due to the increased β. In the region, the radial heat diffusivity becomes large due to the stochasticity of field lines.

Keywords: stochasticity, transport, radial heat diffusivity, HINT2

1. Introduction

Generating and keeping clear flux surfaces are an aim of magnetic confinement researches, because the stochasticity of magnetic field lines leads the degradation of the confinement connecting between core and edge region. There are some analytical works investigating the impact of the stochasticity of magnetic field lines on the radial transport property [1-4]. In those works, Rechester and Rosenbluth pointed out the radial heat diffusivity due to stochastic field lines relates to both the stochastic diffusion parallel and perpendicular to the magnetic field [1].

The stochasticity of field lines due to finite-β effects is an intrinsic property in stellarator/heliotron. Since the pressure-induced perturbed field breaks the symmetry of the field, the structure of magnetic field lines becomes stochastic, especially in the edge. In order to aim stellarator/heliotron reactors, the study of the transport due to stochastic field lines is critical and urgent issue.

The LHD is an L=2 heliotron device. A numerical code to calculate 3D MHD equilibrium without the assumption of nested flux surfaces predicts the field structure becomes stochastic due to the increased β [5,6]. In addition, in numerical simulations, the finite pressure gradient ∇p can exist in the stochastic region [5]. In the edge region of LHD plasmas, the connection length of stochastic field lines is still long compared to the parallel electron mean free path. That is, there is a possibility to keep the finite pressure on stochastic file lines. LHD experiments suggest the plasma pressure spread over the region expected stochastically [7]. This supports above speculation. However, that speculation does not include the effect of stochastic diffusion perpendicular to the field.

In this study, the radial heat diffusivity due to stochastic field lines is investigated in a high-β LHD equilibrium. In next section, the degradation of flux surface quality due to finite-β effects is studied in a LHD configuration. Then, the diffusive property of stochastic field lines is studied. Lastly, results are briefly summarized and shown future subjects.

2. Degradation of flux surface due to plasma β

Figure 1 shows Puncture maps of magnetic field lines for (a) the vacuum field and (b) a finite-β equilibrium on the horizontal cross section. The configuration is an inward shifted configuration (R_{ax}=3.6m, γ=1.254, B_Q=100%). The profile of the normalized plasma pressure p/p_0 is also plotted as the function of R on the equatorial plane. The finite-β field is calculated by HINT2, which is a 3D MHD equilibrium calculation code without the assumption of nested flux surfaces [5]. Since HINT2 uses the real coordinate system, it can treat the magnetic island and stochastic field. The diamagnetic beta $\langle\beta\rangle_{dia}$ is about 3%. For the finite-β, the region with closed flux surfaces decreases and field lines in the edge region becomes stochastic. Chains of small magnetic islands appear. The finite plasma pressure exists in spite of field lines becoming stochastic in the edge (see fig. 2(b)). Two arrows indicate the position of the vacuum last closed flux surface (LCFS) on the equatorial plane. The finite pressure spreads over the vacuum LCFS.

In fig.2, profiles of the electron temperature T_e (#46465, t=1.625), the distance along the magnetic field L_C started along R on the equatorial plane, contour lines with p=*const*. (Z<0) and puncture map of field lines (Z>0) for comparison are shown, respectively. The length of the calculation tracing field lines is limited to 2000m.

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In figs, contour lines p=*const*. exists in the stochastic region with keeping the surface structure. HINT2 calculates converged pressure distribution in the finite-β field by

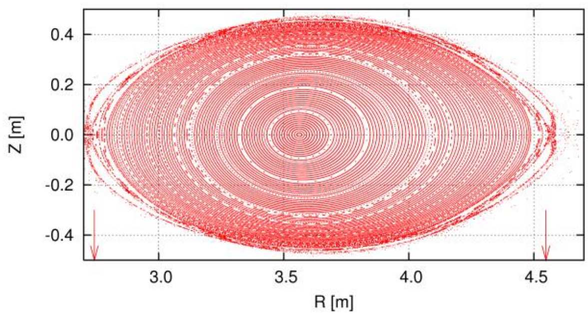
$$p^{i+1} = \bar{p} = \frac{\int_{-L_{in}}^{L_{in}} \mathcal{F} p^{i} \frac{dl}{B}}{\int_{-L_{in}}^{L_{in}} \frac{dl}{B}}, \tag{1}$$

$$F = \begin{cases} 1: \text{for } L_C \geq L_{in} \\ 0: \text{for } L_C < L_{in} \end{cases},$$

where, i means a step number of iterations, L_C is the connection length of a magnetic field line starting each grid point (L_C is finite for open magnetic field lines), and L_{in} is prescribed as an input parameter to control the calculation. Equation 1 calculates the '*averaged*' plasma pressure on the flux tube. This corresponds to simulate the radial diffusion of field lines. In order to consider this effects, profiles of plasma pressure with different L_{in} (=30m and 300m) are shown in fig. 3. For L_{in}=300m, contour lines are different, especially in the stochastic region. If the distance along *B* is shorter than L_{in}, the averaged pressure $\bar{p}$ is set to zero. In fig. 2, since L_C is 10^1~10^2m, the distribution of $\bar{p}$ is sensitive to L_{in}. This study has an assumption that the electron temperature is low because of the consideration of high-β experiments (see fig. 2). Thus, we adopt L_{in} is 30m. As a result, contour lines of p/p_0 is consistent to the temperature profile.

In order to study the degradation of flux surfaces due to the increased β, the change of positions of the LCFS and magnetic axis is shown in fig. 4 as the function of $\langle\beta\rangle_{dia}$. At first, the change of the outward torus is noted. For low-β equilibria (< 1%), the LCFS slightly expands compared to the vacuum field. Then, increasing β (>1%), the LCFS still sustains near the vacuum LCFS. For high-β (>2%), the LCFS shrinks sharply. On the other hand, the inward region, the LCFS degrades monotonically due to the increased β. Thus, we guess the degradation of the transport is significantly important at high-β (>2%). The magnetic axis also monotonically changes due to the increased β. At a high-β ($\langle\beta\rangle_{dia}$~3%), the Shafranov shift Δ/a is about 0.5. However, the MHD equilibrium does not collapse and it is sustained.

(a) vacuum



(b) $<\beta>_{dia}\sim 3\%$

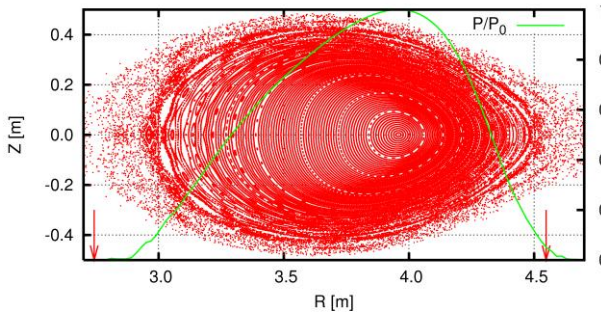


Fig.1 Puncture maps of magnetic field lines for the vacuum field and a finite-β equilibrium ($<\beta>_{dia}\sim 3\%$) are plotted at the horizontal cross section (ϕ=π/M). A green line indicates the normalize plasma pressure p/p_0 as the function of R on the equatorial plane. Two arrows in figs indicate the position of the vacuum LCFS on the equatorial plane.

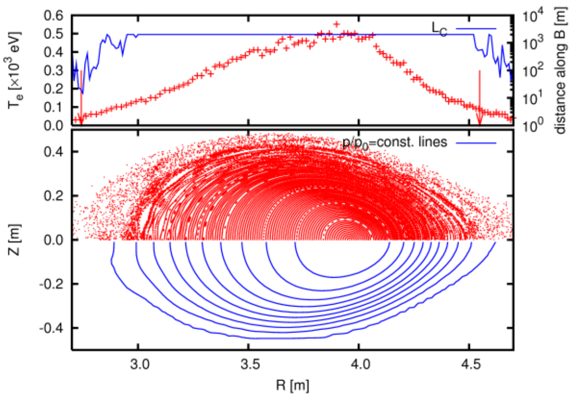


Fig.2 Profiles of the electron temperature T_e (#46465, t=1.625) and the distance along the magnetic field L_C on the plane corresponding to fig. 1(b) are plotted as the function of R. Contour lines with p=const. are also shown for the comparison.

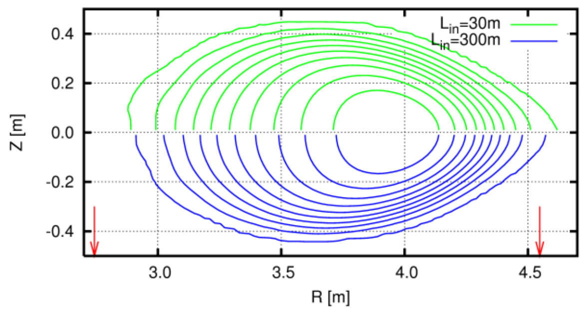


Fig.3 contour lines with different L_{in} (Z>0 and Z<0) are shown at the plane corresponding to fig. 1. Green lines indicate contour lines with L_{in}=30m and blue lines indicate L_{in}=300m. Lines in the edge are different.

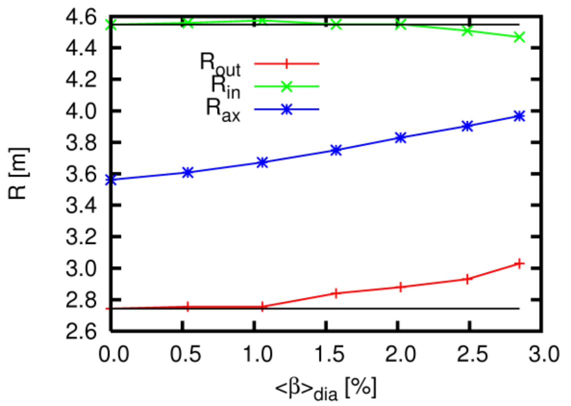


Fig.4 The change of positions of inward (red) and outward (green) LCFS on the plane corresponding to fig. 1is plotted as the function of $\langle\beta\rangle_{dia}$. The shift of the axis is also plotted for the reference (blue).

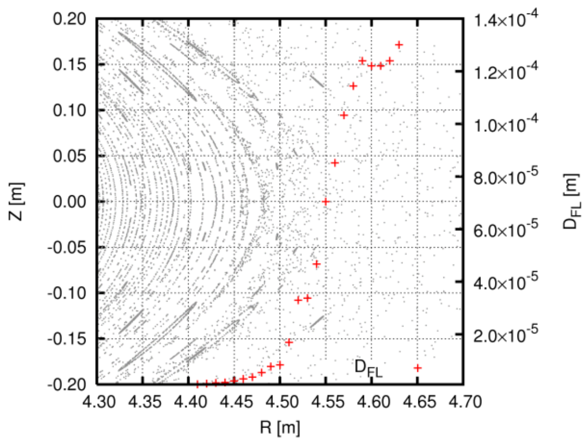


Fig.5 The radial profile of the diffusion coefficient D_{FL} is plotted as the function of R. The puncture map of field lines is also plotted as the reference.

3. Radial heat diffusivity due to stochastic field lines

The radial heat transport increases as it gains the stochasticity. In the collisionless plasma, where the electron mean free path λ_e is very long, the radial heat diffusivity χ_r due to '*only*' the stochasticity of magnetic field lines is given by

$$\chi_r = D_{FL} v_{th} \tag{2}$$

where v_{th} is the electron thermal velocity and D_{FL} is the diffusion coefficient of magnetic field lines and defined by

$$D_{FL} = \langle\Delta r^2\rangle / L_C \tag{3}$$

L_C is the correlation length to calculate the diffusion coefficient. Since χ_e is the contribution of only the stochasticity of magnetic field lines, the effective radial transport χ_{eff} is given by

$$\chi_{eff} = \chi_r + \chi_\perp . \tag{4}$$

On the other hand, in the collisional plasma, Krommes *et al*. identifies three different subregimes with decreasing collisionalty [4], which are fluid regime ($\tau_\perp < \tau_\parallel < \tau_k$), Kadomtsev-Ppgutse ($\tau_\parallel < \tau_\perp < \tau_k$) and Rechester-Rosenbluth ($\tau_\parallel < \tau_k < \tau_\perp$) regime. In typical parameters of LHD experiments, the collisionalty is Rechester-Rosenbluth (RR) regime in the region expected stochastically. The radial heat diffusivity due to the stochasticity of field lines is given by

$$\chi_r = D_{FL} \chi_\parallel / L_k \tag{5}$$

in the RR regime, where L_k is the Kolmogorov length. The Kolmogorov length L_k is a characteristic parameter to mesure the stochasticity [8]. Thus, equation 5 means the parallel contribution of the stochasticity is very important as well as the perpendicular contribution, because L_k plays the role of the correlation length along field lines.

In order to study χ_r, the diffusion coefficient D_{FL} is estimated at first. In fig. 5, the radial profile of the diffusion coefficient is plotted as the function of R. The puncture map of field lines is also plotted as the reference. The procedure to calculate the mean squared radial displacement $\langle\Delta r^2\rangle$ of field lines is following; (i) the distribution of the normalized toroidal flux $s = \Phi/\Phi_{edge}$ is given at first, where Φ is calculated by integrating inside contour lines at p=*const*. (ii) then, the normalized minor radius ρ is calculated and field lines are traced from distributed points on ρ=cont. plane. (iii) in the last, the mean squared displacement of $\langle\Delta\rho^2\rangle$ is calculated with tracing field lines and the distribution coefficient is given by

$$D_{FL} = r_{eff}{}^2 \langle\Delta\rho^2\rangle / L_C , \tag{6}$$

where r_{eff} is the effective minor radius. In fig. 5, D_{FL} is small in clear flux surfaces. However, in the stochastic region, the diffusion coefficient increases rapidly toward the outside of the torus. In the stochastic region, it is expected the perpendicular diffusion is very large.

The Kolmogorov length is also estimated to consider the parallel contribution of the stochasticity. In analyses of edge plasmas, especially the Dynamic Ergodic Divertor (DED), the Kolmogorov length is given by the quasi-linear form [4]. However, since the stochasticity in stellarator/heliotron is caused by pressure-induced perturbation, the number and amplitude of the mode of perturbations are unclear and the calculation of those values is difficult. Thus, we estimate the Kolmogorov length using a following definition,

$$d = d_0 \exp\left(\frac{l}{L_k}\right) \tag{7}$$

where, d is the circumference of small flux tube and l is the length of the flux tube. Using this definition, the impact finite-β effects on L_k is studied in vacuum configurations in LHD [7] and finite-β equilibria in Wendelstein 7-X [8]. In fig. 6, the profile of the inverse of the Kolmogorov

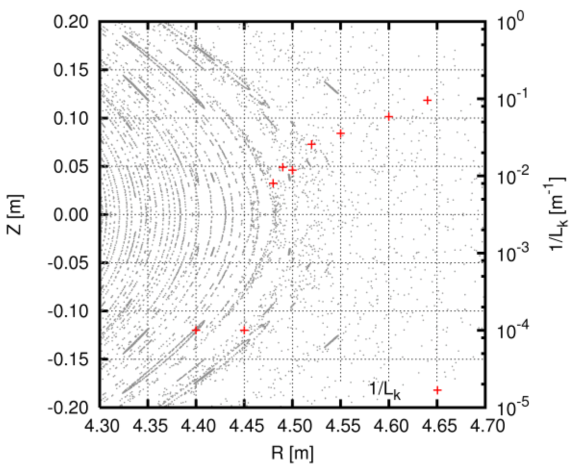


Fig.6 The radial profile of the inverse of the Kolmogorov length L_k is plotted as the function of R. The puncture map of field lines is also plotted as the reference.

length is plotted as the same plot corresponding to fig. 5. The inverse of the Kolmogorov length rapidly becomes long exponentially. This suggests the stochasticity of field lines increases with short length. In the outermost position to calculate L_k (R=4.64m), L_k is about 11m.

Finally, we estimate the radial heat diffusivity χ_r. At R=4.64m, D_{FL} and L_k are about 10^{-4} and 11, respectively. In fig. 2, the electron temperature is about 20~30eV. If T_e = 30eV and $n_e = 10^{19}m^{-3}$, $\chi_r \sim 25m^2/s$. This is very large compared to χ_{eff} of the local transport analyses in the plasma core [9]. The comparison of the experiments and other estimation, which are obtained from the transport code for the edge plasma [10], is a future subject.

4. Summary

The stochasticity of magnetic field lines and effects on the transport properties due to finite-β effects are investigated. Flux surfaces keeps clear structure until the intermediate-β (<2%). However, for high-b, flux surfaces rapidly degrades due to the increased b. Characteristic properties, which are the diffusion coefficient of magnetic field lines and the Kolmogorov length are estimated. In a high-b equilibrium, stochastic properties appear in the edge. Using Rechester-Rosenbluth formulation, the radial heat diffusivity due to only the stochasticity of magnetic field lines. The estimated diffusivity is very large. It is necessary the comparison to the experiments and other estimation.

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