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Particle Orbit Analysis and Magnetic Surface Measurement Plan for LHD

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Abstract

The simple method for evaluating the cleanness of the magnetic surface is presented. The parameter residue is applied to analysis of the magnetic surface in LHD in the case with vertical displacement of a poloidal coil. The magnetic surface measurement plan and the analysis of the trajectory of the high energy particle are also described.

Keywords:

magnetic surface measurement, residue, lanthanum hexaboride cathode, particle orbit, magnetic island

1. Introduction

In helical systems, clear magnetic surface is crucial to produce high confinement and high temperature plasmas. Huge electromagnetic force, thermal contraction by liquid helium cooling and coil alignment error can cause the slight deformation of coils in LHD. Since the coil deformation can destroy the magnetic surface [1], we plan to measure the magnetic surface of LHD in the high magnetic field (~ 4 Tesla) before plasma discharge experiments. This plan is described in section 2.

The magnetic island induced by deformation of coils can deteriorate the plasma confinement and can affect the heating efficiency by the high energy protons injected from the NBI. We analyze the trajectory of the high energy proton in the case with the magnetic islands in section 3.

In order to diminish magnetic island size, the compensation coils have been used in helical systems. Since finding the optimized configuration of compensation coils is time consuming, it is useful to define a parameter measuring the magnetic surface cleanness. Using this parameter, we can obtain the most optimized configuration of the compensation coils. In LHD, twenty local island divertor (LID) coils which can be used as compensation coils are installed on the cryostat. In the case that the error magnetic field is not negligible, we can find the most optimized current configuration of LID coils by using the residue. We introduce the parameter residue to analyze the magnetic surface cleanness and the stochasticity of the magnetic field line, and apply this parameter to investigation of the magnetic field configuration with poloidal coil deformation in section 4.

2. Magnetic Surface Measurement Plan

In a standard magnetic surface measurement, a fluorescent rod which is scanned across the poloidal torus cross-section has been used. A fluorescent compound emits photons when struck by the electron beam. Since the rod usually emits light at both intersection points with the magnetic surface, we can easily measure the magnetic surface.

A thin tungsten filament has been used as an electron source of the electron gun for conventional

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magnetic surface measurement in low magnetic field [2]. Since the LHD is the superconducting device, we can measure the magnetic surface in high magnetic field (~4 Tesla) which is the same condition in plasma discharge experiments. In high magnetic field, the thin tungsten filament can be broken by the strong electromagnetic force. For this reason, we have a plan to use the lanthanum hexaboride (LaB_6) ceramic cathode in LHD [3, 4]. This cathode has wide electron emission area, high emission current density, and stiff structure. We improved the cathode structure to sustain the strong electromagnetic force. Figure 1 shows the cathode structure. This cathode is directly heated by the electric current of about 30 A. We carried out the operation test for the cathode using a small superconducting magnet to confirm that the cathode can be operated in a high magnetic field of 4 Tesla.

The experiment for extracting the electron beam from the cathode was also carried out. We installed the extraction plate with small aperture (diameter 2 mm) in front of the cathode. Figure 2 shows the dependence of the extracted beam current on the extraction voltage. The maximum beam current of about 7 mA is achieved in high extracting voltage (~250 V). This current is more than 100 times larger than that by the conventional tungsten filament [2]. The maximum current saturates at about 7 mA. The reason for this phenomenon is now under investigation. Since the intensity of photons on the rod depends on the extracted beam current, we can measure the detailed magnetic surface by using the lanthanum hexaboride cathode in high magnetic field.

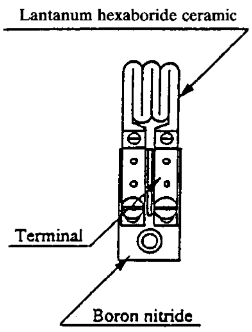

Fig. 1 Lanthanum hexaboride cathode for the magnetic surface measurement in LHD.

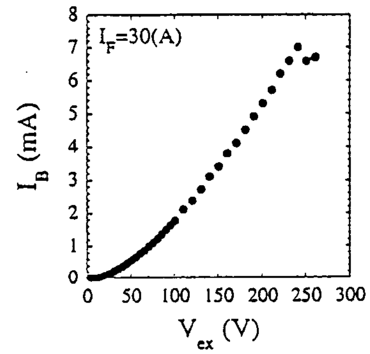

Fig. 2 The measured extracted electron beam current as a function of extracting voltage.

3. Particle Orbit Analysis in LHD

The magnetic surface can be destroyed by subtle deformation of coils. The magnetic surface directly affects the particle orbit and the particle confinement in plasmas. The criterion of the accuracy of magnetic coil installation is within 2 mm in LHD design. Using the helical system design (HSD) code, we investigate the high energy proton (E=100 keV) orbit in the case that the Z-directional deformation of an outer vertical poloidal coil (OV coil) is 20 mm which is ten times larger than the design criterion. In calculation, the current center of poloidal coils is given by using rectangular (X, Y, Z) and cylindrical (R, ϕ, Z) coordinates as following formula:

$$X = R_0 \cos\phi ,$$
$$Y = R_0 \sin\phi ,$$
$$Z = Z_0 + \Delta_Z \cos(N_Z\phi) ,$$

where, Δ_Z means the vertical deformation of an OV coil and N_Z is deformation mode number. The parameter Z_0 and R_0 are determined from the original position of the current center of the coil. Now, we define these parameters Δ_Z, N_Z as 2.0 cm and 1, respectively. Figures 3 (a) and (b) show the standard magnetic surface without and with the coil deformation, respectively. In the case with the deformation, irregular magnetic field produces the poloidal mode number $m=1$ and 2 magnetic islands which resonate with the rotational transform $\iota=1$ and 0.5 magnetic surfaces, respectively.

These islands can degrade the particle and energy confinement in plasmas. To investigate the effect of the magnetic island on the particle confinement and particle heating, we analyzed the trajectory of high energy proton. The large closed circles in Figs. 3 (a) and (b) show the position where the proton emitted from the same position (R=4.16 m, ϕ=0, Z=0.0 m) penetrates $\phi=0$ plane without and with magnetic islands cases, respectively. The proton energy and the pitch angle are

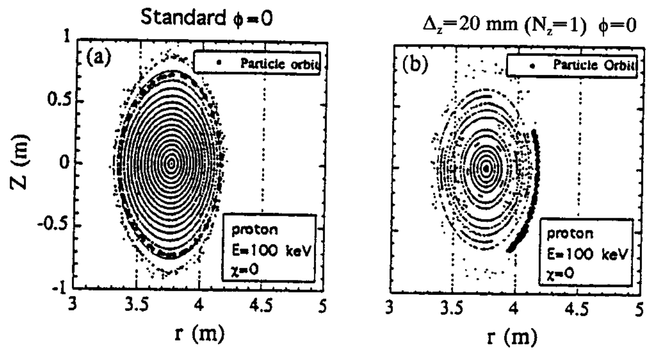

Fig. 3 The magnetic surfaces and the trajectory of the high energy proton (E= 100 keV) in (a) standard operation case and (b) in the case with the 2.0 cm vertically deformation of an OV coil.

set to be 100 keV and 0 degree, respectively. In the case with the magnetic islands, the high energy proton is trapped in the island and the trajectory is limited inside the island. The main plasma heating source in LHD is high energy protons injected from NBI. In the case with the island, the trapped protons can heat plasma locally, which can cause a thermal instability and degrade the plasma confinement. Since the diffusion coefficient of the trapped proton is very large due to the finite island width, the island can decrease the plasma heating efficiency. Therefore magnetic island should be diminished and we must find the most optimized magnetic field configuration without islands. We propose a simple optimization method to achieve this requirement in the next section.

4. Analysis of the Stochasticity of Magnetic Field Line

Conventionally, the compensation coils have been used to modify destroyed magnetic surfaces and to diminish the magnetic islands [5]. To find the most optimized magnetic configuration of compensation coils is very time consuming, and judgment of the cleanness of the magnetic surface is highly subjective. It is useful to define a parameter representing the cleanness of the magnetic surface and the stochasticity of the magnetic field line configuration. For this reason, we introduce the parameter residue $\mathscr{R}$.

The parameter $\mathscr{R}$ is essentially a measure of the magnetic island size and indicates the degree of the stochasticity [6-8]. This indicates that to increase the residues makes the magnetic field configuration more stochastic. For calculating the residue, we must find a point on a rational surface, which is called a fixed point. We calculate the point along the magnetic field line from the fixed point until the calculated point returns to the initial fixed point. We can also calculate the other point along the magnetic field line from near the fixed point. Using the calculated results of the distance of the returned point from the fixed point and that from near the fixed point, we can easily obtain the residue.

Conventional method for evaluating the cleanness of the magnetic surface is to trace the magnetic field line for long time. On the other hand, the calculation scheme of the residue is very simple and not time consuming, but selection of fixed points is important for precise evaluation of the stochasticity. Since magnetic islands on $\iota=1$ and 0.5 surfaces can be easily produced by low N_Z slight deformation of coils, we define the fixed points on $\iota=1$ and 0.5 surfaces. For simplicity, the fixed points are on the line $Z=0$ and the $\phi=0$ plane. In each magnetic surface, we can calculate two residues (inner residue $\mathscr{R}_I$ and outer residue $\mathscr{R}_O$) across the magnetic axis.

We apply the residue to evaluation of the magnetic surfaces in LHD, and investigate the dependence of the residue on the vertical deformation of an OV coil (Δ_Z) and deformation mode number (N_Z), respectively. Figures 4, 5 and 6 show the calculated magnetic surfaces in $N_Z=0$, 1 and 2 cases, respectively. Figures 7 (a), (b) and (c) are the dependence of $\mathscr{R}^2$ on the vertical deformation in $N_Z=0$, 1 and 2 cases, respectively. The value of residues in $N_Z=0$ case is much smaller than that in other two cases, and the magnetic surface is clear with no magnetic islands. In the case of $N_Z=1$, $m=2$ islands are formed across the magnetic axis, and $m=1$ island is also formed in outer peripheral region. In this case, the residues of $m=1$ and 2 increase with the vertical deformation, and the value of outer $m=1$ residue is much larger than inner one as expected from the magnetic surfaces shown in Fig. 5. Finally, in $N_Z=2$

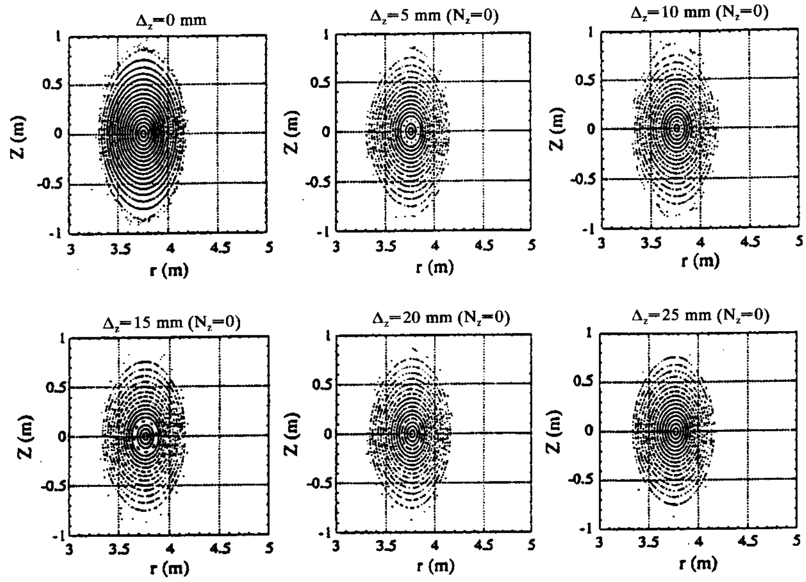

Fig. 4 Magnetic surface destructions due to vertical deformation of an OV coil in the coil deformation mode number N_Z= 0 case.

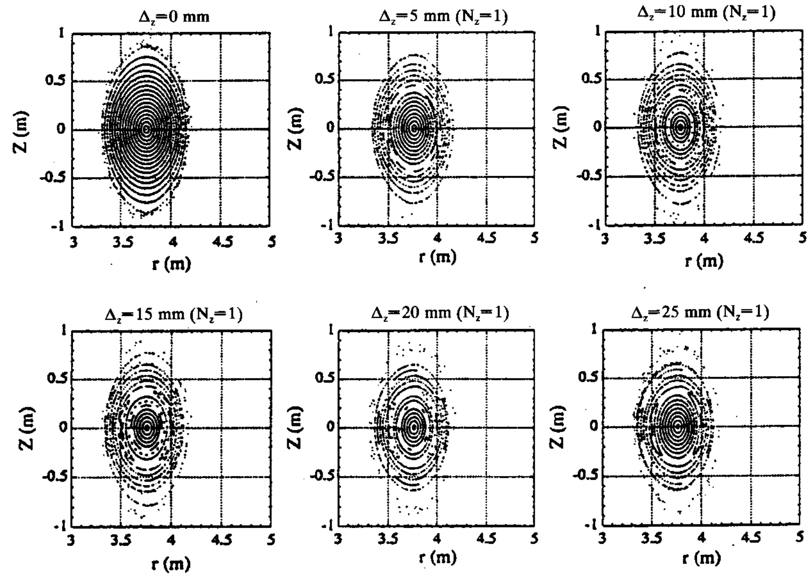

Fig. 5 Magnetic surface destructions due to vertical deformation of an OV coil in the coil deformation mode number N_Z= 1 case.

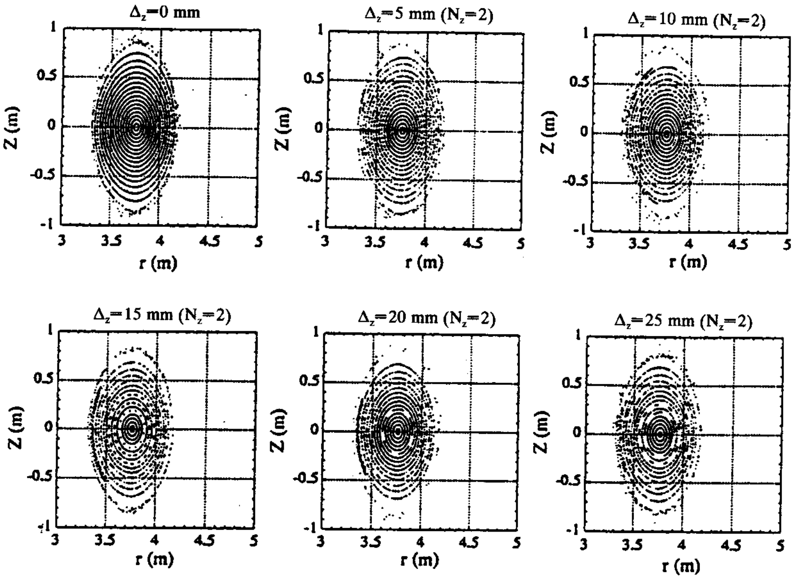

Fig. 6 Magnetic surface destructions due to vertical deformation of an OV coil in the case of the coil deformation mode number N_Z= 2.

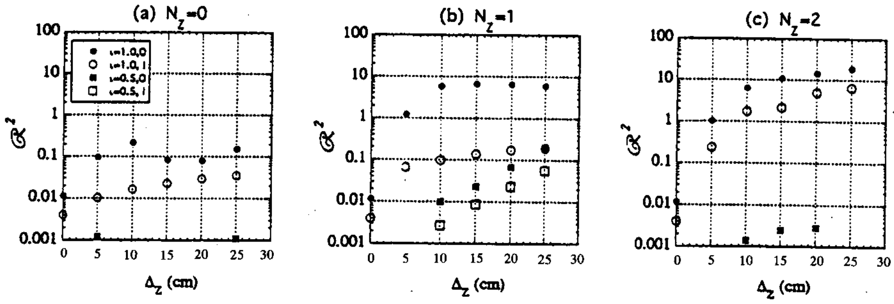

Fig. 7 The residues as a function of the deformation of an OV coil in the deformation mode number N_Z=0(a), 1(b), 2(c) cases. The residues are calculated on the line Z=0 and ϕ=0 plane. The residues on the ι=1 and 0.5 magnetic surfaces in the inner and outer region are described.

case, the islands on $\iota=0.5$ surface vanish completely. On the other hand, $m=2$ islands appear in periphery ($\iota=1$ surface). As shown in Fig. 6, the residues on $\iota=0.5$ surface are negligible, and the residues on $\iota=1$ surface in the outer and inner region are roughly comparable and increase with vertical deformation.

5. Summary

For the magnetic surface measurement in high magnetic field, the lanthanum hexaboride cathode is developed. The extracted electron beam current is more than 100 times larger than that by conventional electron source, which is effective in detailed magnetic surface measurement.

From the results of the orbit analysis of the high energy proton, the magnetic island can deteriorate the particle confinement and decrease the plasma heating efficiency. To find the most optimized magnetic surface configuration, the simple method for evaluating the cleanness of the magnetic surface is investigated. We applied the parameter residue to investigation of the magnetic surface in LHD. The residue proved to be effective for analyzing the cleanness of the magnetic surface. Our near future plan is to apply this method to find the most optimized configuration of the compensation coil in the case that the error field is not negligible. Since LID coils can be used as compensation coils, we can easily find the most effective LID coil current configuration by using the residues and the multidimensional optimization technique.

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