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Effects of Net Toroidal Current on LHD Equilibrium with n = 1 Island

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Abstract

A Large Helical Device (LHD) equilibrium is studied by using the three dimensional MHD equilibrium code HINT, which does not assume the existence of nested magnetic flux surfaces. Especially, effects of a net toroidal current on an LHD equilibrium with n = 1 islands are investigated because they are deeply related to the local island divertor operation, which is proposed to control the edge plasma of LHD. The edge control is one of key issues for the realization of steady state plasmas. To carry out this analysis we treat full torus calculations and modify the code. We show that an island structure with n = 1 is affected by an Ohmic-like toroidal current.

Keywords:
LHD equilibrium, n = 1 island, net toroidal current, full torus calculation, HINT code

1. Introduction

Effects of a net toroidal current on a Large Helical Device (LHD) [1] equilibrium with n = 1 islands are numerically studied by using the three dimensional (3D) MHD equilibrium code HINT with full torus calculations. Here, m is a poloidal mode number and n is a toroidal mode number. The HINT computation is constructed by three steps [2-6]. The first step (A-step) is a relaxation process of pressure along magnetic field lines under a fixed magnetic field. In the second step (B-step), calculation of a net toroidal current is performed under conditions of a fixed pressure profile and a fixed magnetic field. Here, the net toroidal current comprises non-vanishing currents after the flux surface average: e.g. an Ohmic current, a bootstrap current and an Ohkawa current, and in this paper we consider an Ohmic-like toroidal current. The third step (C-step) is a relaxation process of magnetic field under a fixed pressure profile. Solving iteratively the above steps, we find a 3D MHD equilibrium with a net toroidal current. In this scheme, the most important advantage is that the HINT code does not assume the existence of nested flux surfaces in an equilibrium. We can calculate an equilibrium with islands under the existence of a net toroidal current. Recently, we applied the HINT code to a helias equilibrium with islands, and had the result that a bootstrap current makes a rapid ascent of the rotational transform at the island as compared with in the currentless case. As a result the island region is healed and reduced to a rational surface [6].

Previous HINT computations were carried out under the condition of the stellarator symmetry. If an equilibrium has the stellarator symmetry, we can reduce a solving load of the relaxation equations, from calculations over a full torus to a half pitch. In this case, Fourier components of magnetic fields have toroidal mode numbers of $n = Nk$, where N is the field period: N = 10 for LHD, and $k = 0, \pm1, \pm2, \pm3, \cdots$. Properties of an LHD equilibrium have been examined in refs. [7-10] by using the VMEC code [11] under assumptions that nested good flux surfaces exist and the equilibrium has

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the stellarator symmetry. The VMEC code can not treat an equilibrium with islands and/or the stochastic region. Such an LHD equilibrium has been studied by using the HINT code [12,13]. However, an LHD equilibrium with $n = 1$ islands is out of the stellarator symmetry, because the island makes Fourier components of magnetic fields with a period of full torus. In particular, such an equilibrium is required in the local island divertor (LID) experiment. The LID has been proposed to control the edge plasma of LHD [14,15]. The LID is a divertor which uses an $m/n = 1/1$ island formed at the edge region. The island is useful for control of heat and particle fluxes. Control of the edge plasma by means of the LID is expected to realize the high temperature divertor operation which leads to a significant energy confinement improvement, thus the edge control is one of key issues for the realization of steady state plasmas. On the other hand, there is a possibility that an $m/n = 2/1$ island is produced by error magnetic fields. Fortunately, the LID coils have the ability to cancel the island. Of course, the $m/n = 2/1$ island can be also produced intentionally by using the LID coils. We will dare to analyze the equilibrium with an $m/n = 2/1$ island in the later section, to counter a case where the island is not canceled completely and remain in the plasma region. To analyze an equilibrium with $n = 1$ islands, we need to treat a full region of torus and modify the HINT code. We apply the modified HINT code to an LHD equilibrium with the islands, and investigate effects of a net toroidal current on the island structure.

2. HINT Computation

In the HINT code, an MHD equilibrium is obtained starting from an arbitrary non-equilibrium initial plasma and vacuum field configuration by means of a time-dependent relaxation method with small values of resistivity η and viscosity ν [2,3]. The calculations are performed in the following three steps [4-6].

The first step (A-step) is a relaxation process of pressure along magnetic field lines. To expedite the pressure relaxation, we make an average of pressure, $\bar{p}$, along a field line, and interpolate a value of pressure at each grid point by using the averages $\bar{p}$.

In the second step (B-step), calculation of a net toroidal current, e.g. an Ohmic-like current, is performed under conditions of a fixed pressure profile and a fixed magnetic field, if the current exists in the equilibrium. An Ohmic-like current is given as a function of the pressure; $|j_{Ohmic}| \propto p$ is assumed in this paper.

The third step (C-step) is a relaxation process of magnetic field under a fixed pressure profile. To calculate an MHD equilibrium with a net toroidal current, we revise the Faraday equation in the C-step, according to refs. [4]. If there are closed flux surfaces in the plasma region, the Faraday equation can be generalized as

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E} = \nabla \times \left(\boldsymbol{v} \times \boldsymbol{B} - \eta \{ \boldsymbol{j} - \boldsymbol{j}_{net} \} \right), \quad (1)$$

where $\boldsymbol{j}_{net} \equiv \boldsymbol{B}\langle \boldsymbol{j}\cdot\boldsymbol{B}\rangle / \langle B^2 \rangle$ is a net toroidal current. Here, $\langle \cdots \rangle$ means the flux surface average. A time-dependent relaxation method [3] is carried out for the above Faraday equation and the equation of motion:

$$\rho_m \frac{\partial \boldsymbol{v}}{\partial t} = -\nabla p + \boldsymbol{j} \times \boldsymbol{B} + \upsilon \nabla^2 \boldsymbol{v} \quad \text{for a fixed } p, \quad (2)$$

where $\mu_0 \boldsymbol{j} = \nabla \times \boldsymbol{B}$.

Solving iteratively the above relaxation equations in the HINT computation, we find a 3D MHD equilibrium satisfying $\nabla p = \boldsymbol{J} \times \boldsymbol{B}$ with/without a net toroidal current in a helical system [6]. In the next section, we apply the HINT code to an LHD equilibrium with an $m/n = 2/1$ island.

3. Effects of Ohmic-like Current on LHD Equilibrium

An LHD equilibrium with an $m/n = 2/1$ island, which are produced by error magnetic fields, is calculated. Here, we assume that in this calculation, the outside of a flux surface with the rotational transform of $\iota/2\pi = 1$ is deleted by a limiter. Poincaré plots of magnetic field lines for the vacuum are given in Fig. 1(a). The vacuum magnetic field is defined in a case of

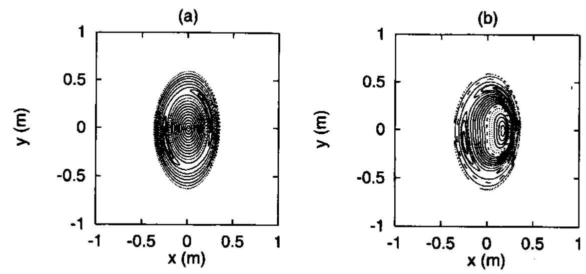

Fig. 1 Poincaré plots of field lines at the vertically elongated poloidal cross-section: (a) the vacuum and (b) β_0 = 2.8% without a net toroidal current. Here β_0 means the central beta.

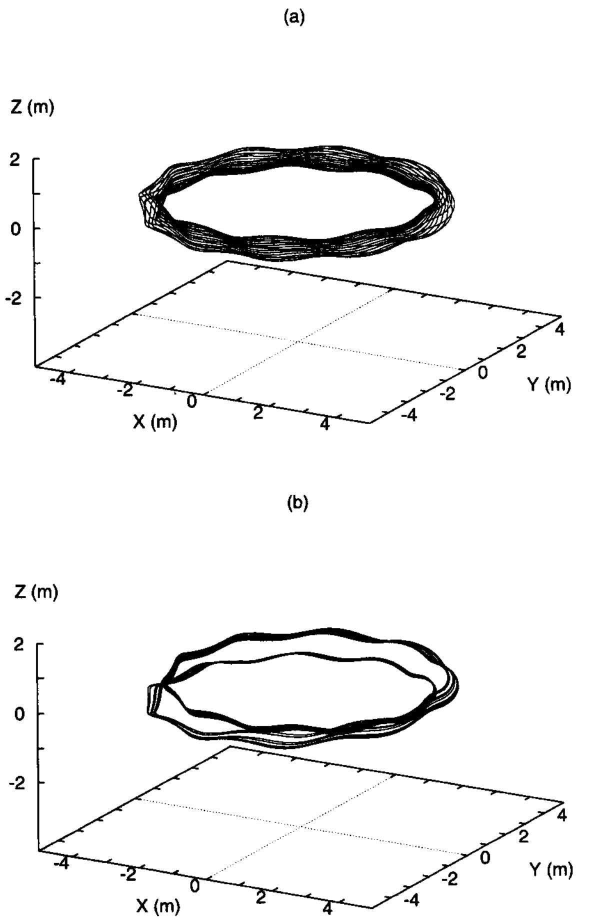

Fig. 2 A magnetic field line covering (a) a magnetic torus and (b) a magnetic island with $m/n = 2/1$ for the case of $\beta_0 = 2.8\%$ without a net toroidal current.

$B_0 = 3$ T and $R_0 = 3.75$ m, where B_0 and R_0 are the strength of magnetic field at the magnetic axis and the major radius of the axis for the vacuum, respectively. A pressure, defined by the peaked profile $p = p_0(1-s)^2$, is provided into the vacuum field, and this situation is chosen to be the initial condition of relaxation equations. Here, p_0 is a value of pressure at the axis and s the normalized toroidal flux. The island structure with $m/n = 2/1$ in Fig. 1(a) remains in the equilibrium with $\beta_0 = 2.8\%$ as shown in Fig. 1(b), where β_0 is a central beta value. A magnetic surface and an island with $m/n = 2/1$ in this case are shown in Fig. 2 by tracing a magnetic field line. Here, in Fig. 2(b), we find that the island tube changes its thickness, as also shown in Fig. 1(b). Making a comparison between Fig. 2(a) and Fig. 2(b), we see clearly that the island breaks the stellarator symmetry and has a period of full torus. We can easily

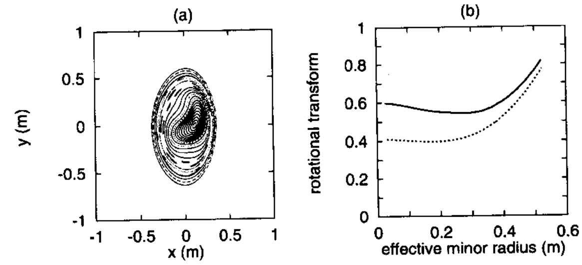

Fig. 3 (a) Poincaré plots of field lines at the vertically elongated poloidal cross-section for a case of $\beta_0 = 2.3\%$ with an additive Ohmic-like current of about 50 kA and (b) profiles of the rotational transform for cases without a net toroidal current (dot line) and with the current (solid line). Here, the dot and solid lines correspond to the cases of Fig. 1(b) and (a) in this figure, respectively.

expect that if the beta value increases under the currentless condition, the island grows and finally destroys magnetic surfaces.

To eliminate the island, we change a profile of the rotational transform by using a net toroidal current. If the resonant surface with $m/n = 2/1$ does not exist in the equilibrium, the island can not appear. We calculate the equilibrium with an additive Ohmic-like current for $\beta_0 = 2.3\%$ and find that the island disappears because there is no resonant surface with $m/n = 2/1$, see Fig. 3. Here, a profile of the rotational transform $\iota/2\pi$ is obtained by calculating a poloidal rotating angle of a field line and an effective minor radius is given by estimating a radius of a corresponding circle to a flux surface, i.e. the effective radius is evaluated by averaging minor radii over the flux surface. The profile of $\iota/2\pi$ for the currentless case (the dot line in Fig. 3(b)) is flattened in the island region with $\iota/2\pi = n/m = 1/2$; this region is very narrow in Fig. 3(b). The island region disappears for the case with the net toroidal current (the solid line in Fig. 3(b)), because the iota profile does not cross the resonance of $\iota/2\pi = 1/2$. As a result, we expect that by using a net toroidal current, properties of an LHD equilibrium with $n = 1$ islands can be controlled in the LHD experiment.

4. Conclusions

We have reported the first analysis of an LHD equilibrium with $n = 1$ islands under the existence of a net toroidal current. In this paper, we have calculated the equilibrium with an $m/n = 2/1$ island and have shown that the island can be eliminated by adding a net toroidal current, because the resonant surface disappears.

We focused on properties of an LHD equilibrium with the m/n = 2/1 island in this paper. When an m/n = 1/1 island of the LID is formed at the edge region in order to improve the transport, the island should not suppress the equilibrium beta limit and not be eliminated by a net toroidal current. The analysis of the equilibrium with an m/n = 1/1 island is not performed in this paper because there is a difficulty that the island is formed close to the helical coils and the HINT code can not treat coils yet. We are developing a modified HINT code where the existence of coils is allowed in the code. We will report these problems in the near future.

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