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The Exploration for New Concepts of Quasi-Symmetric Stellarator/Heliotrons

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Abstract

The quasi-bumpy symmetric (QBS) $L=0$ stellarator and quasi-helically symmetric (QHS) $L=2$ heliotron configurations have been explored to improve plasma confinement properties, especially focusing on the collisionless particle confinement improvement. Here, L denotes the poloidal mode number of the principle magnetic field component. The obtained QBS configuration still has some helical field contribution, which deteriorates the collisionless particle confinement, however; there is a possibility to restore bumpy-symmetry through the more careful plasma boundary modulations. The QHS $L=2$ heliotron configuration has not yet been achieved, however; the elimination of the toroidicity in the magnetic field has been already successfully demonstrated with the spatialization of the magnetic axis.

Keywords:
quasi-bumpy symmetric (QBS) stellarator, quasi-helically symmetric (QHS) $L=2$ heliotron, magnetic field spectra, collisionless particle confinement

1. Introduction

Several innovative concepts have been proposed to improve plasma confinement properties in stellarator/heliotrons such as quasi-helically symmetric (QHS) [1], quasi-axisymmetric (QAS) stellarators [2] and the helical axis heliotron [3]. The magnetic field spectrum with poloidal mode number L of 1 is predominant in these concepts. In this study, the exploration for new concepts of quasi-symmetric configurations with a different predominant L number are explored to improve plasma confinement properties. The control of magnetic field spectra by the plasma boundary modulations [4] are employed, and therefore, the coil system for the realization is a future problem.

This paper is organized as follows. The quasi-bumpy symmetric (QBS) $L=0$ stellarator is presented in the "PART. A" and an example $L=2$ heliotron configuration with significantly reduced toroidicity in the magnetic field is described in the "PART. B" in Section 2. A brief summary and future works will be mentioned in Section 3.

2. Recent Results for New Concepts of Quasi-Symmetric Magnetic Configurations

In this section, the explorations for QBS $L=0$ configurations and QHS $L=2$ configurations are explained. Collisionless particle confinement efficiency has been studied in the obtained QBS-like configuration to grasp the approach to a real QBS configuration. The effects of plasma boundary modulations on the magnetic field spectra, (especially, the toroidicity) has been investigated to restore the helical symmetry in $L=2$ heliotrons.

2.1 QBS $L=0$ stellarator

The bumpy field component is easily caused by the variation of the area of magnetic surface cross sections

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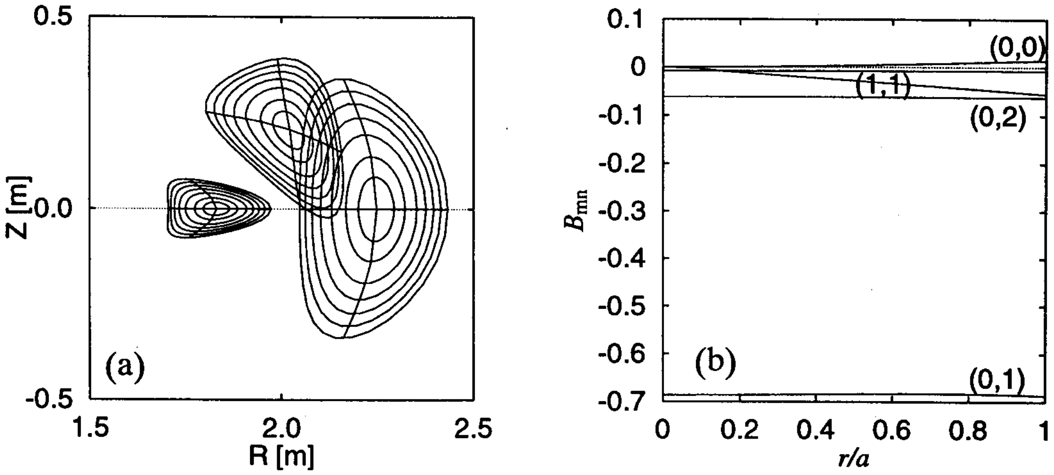

Fig. 1 (a) Magnetic surface cross sections for a QBS-like configuration. (b) Magnetic field spectra in the Boozer coordinates for the configuration shown in Fig. 1(a).

in the toroidal direction due to the magnetic flux conservation. The toroidicity in the magnetic field can be controlled (even eliminated) by the appropriate spatialization (helical magnetic axis) as in QHS configurations. Thus a QBS-like configuration can be relatively easily obtained from a QHS configuration through the helical modulations of the plasma boundary [4]. Figure 1(a) shows the obtained example QBS-like configuration based on this approach and Fig. 1(b) the magnetic field spectra in the Boozer coordinates [5]. The magnetic field strength B is expressed as

$$B = \sum_{mn} B_{mn}(r)\cos(\mathrm{m}\theta_{\mathrm{B}} - nM\zeta_{\mathrm{B}}),$$

where θ_B (ζ_B) is the poloidal (toroidal) angle in the Boozer coordinates and r denotes the average radius with m (n) the poloidal (toroidal) mode number. The M is the number of the field period. It is noted that B_{00} line denotes the difference of B_{00} between at r and at the magnetic axis, that is $B_{00}(r) - B_{00}(0)$, and all other components are normalized with $B_{00}(0)$. Three magnetic surface cross sections are shown at $\zeta_V=0$, $(1/4)(2\pi/M)$ and $(1/2)(2\pi/M)$, where ζ_V denotes the toroidal angle in the VMEC coordinates [6]. The area of magnetic surface cross sections is varied significantly in the toroidal direction to make the bumpy field component B_{01} dominant. It is noted that the principle helical component B_{11} exists about 6% at $r/a=1$, where a denotes the plasma minor radius, however; the toroidicity B_{10} is successfully suppressed due to the appropriate spatialization of the magnetic axis. From the viewpoint of the magnetic field structure, this configuration can be considered as a QBS-like configuration or an endless linked mirror configuration. The rotational transform per a field period is about 0.18, which clearly distinguishes this configuration from a so-called bumpy torus. The vacuum magnetic well (about 1.5%) exists in the entire plasma region.

Collisionless particle confinement property is studied based on the guiding center drift equations in the Boozer coordinates [7] to measure how is this configuration close to a QBS configuration. It is noted that only the vacuum configuration is considered. Collisionless protons are followed with assuming the average magnetic field strength of 1 T on the magnetic axis. They are initially launched from the magnetic surface located at $r/a=0.5$ with a uniform distribution in the pitch angle of the velocity space (15 points), in the poloidal (10 points) and toroidal (10 points) angles. The total number of followed particles is 1500. The proton temperature profile is assumed as $T_i(r/a)=1.0[1-(r/a)^2]$ keV, which gives $T_i=0.75$ keV at $r/a=0.5$. The particles are followed for 2 ms, during which an 0.75 keV proton with only parallel velocity makes about 70 circuits of a torus, or until they cross the plasma boundary. Table 1 lists the fraction of trapped particles and lost particles for three model configurations based on the configuration shown in Fig. 1. The configuration **A** has the same magnetic field spectra as shown in Fig. 1(b). The bumpy field component B_{01} is twice smaller in **B** (about $B_{01}/B_{00}(0) \sim -0.34$) and the principle helical component B_{11} is set to zero in **C**. In configuration **A**, almost all trapped particles are lost within 2 ms, due to the lack of bumpy-symmetry caused by the remaining B_{11}. If the B_{11} is suppressed further as in **C**, the fraction of lost particles is drastically decreased in spite

Table 1 The fraction of trapped particles and lost particles among followed 1500 collisionless particles in the configurations **A**, **B** and **C** (cf., Section 2).

Configuration	Trapped (%)	Lost (%)
A	37.7	36.0
B	26.1	24.1
C	37.7	0.3

of the same fraction of trapped particles as in **A**. As in **B**, the reduction of the dominant B_{01} is also effective to decrease the fraction of lost particles through the reduction of trapped particle fraction. These results indicate that the plasma boundary modulations which reduce B_{01} and/or B_{11} are effective to obtain good collisionless particle confinement starting from the configuration **A** shown in Fig. 1.

2.2 QHS $L=2$ heliotron

The $L=2$ heliotrons have been successfully progressed in Kyoto University (Heliotron-E [8]) and the Large Helical Device (LHD) [9] at the National Institute for Fusion Science (NIFS) is the successor, which will have experiments from March 1998. However, the Heliotron-E experiments have faced a difficulty in the full compatibility of good energetic particle confinement with MHD stability [10]; the inward magnetic axis shift is favorable for energetic particle confinement and, on the other hand, the outward shift is favorable for MHD stability. To resolve this contradiction for further improvement in $L=2$ heliotrons, a QHS $L=2$ configuration has been explored, because the energetic particle confinement is guaranteed due to the symmetry. In this case, the inward magnetic axis shift would not be necessary for good energetic particle confinement, and therefore, there is a possibility of compatibility with MHD stability.

As the first step, efforts to eliminate the toroidicity in the magnetic field (B_{10}) have been made to approach a QHS $L=2$ configuration. Here a magnetic configuration with $M=6$ and the aspect ratio of about 11 is considered for an example. It is noted that this aspect ratio is almost the same as that of Heliotron-E. As described in Ref. [4], the spatialization of the magnetic axis is effective to suppress B_{10}. Figure 2(a) shows magnetic surface cross sections at $\zeta_V=0$, $(1/4)(2\pi/M)$ and $(1/2)(2\pi/M)$ for the obtained configuration. The magnetic field spectra in the Boozer coordinates are shown in Fig. 2(b). The B_{21} is predominant although B_{11} still has some amplitude. It should be noted that B_{10} is successfully suppressed compared to the geometrical inverse aspect ratio. The negative large B_{00} component implies that the vacuum magnetic hill is significantly high, which is not appropriate for interchange stability. For reference, the rotational transform per a field period is $(\iota(0)/M,\ \iota(a)/M)$ ~ (0.33, 0.56), which has a large shear as is frequently the case for $L=2$ heliotrons. The reduction of B_{11} component and vacuum magnetic hill is now under investigations to approach QHS $L=2$

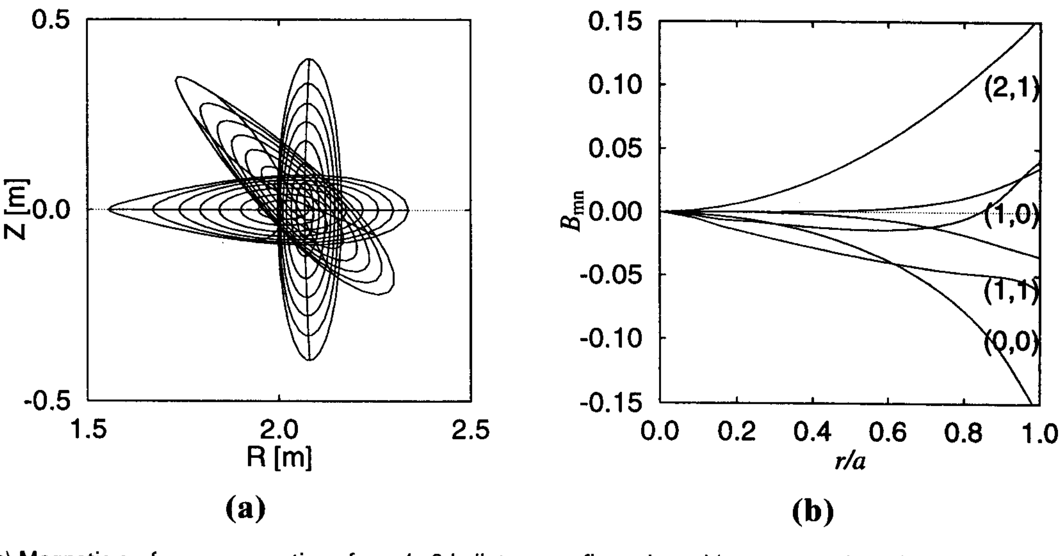

Fig. 2 (a) Magnetic surface cross sections for a $L=2$ heliotron configuration with suppressed toroidicity. (b) Magnetic field spectra in the Boozer coordinates for the configuration shown in Fig. 2(a).

configurations. However; the magnetic configuration shown in Fig. 2(a) implies that there is a possibility of the flexible control of magnetic field components through plasma boundary modulations not through the parameter variations of the prescribed coil configurations as have been done in conventional $L=2$ heliotrons. This approach would give a wider variety of $L=2$ heliotrons and make it possible for them to be improved or optimized further.

3. Summary and Future Works

The quasi-bumpy symmetric (QBS) $L=0$ stellarator and quasi-helically symmetric (QHS) $L=2$ heliotron configurations have been explored through the magnetic field spectrum control based on the plasma boundary modulations.

The obtained QBS configuration still has some helical field contribution, which causes the collisionless particle orbit loss, however; there is a possibility to restore bumpy-symmetry through the more careful plasma boundary modulations. When a purified QBS configuration is obtained, finite beta effects on MHD equilibria, stability and collisionless particle confinement should be investigated for the compatibility between good energetic particle confinement and MHD stability.

The QHS $L=2$ heliotron configuration has not yet been achieved, however; the reduction of the toroidicity in the magnetic field has been already successfully demonstrated with the spatialization of the magnetic axis. The reduction of significant vacuum magnetic hill and elimination of existing helicity (with the poloidal mode number of 1) are the essential tasks to obtain an attractive QHS $L=2$ heliotrons.

This study is based on the plasma boundary modulations and the appropriate coil configurations have not been considered. Once the favorable magnetic configurations are obtained based on this study, the appropriate coil configurations also should be investigated by utilizing the NESCOIL code [11] for its realization.

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