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Conceptual Design of a Quasi-Axisymmetric Stellarator (CHS-qa)

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Abstract

A new type of stellarator which has very small non-axisymmetric ripple has been designed. It has an aspect ratio 4.2 which is lower than any existing helical device. A rotational transform $\iota \sim 0.4$ is created without a net toroidal current for a tokamak-like axisymmetric magnetic field structure. A bootstrap current increases the rotational transform giving a reversed shear equilibrium. Twenty modular coils (ten per period) are designed and the effect of positioning error is estimated.

Keywords:

axisymmetric stellarator, low aspect ratio, bootstrap current, reversed shear, modular coil

1. Introduction

Recent progress of magnetic confinement study using helical devices has led to two large next generation projects: LHD and W-7X. The CHS experiment has been resolving various physical problems found in the Heliotron/Torsatron systems and exhibited the good performance of low-aspect-ratio helical device ($A_p = 5$). Since the step from CHS to LHD is very big (35 times larger volume), the magnetic configuration of LHD was selected as an extension of CHS (A_p is even a little higher) making much of reliability of performance.

On the other hand, the direction of configuration study to a low-aspect-ratio system is still very important when we need to realize high beta operation of helical systems ($\beta > 5\%$) and when the economical aspect of future reactor is discussed. However the neo-classical transport of conventional helical systems becomes inevitably worse due to the increase of ripples when A_p gets lower. A com pletely different concept of new design is required for realizing low-aspect-ratio helical systems with a good confinement.

2. Quasi-Axisymmetric Configuration

Since it is possible to determine the 3-D equilibrium based on the plasma boundary shape and small number of surface quantities (*e.g.*, pressure profile, current profile, etc.), the optimization of magnetic configuration was made by tuning Fourier modes of plasma surface. The primary conditions which were taken into account during the optimization procedure were 1) rotational transform at the boundary must be 0.4, 2) relative amplitude of non-axisymmetric components of Boozer spectrum must be sufficiently small, 3) sufficient level of magnetic well must be formed in the whole plasma.

The effect of residual field ripples in the quasi-axisymmetric configuration is similar to tokamak ripple problems for high energy particles which are brought by finite number of toroidal coils [1]. The condition for banana particles not to be trapped in the local ripple is given by

$$\frac{B_{\text{ripple}}}{B_0} < \frac{\iota}{A_p(N-\iota)} |\sin\theta_t| \qquad (1)$$

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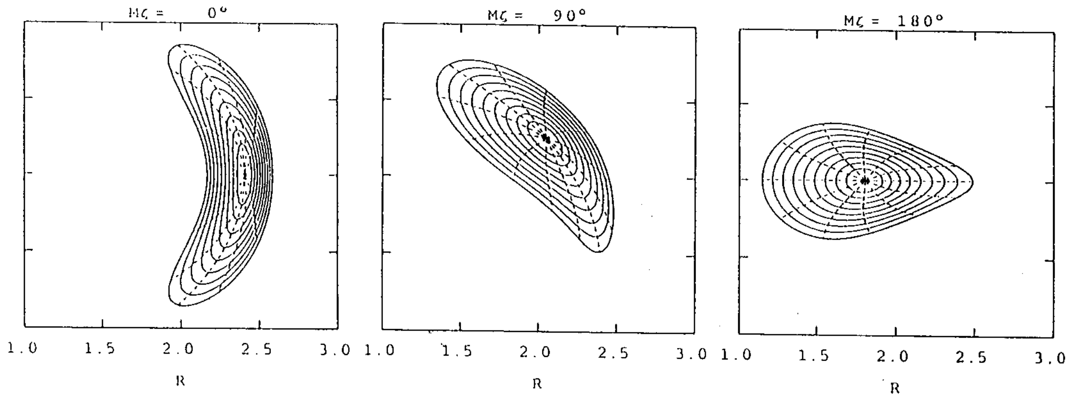

Fig. 1 Cross sections of magnetic surfaces for an equilibrium with bootstrap current.

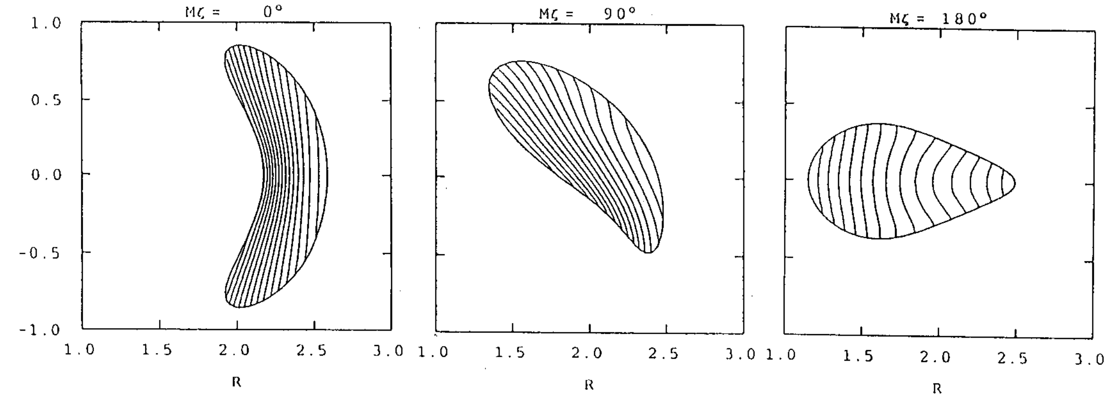

Fig. 2 Contour plots of magnetic field strength for an equilibrium with bootstrap current.

where N is a number of toroidal periods, ι is the rotational transform and θ_t is the poloidal angle of turning point of banana particle. A low aspect ratio and a small number of toroidal periods are both advantageous for the quasi-axisymmetry. The quasi-axisymmetric configuration is suitable choice for the direction of low aspect ratio helical systems.

N=2 was selected for toroidal periods which leads to $A_p \sim 4$ because it has been known that $A_p/N \sim 2$ is most efficient number for the optimization procedure with boundary shape control. Figure 1 shows three poloidal cross sections of present CHS-qa configuration which has a higher rotational transform (~ 0.4) than the previous design [2]. It belongs to the recent developments of quasi-symmetric helical systems [3, 4]. Because the magnetic field variation is mostly from the toroidicity, the Mod-B structure is similar to tokamak as shown in Fig. 2. Profiles of major Fourier components of magnetic field ripple is shown in Fig. 3 as functions of average minor radius. Modes are represented by

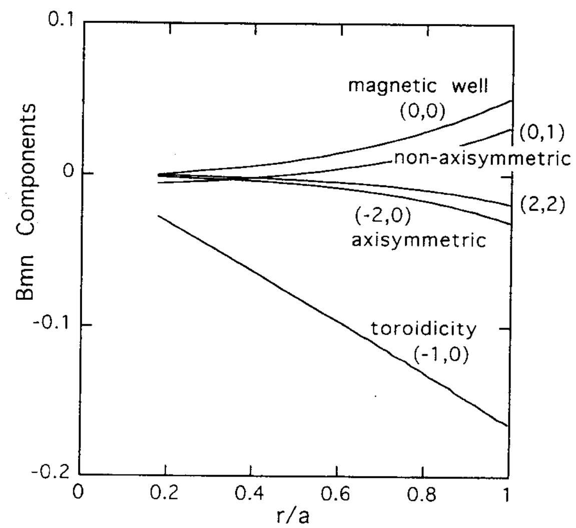

Fig. 3 Profile of Boozer spectrum for vacuum configuration.

(m, n) where m/n is poloidal/toroidal mode number. Largest non-axisymmetric ripple is a bumpy ripple (0, 1) which can be suppressed by the finite adjustment of individual modular coil current. Other modes which are not shown have amplitudes less than 1%.

3. Rotational Transform Control

Because of the axisymmetry of magnetic field structure, relatively large bootstrap current is expected to appear in the direction of increasing vacuum rotational transform. The current profile is calculated for the parameters listed in Table 1. The total bootstrap current is about 50 kA which modifies the rotational transform profile significantly. Figure 4 and 5 show the profile of toroidal current and resulting rotational transform. Figure 5 shows also the vacuum rotational transform with a dotted line. A shear reversal point appears which gives possibility of similar transport barrier to tokamak reversed shear experiments [5, 6].

The plasma parameter shown in Table 1 gives a central beta ~3.6%. The quasi-axisymmetry of CHS-qa does not suffer from such level of beta. In truth,

Table 1 Reference parameters for calculation of bootstrap current

R	2 m
Bt	1 T
n(0)	5×10^{13} cm^{-3}
Te(0)	1.0 keV
Ti(0)	0.8 keV
n(r),Te(r),Ti(r)	$(1 - r^2)$

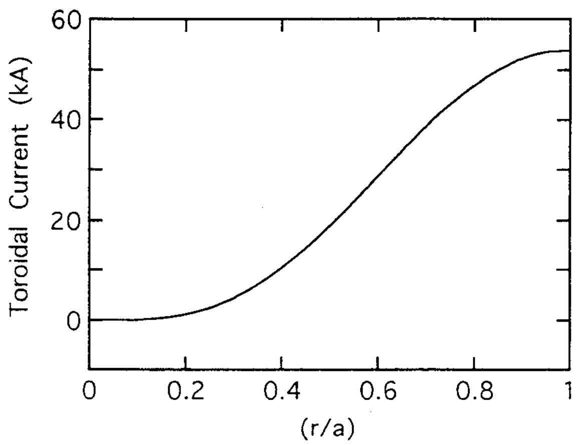

Fig. 4 Profile of bootstrap current as a function of average radius.

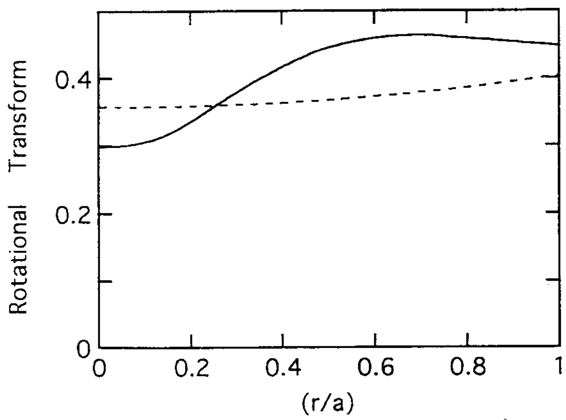

Fig. 5 Rotational transform profile with bootstrap current. Vacuum rotational transform is also plotted with dotted line.

Fig. 1 and 2 are the result of fixed boundary VMEC calculation which shows the identical boundary shape to the vacuum configuration but the magnetic surfaces and Mod-B contours are for the finite beta equilibrium with a bootstrap current.

As for the external control of the rotational transform, auxiliary toroidal coils and inductive current transformer (OH coil) are considered as options. The application of simple axisymmetric toroidal field ($\Delta B_t = +10\%$) is useful for avoiding low rational number resonance (island problem). OH coil is used to control central rotational transform (small current should be enough) which cannot be modified much by the bootstrap current.

4. Modular Coils and Vacuum Chamber

Design of modular coils is made using the extended NESCOIL code [7]. Total number of coils is 20 which is determined from the viewpoint of ripple level caused by discrete coils and necessary space between individual coils for diagnostic and heating devices. Since existing helical devices with modular coils have a high aspect ratio ($A_p > 8$), technical problems which arise from the low-aspect-ratio design should be newly solved for this device. The engineering design has been made for the reference value of the device: $R = 2$ m, $B_t = 1$ T (2 T is optional).

The continuous supporting structure for modular coils are designed which works as a vacuum chamber as well. This mechanical design is direct extension of CHS vacuum chamber design. The present design of modular coils allows more than 20 cm spacing between vacuum chamber and plasma boundary. Such spacing is favorable for the divertor study but makes the distance between coils very small inside the torus. Additional modification of coil design (especially inside torus) might be necessary for the 2 T option.

The vacuum chamber is connected from two or four pieces. Though the accuracy of coil positioning is very high within one piece, a relative positioning of coils on different pieces are very difficult. The effect of coil positioning error caused by the shift of connection of two separate pieces is calculated in the magnetic surface plots. The effect is very small for the shift of 1% (2 cm shift which is easily controlled) with various patterns of shift.

5. Major Topics in Experiments

The most important topic of the experiment should be to examine the improved confinement characteristics of a quasi-axisymmetric system in the low collisionality regime, where it is expected that the conventional helical systems would suffer from the enhanced neo-classical loss caused by the helically trapped particles. The confinement study of ECH collisionless plasmas and the measurement of high energy particles confinement with perpendicular NBI and ICRF are planned.

The beta limit study is also an important topic. It is already found that the beta limit depends very much on the pressure and rotational transform profile. The effect of bootstrap current and the additional inductive current should be examined.

In order to overcome the anomalous transport, three special conditions are prepared for the confinement improvement. The enhanced plasma toroidal rotation produced by all co-injection NBIs is planned which should give large velocity shear at the plasma boundary. In addition, it is confirmed that the neo-classical viscosity for the poloidal rotation is much smaller than conventional helical devices which should help good H mode transition. Secondly the reversed shear profile of rotational transform is expected with a bootstrap current for the steady state operation. Finally there is enough spacing for the island divertor configuration and the external control of rotational transform allows the fine control of island divertor structure.

6. Conclusion

A low-aspect-ratio helical device ($A_p = 4.2$) is designed which has a quasi-axisymmetric magnetic field structure. Bootstrap current modifies significantly the vacuum rotational transform profile in the direction to the higher beta and better confinement. The experimental plan is prepared for the improved confinement study.

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