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# Control of Magnetic Ripple Component in CHS-qa

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## Abstract

A quasi-axisymmetric helical device CHS-qa is being designed as a post-CHS device in National Institute for Fusion Science, of which primary purpose is to investigate the transport improvement in helical plasma by reducing the neoclassical parallel viscosity and by applying max. J criterion. To study how the plasma performance is changed by controlling the residual magnetic field ripples that are closely related to the viscosity and the adiabatic invariance J, sufficient flexibility on magnetic field configuration should be required. For this purpose the following coils, 20 main modular coils, 8 auxiliary toroidal field coils and 3 pairs of poloidal field coils, are used.

It is shown that a variety of magnetic ripple components can be controlled in the actual experiment. A control of mirror ripple component $B_{0,1}$, which is important to study the effect of the neoclassical parallel viscosity, is possible by changing the current ratio in main modular coils without any significant change in other ripple components. In addition to the mirror ripple, residual helical ripple components can be changed by using poloidal field coils. Furthermore, newly designed auxiliary toroidal field coils make more effective control of a residual helical ripple component $B_{1,1}$ possible.

## Keywords:

helical system, advanced stellarator, CHS-qa, quasi-axisymmetry, modular coil, auxiliary toroidal field coil

## 1. Introduction

In recent researches on advanced stellarator concepts, several magnetic field configurations have been proposed and developed. QAS (quasi-axial symmetric), QHS (quasi-helical symmetric) and QO (quasi-omnigeneous) configurations [1-3], of which development owes to the recent numerical optimization technique, have good properties not only in the neoclassical transport but also in MHD stabilities, alpha particle confinement *etc*.

A low aspect-ratio device is required for a low-cost, compact reactor in the future. A quasi-axisymmetric configuration is suitable to realize a low aspect-ratio device and has been selected as the post CHS device, CHS-qa [4]. Moreover, the top priority was put on the transport improvement in its design. The magnetic field configuration of CHS-qa has a low neoclassical parallel viscosity in the toroidal and poloidal directions in comparison with conventional stellarators [5]. If the low viscosity is prerequisite to obtain a large rotation shear for the transport barrier, the reduction in the anomalous transport is expected in CHS-qa. Furthermore, residual magnetic ripples except for the toroidicity make max. J criterion satisfied because the parallel velocity in the J integral is damped by the ripples [6]. The validity of max. J criterion in realizing high performance toroidal plasma has been well established, for example, in the FM-1 spherator experiment [7].

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As an experimental device, the magnetic configuration should be flexible so as to verify its design principle. The current ratio of the modular coils can be changed for controlling the mirror ripple $B_{0,1}$. This ripple damps the plasma rotation, making the neoclassical toroidal viscosity large. Quasi-axisymmetry is also somewhat spoiled and the effect of the mirror ripple on the anomalous transport through max. J criterion and through the enhanced non-ambipolar neoclassical transport can be investigated experimentally. Three pairs of poloidal field coils and auxiliary toroidal field coils are equipped, with which we can control several characteristics of magnetic configuration such as rotational transform, magnetic axis position, ellipticity of cross section and so on. Residual helical ripples can also be changed through the magnetic axis shift and ellipticity control. New auxiliary toroidal field coils have been designed so as to control the helical ripple component $B_{1,1}$ effectively, while normal auxiliary toroidal field coils are designed to control the rotational transform. Other non-axisymmetric residual ripples can also be controlled with the coils. For controlling the rotational transform, this auxiliary toroidal coil function and the other controlling methods, such as the axis shift by poloidal field coils and the current ratio control of main modular coils, are to be combined.

## 2. Effect of Poloidal Field Coils

CHS-qa has three pairs of poloidal field coils. Vertical and quadrupole fields can be added to change the rotational transform, magnetic shear and well depth etc. With the vertical field, we can shift the magnetic axis of configuration, by which the rotational transform and magnetic shear can be controlled. In Fig. 1 (a), Poincare plots are shown in which the vertical field, whose strength corresponds to ±1 % (+ and − mean upward and downward vertical fields, respectively) of main toroidal magnetic field of 1.5 T, is applied to the vacuum magnetic field configuration of 2w39. (2w39 is one candidate for CHS-qa. Toroidal period number $n_p$ is 2, aspect ratio is 3.9 and this configuration is characterized by the magnetic well over the plasma.) In the case of inward shift, residual non-axisymmetric components are reduced except for mirror ripple, $B_{0,1}$ as shown in Fig. 1 (b). In the case of outward shift, residual non-axisymmetric components, such as $B_{1,1}$, increase as shown in Fig. 1 (b). Residual ripples have important roles to produce the Max. J configuration. In the case of outward shift, the region where the Max. J

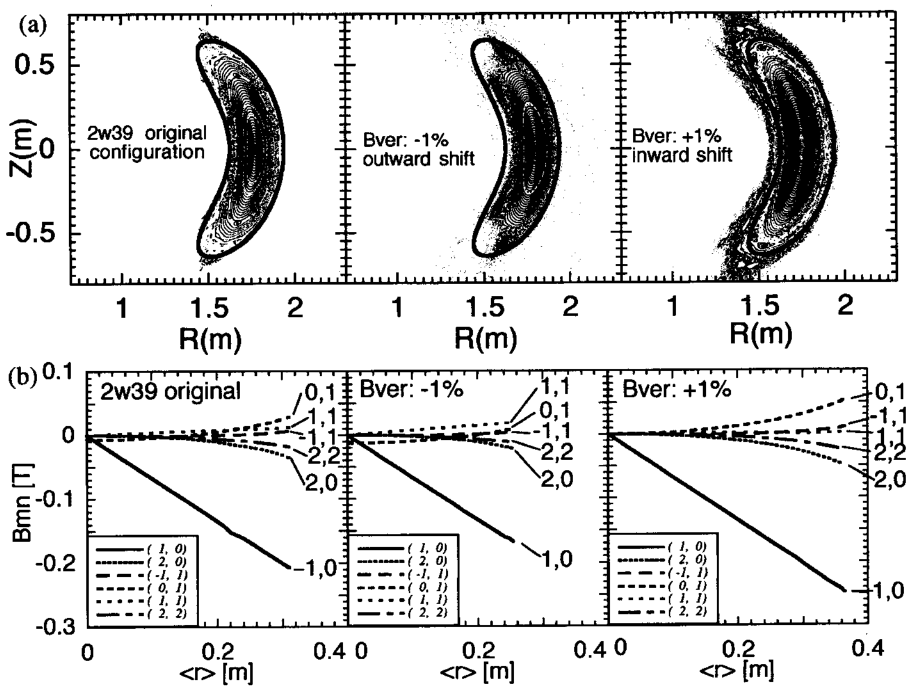


Fig. 1 a) Poincare plot of the original configuration 2w39, and the configurations where ±1 % vertical fields are added to the original one, and b) Boozer spectra of these configurations as a function of averaged minor radius.

criterion is satisfied is extended. The rotational transform decreases in the case of inward shift because the toroidal field is larger on the inside. On the contrary, outward shift increases the rotational transform.

With the shaping control by applying the quadrupole field, magnetic ripples can also be changed. Quadrupole field allows us to control the elongation of CHS-qa. There are two types of elliptic deformation: vertical elongation and horizontal elongation. In Fig. 2 (a) and (b), Poincare plots of these two types of deformation are shown. In the case of the vertical elongation, the sign of the helical ripple component, $B_{1,1}$, changes from positive to negative as shown in Fig. 2 (b). The absolute value of $B_{1,1}$ becomes larger than that of original configuration. The deformation of vertical elongation makes $B_{1,1}$ change to the negative direction. If we elongate the cross-section with additional toroidal field coils, the component, $B_{1,1}$, can be controlled more effectively as discussed in section 4. On the contrary, the deformation of horizontal elongation makes the helical ripple component, $B_{1,1}$, change to the positive direction. However, the change in the component, $B_{1,1}$, is smaller than in the case of vertical elongation, under the condition of the same amount of current in poloidal field coils.

## 3. Mirror Ripple Control by Changing the Ratio of Modular Coil Current

A mirror ripple component $B_{0,1}$ can be controlled effectively by changing the current ratio of modular coils. The mirror ripple $B_{0,1}$ increases the toroidal viscosity [5], therefore the control of this ripple is meaningful to study the viscosity effect on the plasma rotation and on deduced radial electric field. In Fig. 3 (a) and (b), an example of operations envisaged in the experiment is shown, in which the current of 8 modular coils nearby the cross section of $\phi = 0$ and $\pi$ (the cross section at $\phi = 0$ corresponds to the vertically elongated one.) is decreased to 80 % of other modular coils. Boozer spectrum is shown in Fig. 3 (b). At the normalized minor radius $\rho = 0.5$, the magnitude of mirror ripple component, $B_{0,1}$, is comparable to the axisymmetric component of $B_{1,0}$. Poincare plot of magnetic surfaces is shown in Fig. 3 (a). Original boundary of 2w39 is shown with the solid line. Irrespective of the large change in the mirror ripple, the magnetic surface is clean and the disturbance from the original one is small. In fact, even if the current of one modular coil is forced to be zero, magnetic surfaces still exist showing their robustness. Other helical ripples do not change so much.

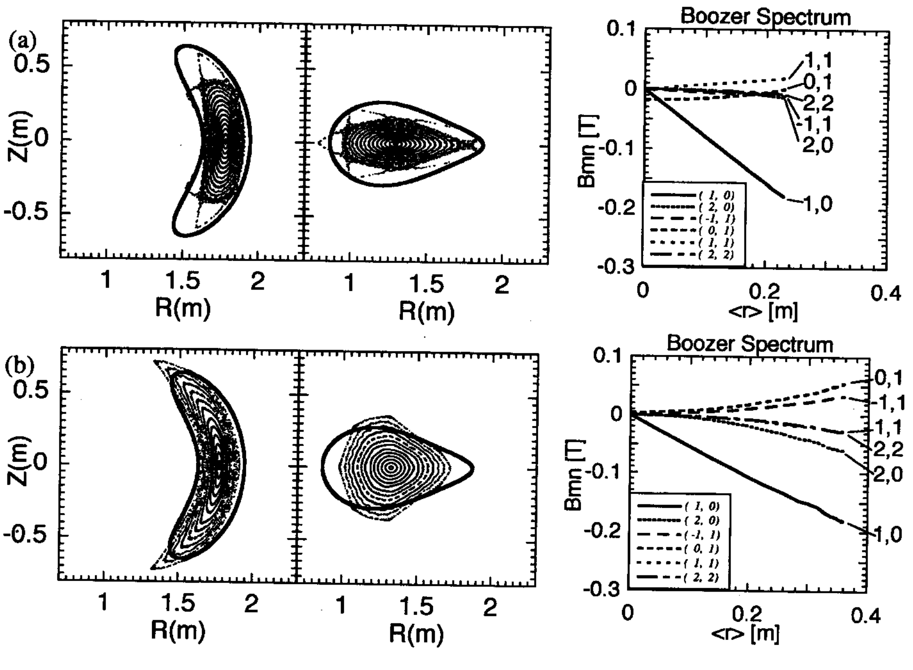


Fig. 2 Examples of shaping control with quadrupole fields: a) deformation of horizontal elongation, b) deformation of vertical elongation.

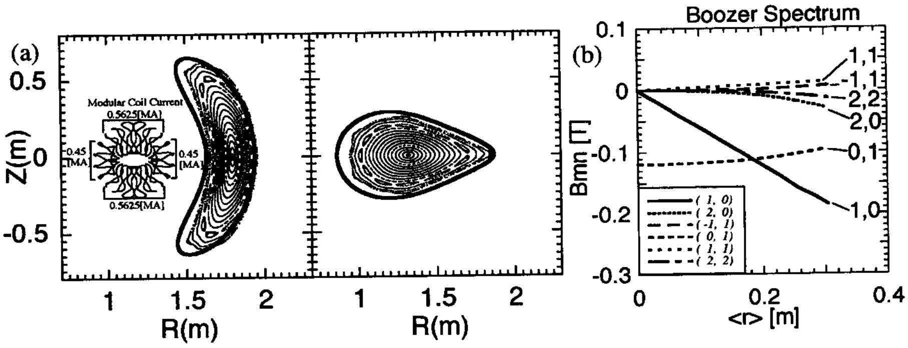


Fig. 3 The mirror ripple changes with the control of the main modular coil current ratio. Each current of 8 modular coils nearby the vertically elongated cross sections ($\phi = 0, \pi$) is reduced to 80 % of other modular coil current. Mirror ripple becomes large, however the magnetic surface remains clean and disturbance from the original one is small.

Break of quasi-axisymmetry leads to deterioration of the neoclassical confinement. However, if the large electric field is induced due to a large loss of particle, this electric field may improve the anomalous transport [8]. The transition phenomena related to this radial electric field could be expected.

## 4. Helical Ripple Control with Auxiliary Toroidal Field Coils

Helical ripple component is a very important factor for the confinement of plasma. This ripple has a bad effect on the single particle confinement in the quasi-axisymmetric configuration. However, in Heliotron/Torsatron, this component plays important roles in inducing the non-ambipolar particle fluxes which result in the internal transport barrier as was shown in CHS experiment [9]. The configuration 2b32, which is also a candidate of CHS-qa configuration, has a relatively large residual ripple of $B_{1,1}$. If this ripple can be controlled, we can investigate effects of this ripple on the radial electric field, particle transport and so on. Auxiliary toroidal field coils are designed to control the helical ripple component, $B_{1,1}$. Coil shapes are deduced by using NESCOIL code [10]. The total ampere-turn of auxiliary toroidal coil is restricted to 5 % of that of main modular coils. This is because of the limitation of the power supply for the standard operation of CHS-qa. In a low field operation, this limitation is relaxed. In NESCOIL code, coil shape is expressed as components of Fourier series. The shape of auxiliary toroidal coils is optimized so that the helical component $B_{1,1}$ is changed more largely under the total current restriction of 5 % of main modular coil current. Following this procedure, we have designed new auxiliary toroidal coils shown in Fig. 4. These 8 coils are of mirror symmetry and consist of 2 types of shape. At a glance, the configuration of these coils is similar to helical coils of heliotron/torsatron. Poincare plot, when these auxiliary toroidal coils carry 5 % of main modular coil current, is shown along with the Boozer spectrum in Fig. 5 (central figure of a). The helical ripple component, $B_{1,1}$, becomes larger than that of the original configuration, and its amount reaches about 50 % of an axisymmetric component $B_{1,0}$ as shown in Fig. 5 (central figure of b). The mirror component $B_{0,1}$ also becomes larger. However, this component can be adjusted, by controlling the ratio of main modular coil current, so that its amount is forced to be zero on axis, because this component is more

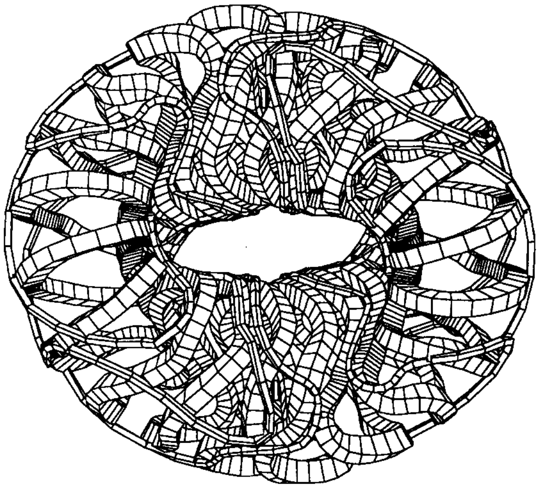

Fig. 4 The auxiliary toroidal field coil which is designed to control a helical ripple component. These 8 coils are of mirror symmetry and consist of 2 types of shape.

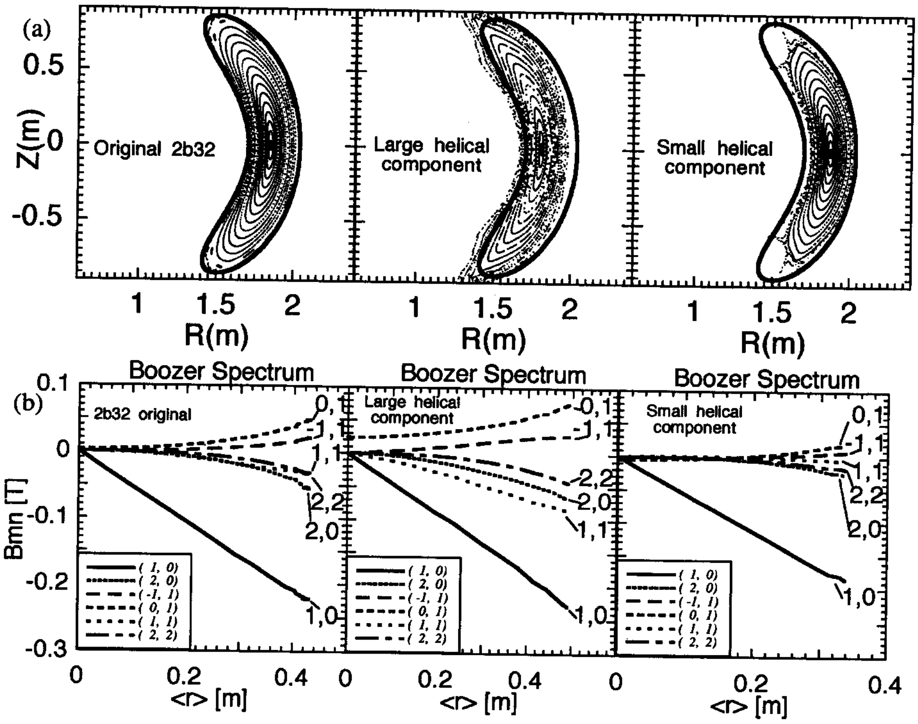


Fig. 5 a) Poincare plots and b) Boozer spectrum of the configuration 2b32, of which helical ripple component is controlled. When the $B_{1,1}$ is controlled to be small with the auxiliary toroidal field coil, other non-axisymmetric components are also decreased (as seen in the right figure).

sensitive to the ratio than other ripple components. By adjusting the current of this auxiliary toroidal coils, we can also reduce the helical ripple $B_{1,1}$. Poincare plot and Boozer spectrum in this case are also shown in Fig. 5 (right figures of a and b), where $B_{1,1}$ is reduced effectively and other non-axisymmetiric components also become less.

This auxiliary toroidal field coil can not be used, for itself, to control the rotational transform. For this purpose, we can use other control coils, such as poloidal field coils and main modular coils, together with the auxiliary toroidal field coils. The work to design more advanced auxiliary toroidal field coils is now in progress.

## 5. Summary

The mirror ripple can be controlled by changing the ratio of main modular coil current, which make it possible to investigate the effect of the parallel viscosity on the anomalous transport in CHS-qa experimentally. Residual helical ripples can be controlled with poloidal field coils of which primary purpose is to control the magnetic configuration. With newly designed auxiliary toroidal field coils, more effective control of a helical ripple $B_{1,1}$ is possible.

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