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The Effect of Coil Misalignment on Particle Transport in Quasi-Axisymmetric Systems

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Abstract

The effect of the misalignment of modular coils on neoclassical transport in CHS-qa is discussed in this paper. In order to calculate the effective helical ripple that characterizes the neoclassical transport of the stellarator configuration, NEO code is used which gives the effective helical ripple numerically. A displacement is put artificially on the modular coils of the CHS-qa, and the effect of this on the profile of the effective helical ripple is evaluated quantitatively. One objective of this study is to obtain useful information to determine the acceptable error level for the assembly of modular coils from the viewpoint of engineering. The calculation results of the NEO code show that if the level of displacement is smaller than a few centim eters, it has only a very small effect on the neoclassical transport. The a mount of change in the effective helical ripple is small. Therefore the displacement of the modular coils caused by the electromagnetic force at a 1.5 T operation of CHS-qa does not lead to significant problems in terms of neoclassical transport.

Keywords:

quasi-axisymmetric stellarator, modular coil, effective helical ripple, error magnetic field

1. Introduction

In recent years, we have continued our design work of an advanced stellarator device, CHS-qa, that has a quasi-axisymmetric configuration [1,2]. By using a numerical optimization method, a modular coil system was designed for it, which was reported on in our previous paper [3]. In the subsequent paper, we reported on the property of neoclassical transport for the configuration produced by this modular coil system [4].

In this paper, we will discuss the effect of the error in the position of the coil on neoclassical transport. Its investigation is important for determining the acceptable level of error for the modular coils, since it influences the total cost of the device. We are also interested in the sensitivity of the error in the position of the coil in terms of the transport, because in the machine operation the modular coil is subject to a large electromagnetic force, which causes changes in its shape and position.

In order to calculate the effect of the error in the position of the coil on neoclassical transport, NEO code [5] is used. The advantage of this code is that, 1) the code can include the effects of particles trapped in any magnetic field ripples. Therefore, it can calculate quantitatively the effect of the complicated geometry of the magnetic field. 2) Since the code uses the solution for the distribution function of the bounce averaged kinetic equation, the calculation time is shorter than for a Monte Carlo calculation. In this paper we will show the dependence of the error in the position of the coil on neoclassical transport and give useful information for determining the acceptable level for the error in coil position.

2. Modular coil system

The reference configuration of CHS-qa, “2b32” version [6], is used in this paper. The major radius is 1.5 m, the toroidal periodic number is 2, and the aspect ratio is 3.2. The maximum magnetic field is 1.5 T.

The modular coil system optimized for this configuration is used. The total number of modular coils is 20, and for the stellarator symmetry the coils consist of only five types of shapes. All coils are located between two surfaces. One is a surface that is 26 cm away from the plasma boundary, and the other is 45 cm away from the plasma boundary. The averaged minor radius of the coil is about 70 cm. The minimum radius of curvature is 25 cm, and the minimum distance between adjacent coils is 22 cm. The top view of the modular coil system is shown in Fig. 1a). We will refer to the coil by the number written in this figure. We use the vacuum mag-

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netic field configuration produced by this modular coil system and ignore the finite beta effect of the plasma.

In order to evaluate the effect of the error in the coil position, the modular coil is moved artificially. The displacements put on the modular coil system are as follows: In Case A, COIL 2, COIL 4, COIL 8, COIL 12, COIL 14, C OIL 18 are moved in the positive direction along the z axis, and COIL 3, COI L 7, COIL 9, COIL 13, COIL 17 and COIL 19 are moved in the negative direction along the z axis, as shown in Fig. 1b). The amount of coil displacement is given by Δz. The coils are moved by the same distance, only the direction is different. For the sake of simplicity of the calculations, the displacement is assumed to have stellarator symmetry. In Case B, COIL 2, COIL 4, COIL 7, COIL 9, COIL 12, COIL 14, COIL 17 and COIL 19 are moved in the +R direction, while COIL 3, COIL 8, COIL 13, COIL 18 are moved in the -R direction, as shown in Fig. 1c). The amount of coil displacement is given by ΔR in this case.

Firstly, we will present Poincare plots of the magnetic surfaces. It is interesting to note the extent to which the magnetic surfaces are broken by the displacement of the coils. In Fig. 2, the poincare plots for the displacement of Δz = 6 cm in Case A and ΔR = 6 cm in Case B are compared with those of the standard configuration. In this figure, two poloidal cross sections for each of the cases are shown. One is at the toroidal angle of 0 degrees and the other is at 90 degrees. The change in the volume of the confinement region is little, and the magnetic surfaces are insensitive to the displacement of the coils. A good magnetic surface is maintained, even for a relatively large displacement in Δz = 0.1 m or ΔR = 0.1 m. In the poincare plot for Δz = 6 cm in Case B, islands appear near the center of the plasma, since the rotational transform has the rational number 0.4 at this position. However, the size of the island is small in this case.

3. Calculation result

For the standard stellarator configuration for which the magnetic field is characterized only by the toroidal ripple ε_t and the helical ripple ε_h, the neoclassical diffusion coefficient in the $1/\nu$ regime is proportional to $\varepsilon_h^{3/2}$. If the configuration has multi-helicity, the diffusion coefficient is no longer proportional to $\varepsilon_h^{3/2}$. In this case, by replacing ε_h with ε_{eff}, the diffusion coefficient of the neoclassical transport can be characterized. The NEO code calculates numerically this effective helical ripple, ε_{eff}, by using the solution of the bounce averaged kinetic equation for the distribution function of the trapped particle. As described in paper [5], ε_{eff} can be calculated as

$$\varepsilon_{eff}^{3/2} = \frac{\pi R_0^2}{8\sqrt{2}} \lim_{L_s\to\infty} \left(\int_0^{L_s} \frac{ds}{B}\right)\left(\int_0^{L_s} \frac{ds}{B}\,|\nabla\psi|\right)^{-2} \int_{B_{min}^{abs}/B_0}^{B_{max}^{abs}/B_0} db' \sum_{j=1}^{jmax} \frac{\hat{H}_j^2}{\hat{I}_j},$$

$$\hat{H}_j = \frac{1}{b'} \int_{s_j^{min}}^{s_j^{max}} \frac{ds}{B} \sqrt{b' - \frac{B}{B_0}} \left(4\frac{B_0}{B} - \frac{1}{b'}\right) |\nabla\psi| k_G,$$

$$\hat{I}_j = \int_{s_j^{min}}^{s_j^{max}} \frac{ds}{B} \sqrt{1 - \frac{B}{B_0 b'}}. \tag{1}$$

Here, R_0 is the major radius, B_0 is the reference magnetic field, ψ is the magnetic surface label, $k_G \equiv (\boldsymbol{h} \times (\boldsymbol{h} \cdot \nabla) \cdot \nabla \psi / |\nabla\psi|$ is the geodesic curvature of a magnetic field line, and $\boldsymbol{h}$ is a unit vector $\boldsymbol{B}/B$. B_{min}^{abs} and B_{max}^{abs} are the minimum and maximum values of B within the interval from 0 to L_s, respectively. L_s is a maximum value of path length in the integral along a magnetic field. s is the magnetic field length,

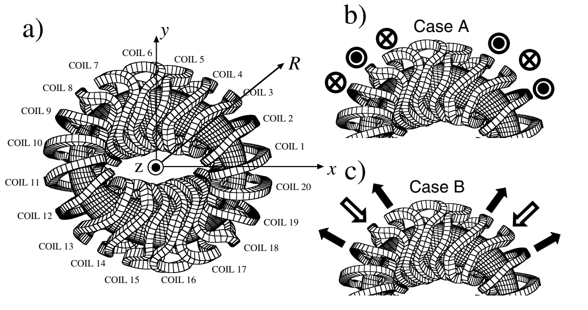

Fig. 1 a) Top view of a modular coil system for CHS-qa. The plasma boundary of "2b32" configuration is also shown. The axis of the Cartesian coordinate system and the *R*-axis of the cylindrical coordinate system shown in this figure are used in this paper. b) The displacement of the coils in Case A. c) The displacement of the coils in Case B.

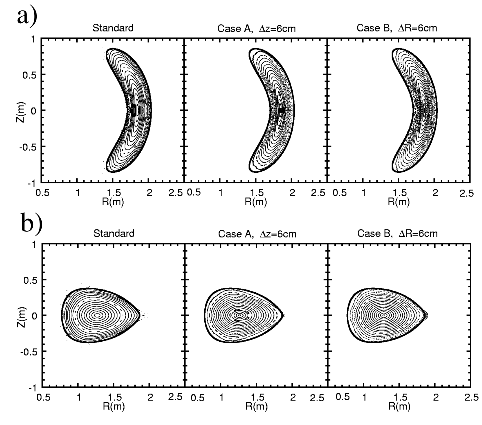

Fig. 2 a) Poincare plots at the toroidal angle of 0°, where th e cross section is vertically elongated. Left: for the standard configuration. Center: for Δz = 6 cm in Case A. Right: for ΔR = 6 cm in Case B. b) Poincare plots at the toroidal angle of 90° where the cross section is horizontally elongated. The solid line represents the outermost magnetic surface of the "2b32" configuration.

and s_j^{min} and s_j^{max} are the turning points of the trapped particle j. b' is an integration variable, which corresponds to $v^2/(J_\perp B_0)$, v is velocity and $J_\perp$ is the perpendicular adiabatic invariant.

The calculation result of the NEO code for Case A is shown in Fig. 3a). Δz is changed from 0 to 10 cm. If the displacement is smaller than 2 cm, its effect is not seen in the profile of the effective helical ripple. The local increase appears at the averaged minor radius of 0.1 cm for Δz = 6 cm and at 0.2 cm for Δz = 10 cm. This is for the effect of the island. By the way, the $\varepsilon_{eff}^{3/2}$ of CHS, which is of the same order as the standard stellarator, is about 1.0×10^{-4} at the plasma center, and 0.2 at the edge. All of the effective helical ripples in Case A are smaller than for CHS and good characteristics are maintained. Thus, the property of the neoclassical transport of CHS-qa is insensitive to the vertical displacement of the modular coils.

The calculation result for Case B is shown in Fig. 3b). The dependence of the displacement of coils on the transport is similar to that in Case A. Therefore, the property of transport is also insensitive to the horizontal displacement of the coils. The difference from Case A is that the local increase in the effective helical ripple does not appear in Case B. This is because the profile of the rotational transform is different. In Fig. 4a) and 4b), the profiles of the rotational transform for Case A and B are shown. The change in the rotational transform in Case A is larger than in Case B. In Case A, for Δz = 6 and 10 cm, the rational number 0.4 is crossed and n/m = 2/5 islands appear. This island structure causes the increase in the effective helical ripple, as seen in Fig. 3a). On the other hand, in Case B, the change in the rotational transform is small. Therefore, the rational number 0.4 is not crossed.

4. Conclusion

The effect of the displacement of the modular coils on neoclassical transport was investigated using NEO code. If the displacement is smaller than 2 cm, its effect on the neoclassical transport is very small. By the way, we already knew that the displacement of coils by the electromagnetic forces in the machine operation of 1.5 T is below about a few millimeters. Therefore, from the point of view of neoclassical transport, this displacement can be neglected. We can conclude that it is sufficient that the accuracy of the coil assembling should be below a few centimeters.

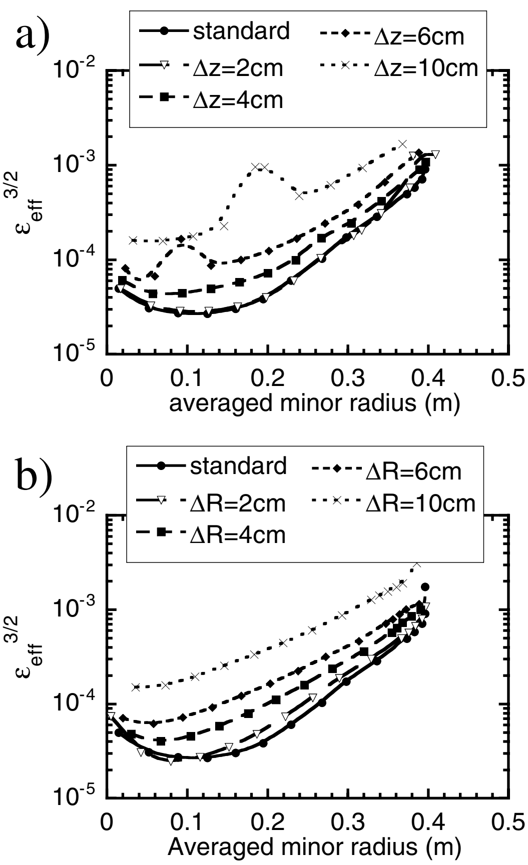

Fig. 3 a) The profiles of the effective helical ripple when the displacement of Case A is considered. At the averaged minor radius of 0.1 m for Δz = 6 cm cm and 0.2 m for Δz = 10 cm, the increase in the effective ripple can be seen. This is because of the effect of an island, n/m = 2/5. b) The profiles of the effective helical ripple when the displacement in Case B for a coil system is considered.

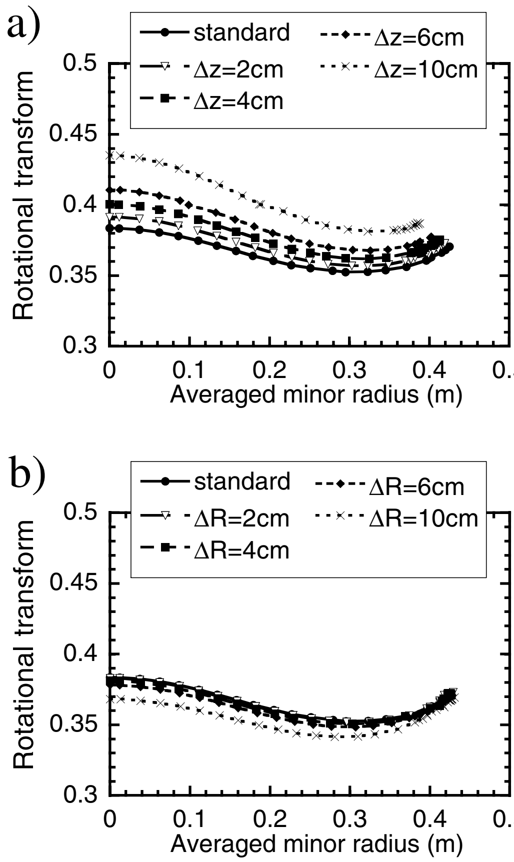

Fig. 4 a) The profiles of the rotational transform when the displacement of Case A for the coil system is considered. b) The profiles of the rotational transform when the displacement of Case B is considered.

However, there are issues remaining that should be considered. (1) In the calculation of the NEO code shown in this paper, toroidal periodicity and stellarator symmetry are assumed for the magnetic configuration, namely for the geometry of the displacement of the modular coils. In the more general case, this assumption may be inappropriate. In order to calculate the effective helical ripple for this situation, a modification of the NEO code is needed. This will be carried out in a future study. (2) The profile of the rotational transform of CHS-qa is low shear. Therefore, low mode large islands may appear in the confinement region through a change in the rotational transform caused by the error in the coil position. This may lead to a significant deterioration for confinement. In addition, the appearance of a low mode rational number of the rotational transform in the confinement region causes MHD (Magnetro Hydro Dynamics) instability, which may also adversely affect the confinement through such as disruption.

Further detailed calculations on these two remaining issues are required to determine the acceptable error level more safely.

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