Design study of the magnetic field coils and configuration for the Chinese First Quasi-axisymmetric Stellarator

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Introduction

Recent research of helical devices showed remarkable progress, e. g., Wendelstein 7-X started the operation in 2015, and the Large Helical Device (LHD) begun the deuterium experiment in 2017. Compared with tokamak, helical devices have an advantage in steady state operation as a future nuclear fusion reactor, because its magnetic field configuration is produced by external magnetic field coils and the current drive is not required. However, it is considered that the neoclassical transport of helical devices is not good in the collision less regime, so called in the $1/\nu$ regime (ν is collision frequency), and the confinement property degrades in the reactor relevant plasma parameters.

However various optimized stellarator configurations have been proposed and experiment devices have been constructed. A quasi-axisymmetric stellarator (QAS) is one of the optimized stellarators, of which magnetic configuration has axisymmetry in magnetic coordinates, *i. e.* the Boozer coordinates [1,2]. Therefore, the neoclassical transport properties become similar to that of tokamaks, although the inductive driven current is not essentially required. The Chinese First Quasi-axisymmetric Stellarator (CFQS) [3-6] is the first experiment device of QAS, which will be constructed in Southwest Jiaotong University (SWJTU) in China. This is the international joint project with National Institute of Fusion Science (NIFS) in Japan and SWJTU, and its design work has been performed jointly based on the CHS-qa designed by NIFS [7]. Physics design for the CFQS was almost completed, and engineering design is now ongoing.

Properties of equilibrium configuration and modular coil system for the CFQS

The equilibrium configuration of the CFQS was designed based on the CHS-qa designed as the 2b32 configuration [7]. Therefore, the toroidal periodic number N_p of 2 was chosen. The major radius R of 1 m and the magnetic field strength Bt of 1 T were determined to perform fully ionized plasma experiments in a compact device. To reduce the difficulty in the fabrication of modular coil system, the aspect ratio A_p of 4.0 was selected for the CFQS, although A_p of the CHS-qa was 3.2. The typical rotational transform is 0.4, and in the all radial region, the magnetic well property is achieved, which leads to a favourable MHD stability of the magnetic field configuration.

Modular coil shape was optimized by the NESCOIL code [8,9]. By this optimization, the total number of the modular coil was chosen to be 16 [6], to increase the space between the two neighbouring coils at the inboard side. The size of the rectangular cross section of the coil is 132 × 69 mm. In Fig.1, the top view of the CFQS plasma geometry and modular coil system is shown. Each modular coil is composed of 72 (= 6 × 12) hollow cooper conductors, of which each size is 8.5 × 8.5 mm with a 4 mm ϕ hole for water cooling.

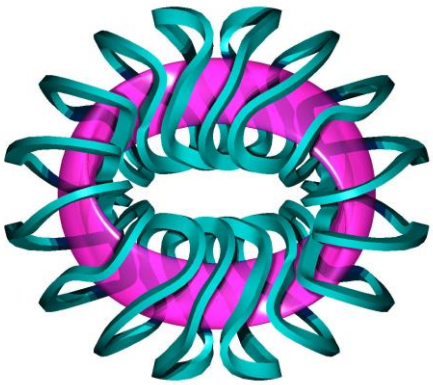

Fig.1 Top view of the CFQS plasma geometry and modular coil system is shown. Total of 16 coils produce magnetic field configuration of the CFQS [6].

Neoclassical bootstrap current and its effect on the configuration

In the QAS configuration, the large neoclassical bootstrap current is expected, because the neoclassical properties are similar to that of tokamaks. The magnitude of neoclassical bootstrap current was estimated by using the BOOTSJ code based on semi-analytic formula in the collision-less limit [10]. Temperature and density profiles were assumed to as $T_{i,e} = T_{i,e\,0}$ (1-ρ^2) and $n_e = n_{e0}$ (1-ρ^2), respectively. Here, ρ is the normalized minor radius. The ratio of T_e/T_i was assumed to be 10, and n_{e0} was fixed to be 1.0×10^{19} m^{-3}, *i. e.*, ECH discharge case is considered here. The estimated radial profile of the neoclassical bootstrap current density at the volume-averaged beta $<\beta>$ of 0.59% is shown in Fig.2. The T_{e0} and T_{i0} are 3.3 and 0.33 keV in this case. In this calculation, the VMEC free boundary calculation was performed, in which the modular coil system described in Ref.6 (and shown in Fig.1) was used. The total neoclassical bootstrap current was evaluated to be 20.0 kA. The radial profile of Fourier components of the magnetic field strength in the Boozer coordinates are shown in Fig.3 for (a) $<\beta>$ = 0.0 % and

(b) for <β> = 0.59 % cases. The magnetic field strength is expressed as follows: $B = \Sigma B_{mn} \cos (m \theta_B - n N_p \varphi_B)$. Here, θ_B and φ_B are the poloidal and toroidal angle in the Boozer coordinates, respectively. The B_{10} is dominant due to the QAS property, and the absolute values of non-axisymmetric components are below 0.02 T. The QAS property is not degraded by the finite <β>.

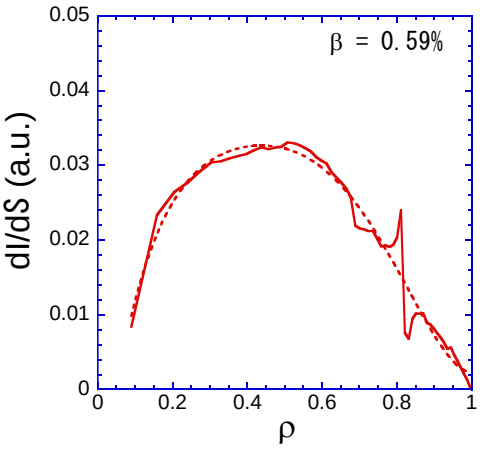

Fig.2 Radial profile of the neoclassical bootstrap current density. Dotted line is a fitting line of the calculation result.

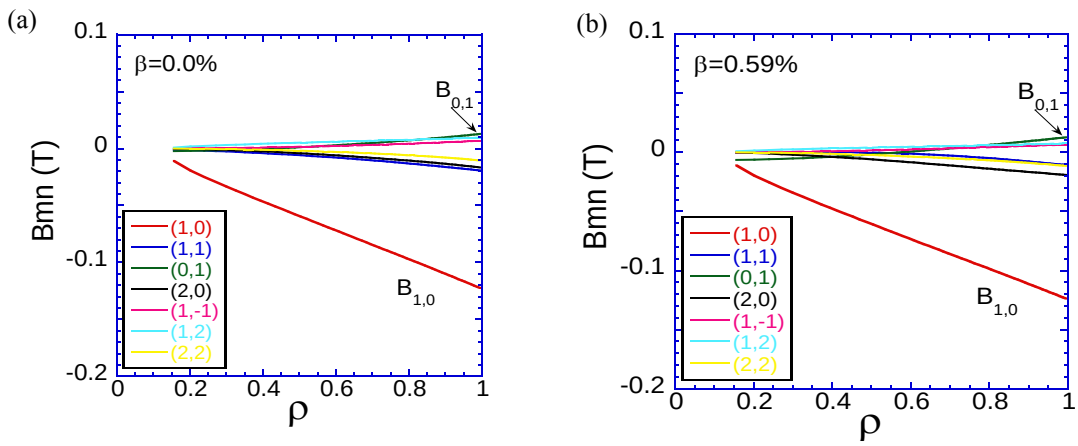

Fig. 3 Fourier components of the CFQS magnetic field strength of the VMEC free boundary equilibrium, (a) <β> = 0.0 %, (b) <β> = 0.59 %.

By scanning the plasma <β> value by changing T_e and T_i on the condition of the fixed density (n_{e0} = 1.0 × 10^{19} m^{-3}), the dependence of the neoclassical bootstrap current on the <β> was examined. Fig.4 shows the neoclassical bootstrap current as a function of plasma <β>. At the <β> of 1.52 %, the neoclassical bootstrap current reaches to 45 kA.

In QAS, the rotational transform is increased by the bootstrap current like tokamaks. The radial profiles of the rotational transform for various <β> are shown in Fig.5. This result shows that the rotational transform profile crosses the rational value (=1/2) in the case of <β> ~ 1.0%, therefore the calculation to check MHD stability is required in the future. The radial profile of the effective helical ripple ε_{eff} were calculated by the NEO code to investigate the effect of the finite <β> with neoclassical bootstrap current on the neoclassical transport, as shown in Fig.5. Here, $\varepsilon_{eff}^{3/2}$ is shown because the neoclassical diffusion coefficient is proportional to this value. For the reference, the profile of the CHS is also shown, and the

$\varepsilon_{eff}^{3/2}$ of the CFQS is two order less than that of the CHS at $\rho \sim 0.5$. The degradation of the $\varepsilon_{eff}^{3/2}$ due to finite $<\beta>$ is small, so a good confinement property of the neoclassical transport can be kept, although $<\beta>$ is increased.

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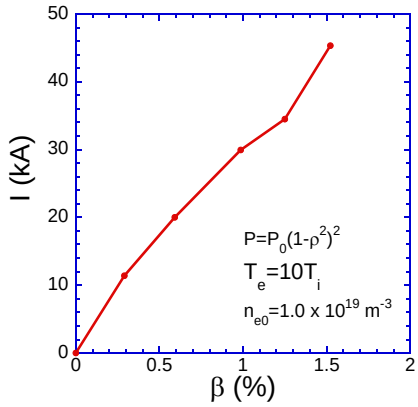

Fig. 4 The neoclassical bootstrap current as a function of $<\beta>$. The neoclassical bootstrap current at the $<\beta>$ of 1.52 % reaches to 45 kA.

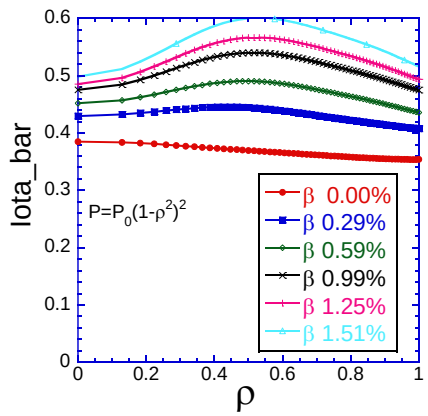

Fig. 5 Radial profile of the rotational transform for various $<\beta>$ with the neoclassical bootstrap current.

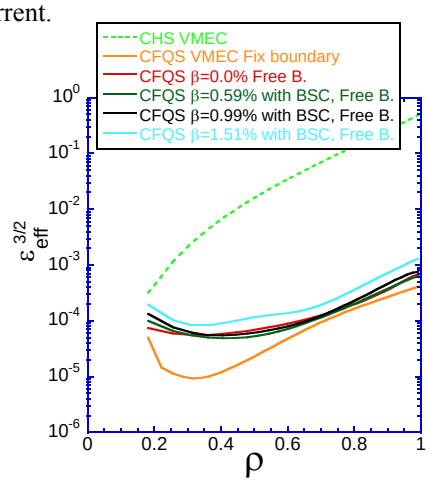

Fig. 6 Radial profile of the $\varepsilon_{eff}^{3/2}$ for various $<\beta>$ with the neoclassical bootstrap current. For the reference, the result of CHS (R_{ax} = 92.1cm, $<\beta>$ = 0.0%) is also shown.