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Design of a New Compact Helical System CHS-qa with a Quasi-Axisymmetry

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Introduction

CHS is a compact stellarator which has an aspect ratio 5. The CHS experiment has been run for 11 years and lots of physical results were obtained. Based on the understanding of the characteristics of helical plasma confinement in CHS, we plan to upgrade CHS to a new device CHS-qa [1]. Two major objectives for this new experiment are (1) to study the helical plasma confinement in an optimized low aspect ratio configuration, and (2) to find an improved confinement scenario of stellarators associated with a strong plasma rotation. The second objective is a consequence of our intensive study of a plasma rotation in CHS.

New approaches of designing advanced stellarators have become widely used based on the powerful numerical analysis techniques using super-computers. Three types of concepts are distinguished: quasi-axisymmetric, quasi-helical symmetric and quasi-isodynamic configurations. We selected the first type because the quasi-axisymmetric configuration is more naturally created in a low aspect ratio design. Another important characteristics of this configuration is low neoclassical viscosity for both toroidal and poloidal directions.

Configuration design and MHD characteristics

Low toroidal period number is commonly adopted for advanced stellarator designs. We selected N = 2 for CHS-qa which is much lower number compared with CHS (N = 8). The aspect ratio is within a range of 3.2 to 3.9 depending on the physics design version. This number is smaller than that of any existing stellarator. Final value should be determined in the synthetic work with engineering design. Rotational transform profile is rather flat compared with CHS and gradually increasing to the edge value of 0.4. Magnetic shear is much smaller than CHS especially in the edge region. However CHS-qa has a magnetic well for the whole confinement region while CHS has the magnetic well only in the region near the magnetic axis.

Configuration design was made with an optimization code which evaluates several physical properties of the equilibrium. Reduction of non-axisymmetric components of the Boozer spectra and the control of the rotational transform bounded within the assumed range of values avoiding dangerous low-order rationals are basic optimization keys. Figure 1 shows a comparison of Boozer spectra for CHS and CHS-qa (2w39 configuration). CHS has a dominant helical ripple B(8, 2) but CHS-qa does not have any big ripple component. This difference is the most important characteristics of a quasi-axisymmetric design.

MHD stability was examined for the equilibrium with zero averaged toroidal current. By using Mericier criterion, stability for the average beta of about 5% is obtained in CHS-qa (2b32 configuration). A strong reduction of the Shafranov shift is also given in CHS-qa while a large Shafranov shift determines the theoretical beta limit of CHS well below 5%. Relatively large bootstrap current is expected to arise in CHS-qa because the magnetic structure is very similar to tokamak. As an example, about 50 kA bootstrap current is estimated for the 1.3% beta equilibrium [2]. The global stability analysis of those equilibria with significant plasma current is the next important topic of MHD analysis.

Particle orbits and neoclassical transport

Common basic philosophy of new advanced stellarator design is to reduce the orbit loss of ripple trapped particles. The goal of quasi-axisymmetric configuration is to eliminate helical ripple itself. In the present design of CHS-qa, a few percent of non-axisymmetric components remain at the edge. But the orbit losses caused by these ripples are greatly suppressed compared with CHS. More important processes to cause collisionless orbit losses is the stochastic ripple losses of toroidal banana particles. This is the same process discussed in tokamaks in the consideration of bumpy ripples introduced by the finite number of toroidal coils.

To evaluate the neoclassical transport property of CHS-qa, a neoclassical diffusion coefficient D is calculated by using DCOM code. Monte Carlo method is used in the code of following test particle orbits in the Boozer coordinates including the pitch angle scattering. The value of D is determined by the radial distribution of test particles. Figure 2 shows the comparison of the neoclassical diffusion coefficients between CHS and CHS-qa (2a36 configuration). Assumed calculation parameters are chosen from the real device designs: magnetic field is 1.8 T and 1.5 T, major radius is 1 m and 1.5 m for CHS and CHS-qa, respectively. Diffusion coefficients for 1 keV electrons are plotted as a function of collision frequency (by varying electron density) for $1/\nu$ region. CHS case clearly shows the increased diffusion coefficient in the $1/\nu$ region. On the other hand, diffusion coefficient goes down in CHS-qa which is similar to tokamaks.

Neoclassical viscosity

One of the main objectives of CHS-qa experiment is to study the effect of helical ripples on the plasma rotation. The investigation of improved confinement mode created by the plasma rotation shear is also an important topic of the experiment. Because the magnetic field structure is quasi-axisymmetric, the neoclassical viscosity of CHS-qa is supposed to be similar to tokamak. Simple estimate of viscosity is made by evaluating the magnetic field variation ratio γ along the direction of plasma flow: viscosity $\mu = \gamma^2$, $\gamma = (\delta B/\delta s)/B$.

Large difference of neoclassical viscosity between CHS and CHS-qa is expected in the toroidal plasma flow. Figure 3 shows the radial profiles of magnetic field variation ratio γ for two devices calculated in the toroidal direction. Field variation is reduced by 1/15 to 1/20 for CHS-qa compared with CHS. The reduction of parallel viscosity is more than two orders. Although the strong toroidal rotation is expected for CHS-qa with external momentum input by tangential NBIs, the velocity shear or the radial electric field shear is supposed to be important for the improved confinement. Bifurcation of the electric field is generally required to create sufficiently high electric field shear. The poloidal rotation physics is more important in this context. Figure 4 shows the comparison of field variation ratio γ in the poloidal direction for CHS and CHS-qa. The difference is larger near the edge and the viscosity is reduced by a factor of 20.

In helical systems, the force balance related to the electric field is determined by the dominant terms of neoclassical non-ambipolar current and the neoclassical parallel viscosity. In the quasi-axisymmetric stellarator, the neoclassical current is supposed to exist still at non-negligible level due to small residual ripple components. Strong rotation is expected to be driven by the non-ambipolar current (which does not exist in tokamak) with a parallel viscosity reduced to the tokamak level.

Device engineering design

The engineering design was made for a middle-size experimental device with 1.5 m major radius and 1.5 T magnetic field. Because of the smaller aspect ratio of CHS-qa than CHS, minor radius will be about 0.4 m which is double size of CHS. The energy confinement time estimated with in ISS95 scaling is 30 msec for 5×10^{19} m^{-3} density with 2 MW heating. The main coil system is designed as 20 modular coils for two toroidal periods. The distance of the coils from the plasma surface is about 0.4 m which was determined by the consideration of divertor space and the limit of total energy of the magnetic field. The most difficult point of the modular coil design is at the inboard side of the bean-shaped cross section. The distance between adjacent coils is of acceptable level considering the device manufacturing. The mechanical support structure for the modular coils was also designed. It is composed of individual modular coil support frames and connecting rods between coils. This design gives fully open spaces on the outboard side of the torus allowing the installation of more than 50 ports.

Additional coils are installed to give various flexibility of the field configuration control. Three sets of poloidal-field coils allow plasma shaping control and inductive current control by ramping the current. Auxiliary toroidal-field coils give an external control of the rotational transform which is one of the most important knobs to deal with bootstrap current effects in the experiment. A schematic picture of whole device is shown in Fig. 5.

References

[1] K. Matsuoka et al. Pl. Phys. Rep. **23** (1997) 542.
[2] S. Okamura et al., J. Plasma Fusion Res. SERIES **1** (1998) 164.

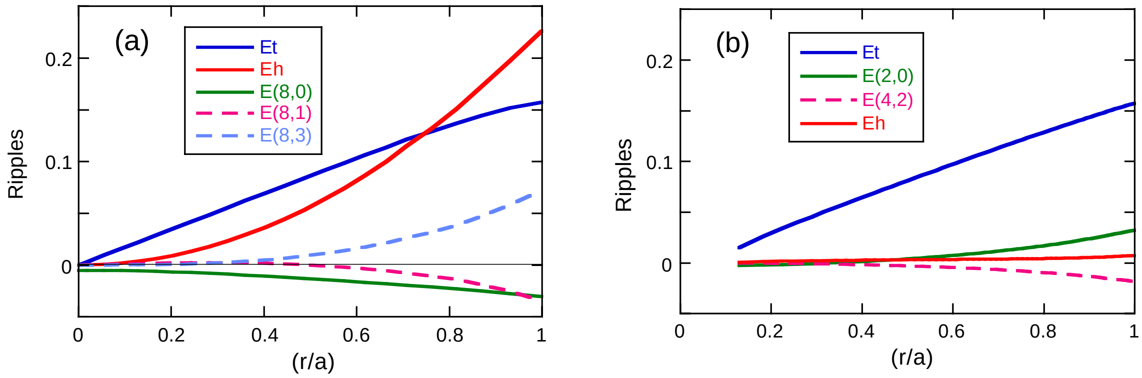


Fig. 1 Boozer spectrum of (a) CHS and (b) CHS-qa

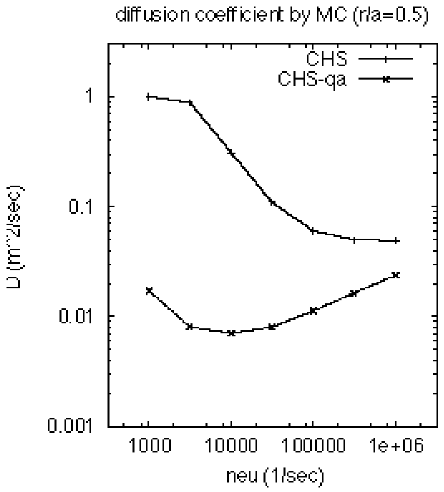


Fig. 2 Neoclassical diffusion coefficient for CHS and CHS-qa

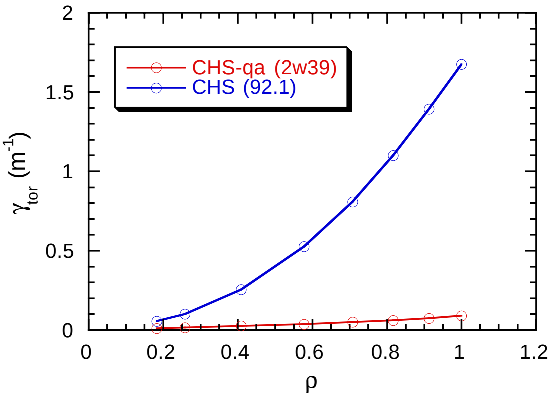
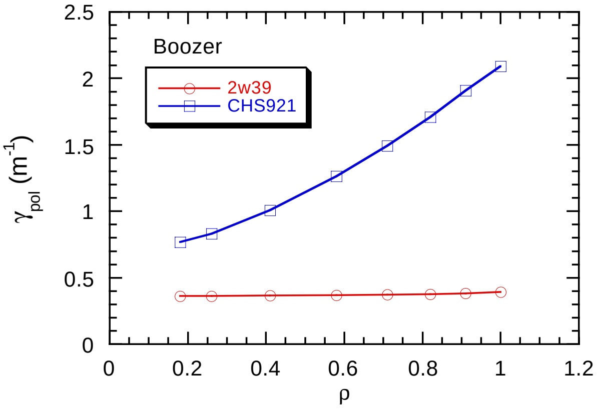


Fig. 3 Neoclassical viscosity in toroidal direction for CHS and CHS-qa



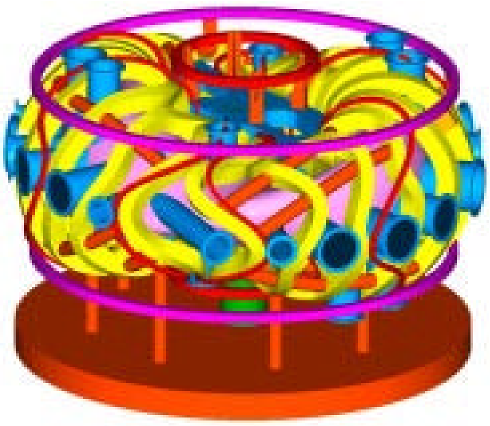


Fig. 4 Neoclassical viscosity in poloidal direction for CHS and CHS-qa

Fig. 5 Engineering design of CHS-qa