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Physics and Engineering Design of a Low-Aspect-Ratio Quasi-Axisymmetric Stellarator CHS-qa

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Abstract. A low-aspect-ratio quasi-axisymmetric stellarator CHS-qa was designed. An optimization code was used to design a magnetic field configuration with evaluations of physical quantities of quasi-axisymmetry, rotational transform, MHD stability and alpha particle collisionless confinement. It is shown that the electron neoclassical diffusion coefficient is similar to tokamaks for the low collisional regime. A self-consistent equilibrium with bootstrap current confirms the global mode stability up to 130 kA for R = 1.5 m and Bt = 1.5 T device. The evaluation of plasma rotation viscosity is greatly suppressed compared with conventional stellarators. Engineering design was completed with 20 main modular coils and auxiliary coils which provide flexibility of configuration study for confinement improvement and MHD stability.

1. Introduction

In the magnetic fusion research, helical systems (stellarators) have made a remarkable progress in these two decades. The plasma parameters obtained in small size devices became comparable to those of similar size tokamaks and the initial results of LHD showed prospective plasma qualities close to those of large size tokamaks. The configuration design of helical systems has also been developed greatly and a number of new configurations have been proposed owing to a large geometric freedom of 3-D structure of helical systems. For most of new configuration studies, primary objective was to improve neoclassical transport by reducing orbit losses of helical ripple trapped particles.

A concept of quasi-axisymmetric stellarator is one of these new proposals which has a tokamak-like 2-D symmetry of magnetic field structure [1, 2]. It can solve the essential problem of stellarator transport by strongly reducing the helical ripple structure itself. From the tokamak point of view, because the rotational transform is given by the external coils, it gives new concept improvements such as avoidance of disruptions, avoidance of current drive and creation of negative shear.

A low-aspect-ratio stellarator CHS-qa has been designed based on such a quasi-axisymmetric concept [3, 4]. As well as good neoclassical transport characteristics, MHD stability for high beta equilibrium is also very important to make a new concept promising as a fusion reactor concept. We basically designed CHS-qa to realize those characteristics as necessary bases of new experiment device. On the other hand, it is well known that the transport phenomena occurring in present toroidal experiments are mainly dominated by the anomalous transport. The optimization of the configuration must take big care of those facts if we hope to achieve good confinement in a real experiment. The device design is also strongly related with the engineering problems for manufacturing. We tried to take all these aspects inclusively to make the best optimization design of the device.

In the quasi-axisymmetric configuration, the tokamak-like bootstrap current (increasing the rotational transform) is expected, especially for high-beta and high-temperature operation. It is possible to design a device targeting tokamak-stellarator hybrid operations. However in our present work, we tried to make a device design more flexible to a wide range of operations avoiding the configuration design which largely depends on the existence of a dominant internal current.

2. Configuration Design

The configuration design was made with an optimization code which evaluates several physical properties. 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 goals. The number of toroidal periods (N) is very important to determine basic characteristics of the configuration. We selected N=2, which allows a secure modular coil design for a low aspect ratio device, but with a disadvantage of accepting a relatively lower rotational transform. The resulting rotational transform profile is above 1/3 at the center and slightly increasing to the edge value of 0.4. The aspect ratio is 3.2. Fig. 1 shows three poloidal cross sections of the equilibrium magnetic surfaces of 2b32 configuration for 3% average beta with zero toroidal current.

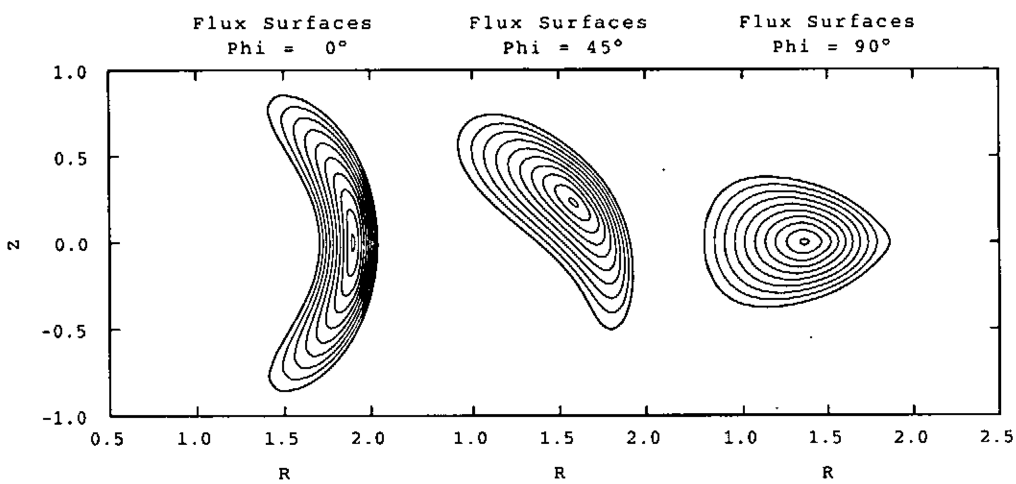

FIG. 1. 2b32 magnetic surfaces for 3% beta equilibrium.

The evaluation of the MHD stability in the optimization run was made based on the local ballooning stability. The configuration 2b32 has a Mercier stability for more than 5% average beta and the local ballooning stability up to 3%. In most cases, we evaluate MHD stability with zero average toroidal current. The optimization procedure with the local ballooning stability gave an additional effect of strong reduction of the Shafranov shift for a high beta equilibrium.

3. Particle Transport

Boozer spectrum of 2b32 configuration is shown in Fig. 2(a). The relative amplitude of the largest non-axisymmetric component B(1,-1) is about 3% at the edge and 1.5% at the half radius. Such residual ripples cause the stochastic ripple losses of toroidal banana orbits of highly energetic particles, e.g., alpha particles in a reactor. The dependence of the banana particle losses on each non-axisymmetric Boozer component is not obvious. For example, in Fig. 2(a), the amplitude is largest for the mirror term with zero poloidal mode number. This component usually remains with almost unchangeable amplitude for any optimization process. But fortunately, this component is not an important one to influence the losses of high-energy banana particles. A smaller component with higher poloidal mode number is affecting the losses more strongly.

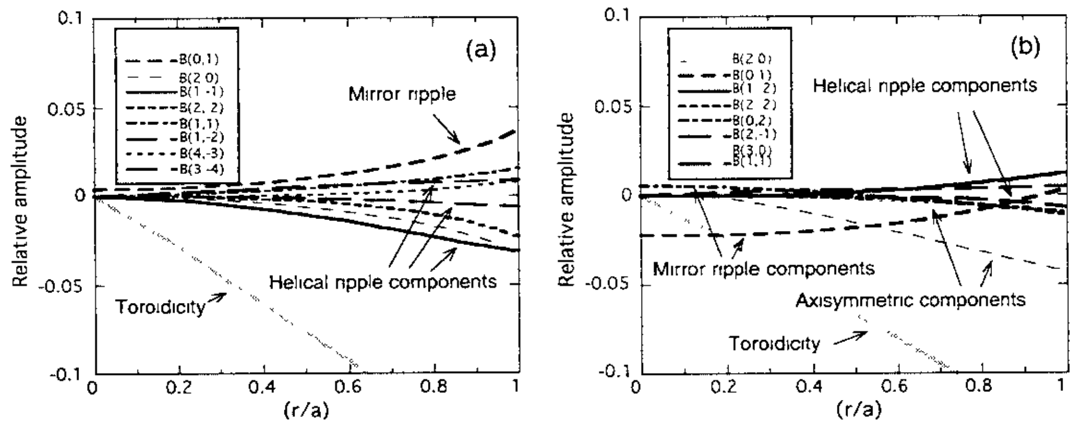

FIG. 2. Boozer spectrum of magnetic field ripple components for (a)2b32 configuration and (b)2a36 configuration. B(m,n) [m: poloidal, n: toroidal mode numbers] is the relative amplitude to the toroidal field.

Another new optimization procedure -- the evaluation of high-energy particle confinement -- gave a new solution of the configuration with a dramatically improved high-energy particle confinement [5]. Figure 2(b) shows a Boozer spectrum of 2a36 configuration obtained by the new optimization procedure. Although non-axisymmetric components (except the mirror term) are suppressed below 1.5% at the edge in this new configuration, the special effect given by the combination of the components with different mode numbers is a possible mechanism for such large reduction (more than one order of magnitude) of the stochastic ripple losses of high-energy banana particles.

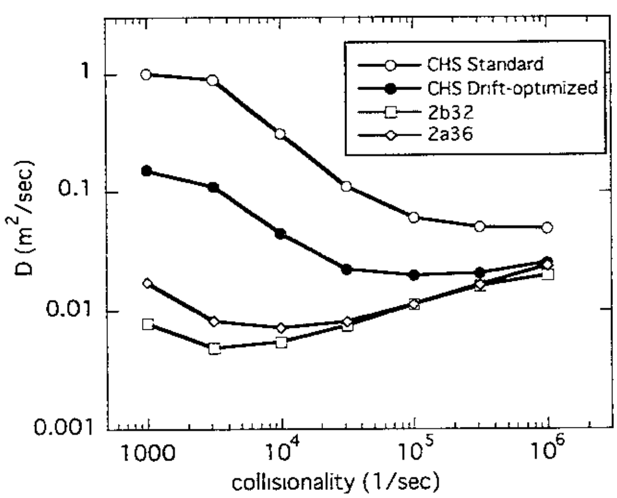

FIG. 3. Neoclassical diffusion coefficients for CHS and CHS-qa. Electric field is not included.

Figure 3 shows a diffusion coefficients of 1 keV electrons for two types of helical devices. CHS is a low-aspect-ratio heliotron/torsatron-type conventional stellarator. Two magnetic configurations are calculated for CHS which are obtained by shifting magnetic axis position. CHS drift-optimized configuration has an inward shifted magnetic axis position compared to the standard one, where the drift orbits of helically trapped particles approximately coincide to the magnetic surfaces. The R_{ax} = 3.6 m configuration of LHD [6] is similar to this drift-optimized configuration of CHS.

The neoclassical diffusion coefficient D is calculated by using DCOM code with no electric field effect. Monte Carlo method is used to follow test particle orbits on the Boozer coordinates with the effect of pitch angle scattering. The value of D is determined from the radial distribution of test particles at minor radius (r/a) = 0.5. Parameters in the calculations are chosen from the real device dimensions: 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 collisionality (by varying electron density) for 1/ν regime. CHS case clearly shows the increased diffusion coefficient in the 1/ν region. The drift optimization gives improvement in the neoclassical diffusion property, but the increase in diffusion coefficient for low collisionality regime still exists. On the other hand, diffusion coefficient goes down in CHS-qa which is similar to tokamak cases.

The difference of neoclassical diffusion coefficient for 2b32 and 2a36 configurations of CHS-qa is not significant in this calculation. Although residual ripples in 2b32 configuration are larger than 2a36, these do not affect the electron neoclassical transport for the bulk plasma confinement.

4. Bootstrap Current and Global Kink Stability

The assessment of the importance of the bootstrap current is one of the most difficult problems in this design work. Because the bootstrap current depends largely on the transport process which cannot be predicted reliably at present, bootstrap current effects will be a major area of the investigation in the experiment. However theoretical model calculations were made for limited cases of 2b32 configuration. Figure 4 shows the rotational transform profile of self-consistent plasma equilibrium for 1.3% plasma beta. The rotational transform profile for the zero current equilibrium with the same beta is also plotted for the reference purpose. The assumed plasma parameters are $n(0) = 2 \times 10^{19}$ m^{-3}, $T_e(0) = 2$ keV and $T_i(0) = 1.5$ keV for 1 T magnetic field. Profiles are shown in the insertion of Fig.4. Total current is 56 kA.

The effect of a toroidal current to degrade the quasi-axisymmetry was generally very small. Although we found examples where an addition of a positive current (in the direction of increasing the rotational transform) improves the local stability, the global stability such as a kink stability generally becomes worse with a plasma current. For this example case, we examined the global MHD stability (external kink mode) using CAS-3D code [7]. The rotational transform is modified to the one shown by dotted line in order to exclude the resonance effect in the plasma. We think such modification is reasonable if we consider the beam driven current of co-injection NBIs (see, Sec. 6). The CAS-3D analysis shows that all low mode perturbations are stable for this configuration. We made a similar stability analysis with model rotational transport profiles for higher beta cases. The stability was obtained for 130 kA case but it was lost for the equilibrium with a current above 185 kA.

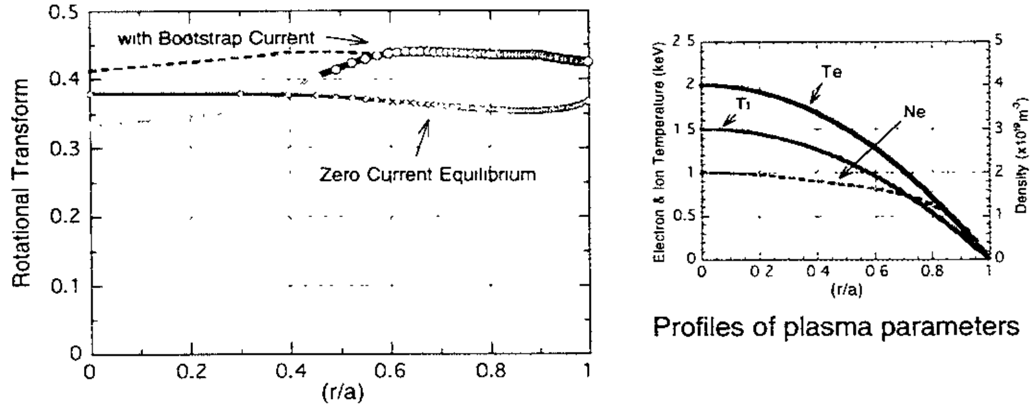

FIG. 4. Rotational transform profile with self-consistent bootstrap current. Right figure shows plasma profiles used in the calculation. The rotational transform of the equilibrium with the assumption of zero average current is also shown for comparison.

5. Neoclassical Viscosity for Plasma Rotation

When we consider the scenario of obtaining improved confinement, one of the most important keys is the plasma rotation and its radial structure. We have many experimental examples of the formation of transport barrier both in tokamaks [8] and helical systems [9]. Since the structure of plasma rotation is determined by the balance of driving force and viscosity, there are various types of transport barrier depending on these components. For example, the plasma rotation in helical systems are mainly caused by the strong driving force of non-ambipolar diffusion and, on the other hand, the rotation in tokamaks are maintained by the low rotation viscosity of axisymmetric configuration with relatively weak driving force. Clear difference of these two types of barrier formation appears as a polarity of potential at the internal transport barrier: in most cases, positive in helical systems and negative in tokamaks.

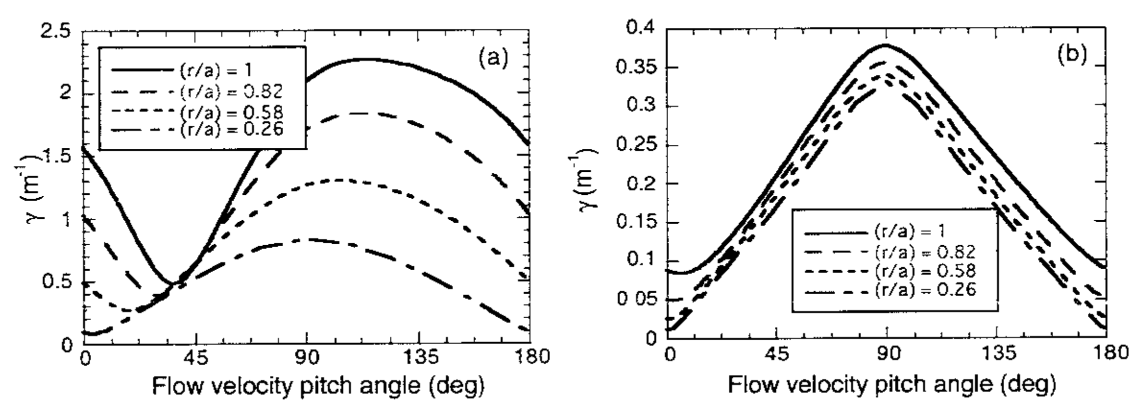

FIG. 5. Comparison of magnetic field variation γ for (a) CHS and (b) CHS-qa (2b32 configuration). γ is calculated for four selected magnetic surfaces. As for the flow velocity pitch angle, zero degree approximately corresponds to toroidal direction and 90 degrees to poloidal direction respectively.

The configuration of CHS-qa gives a good place to experimentally study these important physics. Because it has a quasi-axisymmetric configuration, the neoclassical rotation viscosity is very low compared with a conventional stellarators. Figure 5 shows the averaged magnetic field variation γ on magnetic surfaces along a stream line in CHS and CHS-qa 2b32 configuration ($\gamma^2 \equiv <[(dB/ds)/B]^2>$). The neoclassical viscosity is approximately proportional to γ^2. The stream line is defined as a line which has a constant angle to the toroidal axis of Boozer coordinates (constant poloidal coordinate line). The lowest γ is obtained in CHS for the flow angle of about 40 degrees to the (Boozer) toroidal direction which corresponds to the pitch angle of helical coil windings. We observed experimentally that, in a particular plasma condition, the electric field was formed to make the plasma rotation flow along this direction [10]. On the other hand, CHS-qa configuration has the lowest neoclassical viscosity in the toroidal direction. The ratio of minimum values of γ for CHS and CHS-qa is about 7 at the plasma edge and 20 at a quarter of radius. We hope such a reduction of neoclassical viscosity supply a good condition for the tokamak-like internal transport barrier formation.

When non-axisymmetric ripple components are reduced to the order of 1%, the non-ambipolar current due to the residual ripples becomes comparable to the effective radial current of the bulk rotation viscosity for the typical rotation speed of tokamaks. New area of plasma rotation physics could appear in such an intermediate region of configuration. Important key in the experiment is to prepare various control knobs to vary the configuration with different physical characteristics. We designed CHS-qa with a large configuration flexibility for the purpose of studying confinement physics in this new area of magnetic field configuration.

6. Engineering Design with Configuration Flexibility

The engineering design was made for a middle-size device with 1.5 m major radius and 1.5 T magnetic field. Figure 6 shows the schematic view of the whole device with main modular coils and auxiliary coils. The main coil system was 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 acceptable shape of windings of modular coils. 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 from the aspect of 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. Two tangential ports are installed for two co-injection neutral beams which are designed to drive a strong plasma toroidal rotation with a good heating efficiency.

Although the target magnetic configuration is created by main modular coils by themselves, various additional coils are installed to give flexibility of the field configuration control. Three sets of poloidal-field coils allow plasma positional and shaping control which can be the method of controlling residual ripple structures. A combination of these poloidal coils works also as an Ohmic coil by ramping currents within 0.1 sec. The control of plasma current of up to 100 kA is available. Auxiliary modular coils (eight small coils in red color) give an external control of the rotational transform which is one of the most important knobs to deal with bootstrap current effects on stability and confinement in the experiment.

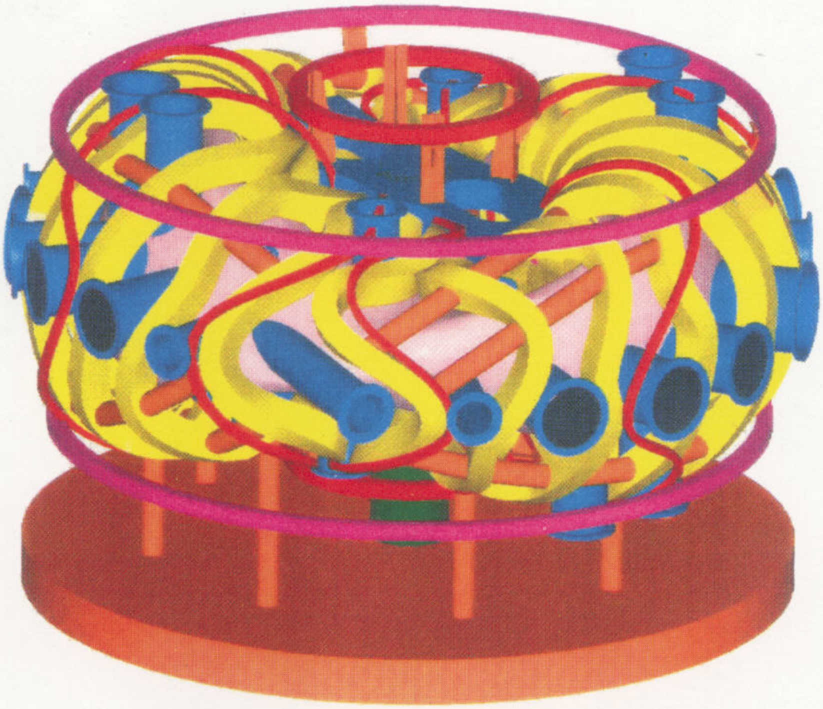

FIG. 6. Schematic view of CHS-qa engineering design.

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