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Low-aspect-ratio Quasi-axisymmetric Stellarator CHS-qa

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Abstract

CHS-qa is planned to succeed CHS as a satellite experiment device. It is designed as an advanced stellarator based on the quasi-axisymmetric concept. The main objectives of the experiment are the further exploration to the low aspect ratio helical experiment and the enhanced confinement due to the fast toroidal plasma rotation. The ballooning stability optimization procedure gave the MHD stability limit at about 5%. The optimization for the energetic particle confinement was also successful. The total engineering design has been completed for R = 1.5 m and B_t = 1.5 T device.

Keywords:

CHS, quasi-axisymmetric, advanced stellarator, low aspect ratio, toroidal rotation

1. Introduction

People have been discussing long time that fusion reactors must be operated in a steady state. From this point of view, it would be very unreasonable to consider a tokamak device as a candidate for a commercial fusion reactor. But because of its prominent performance of the plasma confinement, no other confinement scheme could push it out of the world of confinement concepts for the fusion research. Of course, such situation has been strongly supported by the respective efforts of tokamak community to improve the technique for sustaining plasma current without inductive force. Helical devices (stellarators) have been considered to be the most reliable alternative to tokamak because it can be operated intrinsically in a steady state. However it is also true that the obtained plasma parameters so far in helical devices were inferior to those of tokamaks and, consequently, the community of helical research was much smaller than tokamak research. Biggest reason for such situation comes from the full three dimensional (3-D) magnetic field structure of helical system. One aspect is the difficulty in analysing 3-D configurations, which has been preventing precise calculation of physical characteristics of the system and hence making the device design incomplete. Another aspect is the more complicated characteristics of particle orbits, that causes the additional neo-classical losses compared with tokamaks which have a two dimensional magnetic field structure.

Recently a remarkable development of the computer technology has changed such a situation. Lots of computer analysis tools for the 3-D configuration have been developed and more precise and reliable results were given. Based on these developments, the configuration optimization of the helical systems have been done more thoroughly. As a result, variety of advanced helical configurations were proposed. These

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configurations can be grouped into three concepts of advanced stellarators: quasi-helical symmetric, quasi-axisymmetric and quasi-isodynamic configurations. Among them, a quasi-axisymmetric configuration [1,2] is the one which can improve the confinement characteristics of helical device towards a simpler structure of two dimensional configuration. We can call it as either an intrinsically steady state tokamak or an advanced stellarator with improved tokamak equivalent confinement. There is a possibility that we have found a final solution of a steady state high performance toroidal device.

2. CHS-qa as a Succeeding Device to CHS

CHS is a low aspect ratio torsatron device which has an aspect ratio 5 and toroidal period number 8. It has been operated for 11 years leading the stellarator experimental activity of NIFS in advance to LHD. Recently it was moved to the new site of NIFS in Toki to continue the experiment with a new arrangement of heating systems and diagnostics. Now LHD experiment started, CHS is requested to work as a satellite machine where both a stable operation of the experiments and the exploring concept development are supposed to be realized simultaneously. In a such context, a plan of upgrading CHS has been discussed since 1995 to explore a new direction of advanced stellarators [3]. Two important objectives were discussed: (1) to make a further step to the low aspect ratio design of helical system and (2) to find out an improved confinement regime against anomalous transport with a condition of strong toroidal rotation. For the second objective, it is necessary to reduce the helical ripples as much as possible. The quasi-axisymmetric configuration is a best solution for both objectives since it naturally accepts a low-aspect-ratio design. $N = 2$ was selected as a toroidal period number which also makes a low-aspect-ratio design easier. Figure 1 shows the comparison of major components of Boozer spectrum for CHS and CHS-qa. While the toroidicity E_t is almost the same for both devices, it is very clear that the major helical ripple component E_h is completely suppressed for CHS-qa.

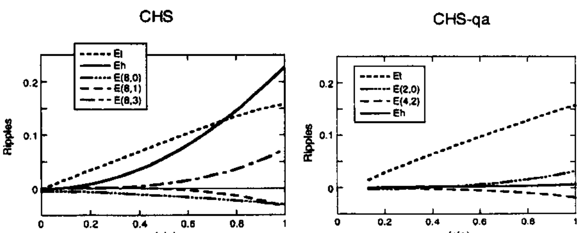

Fig. 1 Comparison of Boozer spectrum for CHS and CHS-qa. Mode numbers in the bracket are for toroidal and poloidal modes. E_t is toroidicity and E_h is main helical ripple.

Because a quasi-axisymmetric configuration is very promising as a candidate for the steady state fusion reactor, active discussions have been made to design configurations with a sufficiently high beta equilibrium assumed for the advanced reactor. In such a condition, a large bootstrap current is theoretically expected because of the tokamak like curvature. Then a configuration design is made with a comparable rotational transform given by the plasma current. It turns out to be a kind of design for a tokamak-helical hybrid machine. Though such direction is a very important topic in the fusion research, we take it more important to make a stellarator approach to the quasi-axisymmetric configuration of CHS-qa. In the real experiment, the plasma parameters are not always at the best point. In addition, reliable and steady operation of the plasma experiment must be given in CHS-qa as a satellite experiment. Therefore our procedure of physical analysis is such that the configuration with no net toroidal current is first studied and then the configuration with bootstrap current is checked for the quasi-axisymmetry and the MHD stability. We did not take a procedure to start from the high beta equilibrium with a large amount of bootstrap current.

3. Configuration Optimization

Basic physical characteristics of the quasi-axisymmetric configuration had been studied for the configuration 2w39 [4]. The first engineering design described below was made for this configuration. It has an aspect ratio $A_p = 3.9$ and a very weekly increasing rotational transform profile approaching to 0.4 at the plasma edge. The configuration optimization for the MHD stability was made based on the depth of magnetic well. The evaluation of the Pfirsch-Schlüter current is not included. The MHD stability was calculated using the Mercier criterion for the fixed boundary VMEC equilibrium with zero average toroidal current. The beta value of this configuration is limited below 2% where the large Shafranov shift appeared which is accompanied by a drop of central rotational transform.

The existence of the internal current generally helps stability. If a plasma current of a parabolic profile is added with the amplitude which increases the edge

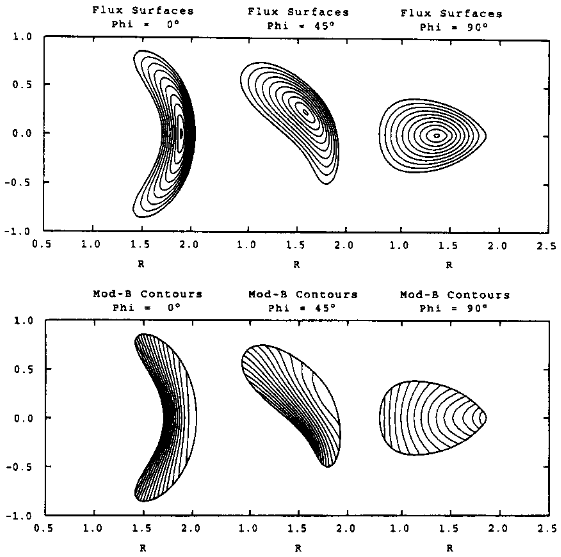

Fig. 2 Magnetic surfaces and mod-B contour plots of 2b32 configuration.

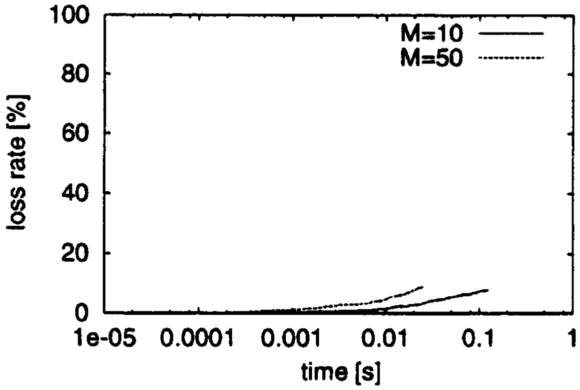

Fig. 3 Monte Carlo calculation of Alpha particle confinement. M denotes the number of Boozer spectrum modes used in the calculation.

rotational transform by 30%, the beta limit is improved above 4%. The central rotational transform becomes close to 0.8 which is almost two times the value created by the external coil. We do not take such a case as a standard operation of CHS-qa.

A new optimization code was developed to include the evaluation of the local ballooning stability. The stability beta limit was increased by this optimization especially for a reduced aspect ratio configuration. Figure 2 shows the magnetic surfaces and the mod-B contour plots of the 3% beta equilibrium for the configuration with A_p = 3.2 obtained by the new optimization procedure (2b32). Compared with the 2w39 configuration, larger elongation is introduced with an enhanced indentation in the vertically elongated cross section. The rotational transform is designed to be limited between 1/3 and 4/5. It has a zero shear point at about half radius which is not the case for the 2w39 configuration.

The examination of the Mercier criterion shows the beta limit of this new configuration is above 5% with zero plasma current. A final ballooning stability must be checked with the global mode analysis of the ballooning stability. The additional effect of the new optimization procedure is a strong reduction of the Shafranov shift by about 30% compared with 2w39 configuration. The drop of the central rotational transform is also suppressed.

The most important process to determine the neoclassical transport property of the quasi-axisymmetric stellarator is the stochastic ripple losses of toroidal banana particles. The orbit losses of helical ripple particles are almost negligible because of the sufficient level of quasi-axisymmetry of the configuration. The dependence of the banana particle losses on each non-axisymmetric Boozer component is not obvious. For example, 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 banana particles. A smaller component with higher poloidal mode number is affecting the losses more strongly.

Another new optimization procedure with the evaluation of high energy particle confinement gave a new solution of the configuration with a dramatically improved high energy particle confinement [5]. Figure 3 shows the result of Monte Carlo calculation for the collisionless loss of particles with 3.5 MeV energy in the device with 1000 m^3 volume and 5 T magnetic field. Particles are confined almost for the collisional damping time in the reactor plasma. It is surprising that this solution still has a considerable level of non-axisymmetric components. The special combination of the components with different mode numbers is a possible mechanism for the reduction of the stochastic ripple losses of banana particles.

4. Engineering Design of CHS-qa

The engineering design was made for the middle size device with 1.5 m major radius and 1.5 T magnetic field. 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 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 acceptable level in the aspect of the device manufacturing. The mechanical support structure for modular coils was also designed, which is composed of individual modular coil support frames and connecting rods between coils. This design gives full 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 coils allow plasma shaping control and inductive current control by ramping the current. Auxiliary toroidal coils give an external control of the rotational transform which is the most important knob to deal with bootstrap current effects in the experiment.

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