Special Topic Article

Quasi-Symmetry in Stellarator Research

5. Status of Physics Design of Quasi-Axisymmetric Stellarators

5.2 Physics and Engineering Design of CHS-qa

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Abstract

A low aspect ratio helical device CHS-qa has been designed based on the quasi-axisymmetric configuration which is one of the new advanced stellarator concepts. As the basic necessary conditions for the new confinement experiment, ideal MHD stability has been examined for the Mercier, ballooning and kink stability criteria. A good quasi-axisymmetry was also realized keeping the good stability condition. As well as making efforts to reduce the neoclassical transport based on the quasi-axisymmetry, various considerations were made with respect to the experimental study of the improved confinement of helical systems from the viewpoint of the anomalous transport. In addition to the main modular coils, auxiliary coil systems are designed to give flexibility of the magnetic field configuration in CHS-qa, which are important to make good experimental study of the confinement physics.

Keywords:

quasi-axisymmetry, advanced stellarator, CHS-qa, improved confinement, high beta

5.2.1 Introduction

The proposal of starting a new advanced stellarator experiment CHS-qa originated from the discussion of the post-CHS satellite machine in the National Institute for Fusion Science (NIFS) in 1995. During seven years after the CHS experiment was started in 1988, basic confinement characteristics of the low aspect ratio helical device had been investigated experimentally. Main research objective of CHS, which was the confirmation of the potentiality of helical device with a low aspect ratio ($A_p = 5$), was positively achieved and the construction of Large Helical Device (LHD) was safely started. The final design of LHD took a larger aspect ratio ($A_p = 6.5$) than CHS but this value is still much lower than existing helical devices at that time.

LHD took an optimized design in the heliotron/torsatron concept.

Having established the direction of the confinement research in the low aspect ratio heliotron/torsatron, discussion of post-CHS device started by looking for the new concept of helical system in a wide area of the configuration varieties. Three issues were considered as important subjects to discuss. First one is how to reduce the helical ripples. It is not only from the aspect of the neoclassical ripple transport but also with respect to the plasma rotation which had been intensively studied in CHS experiment. The helical ripple, which is usually considered as an indispensable element of the helical magnetic field structure, is the essential component for the confinement in stellarators. It works very well in

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heliotron/torsatron devices especially for the configuration with inward shifted magnetic axis. However there is a general dependence in the conventional stellarators that larger helical ripple increases the neoclassical transport. On the other hand, it was shown clearly in the CHS experiment that the helical ripple gave rise to the strong damping of the toroidal plasma rotation which is considered to be one of very important elements in the mechanism of transport barrier formation. If it were possible to design a helical device with reduced helical ripples, the problems of the neoclassical transport and the plasma rotation would be solved simultaneously.

The second issue was the magnetic well. In heliotron/torsatron type configuration, the outer region of the confined plasma is always in the magnetic hill. The ideal MHD stability theory predicts the instability for the configuration with inward shifted magnetic axis with which good particle confinement is given by the helical ripples. There is also the discussion about the resistive interchange instability, which is unstable in the magnetic hill region, as a candidate of anomalous transport mechanism in heliotron/torsatron devices. A new helical configuration with magnetic well could be very favorable from the aspect of both MHD stability and the anomalous transport. On the other hand, the experimental results of CHS and LHD have not shown serious MHD stability problems for magnetic hill configurations so far. The problem of the magnetic well is very active and important topic in the theoretical and experimental research of helical systems.

The last issue is the low aspect ratio. Since CHS successfully demonstrated the usefulness of the low aspect ratio design of stellarator, the motivation appeared to extend further to the similar level of the aspect ratio to tokamaks. Low aspect ratio design is not only attractive for the future reactor design, but also practically useful for designing an experimental device for the physics study of the confinement, because it can give larger plasma size with limited size of the whole device. The aspect ratio of CHS was almost at the smallest limit for the helical device with normal copper conductors with helical winding structure. From this aspect, the modular coil design was included in the discussion of post-CHS device in order to break such a limiting condition.

As a solution to satisfy these three conditions, we finally selected the quasi-axisymmetric configuration as a first candidate of the post-CHS experiment [1], which was published in a concrete form in late 1995 [2]. We believe this selection is also very appropriate for the

main research objective of our institute NIFS, which is to obtain the comprehensive physical understanding of toroidal confinement. Since the quasi-axisymmetric configuration has physical characteristics of both tokamak and stellarator, it is very useful device for such a research objective. As is described in Chap. 5.1, it can also contribute to tokamak research because there are possibilities of finding solutions to the important issues of advanced tokamak research, such as the neoclassical tearing mode and the resistive wall mode instability [3].

Because the magnetic configuration and physical characteristics of quasi-axisymmetric stellarator are in between tokamak and stellarator, there can be basically two different approaches to design a device and make an operational scenario in experiments. From the tokamak point of view, it is a middle aspect ratio tokamak with three dimensional shaping and additional external rotational transform which is expected to help MHD stability and to reduce the current drive power. From the stellarator point of view, it is a low aspect ratio design with very small helical ripples and relatively large bootstrap current. We basically followed the latter approach. We examined the MHD stability and transport characteristics from the configurations with low beta and zero toroidal current. We then increase the beta (accompanied by the increase of bootstrap current) and continue to check stability and transport. The operational scenario of obtaining high beta discharge is also based on the conventional way of helical experiment, i.e., to increase gradually the density and temperature by increasing the heating power. Although the device design includes a function of inductive current drive using ramped currents in the poloidal coils, it is considered to be only a knob for the plasma current control and will not be considered as an essential component of the plasma operation.

It has been seriously discussed that the improvement of confinement is very important to make the fusion reactor design acceptable for our society. Very fortunately various types of improved confinement were found in tokamaks and the recent finding of the Internal Transport Barrier (ITB) was one of greatest topics in the history of the magnetic fusion research. On the other hand, in the helical confinement research, we discussed more frequently about the method to mitigate the helical ripple transport, namely the neoclassical transport, and the discussion for the improved confinement had been taken as an auxiliary topic. Several modes of the improved confinement were found in CHS [4] and Wendelstein 7-AS [5], but these findings did not lead to

the large enhancement of the plasma parameters. The important break through was the finding of the internal transport barrier in CHS in 1998 [6]. The mechanism of this phenomena was very clearly discussed owing to the detailed physical information of plasma profiles with electric potential measurement by the Heavy Ion Beam Probe (HIBP) [7]. The characteristics of electric field bifurcation is essentially different from the transport barrier formation mechanism observed in tokamaks. The non-ambipolar neoclassical radial current takes an important role (it is called neoclassical ITB with this reason). We think it is very important to expand this area of research to more general understanding of the toroidal confinement. From this point of view, the quasi-axisymmetric configuration is very appropriate because of its unique feature of having characteristics of both tokamak and stellarator. Various aspects of confinement improvement scenarios were considered in the design of CHS-qa and this topic is now taken as a major objective of CHS-qa experimental plan.

Basic physical characteristics and the engineering designs of CHS-qa (2b32 configuration) have been reported [8,9]. In this review, we tried to describe more

about the motivation and the planning of the CHS-qa experiment.

5.2.2 Magnetic Field Configuration

The configuration design is made with the design parameters for the boundary shape of the last closed magnetic surface. Since this methods were first applied in the design of Wendelstein 7-X, it has been widely used in the designs of new generations of stellarators because it can design very large variety of configurations in three dimensional toroidal geometry. The quasi-axisymmetry of the magnetic field in the Boozer coordinates and the several criterions of ideal MHD stabilities are taken as guiding principles of configuration design.

Figure 1(a) shows the magnetic surfaces with 3% average beta at three poloidal cross sections ($\phi = 0^\circ, 45^\circ$ and 90°) of 2b32 configuration which is the present design basis of CHS-qa device. Contour lines for the constant magnetic field strength are shown in Fig. 1(b) for the purpose of giving the images of how the magnetic field strength varies producing the quasi-axisymmetric magnetic field structure (the magnetic

Fig. 1 Magnetic surfaces and contour plots of magnetic field strength of CHS-qa for cross sections at three toroidal angles.

field strength in the Boozer coordinate varies proportional to $1/R$). The 2b32 configuration has the toroidal periods $N = 2$ which is a smallest number for the present designs of stellarators. The major radius is $R = 1.5$ m and the averaged minor radius is 0.47 m making the averaged aspect ratio of 3.2. If we take the horizontal minor radius of the toroidally averaged cross section following to the definition in tokamaks, the aspect ratio is 3.9.

In order to make the configuration quasi-axisymmetric, smaller aspect ratio is more favorable because the larger toroidicity makes the residual helical ripples ineffective. It is general features of helical configuration that the number of toroidal period is roughly proportional to the aspect ratio. It is also commonly observed that the rotational transform created within a part of torus for one period of helical structure has maximum value at about 0.2 which is limited by the realistic coil design. Therefore smaller aspect ratio leads to the lower value of the total rotational transform for the whole torus. We selected the toroidal period $N = 2$ with the vacuum rotational transform below 0.4. In the configuration design, we set a constraint that the vacuum rotational transform stays between $2/6$ and $2/5$ in order to avoid a low rational value resonance.

The quasi-axisymmetry of the magnetic field structure is shown in Fig. 2 which gives the Fourier spectra of magnetic field strength in the Boozer coordinates. The amplitudes of spectra are the relative values to the averaged magnetic field strength at the plasma boundary. Mode numbers (m, n) correspond to the poloidal and toroidal modes in a single toroidal period. The amplitude of $(1, 0)$ component, usually called the toroidicity, is about 14% at the plasma edge, which is much smaller than the inverse of the aspect ratio of 3.9 (in tokamak definition). It is an example of how the three dimensional structure can create the unique characteristics that is not given by the (averaged) two dimensional structure. The $(0, 1)$ mode (mirror ripple) is the largest non-axisymmetric component and the $(1, 1)$ mode is the largest helical component, which are the result of imperfectness of the symmetrization. However, as will be discussed in Sec. 5.2.6, they become useful in the maximum-J criterion for the confinement improvement.

From the viewpoint of the reactor design based on the quasi-axisymmetric configuration, the axisymmetry of 2b32 is not sufficient for the good confinement of alpha particles. This level of axisymmetry is the present solution of the symmetrization which results from the

Fig. 2 Boozer spectrum of 2b32 configuration with 3% average beta.

trade off with the ideal MHD stability. If we are interested solely in the axisymmetry, other configurations are found for much better axisymmetry (one order smaller ripples) with the reduction of the ideal MHD stability.

Although the basic configuration design was made based on the parameters of the boundary shape, the real equilibrium of the plasma in the experiment is determined by the combination of the vacuum magnetic field produced by the external coils and the equilibrium plasma current. Such a free boundary equilibrium is calculated with two numerical calculation methods. With the free boundary VMEC calculation [10], which is the equilibrium solver with the modelling assumption of the existence of the magnetic surfaces, the conservation of the quasi-axisymmetry is confirmed for the finite beta equilibrium with the additional vertical field to keep the plasma position unshifted. The free boundary equilibrium is also calculated by the HINT code [11], which solves the equilibrium without assuming the existence of the magnetic surfaces. This code can calculate the equilibrium solution with islands which the VMEC code cannot handle. For the high beta equilibrium, the mode coupling of the external magnetic field and the finite beta plasma current could create the islands. Figure 3 shows the results of HINT code calculation for the vacuum magnetic surfaces of 2b32

Fig. 3 Equilibrium calculated by HINT code for (a) vacuum configuration and (b) 3.3% average beta equilibrium. In each figure, right plot is for the toroidal position $\phi = 0^\circ$ and left plot for $\phi = 90^\circ$ rotated by 90° .

configuration and the 3.3% average beta equilibrium. It is shown that clear magnetic surfaces exist for such a range of plasma beta. In this calculation, it is assumed that the pressure profile is proportional to $(1-\psi^2)$, where ψ is the toroidal flux, and the plasma current is zero in the average on each magnetic surface. Because a large bootstrap current is expected to appear in the high beta quasi-axisymmetric configuration, the calculation of the equilibrium with plasma current is the important issue. In the long history of the helical confinement research, although the robustness of the magnetic surfaces of a high beta equilibrium has been one of the most critical topics, there have been very limited experimental studies for them. The CHS-qa experiment will be very interesting experiment to give a solution for this important problem.

5.2.3 Confinement

The most essential characteristic of the quasi-axisymmetric stellarator is the improvement of the neoclassical transport due to the reduction of helical ripples. The effect is evaluated by calculating the transport coefficients using the Monte Carlo calculation of particle orbits with collisions in a real device configuration. Figure 4 shows the transport coefficients calculated by DCOM code [12] for several helical devices for the comparison of different type of configuration. The diffusion coefficients are calculated for 1 keV electrons using the magnetic field strength and the machine size of individual device. Coefficients are normalized to the theoretical plateau values of circular tokamaks equivalent to each device. The plots of “CHS $R_{ax} = 92.1$ cm” and “LHD $R_{ax} = 3.75$ m” are the transport coefficients for the standard configurations

Fig. 4 Diffusion coefficients of CHS, LHD and CHS-qa devices normalized to the neoclassical plateau value. Monte Carlo calculation results for 1 keV electrons at half minor radius are used. No electric field is included.

of heliotron/torsatron type devices. The increase of transport coefficients for the low collisionality regime is a typical feature of conventional stellarators with helical ripples. These transport coefficients can be reduced for the configuration with inward shifted magnetic axis shown by the data “CHS $R_{ax} = 87.7$ cm”. The LHD configuration with $R_{ax} = 3.6$ m has similar characteristics. Although the transport level is significantly

Fig. 5 Effective helical ripples calculated for CHS and CHS-qa.

reduced, the transport coefficient is still increasing in the low collisionality regime. On the other hand, the transport coefficient for CHS-qa (2b32 configuration) decreases in the low collisionality regime which is similar dependence to tokamaks. The small increase of the coefficients for the very low collisionality regime is caused by the residual ripples of 2b32 configuration. For the configuration with much more reduced residual ripples, such small increase disappears. Figure 4 shows also the coefficient for CHS-qa with bootstrap current (described in the next section) which shows a small improvement of the neoclassical transport.

The improvement of the neoclassical transport is also shown by the effective ripples calculated by the NEO code [13] (cf. Sec. 5.1.3). Figure 5 shows the effective ripples of 2w39 configuration as a function of minor radius [14]. It also shows the values for two configurations (standard and inward shifted) of CHS as a reference. The improvement of the transport is observed similar to the DCOM code results in Fig. 4. A small hump in the coefficients of 2w39 configuration at $r/a = 0.7$ is due to the effect of the low rational number resonance in the field line tracing calculation to obtain the Boozer spectrum.

The confinement of the alpha particles is also calculated for the model configuration scaled up to the reactor size. The particle confinement time is not sufficiently long in the 2b32 configuration compared to the energy relaxation time of alpha particles. For the solution of this particular problem, we have proposed a different version of the quasi-axisymmetric configuration for the improvement of alpha confinement [15]. Another version with reduced helical ripples also shows good alpha confinement. However we presently selected 2b32 configuration as a candidate for the CHS-qa experiment because of its good overall characteristics. The problem of alpha confinement in the quasi-axisymmetric stellarator should be studied more carefully because the discussion must include the analysis of the distribution profile of escaping alphas on the wall which has not been sufficiently analyzed for this concept compared with tokamak type reactors.

5.2.4 Bootstrap Current and MHD Stability

As the basic criterion for the MHD stability in the configuration design of CHS-qa, ideal linear stability was evaluated. However, we should be careful to note that the compilation of the experimental database and the understanding of the MHD stability for the helical systems are presently relatively poor compared with tokamaks. It is partly because there were not many experiments where the plasma beta was high enough to come close to the theoretical beta limit. The theoretical analysis of the phenomena was also very difficult due to the three dimensional structure. We obtained a number of experimental results in CHS and LHD which describe stable plasmas in spite of predicted instability from the linear ideal MHD theory. We didn't have any experimental database for the kink instability with large contribution of the external rotational transform. We should remember that the MHD stability problem is one of the most important research target of CHS-qa experiment.

In the configuration optimization process, we evaluate local ballooning stability to determine the direction to which the plasma boundary shape should be modified for getting better stability. Although we know, in three dimensional configuration, that the local ballooning criterion and the result of global mode analysis for the ideal MHD stability give different beta limit, we believe that the dependence of stability on the configuration of the plasma should be approximately the same. It should be noted again that the ballooning stability has never been experimentally studied yet in

Fig. 6 (a) Rotational transform profiles with self-consistent bootstrap current for three different density profiles. (b) Model plasma density profiles.

helical systems. We obtained so far in the ideal MHD stability analysis with Terpsichore code [16] that the beta limit for 2b32 configuration is about 4% with bootstrap current. The mode analysis includes kink, vertical and ballooning modes. We didn't owe to the wall stabilization effects because we set the position of the conducting wall in the code sufficiently far from the plasma boundary.

The bootstrap current is calculated based on the analytic formula and the equilibrium is reconstructed to make the results self-consistent [17]. From the experimental experiences of CHS and LHD, we assumed the temperature profile as parabolic: $\propto (1-\psi)$. As for the density profile, we observed very wide varieties of profiles in the experiments. In Fig. 6(a), the rotational transform profiles are shown for three equilibria with the bootstrap current produced by three typical density profiles which are also shown in Fig. 6(b) [18]. In these calculations, the central temperatures of electrons and ions are assumed to be 2 keV and 1.5 keV respectively. The central density is kept the same at $2 \times 10^{19} \text{m}^{-3}$ for three cases. The magnetic field is 1 T. For the case of flat density profile $\propto (1-\psi^3)$, the rotational transform has reversed shear (in tokamak sense) which must be favorable from the aspect of neoclassical tearing mode suppression.

When the rotational transform is increased by the bootstrap current above 0.5, the kink mode becomes unstable. This characteristics was shown in the calculation with Terpsichore code and it was also confirmed in the calculation with CAS3D code [19]. Such an unstable situation appears in the case that the

plasma current exceeds 150 kA for 1 T operation, which is not expected in CHS-qa experiment with the average beta below 4%. But in the reactor relevant plasma parameters where a large bootstrap current is expected, more dedicated calculation will be necessary. However again, such calculation may be valuable only when we obtain sufficient data in the experiment and understand the kink stability in stellarators. It is expected that the nonlinear analysis of the evolution of the instability would be much more important for the stellarators, in which a large part of the rotational transform is supplied by the external coils.

5.2.5 Control of Axisymmetry

As is described in Sec. 5.2.1, main objective of CHS-qa experiment is to study the physical mechanism of confinement improvement. We found already the neoclassical ITB in CHS [4], which is caused by the radial structure of the neoclassical non-ambipolar currents and the related plasma rotation profile. If the residual ripples (non-axisymmetric structure) of CHS-qa remains to be important in determining the force balance of the plasma rotation, the similar kind of ITB would be observed in CHS-qa. On the other hand, there is possibility of finding different types of ITB which have been observed in tokamak experiments, if the axisymmetry of CHS-qa is good enough to reduce the non-ambipolar current below the ineffective level for the dynamics of the plasma rotation. Because the structure of plasma rotation shear, namely the profile of the radial electric field, is determined by the force balance of the plasma rotation driving term and the damping

mechanism, we can compare the neoclassical non-ambipolar current caused by the helical ripples with other equivalent radial currents corresponding to the various driving force and the rotation damping mechanism, such as the external momentum input, the neoclassical viscosity, charge exchange ion energy loss, etc. Although our understanding of these physics is not sufficient to give a clear quantitative prediction, if we take typical quantities from the existing tokamak and helical experiments, the residual helical ripples of CHS-qa is just at the intermediate level. Therefore it is necessary to have the controllability of the axisymmetry in order to obtain the clear understanding of the ITB formation mechanism for axisymmetric and non-axisymmetric toroidal confinement.

It is planned in CHS-qa to add the mirror ripple as a controlling knob of the axisymmetry. The magnetic coil design of CHS-qa has 20 modular coils. Because the number of toroidal periods is $N = 2$ and owing to the stellarator symmetry, they are divided into four identical groups of 5 modular coils. Modular coils are designed to produce the quasi-axisymmetric configuration with the same currents in all coils. The mirror ripple can be created by reducing the currents in two of five coils. In order to estimate the non-axisymmetry produced by the mirror ripple, we take a modelling by M. S. Smirnova

Fig. 7 Dependence of averaged helical ripple on the ratio of current in two groups of modular coils. Averaged variation of magnetic field in poloidal and toroidal direction are also shown.

for the averaged helical ripple in the multi-helicity configuration [20]. Figure 7 shows the dependence of the averaged helical ripple at the normalized radius (r/a) = 0.5 on the ratio of the currents in two groups of modular coils [21]. It is possible to increase the averaged ripple 10 times larger by changing the current ratio of modular coils. We expect this level of ripples will make CHS-qa configuration completely non-axisymmetric from the aspect of the rotation force balance dynamics.

Such mirror ripples enhance also the neoclassical viscosity for the toroidal plasma rotation. Figure 7 shows also the averaged variation of the magnetic field strength γ for poloidal and toroidal flow directions. The neoclassical viscosity is roughly proportional to γ^2 . For the toroidal direction, the neoclassical viscosity can be increased by about two orders of magnitude with mirror ripple control. We hope this controllability is also useful in studying the ITB formation physics.

5.2.6 Maximum-J Criterion

In the relation with the anomalous transport, the drift reversal condition for the trapped particle instability has been discussed in tokamak research and other axisymmetric toroidal confinement [22, 23]. Many theoretical analyses tell that, when the toroidal direction of the precessional motion of the trapped particles is opposite to the direction of diamagnetic drift, the trapped particle instability is stabilized. There was also a discussion of this condition for the helical systems [24]. The drift reversal condition has been examined for CHS-qa with a scope of controllability of the condition in the experimental flexibility [25]. The favorable condition to give the drift reversal can be written by $dJ/dr < 0$, where J denotes the second adiabatic invariant defined by the following formula ($v_{\parallel}$ is the velocity of the trapped particle parallel to the magnetic field).

$$J \equiv \int v_{\parallel} dl$$

If we can find a radius at which the J value takes the maximum value, the area outside of that radius is supposed to be the stable region for the trapped particle instability. This condition generally holds for the magnetic well region if the rotational transform is increasing towards the plasma edge (stellarator shear). One example is the reversed shear operation of tokamaks. Although helical systems have normally stellarator shear, this condition is not usually held in the conventional heliotron/torsatron type stellarators

Fig. 8 Contour plot of the second adiabatic invariant J as a function of minor radius and toroidal angle for (a) 2w39 standard configuration and (b) outward shifted configuration. $\zeta_N = 0$ corresponds to the vertically elongated cross section and $\zeta_N = 0.5$ to the horizontally elongated cross section.

because of the magnetic hill condition.

Figure 8 shows an example of the controllability of the maximum- J condition for the quasi-axisymmetric configuration 2w39 with zero beta. The contour plot of J is shown as a function of minor radius and the toroidal angle. The calculation of J is made by following the particle orbits starting from the outboard side of the torus with different toroidal angles. $\zeta_N = 0$ corresponds to the vertically elongated cross section and $\zeta_N = 0.5$ to the horizontally elongated cross section. Fig. 8(a) shows a standard configuration without additional vertical field. There is a maximum point of J near the plasma edge at the normalized radius (r/a) = 0.8. Boundary area outside of that radius satisfies the maximum- J condition. For the experimental study of the effect of this condition on the confinement, it is important to have the controllability of this condition. With an additional vertical field, such an area can be expanded and the gradient of J is increased for the outward shifted configuration shown in Fig. 8(b). It is also possible to reduce the area by shifting in the plasma position.

5.2.7 Engineering Design

Twenty modular coils are designed with normal copper conductor for 1 second flat top duration of the magnetic field of 1.5 T. Because of the low aspect ratio, the mechanical arrangement of modular coils is difficult for the inside of torus. However we could find a final solution with the structure of coil frames working as a part of mechanical support.

In the mechanical design of the device, we took a big care for the accessibility of the ports for the diagnostics. It is very essential since our major objective of the experiment is to find out and learn the mechanism

Fig. 9(a) Internal mechanical support structure of CHS-qa device.

Fig. 9(b) Engineering design of CHS-qa device with additional coils for configuration flexibility.

of the improved confinement. From this aspect, the design of coil support structure is important because those support very often interfere the port access. In order to avoid large support structure outside of the torus, we design the main support of modular coils at the central region of the torus. A schematic picture is shown in Fig. 9(a). In addition to this central support structure, we arranged supporting rods connecting modular coil frames carefully avoiding the interference with ports for the major diagnostics. These mechanical design was made for the operation of $B = 1.5$ T and the device size of $R = 1.5$ m. Whole design is shown in Fig. 9(b).

The quasi-axisymmetric magnetic field configuration is produced by only modular coils. However the flexibility of the configuration is very important for the experimental research to understand the physics involved in various phenomena. Figure 9(b) shows three pairs of poloidal coils which are designed for two different purposes: (1) vertical and quadrupole poloidal field for the plasma position and shaping control and (2) inductive current drive capability for the control of plasma current. Figure 9(b) also shows additional small modular coils (in red color) designed for varying the rotational transform with minimum change of the Boozer spectrum. Another flexibility control is the variation of the current ratio for two groups of modular coils for controlling the mirror ripples, which is described in Sec. 5.2.5.

The port design was made with lists of existing heating and diagnostic components which are in operation in CHS. We believe that the design work of the device and port arrangement with real dimensions of the working components is very practical to make the machine useful for the real experiment.

5.2.8 Conclusion

A low aspect ratio quasi-axisymmetric helical device was designed with the toroidal periods of 2 and the average aspect ratio of 3.2. Basic guiding criteria of the confinement characteristics in the configuration design are the ideal MHD stability and the improved neoclassical transport. From this aspect, 4% average beta and the two orders of improvement in the neoclassical transport coefficient have been achieved compared to the conventional type of stellarator CHS. It is confirmed that the maximum-J criterion is satisfied in the boundary region of CHS-qa. Big care was taken for the experimental flexibility in the anomalous transport study using the configuration that has characteristics of

both helical and axisymmetric torus.

5.2.9 Acknowledgement

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