Physics Design of Quasi-Axisymmetric Stellarator CHS-qa

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Abstract. A low aspect ratio stellarator CHS-qa with a quasi-axisymmetric configuration is designed at NIFS with the experimental confinement study as the main objective. The high beta equilibrium was confirmed with the HINT code which does not need the assumption of nested magnetic surfaces. The equilibria with bootstrap current were calculated with the SPBSC code and their global MHD stability was evaluated with the TERPSICHORE code. The boundary structure of the magnetic field was examined to scope divertor options. A new method of calculating the neoclassical transport properties was developed for toroidal configurations with very small nonaxisymmetry. The control knobs of the configuration properties are proposed for the study of improved confinement.

1. Introduction

Plasma confinement study in the stellarator configuration with quasi-symmetry has become a new steady stream in the fusion research. First experiment based on the quasi-helical symmetry has already started with the HSX device [1]. The experiments for two other types of symmetry are also proposed as NCSX [2] (quasi-axisymmetry) and QPS [3] (quasi-poloidal symmetry) projects. In this paper, we discuss the confinement characteristics of CHS-qa which is designed in NIFS, Japan as a quasi-axisymmetric stellarator with a low aspect ratio [4]. For these new generation of devices, most of classical problems of the conventional stellarators have been successfully solved owing to the recent high computing technology, which makes full use of high freedom of configuration design in three dimension. However, as we see in the axisymmetric tokamak experiment, the problem of anomalous transport is the dominant channel for the toroidal plasma confinement. The development of the improved confinement scenarios is still the most important issue for stellarators. In the design of CHS-qa configuration, we took care about such an aspect as well as the optimization in the classical problems.

2. Basic CHS-qa Configuration and Free-boundary Equilibrium

The number of toroidal periods of CHS-qa is two and the average aspect ratio is 3.2 (2b32 configuration). The vacuum rotational transform is designed between 2/6 and 2/5 avoiding low order resonances. The quasi-axisymmetry is evaluated with the Fourier components of the Boozer spectrum and the largest non-axisymmetric component is 3% at the edge and 1.5% at the half radius in the amplitude relative to the toroidal magnetic field. One of the limiting factors for the low aspect ratio design is the availability of the coil design for the practical size of the experimental device. The engineering design of 20 modular coils (for full torus) have been successfully made for the major radius R = 1.5 m and the toroidal magnetic field Bt = 1.5 T. Auxiliary poloidal coils are also designed for the plasma shape and the position control.

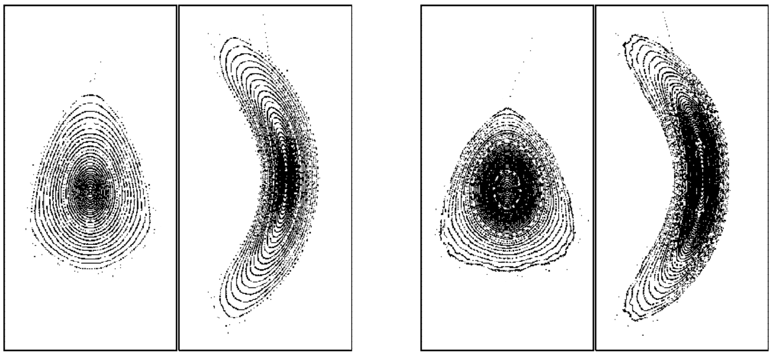

Fig. 1. Puncture plots of magnetic surfaces for vacuum (left) and 3.3% average beta (right) equilibria of CHS-qa calculated by HINT code.

It is necessary to make equilibrium calculations with magnetic coil current so as to confirm whether the obtained configuration is robust against the island formation caused by the equilibrium current of finite beta plasma. For this purpose, free boundary equilibrium calculations were made using HINT code [5]. The vacuum magnetic field created by designed 20 modular coils are used. Figure 1 shows the puncture plots of magnetic surfaces of CHS-qa for the vacuum configuration and the 3.3% average beta equilibrium with zero average toroidal current for each magnetic surface. The vertical field is adjusted to push back the plasma position for high beta equilibrium. It is observed that the magnetic surfaces are robust against the high beta perturbation. In the case of no vertical field control, large part of the closed magnetic surfaces are lost because of the outward shift of the plasma column.

3. Bootstrap Current and Global MHD Stability

The self-consistent bootstrap current (BSC) is calculated using SPBSC code [6] with the connecting formula of the neoclassical theory predictions for different collisionality regime. Calculations are made for several cases taking all Boozer spectra as the information of magnetic configuration. They were compared with the approximate calculation taking only axisymmetric terms of Boozer spectra (pure QA model). The approximate calculations gave generally 20 to 30 % higher current than the full mode calculations. Since the full mode calculation is sometime unstable, we use the approximate calculation for the discussion of pressure profile dependence.

We calculated BSC profiles for two types of high beta plasma: high temperature with low density case and high density and low temperature case. Figure 2(a) shows the rotational transform profiles of high temperature case for two model profiles of the plasma density. The temperature profile is kept constant as parabolic ($T_{e,i} \propto (1-\psi)$: ψ is the toroidal flux, $T_e(0)$ = 5.2 keV, $T_i(0)$ = 3.9 keV) and the density profiles are chosen for peaked ($n_e \propto (1-\psi)^{0.5}$) and flat ($n_e \propto (1-\psi^3)$), with the fixed central density $n_e(0) = 2 \times 10^{19}$ m^{-3}. The magnetic field B = 1 T and the major radius R = 1.5 m are assumed. The average beta is 3% for the peaked profile case. For high temperature plasma, the stellarator shear is created with the flat density profile for a wide range of radius. Highest value of the rotational transform rises close to 0.6. Figure 2(b) shows the rotational transform profiles for high density case: the central density $n_e(0) = 1 \times 10^{20}$ m^{-3} and the ion and electron temperatures are 1/5 of the previous case. In this case, the rotational transform at the edge is below 0.5 which is critical value for the external kink stability in CHS-qa.

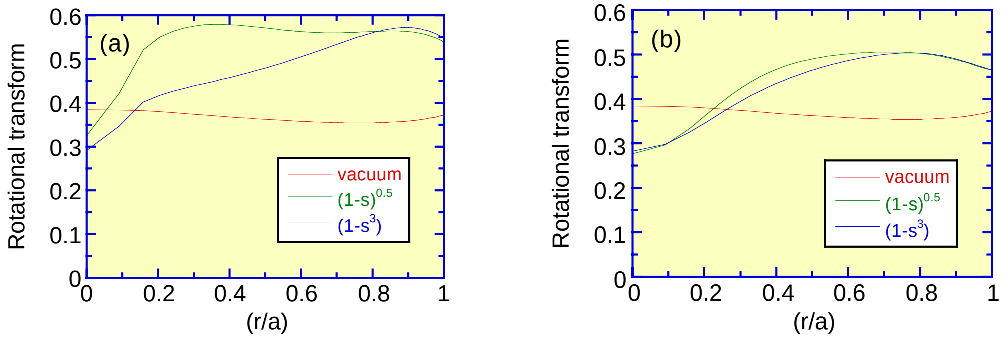

Fig. 2. Rotational transform profiles for different pressure profiles. (a) high temperature and low density case, (b) high density and low temperature case.

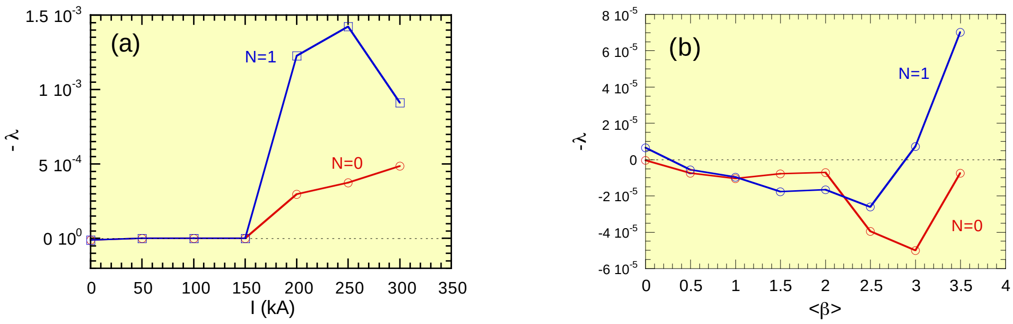

Fig. 3. Global MHD stability analysis. (a) external kink stability with 1% average beta, (b) stability for the pressure driven mode.

The global stability analysis was made using TERPSICHORE code [7] for the plasma pressure profiles described above. The ranges of Fourier modes in the calculation are $m < 36$ and $n < 11$ for the poloidal and toroidal mode, respectively. The shape and the location of the conducting wall in the calculation is designed sufficiently far from the plasma boundary in order to eliminate its effect for the stability. Figure 3(a) shows the growth rate of the external kink mode as a function of the plasma current. In this calculation, the plasma average beta was kept constant at 1% and the current density profile is proportional to the bootstrap current for 1.2% beta. The plasma current, however, is artificially varied which causes the rotational transform to change. The growth rates shown are for the most unstable mode in the two decoupled families (N=0 and N=1 family) of eigen modes. The stability is determined by the rotational transform at the edge, i.e., the iota value higher than 0.5 is unstable. This dependence is insensitive to the plasma beta value. Actually the equlibria shown in Fig. 2(b) for high density plasma are stable for the external kink mode. The stability for the pressure driven mode is also examined with zero plasma current. Figure 3(b) shows the growth rate of two families as a function of the plasma average beta. Full stability is obtained up to 3% average beta.

4. Structure of Boundary Magnetic Field

Although the optimization of the magnetic field configuration is made for the confinement region, namely, for the inside of the last closed magnetic surface (LCMS), the magnetic field structure of the outside of LCMS is very important from the aspect of the plasma surface interaction and the future divertor design. Such problem for CHS-qa was studied by using the conventional way of field line tracing for the vacuum field produced by modular coils starting from the aligned points just outside of LCMS. Figure 4(a) shows the puncture plots

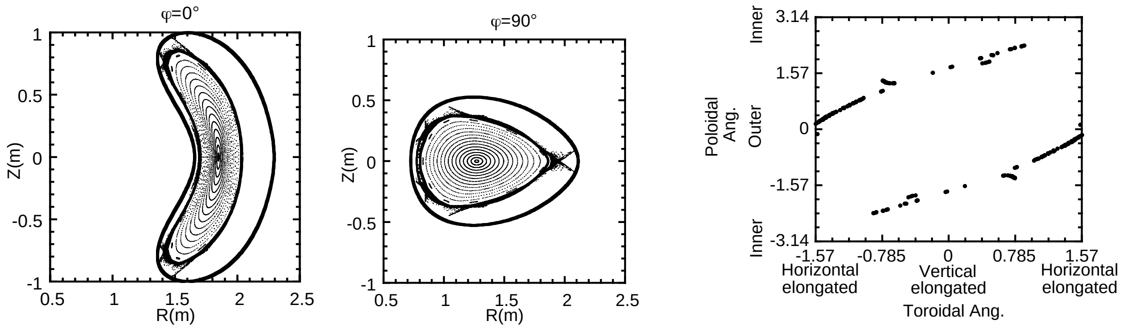

Fig. 4. (a) Puncture plots of magnetic field lines starting from outside of LCMS. (b) Distribution of foot prints of divertor field lines on the model surfac.

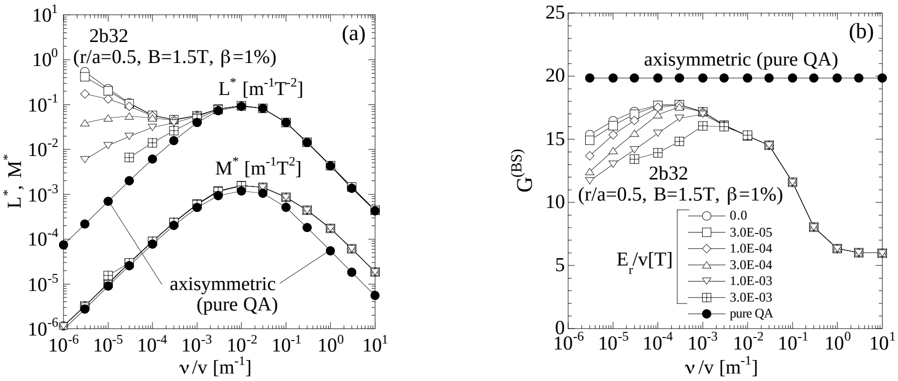

Fig. 5. The mono-energetic viscosity and transport coefficients as a function of collisionality. The open symbols denote 2b32 results and closed circle denotes pure QA model. (a) The ripple and banana-plateau diffusion L and the parallel viscosity M^*, and (b) the geometrical factor $G^{(BS)}$.*

of these field lines (starting from 2 mm outside of LCMS. For the purpose of the divertor design, foot points of the field lines on the model surfaces (shape is given for each plot in Fig. 4a) are calculated and the result is shown in Fig. 4(b) on the unfolded. Such aligned foot points are obtained only by the proper design of modular coils and the model surface shape.

5. Neoclassical Transport Calculation

For the transport study of quasi-axisymmetric stellarators, the momentum conservation must be treated properly which was often not the case in the analysis of stellarators. DEKS code [8] is a well known numerical tool for calculating transport matrix but the results does not guarantee the momentum conservation. A new method of calculating the transport matrix was developed in NIFS [9] which incorporates numerical results from DKES code but formulate the transport matrix in a different form. Using this new method, the correct evaluation of transport coefficients becomes possible for quasi-axisymmetric system with a full consideration of friction forces between different species. Figure 5(a) shows the diffusion coefficient L* and the parallel viscosity coefficients M* for a mono-energetic particle as a function of collisionality. It compares CHS-qa and pure QA model. In addition to the parallel viscosity, both poloidal and toroidal viscosity coefficients are calculated by DKES with our new method so that we can identify the direction in which plasma flows are easily generated. Together with the neoclassical geometric factor calculated also by DKES shown in Fig. 5(b), full transport matrix can be evaluated for all species including self-consistent friction forces

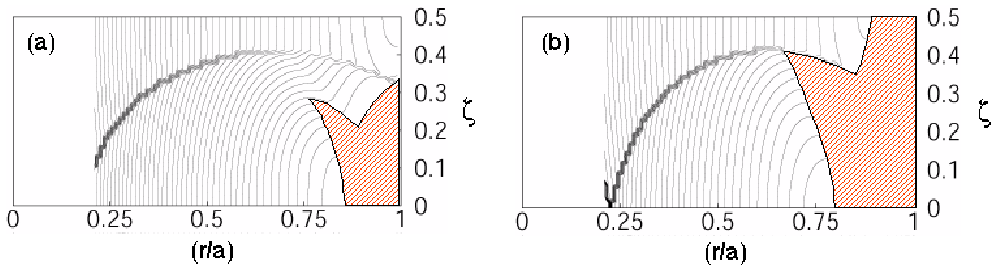

Fig. 6. Contour plot of adiabatic invariant J for (a) standard configuration and (b) outward shifted configuration. Shaded area satisfies maximum-J criterion.

among them.

6. Maximum-J Condition and Its Control

The maximum-J condition (J denotes the second adiabatic invariant) [10], which is favorable for the stabilization of the trapped particle instability, is evaluated. Figure 6 shows an example of the controllability of the maximum-J condition for vacuum configuration. The contour plot of J is shown as a function of minor radius and the toroidal angle. $\zeta = 0$ corresponds to the vertically elongated cross section and $\zeta = 0.5$ to the horizontally elongated cross section. Fig. 6(a) shows a standard configuration without additional vertical field. There is a maximum point of J near the plasma edge for $\zeta < 0.25$ at the normalized radius $(r/a) = 0.8$. Boundary area outside of that radius satisfies the maximum-J 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. 6(b). It is also possible to reduce the area by shifting in the plasma position. For the high beta plasma with bootstrap current, the area for the maximum-J condition expands due the enhanced stellarator shear shown in Fig. 2.

7. Summary

The equilibrium calculation of CHS-qa with the HINT code gave good magnetic surfaces for 3.3% average beta with zero plasma current. The external kink stability is confirmed for the edge rotational transform value below 0.5. The global linear MHD stability for the pressure driven mode was evaluated and stability up to average beta 3.5% was obtained. Good divertor trace of boundary magnetic field lines was found with a proper selection of modular coil design and the divertor plate position. A new method of neoclassical diffusion calculation was applied to obtain reliable physical quantities for quasi-axisymmetric configuration. For the experimental control in the study of anomalous transport, the maximum-J condition was examined for CHS-qa.

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