

Equilibrium and Boundary Structure of Quasi-axisymmetric Stellarator CHS-qa

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1. Introduction

Physics design of an advanced stellarator CHS-qa has been in progress in the National Institute for Fusion Science (NIFS) as a candidate of a new generation of satellite experiment [1]. The design work is executed by the joint team of the experimental group of CHS (heliotron/torsatron type device experiment) and the theory group in NIFS. Basic configuration was decided to be a compact stellarator with the quasi-axisymmetric (QAS) magnetic field structure [2]. The toroidal period number is two and the averaged aspect ratio is 3.2. The rotational transform is between 0.35 and 0.39 for the vacuum configuration avoiding the low order rational resonances. The basic engineering design is completed for the device parameters: major radius $R = 1.5$ m and the magnetic field strength $B_t = 1.5$ T.

The configuration optimization was made based on the fixed boundary solution of the three dimensional equilibrium solver, VMEC code [3]. Because this code calculates equilibrium with assumed existence of good magnetic surfaces, it is uncertain whether the magnetic surfaces are clearly formed without dangerous islands. Even the position of the last closed magnetic surface (LCMS) is not given from the code calculation. It is necessary to examine the magnetic surfaces with the field-line tracing for the vacuum field and the finite beta equilibrium calculated without the assumption of magnetic surfaces. The first step for such a study is designing of magnetic coils which can produce, in a good accuracy, the optimized fixed boundary equilibrium solution. With NESCOIL code [4], 20 modular coils were designed for full torus (four groups of five different shapes). For the vacuum field produced by these coils, the plasma equilibria were calculated with HINT code [5] which does not require the existence of magnetic surfaces.

2. Free boundary calculation without vertical field

The equilibrium calculation with HINT code is basically the free-boundary calculation since no restricting condition for the boundary is applied. We would like to compare HINT code results with free-boundary VMEC calculation. Figure 1 shows two equilibria for zero beta (left) and 1.5 % average beta (right) calculated with HINT code for 2b32 quasi-axisymmetric configuration of CHS-qa. It shows puncture plots of magnetic field-line tracing on the obtained equilibrium field. Since no vertical field is applied, the total plasma position is shifted outward for higher beta. In this calculation, the plasma current is assumed vanishing in the average for each magnetic surface. The position of the LCMS is a part of code calculation results. Because a considerable part of boundary region is lost for 1.5 % beta equilib-

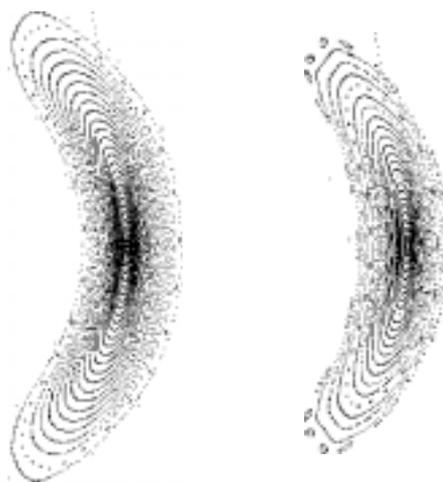


Fig. 1 Equilibria with HINT code

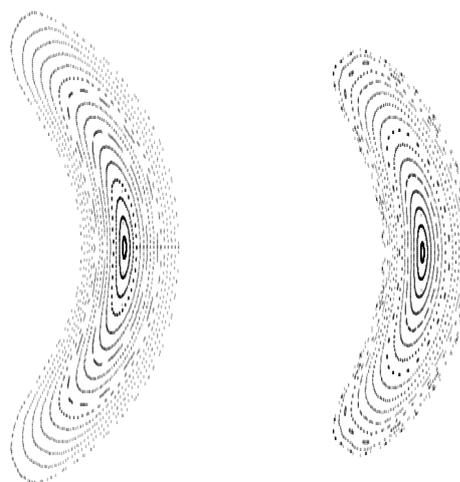


Fig. 2 Vacuum field-line tracing with MAGN code

rium, we would like to examine whether it is due to magnetic surface destruction for higher beta equilibrium.

In order to understand how the position of LCMS is determined in QAS configuration, vacuum magnetic surfaces are calculated for different surface position with the control of vertical field. It is known for the conventional stellarators (e.g., CHS and LHD), that there are two fixed points in the boundary region (in-board side and outboard side of LCMS) so that the magnetic surfaces can be formed only in the region between them. Figure 2 shows two vacuum field-line tracing results for 2b32 configuration: no vertical field (left) and 0.015 T vertical field for 1 T toroidal field (right). It is found

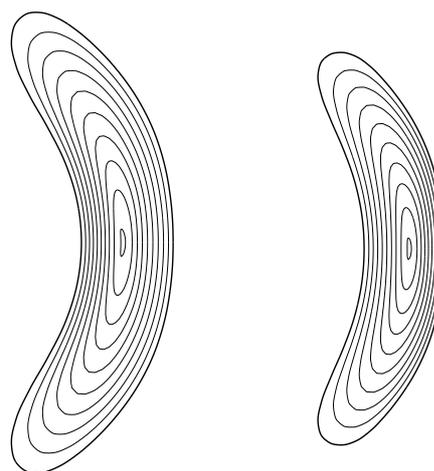


Fig. 3 Free-boundary VMEC calculation

that the right edge of LCMS for two cases lie on the same position. This position is similar to the outboard fixed point for conventional stellarators described above. The vertical shift 0.015 T for the right plot is selected to make its boundary shape similar to the right plot in Fig. 1. Although the relative magnetic axis positions are slightly different for these two, the boundary shapes are very close. The loss of outer magnetic surfaces for 1.5 % equilibrium in Fig. 1 is simply due to the position shift effect which is observed in the vacuum configuration as well.

It is necessary to give the plasma volume for the free-boundary VMEC calculation. Figure 3 shows two results of VMEC run with the same volume as the original fixed boundary solution (left) and by keeping the width of the waist of LCMS the same as the right plot in Fig. 2. The resulting shapes of boundary are very close to the HINT results in Fig. 1. The iota

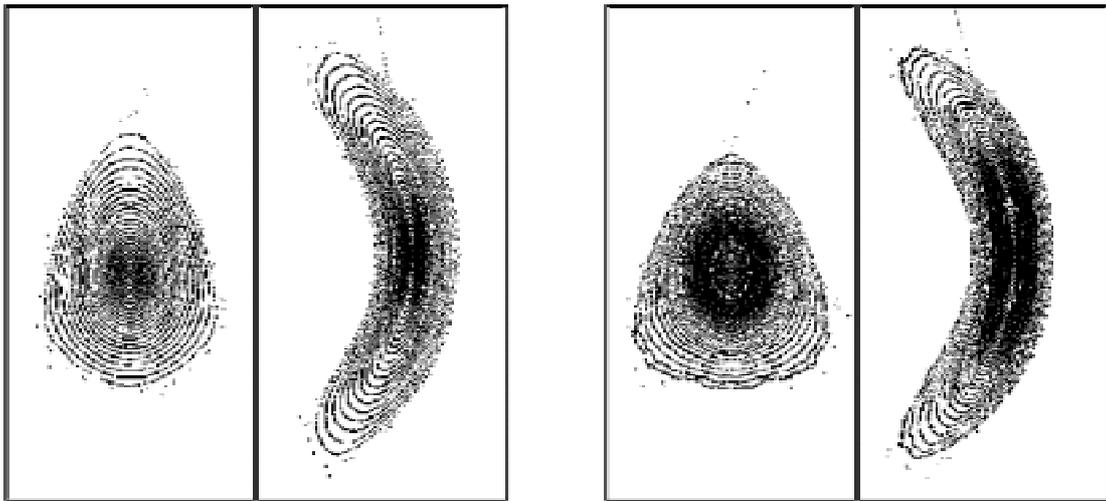


Fig. 4. Puncture plots of magnetic surfaces for vacuum (left) and 3.3% average beta (right) equilibria of CHS-qa calculated by HINT code.

profiles obtained from HINT and VMEC are also very similar. For this level of beta, we confirmed the equilibria given by two codes are in a good agreement. However we found that the iota value in VMEC calculation for 2.4% beta is significantly lower than HINT result. A further study is necessary for the comparison of HINT and VMEC equilibrium calculation with free boundary condition.

3. High beta equilibrium calculated by HINT code

Because the loss of outer magnetic surfaces in Fig. 1 is caused by the outward shift of the surface position, an automatic control of vertical field is introduced in the HINT code calculation to push the position back recovering the lost magnetic surfaces. Figure 4 shows the equilibrium calculation with HINT code for vacuum and 3.3 % average beta. The left parts of two cases are for the horizontally elongated cross section with 90 degree rotation. The pressure profile is very sensitive to the robustness of the magnetic surfaces in the boundary region. In this calculation, the profile $p(\Delta) \propto (1 - \Delta)$ is assumed. This profile is one of typical profiles observed in the existing helical experiments. More peaked pressure profiles give larger perturbation of the magnetic field for high beta equilibrium causing loss of boundary magnetic surfaces.

Plasma current was assumed zero in average on each magnetic surface. It is expected that comparable order of bootstrap current as tokamaks will be created in high beta plasma in QAS stellarators. The estimated value reached to 100 kA for high beta discharges in CHS-qa. HINT code calculations including the plasma current with self-consistent profile to the pressure profile has not yet been made.

4. Divertor field-line tracing for vacuum configuration

The divertor magnetic field structure design is one of most important key issues of magnetic confinement research for fusion. Since the optimization of QAS stellarator is mostly

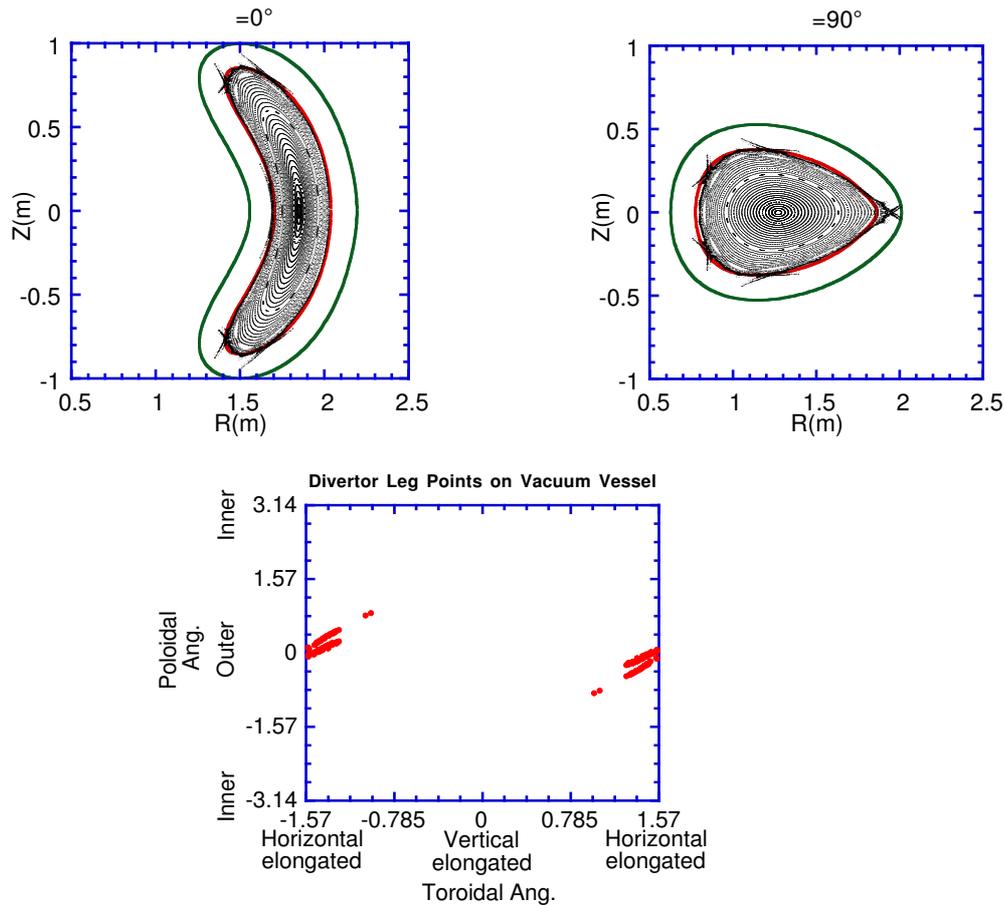


Fig. 5 Divertor field line tracing for 2b32 configuration. Intersecting points on the wall are plotted on toroidal and poloidal angles

done for the magnetic surface quantities, this important problem is left over in the QAS configuration discussion. Although lots of people recognize this issue important, it is not yet included into the list of figure of merits in the optimization loop.

Several modular coil design can be made for the same optimized configuration depending on the design conditions of the coils. We found that two sets of modular coil design give very different divertor trace structures. Since they are both designed to satisfy the given magnetic surface quantities for QAS configuration, the magnetic surfaces inside LCMS are very similar for both cases. However one set of modular coils gives clearer island divertor structure shown in Fig. 5 while another does not. It suggests that if the quality of the divertor field structure could be evaluated as a figure of merit, much better coil design would be possible satisfying both good magnetic surface quantities and good divertor structure.

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