Physics and Engineering Design Study of a Quasi-Axisymmetric Stellarator CHS-qa


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Abstract

The MHD stability of several quasi-axisymmetric configurations was examined without and with net toroidal current case. Among several configurations examined, a low aspect ratio configuration, which was newly designed with the ballooning stability evaluation, gave good Mercier stability. The engineering design was made for one of these configurations, which resulted in the fact that most of essential engineering design problems were solved for device dimensions of a major radius 1.5 m and the magnetic field 1.5 T. This design gives high flexibility of the configuration with additional toroidal coils for the rotational transform control and poloidal coils for the plasma shape control and the inductive current control.

I. Introduction

Design work of the quasi-axisymmetric stellarator in NIFS (CHS-qa) [1, 2] has proceeded both in the improvement of the physical configuration study and the engineering study of the overall device design. This work has two major challenging subjects which are both new and difficult: realization of the quasi-axisymmetric plasma [3, 4] and the construction of a low aspect ratio modular coil device. Although the main objective of the configuration optimization is to find out the best physical solution, it is not always possible to make the modular coil device design for that configuration especially under the condition of a given machine size and the magnetic field strength. So we planned to prepare optimized configurations for a sufficiently wide range of parameters and select one of them as a candidate for the engineering design work for the experimental device.

For the physical configuration study, we planned to survey the toroidal period number (N) in the range from 1 to 3 and the aspect ratio (A_p) from 2 to 4 because our target is a low aspect ratio quasi-axisymmetric device. We intend to find a solution for each selection of N and A_p. In this paper, results of varying the aspect ratio for the N = 2 configuration are described. For the engineering work, it is necessary to fix the target configuration during a series of tasks of engineering design. A complete machine design was made for the configuration with N = 2 and the aspect ratio A_p = 3.9 (case 2w39) which has relatively larger aspect ratio in our series of configurations. During this study, difficulties in manufacturing modular coils and designing
mechanical coil support structures have been clarified and the solution for these problems was found. Such engineering study can be applied next to a different target configuration. The constraints from the engineering aspects influence strongly the final selection of the configuration, especially for the small-scale device as a satellite experiment.

II. Configuration Studies

1. Beta limit evaluated with the Mercier criterion

The MHD stability was examined using Mercier criterion for the fixed boundary VMEC equilibrium. We first study the configuration which was used as the target of engineering design work (N = 2, \( A_p = 3.9 \), rotational transform = 0.4 at the boundary) and then compare with it a new configuration with a lower aspect ratio. The pressure profile is assumed to be \( p(r) \propto (1-r^2)^{1.5} \). The equilibrium with no toroidal current was studied and the effect of the toroidal current for the stability was also examined. However our interest is directed towards a relatively small toroidal current whose contribution to the boundary rotational transform is less than 30% of the total rotational transform.

Closed circles in Fig. 1 shows the Mercier criterion \( D_I \) calculated for the 2w39 configuration with no toroidal current evaluated at the radius \( r/a = 0.7 \) and 0.8 where the pressure gradient

![Graph]

Fig. 1 Evaluation of Mercier stability \( D_I \) as a function of average beta for the 2w39 configuration with no toroidal current (closed circles). \( D_I \) values for 2w39 with 100 kA plasma current are also plotted with squares (for \( r/a = 0.7 \)) and crosses (\( r/a = 0.8 \)). For clarity, these values multiplied by 10 are also plotted with open circles.
is largest for the given profile. Negative value of $D_I$ indicates stability. Ideal interchange stability is obtained up to 3% average beta. The closed circles in Fig. 2 show the rotational transform at the magnetic axis and at the edge for the same configurations. It is usually observed that the Mercier stability is lost at the beta value where a drop of the central rotational transform and an enhanced Shafranov shift appear.

The effect of the plasma current on the stability was examined for the same configuration ($R = 1.5$ m, $B = 1.5$ T) with a 100 kA plasma current. A parabolic profile \[ I(r) = (1-r^2) \] is assumed for the current. The contribution of the plasma current to the edge rotational transform is about 30% as is shown in Fig. 2 (blue squares). The central rotational transform is about 0.8. The Shafranov shift is strongly suppressed with this current as is shown by gray squares in Fig. 2. The Mercier stability was calculated for this configuration shown by the squares and crosses in Fig. 1 improving the stability up to 5% beta. The effect of plasma current on the stability was also examined for a model current profile with zero current density at the axis in order to simulate a bootstrap current without any additional external current generation. In this case, the drop of the central rotational transform due to high beta was not cured and no improvement in the stability was obtained for such current profile.

2. Low aspect ratio design

Recently evaluation of the ballooning stability has been incorporated in the optimization program [5]. Stability is checked with the local ballooning calculation for selected points of radius (here, three radii are selected: $s (\equiv r^2) = 0.25, 0.5, 0.75$). The stability beta limit is increased by this optimization especially for a reduced aspect ratio configuration. Figure 3
Fig. 3  Three poloidal cross sections of magnetic surfaces of low aspect ratio configuration (2b32) with $A_p = 3.2$. Average beta is 3 %.

Fig. 4  Comparison of Mercier criterion $D_M$ evaluated for 2w39 and 2b32 configuration. Stability is obtained for positive $D_M$ value. Mercier stability is obtained for the low aspect ratio configuration 2b32.
shows the magnetic surfaces of the configuration with \( A_p = 3.2 \) (2b32) obtained with the new optimization procedure. Here, the plasma current is assumed zero in average for each magnetic surface. 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 MHD stability was examined for this configuration with the Mercier criterion \( D_M \). \( D_M \) is used instead of \( D_I \) because \( D_I \) has a singularity for this configuration due to the denominator containing the shear. Figure 4 shows the Mercier criterion \( D_M \) for the low aspect ratio configuration 2b32 in comparison with the same criterion \( D_M \) for the configuration 2w39. Here, positive value of \( D_M \) indicates stability. It is observed that the ballooning optimized low aspect ratio configuration has the Mercier stability up to 5% beta.

As was mentioned above, the Mercier stability and the Shafranov shift are closely related for the configuration 2w39. In Fig. 5, the Shafranov shift is plotted for the 2b32 configuration as a function of the average plasma beta. These values are reduced by about 30% compared with 2w39 configuration. The drop of the central rotational transform is also suppressed in the 2b32 configuration which shows again good coincidence with the Mercier stability criterion. The orange line shows the edge value of the rotational transform for 2b32 configuration. For beta in the range 2-3%, there exists a zero shear region.

![Figure 5](image)

Fig. 5 Comparison of Shafranov shift for the 2w39 \( (A_p = 3.9) \) and 2b32 \( (A_p = 3.2) \) configurations (closed circles). The rotational transport on the magnetic axis is also plotted for both cases (open circles). Red lines are for 2b32 configuration and blue lines for 2w39. The rotational transport at the edge is also plotted for 2b32 which shows decreasing iota profile for low beta equilibrium.
III. Engineering design

The engineering design work has been made for the configuration 2w39. This configuration has the conventional parameters of existing modular coil stellarators. The aspect ratio per one toroidal period is about 2 and the rotational transform per period is about 0.2 which are both similar values as in Wendelstein 7-X. The selection of these values makes it possible to apply the established technique to the present design work. Once such a reference design is made, we can extend the results to the more advanced configurations.

A complete engineering design has been made for a device with a major radius 1.5 m and the magnetic field 1.5 T. Almost all essential engineering problems have been solved. The

Fig. 6 Total engineering image for $R = 1.5$ m and $B = 1.5$ T device. The number of modular coils is 20 for two toroidal periods. Three pairs of poloidal coils (OVF with violet, MVF with red and IVF invisible) have the capability of creating an inductive current as well as full poloidal field control. The thin red coils wound on the modular coils are auxiliary toroidal coils for controlling the rotational transform.
total image of the final design is shown in Fig. 6.

Important features of the mechanical support design are to avoid interfering structures outside of the torus. The main mechanical structure consists of three plates installed on the inner side of the torus which support the compressional and torsional forces of the modular coils. The remaining forces are supported with connecting rods (in orange) between the coils. By swinging currents in three sets of poloidal coils, inductive current drive is possible without introducing an additional vertical field. Non planar toroidal coils (in red) can vary the rotational transform without degrading quasi-axisymmetry.

The procedure of assembling the device is as follows. One quarter of the torus is assembled by putting five modular coils on one quarter of the vacuum chamber. Afterwards ports are welded on the vacuum chamber and the four quarters are combined into the full torus.

Six individual power supplies are ready. Two separate power supplies are prepared for the modular coils, three are for the poloidal coils and one is for the auxiliary toroidal coils. So, sufficient flexibility is obtained for the magnetic configuration study.

IV. Summary

MHD stability analysis using the Mercier criterion gives a 3 % beta limit for the no current equilibrium of the 2w39 configuration. The lower aspect ratio configuration with ballooning stability optimization (2b32) extends the Mercier stability limit up to 5 %. A complete engineering design was made for the 2w39 configuration with R = 1.5 m and B = 1.5 T.

References