J. Plasma Fusion Res. SERIES, Vol.1 (1998) 433–436

Physical Property of Plasmas in the $L=1$ Heliotron

NAKAMURA Yuji, WAKATANI Masahiro[1] and YOKOYAMA Masayuki[2]
Graduate School of Energy Science, Kyoto University, Uji, Kyoto 611-0011, Japan
[1]Institute of Advanced Energy, Kyoto University, Uji, Kyoto 611-0011, Japan
[2]National Institute for Fusion Science, Toki 509-5292, Japan

(Received: 30 September 1997/Accepted: 22 October 1997)

Abstract

The design study of the $L=1/M=4$ helical axis heliotron device is now undertaken at Kyoto University. This device will have an $L=1$ helical coil with two sets of toroidal coils and three sets of poloidal coils to control the rotational transform, toroidal mirror component of the magnetic field strength, plasma position and shape. Current status of the physical studies of plasmas in this device is presented using detailed and realistic parameters of the machine.

Keywords:

$L=1$ heliotron, helical axis heliotron, toroidal mirror field, MHD equilibrium, MHD stability, neoclassical transport

1. Introduction

An $L=1/M=4$ helical axis heliotron device, whose major radius is 1.2 m and averaged magnetic field strength at the axis is 1.0–1.5 T, is proposed at Kyoto University [1]. Typical averaged minor radius of plasmas is 0.1–0.2 m. One of the main purpose of this machine is to do the basic study of configuration optimization experimentally, investigating the effect of the magnetic well, the rotational transform, Fourier components of magnetic field on the plasma confinement.

This device has an $L=1/M=4$ continuous helical field (HF) coil with pitch modulation of $\alpha=-0.4$, where the helical coil winding law is defined as $\theta=\pi+(M/L)\phi-\alpha\sin(M/L)\phi$. Negative value of α enables the magnetic well to be realized in the entire plasma region easily. Recent studies have shown that the toroidal mirror component of the magnetic field strength plays significant roles on the particle transport and the bootstrap current. Two sets of toroidal field (TF) coils with different power supply for each other can be used to control the toroidal mirror component of the field strength in a wide range of parameters. The TF coils are also used to control the rotational transform. Plasma position and shape can be controlled by three sets of poloidal field (PF) coils.

We are surveying these coil parameters to investigate the effect on the MHD equilibrium and stability properties, collisionless particle orbit, neoclassical transport properties theoretically using detailed and realistic parameters of the machine. In this paper, we will show the current status of the theoretical study of the plasma properties.

2. Coil Configurations

Coil configuration of the $L=1$ helical axis heliotron (we call HAH-1 in this paper) is shown in Fig. 1. The ratio of total coil current of the each outer PF coil, I_V, and that of the HF coil, I_{HF}, is fixed as $I_V:I_{HF}=7:8$. The middle PF coil (total coil current; I_{AV}) is used for plasma position control. The inner PF coil (total coil current; I_{IV}) is used for plasma shaping by combination with the middle PF coils. Thicker TF coil (total current of I_{TA}) and thinner TF coil (total current of I_{TB}) are

Corresponding author's e-mail: nakamura@energy.kyoto-u.ac.jp

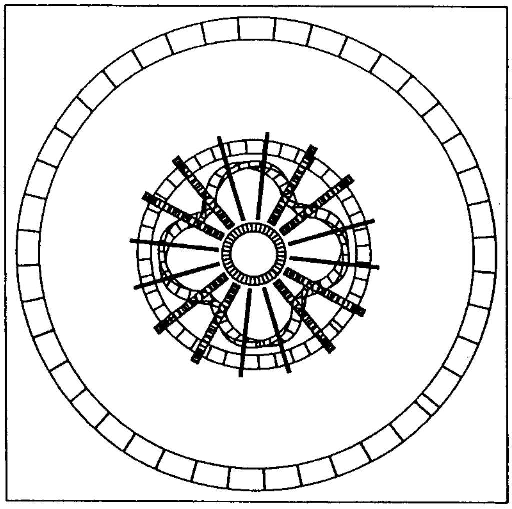

Fig. 1 Top view of the coil configuration.

used to control the plasma rotational transform and toroidal mirror component of field strength. Figure 2 shows vacuum flux surfaces of a configuration with typical coil currents ($I_{HF}=0.96$ MA, $I_V=0.84$ MA, $I_{AV}=0$ MA, $I_{IV}=0$ MA, $I_{TA}=0.5$ MA, and $I_{TB}=0.2$ MA). The rotational transform at the magnetic axis is 0.54.

3. Effect of Vertical Field and Toroidal Field

To see the effect of the vertical field by the middle PF coils and toroidal field by the TF coils, the ratios, I_{AV}/I_{HF} and I_{TA}/I_{HF}, are varied with fixed $I_V/I_{HF}=0.875$ (we cannot change this value in the HAH-1) and fixed $I_{TB}/I_{TA}=0.4$ at first. Change of the position of the magnetic axis is shown in Fig. 3. Here $<R_{ax}>$ is the major radius of the magnetic axis averaged along toroidal direction.

When the value of I_{TA}/I_{HF} is fixed to be 0.52083 ($I_{TA}:I_{HF}=0.5:0.96$), plasma shift due to I_{AV} changes the rotational transform (Fig. 4). Larger $<R_{ax}>$ due to vertical field gives higher rotational transform as in the usual $L=2$ heliotron. Since the current plasmas have only weak magnetic shear, proper choice of I_{AV} is necessary to avoid wide magnetic island in a plasma.

Interchange stabilities are roughly evaluated by the magnetic well depth. Since the plasma minor radius changes by the configuration, we see the magnetic well at the flux surface whose averaged minor radius is 10 cm. Here we define the magnetic well depth as ($V''(r=0) - V'(r=10\text{cm}))/V''(r=0)$. Figure 5 shows I_{AV}/I_{HF} and I_{TA}/I_{HF} dependencies of the magnetic well. Though inward shift decreases the magnetic well depth,

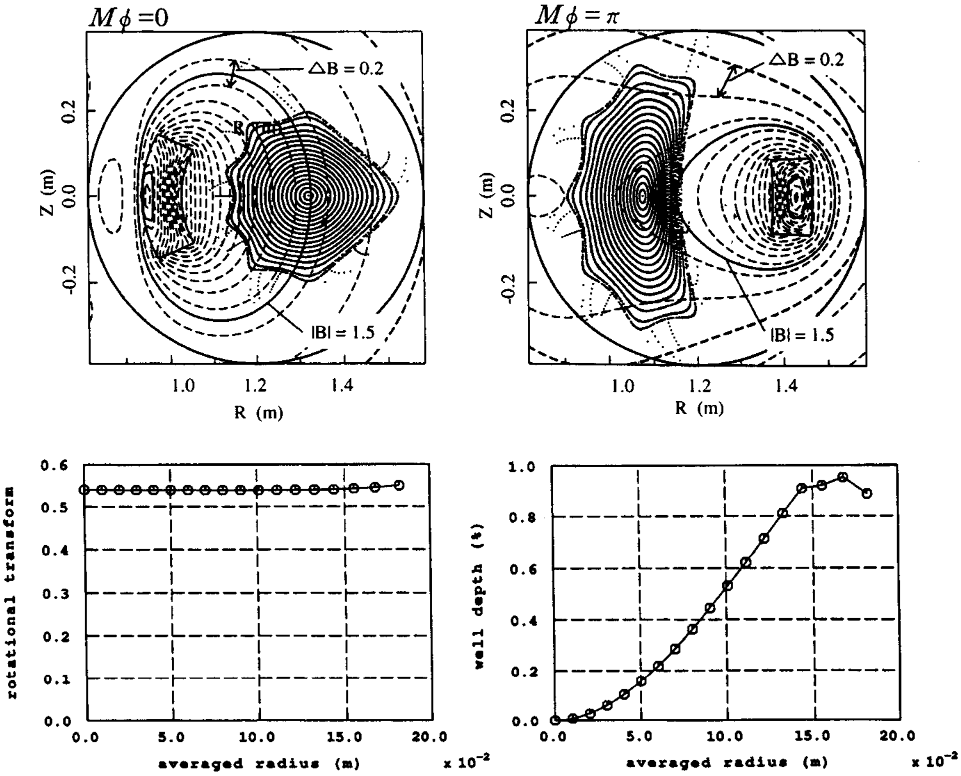

Fig. 2 Vacuum flux surfaces of a configuration with typical coil currents.

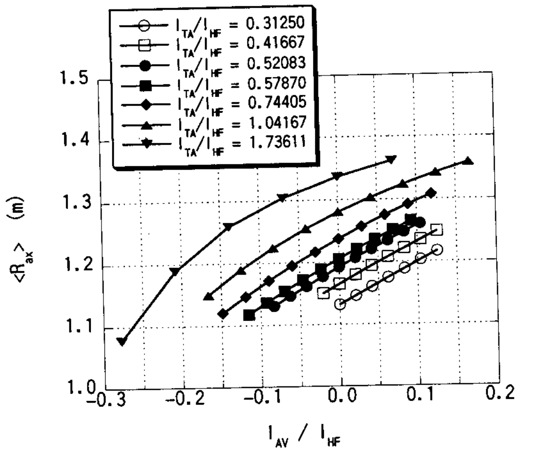

Fig. 3 Change of the position of the magnetic axis by the middle PF coils.

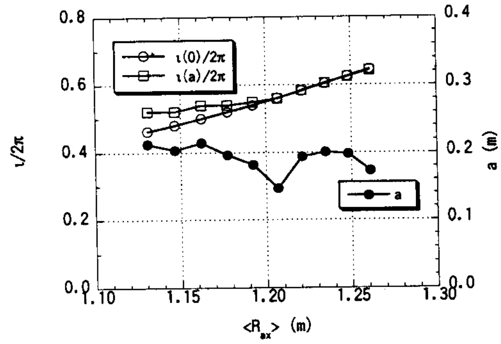

Fig. 4 Rotational transform versus the magnetic axis position.

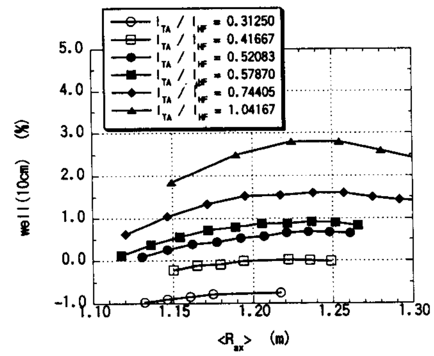

Fig. 5 $<R_{ax}>$ dependencies of the magnetic well depth at averaged minor radius of 10 cm.

the magnetic well does not change so much when $<R_{ax}>$ is larger than 1.19 m. The value of I_{TA}/I_{HF}, that is the value of the rotational transform, has more influence on the magnetic well.

4. Fourier Spectrum of the Magnetic Field Strength

Fourier spectrum of the magnetic field strength in the Boozer coordinates is important property determines particle orbit and neoclassical transport. The Fourier spectrum of the plasma corresponding to Fig. 2 is shown in Fig. 6. The major Fourier harmonics are $(m,n)=(1,4)$ (helical component), $(m,n)=(1,0)$ (toroidicity), and $(m,n)=(0,4)$ (toroidal mirror component), where m (n) is poloidal (toroidal) mode number. This is very similar to the Fourier harmonics given in Ref. [2] and this configuration has similar particle orbit and neoclassical transport properties qualitatively.

This type of configuration has very weak gradient B drift at toroidal mirror position where the most of deeply trapped particles exist. Therefore, the effect of radial electric field and the diamagnetic effect on the trapped particle orbit can be expected. It has been shown that even weak radial electric field improves collisionless particle orbit significantly. It has been also shown that the collisionless particle orbit loss decreases with increase of beta.

5. MHD Equilibrium and Stability

Three-dimensional equilibrium is calculated by the VMEC code [3]. Here we use radial mesh numbers of 101, and Fourier modes in the range of $0 \leqq m \leqq 11$, $-12 \leqq n \leqq 12$. We have calculated an MHD equilibrium corresponding to the configuration in Fig. 2 and obtained an equilibrium whose average beta is up to 3%.

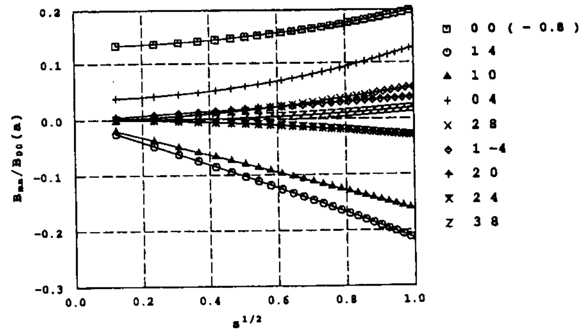

Fig. 6 Fourier spectrum of the magnetic field strength in a plasma corresponding to Fig. 2.

Mercier criterion is evaluated by neglecting parallel current related to the resonant rational surface. If the effect of the resonant rational surface is not negligible, we need to calculate 3-D equilibrium without assuming nested flux surfaces (HINT code or PIES code). The Mercier criterion shows that the equilibria are stable against ideal interchange mode except near the axis and edge where we could not have reasonable accuracy.

6. Summary

Current status of theoretical study of HAH-1 is presented. Though we have not shown the effect of changing toroidal mirror ratio, we showed that the wide range of parameter survey for experimental optimization study can be possible in the proposed $L=1$ helical axis heliotron device.

Further investigations, such as the effect of changing toroidal mirror ratio, ballooning stability, magnetic island formation in an equilibrium, are necessary to be done.

References

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