STUDIES OF HELICAL-AXIS HELIOTRON

M. WAKATANI, Y. NAKAMURA, K. KONDO, M. NAKASUGA, S. BESSHOU
Graduate School of Energy Science, Kyoto University, Uji, Japan

T. OBIKI, F. SANO, K. HANATANI, T. MIZUUCHI,
H. OKADA, K. NAGASAKI, N. INOUE
Institute of Advanced Energy, Kyoto University, Uji, Japan

M. YOKOYAMA
National Institute for Fusion Science, Toki, Japan

Abstract

Optimization studies have been done for the helical-axis heliotron configuration. One purpose is to find a configuration suitable for experimental studies of basic properties of helical-axis heliotron. In this study, the role of the bumpy field component (toroidal mirror ratio) on MHD stability and neoclassical confinement for this type of configuration is examined. The physical mechanism of the improvement of the neoclassical transport by controlling bumpy field component is clarified. Physics design and the current status of the new helical-axis heliotron device (Heliotron J) are also described.

1. INTRODUCTION

Recently, many theoretical optimization studies have been done for stellarators. Concepts of quasi-helical symmetry[1], quasi-axisymmetry[2] and quasi-isodynamicity [3], for example, are proposed from these studies. However, it is considered that experimental studies with a sufficient heating power are necessary to verify these ideas because there are still uncertainties in theoretical optimization studies particularly for the anomalous transport. Here we describe an optimized configuration suitable for experimental studies of basic properties of helical-axis heliotron plasmas. In a small size of experimental device (major radius of ~ 1 m), in order to keep experimental flexibility and easy access to the plasma, we employ a continuous helical field (HF) coil. Here, the configuration produced by an $L = 1 / M = 4$ continuous HF coil with pitch modulation of $\alpha = -0.4$ has been chosen, where the helical coil winding law is defined as $\theta = \pi + (M / L)\,\phi - \alpha \sin\{(M / L)\,\phi\}$ [4]. Here θ (ϕ) is a poloidal (toroidal) angle variable. Positive α has an advantage to make toroidicity component of the magnetic field strength $\varepsilon_t \equiv B_{1,0}/B_{0,0}$ small and, therefore, Pfirsch-Schlüter current is reduced. Here $B_{m,n}$ is a Fourier component of magnetic field strength in the Boozer coordinates, where the subscription m (n) denotes poloidal (toroidal) mode number. In the positive α case, however, the magnetic hill region tends to be wide and the minor plasma radius becomes small. One of the reasons to choose the negative value of α is to produce the magnetic well in the entire plasma region easily. The magnetic well is necessary to suppress the pressure driven instabilities up to $<\beta> \geq 3\%$. Another advantage of negative α is that the bumpy field component is easily controlled to reduce the neoclassical transport as discussed in Section 2. Two sets of eight toroidal field (TF) coils with different coil currents (I_{TA} and I_{TB}) are equipped to control the bumpy component. It is noted that the type A coils are distributed uniformly and the type B coils are located between two type A coils. The TF coils can also be used to control the rotational transform. To control the plasma position and the shape, three sets of poloidal field (PF) coils are used.

Quantities of vacuum magnetic flux surfaces are analyzed by the KMAG code based on the Biot-Savart law by taking the finite size of magnetic field coils into account. Three dimensional MHD equilibria are firstly calculated by the VMEC code[5], then Mercier stability, collision-less particle confinement, and the neoclassical ripple transport are analyzed with several numerical codes. The obtained optimized configuration is discussed in Section 2. The Heliotron J device is introduced in Section 3, which is designed for studying the helical-axis heliotron experimentally.

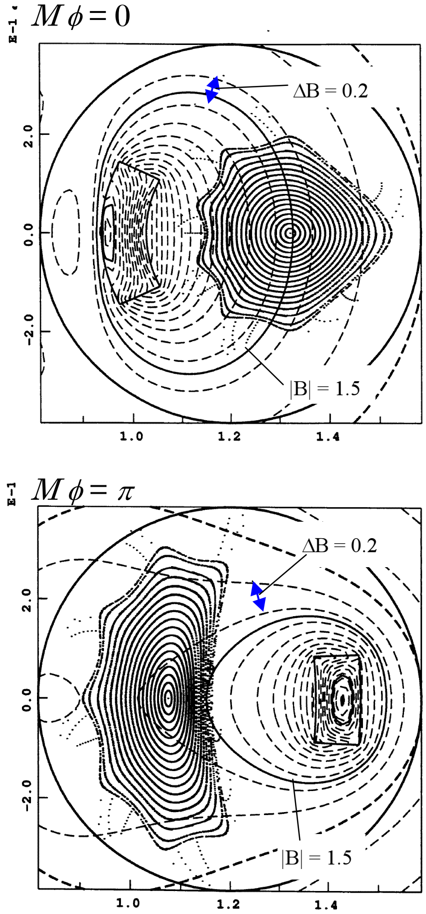

Fig.1 Poincáre plots of typical vacuum magnetic surfaces. Dashed lines denote contour of |B|.

2. OPTMIZATION OF PARTICLE CONFINEMENT AND NEOCLASSICAL TRANSPORT WITH BUMPY FIELD

Figure 1 shows vacuum flux surfaces of a typical configuration with $\varepsilon_b / \varepsilon_h \sim -0.5$ at the half radius (the coil current ratio of two sets of TF coils, $R_{TF} \equiv I_{TA} / I_{TB}$, is 2.5), where $\varepsilon_b \equiv B_{0,4} / B_{0,0}$ is the bumpy component and $\varepsilon_h \equiv B_{1,4} / B_{0,0}$ is the helical component of the magnetic field strength. Here we define the toroidal angle of the Boozer coordinates becomes zero when the geometrical toroidal angle ϕ, which determines the helical coil winding law, is zero. Radial profiles of $B_{m,n}$ components are shown in Fig.2. The rotational transform at the magnetic axis is 0.54 and almost constant in the whole region. Vacuum rotational transform can be controlled for 0.2 ~ 0.8 by changing TF coil currents.

Since an $L = 1$ helical coil naturally produces ε_b with the same sign of ε_h, $\varepsilon_b / \varepsilon_h$ becomes positive ($\varepsilon_b / \varepsilon_h \sim +0.8$ at the half radius) when $R_{TF} = 1.0$, *i.e.* the bumpy field is not optimized. It is found from the vacuum magnetic field line tracing calculation that the magnetic well becomes deeper but averaged plasma radius becomes smaller as R_{TF} increases. If we need a plasma with a smaller aspect ratio than 8, an optimum value of R_{TF} which makes a sufficient magnetic well simultaneously is around 2.5.

It has been shown from the analytical expression for a simple magnetic field model that the negative value of $\varepsilon_b / \varepsilon_h$ reduces the neoclassical ripple transport if $\varepsilon_t / \varepsilon_h$ is finite, though these are symmetry breaking components [4]. We will show the physical mechanism of ripple transport reduction due to negative $\varepsilon_b / \varepsilon_h$. When we apply negative values of $\varepsilon_b / \varepsilon_h$, most of the deeply trapped particles are located at the position where the magnetic axis looks nearly straight (bottom figure of Fig.1; $M\phi = \pi$). It is expected that grad-B drift of ripple trapped particles is small there since the gradient of the magnetic field strength becomes small (see contour plots of |B| in Fig.1 denoted by dashed lines). The concept of placing trapped particles at the position where the gradient of B is small is known as "quasi-isodynamicity" [3]. Collisionless particle orbit calculations have been done to verify the smallness of grad-B drift. Time evolutions of loss fractions of 1keV protons launched from the half radius position of plasmas with uniform spatial and pitch angle distribution are shown in Fig.3. We may evaluate an averaged grad-B drift roughly from the time when trapped particles start to be lost if we compare the configurations whose minor radius and magnetic field strength are similar. It can be seen in Fig.3 that the starting time indicated by the arrow is delayed for the case of $R_{TF} = 2.5$ compared to the case of $R_{TF} = 1.0$. This result suggests that the ripple diffusion becomes slower in the case of $R_{TF} = 2.5$ when the collisions are taken into account. It is pointed out that the radial profile of the bumpy component plays a role for particle confinement. If we assume

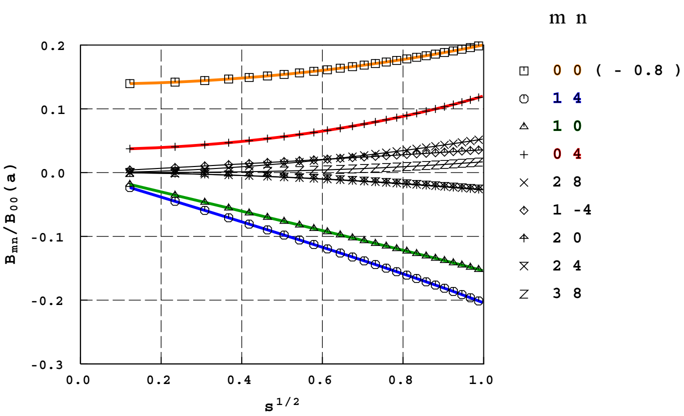

Fig.2 Radial profile of Fourier harmonics of the magnetic field strength in the optimized case.

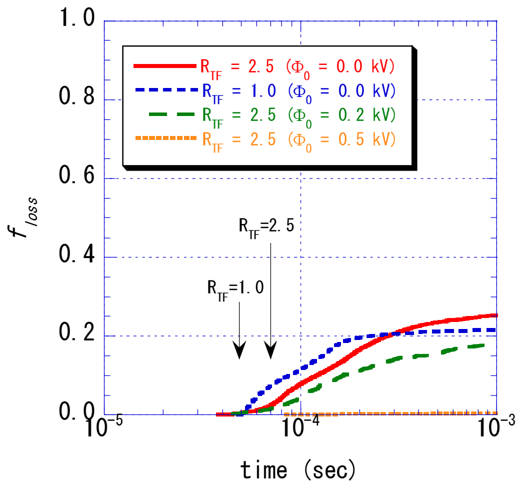

Fig.3 Time evolution of particle loss fraction (B_0=1T).

$\varepsilon_b=\varepsilon_{b0}[1+\delta_b(r/a)^2]$ for the bumpy field, the larger δ_b gives the better particle confinement as shown in Fig.4. Although we changed δ_b artificially in Fig.4, it is noted that $B_{0,4}$ in Fig.2 has a radial dependence.

Figure 5 shows the neoclassical diffusion coefficients at the half radius of a plasma column for the case of R_{TF} = 1.0, 2.5 and I_{TB} = 0. Here the rotational transform and toroidally averaged magnetic axis position are kept constant. The bumpy field is negative and largest when I_{TB} = 0 (ε_b / ε_h ~ −2.5 at the half radius). The neoclassical diffusion coefficients are calculated by the DKES code[6] with monoenergetic distribution function and normalized by the value of the equivalent tokamak at ν^* = 1, where $1/\nu^* \equiv (v/\nu)/(\pi R_0/(\iota/2\pi))$ is the mean free path normalized by the half connection length. With the increase of $-\varepsilon_b/\varepsilon_h$, the neoclassical diffusion becomes comparable to the equivalent tokamak. However, it is noted that, for I_{TB} = 0 case, total trapped particles increase and minor radius decreases. Thus, for realizing an aspect ratio of eight, R_{TF} = 2.5 seems to be close to the optimum and it does not contradict the MHD stability property that the Mercier stability criterion is satisfied up to <β>~4%[4]. It is also pointed out from Fig.3 that collisionless particle orbit confinement improves significantly when we include the radial electric field. Since the grad-B drift is sufficiently slow, E×B drift is effective even if Φ_0 is less than 1kV. For finite beta plasmas, we confirmed that the collosionless orbit loss decreases with the increase of beta, which was firstly shown for W7-X[7].

The radial electric field E_r is also effective to reduce the neoclassical diffusion with the similar strength of electric field, which was confirmed with the DKES code. Thus, when E_r is finite, it is fairly easy to obtain $D_{DKES} \sim D_{eq.tok}$.

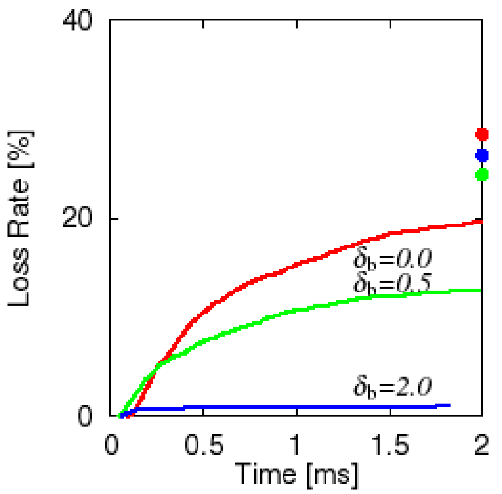

Fig.4 Particle loss rate as a function of time for δ_b=0.0, δ_b=0.5 and δ_b=2.0. When the particle crosses the outermost flux surface, it becomes a loss particle. The marks at the right hand side show the ratio of trapped particles.

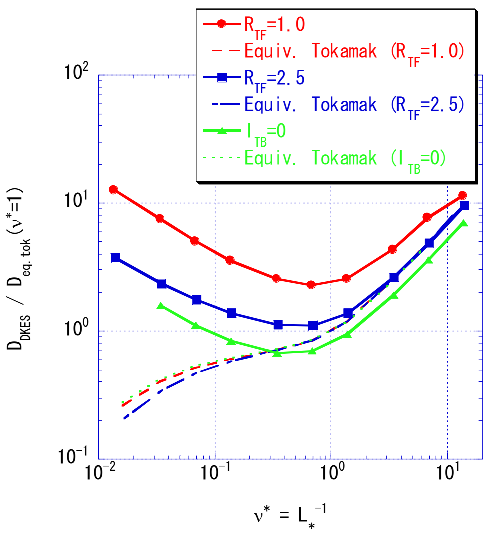

Fig.5 Neoclassical diffusion coefficient as a function of collisionality obtained by the DKES code.

3. A BRIEF DESCRIPTION OF HELIOTRON J

Based on the above theoretical results, a helical-axis heliotron device for the joint experiment of plasma and materials (Heliotron J in Fig.6) is now being constructed at the Institute of Advanced Energy, Kyoto University, with a goal of demonstrating the improved confinement property. The design parameters of the proposed device are as follows: the major plasma radius of 1.2 m, the average plasma radius of 0.1 ~ 0.2 m, the field strength on magnetic axis of 1 ~ 1.5 T, the vacuum rotational transform of 0.2 ~0.8 with low magnetic shear, and the magnetic well depth of ~ 1% at the plasma edge, with heating systems such as 0.5 MW-ECH, 1.5 MW-NBI, and 2.5 MW-ICRF. The $L = 1$ helical coil will be wound on numerically-machined groove of the vacuum chamber. The Boozer magnetic field spectrum will be varied with two sets of toroidal coils, the auxiliary mid-vertical coil, the inner vertical coil as well as a fixed vertical coil connected to the helical coil. Thus, the flexible helical-axis heliotron device will have capability for studying both the core confinement and the divertor plasmas. The first plasma of this device will be produced in 1999-2000.

4. SUMMARY

An optimized low shear helical-axis heliotron configuration called Heliotron J with the L=1 helical coil is designed to keep good particle confinement for the MHD beta limit on the order of $\langle\beta\rangle$~4%, where $\langle\beta\rangle$ is an average beta. The key control parameter is the bumpy field and the obtained configuration is close to a quasi-poloidally symmetric stellarator. The finite beta effect is also favorable to improve the collisionless particle confinement[4] like W7-X. This device is also intended to study plasma-wall interaction by making a sufficient space between the last closed flux surface and the wall of the vacuum chamber.

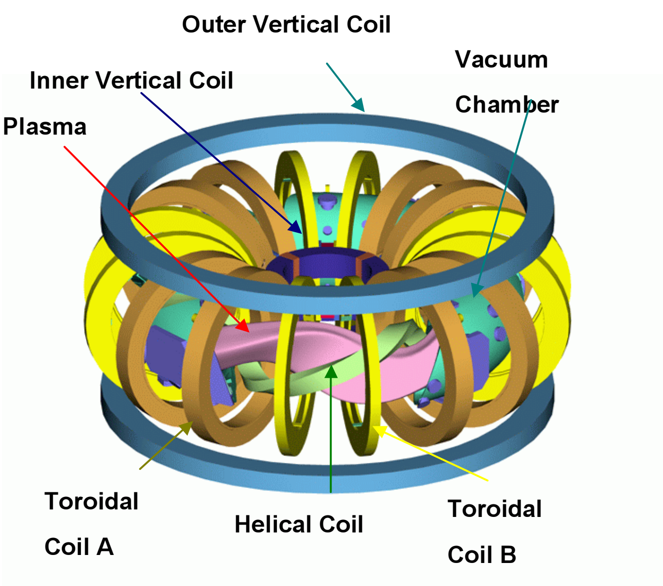

Fig.6 Schematic view of Heliotron J. The external vertical coils with a radius of 3.5m are not shown here.

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