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Shafranov Shift Measurement Using Soft X-ray CCD Camera on Large Helical Device

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1. Introduction

High beta operation with good confinement of high energy particles has been a critical issues for helical fusion reactor design. To measure position of the magnetic axis is the most important to determine the beta limit of the plasma. To reduce the magnetic axis shift (Shafranov shift) due to vertical field created by Pfirsch-Schluer currents is useful technique to achieve high beta of plasma. The reduction of the magnetic axis shift can be realized by elongate plasma vertically or driving a current in the direction anti-parallel to equivalent plasma current. Oblate magnetic configuration and neutral beam current drive (NBCD) experiment are carried out to test the usefulness of these techniques.

It is important to investigate the effect of the magnetic axis shift on confinement properties. A net toroidal current affects the MHD stability in heliotron/torsatron configurations. The effect of direction of the net toroidal currents on the local ideal MHD stability or Mercier criterion for plasma in the heliotron/torsatron configuration of the LHD [1] have been investigated by Ichiguchi et al. In this calculation, the toroidal current in the direction opposite to equivalent plasma current is expected to cause the inward magnetic axis shifts in low beta value.

In this paper, the effects of oblate magnetic configuration and net toroidal current on the reduction of magnetic axis shift are investigated. The magnetic axis shifts measured with the soft x-ray CCD camera are compared with those calculated with an equilibrium code.

2. Shafranov shift measurement with soft x-ray CCD camera in LHD

The Large Helical Device (LHD) is a heliotron/torsatron device, which has superconducting coil with polarity $l = 2$ and the toroidal field period $m = 10$ and major radius $R = 3.9$ m and minor radius $a = 0.65$ m [2]. The major radius of vacuum magnetic axis, R_{ax}^{v} and the toroidal averaged ellipticity of cross-section of flux surface, κ, are set by controlling the vertical field and quadrupole field produced by helical coils using the vertical field produced by outer vertical coils and quadrupole field produced by the axisymmetric poloidal coils, respectively. B_Q is the rate which canceled the quadrupole field produced by helical coils in the quadrupole field produced by the axisymmetric poloidal coils at the center of vacuum vessel. When B_Q = 100 % at R_{ax}^{v} = 3.90m, the average cross-section of flux surface over one field pitch length becomes circular. The magnetic configuration with κ = 1.02 at R_{ax}^{v} = 3.60 m is referred as the 'standard configuration'. The cross-section averaged over one field pitch length becomes vertically (horizontally) elongated when B_Q decreases (increases).

The magnetic axis is derived from the tangential soft x-ray image measured with the soft x-ray CCD camera system in LHD. The soft x-ray CCD detector camera system consists of pinholes, Be filters, shutter and a soft x-ray sensitive CCD detector, which has been installed to the tangential port on LHD to measure the shape of the magnetic flux surfaces [3]. By choosing the appropriate combinations of pinhole size and thickness of Be filters, the x-ray image can be measured for the plasma in a wide range of electron temperature and density.

The position of the magnetic axis, R_{ax}, is derived from the magnetic flux surface in a database, which give the best fit to the two-dimensional x-ray profile measured. The database consists of the magnetic flux surface files about 200 files for one magnetic flux configuration with pressure profile of 4 types,

$(1-\rho^2)^2$, $(1-\rho^8)(1-\rho^2)$, $(1-\rho^8)(1-\rho^4)$, $(1-\rho^8)^2$, volume averaged beta, $<\beta> = 0 \sim 3.7$ % and net toroidal currents from –100 kA/T to 100 kA/T, in LHD, which has been calculated with three-dimensional free boundary equilibrium code, VMEC [4]. The Shafranov shift is the migration length of magnetic axis from vacuum magnetic axis $R_{ax}^{\,v}$ due to plasma pressure.

The effect of plasma ellipticity on the Shafranov shift is studies in the NBI heated plasma with vacuum magnetic axis $R_{ax}^{\,v} = 3.60$ m and various quadrupole components; B_Q = 200 % ($\kappa = 0.8$, prolate configuration), B_Q = 100 % ($\kappa = 1.02$, standard configuration) and B_Q = 0 % ($\kappa = 1.4$, oblate configuration).

Figure 1 (a) - (f) show the poloidal cross-sections of vacuum flux surfaces calculated with the VMEC code and the tangential images of soft x-ray intensity measured with a soft x-ray CCD camera for the experiment with magnetic configurations of $\kappa = 0.8$, 1.02 and 1.4 at $R_{ax}^{\,v} = 3.60$ m. The flux surfaces in Fig. 1 (a)-(c) correspond to the cross-sections horizontally and vertically elongated. As shown in Fig 1 (d)-(f), the prolate and oblate images of soft x-ray intensity were measured with a soft x-ray CCD camera.

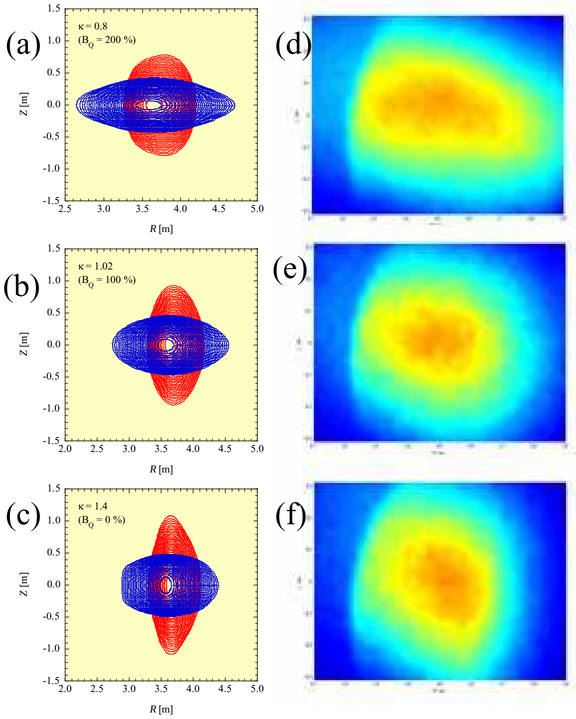

Fig. 1 (a)-(c) cross-sections of vacuum magnetic flux horizontally and vertically elongated calculated with the VMEC Code for the prolate and oblate configurations with k = 0.8, 1.02 and 1.4. (d)-(f) tangential images of soft x-ray intensity measured with the soft x-ray CCD camera for three configurations.

3. The effect of the elongated configurations for Shafranov shift

Figure 2 shows the Shafranov shifts measured with the soft x-ray CCD camera as a function of volume averaged beta estimated with diamagnetic loop, $<\beta_{dia}>$, for plasma with $\kappa = 0.8$, 1.02 and 1.4 at $R_{ax}^{\,v} = 3.60$ m during NB injection. The figure shows that the Shafranov shifts measured increase linearly as $<\beta_{dia}>$ for all κ, and the shift of magnetic axis in the prolate configuration ($\kappa = 0.8$) is larger than that in the standard configuration ($\kappa = 1.02$) and the shift in oblate configuration ($\kappa = 1.4$) is smaller than that in the standard configuration. The reduction of the Shafranov shift due to the vertical elongation is clearly demonstrated in this experiment.

The Shafranov shifts are calculated from pressure profile using the 3-D equilibrium code, VMEC for three experiments. The electron density and temperature profiles used in this calculation are $n_e \sim n_0(1-\rho^8)$ and $T_e \sim T_0(1-\rho^2)$, that are consistent with measurements with FIR interferometer and YAG Thomson. These magnetic axes are shifted greatly as averaged beta increase. The shift of the magnetic axis for the plasma with the prolate configuration ($\kappa = 0.8$) is much larger than that in oblate configuration ($\kappa = 1.4$) by a factor of 5 at $<\beta_{dia}> = 0.5$ %. Although the Shafranov shift has a difference quantitatively between the measured and calculated results, it is qualitatively in agreement.

The Shafranov shift of magnetic axis due to the Pfirsch-Schluter current for the low β limit can be expressed as

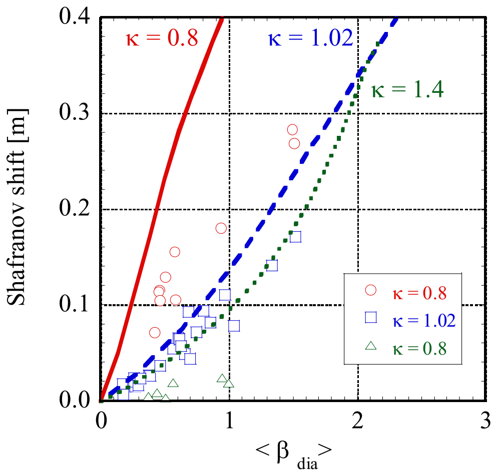

Figure. 2 Comparison the Shafranov shift measured (symbols) with theoretical prediction (lines) calculated by VMEC code for the plasma with different ellipticity of κ = 0.8, 1.02 and 1.4.

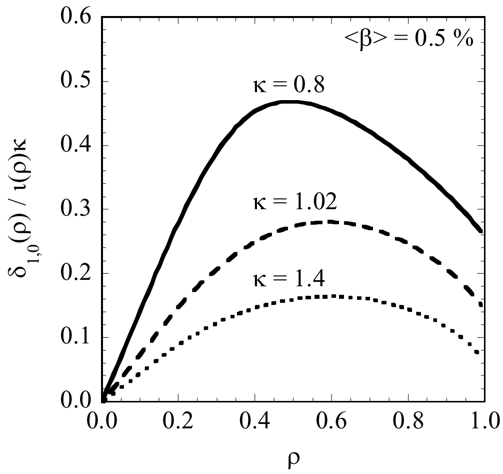

Figure. 3 Radial profiles of $\delta_{1,0}/\kappa\iota$ for plasma with different magnetic elongated configurations, κ=0.8, 1.02 and 1.4.

$$\Delta \cong \frac{a\left(R/a\right)^2 \beta_0}{\iota(1)} \int_0^1 \frac{\delta_{1,0}(\rho)}{\iota(\rho)\kappa} d\rho, \qquad (1)$$

where β_0 is the central β, ι(ρ) is the rotational transform, and $\delta_{m,n}$ is Fourier component of $1/B^2$ given as

$$\frac{1}{B^2} = \frac{1}{\overline{B}^2}\left(1 + \sum_{m,n} \delta_{m,n}(\rho)\cos(m\theta - n\zeta)\right) \qquad (2)$$

with m (n) and θ (ζ) being the poloidal (toroidal) mode number and angle, respectively [5, 6]. Here ρ is the square root of the normalized toroidal magnetic flux used as the radial co-ordinate. The Pfirsch-Schluter current is generated by (m, n) = (1, 0) component of magnetic field.

Figure 3 shows radial profile of $\delta_{1,0}/\iota\kappa$ for plasma with finite beta, <β> = 0.5 %, and different magnetic configurations of κ = 0.8, 1.02 and 1.4, respectively, in LHD. The value of $\delta_{1,0}$ represent the magnitude of the toroidal effect. As seen in Eq. (1), the Shafranov shift is proportional to the integration of $\delta_{1,0}/\iota\kappa$ and $a(R/a)^2\beta_0/\iota(1)$ changes only few persent in this experiment. The ratio of integration of $\delta_{1,0}/\iota\kappa$ (= S_κ) changes by a factor of three in this experiment; $S_{0.8}/S_{1.02}$ = 1.7 and $S_{1.4}/S_{1.02}$ = 0.59. The contribution of $\delta_{1,0}/\iota\kappa$ on the magnetic axis shift has been confirmed in the plasma with the prolate and oblate configurations in LHD.

4. The effect of net toroidal current for Shafranov shift

It has been known that, in low beta, current decreasing (increasing) the rotational transform causes the magnetic axis shift to the outward (inward) at the R_{ax}^{v} = 3.60 m [7]. In LHD, the vertical field is constant regardless of the toroidal plasma current, apart from the operation in Tokamak. Therefore, the magnetic axis shifts outward (or inward) by hoop force when there is a toroidal plasma current in the co (or counter) direction. Then the toroidal plasma current in the counter direction contributes the reduction of magnetic axis. However, this toroidal plasma current decreases rotational transform and hence increase Shafranov shift. Therefore, the effect of net toroidal current on magnetic axis shift is not straight forward and the direction of magnetic axis shift (inward or outward) depends on current profile and β profile. When the current profile is peaked the increase of Shafranov shift due to lower the rotational transform overcomes the inward shift of magnetic axis due to lower hoop force. In order to investigate

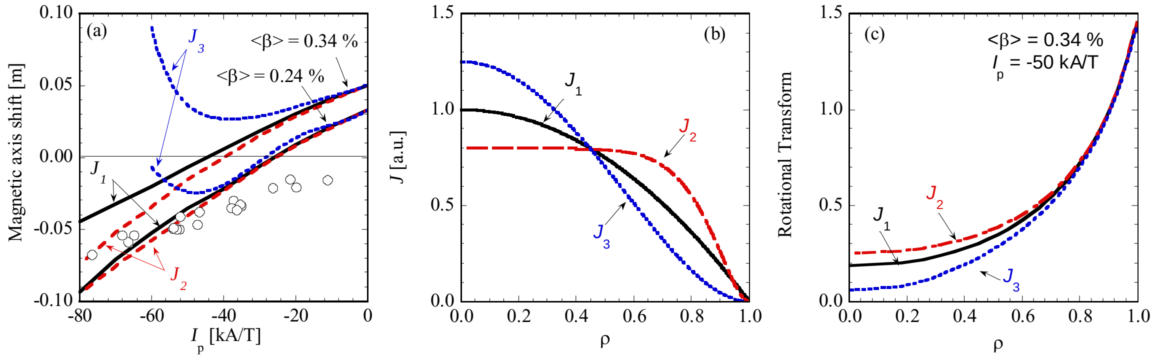

Figure. 4 (a) The shifts of magnetic axis measured by soft x-ray CCD camera (symbols) and calculated with VMEC code (lines) for three type of net current profiles in finite beta as a function of the net toroidal current, (b) net toroidal current profiles using theoretical calculation (c) radial profiles of rotational transform for typical (J_1 ~ $(1-\rho^2)$), broad (J_2 ~ $(1-\rho^8)^2$) and peaked (J_3 ~ $(1-\rho^2)^2$) current profiles with I_p = -50 kA/T in <β> = 0.34 %.

the effect of toroidal current on magnetic axis shifts, NBCD experiment was carred out with H_2 and neon puff, the vacuum magnetic axis of R_{ax}^{v} = 3.60 m, the toroidal field of B_t = 1.5 T and the magnetic configuration of κ = 1.02. The NB drives net current of -110 kA in the direction to anti-parallel to equilibrium plasma current. The central electron density, $n_e(0)$, measured by FIR interferometer and the stored energy, W_p, estimated by diamagnetic loops increase up to 5×10^{19} m^{-3} and 310 kJ, respectively.

Figure 4 (a) shows the magnetic axis shift measured in this experiment, which is plotted as a function of net toroidal current. Figure shows that the magnetic axis shifts inward from position of the magnetic axis in vacuum magnetic flux surface at R_{ax}^{v} = 3.60 m as the magnitude of toroidal plasma current increase in counter direction. The plasma for this experiment is in the line averaged electron density $\langle n_e \rangle$ range of 0.3-0.8 × 10^{19} m^{-3} and W_p range of 70-180 kJ.

In order to compare the experimental results with equilibrium calculation, the magnetic axis shifts are calculated with VMEC code in finit beta, <β> = 0.24 % and 0.34 % for different profiles of toroidal plasma current as seen in Fig. 4 (b). The electron density and temperature profiles used in this calculation are n_e ~ $(1-\rho^8)$ and T_e ~ $(1-\rho^2)$, respectively. In LHD the typical current profile is expected to be J_1 ~ $(1-\rho^2)$ by current diffusion calculation. When the net toroidal current profile is J_1 and J_2 profile, the magnetic axis keep shifting inward as the magnitude of toroidal current is increased. This trend is consistent with the measurements. On the other hand, in J_3 profile, the magnetic axis start to shift outward at large toroidal current in the region $I_p \leqq$ -40 kA/T due to lower the rotational transform as seen in Fig. 4 (c).

The NBCD experiment demonstrates that the magnetic axis shift can be reduced by driving the toroidal plasma current in the direction anti-parallel to equivalent plasma current (counter injection) without increase of the Shafranov shift due to lower the rotational transform.

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