MEASUREMENT OF SHAFRANOV SHIFT WITH SOFT X-RAY CCD CAMERA ON LHD

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The major radius of the plasma magnetic axis was derived from the two-dimensional profile of x-ray intensity measured with soft x-ray CCD camera in Large Helical Device (LHD). The measured Shafranov shift increases linearly up to 28cm, which is 47% of minor radius of LHD as the averaged beta $<\beta_{dia}>$ (measured with diamagnetic loop) is increased up to 2.6%. The Shafranov shift measured in plasmas with vacuum magnetic axis R_{ax}^{v}=3.75m are larger than those in plasmas with R_{ax}^{v}=3.5m in LHD where the $<\beta_{dia}>$ less than 1.5% as predicted by VMEC calculation based on measured $<\beta_{dia}>$.

LHD is Heliotron type device, which has superconducting coil with poloidal and toroidal period numbers of *l/m*=2/10, and the major and minor radii of R/a=3.9m/0.6m [1]. The various heating methods, electron cyclotron heating (ECH), neutral beam injection (NBI), and ion cyclotron resonance heating (ICRH) are available in LHD experiments. Five gyrotrons with the frequency of 82.6GHz (2) and 168GHz (3) are used for plasma production and electron heating, and the main heating devices for LHD plasmas are two NBI injectors with beam energy of 130-150keV.

The x-ray imaging system with soft x-ray back-illumination CCD detector sensitive to the energy range of 1keV to 10keV has been applied to measure magnetic axis in LHD [2]. Although the time resolution determined by mechanical shutter is poor (0.25s), the system has good spatial resolution (1024x512 pixels in image area). By choosing appropriate combinations of size of pinholes and thickness of Be filters, the x-ray image can be measured for the plasmas in the wide range of electron temperature and density. Since the total x-ray emission is considered to be constant on the magnetic-flux surface, the x-ray image represents the magnetic-flux surface. The Shafranov shift of the plasma magnetic axis is derived from x-ray image measured with soft x-ray CCD camera [3].

The inversion of integrated x-ray intensity along the line of sight to the local x-ray emission is not possible, without the equilibrium calculation based on the measured pressure profile, because the inversion needs the shape of magnetic flux surface. The x-ray emission are integrated by using the database of magnetic flux surface which has been calculated for various pressure profiles in LHD, using the three-dimensional free boundary equilibrium code VMEC [4]. The major radius of magnetic axis, R_{ax}, is derived by choosing the magnetic flux surface from databases, which is consistent with the two-dimensional x-ray profile measured [3].

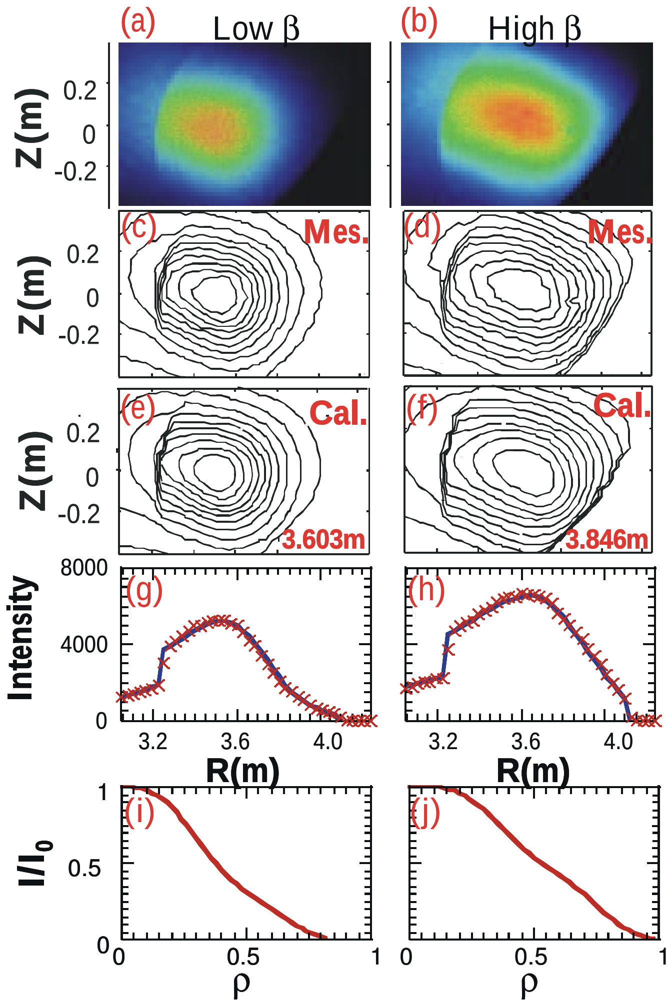

Fig. 1 (a) (b) Images and (c) (d) contour plots of Soft x-ray intensity measured with soft x-ray CCD camera with 190μm and 100μm Be filter, respectively. (e) (f) The best fit contour plots calculated with VMEC code (R_{ax}=3.603 and 3.846m). (g)(h) The horizontal cross-section profiles and (i) (j) normalized x-ray emission profiles.

Figure 1 (a) and (b) show the soft x-ray images measured with soft x-ray CCD camera for a low β plasma (R_{ax}^{v} = 3.6 m; B_t = 2.65 T; $\langle n_e \rangle$ = 1.4x10^{19} m^{-3}) and for a high β plasma (R_{ax}^{v} = 3.6 m; B_t = 0.75 T; $\langle n_e \rangle$ = 4.9x10^{19} m^{-3}), respectively, in LHD. The low β plasma is sustained by ICRH while the high β plasma is heated by NBI. The steep gradients of the x-ray intensity at the left-hand side and lower right-hand side are due to the shadows of inner wall and outer wall, respectively, which give excellent references for the position The clear outward shift of the peak of soft x-ray intensity is observed in the plasma with high β. The Shafranov shift of the plasma magnetic axis is derived by choosing the magnetic flux surface, which gives the best fit to the soft x-ray intensity measured. Fig.1 (c) and (d) show the contour plots of soft x-ray images measured with soft x-ray CCD camera. The magnetic axis of best fit contour plot of soft x-ray image is 3.603m for low beta plasma and 3.846m for high beta plasma. Figure 1 (g) and (h) show a good agreement in the radial profile of x-ray intensity at Z=0 between the best fit of x-ray intensity (solid line) and measured one (cross point). The normalized soft x-ray emission profile for the best fit for low beta plasma is more peaked than that for high beta plasmas.

Figure 2 shows the Shafranov shift measured with soft x-ray CCD camera as a function of averaged-beta $<\beta_{dia}>$ measured with diamagnetic loop. The accuracy determining the major radius of magnetic axis depends on the radial profile of soft x-ray intensity, and is typically few mm and 10mm for the plasma with peaked and flat profile of soft x-ray intensity, respectively. The measured Shafranov shift increases linearly as the averaged beta $<\beta_{dia}>$ is increased up to 2.6%. The Shafranov shift calculated with VMEC code for different plasma pressure profiles of $\alpha 1$=2, 8 and $\alpha 2$=2, 8, where the plasma pressure profile is simplified as $P=P_0(1-\rho^{\alpha 1})(1-\rho^{\alpha 2})$. Here ρ is normalized averaged minor radius. For the high beta discharge with low magnetic field of 0.5T, the Shafranov shift increases up to 28cm (47% of minor radius), and approaching to the calculation with more flat profile as indicated in the magnetic flux surface in Fig. 2.

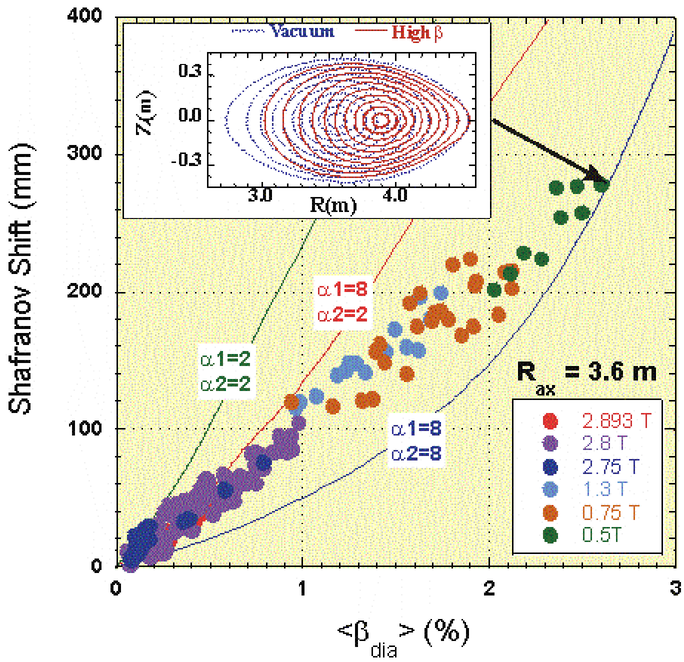

Fig. 2 The Shafranov shift as a function of the averaged-β $<\beta_{dia}>$ for the plasmas with R_{ax}^{v}=3.6m. The horizontal elongated magnetic flux surfaces are plotted for high β plasma and vacuum condition, respectively.

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

$$\Delta \cong \frac{aA_p^2\beta_0}{\iota(1)}\int_0^1 \frac{\delta_{1,0}(\rho)}{\iota(\rho)}d\rho ,$$

where β_0 is the central β, A_p is the aspect ratio, $\iota(\rho)$ is the rotational transform, and $\delta_{m,n}$ is Fourier component of $1/B^2$ as

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

with m (n) and θ (ζ) being the poloidal (toroidal) mode number and angels, respectively [5, 6]. The Pfirsch-Schlüter current is generated by (m,n)=(1,0) component of magnetic filed. Figure 3 shows radial profiles of $\delta_{1,0}/\iota$ for plasmas with a finite $<\beta_{dia}>$ of 0.5% and different vacuum magnetic axes of 3.5 and 3.75m, respectively, in LHD. The value of $\delta_{1,0}$ represent the magnitude of toroidal effect ($\delta_{1,0}$ ~$2\varepsilon_t$ in tokamak plasma). The toroidal effect can be reduced by a large inward shift (ΔR) of magnetic axis from the helical coil center (R_{coil}=3.9m), because the high harmonics of Fourier component of magnetic field, (m, n)=(3, 10), can be large enough to cancel the toroidal effect in some extend.

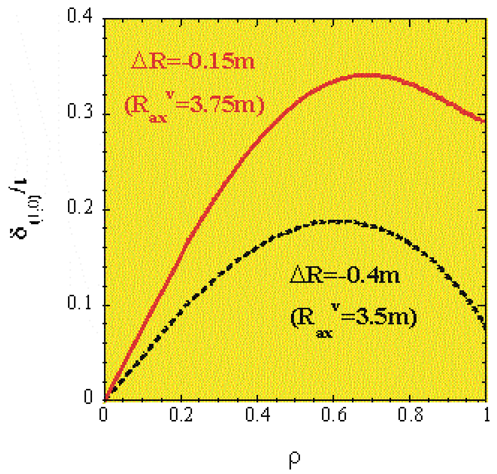

Fig. 3 Radial profiles of $\delta_{(1,0)}/\iota$. for plasmas with different shift ΔR of vacuum magnetic axes of –0.15m (solid) and –0.4m (dashed), where $\Delta R=(R_{ax}^V-R_{coil})$ and R_{coil}=3.9m.

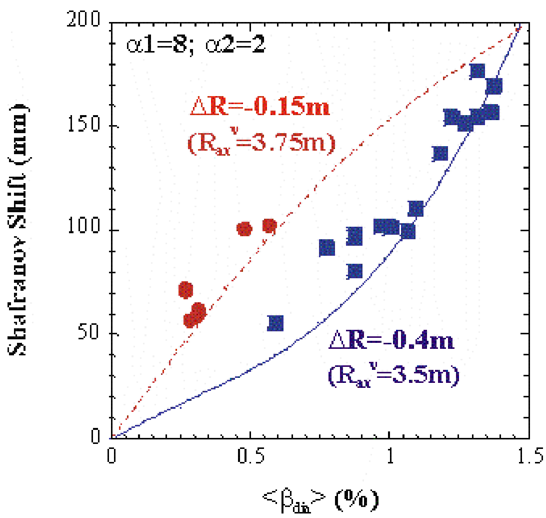

Fig. 4 The Shafranov shift measured with soft x-ray CCD camera as a function of the averaged-β $<\beta_{dia}>$ for the plasmas with R_{ax}^V=3.75m (circle) and R_{ax}^V=3.5m (square), respectively. The Shafranov shifts calculated with VMEC code are also plotted for R_{ax}^V=3.75m (Solid line) and 3.5m (dashed).

Figure 4 shows the Shafranov shift measured with a soft x-ray CCD camera as a function of averaged beta for R_{ax}^V=3.5m and 3.75m in LHD. The electron densities in these discharges are larger than $2x10^{-19}m^{-3}$. The Shafranov shifts measured with soft x-ray CCD camera show that the shift of magnetic axis in the plasma with R_{ax}^V =3.75m is larger than those measured in plasmas with R_{ax}^V=3.5m in a range of $<\beta_{dia}>$ <1.5%. The Shafranov shift measured with CCD camera agrees with that calculated using VMEC code with reasonable pressure profile both for the plasmas with R_{ax}^V=3.5m and 3.75m.

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