J. Plasma Fusion Res. SERIES, Vol.1 (1998) 386–389

Role of Magnetic Measurements for LHD Equilibrium Database

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

Abstract

A construction of MHD equilibrium database shot by shot will be planned in Large Helical Device for the efficient operation, and a validity of magnetic measurements for it has been investigated. In this study, the dependence of volume averaged beta value $<\beta>$, pressure profile and plasma boundary on magnetic probe signals in currentless plasmas has been estimated by using 3-D magnetic field analysis code. In conclusion, the quick estimation of $<\beta>$ and pressure profile using magnetic probe measurements may be possible if toroidal flux Φ_0 or magnetic axis position R_{ax} is already known.

Keywords:
magnetic measurements, Large Helical Device, MHD equilibrium, pressure profile, plasma boundary

1. Introduction

For an experimental study on MHD equilibrium in helical devices, measurements of magnetic field and flux due to local currents which arise to satisfy ideal MHD equilibrium condition $\boldsymbol{J}\times\boldsymbol{B}=\nabla\boldsymbol{P}$ are main subjects. In particular, the poloidal magnetic field and flux due to Pfirsch-Schlüter currents (P.S. currents) along magnetic field line causes the outward shift of magnetic axis (Shafranov shift), and this shift decides equilibrium β-limit and affects MHD characteristics such as rotational transform, magnetic shear and magnetic well/hill. Also, there is some possibility that it destroys the peripheral magnetic surfaces. The magnetic measurements may give us information on not only the above-mentioned MHD characteristics but also physical quantities required for decision of MHD equilibrium such as pressure profile, current profile, magnetic axis and plasma boundary position. In particular, the subject whether magnetic measurements can define the plasma boundary is very important for decision of equilibrium because plasma boundary is not clear in helical devices and the peripheral region is ergodic [1]. Also, theoretical prediction suggests that outward shift of plasmas lead to a decrease in plasma volume because of an existence of separatrix in outer region of torus [2-4].

To prove the validity of these measurements for reconstruction of equilibrium, the parameter dependence on magnetic probe signals has been investigated using the 3-D magnetic field analysis code [5-6], which calculates the response from finite-β-equilibria constructed by the 3-D equilibrium code [7]. In this study, the sensitivity of magnetic probe signals to $<\beta>$, pressure profile and plasma boundary position is quantitatively estimated, and validity of these measurements on LHD equilibrium database is discussed.

2. Magnetic Measurement System in LHD

The LHD is a heliotron device which has the toroidal field period number of $m=10$ with $l=2$ helical coil, the plasma major radius $R=3.9$ m and the plasma minor radius $\bar{a}\sim 0.6$ m [8]. The rotational transform in vacuum condition monotonically increases from 0.4 at magnetic axis to around 1.3 at the last closed flux

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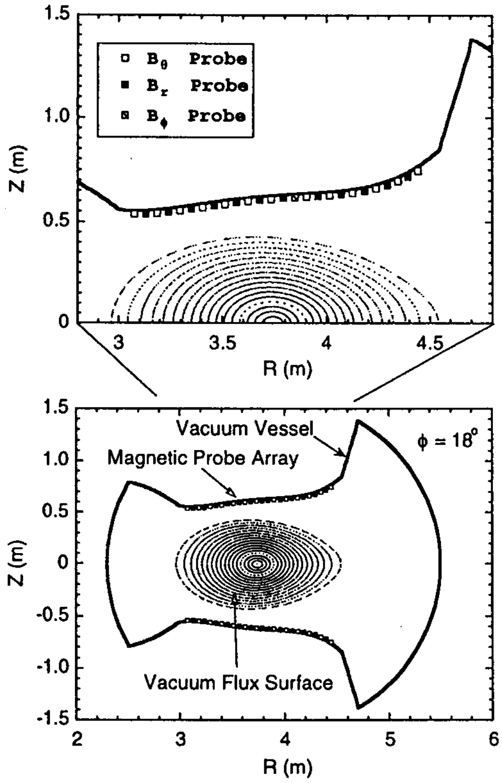

Fig. 1 Vacuum magnetic surface and position of magnetic probe array **B**.

surface (LCFS). Since the LHD has three pairs of poloidal coils, the operation with various magnetic configurations is available. This enables flexible operation such as real-time control of magnetic configuration in steady-state operation oriented superconductive coils.

As basic magnetic measurement systems, Rogowski coils, one-turn loops, diamagnetic loops, magnetic probes and saddle loops are planned to be installed inside vacuum vessel [9]. Three-type magnetic probes are installed inside the vacuum vessel to measure poloidal, radial and toroidal components of magnetic field due to local currents, respectively, and these are also used to identify MHD mode number. These probes are installed at two kinds of poloidal section. The probe array which is composed of thirteen B_θ probes, twelve B_r probes and one B_ϕ probe is arranged at the upper and lower sides of inner wall of vacuum vessel at a poloidal cross section (array **A**, Fig. 1), while one pair of probes are installed on an equatorial plane at different cross section (array **B**).

3. Calculation Results

Measured magnetic flux as well as local magnetic field has been estimated using the 3-D magnetic field analysis code DIAGNO, which calculates the response from finite-β-equilibria constructed by the 3-D equilibrium code VMEC (In detail, see Ref [5]). Figure 2 shows peripheral magnetic field structure when the volume averaged beta value $<\beta>$ is 2 %. The dipole structure is formed by P.S. currents and an outward shift of magnetic axis ΔR_{ax} reaches about 0.32 m. Figure 3 shows signals from probe array on the upper side of vacuum vessel in currentless plasmas with $<\beta> = 2\%$ and different pressure profiles. The pressure profile is assumed as $P = P_0(1-\psi)^\alpha$, where ψ is the toroidal flux function which is normalized by the value at the LCFS and α is in the range of $1 \sim 3$. It should be noted that θ^* and r^* mean the parallel and perpendicular direction to vacuum vessel, respectively, and δB_{θ^*}

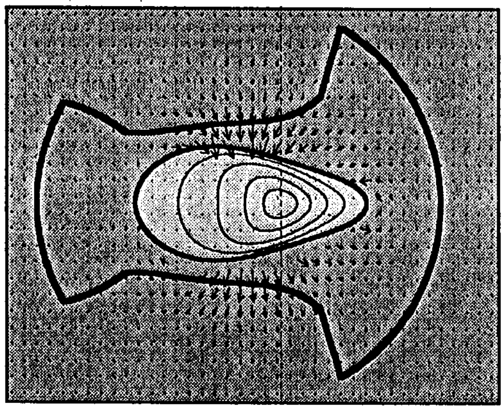

Fig. 2 Peripheral magnetic field structure due to equilibrium currents when $<\beta> = 2\%$.

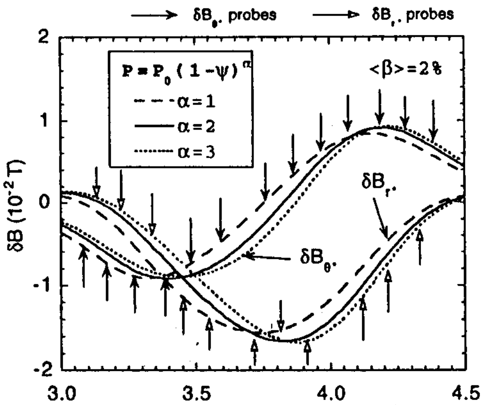

Fig. 3 Profiles of δB_{θ^*} and δB_{r^*} components measured with magnetic probe array **B** in currentless plasmas with $<\beta> = 2\%$ and different pressure profile ($\alpha = 1 \sim 3$).

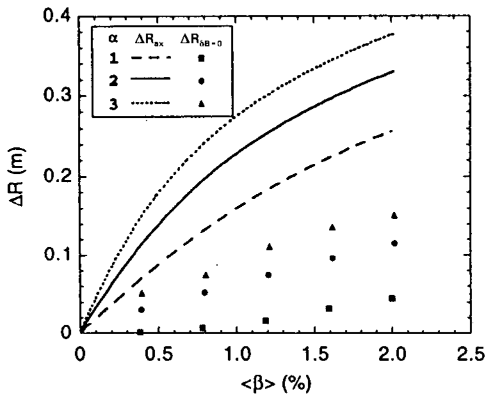

Fig. 4 Changes in magnetic axis R_{ax} and a position with $\delta B_{\theta *}=0$ as a function of $<\beta>$.

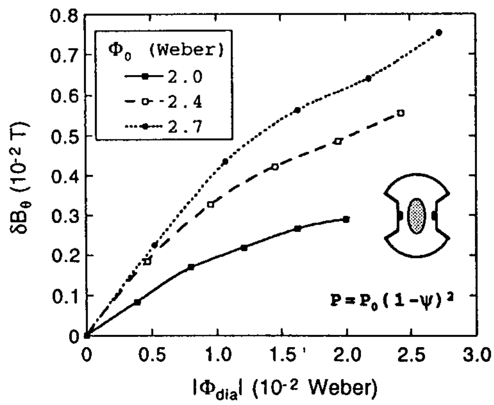

Fig. 5 Changes in a difference between *inside* probe signals and *outside* those as a function of diamagnetic flux Φ_{dia} when $\Phi_0=2.0$, 2.4 and 2.7.

and δB_{r^*} components correspond to those measured with magnetic probe signals shown in Fig. 1. Each profile of δB_{θ^*} and δB_{r^*} components form cosine and sine-like structure. If the toroidal flux Φ_0 and $<\beta>$ are exactly known, it may be possible to obtain the peaking factor α of pressure profile using the above magnetic field profiles. However, theoretical prediction suggests that outward shift of plasmas lead to a decrease in the Φ_0 because of an existence of separatrix in outer region of torus, and so some analysis method which is not affected by the Φ_0 must be established if it is not measured. The different pressure profile causes the profile phase of these components rather than the amplitude as shown in Fig. 3. This phase shift must correspond to the outward shift of magnetic axis if P.S. currents flowing along the simple toroidal ring are assumed. Figure 4 shows the changes in the magnetic axis R_{ax} and the position $R_{\delta B=0}$ where the δB_{θ^*} is equal to zero as a function of $<\beta>$. The difference of $\Delta R_{\delta B=0}$ in between peaked ($\alpha=3$) and flattened ($\alpha=1$) cases is roughly equivalent to that of the ΔR_{ax}. However, $\Delta R_{\delta ax}$ is about three times as large as $\Delta R_{\delta B=0}$. One of the reasons is that the δB_{θ^*} includes not only poloidal component but also the radial one. If the R_{ax} is known and the Φ_0 is unknown, the measurement of the $\Delta R_{\delta B=0}$ is valid for an estimation of the α because the Φ_0 dependence of $\Delta R_{\delta B=0}$ is relatively weak and the error is about 20 % even when the Φ_0 changes from 2 to 3.

Figure 5 shows changes in the difference between *inside* probe signals and *outside* those at array **B** as a function of a diamagnetic flux. The diamagnetic flux is estimated as $\Delta\Phi_{dia}=-<\beta>\Phi_0/2$ in cylinder plasmas and is able to fit the results calculated by 3-D code within the limits of 6%. The reason that this parameter is used in Fig. 5 is that this flux is directly measured with the diamagnetic loop in currentless plasmas, and so the Φ_0 can be estimated by real measurement signals only. The difference of δB_θ in between peaked and flattened cases is about 40 % when $<\beta>=2$ % and the $\Phi_0=2.7$. If the pressure profile is known (by the estimation of $\Delta R_{\delta B=0}$), it may enable us to estimate more accurate Φ_0.

4. Discussion and Summary

The dependence of magnetic probe signals on $<\beta>$, pressure profile and plasma boundary has been investigated from a viewpoint of a validity of magnetic

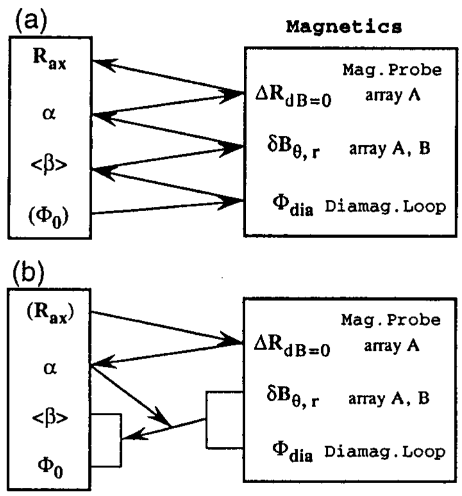

Fig. 6 Parameter survey using magnetic probes and diamagnetic loops when (a): toroidal flux Φ_0 or (b): magnetic axis position R_{ax} is given.

measurements for a construction of MHD equilibrium database shot by shot. The plasma parameters which can be given by the magnetic probe and diamagnetic loop are summarized in Figure 6. Figure 6 (a) shows the parameter survey when the Φ_0 is given by Li beam probe, etc. The signals from probe array **A** and/or **B** make it possible to obtain the pressure profile index α with the $<\beta>$ derived by diamagnetic loop signals and Φ_0. Also, the R_{ax} can be given by $\Delta R_{\delta B=0}$ measured with array **A** signals with the α. On the other hand, $<\beta>$, Φ_0 and α can be given by probe measurements if R_{ax} is already known by the profile measurements with Thomson scattering, CXRS and so on.

The magnetic measurement system can become a powerful tool for a construction MHD equilibrium database, especially, when quick analyses are required such as shot by shot.

Acknowledgement

I would like to thank Dr. H.J. Gardner for making his numerical code available.

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