New Calibration Method of Magnetic Measurements Based on the MHD Equilibrium with the Ergodic Region

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A new calibration method for evaluating equilibrium parameters such as the beta value and its radial profile is introduced. The method is based on a real-coordinate equilibrium code (HINT), which does not assume nested flux surfaces, and on a signal-analysis code (JDIA), which evaluates the flux of magnetic measurements from the result of the HINT. Results of the present work are closer to experimental data than results of a conventional method which assumes nested flux surfaces.

Keywords: magnetic measurement, MHD equilibrium reconstruction, HINT, JDIA, LHD

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The relation between a signal of magnetic measurement and equilibrium parameters such as the beta value and its radial profile can be studied using an equilibrium-analyzing code and a signal-analyzing code that calculates signals of magnetic measurements from a result of the equilibrium code. Calibration using the relation is necessary to evaluate equilibrium parameters from magnetic measurements. A conventional method of calibration is based on a three-dimensional free-boundary MHD equilibrium solver (free-boundary VMEC [1]), which assumes nested flux surfaces and the signal-analysis code (DIAGNO [2]). However, an ergodic region penetrates into the plasma-core region, according to theoretical studies based on a real-coordinate MHD equilibrium solver (HINT [3]). This phenomenon may affect the accuracy of the evaluation of the size and the shape of peripheral flux surfaces, and hence of equilibrium parameters of a high-beta plasma. A new method for evaluating the equilibrium parameters with the use of a HINT code improves the accuracy. The original version of HINT has been developed more than 15 years ago. Recently, it was modified to treat real shapes of external coils [4]. The modification has made it possible to compare with experimental data. The DIAGNO evaluates the magnetic flux of external measurements through the magnetic potential on the plasma boundary which is calculated with the free-boundary VMEC. The same code cannot be applied to the HINT and the fixed-boundary VMEC which does not calculate the magnetic potential.

Instead, we wrote a new signal-analyzing code "JDIA", which evaluates from the plasma current density $\vec{J}$ the magnetic flux to be measured externally. The current density includes a diamagnetic current, a Pfirsch-Schlüter (P.S.) current and a toroidal current. The magnetic flux Φ through a flux loop can be expressed as $\Phi = \int \vec{J} \cdot \vec{a} dV$, where $\vec{a}$ is a vector potential per unit current and V means the plasma volume [5]. The current density $\vec{J}$ at grid points within the plasma region can be calculated and $\vec{a}$ can be evaluated using the Biot-Savart law. The JDIA can evaluate the signal of magnetic measurements from $\vec{J}$ as input data of various sources, not only of the HINT but also of the free-boundary VMEC and the fixed-boundary VMEC. The validity of the JDIA has been confirmed through cross-check between the "free-boundary VMEC+DIAGNO" and the "free-boundary VMEC+JDIA".

We applied the combination of the HINT and the JDIA to the calibration of a diamagnetic loop and a saddle loop in the LHD. Figure 1 shows the location of the loops. The LHD has 6 saddle loops at different poloidal angles. The

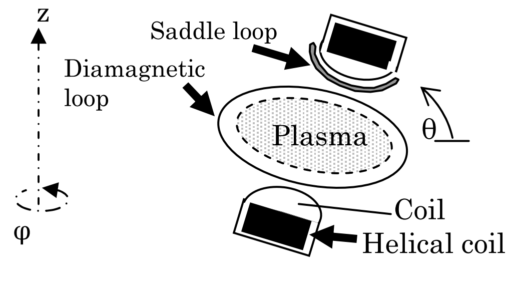

Fig. 1 The poloidal cross sectional view of the saddle loop and the diamagnetic loop in LHD.

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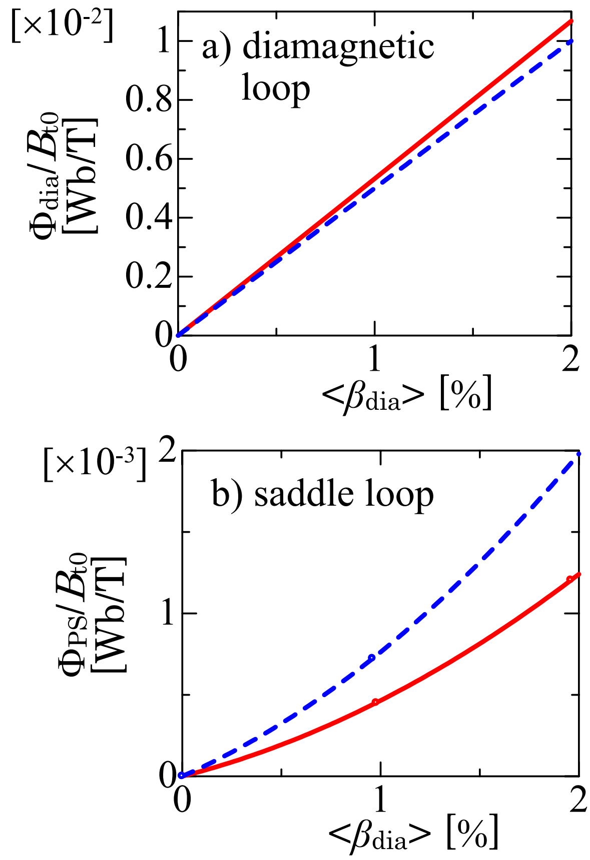

Fig. 2 The comparison between "HINT+JDIA" (solid line) and "free-boundary VMEC+DIAG NO" (broken line) for a) the diamagnetic loop and b) the saddle loop. Here those fluxes are normalized by toroidal magnetic field.

saddle loop on the upper side is used in the present study. The diamagnetic loop is sensitive to the diamagnetic current and the saddle loop is sensitive to the P.S. current because of their locations. Figure 2 shows the dependence of the diamagnetic loop flux (a) and the saddle loop flux (b) on the volume-averaged beta value $\langle\beta_{\rm dia}\rangle$, which is defined as $(2W_{\rm p}/3V_{\rm p0})/(B^2_{\rm ave0}/2\mu_0)$, where $W_{\rm p}$ is the volume plasma energy, $V_{\rm p0}$ is the plasma volume, and $B_{\rm ave0}$ is the averaged toroidal magnetic field inside the plasma boundary. Values of $V_{\rm p0}$ and $B_{\rm ave0}$ are estimated for the vacuum. Calculations are carried out for the following conditions: 1) the LHD standard magnetic configuration in which the magnetic axis is 3.6 m long, 2) the pressure profile is $\beta = \beta_0(1 - \rho^8)(1 - \rho^2)$, where ρ is the normalized radius and β_0 shows a central beta, and 3) a zero toroidal current on each flux surface.

Main results of the calculations are as follows. As Fig. 2 shows, the magnetic flux evaluated with the present method differs from the conventional evaluation by ∼ 40 % in the saddle loop, and by ∼ 5 % in the diamagnetic loop. Figure 3 shows comparison with some of our experimental data. The data set selected for Fig. 3 was obtained with the pressure profile given by the above equation, as observed through Thomson scattering and far-infrared interferometry, and with a minimal toroidal current measured with a Rogowsky coil. Another criterion for the data selection is a minimal anisotropy of pressure, more precisely subject to the condition that (beam pressure/thermal pressure) < 20 %, although the plasma is heated by neutral beams [6]. Clearly, the result from the combination of the HINT and JDIA is close to the experimental data, and indeed much closer than the result from the combination of the free-boundary VMEC and DIAGNO. Thus, it is established that the method based on the HINT is useful for calibration by means of $\langle\beta\rangle$ and the pressure profile.

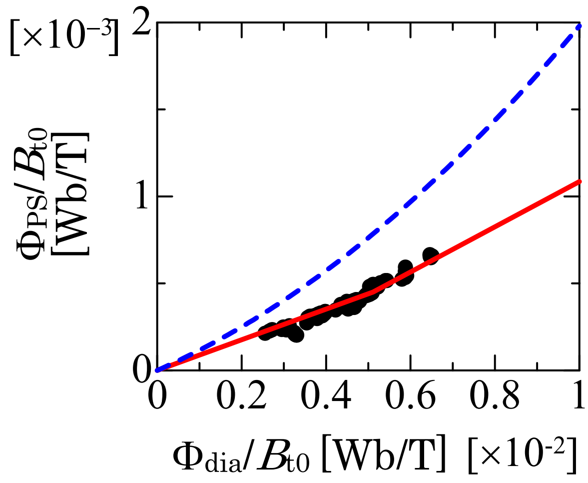

Fig. 3 The comparison of "HINT+JDIA" (solid line), "free-boundary VMEC+DIAGNO" (broken line) and experimental data (dot).

A previous report [7] showed that the HINT reproduces the experimentally observed Shafranov shift much better than the free-boundary VMEC. The present result shown in Fig. 3 is consistent with that report because the Shafranov shift depends on the P.S. current. The difference shown in Fig. 2 (b) is considered to be due to (i) an effect of P.S. current within an ergodic region and/or (ii) a difference of a shape of the outer most flux surface in both equilibrium codes. We thought that a major reason is (ii) mentioned above because the saddle loop flux induced by the current on the ergodic region, is within 10 %. The simultaneous identification of the pressure profile and the pressure anisotropy using saddle loops at some poloidal angles and the diamagnetic loop, is a future plan.

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