The diamagnetic flux measurements in the pulsed magnetic mirror plasma

M. Choe[1], D. Oh[1], J. G. Bak[2], G. W. Baek[1], C. Sung[1],
[1]Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea
[2]Korea Institute of Fusion Energy, Daejeon 34133, Republic of Korea
E-mail: choongkisung@kaist.ac.kr

1. Introduction

The diamagnetic flux measurements are essentially utilized in studying plasma physics since we can estimate important parameters, such as the stored energy in the plasma and energy confinement time, from the diamagnetic flux levels generated by the plasma [1]. However, the diamagnetic flux measurements are difficult since the signal level of the diamagnetic flux is much smaller than the background magnetic flux [2]. Therefore, various techniques to estimate the diamagnetic flux have been developed [3,4]. The aim of this research is to estimate the diamagnetic flux based on the modeling of background magnetic flux without additional installation of loops for background magnetic flux measurements.

The current study has been performed in KAIMIR (KAIST Magnetic Mirror device), the linear magnetic mirror device at KAIST [5]. KAIMIR device is composed of three parts, source, center, and expander. The diamagnetic loops are installed at the source and center parts of KAIMIR. The loops installed at the center chamber will be utilized to estimate the magnetic mirror plasma performance. We will monitor plasma gun performance installed at the source chamber through diamagnetic flux signal measured by the loop installed there.

2. The diamagnetic flux measurement

2.1. The installation of the diamagnetic loops

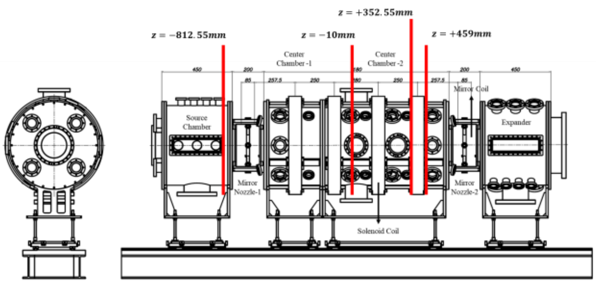

Figure 1 The configuration of KAIMIR chamber (The red solid line indicates the location of each diamagnetic loop) [5]

The length of KAIMIR device is 2.48 m and the diameter of the inner chamber is 0.50 m. There are two types of magnetic field coils installed in KAIMIR, one is solenoid coil which flatten the magnetic field at the center cell and the other is mirror coil which generates the magnetic mirror configuration. When the center of the chamber is at z=0, the solenoid coils are located at z=±388 mm, ±138 mm, and the mirror coils are at z=±730 mm, ±645 mm. Four diamagnetic loops are installed in the chamber, each located at z=-812.5 mm(source), -10 mm, +352.5 mm, and +459 mm, respectively.

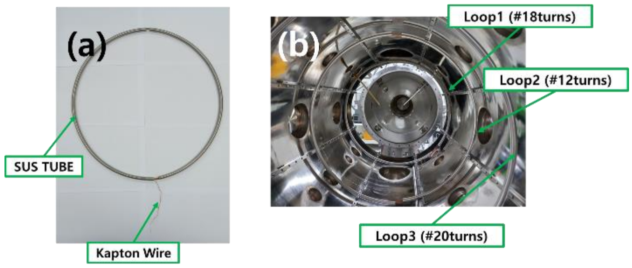

Figure 2 (a): The diamagnetic loop (b): The diamagnetic loops installed at KAIMIR

The diamagnetic loops, which are depicted in Figure 2(a), have a simple circular shape, and they are surrounded by Kapton wires that are wrapped around a metal circular tube made of STL316. To measure the magnetic flux in the axial direction of the magnetic mirror device, KAIMIR, the diamagnetic loops are wound in the azimuthal direction and installed as shown in Figure 2(b).

2.2. Estimation of the background magnetic flux measured by diamagnetic loop

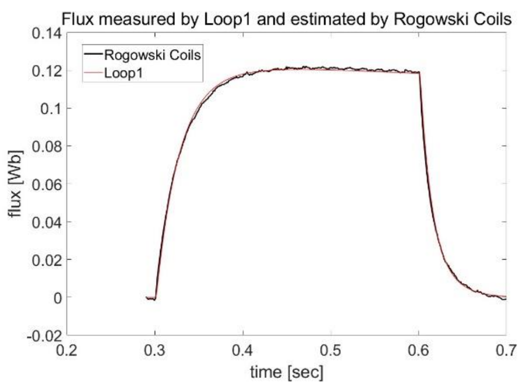

Figure 3 Magnetic flux measured by Loop1 and estimated based on the circuit model and coil current measured by Rogowski coils

In order to estimate the diamagnetic flux induced by the diamagnetism of plasma through the diamagnetic loops, the background magnetic flux, which is externally applied by the magnetic coils, must be removed from the measurement signal. In this study, the background magnetic flux was modeled through the simple circuit model considering KAIMIR magnetic field configuration. Afterwards, we attempted to remove the background signal from the measurement signal. The background magnetic flux (Φ) measured by the diamagnetic loop utilized in this study can be expressed in terms of each current level applied to mirror coils (I_{Mi}) and solenoid coils (I_{Si}), the mutual inductance between mirror coils and diamagnetic loops (L_{Mi}), and the mutual inductance between solenoid coils and diamagnetic loops (L_{Si}).

$$\Phi = \sum_i L_{Mi} I_{Mi} + \sum_i L_{Si} I_{Si} \quad (1)$$

I_{Mi} and I_{Si} will have $\sim \sum_\lambda a_\lambda e^{-\lambda t}$ form from the magnetic coil circuit, because the magnetic coil system corresponds to an RLC circuit. That is, the background magnetic flux in the diamagnetic loops is expected to have a form such as $\Phi = \sum_\lambda a_\lambda e^{-\lambda t}$, similar to the coil current waveform. To validate the use of $\sum_\lambda a_\lambda e^{-\lambda t}$ in modelling a background magnetic flux, it is necessary to verify the RLC circuit model in KAIMIR magnetic coil system. We first estimated the mutual inductances L_{Mi} and L_{Si} through fitting Eq. (1) on the diamagnetic loop signal without plasma, i.e., measured in the vacuum. In this fitting, coil current waveforms measured by the Rogowski coils were utilized. Figure 3 shows that the vacuum magnetic flux measured by the diamagnetic loop and the fitted values based on Eq. (1) agrees well, within 0.83 % ($= \sqrt{\sum_{i=1}^{N}(a_i - b_i)^2}/(N(max\, b_i)) \times 100$, where a_i represents the background magnetic flux measured by the diamagnetic loop, and b_i represents the estimated background magnetic flux by the Rogowski coil). It follows that the circuit model is appropriate to express a vacuum magnetic flux. In other words, it is possible to model the background magnetic flux in the form $\sum_\lambda a_\lambda e^{-\lambda t}$. Furthermore, since we know the resistance, inductance, and capacitance in the KAIMIR magnetic coil system, we can calculate λ from the RLC circuit model. Thus, it is sufficient to estimate a_λ from the form $\sum_\lambda a_\lambda e^{-\lambda t}$ to compute the background magnetic flux.

2.3. In-situ calibration of the diamagnetic loop signal

The diamagnetic loop is a type of coil, and the measured signal is proportion to the number of turns wound on it. In other words, the signal measured by diamagnetic loops is the rate of change of magnetic flux ($V_{\text{loop}} = -N_{eff} d/dt(\int_A \vec{B} \cdot d\vec{A})$). Here, the effective turns (N_{eff}) should be estimated through in-situ calibration. In this case, the effective turns of diamagnetic loops can be estimated as follows.

$$N_{\text{eff}} = -\frac{\int V_{\text{loop}} dt}{\int_A \vec{B} \cdot d\vec{A}} = \frac{(\text{flux by diamagnetic loop})}{(\text{flux by Rogowski coils})} \quad (2)$$

Through in-situ calibration, the effective turns of loop1, loop2, and loop3 were estimated to be 10.90, 7.29, and 12.33, respectively. In this calibration, the magnetic field calculated based on the current applied to the magnetic field coils measured by the Rogowski coils were utilized. We first confirmed that the calculated flux based on magnetic coil current was valid by comparing the calculated magnetic flux with the magnetic field measured by the Gaussmeter, as shown in Figure 4(a). Figures 4(b)-(d) show the comparison between the magnetic field estimated using N_{eff} for loop1-3 and the magnetic field calculated using the Rogowski coil, revealing that the magnetic field measured by the diamagnetic loop and the magnetic field calculated using the Rogowski coil are matched within the noise level. This confirms that the calibration of the diamagnetic loop was properly performed.

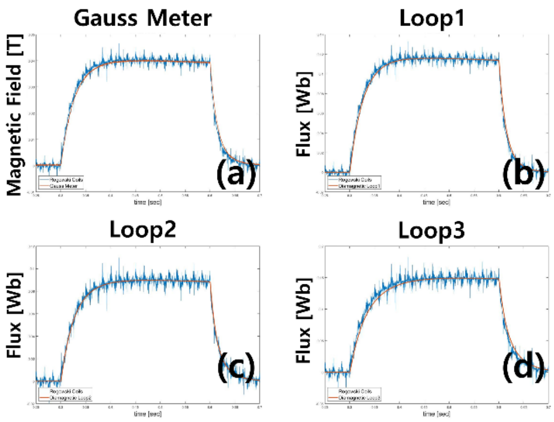

Figure 4 (a) Comparison of magnetic fields estimated by Rogowski coil and measured by Gaussmeter (b) Comparison of magnetic fields measured by Loop1 and estimated by Rogowski coil (c) Comparison of magnetic fields measured by Loop2 and estimated by Rogowski coil (d) Comparison of magnetic fields measured by Loop3 and estimated by Rogowski coil.

2.4. The estimation of the diamagnetic flux

Figure 5(a) shows the raw data measured by loop1 in one KAIMIR discharge (shot 377) and the fitted background signal. Here, we determined the background magnetic flux signal by fitting the magnetic flux signal measured by diamagnetic loop before and after 80ms of plasma generation on the form $\sum_\lambda a_\lambda e^{-\lambda t}$ under the assumption that the plasma is completely extinguished after 80ms. Figure 5(b) shows the results after the plasma discharge the background magnetic flux is removed from the raw flux signal by using the method mentioned earlier. We compared the estimated diamagnetic with the ion saturation current (I_{sat}) measured by a Langmuir probe. Since the ion saturation current is proportional to the plasma density and temperature ($\propto n\sqrt{T}$), and the diamagnetic flux is proportional to the energy in the plasma ($\propto nT$), they are expected to have similar trends. Figure 5(c) shows that their trends with time are qualitatively similar, indicating that the diamagnetic loop measurement is being performed properly. In addition, the diamagnetic flux measured as a function of the applied voltage to the plasma source was compared with the ion saturation current. Since it is generally expected that the stored energy of the plasma increases as the power applied to the plasma source increases, both the diamagnetic flux and ion saturation current are expected to increase as the plasma source voltage increases. Figure 5(d) confirms that the diamagnetic flux and ion saturation current increase as predicted with increased plasma voltage source, supporting that the diamagnetic flux was appropriately estimated.

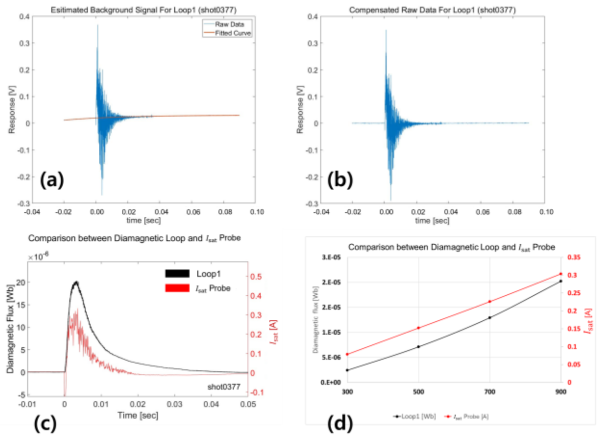

Figure 5 (a) Signal from the diamagnetic loop with the estimated background signal (b) Signal with the background magnetic flux removed from the loop signal (c) Estimated diamagnetic signal and signal from the ion saturation current ($\mathbf{I_{sat}}$) probe (d) Comparison between the diamagnetic flux level and $\mathbf{I_{sat}}$ averaged from 2.0 ms to 2.5 ms when plasma is discharged at 0.0 ms

3. Summary

Diamagnetic loops were installed in KAIMIR device and utilized for diamagnetic flux measurements. It was confirmed that the background magnetic flux measured by the diamagnetic loop could be estimated through fitting based on the circuit model. In-situ calibration of the loop signal was also performed. Afterwards, we attempted to measure diamagnetic flux generated by KAIMIR plasmas. In the experiment, we observed a qualitative agreement between the measured diamagnetic flux and the ion saturation current signal measured by the Langmuir probe. This result supports that the diamagnetic flux measurements performed here is valid.

4. Acknowledgments

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