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Diamagnetic Measurement Based on QUEST TFC Current Signal
QUESTにおけるTFC電流信号に基づく反磁性測定

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In the spherical tokamak QUEST, when plasma energy increases by heating, toroidal magnetic field in the plasma varies from the toroidal magnetic field in vacuum due to diamagnetic effect. If the voltage induced in the toroidal magnetic field coil is measured, the increase in the plasma energy can be estimated inversely. And when the voltage applied to the toroidal field coil is constant, the increase in the plasma energy can be estimated inversely by measuring the induced current change with optical CT (Cuurent Transformer based on Faraday rotation). The voltage and current waveforms of the toroidal field coil in QUEST, and the experimental results in the optical CT circuit are reported.

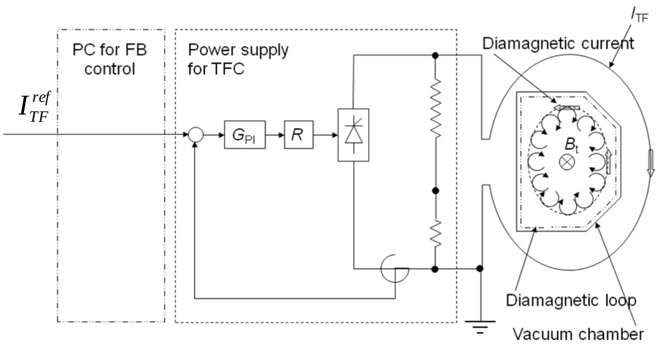
1. Introduction

As a measuring method of plasma energy of spherical tokamak, we can detect the change in toroidal magnetic flux due to increase in plasma energy according to diamagnetic effect of plasma. In the past, this change in toroidal magnetic flux has been measured by a diamagnetic loop, which is wound in the poloidal direction around the tokamak plasma. Due to Faraday's law, however, a voltage is induced also in TFC (Toroidal Field Coil) in the direction so as to compensate the change in the magnetic flux. If we measure this induced voltage, we can estimate the increase in plasma energy inversely. On the other hand, in case of constant voltage applied to TFC, we can estimate the plasma energy increase by measuring the induced current. Namely, even though we don't set a diamagnetic loop around the plasma, we can estimate the plasma energy inversely by measuring (sensorless diamagnetic measurement) of the voltage or current induced in TFC.

2. Diamagnetic Measurement

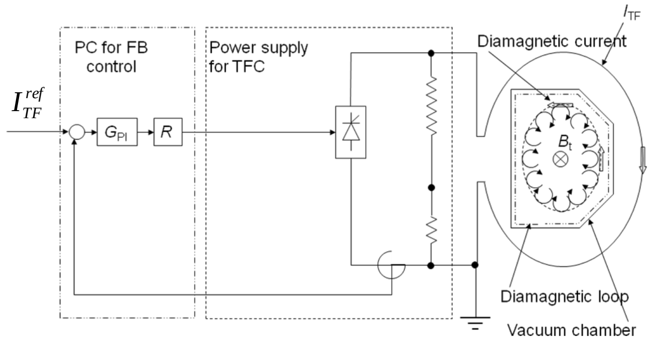
Such small voltage and current induced in TFC due to diamagnetic effect, can be measured and analyzed by several kinds of methods. In the first half experiment, the induced voltage was measured in the usual constant-current control state (Fig. 1). In the TFC power supply, there appears large voltage ripples, which are about one tenth of the rated voltage, due to power electronics such as phase control in thyristor, PWM control in GTO, etc. Though the induced current cannot be detected due to the large control gain, we can extract the very small voltage signal induced due to diamagnetic effect, which less than one ten thousandth of the ripple voltage.

Next, TFC power supply is changed to be operated in constant-voltage control mode (Figs. 2 and 3), and the induced current is measured. TFC power supply current is now measured by DCCT with Hall-effect sensors. Also in this case, we must extract a very small current signal, which is about one ten thousandth of the current.



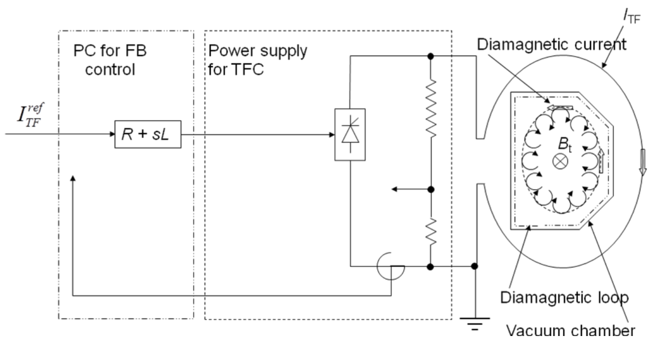
$$I_{TF} = \frac{G_{PI}R\frac{1}{R+sL}}{1+G_{PI}R\frac{1}{R+sL}} I_{TF}^{ref} + \frac{R\frac{1}{R+sL}}{1+G_{PI}R\frac{1}{R+sL}} \frac{\Delta V_{diamag}}{R}$$

Fig. 1 Constant-current control in the power supply for TFC. Though the induced current due to diamagnetic effect cannot be detected, the induced voltage can be.



$$I_{TF} = \frac{G_{PI} R \frac{1}{R+sL}}{1 + G_{PI} R \frac{1}{R+sL}} I_{TF}^{ref} + \frac{R \frac{1}{R+sL}}{1 + G_{PI} R \frac{1}{R+sL}} \frac{\Delta V_{diamag}}{R}$$

Fig. 2 Voltage control in the power supply for TFC but constant-current control in PC for FB control. Though the induced current due to diamagnetic effect cannot be detected due to the large current control gain, the induced voltage can be.



$$I_{TF} = \frac{(R+sL) I_{TF}^{ref}}{R+sL} + \frac{\Delta V_{diamag}}{R+sL}$$

Fig. 3 Voltage control in the power supply for TFC and voltage control in PC for FB control. The induced current can be detected, since it is not affected by either control.

In case of optical CT, we utilize Faraday effect that polarizing plane of electromagnetic wave rotates due to magnetic field in the propagation direction in the optical fiber wound around the TFC current feeder. It is a merit that we don't have to integrate in time, which is necessary in case of Rogowski coil and becomes an origin of the signal drift.

The amount of the optical CT signal is as follows:

$$RI_{TF} = 0.94 m\Omega \times 50 kA = 47V$$

$$\Delta V_{TF} = V_{\max} - V_{\min} = 78 - 8 = 70V$$

$$\Delta I_{TF} = \frac{\Delta V_{TF}}{R + j\omega L} = \frac{70}{0.94 + j2\pi * 720 * 0.75} = \frac{70}{3.4} = 21A$$

$$\frac{\Delta\Phi / S_P}{B_{za}} = -\frac{\beta_p - 1}{2}\left(\frac{B_{\theta a}}{B_{za}}\right)^2 = \frac{0.5}{2}\left(\frac{0.05}{0.25}\right)^2 = \frac{1}{10^2}$$

$$\frac{\Delta I_{TF}}{I_{TF}} = \frac{N}{I_{TF}} \frac{\Delta\Phi}{\Delta t} \frac{\Delta t}{L} = \frac{\Delta\Phi / S_P}{B_{za}} \frac{S_P}{S_{TF}} = \frac{1}{10^2} * \frac{\pi(0.40)^2}{\pi(1*2)} = \frac{1}{10^2} * \frac{8}{10^2} = \frac{8}{10^4}$$

$$\Delta I_{TF} = I_{TF} \frac{\Delta I_{TF}}{I_{TF}} = (50 * 10^3) * \frac{8}{10^4} = 40A$$

We can ensure dynamic range larger than ten thousand by winding the optical fiber over 100 times around the TFC current feeder. In order to extract a small induced current component due to diamagnetic effect, Faraday effect sensitivity (Verdet constant) must be prevented from drift due to the ambient temperature change. We need heat insulation from TFC current feeder and need to keep the ambient temperature in constant. If we adopt Sagnac type interferometer [1], which fits together well with optical fiber, and in which detecting error does not appear even if the shape of the optical fiber changes due to the ambient temperature change or the mechanical oscillation. In the fiscal year 2013, we intended to measure the TFC current in the real circumstance by utilizing the minimum optical devices (SLD light source, polarizer, optical fiber, power meter, etc.), which are necessary to measure Faraday rotation.

3. Summary

(1) Sensorless diamagnetic measurement:
The diamagnetic effect appears an order of magnitude greater in spherical tokamak.
(2) Voltage control in TFC power supply:
It is necessary for FB controlled power supply to be voltage controlled.
Need to remove the effect of voltage ripple.
(3) Optical CT:
The optical fiber need to be wound several hundred turns.
(4) Sagnac type interferometer:
In reflection type, the sensitivity is improved to be two times as large as the one in loop type.

Acknowledgments

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References

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