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Interaction between the Helical Coil Current and the Toroidal Plasma Current in the Large Helical Device

YANAGI Nagato, CHIKARAISHI Hirotaka, IMAGAWA Shinsaku, SEKIGUCHI Haruo, SAKAKIBARA Satoru, HAMAGUCHI Shinji, MITO Toshiyuki, SATOW Takashi and MOTOJIMA Osamu

National Institute for Fusion Science, Toki 509-5292, Japan

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Abstract

The current of the superconducting helical coils is affected by the change of the toroidal plasma current in the Large Helical Device due to the tight magnetic coupling between the helical coils and the toroidal plasma current as well as to the relatively slow response of the present PID control of the DC power supplies. Since the helical coils are operated in a marginally stable condition, where a finite and temporal propagation of a normal-zone is allowed, it is important to precisely evaluate the deviation of the coil current due to the change of the toroidal plasma current. The temporal change of the helical coil current is also examined by incorporating a simple circuit equation.

Keywords:

LHD, helical coils, cryogenic stability, toroidal plasma current, PID control

1. Introduction

During the five experimental cycles of the Large Helical Device (LHD), which is steadfastly advancing reactor-extrapolative plasma experiments with a helical confinement approach [1], the superconducting coil system has been successfully providing the static magnetic field with a heliotron configuration.

Since the pair of helical coils (major radius: 3.9 m, minor radius: ~1 m, toroidal pitch number: 10 and temperature: 4.4 K) generate both the toroidal and poloidal magnetic fields, they are tightly coupled with the toroidal plasma current which mainly generates the poloidal field. Thus, the transport current in the helical coils is inherently affected by a fast change of the plasma current. This is unavoidable when the characteristic time of the change of the plasma current is relatively shorter than the characteristic time of the power supply control. Since the cryogenic stability of the LHD helical coils is presently marginal near the maximum central toroidal field of 2.9 T [2-4], a sudden and significant increase of the coil current in this region may trigger a normal-transition, and in some cases lead to a coil quench which will activate an emergency shutdown sequence of the system and terminate the plasma experiment. In this respect, the relationship between the change of the helical coil current and the amount of the toroidal plasma current should be clarified. This is also important for designing the future reactor-size machine with a helical approach.

2. Cryogenic Stability and Mechanical Properties of the Helical Coils

During the excitation tests systematically conducted up to the present time, it has been confirmed that the helical coils allow temporal normal-transition at a current and magnetic field slightly lower than the specified operation point (coil current: 13 kA, magnetic

Corresponding author's e-mail: yanagi@LHD.nifs.ac.jp

field: 7 T). Eight of the observed transition events were temporal where the generated normal-zone shrank after a few seconds to result in the recovery of the superconducting state [3,4]. One event that occurred in 1998, however, did not recover and an emergency shutdown program was activated as the quench detectors were triggered [2]. In this event, a large amount of helium gas was vaporized due to the Joule heating as well as AC losses during the fast discharge with a time constant of 20 s. It was estimated from the signals of the temperature sensors distributed on the helical coil cans that the propagation of the generated normal-zone was finite in the longitudinal direction, and it seems probable that the final quench was triggered by the deterioration of the cooling condition due to accumulation of helium bubbles at one cross-section in the coil blocks.

For the helical windings, a composite-type superconductor is used, which consists of a NbTi/Cu Rutherford cable, a pure aluminum stabilizer, and a copper sheath with electron beam welds. The characteristics of this superconductor have been intensively studied by carrying out short sample tests as well as small R&D coil tests. It has been confirmed that the conductor becomes transiently unstable even when the transport current is lower than the steady-state "cold-end" recovery current, and an initiated normal-zone propagates over a finite length along the conductor. It should be noted that the magnetic diffusion time constant in the pure aluminum stabilizer is relatively long due to its low resistivity. Therefore, within this characteristic time, the longitudinal resistance of the stabilizer remains considerably higher than that in the steady state, and this might cause a temporal degradation of the cryogenic stability [2-4].

On the other hand, one also needs to pay attention to the mechanism that initiates a normal-transition. We consider that this can be explained by mechanical disturbances in the windings due to large electromagnetic force. During excitation tests, a number of spike signals are observed on the balance voltage of the corresponding blocks of the pair of helical coils. Pulse height analysis (PHA) has been applied to analyze these spike signals, and it is observed that the spike signals have clear exponential-like distribution functions with a high-energy tail component [4]. Thus, the spike signals are found to be very useful to examine the mechanical properties of the coil windings. It should be noted that when the coil current is slightly decreased, the spike signals do not appear as is shown in Fig. 1. In this case, a few spike signals are observed when the field is raised up to the original level. As is described in the following section, it has been observed that the current of the innermost blocks (H-I) of the helical coils actually experiences a temporal deviation from the set value when the toroidal plasma current is induced especially in neutral beam heated discharges. The maximum deviation in the positive direction stays less than 100 A with the present experimental condition. In this respect, the H-I coil current is always decreased by 200 A before starting the plasma experiment.

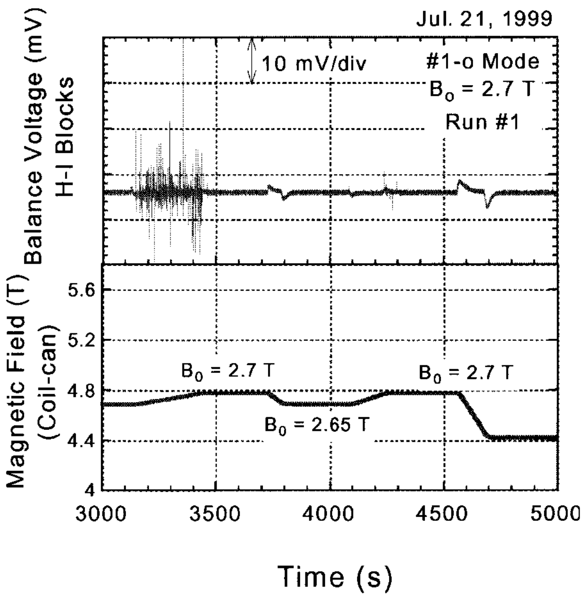

Fig. 1 Typical example of the (H-I) balance voltage signals observed during excitation tests.

3. Perturbation of the Helical Coil Current by the Toroidal Plasma Current

During plasma discharges, the toroidal plasma current is induced mainly by the two mechanisms: momentum injection by neutral beams (the generated current is so-called Ohkawa current) and self-induction by the plasma pressure (so-called boot-strap current) [5]. It has been observed that the H-I current is most significantly affected by the generation of the toroidal plasma current and two typical examples are shown in Fig. 2. In Fig. 2(a), the toroidal plasma current is induced in the positive direction (the same direction with the toroidal magnetic field) with a co-injection of neutral beams (NB) as the dominant heating source. The plasma current reaches up to 80 kA in 10 s and it terminates as the NB is turned-off. Along with the increase of the toroidal plasma current, the H-I current is decreased by 60 A. This can be explained by the magnetic flux conservation. When the plasma current

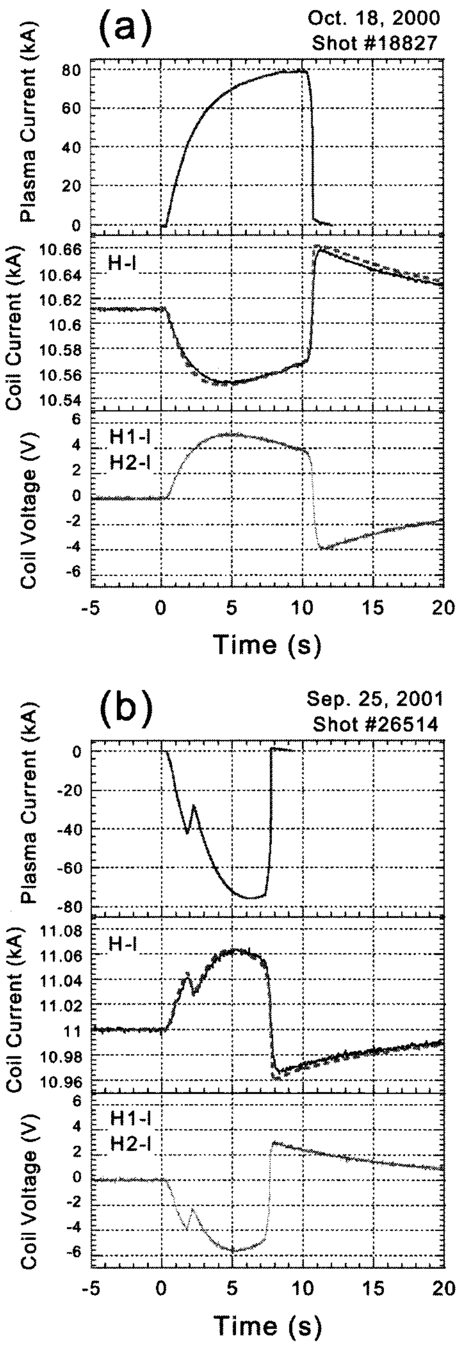

Fig. 2 Waveforms of the toroidal plasma current, the coil current and the terminal voltages of the innermost blocks (H-I) when the toroidal plasma current is induced in (a) the positive and (b) negative directions. The two helical coils (H1 and H2) are connected in series and the current is common. The terminal voltages for the two blocks (H1-I and H2-I) are separately measured.

terminates, the H-I current shows a sharp increase up to +50 A, again to conserve the magnetic flux. It should be noted that during this process, the terminal voltage of each coil is controlled by the DC power supplies, however, the time constant of the present PID control is rather long (typically 10 s), and it is not sufficient to keep the coil current at the constant value.

On the other hand, the plasma current is induced in the negative direction in Fig. 2(b). This is typically observed in the fifth cycle of LHD experiments after the new counter-injection NB line is installed. In this case, the H-I current is first increased by 60 A, and shows a sharp decrease of –40 A when the toroidal plasma current terminates. We note that during these processes, the currents in the middle (H-M) and outer (H-O) blocks of the helical coils are almost unaffected. We consider that this can be explained by the shielding effect of the H-I blocks. On the other hand, the currents in the three sets of poloidal coils show similar waveforms as that of the H-I blocks.

Figure 3 summarizes the relationship between the deviation of the H-I current and the amount of the toroidal plasma current. In Fig. 3, the closed squares correspond to the maximum change of the H-I current observed in the phase that the toroidal plasma current develops as the plasma is heated, while open squares correspond to the sharp change of the H-I current after the plasma current terminates. As is seen in Fig. 3, when the plasma current (I_p) is limited within the range of $-100 < I_p < +100$ kA, the change of the helical coil current (ΔI_H) remains within the level of $-100 < \Delta I_H <$

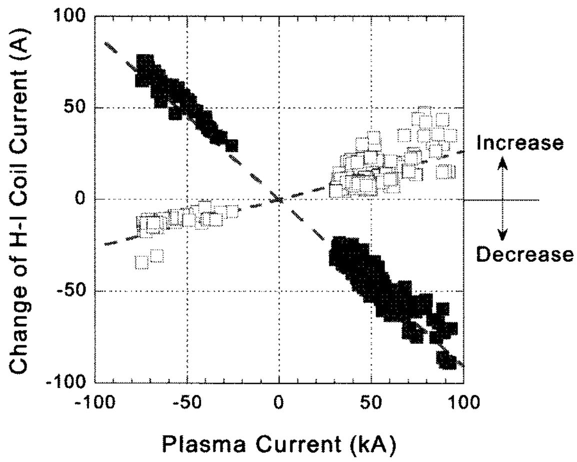

Fig. 3 Relationship between the change of the H-I coil current and the amount of the toroidal plasma current.

+100 A, and there is no concern about the stability deterioration of the helical windings under the present experimental condition.

4. Discussion

Here we examine whether the change of the helical coil current can be simulated by the temporal change of the toroidal plasma current and the terminal voltage which is controlled by the DC power supply. We consider a simple equivalent circuit formed by the H-I blocks, the poloidal coils and the toroidal plasma current. The circuit equation gives

$$L_{\mathrm{HI}}\frac{\mathrm{d}I_{\mathrm{HI}}}{\mathrm{d}t}+M_{\mathrm{HI-PC}}\frac{\mathrm{d}I_{\mathrm{PC}}}{\mathrm{d}t}+M_{\mathrm{HI-p}}\frac{\mathrm{d}I_{\mathrm{p}}}{\mathrm{d}t}-V_{\mathrm{HI}}=0 \qquad (1)$$

where L_{HI} denotes the self-inductance of the H-I blocks, $M_{\mathrm{HI-PC}}$ is the mutual inductance between H-I and the poloidal coils, $M_{\mathrm{HI-p}}$ is the mutual inductance between H-I and the toroidal plasma current, I and V are the current and voltage of the corresponding circuits. We should note that the waveforms of all the poloidal coil currents are found to have very similar shape as that of the H-I current, and the following equation holds:

$$L_{\mathrm{HI}}\frac{\mathrm{d}I_{\mathrm{HI}}}{\mathrm{d}t}+M_{\mathrm{HI-PC}}\frac{\mathrm{d}I_{\mathrm{PC}}}{\mathrm{d}t}=L_{\mathrm{eff}}\frac{\mathrm{d}I_{\mathrm{HI}}}{\mathrm{d}t},$$

where L_{eff} means an effective self-inductance of the overall coils. Thus, by integrating eq. (1) in time, we obtain

$$I_{\mathrm{HI}}=\frac{1}{L_{\mathrm{eff}}}\left(\int V_{\mathrm{HI}}\,dt-M_{\mathrm{HI-p}}I_{\mathrm{p}}\right). \qquad (2)$$

By conducting numerical calculations regarding the magnetic field generated by the coils and the toroidal plasma current, L_{eff} and $M_{\mathrm{HI-p}}$ are evaluated as 1.57 H and 1.86 mH, respectively. In Fig. 2, the waveforms of the H-I current obtained by Eq. (2) is plotted with dashed lines for the two cases. The simulated curves show fairly good agreement with the measured H-I current. The small deviation from the actual waveforms might be explained by the skin effect in the stainless steel plates used for the helical coil case, the plasma vacuum vessel and the 80 K radiation shield panels.

It should be noted that by reducing the characteristic time constant of the DC power supplies by having a higher gain in the present PID control or by incorporating a more sophisticated control logic, such as the so-called H-infinity control [6], it might be possible to reduce the deviation of the coil current.

5. Summary

The helical coil current is affected by the magnetic coupling with the toroidal plasma current in LHD. The current in the innermost blocks changes with the development of the toroidal plasma current in order to satisfy the magnetic flux conservation under the present condition with a relatively slow response of the PID control in the DC power supplies. It has been confirmed that the deviation of the coil current is within the range of ±100 A when the amount of the toroidal plasma current is limited within ±100 kA. This condition is acceptable from the standpoint of the cryogenic stability of the helical coil superconductors. The coil current can be well simulated by a simple circuit equation

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