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Real-Time Sweep Experiments of γ Parameter with the Superconducting Helical Coils and Its Effect on the LHD Configuration

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Abstract

The γ parameter, i.e., the effective minor radius of the helical coil (HC) current, was changed quickly in time as one of the LHD engineering experiments. This is realized by commuting the currents between the inner and outer blocks of HC utilizing the tight mutual coupling characteristics. The required voltage for current commutation agrees well with the expected value given by a simple circuit model. Application of a fast sweep of the γ parameter might be useful in steady-state plasma discharges for examining the configuration dependence in single shots as well as for reducing the peak heat flux on divertor plates.

Keywords:

superconducting helical coils, LHD, γ parameter, divertor

1. Introduction

The eight-year construction program of the Large Helical Device (LHD) has been successfully completed with its fully superconducting coil system [1], and high temperature plasma experiments are ongoing with a heliotron magnetic configuration that requires no toroidal plasma current. The one pair of superconducting helical coils (HC) have the major radius of 3.9 m and are pool-cooled with 4.4 K liquid helium under the present Phase I operation condition [2]. During the third experimental campaign of LHD, toroidal magnetic field of up to 2.91 T (with the magnetic axis located at the major radius of 3.6 m) was successfully achieved and effective electron cyclotron heating has been observed in the central plasma region.

Each of the two helical coils consists of three independent blocks: H-I (inner), H-M (middle) and H-O (outer), and the whole windings are contained in thick stainless steel coil-cans. The corresponding blocks of the two coils are connected in series with three independent DC power supplies through six superconducting bus-lines. Thus, the current in each block can be controlled separately, and it is possible to vary the average minor radius of the HC current, or the so-called γ parameter which is defined as

$$\gamma=\frac{m}{l}\frac{a_c}{R_c}, \tag{1}$$

where m is the toroidal pitch number (10 for LHD), l the poloidal pole number (= 2), a_c the average minor radius of the HC current, R_c the major radius of HC (= 3.9 m). In the standard configuration of LHD, γ is set at 1.254 with a_c of 0.978 m. By changing this γ parameter, various characteristic properties of the magnetic

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configuration can be changed, such as the plasma minor radius, rotational transform profile, magnetic shear and well. This is useful to investigate the transport characteristics and/or magneto-hydrodynamic stability of LHD plasmas in terms of the configuration change.

On the other hand, variation and optimization of the γ parameter is important also from the engineering standpoint of the superconducting coil system. For example, cryogenic stability of HC can be assured by decreasing the current in H-I blocks where the magnetic field becomes the highest and most frequent mechanical disturbances are expected. Moreover, fast variation of the γ parameter is a valuable test item for the sophisticated control of DC power supplies used for tightly coupled superconducting coil system [3]. In this connection, a real-time γ sweep experiment has been conducted as one of the engineering tests of LHD without plasma production. In this paper, the experimental results are described and a discussion will be given on the possible application of this operation mode in steady-state plasma discharges.

2. Sweep rate with current commutation

In order to vary the γ parameter rather quickly in time with the allowable maximum voltage (±45 V) of the present DC power supplies, it should be important to utilize the fact that the three blocks in HC are inductively coupled tightly. In other words, although the inductance of each block is large (approx. 3 H), the required terminal voltage for commuting the current in different blocks can be significantly reduced.

Here, let us consider a case when the H-I current is decreased while the H-O current is increased simultaneously, and the H-M current is kept constant. From a simple circuit model, the H-I current can be determined by the following two equations if the rate of current change in H-O is set as α times that of H-I (in the opposite direction):

$$\frac{dI_{HI}}{dt} = \frac{1}{\left(L_{HI} - \alpha M\right)} V_{HI}, \qquad (2)$$

$$\frac{dI_{HI}}{dt} = \frac{1}{\left(M - \alpha L_{HO}\right)} V_{HO}, \qquad (3)$$

where I_{HI} is the H-I current, L_{HI} and L_{HO} are the self-inductances of H-I and H-O, respectively, and M is the mutual inductance between the two blocks. From the above equations, it is possible to find the maximum sweep rate of the H-I current under the maximum voltage condition (−45 V for H-I and +45 V for H-O). As is seen in Fig. 1, the cross point of the two curves gives the maximum sweep rate, and by substituting L_{HI} = 1.29 H, L_{HO} = 1.38 H, and M = 1.07 H, it is evaluated as −173 A/s at α = 0.963. This sweep rate is almost 10 times faster than that given by a simultaneous ramp-down condition of the whole HC currents.

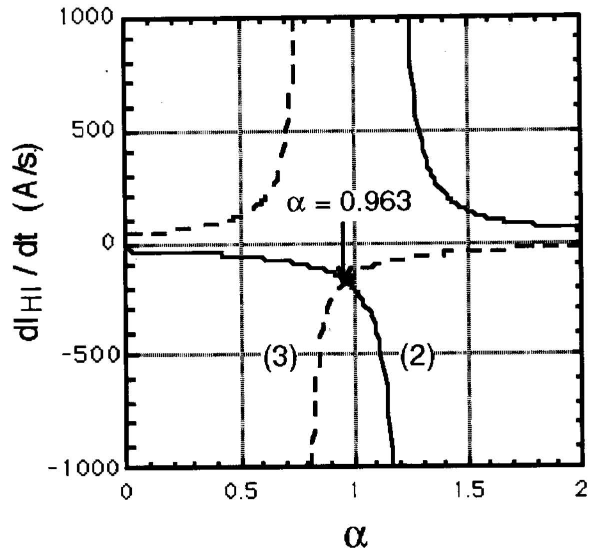

Fig. 1 Maximum sweep rate of H-I current as a function of α. The voltages are taken as maximum: −45 V for H-I and +45 V for H-O.

3. Experimental results

Current commutation between H-I and H-O blocks have been experimentally examined at an average toroidal field of 0.5 T. The H-M current was kept constant, and the H-I and H-O currents were simultaneously changed in the opposite direction. Figure 2 shows an example of the obtained results, when the H-I current was decreased by 1000 A in 10 s (dI_{HI}/dt = −100 A/s) and then increased up to the initial level in 8.33 s (+120 A/s). In this case, the parameter α was taken as 0.96 (optimum condition indicated in Fig. 1) and the H-O current was simultaneously changed by the amount of 960 A. In the present experiments, PID control with a proportional gain of 1.0 was adopted for the control of the DC power supplies. It was confirmed that the H-I and H-O currents could be effectively commuted with the almost equal amplitude of voltage (with opposite signs) for H-I and H-O.

In the experiment, the control of DC power supplies was given by current and not by voltage, and thus the dependence of the circuit response on the

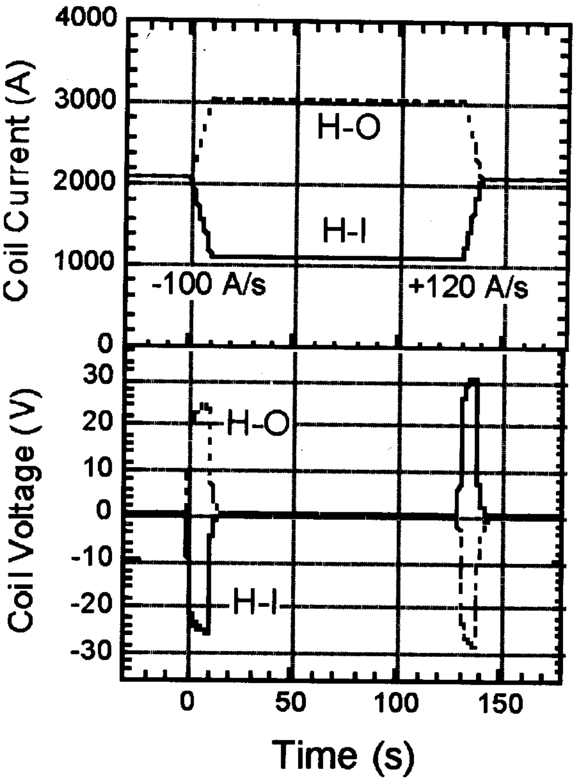

Fig. 2 Experimentally observed current and voltage waveforms during current commutation tests between H-I and H-O blocks.

parameter α was examined with a fixed current sweep rate at 50 A/s for H-I blocks. As shown in Fig. 3, α was scanned from 0.8 to 1.2, and the required voltages show good agreement with the expected values given by the simple circuit model. In the present experiment, current is commuted between the winding blocks inside of the coil-cans and thus the eddy currents induced in the coil-cans and supporting structure might not be significant.

4. Discussion

4.1 Application of real-time γ change operation to steady-state plasmas

It has been demonstrated in the present experiment that the γ parameter, or the average minor radius of the HC current can be changed rather quickly in time with the present DC power supplies by utilizing the tight mutual coupling characteristics of HC blocks. We consider that this method of fast γ variation might be applicable also for the real plasma experiments, especially for steady-state discharges. For example, a real-time variation of the γ parameter might be useful for investigating the response of plasma confinement

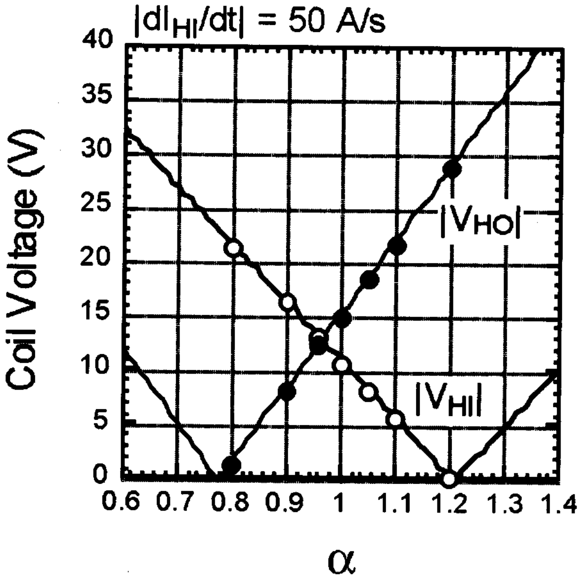

Fig. 3 Dependence of the required coil voltage as a function of the parameter α. Circles indicate experimentally obtained values.

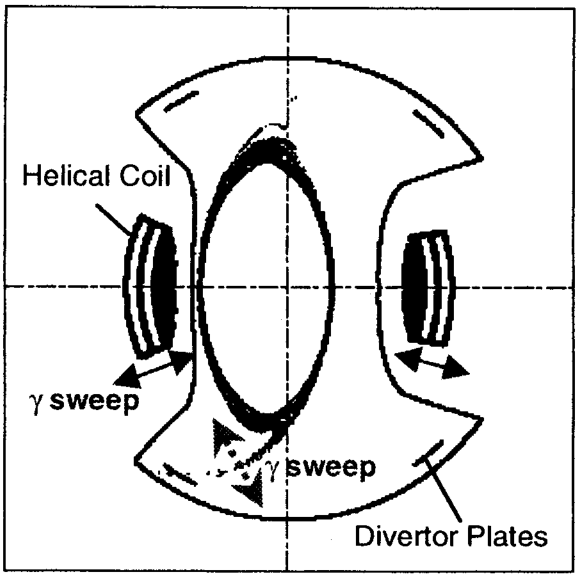

Fig. 4 Numerically calculated divertor traces with vacuum configuration (γ = 1.25). The poloidal locations of divertor plates are indicated by solid arcs.

due to configuration changes even in a single shot.

Another more technological application might be found with the fact that by changing the γ parameter, spatial locaticns of the built-in helical divertor traces are also changed. Thus, by giving a temporal oscillation of the γ parameter, the divertor striking points can be swept, which might be effective for reducing the local peak heat flux on divertor plates in steady-state operations with significant heating power [4]. Figure 4 shows an example of numerically calculated divertor traces at one poloidal cross-section with the standard vacuum magnetic configuration of γ = 1.25. It is estimated with similar calculations that by shifting the γ parameter by ±0.014, the divertor striking points can be scanned approximately by ±6 cm in the poloidal direction on a divertor plate. This amount of γ change corresponds to the H-I current change of ±1000 A at the toroidal field of 1.5 T. According to the above experimental results, it is possible to give this shift in 10 s with the present DC power supplies.

4.2 Evaluation of AC losses for continuous γ sweep operation

In examining the feasibility of the above operation scenario with continuous current commutation between H-I and H-O blocks, the AC loss generation in windings has to be carefully checked. Since the total HC current does not undergo a large change in this operation, the field change is rather small (< 0.1 T) and the resulting AC loss generation is supposed to be not very severe. For continuous linear changes of the H-I and H-O currents, the AC loss is roughly evaluated to be about 95 W based on a simple model using the measured time constant of 0.47 s for the inter-strand coupling currents in the HC conductors [5]. This heat generation is supposed to be still in an acceptable level compared with the measured steady-state heat load of 90 W into HC (due to radiation and conduction). The experimental evaluation of the real AC losses with continuous current commutation will be a future work.

5. Summary

A real-time sweep of the γ parameter (the effective minor radius of the helical coil current) was examined as one of the LHD engineering tests. Currents in H-I (inner) and H-O (outer) blocks were commuted by utilizing the tight coupling characteristics. The required voltage agrees well with the expected value given by a simple circuit model. Application of fast γ sweep operations might also be useful in steady-state plasmas, such as for reducing the local peak heat flux on divertor plates.

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References

[1] A. Iiyoshi *et al.*, Nucl. Fusion **39,** 1245 (1999).
[2] O. Motojima *et al.*, Phys. Plasmas **6**, 1843 (1999).
[3] H. Chikaraishi *et al.*,. Proc. of the Power Conversion Conf., Nagaoka (1997) 747.
[4] J.R. Haines *et al.*, Proc. of 14th IEEE/NPSS Symposium Fusion Engineering (1992) 430.
[5] N. Yanagi *et al.*, Cryogenics **37**, 783 (1997).