J. Plasma Fusion Res. SERIES, Vol. 5 (2002) 265–269

Real-Time Plasma Current Control Experiment

NISHIMURA Kiyohiko, TAKAMI Shigeyuki, NARUSHIMA Yoshiro, CHIKARAISHI Hirotaka, TAKAHASHI Chihiro, TAKEIRI Yasuhiko and LHD Experimental Group
National Institute for Fusion Science, Toki 509-5292, Japan

(Received: 11 December 2001 / Accepted: 4 April 2002)

Abstract

The plasma current control is useful in plasma confinement studies, because a plasma current gives a great influence to the plasma confinement and stability even in a helical system. For this reason, the real-time plasma current control (RCC) system using a standard personal computer, DOS/V machine, was designed and constructed. The coil currents for the plasma current control were calculated using the standard proportional-integral control algorithm in the digital signal processor and sent to the reflective memory with 100 msec period.

Before the 4th experimental campaign, the RCC system was modified to isolate from the present Large Helical Device power supply control system. During the 4th experimental campaign, modified RCC system was used for the real-time feedback control of the plasma current. The plasma was produced and sustained by the Neutral Beam Injection at the magnetic field strength of 1.5 Tesla. The ohmic current was induced by changing the inner vertical coil current that produced the vertical magnetic flux. The plasma current of about 30kA was reduced by the RCC system. This rate was the upper limit of the present coil power supply. The simulation of the plasma current control by ohmic current was carried out using a single filament model. This result shows a good agreement with the experimental result.

Keywords:

superconducting heliotron device, reflective memory, real-time coil current control, plasma current control, PI control

1. Introduction

The Large Helical Device (LHD) [1] is the largest superconducting heliotron type device with a set of $l = 2/m = 10$ continuous helical windings. The major and averaged minor radii are 3.9 m and 0.65 m, respectively. Key issues of the LHD project are the demonstration of currentless steady-state plasma operation and the achievement of reactor-relevant plasma parameters (confinement of a high beta plasma). To achieve these issues, real-time control of plasma parameters is essential [2,3].

There exist some plasma currents like bootstrap current, beam driven current by neutral beam injection and so on. Since the plasma current is not essential for a Heliotron type device to form the confining magnetic field, a Heliotron type device is suitable to investigate the affection of these currents to the plasma confinement. For this reason, real-time plasma current control (RCC) is one of the essential issues for the plasma physics research and the RCC system has been designed and installed in the present power supply (PS) system [3,4] of the LHD.

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

2. Real-Time Coil Current Control (RCC) System

2.1 Construction of the RCC System

The LHD superconducting coils consist of one pair of helical field (HF) coils and three pairs of poloidal coils (OV, IS, IV) as shown in Fig. 1. It is possible to induce the plasma current by changing the inter-linkage flux for plasma. The RCC system was designed to control the plasma current of LHD [3]. The RCC system calculates the necessary coil currents using measured plasma current according to a proportional-integral algorithm, which can be replaced easily by other algorithm, and sends them to the PS system. Then the PS system controls the coil currents using these values.

Figure 2 shows the structure of the modified RCC system connected to the PS system. Previous system was linked strongly with the PS system by the reflective memory (RFM). If the RFM of the previous RCC system stops by the accident, the PS system cannot read the set currents data for coils and stops to work. For this reason, the RFM of the new RCC system was isolated from the RFM chain of the PS system. The data for the coil currents are sent to the RFMs connected to the coil V/I analog monitor. One RFM of the coil V/I monitor is

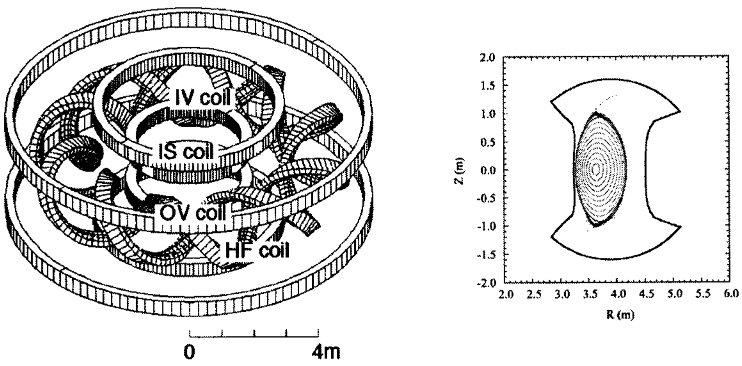

Fig. 1 Schematics of the LHD coils and plasma.

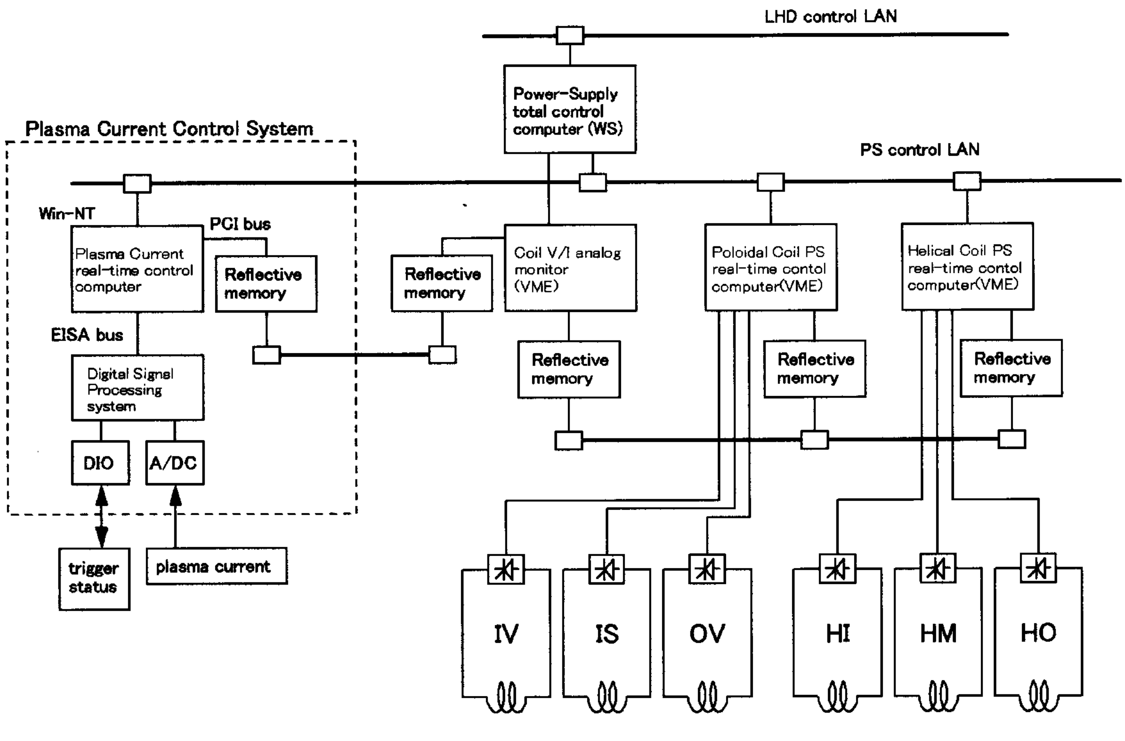

Fig. 2 Structure of the RCC and the PS systems.

connected to the RFMs for the coil PS control and the other RFM to the RFM for the RCC system. Since two RFMs of the V/I monitor are working individually, any troubles on the RFM of the RCC system do not give a serious influence to the PS system. The part surrounded by broken lines is the RCC system and the other part is the present PS system. As shown in Fig. 2, the PS system consists of one PS total control computer and three real-time VME controllers which control poloidal coil power supplies, helical coil power supplies and the analog output voltage and current monitor for all coils. The data communications between the total control computer and VME controllers are done through the PS control LAN and the data communications among VME controllers are done using RFMs.

The coil currents are controlled using the values written on the RFMs by the PS system or the RCC system. When the interlock signal and/or any abnormal signal are detected, the control priority of the power supply is switched to the PS total control computer immediately. The designed value of the control period for the RCC system is 20–100 msec because the time constant of the LHD structure is much larger than 20 msec.

The main computer of the RCC system is a standard DOS/V machine (MMX Pentium 200 MHz) which operating system is Windows-NT. The measured plasma current is inputted to the digital signal processor through an analog digital converter (A/DC). The necessary coil currents are calculated according to the standard proportional-integral control algorithm programmed in the digital signal processor and sent to the RFM. The digital input and output (DIO) are used for the communication of the timing signal and the statements of the RCC system between the RCC system and the central control system computer.

2.2 Control Method of RCC System

The magnetic configuration is characterized by toroidal field B_0, magnetic axis position R_{ax}, ellipticity of cross-sectional shape κ and inter-linkage flux for the toroidal plasma Φ_p. To control the plasma current with keeping B_0, R_{ax} and κ constant, three poloidal coils should be controlled simultaneously. The necessary coil currents are calculated from B_0, R_{ax}, κ and $\Phi_P + \Delta\Phi_P$, where $\Delta\Phi_P$ is the necessary flux calculated from the actual and reference plasma currents. The helical coil currents calculated from B_0 is kept constant. To keep R_{ax} and κ constant, the dipole component (f_D) and the quadrupole component (f_Q) must be kept constant. These components are expressed as follows,

$$f_D = aI_{OV} + bI_{IS} + cI_{IV} , \tag{1}$$

$$f_Q = dI_{OV} + eI_{IS} + fI_{IV} , \tag{2}$$

I_{OV}, I_{IS} and I_{IV} are the coil currents of the OV, IS and IV poloidal coils, respectively. The inter-linkage flux Φ_P produced by the poloidal coils are expressed as follows;

$$\Phi_P = gI_{OV} + hI_{IS} + iI_{IV} , \tag{3}$$

where coefficients *a*-*i* are constants. The poloidal coil currents are derived from eqs. (1)-(3)

$$\begin{bmatrix} I_{OV} \\ I_{IS} \\ I_{IV} \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}^{-1} \times \begin{bmatrix} f_D \\ f_Q \\ \Phi_P \end{bmatrix} . \tag{4}$$

The inter-linkage flux Φ_P is expressed as follows by using the plasma current I_P, plasma self-inductance L_P and plasma resistance R_P.

$$-\Phi_P = L_P I_P + R_P \int I_P dt . \tag{5}$$

Programs for the plasma current control system are coded using eqs. (4) and (5).

3. Experimental Results

The real-time plasma current control experiment using the RCC system was carried out at 1.5 T during the 4th cycle experimental campaign. Figure 3 shows

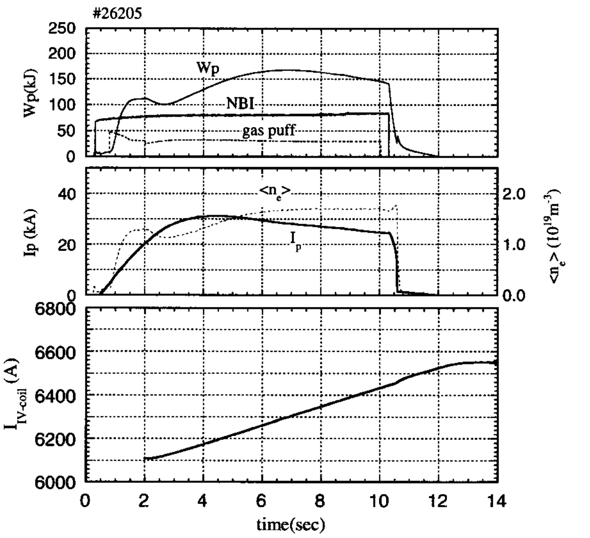

Fig. 3 Time evolution of plasma parameters and the IV coil current in real-time plasma current control discharge.

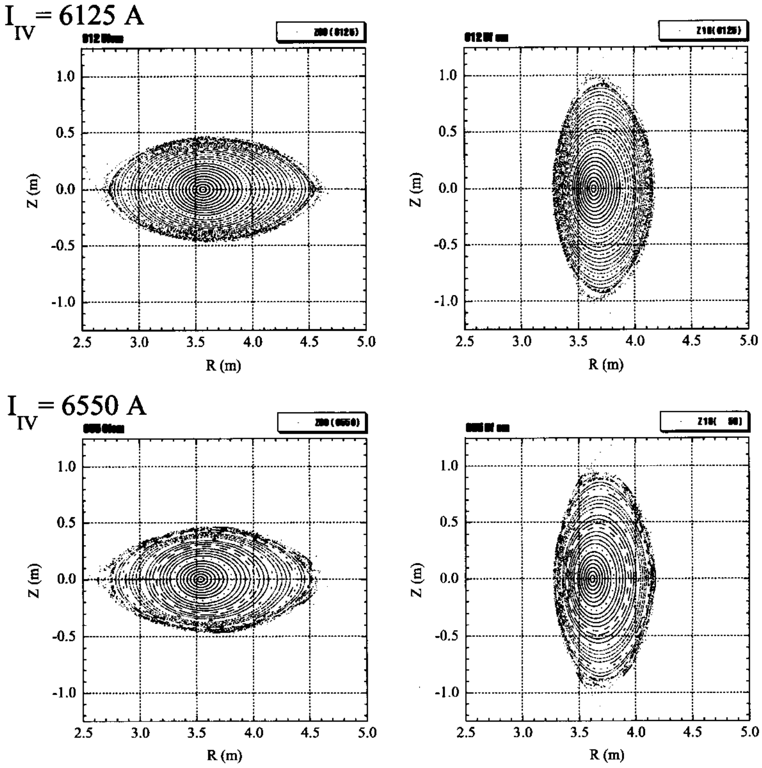

Fig. 4 Magnetic flux surfaces in I_{IV} = 6125 A and I_{IV} = 6550 A.

the time evolution of a plasma stored energy (W_p), neutral beam injection (NBI), gas puffing (gas puff), a line averaged electron density ($<n_e>$) and a plasma current (I_p). Plasma was produced and sustained by the NBI only. The control of the plasma current by the RCC system was started at 2 sec and terminated at the end of the plasma discharge. After 4 second, the plasma current I_p decreases gradually.

The control of the plasma current was carried out by changing the IV coil current that produced the vertical inter-linkage flux. Other coil currents (I_{HF}, I_{OV}, I_{IS}) were controlled to keep them constant to make clear the influence of changing coil current to the other coils. Figure 4 shows the displacement of the magnetic axis in I_{IV} = 6125 A and I_{IV} = 6550 A. These currents were the current at the start and the end of the control. The displacement of the magnetic axis was about 1 cm and does not give serious influence to the plasma confinement.

4. Simulation Results

Figure 5 shows the comparison of the plasma current without control (#17106) and with control (#26205). I_p (ref.) is the target current. The RCC system

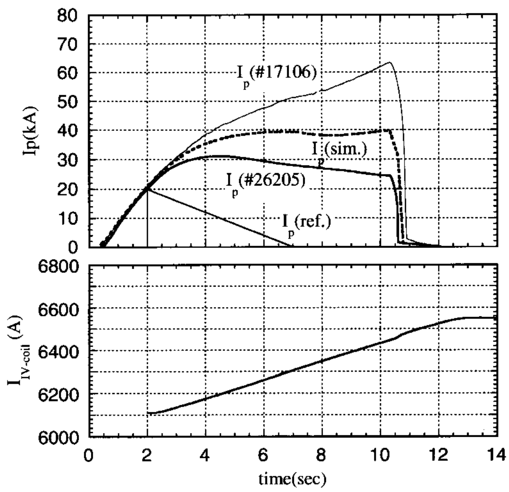

Fig. 5 Comparison between an experimental result and simulation result at 1.5 T.
I_p(#17106) : without current control,
I_p(#26205) : with current control,
I_p(sim) : simulation result,
I_p(ref) : target current for control.

compares the plasma current (I_p) and this target current as a reference, and calculates the needed coil current ($I_{IV\text{-coil}}$). The change of the IV coil current ($I_{IV\text{-coil}}$) was also shown in Fig. 5 bottom. The IV coil current increases continuously at the rate of 40 A/sec. This rate is the upper limit of the present coil PS. The plasma current of about 30 kA was reduced by the RCC system during discharge. The simulation was carried out using a single filament model. Used plasma parameters are T_e = 0.7 keV, $\langle n_e \rangle = 1.7 \times 10^{19}$ m^{-3}, R_p = 3.6 m and a_p = 0.6 m. The plasma resistance and inductance are $r_p = 5.02 \times 10^{-6}$ Ω and $L_p = 9.6 \times 10^{-6}$ H, respectively. The loop voltage is 0.0096 V when the coil current ($I_{IV\text{-coil}}$) changes at the rate of 40 A/sec. The time constant (L_p/r_p) is 1.91 sec. This simulation result shows the similar tendency to the experimental result. A difference between simulation and the experimental result is mainly caused by change of the electron temperature during discharge. The electron temperature decreases gradually in the latter half of the dischage. The plasma resistance has a strong dependence on the electron temperature of $T_e^{-2/3}$.

Since the changing rate of the IV coil current is limited to the 40 A/sec and the increasing rate of the plasma current is about 6 kA/sec., plasma duration of 10 sec. is too short to reduce the plasma current to zero. The changing rate of 40 A/sec in the IV coil current corresponds to about 4 kA/sec in the plasma current.

5. Summary

The RCC system was modified to isolate from the present LHD power supply control system and used for the real-time feedback control of the plasma current. The ohmic current was induced by changing the IV coil current that produced the vertical magnetic flux. This ohmic current controlled by the RCC system reduced the plasma current of about 30 kA. The displacement of the magnetic axis was small to affect the plasma confinement during discharge. The simulation of the plasma current control by ohmic current was carried out using a single filament model. This simulation result shows the similar tendency to the experimental result. The RCC system showed a good performance to control the coil currents.

Acknowledgements

The authors are grateful to the people in the research operation division and the control technology division in NIFS for useful discussions and helps.

References

[1] O. Motojima, H. Yamada, A. Komori, N. Ohyabu, K. Kawahata *et al.*, Phys. Plasmas **6.5**, 1843 (1999).

[2] K. Nishimura, K. Yamazaki, M. Shoji, H. Chikaraishi, H. Yamada, K. Watanabe and O. Motojima, Fusion Eng. Des. **ISFNT-4**, 169 (1998).

[3] S. Takami, K. Nishimura, H. Chikaraishi, C. Takahashi, T. Haga *et al.*, J. Plasma Fusion Res. SERIES **3**, 513 (2000).

[4] S. Tanahashi, T. Satoh, S. Morimoto, S. Yamada, S. Kitagawa *et al.*, Fusion Eng. Des. **20**, 107 (1993).