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Potential measurements with heavy ion beam probe system on LHD^{a)}

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The heavy ion beam probe system in the Large Helical Device (LHD) was improved as follows. At first, the additional new sweeper was installed into the diagnostic port to extend the observable region. By using this sweeper, the potential profile was measured in a wider minor radius range than in previous experiments, in the case of outward shifted magnetic configuration of LHD. Next, the real time control system was installed to control the probe beam orbit for measuring the potential in plasma with large plasma current. In this system, a digital signal processor was used to control the probe beam in real time. The system worked well in the fixed position observation mode. In the sweeping mode for profile measurement, this control system became unstable. The details of this system and the experimental results are reported in this article. © 2010 American Institute of Physics. [doi:10.1063/1.3491317]

I. INTRODUCTION

In toroidal magnetized plasmas, the radial electric field E_r (or potential ϕ) is a very important parameter because the confinement of the device is strongly influenced by this parameter, for example, H-mode^{1,2} and the formation of internal transport barrier.^{3,4} In order to clarify the physics related to E_r and plasma confinement, the measurements of E_r with good temporal/spatial resolution are required. For this purpose, a heavy ion beam probe (HIBP) (Ref. 5) is a very powerful tool because this can measure directly the potential in high temperature plasmas without any disturbance and its temporal/spatial resolution is sufficient. In the Large Helical Device (LHD), the HIBP, of which the maximum beam energy is 6 MeV, was installed and has been developed.⁶⁻⁸

In the recent development of our HIBP system, the ability of measurements was improved. At first, the new electric deflector was installed at the detector side diagnostic port. By this improvement, the observable region was extended. Another improvement is that the real time feedback system to control the beam trajectory was installed and operated for measuring the potential in the plasma with a large toroidal current. In this article, these improvements in the LHD-HIBP system and recent experiment results are reported.

II. POTENTIAL PROFILE MEASUREMENT WITH HIBP

A. New electrical deflector

The maximum strength of the toroidal magnetic field of LHD is 3 T, so Au^+ is used for the probe beam and the maximum acceleration energy of the beam is 6 MeV. The components of the HIBP system in LHD were already stated

in Refs. 6–8 in detail. LHD is a heliotron device, so its magnetic configuration is three dimensional. The probe beam orbit of HIBP in LHD has also a three-dimensional structure. In order to control this complicated orbit, two eight-pole deflectors are used: one is the injector side deflector and the other is the detector side deflector. In the previous experiments, the observable region was from the center to 0.6 in the normalized minor radius and it was difficult to measure the edge region. This is because the maximum voltage of deflector is limited. Costs to increasing the voltage of the power supply are too much and not realistic. So, the additional eight-pole deflector was installed in the diagnostic port of the detector side, as shown in Figs. 1(a) and 1(b). With this additional electric deflector, the observable region of HIBP is extended, especially in the outward shifted configuration. Figure 2 shows the experimental result of the potential profile measurement by using this new deflector. The magnetic field configuration of LHD is characterized by the major radius of the magnetic axis R_{ax} , which was 3.9 m in this experiment. In Fig. 2(a), the timing of heating and the temporal evolution of line averaged electron density are shown. The plasma was produced and sustained by neutral beam heating (NBI). Additional electron cyclotron heating (ECH) was applied from 1.9 to 2.7 s. The line averaged density is about $(0.2 \sim 0.3) \times 10^{19} \text{ m}^{-3}$. The incident angle of the probe beam was changed by the frequency of 10 Hz, so the profile of each 0.1 s was measured. The potential profile in the duration marked by alphabets A and B is shown in Fig. 2(b). In the NBI phase, the profile of the potential was almost flat and E_r was nearly 0. In the additional ECH phase, the profile had the peak at the center and E_r was positive. This is considered to be the so-called electron root in the neoclassical theory.⁹ The observed position was from core to edge region, although the error in the potential was large in the edge region. The maximum error in the position was about

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FIG. 1. (Color online) (a) The new deflector installed in the detector side diagnostic port. (b) Schematic view of a part of LHD-HIBP system and the position where the new deflector was installed.

0.2 in the edge due to the ambiguity of the incident angle of the probe beam.

III. REAL TIME CONTROL OF PROBE BEAM

A. Control system

In the case that large toroidal current exists in a plasma, the probe beam orbit of HIBP is influenced by the magnetic

FIG. 2. (Color online) (a) The temporal evolution of line averaged density and timing of heating. (b) Potential profiles measured with HIBP in phases A and B shown in (a).

FIG. 3. Block diagram of the real time probe beam control system by using DSP.

field produced by this toroidal current. The shift of beam on the probe beam detector is mainly to the toroidal direction because the poloidal magnetic field due to plasma current makes a dominant effect on the probe beam orbit. If the toroidal shift of the probe beam on the detector becomes larger than the size of the detector, the probe beam cannot be detected and the potential measurement becomes impossible. In order to suppress the shift of beam on the detector due to plasma current, we can use the electrostatic deflector located in the detector side beam line. Probe beam detector consists of four plates that are aligned in two vertical columns and two horizontal rows. On the assumption of the current distribution in the beam image on the detector being constant, the position of the beam image on the detector can be estimated from the detected current. The toroidal (horizontal) position of the beam image on the detector, x , is expressed as $x = (I_R - I_L) / (I_R + I_L) \times C$. Here, I_R (I_L) is the current detected with the right (left) column of detector plates. The constant C is the half width of the beam image on the detector. In the real time control, the normalized RL position, $E = x/C$, was used for the simplicity of evaluation. When the toroidal current in the plasma increases, E varies. To suppress the variation of E , the voltage of the detector side deflector in the horizontal (toroidal) direction V_{def} is controlled. The typical time scale of the toroidal current variation is about 0.1 s, so the required frequency of control system is higher than 10 Hz. We designed the feedback control system, of which the typical frequency was 1 kHz, taking account of the sufficient margin of control.¹⁰ In this system, a digital signal processor (DSP) was used because the maintenance of the program code is easy and the control algorithm can be easily modified. The cost is reasonable and the time response is fast enough for our purpose. In our system, C6416 DSP (<http://focus.ti.com/docs/toolsw/folders/print/tmdsdsk6416.html>) was employed, of which the clock frequency is 1 GHz. For the feedback algorithm, the proportional-integral (PI) control was used. The proportional-integral-derivative control is more general; however, the calculation of derivative was not easy because of noise in the signal, so the derivative was not used. Figure 3 shows a block diagram of the control system. The output signal of DSP V_{con} is calculated as $V_{con} = \alpha(K_p e + K_i \int e dt) + V_{offset}$. Here, α is the conversion factor from the normalized RL position to the deflector voltage, K_p is the proportional gain of P control, K_i is the integral gain of I control, and V_{offset} is the constant offset voltage of deflector. In this PI controller, V_{con} is the manipulated value and E is the process value. The error e is evaluated as $e = E_{ref} - E$, where E_{ref} is the set point of the PI controller and in our case $E_{ref} = 0$. (The position of the beam image is on the center of the detector.) DAC (ADC) is the digital to analog convertor (analog to digital convertor), of which the sample frequency

FIG. 4. (Color online) Effects of real time feedback control: the temporal evolution of (a) the normalized horizontal position (NRL) of the probe beam and the voltage of detector side deflector, (b) the sum of the detected current with the detector and the toroidal current, and (c) the measured potential.

is 200 kHz. HV is a fast high voltage power supply (Trek), of which the rate is $350 \text{ V}/\mu\text{s}$. V_{con} is amplified to V_{def} by HV. The process of beam deflection is expressed as the function, β (m/kV), which is the conversion factor from the deflector voltage to the beam position. This function is considered to be almost constant; however, in the experiment, β varied with the sample volume position. The parameter α was set to satisfy $\alpha \sim 1/C\beta$ and this parameter was assumed to be constant during a shot. K_p and K_i were determined by manual tuning in calibration experiments. The noise of the signal was large so the numerical low pass filter (LPF) was used in the DSP to remove high frequency noise. The cutoff frequency of the low pass filter was 1 kHz. The time responses of other components are 40 kHz for HV and deflector and 30 kHz for the isolation amplifier, so the cutoff frequency of LPF is dominant in this system.

B. Experimental results of the real time feedback system

Figure 4 shows the experimental results of HIBP when a large toroidal current exists in a plasma. In this experiment, the voltage of the injector side deflector was constant in the shot, so the observation point (sample volume) of HIBP was fixed at the center of the plasma. In the case of operation without real time control, the probe beam position on the detector moved in the toroidal (horizontal) direction, and the sum of the detected probe beam signal decreased if the toroidal beam current I_p was larger than 40 kA. In the case of

FIG. 5. (Color online) Experimental results in the sweeping mode: (a) the temporal evolution of the voltage of injector side deflector, (b) the normalized horizontal position of probe beam and the voltage of detector side deflector (manipulated value), and (c) the normalized vertical position (proportional to potential) and the sum of the detected current.

operation with the real time control, the position of the probe beam was kept up on the center of the detector, $E=0$ (NRL=0), as shown in Fig. 4(a). The sum of the detected probe beam current was maintained even when I_p was larger than 100 kA. The measured potential is shown in Fig. 4(c), which shows the positive potential when additional electron cyclotron heating was applied (3.3–4.3 s). Thus, the feedback system successfully compensated the probe beam deflection due to the large plasma current.

In the profile measurement mode (sweeping mode), the voltage of injector side deflector is swept in 10 Hz and the incident angle of the beam is changed in this frequency in LHD-HIBP. In this mode, the real time control system was applied, as shown in Fig. 5. In this figure, the half period of one scan is shown. In the duration from 3.758 to 3.774 s (case C), the horizontal position of the probe beam on the detector is kept up on the center. However, before 3.758 and after 3.774 s (case D), the horizontal position of the probe beam oscillates. In this phase, the voltage of detector side deflector, which is the manipulated value in the PI system, also oscillates; therefore, the system is unstable. A possible reason of this problem is the nonlinear dependence of the probe beam position on the voltage of deflector. The function β , which is the conversion factor from the voltage of deflector to the probe beam deflection, was checked at the similar experimental condition of cases C and D. β on the condition of case D was about ten times larger than that on the condition of case C. In the control with DSP, the parameters α , K_p , and K_i are constant in a shot. Therefore, when β increased, the control of the deflector voltage was too large to compensate the probe beam deflection due to the toroidal current. In the experiment, β depended on the sample volume position.

A reason for this is that the finite size probe beam is blocked by the detector side deflector. The distance between the electrodes of the deflector is 0.14 m at the entrance of the detector side deflector, and the width of the probe beam is about 0.04–0.08 m. The estimation by the orbit calculation shows that the probe beam shift is about 0.1 m for the plasma current of 50 kA. In our control system, only the detector side deflector was used to control the beam orbit. The control of the injector side deflector is also needed to avoid the block of beam by the electric rod of the detector side deflector. Another solution is adjusting α . In the profile measurement mode, if the parameter α is changed to satisfy the relation, $\alpha C\beta=1$ in real time, the gain of PI control will be sustained in an appropriate level.

IV. SUMMARY

In LHD, the HIBP system was installed and has been developed to measure plasma potential. This system was improved as follows. At first, new additional sweeper was installed in the diagnostic port and the observable region was extended. Next, the real time control system of the probe beam was installed and it was operated for the plasma with a large toroidal current. This system worked well in the fixed position observation mode; however, the system became unstable in the sweeping observation mode.

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- ¹R. J. Groebner, K. H. Burrell, and R. P. Seraydarian, *Phys. Rev. Lett.* **64**, 3015 (1990).
- ²T. Ido, K. Kamiya, Y. Miura, Y. Hamada, A. Nishizawa, and Y. Kawasumi, *Phys. Rev. Lett.* **88**, 055006 (2002).
- ³A. Fujisawa, H. Iguchi, T. Minami, Y. Yoshimura, K. Tanaka, K. Itoh, H. Sanuki, S. Lee, M. Kojima, S.-I. Itoh, M. Yokoyama, S. Kado, S. Okamura, R. Akiyama, K. Ida, M. Isobe, S. Nishimura, M. Osakabe, I. Nomura, A. Shimizu, C. Takahashi, K. Toi, K. Matsuoka, Y. Hamada, and M. Fujiwara, *Phys. Plasmas* **7**, 4152 (2000).
- ⁴T. Estrada, A. Alonso, A. A. Chmyga, N. Dreval, L. Eliseev, C. Hidalgo, A. D. Komarov, A. S. Kozachok, L. Krupnik, A. V. Melnikov, I. S. Nedzelskiy, J. L. de Pablos, L. A. Pereira, Y. Tashev, V. Tereshin, and I. Vargis, *Plasma Phys. Controlled Fusion* **47**, L57 (2005).
- ⁵T. P. Crowley, *IEEE Trans. Plasma Sci.* **22**, 291 (1994).
- ⁶A. Fujisawa, H. Iguchi, A. Taniike, M. Sasao, and Y. Hamada, *Rev. Sci. Instrum.* **22**, 247 (1994).
- ⁷T. Ido, A. Shimizu, M. Nishiura, A. Nishizawa, S. Katoh, K. Tsukada, M. Yokota, H. Ogawa, T. Inoue, Y. Hamada, and T. P. Crowley, *Rev. Sci. Instrum.* **77**, 10F523 (2006).
- ⁸A. Shimizu, T. Ido, M. Nishiura, S. Nakamura, H. Nakano, S. Ohshima, A. Nishizawa, M. Yokoyama, S. Kubo, T. Shimoizuma, H. Igami, H. Takahashi, N. Tamura, I. Yamada, T. Minami, K. Narihara, T. Akiyama, T. Tokuzawa, K. Tanaka, K. Kawahata, K. Toi, M. Isobe, F. Watanabe, K. Ogawa, K. Nagaoka, K. Ikeda, M. Osakabe, K. Tsumori, Y. Takeiri, O. Kaneko, S. Kato, M. Yokota, Y. Hamada, and LHD experiment group, *J. Plasma Fusion Res.* **5**, S1015 (2010).
- ⁹M. Yokoyama, K. Ida, H. Sanuki, K. Itoh, K. Narihara, K. Tanaka, K. Kawahata, N. Ohyabu, and LHD Experimental Group, *Nucl. Fusion* **42**, 143 (2002).
- ¹⁰S. Nakamura, A. Shimizu, T. Ido, K. Toi, M. Nishiura, and LHD Group, “Real-time control of beam trajectories using digital signal processor for heavy ion beam probe on large helical device,” *Plasma and Fusion Res.* (to be published).