Real-Time Control of Beam Trajectories Using Digital Signal Processor for the Heavy Ion Beam Probe on the Large Helical Device

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A real-time control system using a digital signal processor (DSP) was developed to control ion-beam trajectories of a heavy ion beam probe (HIBP) on the Large Helical Device (LHD). The electrostatic potential during temporal evolution of the magnetic field structure by a large plasma current was successfully measured with the help of this system for the first time. It has been demonstrated that the probe beam can be detected even in a plasma having a ~120 kA plasma current at the toroidal field of 1.3 T using the control system, while the beam is substantially lost by only ~40 kA current before arriving at the detector plate in the case without control. However, this system is unstable during operations when the probe beam is swept in time across the plasma cross section to obtain the time evolution of the potential profile. It is caused by a nonlinear character of the system due to the finite beam size.

Keywords: heavy ion beam probe, digital signal processor, plasma current, Nyquist stability criterion

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Heavy ion beam probe (HIBP) [1] is a unique and powerful tool to measure the electrostatic potential and its fluctuation in high-temperature magnetically confined plasmas. The HIBP was installed on the Large Helical Device (LHD) and employed for potential measurements in almost current-free plasmas [2]. Recently, HIBP was also applied to plasmas with large amount of plasma current in order to study plasma transport and energetic-ion driven MHD instabilities. However, in the case that the magnetic field structure of the LHD is considerably modified temporally by large plasma current, the probing beam deviates from the required orbit and does not reach the detectors. In order to overcome this difficulty, we have developed a real-time feedback control system to compensate the deviation of the beam trajectories due to the plasma current. In this system, a digital signal processor (DSP) is used for such control because it is not so expensive and widely used for feedback control of various systems [3, 4]. Moreover, the time response (< 1 ms) is much faster than the time constant of the variation of the plasma current (> 0.1 s) and the control algorithm can be easily modified by updating the control program.

Figure 1 shows a block diagram of this control system. In this control system, the deflector voltage is controlled so that the probe beam would reach the center of the detector. The detector consists of four split plates which are aligned in two vertical columns and two horizontal rows as shown in Fig. 2. The beam position will move in the horizontal direction due to the plasma current.

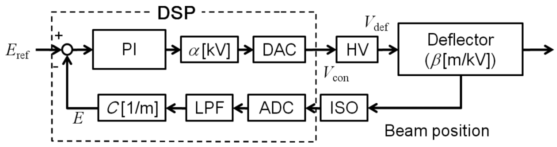

Fig. 1 Block diagram of the HIBP beam control system, ISO: Isolation Amplifier, LPF: low pass filter, PI: PI controller, α: conversion factor from E to V_{con}, HV: high voltage power supply, β: conversion factor from V_{def} to the beam deflection distance L(m), V_{con}: control output, C: conversion factor from L to E.

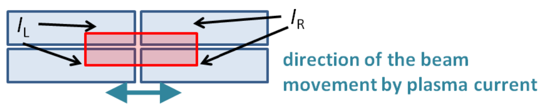

Fig. 2 The relative position of a finite-size beam (red shaded zone) on four split plates of the detector viewed from the vacuum vessel. I_R and I_L stand for the sum currents of two split plates in right- and left-hand sides, respectively.

The deviation of the beam position in the horizontal direction (E) is estimated from the center of the gravity of the beam current: $E = (I_R - I_L)/(I_R + I_L)$, where I_R and I_L are the sum of the currents of the two split plates

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in right- and left-hand sides, respectively. Based on the proportional-integral (PI) control scheme, the control output is calculated using a DSP so that $E = E_{ref}$, where E_{ref} is the desired value and zero in this experiment. The PI control scheme is useful for minimizing a steady-state deviation from the required value. In the HIBP, the deflectors of the beam are placed in both injection and detection sides. In the present control experiment, only the deflector voltage in the detection side was feedback-controlled. The calculated control output of the DSP (V_{con}) is amplified through a high voltage power supply (HV) and fed back as the voltage between two plates arranged horizontally in the deflector. This voltage controls the beam position, where the conversion factor from the deflector voltage (kV) to the beam position (m) is expressed with β. Note that β is a nonlinear function against V_{def}, as discussed later. The factor C in the control equation calculated by the DSP stands for the conversion factor from the beam deflection distance (m) to E. The control parameters in the equation, α and C, were adjusted to be $\alpha\beta C = 1$, where α is the conversion factor from E to the control signal that is output from the DSP. Moreover, the control parameters in the PI control were also adjusted to realize desirable feedback control. Note that this control does not affect potential measurement, because the probe position is only deflected by the control signal in the horizontal direction in the analyzer, as shown in Fig. 2.

The beam trajectory was successfully controlled with the DSP in the plasma with a large plasma current up to 120 kA induced by neutral beam injection, as shown in Fig. 3. The beam energy of the HIBP was 1.134 MeV. In this control experiment, the incident angle of the probe beam was fixed to measure the potential at a fixed position (normalized minor plasma radius $\rho = 0.15$). In the case without the beam control, the probe beam was not detected by the energy analyzer when I_p exceeds 40 kA, as shown in Fig. 3 (a). Note that the diverged E in the phase of $I_p > 40$ kA is caused by a strong reduction of the detected beam current (i.e., SUM $= I_R + I_L$) due to beam loss. On the other hand, in the case with the beam control, the beam position is well-centered on the detector as shown in Fig. 3 (b). The detected beam signal (SUM) is maintained even when I_p increases up to 120 kA. These results demonstrate that the control system successfully compensates the deflection of the probe beam due to the large plasma current when the measurement point is fixed throughout a plasma shot. However, the feed-back system became unstable when the measurement position was swept with the deflector in the injection-side throughout a plasma shot to measure the temporal evolution of potential profiles. The reason for this is that β depends on the injection condition of the probe beam. In the beam control, the deviation of the beam position is evaluated by the effective center of gravity of the beam current using only two detector plates aligned in the horizontal direction. Accordingly, β will depend on the injection condition if the probe beam current has a spatial distribution. The β values in the potential measurements at both positions $\rho = 0.2$ and 0.6 are ten times larger than that at $\rho = 0.15$. When β becomes ten times larger than the expected value, the open loop gain of the control system (Fig. 1) becomes too high to be stable. We analyzed the stability of the system using the Nyquist stability criterion where the system was optimized for the measurement at $\rho = 0.15$ beforehand. The vector trajectory (b) in the case with larger $\beta = 0.02$ is compared to that (a) in the optimized case with lower $\beta = 0.002$ in Fig. 4. From the Nyquist theorem, the case (b) is unstable, while case (a) is stable. The real-time feedback control of the deflector-voltage at the injection port as well as the detector side is necessary to measure the electrostatic potential profiles in a wide range of plasma currents, without falling into an unstable situation of the system.

In summary, the real-time feed-back system was installed on an HIBP to control beam trajectories for the first time. The deviation of the beam trajectories due to the plasma current was successfully compensated. In addition, the control signal contains the information of the internal magnetic field, which can be used for magnetic field mea-

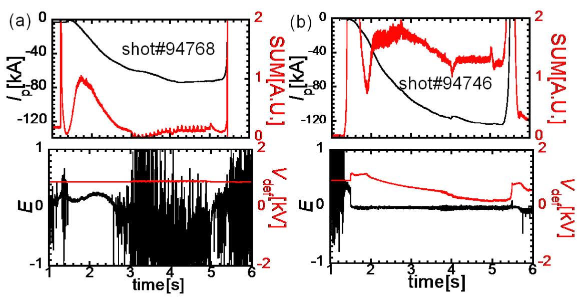

Fig. 3 Effects of the beam control with a DSP in plasmas with large plasma current driven by neutral beam injection: (a) without and (b) with the control. Upper traces show the plasma current (I_p) and the detected beam signal (SUM). Lower traces indicate the deviation of the beam position (E) and the control voltage from V_{def}.

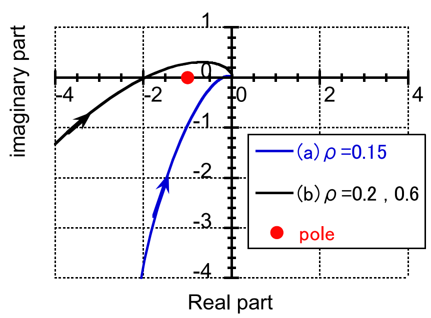

Fig. 4 Nyquist plots for the potential measurement position of $\rho = 0.15$ ($\beta = 0.002$) (a) and that of $\rho = 0.2$ and 0.6 ($\beta = 0.02$) (b).

surements. This control technique is applicable to HIBPs in any other toroidal devices [5, 6].

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