Development of 2D Potential Profile Measurements Using the Heavy Ion Beam Probe on the Large Helical Device*)

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Two-dimensional potential fluctuation profiles were measured with the heavy ion beam probe (HIBP) on the Large Helical Device. For two-dimensional measurements with HIBP, the probe beam energy had to be changed, and subtle adjustment of the beam trajectory along the long beam transport line (~20 m) was required. An automatic beam adjustment system was developed for the beam transport line, and used to easily adjust the probe beam trajectory. Potential fluctuations in the high-frequency range (~200 kHz) were measured, and the probe beam energy was changed shot to shot. Two-dimensional potential phase structures were successfully obtained by analyzing the coherence between potential and magnetic field fluctuation, which is used as a reference signal.

Keywords: heavy ion beam probe (HIBP), two-dimensional potential profile, helical device, the Large Helical Device (LHD)

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1. Introduction

In magnetically confined toroidal plasmas, the radial electric field E_r is an extremely important parameter because it generally influences the plasma's transport property. For example, in the $1/\nu$ regime of the helical device, the large particle flux, which can be predicted by neoclassical theory, is suppressed by ambipolar E_r [1, 2]. The E_r is correlated with the plasma flow through the $E \times B$ drift, and the shear flow structure can improve the confinement properties of the plasma by reducing its turbulence [3], as has been experimentally observed in the H-mode and internal transport barrier (ITB) [4, 5]. In recent theoretical research, the effect of the mesoscale structure of the plasma flow, such as zonal flows and streamers, has been considered important in accurately estimating the turbulent transport [6, 7]. More precise measurements of the flow structure are expected to compare the experimental results with theoretical predictions in detail in order to study and clarify the physics of the zonal flow and their effect on anomalous transport.

A heavy ion beam probe (HIBP) [8] is a useful tool for studying the physics related to E_r because it can measure directly the plasma potential with excellent temporal and spatial resolution. Usually, in HIBP diagnostics, the probe beam energy is fixed and the incident angle of probe beam is varied to measure a one-dimensional potential profile. If the probe beam energy is changed additionally, the observable region is extended and a two-dimensional potential profile can be obtained. In the Large Helical Device (LHD), an HIBP system has been developed to study E_r formation physics [9, 10]. This system has a considerably long beam transport line (~20 m), and thus, it is difficult to change the probe beam energy as many electrostatic deflectors and lenses on the beam transport line must be adjusted to optimize the beam trajectory along the beam transport line. If this beam adjustment is manually performed, 20 - 30 min are required to optimize the beam trajectory, with much time being consumed to adjust the voltages of many electrostatic deflectors. To reduce this adjustment time, a PC-based automatic adjustment system was developed [11]. Using this system, the required time for this optimization has been reduced to under 3 min; therefore, we can easily change the probe beam energy for two-dimensional potential profile measurements. In recent analysis, the two-dimensional phase structures of potential fluctuations were obtained. The detail of the automatic adjustment system and experimental results are presented in this article.

2. HIBP System on the LHD and the Automatic Beam Adjustment System

The detailed principles of the HIBP diagnostics were

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reviewed in Ref. 8, and thus, only a brief explanation is provided here. For the HIBP diagnostics, the primary beam, mostly comprising singly charged ions, is injected into the plasma. The ions of the primary beam are further ionized, and secondary beam of doubly charged ions is created. The secondary beam ejected from the plasma is guided to an energy analyzer to measure its beam energy. Based on the energy conservation law, the energy difference between the injected primary beam and the detected secondary beam corresponds to the plasma potential at the ionization point from the primary to the secondary. Therefore, we can measure the local potential in the plasma by analyzing the energy of the secondary beam. The current intensity of the detected secondary beam reflects the plasma density at the ionization point, although the path integral effect is contained since the beam is attenuated along the beam path. With HIBP, the density fluctuation can be simultaneously measured with the potential fluctuation, which is an advantage for this diagnostics because the particle flux driven by electrostatic fluctuation can be evaluated using the coherence analysis of the density and potential fluctuations.

At the LHD, the required probe beam energy reaches MeV order because the maximum toroidal magnetic field strength is 3 T and the minor radius of the plasma is approximately 0.6 m. We use the tandem accelerator to generate such a high-energy probe beam. This beam is guided from the accelerator to the injection port of the LHD through the beam transport line, which is approximately 20 m in length. A schematic of the LHD-HIBP system is shown in Fig. 1.

The observation point of HIBP, which is called sample volume, is usually varied by controlling the incident angle of the probe beam. This angle is changed by an octupole electrostatic deflector. In Fig. 2, the observation region of the LHD-HIBP is shown. The actual observation points are arranged three-dimensionally; thus, the projections of those points on the vertically elongated cross-section are shown for the ease of understanding. In addition, the part to the right in Fig. 2 shows the projected vertical position Z as a function of the toroidal angle, indicating the actual observation region. When the probe beam energy, E_b, was fixed at 1.176 MeV, the observation point was scanned along the line of 1.176 MeV by changing the incident angle of the probe beam. If E_b is fixed at another value, the observation point is scanned along another line. Therefore, the two-dimensional potential profile can be measured by changing E_b in addition to the beam incident angle.

In the LHD-HIBP system, the length of the beam transport line from the accelerator to the probe beam injection port is approximately 20 m, and we have many electrostatic deflectors and lenses to adjust the beam trajectory along the beam transport line. When E_b is changed, these electrostatic deflectors and lenses must be adjusted. Basically, the voltages of these deflectors are changed in proportion to E_b; however, in the region near the LHD, the

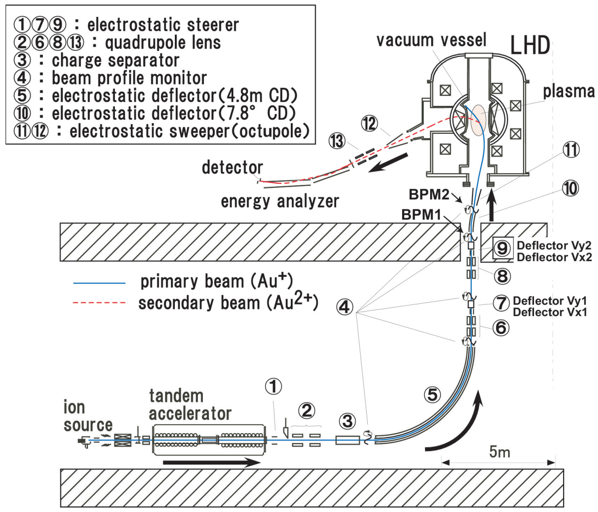

Fig. 1 Schematic of LHD-HIBP system.

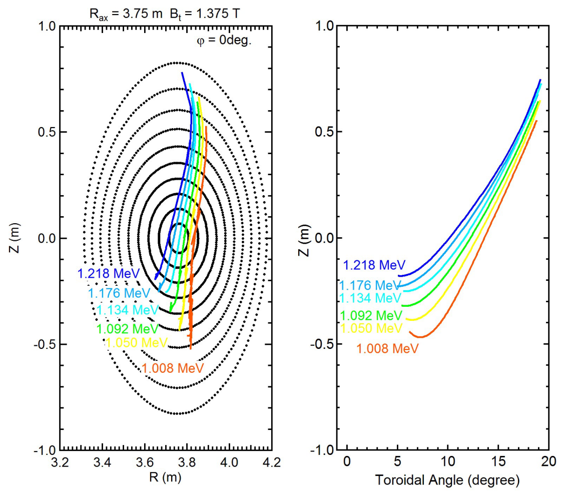

Fig. 2 The observation regions of LHD-HIBP system are shown. The right figure shows the projections of observation regions onto a vertically elongated cross-section whereas left figure shows projected Z as a function of the actual toroidal angle of observation region. Observation point can be scanned along the line of corresponding beam energy by changing the incident angle of probe beam.

leak magnetic field from the LHD influences the beam trajectory and this magnetic field cannot be changed with E_b as its strength is usually fixed. Thus, subtle adjustments are required for electrostatic deflectors in the region near the LHD. To easily adjust the voltages of many high-voltage power supplies, a PC-based automatic adjustment system was developed. The displacements of the probe beam at position i are defined as Δx_i, Δy_i. Here, the x and y axes are orthogonal on the plane perpendicular to the probe beam. The changes in the voltages of the deflector j are defined as ΔV_{xj}, ΔV_{yj}. Basically, the displacements of the beam linearly depend on the deflector voltages; therefore, the following relation can be obtained:

$$\begin{pmatrix} \Delta x_1 \\ \Delta y_1 \\ \Delta x_2 \\ \Delta y_2 \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{pmatrix} \begin{pmatrix} \Delta V_{x1} \\ \Delta V_{y1} \\ \Delta V_{x2} \\ \Delta V_{y2} \end{pmatrix}.$$

In this case, two displacements and deflectors are considered, and for more displacements and deflections, the size of the matrix would need to be enlarged. The matrix A_{ij} represents the transport matrix. Beam displacements on the transport line are measured with beam profile monitors (BPMs), which detect the beam current with helical rotating wires. Raw signals from BPMs are acquired to the PC through the ADC board with a sample frequency of 1 kHz. Beam displacements are analyzed from these raw signals, and the required voltages are calculated to adjust the beam displacements from the center of the beam transport chamber to be zero in all BPMs. The required voltages are calculated using the inverse matrix of A_{ij}, i.e., $\Delta V_j = A_{ij}^{-1}$ $\Delta \boldsymbol{x}_i$. The calculated voltages are applied to high-voltage power supplies through CAMAC DAC modules connected to the PC with the general purpose interface bus (GPIB). One cycle of this adjustment requires a few seconds. This procedure is then repeated until beam displacement at all BPMs becomes less than 1 mm. Visual Basic in the Windows operating system is used to develop the optimization system on the PC. Using this system, the required time for the beam adjustment can be reduced to less than 3 min. In the LHD, the period of the discharge cycle is 3 min; thus, the system enables us to change the probe beam energy E_b between each shot.

3. Experimental Results of Two-Dimensional Potential Fluctuation Measurements

The two-dimensional potential profiles were obtained using the automatic beam adjustment system. For the two-dimensional equilibrium potential profile measurements, experimental results have already been shown in Ref. 11. Here, the experimental results of the two-dimensional potential fluctuation measurements are described.

The parameters of the LHD's magnetic configuration are as follows: the toroidal magnetic field strength B_t is 1.375 T, the major radius of the magnetic axis, R_{ax}, is 3.75 m, the quadrupole component of the magnetic field, B_q, is 100 %, and the pitch parameter, γ, is 1.254. The time evolutions of typical discharge's parameters are shown in Fig. 3. The plasma is produced by balance NBI heating due to NBI#1 (counter-injection) and NBI#2 (co-injection). The short pulse of the ECH is applied with the duration of 4.5 - 4.9 s. At 5.3 s, NBI#1 and #2 are turned off and NBI#3 (counter-injection) is turned on. The line averaged electron density is approximately $0.4 \times 10^{19}\,\mathrm{m}^{-3}$, and the central electron temperature is approximately 1.5 keV. The spectrogram of magnetic fluctuation from the magnetic probe is shown in Fig. 4 (a). Figure 4 (b) is an enlarged graphic of Fig. 4 (a). Although many coherent modes can be observed, we focus on the high frequency mode (~200 kHz) indicated by an arrow in Fig. 4 (b) as

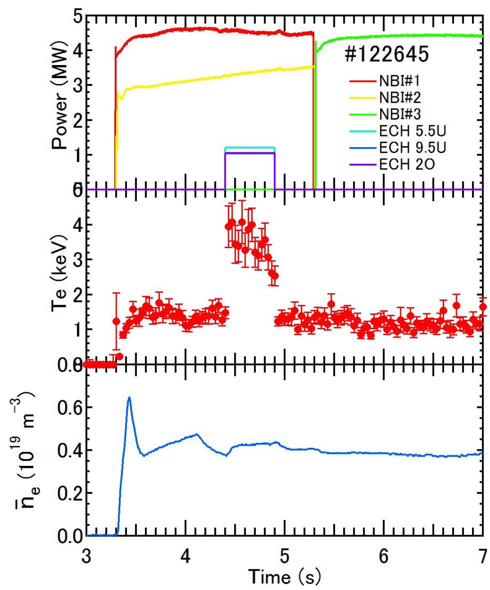

Fig. 3 The temporal evolutions of various heating methods, the central electron temperature, and the line-averaged electron density are shown.

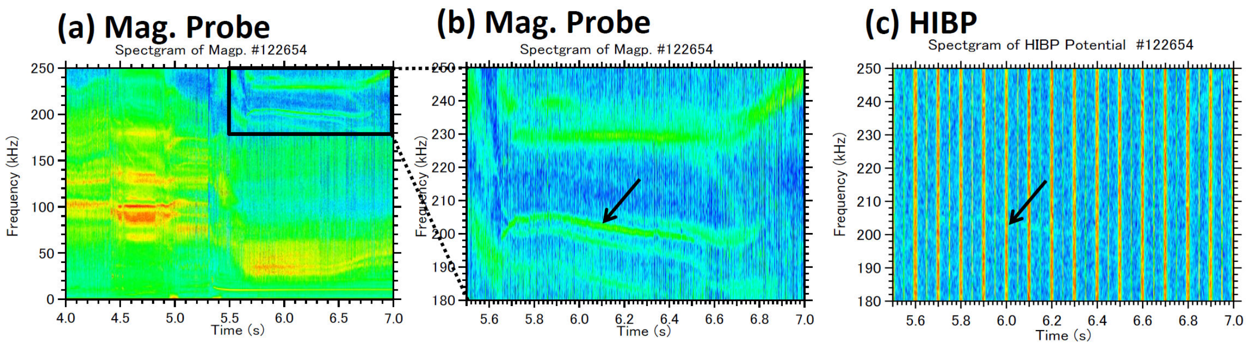

Fig. 4 (a) The spectrogram of magnetic field fluctuation from a magnetic probe, (b) the spectrogram of an enlarged graphic of (a), and (c) the spectrogram of potential fluctuation from the LHD-HIBP system.

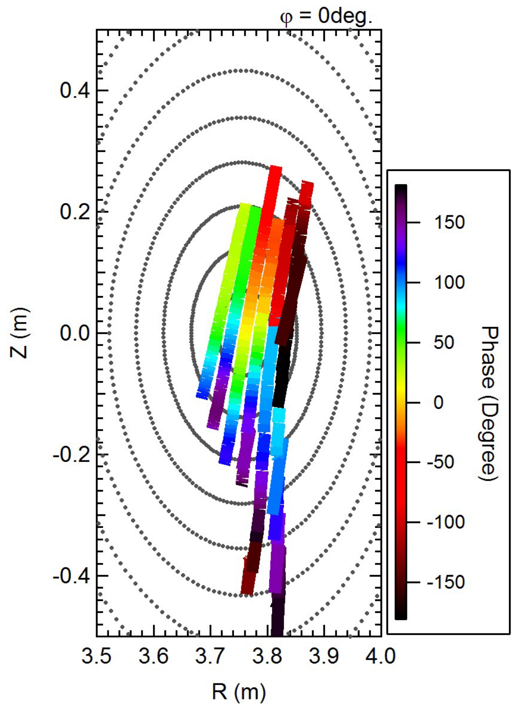

Fig. 5 The two-dimensional phase structure of potential fluctuation with a frequency of approximately 200 kHz. Magnetic surfaces under the vacuum condition are also shown for references.

this mode is observed in the potential fluctuation signal from the HIBP (Fig. 4 (c)). The incident angle of the probe beam is scanned at a frequency of 10 Hz. The potential fluctuation of this mode is localized in the central region of the plasma. From coherence analysis between the HIBP potential fluctuation signal and the magnetic field fluctuation signal (i.e., a reference signal), the two-dimensional phase structures were obtained. To obtain the experimental result, data from six shots were used, with the probe beam energy E_b scanned from shot to shot. In Fig. 5, an experimental result of two-dimensional phase structure is shown with vacuum magnetic surfaces. The reproducibility of the shots was not as expected. However, the poloidal mode number of this fluctuation is considered to be 2. The two-dimensional phase structure of the potential fluctuation was successfully measured with our HIBP system, although the physical aspect of the mode has not been interpreted. In the future, the signal to noise ratio will be improved, and a more detailed mode structure (e.g., the amplitude profile of the potential and density fluctuations) will be analyzed to understand the physical mechanism of this mode.

4. Summary

An automatic beam adjustment system was developed to easily change the probe beam energy in the LHD-HIBP system. Applying this system to the LHD-HIBP system, E_b could be changed within 3 min, which is an interval of time in the LHD discharge cycle. In LHD experiments, E_b was changed from shot to shot and the two-dimensional potential fluctuation structure of a high-frequency mode (~200 kHz) was measured. Coherence analysis between the potential fluctuation and the magnetic field fluctuation signals allowed the two-dimensional phase structure of potential fluctuation to be successfully obtained.

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