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Development of 6 MeV Heavy Ion Beam Probe System on Large Helical Device

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1. Introduction

A heavy ion bam probe (HIBP)[1] is a unique diagnostic technique to measure the electrostatic potential, its fluctuation and density fluctuation directly and simultaneously in high temperature plasmas. Hitherto, HIBPs have been applied for various magnetically confined plasmas and they have obtained significant results related to transport physics in plasmas. The radial electric field is also one of key parameters for the transport in Large Helical Device (LHD). So, we have developed an HIBP for LHD (Figure 1) [2, 3, 4]. The installation of the whole system has been recently completed, and the probing beam was detected and its energy was analyzed successfully. In this paper, the HIBP system and the results of the potential measurement are described.

2. Apparatus of the LHD-HIBP

In principle, the Larmor radius of the probing beam of an HIBP must be comparable with the minor radius of a plasma device. In the case of LHD, since the magnetic field of LHD is up to 3 tesla and the Larmor radius of a few meters is necessary, MeV-range beam of heavy ions is required for the HIBP. In order to obtain such high energy beams, a tandem accelerator is used. An advantage of the accelerator is that the acceleration voltage is required only a half of the final beam energy. In the LHD-HIBP, the acceleration voltage is up to 3 MV and the singly charged positive ions with the energy of up to 6 MeV are extracted.

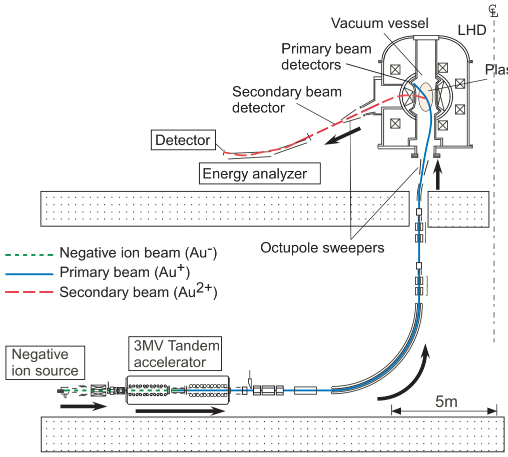

Figure 1 LHD-HIBP

Singly charged gold ions (Au^+) are chosen for the probing beam because the mass is suitable for the HIBP and there are many experienced of gold negative ion beams required in the tandem accelerator. The Au^+ ions are injected into plasma as a primary beam, and doubly

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charged ions (Au^{2+}) ionized on its path due to collision with the plasma are detected (referred to as the secondary beam). Since the energy difference between the primary and the secondary beams is equivalent to the plasma potential where the secondary beam was produced, we can obtain the plasma potential by measuring the secondary beam energy. So far, electrostatic analyzers with parallel plates[6] have been used in HIBPs. This type of analyzer, however, requires unpractical applied voltage (~ 400 kV) for 6 MeV beam. Therefore, we have developed a new analyzer with tandem electrodes[7]. The required voltages can be decreased to 56.5 and 113.6 kV on the 1st and 2nd electrodes for the 6 MeV beam.

One of the predicted difficulties in the LHD-HIBP is that the signal level is quite low, because of the severe attenuation of the probing beam on the long trajectory in plasma. We have employed micro-channel plates (MCPs) as a detector in order to detect the small beam current efficiently. As the results of the development, the secondary beam is detected at the energy analyzer successfully, though the beam current must be integrated for a few milliseconds because of the extremely small secondary-beam current [4]. For the higher temporal resolution, the further development of the negative ion source [5] should be carried out.

The position of the sample volume is determined by the control of the beam trajectory with the octupole sweepers, and it is estimated by using trajectory calculation. Therefore, the verification of the calculation is important. In order to monitor the beam trajectories, we have installed fixed detectors of primary beam with 9 plates on the first wall of LHD and a movable detector of the secondary beam on the beam line between the octupole sweeper and the energy analyzer. Surveying the sweep voltages to detect the beams at the detectors, the calculation does not agree with the experimental results completely. It may be due to the deflection of the probing beam by stray magnetic field of LHD. Thus, in this paper, the estimation of the position of the sample volumes is provisional. Further improvement of the beam transport system and the modification of the trajectory calculation are required.

3. Analysis of the secondary beam energy

The whole HIBP system as a diagnostic tool of the plasma potential has been calibrated. The secondary beam is also produced by the collision with neutral gas in the vacuum vessel. Since there is no electric field in the vacuum vessel without plasmas, the energy of the secondary beam does not change from that of the primary beam. Thus, we can control the probing beam energy by adjusting the acceleration voltage, and the whole HIBP system can be calibrated by using beam with known energy.

Figure 2 shows the results of the energy analysis. The incident energy of the probing beam is scanned, and the energy of the each secondary beam is analyzed. The incident energy is set to 5.042 MeV, 5.045 MeV (+ 3 kV), and 5.046 MeV (+ 4 kV), respectively. The change in the beam energy is analyzed successfully. The error bar in Figure 2, which comes from the signal to noise ratio of the secondary beam signal, is larger than the predicted plasma potential. In the low density plasma ($\leq 1\times10^{19}$ (m^{-3})), however, we will be able to measure the plasma potential with the energy resolution of 200 V or less, because the secondary beam current is at least 10 times larger than that in this calibration experiment.

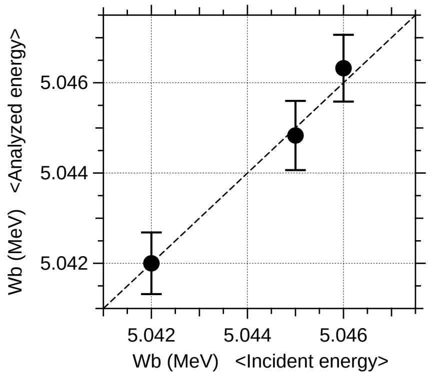

Figure 2 Comparison between the incident and the analyzed beam energy.

4. Potential measurement

The plasma potential has been measured during neutral beam injection (NBI) heating. The magnetic field strength is 2.75 T, and the major radius of the magnetic axis is 3.6 m. The beam energy of the HIBP is set to 5.042 MeV. According to the trajectory calculation, which is provisional as stated above, the potential profile can be measured within the normalized radius (ρ) of about 0.2 during the sweep of the probing beam (Figure 3 (a)).

The waveforms are shown in Figure 3 (b). The plasma is produced by electron cyclotron heating (ECH) and sustained by co- and counter-NBI with the total power of 7.0 MW.

The profiles of the plasma potential are shown in Figure 3 (c). The potential tends to become positive by about 2 kV during NBI. The result suggests that the radial electric field (E_r) of the electron-root is formed predominately in the plasma. The E_r at the plasma edge is measured by charge exchange spectroscopy (CXS), and the positive E_r is observed. The positive potential measured by the HIBP is qualitatively consistent with the positive E_r measured by the CXS. The HIBP measurement is limited around the plasma center because the probing beam is blocked by the vacuum vessel, and the CXS can not measure at the plasma center in this magnetic configuration because of the low emission. Both measurements will be crosschecked quantitatively under a certain condition in future.

A serious problem related to the potential measurement remains. During ECH, the secondary beam profile changes drastically, even though the density and temperature profiles do not change. Judging from the behavior of the secondary beam profile, the probing beam seems to shift, though the sweep voltages are constant. The reason is not understood at present. It must be solved to study the behavior of the potential in the plasma.

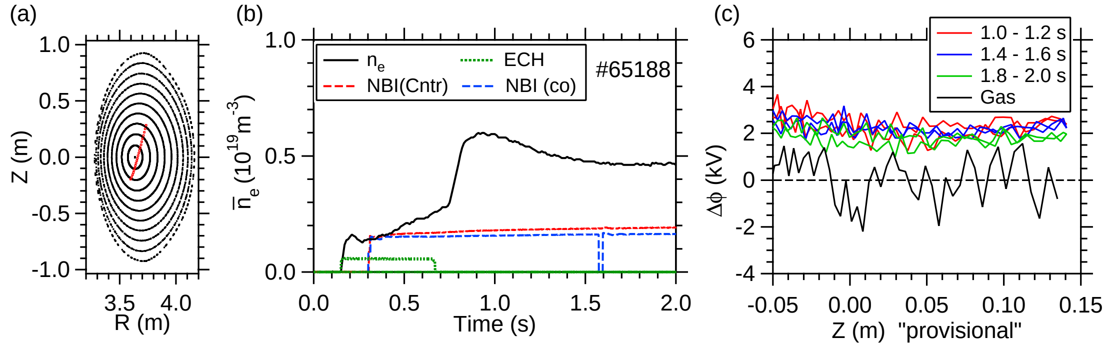

Figure 3 (a)The magnetic surface and the calculated position of the sample volumes(red squares). Note that the calculation is provisional. (b)Line averaged electron density and timing of NBI and ECH. (c)Measured potential profile. The position of the measurement is provisional. The black curve indicated as ”Gas” is the potential of the vacuum vessel.

5. Summary

The 6 MeV HIBP has been installed in LHD. Some components have been developed for using the MeV-range beam. As the results of the development, the secondary beam is detected and the change in the beam energy is analyzed successfully.

The plasma potential in the NBI plasma is measured. The measured potential is consistent with E_r measured by the CXS, qualitatively.

Some issues remain. The trajectory calculation does not agree with the experimental results. And the secondary beam signal shows the strange behavior of the probing beam during ECH. Breaking through the issues is crucial for accurate and flexible measurement.

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