Present Status in the Development of 6 MeV Heavy Ion Beam Probe on LHD

Present Status in the Development of 6 MeV Heavy Ion Beam Probe on LHD

Akihiro SHIMIZU, Takeshi IDO, Masaki NISHIURA, Haruhisa NAKANO, Ichihiro YAMADA, Kazumichi NARIHARA, Tsuyoshi AKIYAMA, Tokihiko TOKUZAWA, Kenji TANAKA, Kazuo KAWAHATA, Hiroe IGAMI, Yasuo YOSHIMURA, Takashi SHIMOZUMA, Shin KUBO, Kenichi NAGAOKA, Katsunori IKEDA, Masaki OSAKABE, Katsuyoshi TSUMORI, Yasuhiko TAKEIRI, Osamu KANEKO, Shinji KATO, Mitsuhiro YOKOTA, Kiwamu TSUKADA, Hideki OGAWA, Akimitsu NISHIZAWA[1)], Yasuji HAMADA and LHD group

National Institute for Fusion Science, Toki, Gifu 509-5292, Japan

[1)]*Tono Geoscience Center, Japan Atomic Energy Agency, Toki, Gifu 509-5102, Japan*

(Received 13 December 2006 / Accepted 6 August 2007)

In order to measure the potential in Large Helical Device (LHD), we have been developing a heavy ion beam probe (HIBP). For probing beam, gold beam is used, which is accelerated by a tandem accelerator up to the energy of 6 MeV. The experiments for calibration of beam orbit were done, and experimental results were compared with orbit calculations. The experimental results coincided fairly with the calculation results. After the calibration of the beam orbit, the potential in plasma was tried to measure with the HIBP. The experimental data showed positive potential in a neutral beam heating phase on the condition of $n_e \sim 5 \times 10^{18}\,\mathrm{m}^{-3}$, and the increase of potential was observed when the additional electron cyclotron heating was applied to this plasma. The time constant for this increase was about a few tens ms, which was larger than a theoretical expectation. In the spatial position of sample volume, we might have an ambiguity in this experiment.

Keywords: potential measurement, heavy ion beam probe (HIBP), Large Helical Device, tandem accelerator

DOI: 10.1585/pfr.2.S1098

1. Inroduction

The radial electric field plays a very important role on transport of toroidal magnetic confinement systems. In recent studies, it was revealed that the shear of electric field, in other words a shear flow, can reduce the correlation length of turbulence in plasma and improve the confinement [1–3]. In helical magnetic configurations, non ambipolar electric field is produced and the particle transport is reduced by it, as is predicted from the neoclassical theory. A stationary state, where the positive (negative) radial electric field is created, is called as the "electron (ion) root" [4]. When the electron root is made in the central region of plasma and simultaneously the ion root is made in the outer region, the strong shear of the electric field can be produced between these different roots. Due to this strong shear of the eclectic field, a transport barrier is created and confinement in the inner region of plasma is improved. This improved configuration was observed experimentally in helical devices such as Compact Helical System (CHS) [5, 6], Large Helical Device (LHD) [7] and other machines [8, 9], which is referred as "internal transport barrier (ITB)" [5–7] or "Core Electron-Root Confinement (CERC)" [10].

In order to study these phenomena in detail in helical devices, measurement of radial electric field is required. Heavy Ion Beam Probes (HIBPs) [11] can directly measure the potential in the inside of high temperature plasma, without any disturbance to plasma. Moreover, a good spatial/temporal resolution can be expected and simultaneous measurement of density fluctuations is also possible, which gives us a function to study particle fluxes caused by electrostatic fluctuations. In LHD, we have been developing an HIBP [12] to study interesting phenomena such as CERC and other issues related to the electric field. In this article, we will report the present status of our HIBP system and recent results of potential measurement in LHD.

2. Heavy Ion Beam Probe in LHD

A schematic view of the HIBP system in LHD is shown in Fig. 1. In order to inject a probing beam to the center of plasma, the Larmor radius of the beam ion must be larger than the minor radius of torus plasma. The toroidal magnetic field strength of LHD reaches to 3 T, therefore the energy of 6 MeV is required for the probing beam of the gold ion (Au^+). To suppress the cost of the high voltage generator, we use a tandem accelerator for our HIBP system on LHD because it can reduce the required voltage to half (3 MV).

For the use of our tandem accelerator, the negative

author's e-mail: akihiro@nifs.ac.jp

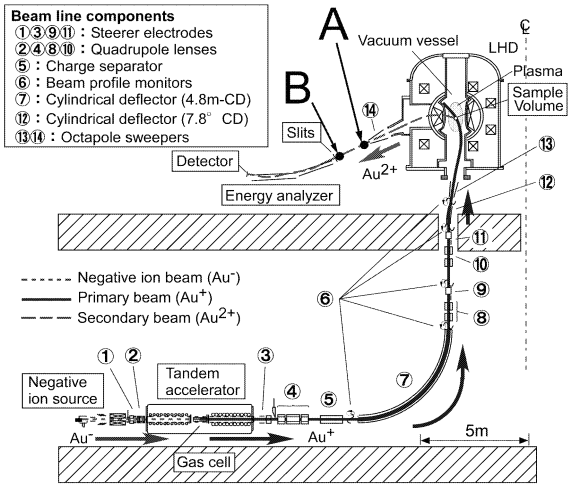

Fig. 1 The schematic view of the Heavy Ion Beam Probe system in LHD.

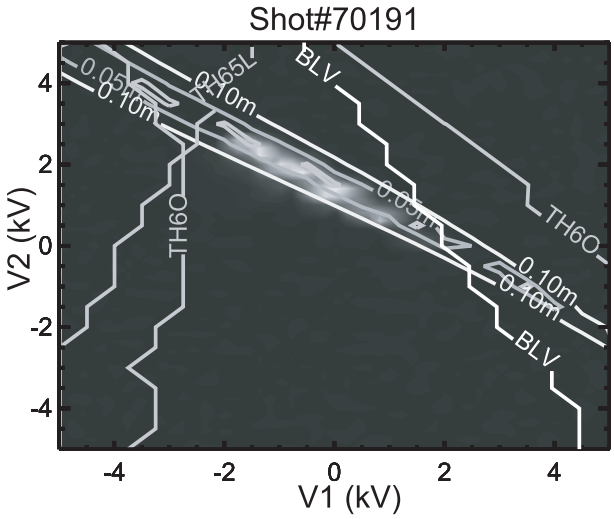

Fig. 2 The dependency of secondary beam current on voltages $V1$ and $V2$ of the injector-side deflector. Lines with notations of "TH65L", "TH6O", "BLV" show limitations on the beam orbit by the port of the injector side, the port of the analyzer side, and the vacuum vessel, respectively. In the outer region of these lines, the secondary beam cannot be observed.

ion beam, Au^-, is injected and accelerated to 3 MeV. At the stripping gas cell located at the center of accelerator, the negative ion (Au^-) is transformed to the single positive charged (Au^+) beam and by the successive acceleration the beam is accelerated to 6 MeV. This beam is guided to plasma through the charge separator (No.5 in Fig. 1), the 4.8 m cylindrical deflector (No.7 in Fig. 1) and the 7.8 degree deflector (No.12 in Fig. 1). The injection angle of Au^+ beam can be changed by the octapole electric deflector (No.13 in Fig. 1). In plasma, ions of Au^+ beam (we call it as primary beam) loose one electron by collisions with plasma, and the Au^{2+} beam (secondary beam) is produced. By the increase of its charge, the total energy of beam increases by the plasma potential energy. The secondary beam from the exit port is guided to the energy analyzer by the another octapole electric deflector (No.14 in Fig. 1) so that the injection angle to the energy analyzer should be an appropriate angle. The energy analyzer has tandem electrodes, by which we can reduce the required voltage to analyze the energy of 6 MeV Au^{2+} beam [13]. If we use a usual Proca-Green type of 30 degree energy analyzer [14], the required voltage reaches to 400 kV, however, our tandem type of energy analyzer needs only 120 kV. For the detector of secondary beam, micro channel plates (MCPs) are used to detect a very small amount of current, a few tens pA. We have been continuing to develop the system of the HIBP and first results of plasma potential measurement was obtained.

3. Calibration of Beam Orbits

In order to check the beam orbit, the signals of the secondary beam at the exit of the analyzer-side octapole deflector (the point A in Fig. 1) and at the entrance of the analyzer (the point B in Fig. 1) were investigated. In these experiments, the beam was injected to neutral gas (which comes from NBI port in the pre-discharge phase) in LHD, and the secondary beam produced by gas scattering was detected. At the first experiment, the injector-side octapole electric deflector (No.13 in Fig. 1) changed the injection angle of beam two-dimensionally: in the radial direction and the toroidal angular direction. The injection angle can be characterized by two voltages of the octapole deflector [15]. These two voltages are expressed as $V1$(toroidal direction) and $V2$ (radial direction) in this paper. If some conditions were satisfied between $V1$ and $V2$, we could detect the secondary beam by the MCP detector located at the point A in Fig. 1. These conditions were compared between calculations and experiments, as shown in Fig. 2. In this figure, the intensity of white corresponds to the intensity of current detected at the point A by the MCP detector, and contour lines are calculated results of the distances between the centers of beam and the detector. Boundary conditions that the beam is limited by diagnostic ports are also shown. The region, where the secondary beam is observed, is within the contour of about 0.1 m in this image. The diameter of MCP detector at the point A is 0.035 m. The maximum width of the secondary beam at the point A was considered to be the order of 0.04 m from the calculation result of the sample volume [16]. Therefore, the beam image should be within the contour of 0.0575 m. However, there is an error in the voltage of the deflector for the fast scan. The voltage of the deflector, $V2$, was swept by 20 cycles per 1 cycle of $V1$ scan, so the error in $V1$ is about 0.5 kV, which corresponds to the distance of 0.05 ~ 0.1 m. Considering this error, the experimental results seem reasonable.

Next, we controlled the injection and exit angle of the

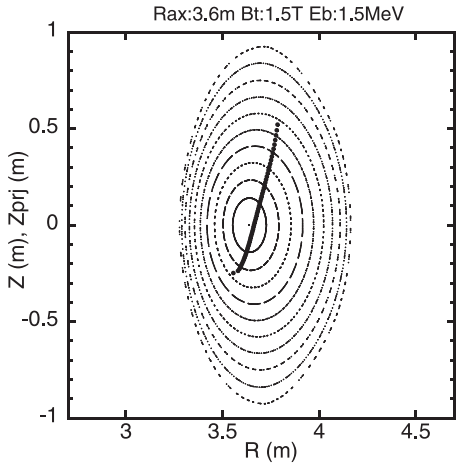

Fig. 3 Magnetic surfaces of LHD in the vacuum and the sample volume positions where we can observe the potential with the HIBP.

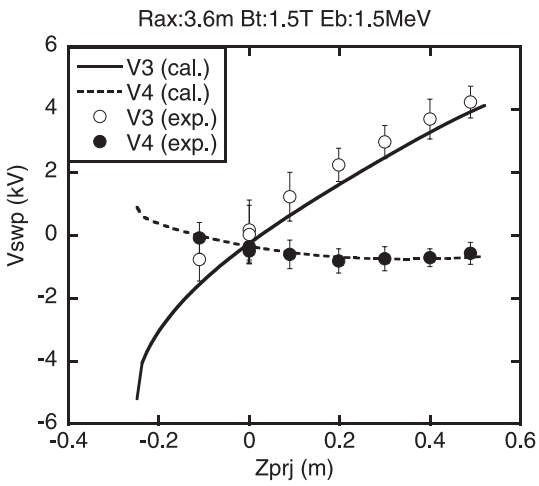

Fig. 4 The condition for voltages of $V3$ and $V4$ to detect the intensive secondary beam current at the entrance of the energy analyzer. The experimental results (open and filled circles) are compared with the calculation.

beam, and investigated the condition so that the secondary beam from the position of sample volume in plasma can be observed. (Here, sample volume means the observation point to measure the potential in plasma with the HIBP, where the transformation of the beam from Au^+ to Au^{2+} occurs due to collisions with plasma.) In Fig. 3, magnetic surfaces of LHD in a vacuum are shown. A configuration of the magnetic field of LHD is characterized by its major radius R_{ax}, the pitch parameter γ, and the quadrupole magnetic field B_q. In our experiment, these parameters were as follows, $R_{ax} = 3.6$ m, $\gamma = 1.254$, $B_q = 100$ %. The strength of the toroidal magnetic field, B_t, was 1.5 T, and the energy of the injected beam, E_b, was 1.5 MeV. Filled circles in the figure are sample volume points where we can measure potential by the HIBP. In this figure, the size of each circle symbol does not correspond to the size of sample

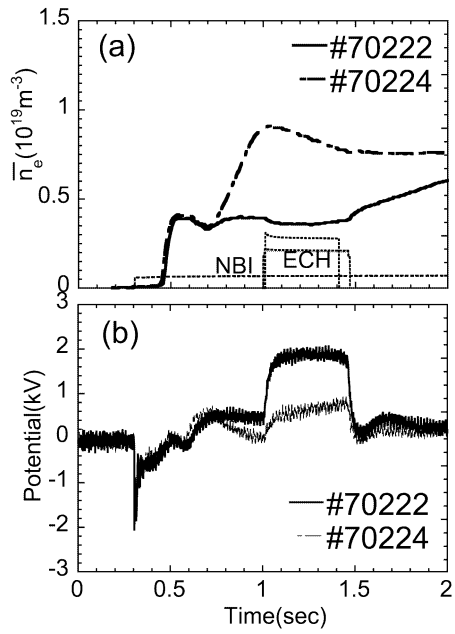

Fig. 5 (a) The time evolution of the density and heating are shown. #70222 is a low density shot. #70224 is a relatively high density shot. (b) Time evolution of potential at the center of plasma measured with the HIBP.

volume and only the position is meaningful. Detail calculation results for estimation of the sample volume size are shown in ref. [16], and a typical size for the width is about 0.04 m. The position of sample volume is characterized by Z_{prj} (m) in this paper. In the next experiment, $V1$ and $V2$ were fixed to observe a sample volume point, and the voltages $V3$ and $V4$ of the analyzer side octapole deflector were changed 2-dimensionally. $V3$ is the voltage supplied to electric plates that produces the toroidally directional electric field, and $V4$ is the voltage that produces the vertically directional field. The condition on which we can obtain the intensive secondary beam at the entrance of the analyzer (the point B in Fig. 1) was compared between the calculation and the experiment. In Fig. 4, the solid and dotted lines are calculation results, which show conditions for $V3$ and $V4$ on which the secondary beam is detectable at the point B, when $V1$ and $V2$ are fixed to observe the sample volume point, Z_{prj}. Open circles and filled circles are results of $V3$ and $V4$ obtained from experiments, respectively. Experimental results coincide fairly with calculation results, although a small amount of discrepancy is seen in the voltage $V3$. This discrepancy may cause the error in the position of sample volume in this experiment.

4. Potential Measurement with the HIBP

After the calibration of the beam orbit, we injected the heavy ion beam to plasma and tried to measure the potential in plasma. The injection angle of the heavy ion beam was fixed to observe the sample volume of $Z_{prj} = 0.0$ m,

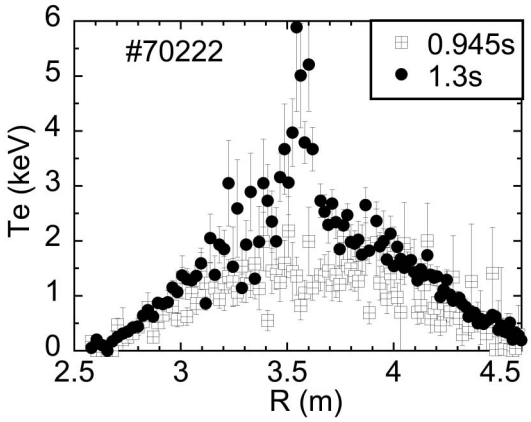

Fig. 6 Temperature profiles of #70222 before ECH and during ECH.

the center of plasma. The plasma was produced by Neutral Beam Injection (NBI), and it was sustained for 3 seconds. Additionally, electron cyclotron heating (ECH) was applied to this plasma. The time evolution of heating and the line averaged density measured with the FIR interferometer is shown in Fig. 5 (a). Additional ECH was applied from 1 to 1.5 sec. In the figure, two signals, which have different density, are shown. In these shots, ITB (or CERC) appeared in the central region of plasma. Figure 6 shows electron temperature profiles of the low density shot measured with Thomson scattering diagnostics at the time of 0.945 sec (before ECH), and at 1.3 sec (during ECH). Taking Shafranov shift into account, the major radius of axis was considered to be in 3.6 m ~ 3.64 m. The averaged electron temperature in the region of R = 3.6 m ~ 3.64 m was 1.4 ± 0.6 keV before ECH and 4.2 ± 0.9 keV during ECH. Potential of these shots measured with the HIBP is shown in Fig. 5 (b). The potential was negative before 0.7 sec, and after that it became positive. When ECH was applied, potential rapidly increased. In the low density case, potential before ECH was 0.4 kV, and 1.8 kV during ECH. A typical time constant of the potential increase was 24 ms, which is large compared with a theoretical prediction, an order of 10 ~ 100 μs [5, 6]. In order to compare our experimental data with a theoretical calculation in detail, we need an estimation based on the neoclassical theory. The temporal evolution of electron temperature obtained from ECE measurements [17] will be helpful for the cross check of our HIBP measurements, so the comparison with this will be done in the future.

In profile measurement of potential with the HIBP, a clear peaked profile of ITB structure could not be observed in these shots. A possible reason is that the sample volume point (observation point) of the HIBP might not be the plasma center due to the slight error in the control of the beam orbit and the potential at the inner region of ITB might not be measured. As described above, in Fig. 4 the small discrepancy between experiments and calculations can be seen in the deflector voltages to observe the potential at the sample volume point, $Z_{prj} = 0$ (the center of plasma). Another possible reason is the Shafranov shift. Although it is only 0.04 m for our experiments because of small beta (~0.5 %), it may make an effect on our HIBP measurement.

5. Summary

We have been developing the HIBP system to measure the plasma potential in LHD. We tried to measure the potential and obtained data of the ECH applied plasma, in which a rapid increase of potential was seen. However, we did not obtain reliable potential data for following reasons, such as insufficient beam calibration and effect of Shafranov shift. For more precise measurements of the potential with the HIBP, more strict calibrations of beam orbits and evaluation of equilibrium are required. In order to theoretically estimate the potential in the ITB, the calculation based on the neoclassical theory including Thomson scattering data is needed, and the comparison between theory and experimental data is a future issue. Other measurements, such as ECE, will be helpful to check the reliability of our experimental data in the ITB plasma.

Acknowledgements

This work was supported by NIFS under contract NO. NIFS06ULBB505-507.

[1] A. Fujisawa *et al.*, Rhy. Rev. Lett. **93**, 165002 (2004).
[2] A. Fujisawa *et al.*, Plasma Phys. Control. Fuision **45**, R1 (2003).
[3] K.H. Burrell, Phys. Plasmas **4**, 1499 (1997).
[4] M. Wakatani, "Stellerator and Heliotron Devices", Oxford.
[5] A. Fujisawa *et al.*, Rhys. Rev. Lett. **79**, 1054 (1997).
[6] A. Fujisawa *et al.*, Phys. Plasmas **7**, 4152 (2000).
[7] Y. Takeiri *et al.*, "Formation of electron Internal Transport Barrier and achievement of high ion temperature in Large Helical Device", IAEA, 2002.
[8] F. Castejon *et al.*, Nucl. Fusion **42**, 271 (2002).
[9] H. Maasberg *et al.*, Phys. Plasmas **7**, 295 (2000).
[10] M. Yokoyama, H. Maasberg, K. Ida, C.D. Beidler *et al.*, "Core Electron-Root Confinement (CERC) in Helical Plasmas", IAEA, 2006.
[11] T.P. Crowley, IEEE Transactions on Plasma Science **22**, 291 (1994).
[12] T. Ido *et al.*, Rev. Sci. Instruments **77**, 10F523 (2006).
[13] Y. Hamada *et al.*, Rev. Sci. Instruments **68**, 2020 (1997).
[14] G.A. Proca, T.S. Green, Rev. Sci. Instruments **41**, 1778 (1970).
[15] A. Fujisawa, H. Iguchi, S. Lee, T.P. Crowley, Y. Hamada, S. Hidekuma and M. Kojima, Rev. Sci. Instrum. **67**, 3099 (1996).
[16] T. Ido *et al.*, "Spatial resolution of the heavy ion beam probe in LHD", this conference.
[17] T. Shimozuma, S. Kubo, H. Idei *et al.*, Nucl. Fusion **45**, 1396 (2005).