The development of potential measurements with 6 MeV Heavy Ion Beam Probe on LHD

A. Shimizu, T. Ido, M. Nishiura, H. Nakano, S. Ohshima, I. Yamada, K. Narihara, T. Akiyama, T. Tokuzawa, K. Tanaka, K. Kawahata, H. Igama, Y. Yoshimura, T. Shimozuma, S. Kubo, K. Nagaoka, K. Ikeda, M. Osakabe, K. Tsumori, Y. Takeiri, O. Kaneko, S. Morita, M. Goto, M. Yokoyama, S. Kato, M. Yokota, K. Tsukada, H. Ogawa, T. Inoue, A. Nishizawa[1)], Y. Hamada and LHD Group

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

1)Tono Geoscience Center, Japan Atomic Energy Agency, Izumi-cho, Toki, Gifu,509-5102, Japan

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In order to measure the potential in Large Helical Device (LHD), 6 MeV heavy ion beam probe (HIBP) has been developed. The temporal evolvements of potential in the central region of plasmas, which were produced by neutral beam injection (NBI) and additionally heated by electron cyclotron heating (ECH), were measured with our HIBP system. The line averaged density of these shots were about $1 \sim 5 \times 10^{18}$ m^{-3}. At the time of ECH was applied, a rapid change of potential to positive direction was observed. In this ECH phase, negative pulses were observed in the potential signal, which were very similar to "pulsation" that was firstly found in Compact Helical System (CHS), however, the time constant of these pulses were larger than in the case of CHS. In the NBI phase, the fluctuation was observed with HIBP, of which frequency was correlated with potential of equilibrium. It is considered that this frequency was influenced by $E \times B$ drift.

Keywords: Heavy Ion Beam Probe, Large Helical Device, helical system, plasma potential, electric field, Internal Transport Barrier

1. Inroduction

In helical magnetic configurations, fluxes are not intrinsically ambipolar and the radial electric field is produced [1, 2]. In the neoclassical theory, the constraint that the ion and electron fluxes be equal determines the radial electric field. The theory gives two roots, so called "ion root" and "electron root". By the strong core heating by ECH, the internal transport barrier (ITB) / the core electron-root confinement (CERC) [3], which is an improved confinement mode, has been realized in various helical devices [4-7]. The study of radial electric field and transport of ITB has been continued in these machines. In order to investigate the physics of ITB in detail, we have been developing heavy ion beam probe (HIBP) system in large helical device (LHD) [8, 9].

By using HIBP, the potential in the inside of high temperature plasma can be measured with good spatial and temporal resolutions, without any disturbances to plasma. Moreover, density fluctuation can be measured simultaneously with potential fluctuation. Therefore flux caused by electrostatic fluctuation can be estimated experimentally. In this article, we will report the present status of HIBP system and recent results of potential measurements in LHD.

2. Heavy Ion Beam Probe System in LHD

Heavy ion beam probe diagnostics is based on the energy conservation low. A beam of single charged heavy ion is injected to plasma and the beam of doubly charged ion arises by the collision with plasma. The energy of the beam of doubly charged ion coming from plasma is measured in the outside. The change of energy between singly charged ion and doubly charged ion corresponds to potential at the ionized point. In order to inject heavy ion beam to the center of LHD plasma, the acceleration energy of 6 MeV is needed for the probing beam of Au^+ when toroidal magnetic field strength is 3 T. In our HIBP system, to reduce the required voltage of accelerator, we use a tandem accelerator and decrease the required voltage to be half (3 MV). In order to use tandem accelerator, negative gold ions (Au^-) are needed. Au^- ions are produced by an ion source of sputtering type. Detail of our negative ion source system is shown in Ref. [10]. The Au^- extracted from this ion source is pre-accelerated up to 50 keV. It is injected to tandem accelerator and accelerated by the voltage of 3 MV. In

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

the gas cell located at the center of the accelerator, Au^- ion is stripped two electrons, and changed to positive gold ion (Au^+). Au^+ is re-accelerated by the voltage of 3 MV, so the 6 MeV Au^+ beam is obtained. This beam is guided to plasma through several components: a charge separator, the 4.8 m cylindrical deflector, the 7.8 degree deflector. At the incident port, the beam incident angle can be changed by octapole deflector, by which the observation point is controlled. Injected Au^+ is stripped an electron by the collision with plasma, and Au^{2+} beam is produced. Here, we call the former the primary beam, and the latter the secondary beam. At the exit port of chamber, the ejection angle of the secondary beam is controlled by another octapole deflector to direct the beam to the energy analyzer. We have 3 slit holes at the entrance of this analyzer, so the potential of neighboring 3 points in plasma can be measured. For the energy analyzer, we apply the tandem energy analyzer [11] to suppress the required voltage and costs. For detecting beam, high gain detector, micro channel plates (MCPs) are used, by which a very small amount of secondary beam current, order of a few pA, can be detected. Detail of our HIBP system is shown in Ref. [8,9].

3. Potential measurements of internal transport barrier

As described above, strong core heating with electron cyclotron heating (ECH) produces an improved confinement region, ITB, which is related to an electron root. Temporal evolution of density and heating, when ITB was observed in LHD, are shown in Fig. 1 (a). The plasma was produced by neutral beam injection (NBI) heating, and ECH was applied at the time of 1 sec. In the figure, two shots which had different density are shown. The configuration of LHD is characterized by the strength of toroidal magnetic field, B_t, the major radius of magnetic axis, R_{ax}, the pitch parameter γ, and the quadrupole magnetic field B_q. In this experiment, these parameters were as follows: B_t = 1.5 T, R_{ax} = 3.6 m, γ = 1.254, B_q = 100 %. The acceleration energy of beam was 1.5 MeV. Temporal evolutions of potential at the center of plasma measured with HIBP are shown in Fig. 1 (b). At the beginning of discharge, the potential was negative. When the additional ECH was applied, the abrupt increase of potential was observed. It is considered that this positive potential was generated by the creation of ITB in the central region. Temperature profiles with Thomson scattering diagnostics before and during ECH are shown in Fig. 1 (c), low density case, and (d), high density case. High temperature region in the core was due to the creation of ITB. The increase of temperature in the low density case was larger than in the high density case. The ratio of temperature increase between high density case and low density case coincides with the ratio of potential increase between these two cases.

4. Fast temporal change of potential

When the ITB appears and multiple states of electron and ion root are allowed, the bifurcation phenomenon can be seen and the fast change of potential is observed. When plasma parameters satisfied some condition, the negative pulses were observed in the potential. In Fig. 2, the observed signal measured with HIBP is shown. This signal is very similar to the pulsation which was firstly found in Compact Helical System (CHS) [12]. The pulse was repeated about a few ms. The typical time constant of the pulse was 90 μs at the potential drop phase and 500 μs at the returning phase as shown in Fig 3. These are

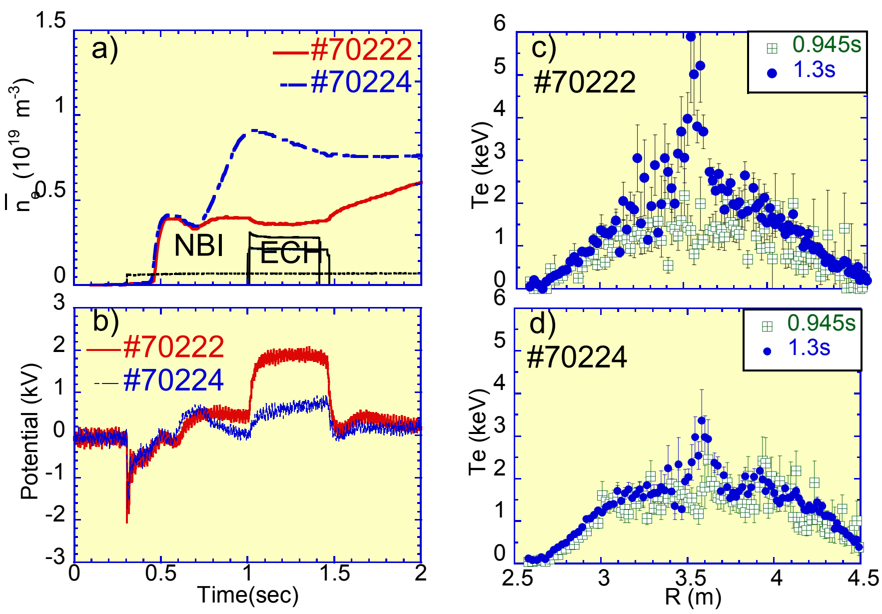

Fig.1 (a) Temporal evolutions of line averaged density and heating. (b) Temporal evolutions of potential measured with HIBP. (c) Temperature profiles of low density case (#70222), and (d), high density case (#70224).

larger than in CHS. This time constant is determined by the neoclassical theory, we will compare this experimental result with the theoretical prediction in a future.

The plasma parameters, in which the ITB and negative pulses were observed, are compared with the neoclassical theory as shown in Fig. 4. In the theoretical estimation, the electron and ion temperature profiles are assumed as $T_{i,e}(0)$ ($1 - \rho^2$). And density profile is assumed as $n_e(0)$ ($1 - \rho^8$). Here, ρ is a normalized minor radius. From the neoclassical theoretical prediction, T_i - T_e space is separated to three regions, in which ion root, electron root and multiple roots are expected. In the figure, boundary lines of these domains are shown. Points show the experimental data, when negative pulses were observed with ITB, no negative pulses with ITB, and no ITB was observed (NBI phase、L-mode). In NBI phase, the parameters exist in the ion root region. The pulses were observed in the region of the multiple roots. As shown in Ref. [12], the pulses are considered to occur in the region of multiple roots, so the experimental results

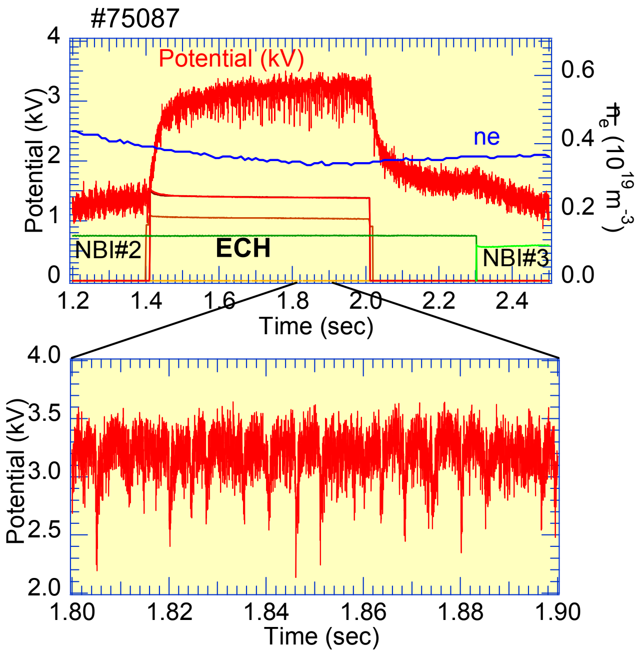

Fig.2 Negative pulses were observed in potential signal measured with HIBP.

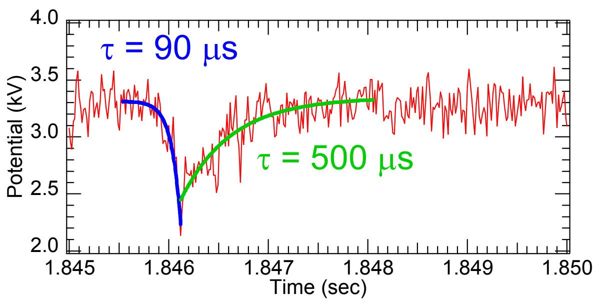

Fig.3 .Time constant of potential change is shown.

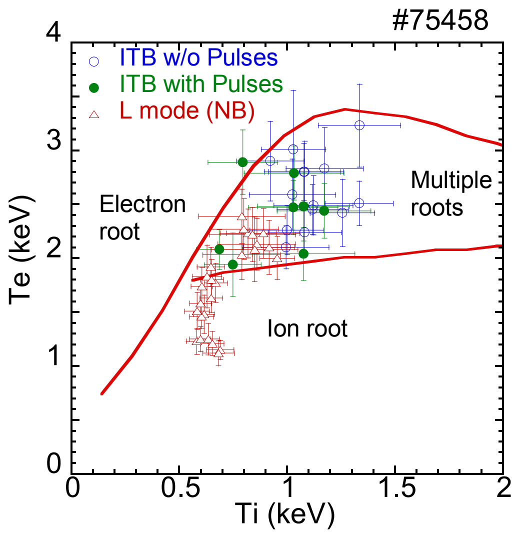

Fig.4 Electron temperature T_e and ion temperature T_i are compared with the neoclassical theory. Boundary lines separate T_i - T_e space to three domains, electron root, ion root, and multiple roots. Negative pulses in potential were observed in the region of multiple roots.

in LHD are consistent with the neoclassical theory.

4. Fluctuation measurements with HIBP

HIBP has a good temporal/spatial resolution in the measurements, so if large S/N ratio is realized, the physics related to various fluctuations, such as MHD instability and micro instability, can be studied with this tool. With HIBP, the measured fluctuation of potential is local one, so interpretation is easy. However the density fluctuation measured with HIBP includes an effect of fluctuation on the beam path as well as at the observed point, due to so called "path integral effect". This effect in LHD is considered in Ref [13] in detail, so we do not discuss about it here.

In Fig. 5 (a), the temporal evolution of potential fluctuation spectrum measured with HIBP in LHD is shown. The vertical axis shows frequency and the color in the image shows power density of potential fluctuation. The fluctuation, of which frequency was changed temporally, can be seen in this figure. In Fig. 5 (b), the wave forms of line averaged density and heating are shown. The frequency of fluctuation has a weak correlation with density, however it is not clear. The frequency correlates more strongly with potential rather than density. In Fig. 5 (c), the temporal evolution of frequency, at which the fluctuation power density has maximum, is shown. The measured potential in the central region of plasma is also shown. The temporal changes of these signals are very similar except the slight time delay in the change of frequency at 0.75 sec. It seems that the rotation of $E \times B$ drift makes an effect on the frequency of fluctuation. The slight difference seen in Fig. 5 (c) may occur from the difference between the potential and electric field. In order to make clearer this effect, we need to measure a radial electric field, namely radial profile of potential. However, the profile could not obtain with a reliable accuracy because of the problem of diagnostics. The temporal character of current amplifier was also slow in this experiment. The improvement of the amplifier and the improved measurements of profile will be done in a near future.

5. Summary

In LHD, heavy ion beam probe system has been continued to develop. The temporal evolution of potential, when ITB was created by ECH, was measured with our system. The rapid increase of potential was observed in ECH phase. The fast negative pulses were observed in potential signal in ECH phase. It was very similar to pulsation, which was firstly found in CHS. The plasma parameter region, in which these pulses were observed, coincides with the region where multiple roots are predicted from the neoclassical theory. The fluctuation of potential, of which frequency changed temporally, was observed. This frequency was considered to correlate with $E \times B$ flow.

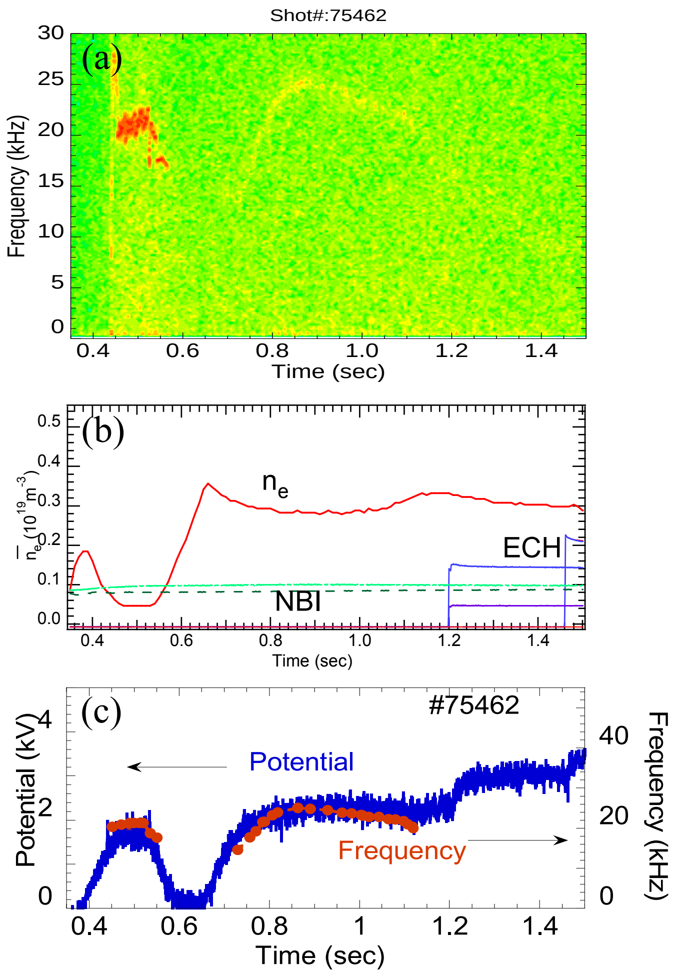

Fig.5 (a) Temporal evolution of spectrum of potential fluctuation measured with HIBP. (b) Line averaged density and heating. (c) Temporal evolution of potential and frequency where fluctuation power density has maximum.

Acknowledgements

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