Calibrations of Fast Ion Flux Measurement Using a Hybrid Directional Probe

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A hybrid directional probe method both “thermal and Langmuir probe” was applied for fast ion measurements in the compact helical system. In order to obtain absolute values of fast ion density and power density, a calibration of the probe was performed using neutral hydrogen beam and a mixture beam of hydrogen and proton, of which beam current and energy were controlled. The conversion factor from temperature increase of the probe head to local power density and secondary electron emission yield was obtained. The density of fast ions was obtained by directional thermal probe (DTP) method inside the last closed flux surface, and the density ratio was $n_{\mathrm{FastIon}}/n_{\mathrm{BulkPlasma}} = 2.7 \times 10^{-3}$ at $r/a = 0.9$. The observation of the directional Langmuir probe (DLP) method is consistent with the DTP results.

Keywords: directional probe method, directional thermal probe, directional Langmuir probe, fast ion measurement, heat flux, particle flux

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1. Introduction

Fast ion confinement is one of the most important issues for fusion burning plasmas such as the international thermonuclear experimental reactor (ITER). The fast ion transport is significantly enhanced by fast-ion-driven MHD activities, such as Alfven eigenmodes (AEs) and energetic particle modes (EPMs). So far, the excitation mechanism and interaction with fast ions of fast-ion-driven MHD modes have been strongly studied [1–3]. The various types of AEs were observed in many tokamak and helical plasmas [4–7], of which frequency and mode location were explained by structure of the shear Alfven continuous spectra. EPMs have frequencies in range of characteristic fast ion frequencies such as transit, bounce and precession frequencies, which are lower than gap frequency of the shear Alfven continuous spectra [8]. The excitation of EPMs depends on fast ion pressure profile. The experimental observation of energetic-particle profile is important to understand the excitation mechanism of EPMs. Moreover, the experimental observations of interaction properties of fast ions with AEs and EPMs are also important because fast ion transport phenomena due to fast-ion-driven MHD modes and nonlinear phenomena such as frequency chirping, intermittent burst are not fully understood yet [9].

In order to observe fast ion profile and interaction properties between fast ions and fast-ion-driven MHD modes, a directional probe method of both thermal probe and Langmuir probe are proposed in this paper. The directional thermal probe (DTP) can observe local power density of fast ions, and the directional Langmuir probe (DLP) method can observe local behaviors of fast ions such as transport properties and interaction with MHD activities. The directional probe method and experimental setup are presented in section 2 and 3, respectively. The calibration of the hybrid directional probe (HDP) and demonstration of fast ion measurements are presented in section 4.

2. Directional Probe Method

In general, a directional probe method is often utilized for a plasma flow measurement [10–14]. The difference of probe signals measured by two probe channels facing opposite direction each other includes information of asymmetric distribution function of the plasma such as particle drifts, electron and/or ion beam, heat flux, and so on. When a flux, for example, particle flux, exists in a plasma, probe signals measured by the channel whose head facing to the flux, Q_{a}, and facing to the opposite direction, Q_{b}, are given by

$$Q_{\mathrm{a}} = Q_{\mathrm{bl}} + Q_{\mathrm{f}} \quad (1)$$

$$Q_{\mathrm{b}} = Q_{\mathrm{bl}} \quad (2)$$

where Q_{bl} and Q_{f} are probe signal coming from the bulk plasma and the flux component, respectively. Thus the flux component is obtained by

$$Q_{\mathrm{f}} = Q_{\mathrm{a}} - Q_{\mathrm{b}}. \quad (3)$$

Here, we consider two applications of the directional

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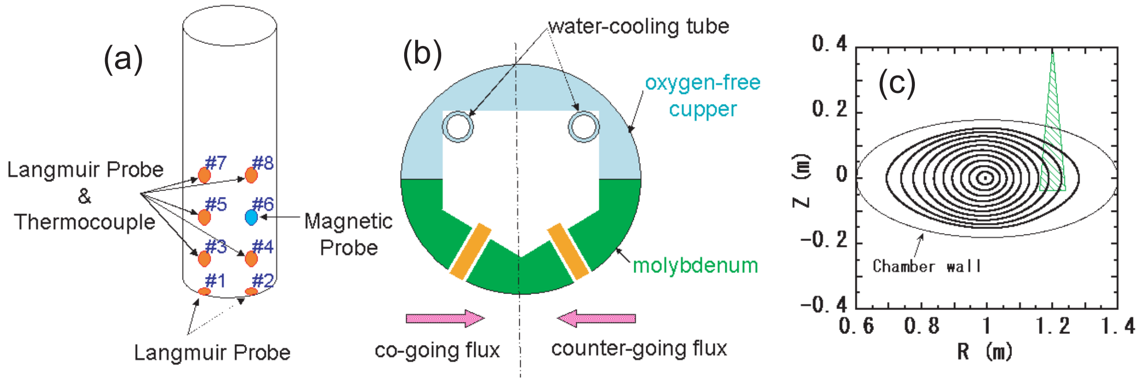

Fig. 1 Schematics of (a) the probe array on the hybrid directional probe, (b) cross-section of the HDP, and (c) the magnetic surface of outward-shifted configuration with $R_{ax} = 0.974$ m and scannable area of the HDP in a horizontally elongated cross-section of CHS.

probe method to a torus plasma heated by tangentially co-injected neutral beam (NB) in order to experimentally examine local behaviors of fast ions. One is power density measurement with thermal probe method, and the other is fast ion current measurement with Langmuir probe.

3. Experimental

A HDP was used for fast ion measurement in NB heated plasmas. The schematic of the HDP is shown in Fig. 1-(a) and (b). Seven Langmuir probes and one Mirnov coil were installed in each 20 mm interval in horizontal and vertical directions, and the five probe heads of them (#3-#5, #7-#8) include thermocouple to measure local power density in plasmas. The channels of odd numbers face to co-going flux and those of even numbers to counter-going one. The probe heads were made of tungsten for #1-#2 and oxygen-free-cupper for #3-5, and #7-8. The half-side of probe body facing to the plasma was made of molybdenum and the other side was of oxygen-free-cupper. The cooling water tube was installed and remove heat load during the interval of plasma discharges. The strong heat resistance makes this probe possible to measure fast ions in NB heated plasmas inside of the last closed flux surface (LCFS). The probe bias can be controlled by a bi-polar DC power supply (−120 V∼ +120 V, 2 A). The time and spatial resolutions of DLP measurement are 1 μsec and 4 mm, respectively, however the time resolution of the DTP is order of 100 msec, which is comparable with the plasma duration.

Our experimental stage is the compact helical system (CHS), which is a helical device with poloidal and toroidal periods of $m = 2/n = 8$, respectively [15]. The HDP was installed by a two-dimensional probe drive in the outboard side of horizontally elongated cross-section in CHS, and the scannable area is shown in Fig. 1-(c). In CHS, two NB injectors with beam power of 1 MW each were installed tangentially. The beam energy is 40 keV for BL1 and 30 keV for BL2. The shine-through beam injected by BL2 attacks the HDP, so the beam of BL2 without plasma discharges was utilized for probe calibration, which is presented in next section. Only BL1 was utilized for plasma heating in this experiment because the beam of BL1 can not attack directly the HDP.

4. Results and Discussions

4.1 Experimental calibration of the HDP

The calibrations of absolute value of power density and fast ion current are required for quantitative measurement of fast ions. In particular, the secondary electron current due to fast ion impact on metal surface may not be neglected for fast ion current measurement. The negative bias of −120 V makes secondary electrons escape from probe surface, and the secondary electron current is counted as the probe current. For the calibration of the HDP, a NB and a mixing beam (neutral hydrogen and proton), of which local powers on the probe were estimated by beam profile, were measured by the HDP. The temperature of the probe head increases depending on total power of the beam, which is shown in Fig. 2. The linear relation was obtained clearly and the conversion factor from the temperature increase to energy is 0.855 J/degree.

The probe current with the probe bias voltage of −120 V was measured. For the H beam case, the probe current I_p is proportional to NB current attacking the probe surface I_{NB}, which is shown in Fig. 3-(a), where the intensity of NB was expressed by the unit of ampere estimated as a single-charged beam. The secondary electron yield obtained for neutral hydrogen beam is 1.8 ± 0.4. The difference of probe currents between neutral hydrogen beam case and mixture beam case corresponds to the probe current produced by the proton beam, which includes the proton beam current and secondary electron current due to the proton impacts. This current was compared with the estimated proton current obtained by the neutralization efficiency of 60 % of the BL2, which is measured by the thermal probe method using this HDP. The secondary electron

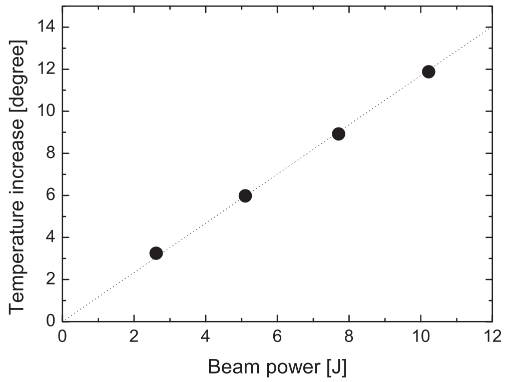

Fig. 2 The temperature increase as a function of neutral hydrogen beam total energy attacking the probe head. The energy scan was obtained by changing pulse duration.

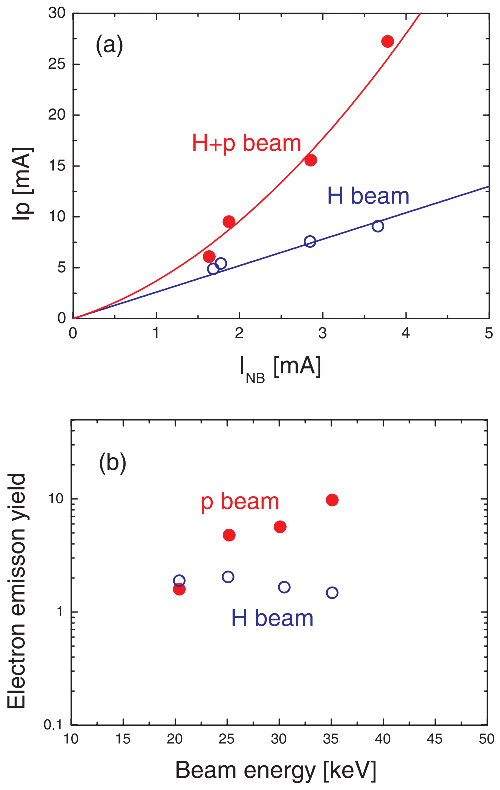

Fig. 3 (a) The probe current as a function of neutral hydrogen current attacking the probe surface. The beam energies are 20-35 keV in this experiments. (b) The yield rate of secondary electron emission for hydrogen atom and proton, evaluated by plots in the figure of (a).

emission yield for proton beam was obtained as a function of beam particle energy, which is shown in Fig. 3-(b).

In this calibration analysis, the energy of the neutral hydrogen and proton beams assumed to be monochromatic beam, that is, only full energy component. The proton ratio of BL2 is almost 85 %, which is obtained by a beam emission spectroscopy. The uncertainty originated by this assumption is considered to be about 25 %.

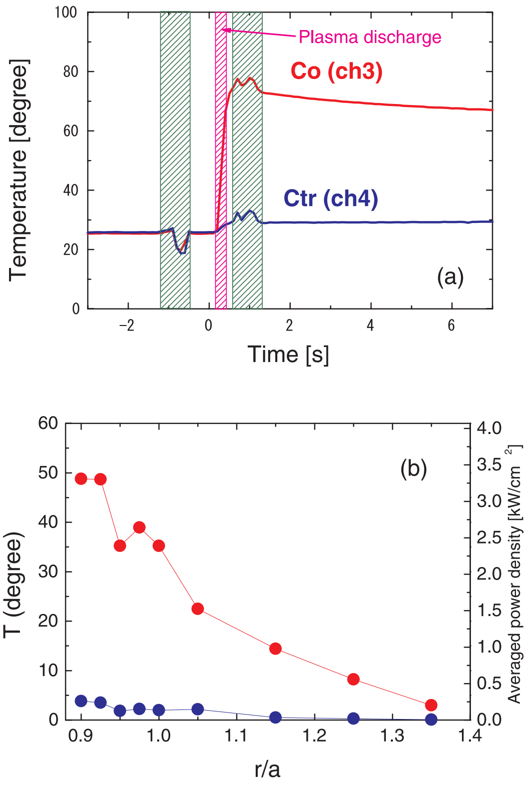

Fig. 4 (a) The time trace of probe head temperature, and (b) the temperature increase as a function normalized minor radius.

4.2 Directional thermal probe method

The fast ion measurement using DTP method was performed in NB heated plasma in CHS. The time traces of temperature of the probe head facing to co- (#3) and counter-fluxes (#4) are shown in Fig. 4-(a). The significant increase of temperature was observed in #3 (co), while that was very small in #4 (counter), which indicates the fast ion component of power density is much larger than that of the bulk plasma. The ramping up and down phases (green hatching in Fig. 4(a)) of the coil currents producing magnetic field of plasma confinement made a noise in temperature measurement, so the temperature increase was estimated by the difference between $t = 0$ sec and $t = 0.58$ sec, which are initial and last periods of flat top of the magnetic field strength (The same procedure was utilized in estimation of temperature increase shown in Fig.3). The profiles of power density measured by #3 (co) and #4 (counter) channels are shown in Fig. 4-(b). The power density averaged during the plasma discharge was estimated by calibrated conversion factor, area of probe surface and plasma duration, which is shown in right-hand side axis in Fig. 4-(b). If the particle energy of fast ions can be assumed to be 40 keV, the fast ion density at $r/a = 0.9$ is $n_{\mathrm{FastIon}} = 1.6 \times 10^{16}\,\mathrm{m}^{-3}$, and the density

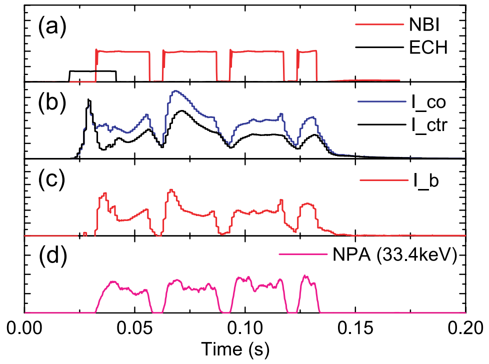

Fig. 5 The time trace of (a) electron cyclotron and NB heating, (b) probe currents of #3 (co) and #4 (counter), (c) fast ion flux estimated by DLP method and (d) neutral particle flux with the energy of 33.4 keV measured by NPA.

ratio is $n_{\mathrm{FastIon}}/n_{\mathrm{BulkPlasma}} = 2.7 \times 10^{-3}$. The beam pressure is $\beta_{\mathrm{FastIon}} = 0.014\,\%$, while the pressure of the bulk plasma is $\beta_{\mathrm{BulkPlasma}} \sim 0.026\,\%$, where the density and temperature of bulk plasma at $r/a = 0.9$ are assume to be $n_{\mathrm{BulkPlasma}} = 6 \times 10^{18}\,\mathrm{m}^{-3}$ and $T_{\mathrm{e}} = T_{\mathrm{i}} = 100\,\mathrm{eV}$, respectively. The passing fast ions in the plasma is distributed inside of $r/a = 1.05$, and power density outside of $r/a = 1.05$ is considered to be dominated by prompt loss and orbit loss components. In the parameter regime of this discharge, fast-ion-driven MHD modes are often excited. The DTP result supports our understanding in previous experiments that fast-ion-drive MHD modes can be excited by fast-ion beam pressure comparable to the bulk plasma pressure [3, 6].

4.3 Directional langmuir probe method

The fast ion current measurement was performed in a modulated NB heated plasma [16]. The NB was modulated by switching on and off. The difference of probe current between #3 facing to co- and #4 facing to counter-going flux were produced by the fast ions (including secondary electron current due to fast proton impact), and is shown in Fig. 5-(c). The DLP result agrees well with the observation of neutral particle analyzer (NPA), which is shown in Fig. 5-(d). The fast ion and bulk plasma densities are estimated using the calibrated secondary electron emission yield (~ 10 for 40 keV), $n_{\mathrm{FastIon}} = 2.2 \times 10^{16}\,\mathrm{m}^{-3}$ for fast ions with the energy of 40 keV and $n_{\mathrm{BulkPlasma}} = 6 \times 10^{18}\,\mathrm{m}^{-3}$, respectively. This observation was carried out at $r/a = 0.84$, thus this results are consistent with the thermal probe observation. The consistency implies that secondary electron emission yield is not so sensitive to the surface circumstance, in vacuum or plasma, and the experimental calibration of the secondary electron emission yield is useful for the plasma experiments.

5. Conclusion

A calibration was performed for quantitative measurement of fast ions using DTP and DLP in plasmas. A NB and a mixture beam of neutral hydrogen and proton, whose power density and particle energy are controlled, was measured by DTP and DLP methods. The conversion factor from temperature increase of the probe head to local power density and secondary electron emission yield were obtained.

The measurements of fast ions in the NB heated plasma using DTP and DLP methods were demonstrated in CHS. The observation of DLP agrees well with NPA one, and is quantitatively consistent with the DTP results. These results show that the DTP and DLP methods can be applicable to NB heated plasmas for fast ion measurements.

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