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Helium Measurements using the Pellet Charge Exchange in Large Helical Device

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In Large Helical Device (LHD), it is possible to perform the simulation experiment of the α particle heating by using the ion cyclotron resonance heating (ICH) because high-energy particle generated by ICH is well confined in the plasma. The neutral particles (mainly hydrogen), which are generated by the charge exchange between the high-energy ion and the background neutrals, can be observed by using them. However a few neutral helium particles can be observed since fully ionized helium like α particle can emit only by double charge exchange process. Therefore we also introduce the pellet charge exchange system (PCX). The diagnostic pellet is injected to the plasma in order to obtain the charge exchange neutral particle, which is produced by the charge exchange reaction between the ablated pellet cloud and high-energetic particle. The helium distribution measurement in helium plasma is also demonstrated.

Keywords: helium, PCX, TESPEL, CNPA, plate voltage, ICH, LHD, resonance, SD-NPA, He/H ratio

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1. Introduction

It is very important to measure the helium ion profile for two different reasons. One is to measure the helium hydrogen ratio because the minority heating in ion cyclotron resonance frequency heating (ICH) is strongly depended on the ratio. Another is to investigate the α particle heating mechanism in future fusion reactor. High-energy particles including α particle are emitted not only by the charge exchange but also by the MHD in the fusion reactor [1]. Their particles give damage to the plasma wall addition to create a poor plasma confinement. Decelerated α particle (or a helium ion) with the energy over 1 keV makes a bubble and gives a serious damage on the wall surface unlike hydrogen. Therefore the suitable method for measuring helium ion distribution should be established immediately.

It is very difficult to use spectroscopic methods or the passive charge exchange neutral particle method for helium ion. Helium ions are almost fully ionized except near peripheral region. A few helium atoms are escaped from plasmas by the double charge exchange reaction between the background helium neutral and the fully ionized helium ion, whose cross section is too small. Some techniques for measuring α particle have been proposed [2]. A pellet charge exchange measurement (PCX) is one of the most powerful candidates to obtain the spatial resolved helium energy spectrum. PCX had been performed in TFTR [3]. However it is not often utilized because there are a few opportunities to obtain nuclear reaction plasma. High-energy particle over 1 MeV can be generated and confined in LHD by using ICH.

2. Pellet Charge Exchange Measurement

The high-energy neutral particles, which are produced by the charge exchange between the injected Tracer Encapsulated Solid Pellet (TESPEL) [4] and the energetic ions, are observed in PCX. TESPEL is the impurity pellet as the polystyrene or the titanium etc. with the velocity of 400-500 m/s. TESPEL is ablated and produces the ablation cloud with several layers of different charge states around the traveling pellet in plasma. The pellet ablation cloud keeps the neutral or partially ionized surrounding the pellet until fully ionization of the pellet. Parts of injected particles into the pellet ablation cloud are escaped from the plasma due to the charge exchange reaction. It is 10^8 times larger than the background neutrals because the cloud density is enough high ($10^{16}\,\mathrm{cm}^{-3}$). Therefore the measurement in the plasma is available because the double charge exchange can be expected if the high-Z material as the carbon or the lithium is used. The neutralization factor is very important in order to obtained energy spectrum in plasma. It is determined by the ratio of the recombination to the ionization. The precise calculation have been done under the LHD plasma parameter by Sergeev [5]. The neutralization factors for the hydrogen and the helium are 0.9 and 0.07, respectively if the polystyrene is used.

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3. Experimental Apparatus

It is one of advantages in PCX to obtain the spatial information. When the compact neutral particle analyzer (CNPA) for measurement of the charge exchanged particle is installed just behind TESPEL trajectory, the time trace of the signal can be transferred to the information of the pellet position. The typical pellet velocity of 500 m/s makes the spatial resolution of 5 cm by the sampling time of 0.1 ms. Full trajectory of the pellet in plasma should be in the viewing cone of the CNPA by minimizing the angle between the sight line and the trajectory. Figure 1 shows the schematic diagram of the CNPA and TESPEL. The detection time of the particle corresponds to the position of the generated particle because the size of the cloud is same as the spatial resolution (5 cm). CNPA is a traditional $E//B$ particle analyzers with a diamond-like carbon film as a stripping foil, the permanent magnet for the energy analysis of the particle and a condenser plate for the particle mass separation. The hydrogen with the energy range from 0.8 to 168 keV can be observed by 40 rectangular-shape channeltrons which is set on the position for the hydrogen measurement.

If the plate voltage is changed, the different mass as helium can be observed in principle. According to simple orbit calculation in CNPA, the beam spot of the helium is different from the channeltron array, which is adjusted to the hydrogen even if the plate voltage is tuned. Figure 2 shows the energy dependence of the position of the beam spots in hydrogen, deuteron and helium. Here we assume the single ionized helium ion after translation of the carbon film of helium. The spot size is assumed to be determined by the aperture size (2 mmϕ) and the geometric configuration of the plasma and the detector. In low energy region, the spot size may be enlarged due to the scattering in the foil.

According to Fig. 2, the helium beam spots do not correspond to the detector array in higher energy channels when the plate voltage is adjusted to a low energy channel because the detector array position is adjusted to the proton. Now we continue accurate calculation for obtaining the detector efficiency of helium. However the helium energy spectrum can be obtained because we are interested in lower energy helium spectra in LHD experiments in current situation if we choose the suitable plate voltage, the beam spot enters with the detector array under about 50 keV according to Fig. 2.

Another important thing is the energy loss in the pellet ablation cloud. The energy loss of the helium is larger than that of the hydrogen due to larger Z. According to Sergeev model calculation, the energy loss strongly depends on the particle energy and the pellet ablation cloud density as shown in Fig. 3. The typical energy loss is 10 % in 10 keV because the pellet ablation cloud density is estimated to be 10^{16} cm^{-3} from the Stark broadening of the H-alpha spectral line.

There are two different measuring modes of the counting and current in the CNPA amplifiers. Both modes can be available at the same time. Therefore accurate measurements can be possible not only in small amount flux but also in huge amounts. The electronics in the CNPA consist of the amplifiers, the scalers/ADCs (Analog digital Converter) and memories controlled by CAMAC.

The pellet velocity of 400-500 m/s is precisely monitored by a photo diode every shot. The spatial resolution of 4-5 cm can be achieved because the sampling time of the scalers/ADCs is set to 0.1 ms. Size of the ablation is monitored by the CCD camera with Hα filter. The cloud density is calculated from the Stark broadening of Hα monitored by a visible spectrometer.

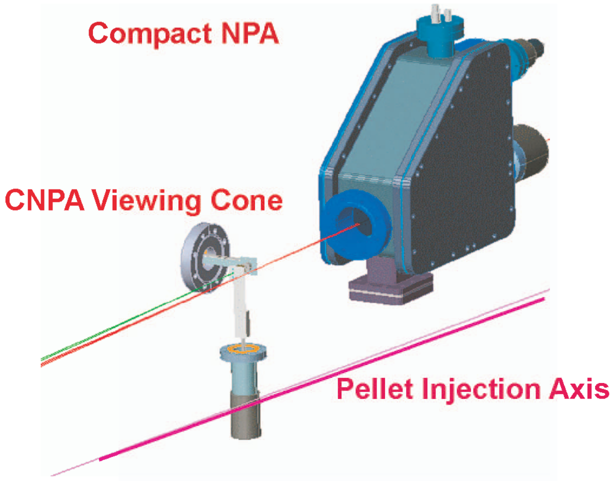

Fig. 1 The configuration of TESPEL and PCX. Both devices are installed at 3-O port on the mid plane. Bright and dark colors show the TESPEL and the PCX, respectively. The sight line of the PCX is closed to the TESPEL trajectory.

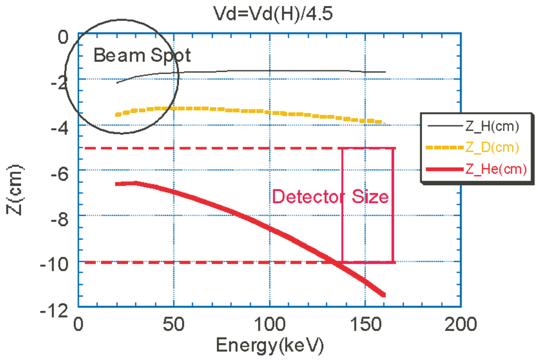

Fig. 2 The beam spot on the detector. When the plate voltage of 1/4.5 against hydrogen setting voltage is chosen, the helium can be separated in lower energy region. Z means vertical distance on the detector. For hydrogen detection, the plate voltage V0(=5500 V) is required. “the plate voltage of 1/4.5” means the plate voltage of 1/4.5 of V0.

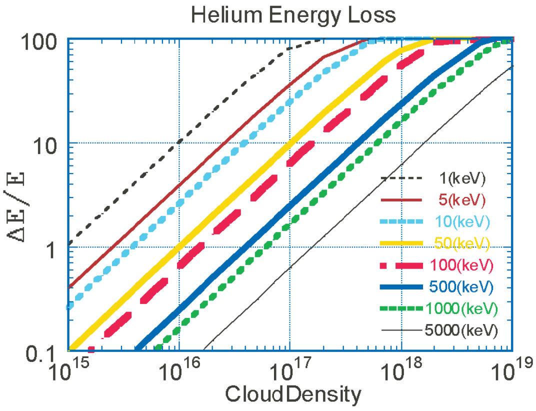

Fig. 3 The energy loss in the pellet cloud.
The cloud density is measured to be 10^{16} cm^{-3} by the Stark broadening of Hα.

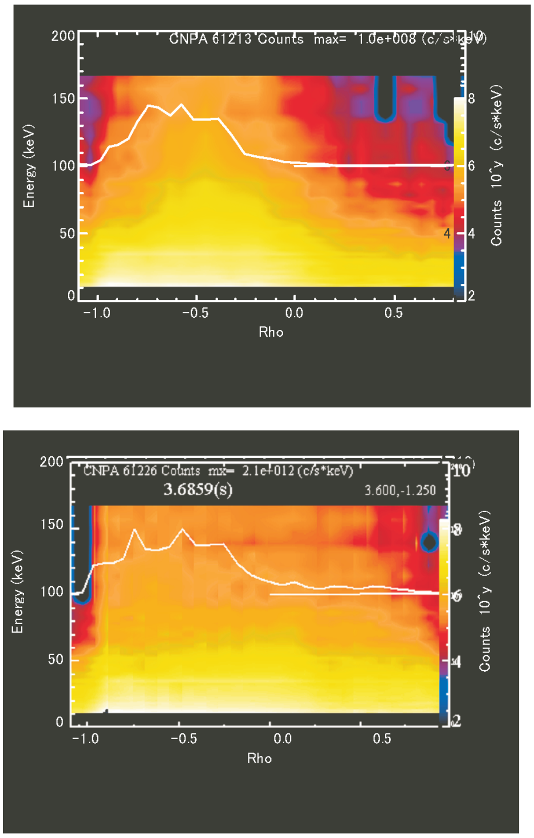

Fig. 4 The radial profile of the high-energy particle obtained from PCX.
The color indicates the flux of the particle. The table of the flux is shown at the right side. The maximum flux can be observed at ρ = 0.5 because that is the location of the resonance layer.
(a) off-axis heating,
(b) on-axis heating.

LHD has a toroidal mode number of m = 10, helical mode number of l = 2. The major radius and minor radius are 3.9 m, 0.6 m, respectively [6]. The helical ripple is 0.25 and a magnetic field is a maximum of 3 T. Although the standard magnetic axis is 3.75 m, it can be changed from 3.4 m to 4.1 m by applying a vertical magnetic field. There are three different heating systems of the electron cyclotron resonance heating (ECH, 2 MW), the neutral beam injection heating (NBI, 15 MW) and ICH (3 MW) [7]. As for electron temperature, a maximum of 10 keV is observed by using a Thomson scattering and an electron cyclotron emission. Electron density can be changed from 0.1 to 4×10^{19} m^{-3}. The density profile is measured with a multichannel interferometer.

4. Experimental Results

It is important to confirm the reliability of the PCX. In the experiment, two different ICH heating have been tried. The ICH and the perpendicular NBI are applied on the tangential NBI plasma in both cases. In the first case, the resonance of the ICH from 2.4 to 3.8 s is set off-axis (the 2$^{\text{nd}}$ harmonics heating mode, the resonance position at the vertical elongated plasma configuration is far from the magnetic axis) (38.47 MHz, −1.375 T), where the hydrogen minority can be easily accelerated and the high-energy tail can be obtained. In the second case, the resonance of the ICH from 2.4 to 3.8 s is set on-axis (the 2$^{\text{nd}}$ harmonics heating mode, the resonance position at the vertical elongated plasma configuration is on the magnetic axis) (38.47 MHz, −1.25 T). TESPELs are injected to the plasmas at the perpendicular NBI timing in both cases. The time behavior of each energy flux during TESPEL injection can be obtained in the off-axis heating. The radial energy profile can be obtained by comparing the pellet traveling time with the signal as shown in Fig. 4 (a). The flux of the high-energy particles is maximized around the normalized diameter ρ = 0.5. To compare the result, Fig. 4 (b) shows the result in the on-axis heating. This means that the resonance position is almost same as that of the calculation. In the LHD, the resonance position on the poloidal cross section is varied by the position of the toroidal position because the magnetic surface is very complicated. In the on-axis heating of ICH, the pellet trajectory cannot be crossed to the resonance surface at the horizontal elongation position although the resonance surface is crossed to the magnetic axis at the perpendicular elongated position. Therefore the flux increase in on-axis heating of ICH cannot be found during TESPEL injection.

A similar experiment result can be obtained in the vertical scan of the SD-NPA [8]. In this experiment, the off-axis heating mode of the fundamental frequency (38.47 MHz, 2.75 T) is used, where the resonance position is same as the 2$^{\text{nd}}$ harmonic heating in the PCX. The long discharge over 50 minutes with 1.6 GJ is successfully achieved in the LHD. Continuous vertical scan of the SD-NPA is performed during the long discharge. The high flux can be observed at the point of inflection of the resonance

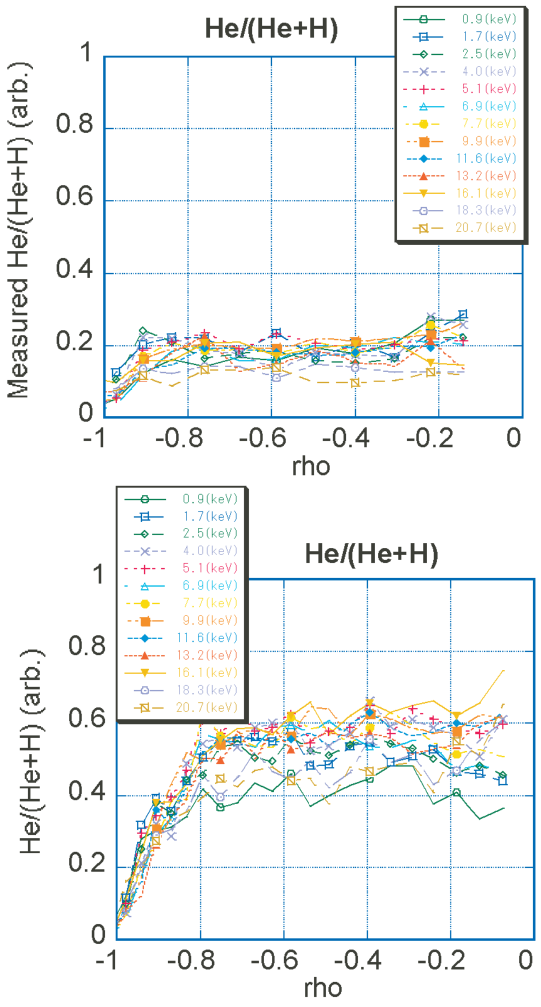

Fig. 5 The He/(He+H) ratio profile.
(a) measured He/(He+H) ratio on the detector
(b) He/(He+H) ratio in the plasma including the hydrogen scattering correction.

surface near the high plasma temperature region. The explanation has been done in the reference [9]. This tendency is more remarkable at the perpendicular sight line rather than at the tangential one. This result (flux increase at the resonance surface) is similar to that in the PCX. Therefore we find that the PCX is a useful tool to observe the radial profile of the energetic particle because the resonance position can be observed by using the PCX.

It is the final target to establish helium measurement through the PCX as mentioned in chapter I. The helium atom is observed by decreasing the plate voltage of the CNPA. The helium atom is generated by the charge exchange between the fully ionized helium and the partially ionized carbon ion in the TESPEL. Figure 5 (a) shows the He/(He+H) ratio on the detector observed by the PCX when the TESPEL is injected to the helium plasma. In LHD, the hydrogen concentration is not small due to the hydrogen NBI in helium plasma. When the TESPEL is injected to the hydrogen plasma, the ratio is almost 0.1. If detected helium signal in the hydrogen plasma comes from the scattering of the hydrogen in the detector, the contribution of the scattering of the hydrogen can be estimated to be 0.11. We assume there is the similar contamination of the hydrogen in helium plasma experiment. According to simple model, the real He/(He+H) ratio in helium plasma is estimated to be 0.12. To take account the difference of neutralization factor of H and He in the pellet ablation cloud, the helium-hydrogen ratio profile in plasma can be shown in Fig. 5 (b). The low concentration of helium may be due to the hydrogen inward flow from the wall.

5. Summary

The PCX has been successfully performed in the LHD. It is very important to establish the helium ion profile measurement because the helium makes a bubble and gives a serious damage on the wall surface. The PCX is one of the techniques to obtain the energetic helium particle distribution in plasma. We make sure the reliability of the PCX by comparing the results from the PCX and the SD-NPA in the ICH plasma. The ratio profile between the hydrogen and the helium can be obtained. Through these experimental results, the PCX can be advanced as a helium measurement method.

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[1] L. Chen, Phys. Plasmas **1**, 1519 (1994).
[2] M. Sasao *et al.*, Plasma Phys. Control. Fusion **46**, S107 (2004).
[3] R. Fisher *et al.*, Phys. Rev. Lett. **75**, 846 (1995).
[4] S. Sudo *et al.*, Proc. of 17th IAEA Fusion Energy Conference (Yokohama, Japan, 1998), **39**, IAEA-CN-69/EXP1/18 (1999).
[5] V. Sergeev, private communication.
[6] O. Motojima *et al.*, Fusion Eng. Des. **20**, 3 (1993).
[7] T. Mutoh *et al.*, Phys. Rev. Lett. **85**, 4530 (2000).
[8] J. Lyon *et al.*, Rev. Sci. Instrum. **74**, 1873 (2003).
[9] T. Ozaki *et al.*, Rev. Sci. Instrum. **77**, 10E917 (2006).