Radial Profiles of High-Energy Particles in NBI and ICH Plasmas Measured by Pellet Charge Exchange Technique on Large Helical Device

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The pellet charge exchange measurement (PCX) is one of the most powerful methods because it can directly provide the profile of high-particle energy spectra in plasma. In Large Helical Device, PCX using Tracer Encapsulated Solid PELlet (TESPEL) has been tried in many NBI and ICH plasmas. In NBI plasmas with the different magnetic axes, the radial profiles of the confined high-energy particle spectra change. At the inner magnetic axis, much neutral flux from the pellet cloud at the wide energy range can be observed. This fact means the high-energy particle confinement can be improved in the inner axis shift same with the simulation. The helium ion by PCX can be observed at the higher harmonic fast wave heating (HHFW) using ICRF antenna. The purpose of HHFW heating is mainly the electron heating. The helium ion is measured by tuning the plate voltage of the analyzer. The large flux of the helium ions can be observed when the electron heating may not be enough.

Keywords: PCX, LHD, TESPEL, magnetic axis, NBI, HHFW, helium ion

1. Introduction

In Large Helical Device (LHD) [1] there are three different heating systems: the electron cyclotron heating (ECH), the neutral beam injection heating (NBI) and the ion cyclotron resonance heating (ICH). In order to obtain the high efficient heating, the control of the high-energy particle profile is one of the essential issues. In helical devices, the particle orbit of the co-injected beam with respect to the direction of the toroidal magnetic field is different from that of the counter injected one. According to the calculation, the guiding center of the particle orbit is close to the magnetic axis and shifted to the high magnetic field side in the co- and counter-injection, respectively [2]. Another important thing is the loss of high energetic particles. High-energy particles including α particles are emitted not only by charge exchange but also by MHD instabilities such as the Alfven eigen mode in ITER and fusion reactors [3]. Their particles damage the plasma wall in addition to creating poor plasma confinement. Decelerated α particles (or helium ions) with an energy over 1 keV makes a bubble and causes serious damage to the walls surface unlike hydrogen. Actually in LHD, where helium plasmas are often used, the helium flux over 10^{19} $m^{-2}s^{-1}$ can be observed by the microscopic measurement of the irradiated materials [4]. Therefore, the suitable method for measuring α particle/helium ion distribution should be established immediately. In LHD, it is easily possible to do a simulation experiment of α particle heating by using ICH.

However, it is very difficult to obtain the radial

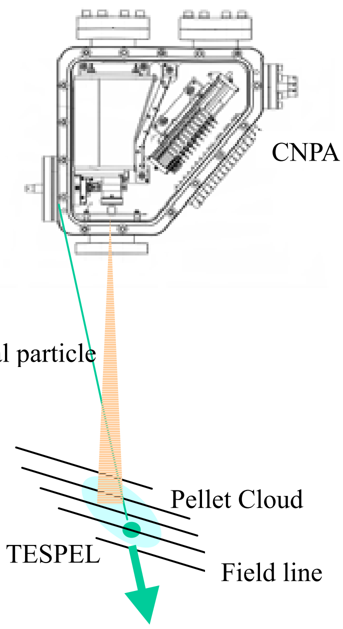

Fig. 1. PCX arrangement.
TESPEL is ablated by the plasma. CX is occurred around pellet cloud.

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information of the high energetic particle profile by the passive charge exchange neutral particle method. The charge exchange combined with the heating or diagnostic beam is another candidate to obtain the radial profile. It is very interesting but also difficult to set the analyzer on the sight line of the beam due to complicated configuration of LHD. Here a pellet charge exchange (PCX) measurement is well known as one of the most powerful methods to obtain the spatial resolved energy spectrum [5,6]. We make clear the radial profile of the high-energy particle spectrum by using PCX for the measurement on NBI and ICH plasmas in LHD.

2. Experimental Apparatus

LHD has a toroidal mode number of m=10, and a helical mode number of l = 2. The major and minor radius are 3.9 m, 0.6 m, respectively. The helical ripple is 0.25 and the 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 ECH (2 MW), NBI, (15 MW) and ICH (3MW). The maximum electron temperature of over 10 keV can be observed by using Thomson scattering and electron cyclotron emission. The electron density can be changed from 0.01 to $1\text{x}10^{20}$ m^{-3}. The density profile is measured with a multi-channel interferometer.

High-energy neutral particles, which are produced by the charge exchange between the injected Tracer Encapsulated Solid PELlet (TESPEL) [7] and the energetic ions, are observed by PCX as shown in Fig. 1. TESPEL in this experiment is an impurity pellet made of the polystyrene with the velocity of 400-500 m/s used as a diagnostic pellet. The TESPEL velocity is monitored by a pair of photo-diodes. The TESPEL is ablated and produces an ablation cloud with several layers of different charge states around the traveling pellet in the plasma. The cloud is expanded along the magnetic line and the pellet trajectory. The pellet ablation cloud keeps the neutral or partially ionized states surrounding the pellet until fully ionized. Parts of the injected particles in the pellet ablation cloud escape from the confinement of the magnetic field in the plasma due to the charge exchange reaction. The neutral density is 10^8 times larger than that of the background neutrals because the cloud density is high enough (10^{16} cm^{-3}). Therefore, the measurement in the plasma is possible because double charge exchange can be expected if the high-Z material such as polystyrene is used. The neutralization factor is very important in order to obtain the energy spectrum in the plasma. It is determined by the ratio of the recombination to the ionization. The precise calculation has been done under the LHD plasma parameter by Goncharov and Toltihina [8]. The neutralization factors for the hydrogen and the helium are 0.06-0.5 and 0.07 at the low energy region, respectively if polystyrene is used. The value is strongly dependent on the distribution of the charge state.

One of the advantages of PCX is the spatial information. When the compact neutral particle analyzer (CNPA) for measurement of the charge exchanged particle is installed just behind the TESPEL trajectory, the time trace of the signal can be converted to the information on the pellet position. The typical pellet velocity of 400 m/s gives a spatial resolution of 4 cm for the sampling time of 0.1 ms. Full trajectory of the pellet in the plasma should be in the viewing cone of the CNPA by minimizing the angle between the sight line and the trajectory. 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 (5-10 cm) [9]. CNPA is a traditional E//B particle analyzer with a diamond-like carbon film as a stripping foil, a permanent magnet for the energy analysis of the particle and a condenser plate for the particle mass separation. Hydrogen with an energy range from 0.8 to 168 keV can be observed by 40 rectangular-shape channeltrons.

3. Experimental Results

We have tried to measure the radial profile of the high-energy particle spectra by perpendicular injection of TESPEL to the NBI plasmas. PCX has been performed in NBI plasmas with different magnetic axes in order to find the suitable magnetic configuration for confinement energetic particles. It is well known that the inner shift of the magnetic axis provides better confinement of energetic particles in helical devices from computer simulation results.

In the experiment, TESPEL is injected to the plasma produced by two tangential NBIs, NBI#1 (counter-injection against the magnetic field, initial energy of 180 keV) and NBI#2 (co-injection, 180 keV), and the perpendicular NBI#4 (maximum energy is 40 keV). Therefore, the initial angular distribution is roughly uniform. Figure 2 shows the main plasma parameters in three different magnetic axis cases, the time history of the energy spectra measured by the CNPA and those spectra in plasma. The flux intensity is colored so we can easily compare those discrepancies. TESPEL reaches ρ=0.7. The time behavior of each energy flux during TESPEL injection can be obtained. The radial energy profile can be obtained by comparing the pellet traveling time with the signal. To obtain the accurate energy spectra in plasma, the signal intensities are divided by the pellet neutralization factor. Neutral fraction of hydrogen flux in the pellet ablation cloud has been calculated taking into account four groups of elementary processes, viz., charge exchange, ion impact ionization, electron impact

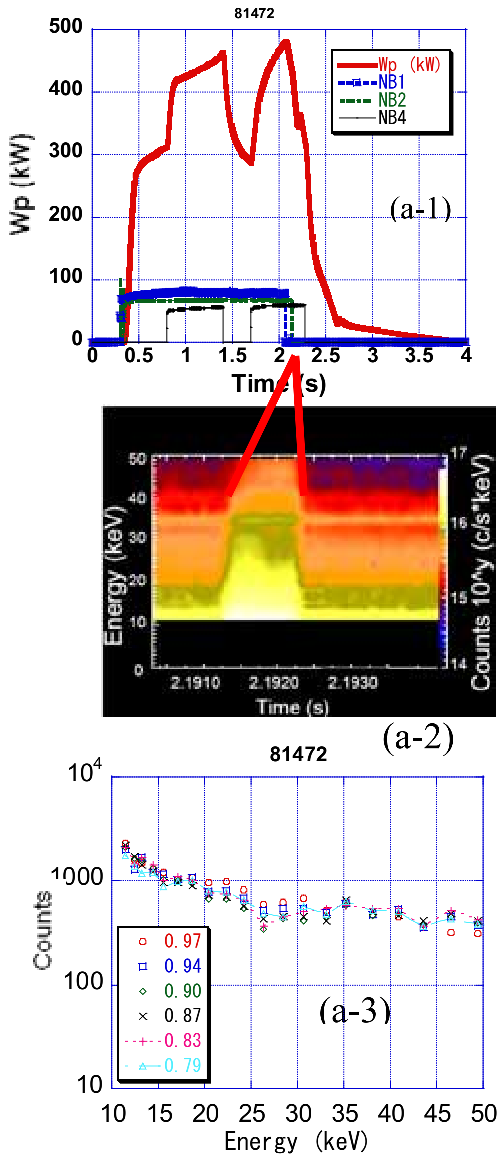


Fig. 2(a). PCX signals in R_{ax}=3.6 m, B=2.8 T, (1) Plasma waveforms, (2) PCX Signals and (-3) energy spectra.

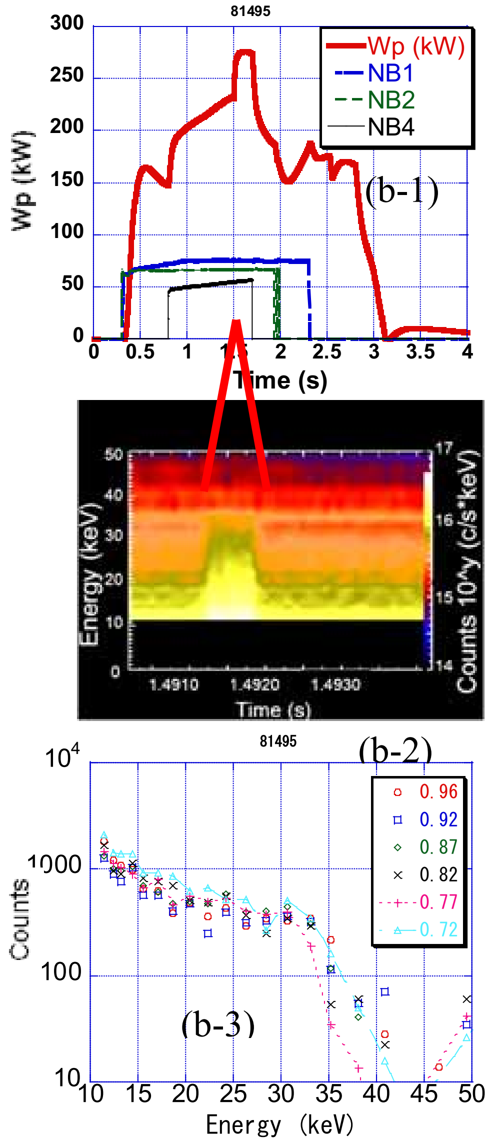


Fig. 2(b). PCX signals in R_{ax}=3.75 m, B=2.5 T, (1) Plasma waveforms, (2) PCX Signals and (-3) energy spectra.

ionization and neutral atom impact ionization. The energy-dependent neutral hydrogen flux attenuation factor calculation has been performed taking into account the measurement geometry and magnetic surface structure. Total hydrogen atom loss cross-section including the fully ionized He, C, O and Fe impurity effect has been used. The detail discussion will be made by Goncharov in reference [8].

The energy of tangentially injected beam particles is reduced by the plasma electron. At <50 keV or less, pitch scattering is remarkably occurred. Therefore some particles can enter the sight line of CNPA. At R_{ax}=3.6m, those particles can be observed at < 50 keV. However at R_{ax}=3.75 m, particles over 40 keV are not confined. Here particles at less than 40 keV are mainly the contribution from NBI#4. At R_{ax}=3.9 m, even particles originated from NBI#4 are not good confined. As mentioned above, better confinement of the energetic particle can be obtained at the inner shift of the magnetic axis in the helical devices because the plasma region is overlapped to the particle orbit. Therefore, the increase of flux from the PCX can be expected at the inner axis shift. The maximum flux over wide energy region can be obtained at the inner magnetic axis shift, especially at the plasma edge.

The dependence on the magnetic field strength has been also studied. At the lower magnetic field strength, the particle confinement becomes worth because the particle orbit goes out from the plasma due to the large Larmor radius. Figures 3 (a) and (b) show PCX signals in two different magnetic strength cases at the same magnetic axis and magnetic configuration. TESPEL is injected at the overlapped timing of NBI#1 (co-injection), NBI#2 (counter-injection) and NBI#4. In the lower magnetic field, the peak of the signal can be always observed at the inner region of the plasma. One of the

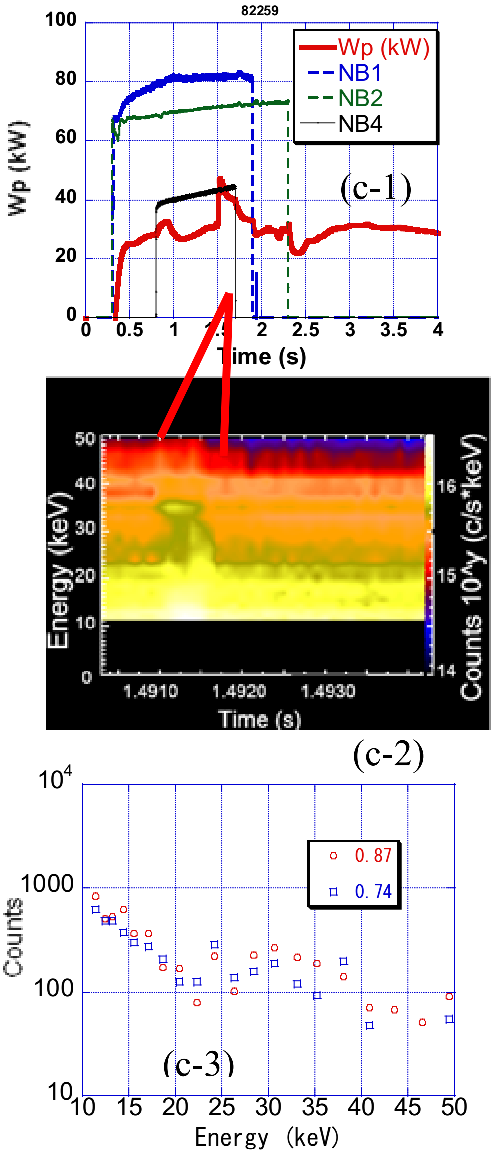
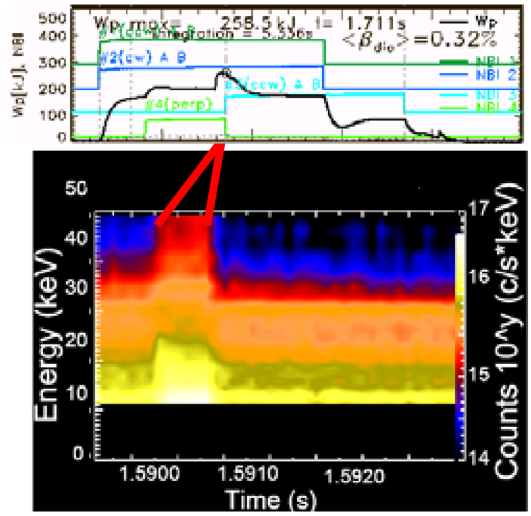
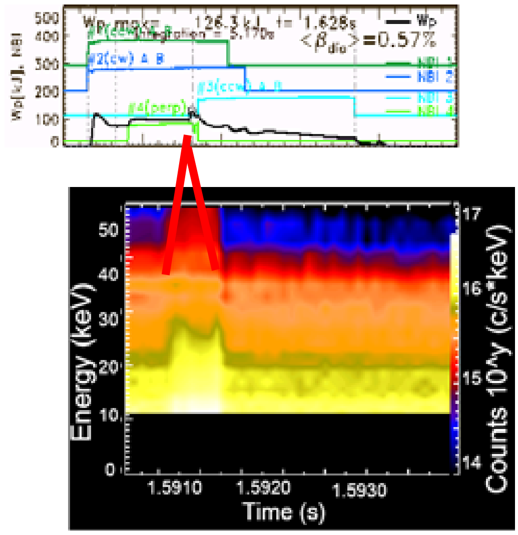


Fig. 2(c). PCX signals in R_{ax}=4.1 m, B=2.842T, (1) Plasma waveforms,(2) PCX Signals and energy spectra.



(a) Rax=3.75m,B=−2.5T



(b) Rax=3.75m,B=−1.25T

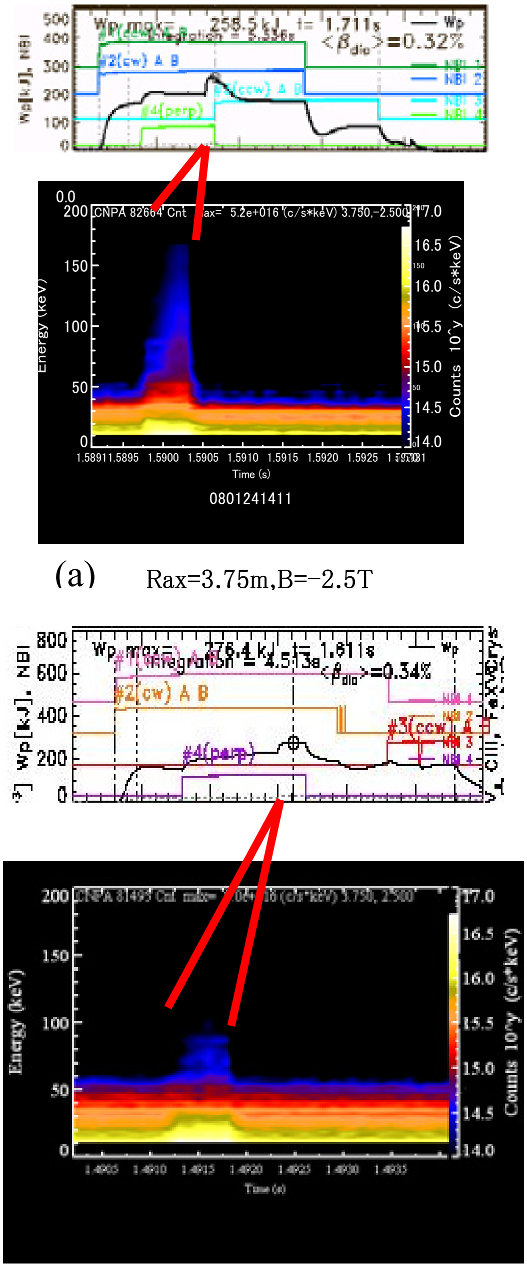
Fig. 3. PCX signals in different magnetic strength.
(a) R_{ax}=3.75 m, B=-2.5 T,
(b) R_{ax}=3.75 m, B=-1.25 T.

candidates to understand the phenomena may be the interaction with the counter beam localized in the core plasma region due to the weak magnetic field.

A comparison between the normal and inverse magnetic fields has been done. The experiment has been performed at the R_{ax}=3.75 m and B=2.5 and –2.5 T. TESPEL is injected at the overlapped timing of NBI#1, NBI#2 and NBI#4. Figures 4(a) and (b) show the PCX signal each other. The signal intensity at the inverse magnetic field is obviously larger than at the normal magnetic field. The large signal can be observe near the core plasma region in the inverse magnetic field. According to the simulation by Watanabe [9], the orbit of the co-injection NBI particle is wider and outer than that of the counter-NBI particle. (The large charge exchange neutral flux can be expected in plasma edge).

The sight line of CNPA can see the NBI#1 (co- and counter- against inverse and normal magnetic fields, respectively) with small scattering angle, rather than NBI#2. Therefore the large signal at the inverse magnetic field means that the co-injection beam surely exists outer region in plasma same as the simulation.

This heating using ICH by the higher harmonic fast wave is utilized mainly for the electron heating using Landau damping [10]. We choose the suitable combination between the magnetic field and the frequency of ICH so that there is no ion cyclotron resonance layer for the hydrogen in the plasma core region. The density of accelerated hydrogen is not large because there is no resonance layer for hydrogen if the combination between the magnetic field of 1.86 T and the ion cyclotron frequency of 38.47 MHz is used. The He^4 resonance layer appears at ρ=1/3 for the 3rd harmonics of the ICH frequency. On the other hand, there are



(a) Rax=3.75m,B=−2.5T

(b) Rax=3.75m, B=2.5T

Fig. 4. PCX signals in different magnetic direction.
(a) R_{ax}=3.75 m, B=-2.5 T,
(b) R_{ax}=3.75 m, B=2.5T.

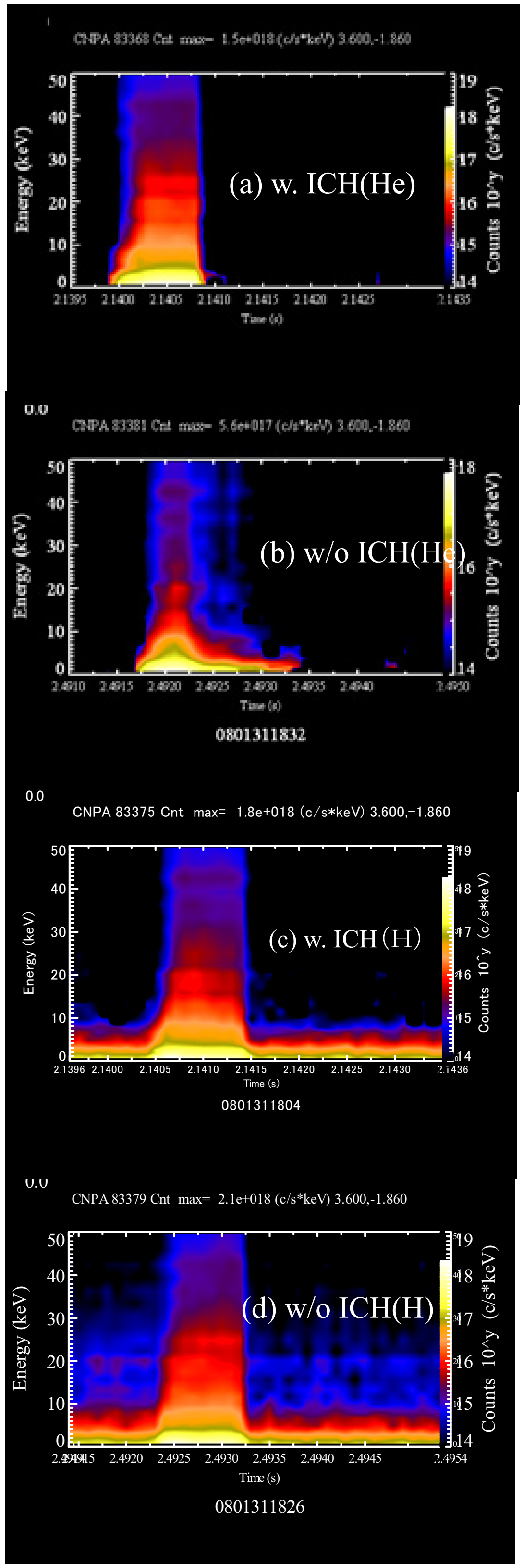


Fig. 5. PCX signals at H/He and with/without ICH.
(a) with ICH, Hydrogen,
(b) without ICH, Hydrogen,
(c) with ICH, Helium,
(d) without ICH, Helium.

hydrogen resonance layers only at the peripheral region of the plasma. The efficiency of the electron heating has been monitored by the helium acceleration. The measurement of the helium ion acceleration is the simulation experiment in α particle diagnostic in fusion plasma.

The helium ion is measured by tuning the plate voltage of the analyzer. At the measurement of helium ion by the PCX, the hydrogen still gets mixed in the detector because the charge and mass of hydrogen is closed to the helium. To simplify, we compare the ratios of He/H with/without ICH. The way to measure helium ion in the neutral particle analyzer for the hydrogen is mentioned in ref. [11].

In the experiment, the plasma is produced by the two tangential NBI#1 and NBI#3. The ICH is intermittently applied. TESPEL is injected to the plasma after NBI injection in order to minimize the effect of proton generated from NBI. Four similar discharges with TESPEL injection are referred. In two discharges with ICH, we measure the helium and hydrogen from PCX. In the next two discharges, the same procedure is performed without ICH.

Fig.'s 5(a)-(d) show the time histories of the hydrogen and helium energy spectra in the four similar shots. TESPELs reach ρ=0.6 in all discharges. The line averaged plasma density of $2x10^{19}$ m^{-3}, the central plasma temperature of 2 keV can be observed. To confirm the helium acceleration, we compare the spectra of the helium and hydrogen by using CNPA with different plate voltages. Fig. 6 shows the energy resolved He/H ratio profiles with/without ICH. The acceleration can be observed at the wide area between ρ=0.7-0.85. We can confirm the acceleration of helium ion by the HHFW heating from the ratio profiles. The large flux of the helium ions can be observed when the electron heating may not be enough.

4. Summary

It is very important to investigate the high-energy particle profile because the confinement is an essential issue to obtain proper plasma parameter. We have performed the energetic particle profile measurement using PCX in NBI and ICH plasmas. The profiles in different magnetic axes have been compared. Better confinement of the energetic particle can be obtained at the inner magnetic shift. Co-injection beam orbit is surely wider than the counter injection beam orbit from the PCX on normal and inverse magnetic field. The helium particle measurement in HHFW experiment has been also tried by adjusting the plate voltage to the He orbit. From these experimental results it follows that the PCX may be useful tool to measure the α particle profile in fusion devices as ITER.

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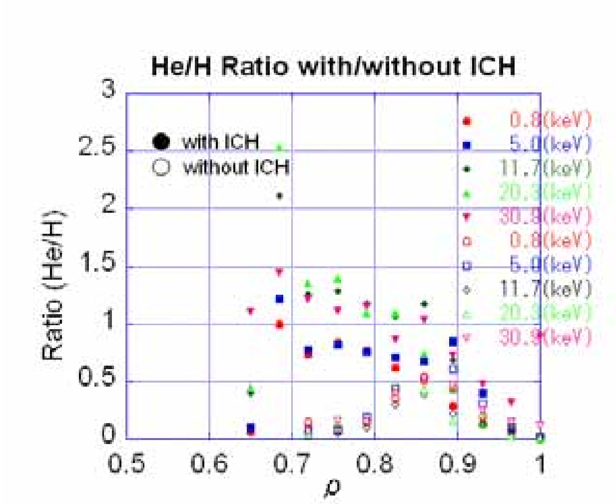

Fig. 6. He/H ratios by PCX with/without ICH.

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