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Helium ion observation during 3rd harmonic ion cyclotron heating in Large Helical Device

Tetsuo Ozaki, Pavel R. Goncharov, Evgeny A. Veshchev[1)], Shigeru Sudo, Tetsuo Seki, Hirofumi Kasahara, Yuichi Takase[2)], Takuya Ohsako[2)], High-Energy Particle Group and LHD Experimental Group

National Institute for Fusion Science, 322-6, Oroshi, Toki, Gifu 509-5292, Japan

1) Graduate University for Advanced Studies, Hayama, Kanagawa, 240-0193, Japan

2) Department of Complexity Science and Engineering, Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa, Chiba, 277-8561, Japan

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In the higher harmonic ion cyclotron resonance heating (ICH) using the fast wave, the resonance layer of helium appears near the plasma core. It is very important to measure the helium ion in order to investigate the confinement of α particle, which is produced by the nuclear reaction in ITER or fusion reactor. In the Large Helical Device (LHD), we try to observe the charge exchange helium particle by using the Compact Neutral Particle Analyzer (CNPA). The helium acceleration at lower than 5 keV, can be confirmed by comparing the signal ratio in adjusted plate voltages of CNPA to helium and hydrogen. The successful helium measurement in LHD leads to the development of the α particle measurement.

Keywords: ICH, 3rd harmonics, helium, α particle, CNPA, LHD, plate voltage, resonance

1. Introduction

It is very important to investigate α particle heating mechanism in future fusion reactor because α particle has a main role to heat the fusion plasma. High-energy particles including α particle are emitted not only by the charge exchange but also by the MHD instabilities 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 bubbles and gives a serious damage on the wall surface unlike hydrogen. In LHD [2], we find the helium flux over 10^{19} m^{-2}*s, whose energy is over 1.2 keV by using the microscopic measurement of the irradiated material [3]. 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. Therefore the helium ion has not been observed until now by the particle measurement. Here we describe that we succeed the observation of helium in higher harmonic ion cyclotron resonance heating (ICH) [4].

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

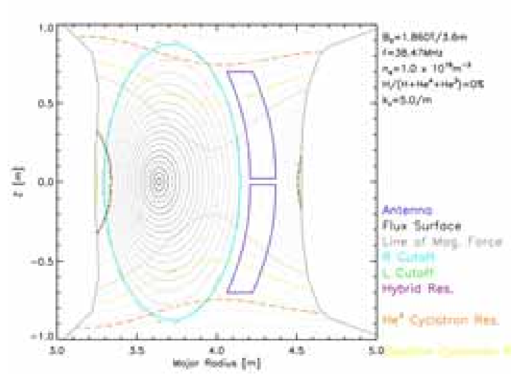

Fig.1. Magnetic surface, ICH antenna and resonance layers.

2. Higher Harmonic Ion Cyclotron Resonance Heating

It is one of most suitable method to use ICH in LHD in order to obtain the accelerated helium ion. We have tried ICH in He^3/He^4 mixture plasma. However the effective heating has not been obtained probably due to the contaminated hydrogen acceleration rather than helium acceleration. Here we propose the higher harmonic ICH without the hydrogen resonance. This technique is utilized in the electron heating using Landau damping [5]. To this purpose, the ICH should not provide its power to the hydrogen ion. If the ions are accelerated, they cannot be confined and their energy cannot be deposited due to the low confinement magnetic field in high beta plasma. We choose the suitable combination between the magnetic field and the frequency of ICH so as there is no ion cyclotron resonance for the hydrogen in the plasma core region. One of their combinations has the resonance for the He^4 around plasma core region. Therefore the hydrogen gas should be used at this combination of the magnetic field and the frequency in order to obtain high electron heating efficiency. If we are interested in the helium acceleration, the helium gas should be chosen in the same combination.

If we detect the helium ion by using the charge exchange neutral particle measurement, the hydrogen ion always behaves as a noise because their masses and charges are too close each other. Fortunately there is a

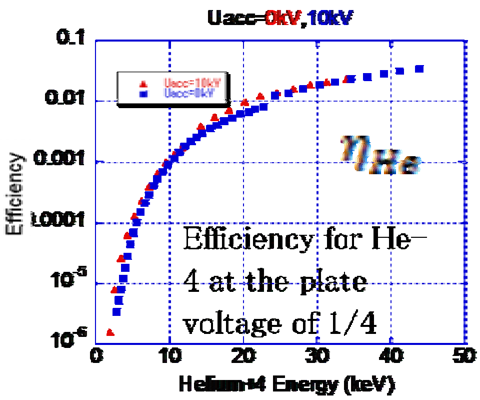

Fig.2(a). Efficiency for He-4 at the plate voltage of 1/4.

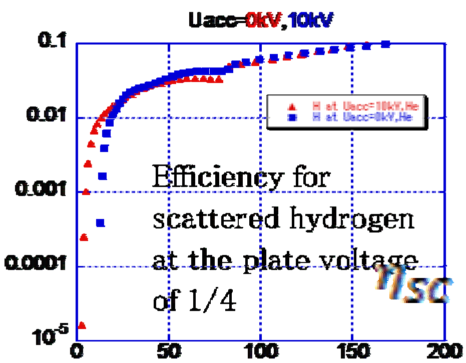

Fig.2(b) Efficiency for scattered hydrogen at the plate voltage of 1/4.

possibility of the helium observation because there is no acceleration of the hydrogen in this combination. Figure 1 shows the resonance layers at the magnetic field of 1.86 T and the ICH frequency of 38.47 MHz, drawn on the vertical cross section of LHD magnetic surfaces [6]. The plasma and the ICH antenna are also shown. The He^4 resonance appears at ρ=1/3 in the 3^{rd} harmonics of the ICH frequency. Therefore the high efficient helium acceleration can be expected. On the other hand, there are the hydrogen resonance layers only at the peripheral region of the plasma. Unfortunately there are the electron cyclotron resonance layers near the plasma edge in the configuration. The electron heating efficiency is not high and is expected to be strongly depended on the power deposition to helium ion.

3. Compact Neutral Particle Analyzer

The compact neutral particle analyzer (CNPA) [7] for measurement of the charge neutral exchanged particle is installed perpendicular direction against LHD plasma almost at the mid-plane. CNPA is a traditional E//B particle analyzer with a diamond-like carbon film as a stripping foil, the permanent magnet for the energy analysis of the particle and condenser plates for the particle mass separation. To precise detection in low energy region, there is a particle acceleration tube of 10 keV. Therefore 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.

The spatial resolution is determined to be 5 cm by the several apertures in the neutral particle flight. Time resolution is set to be 0.1 ms, which can cover the whole plasma duration within the buffer memory with the CAMAC ADC. Data acquisition, data pre-process and analyzing data display are routinely completed within 3 minutes discharge cycle.

If the condenser 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 [8]. 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.

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. The helium energy spectrum can be obtained because we are interested in lower energy helium spectra in LHD experiments.

The calibration procedures are as follows;

(1) Compare the simulation model [9] including accurate orbit calculation and the experimentally calibrated value in hydrogen.

(2) (1) is almost agreed. Therefore we believe the simulation model and calculate the efficiency in helium and the scattered hydrogen when the plate voltage is set to be 1/4 for the hydrogen.

(3) The calculated efficiencies for the helium and the scattered hydrogen are shown in Figs. 2(a) and (b).

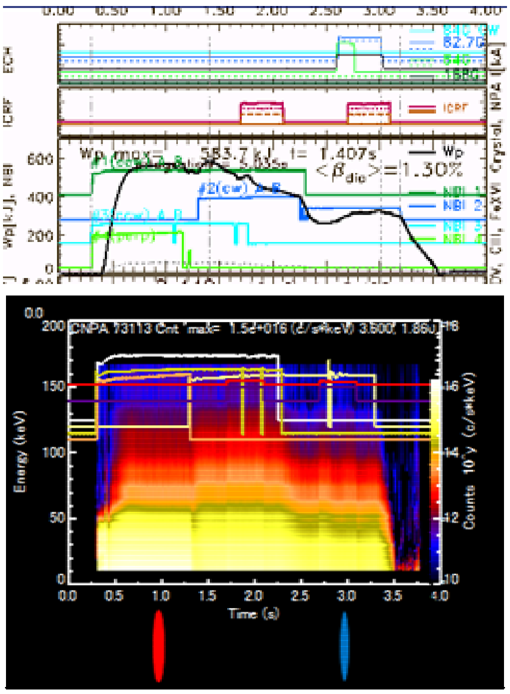

Fig.3(a). The time histories of the plasma parameters and the neutral particle energy spectrum in the voltage setting of hydrogen.

4. Experimental Results

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. 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 (3MW). 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 $4x10^{19}$ m^{-3}. The density profile is measured with a multi-channel interferometer.

In order to obtain the high electron temperature plasma, NBI#1, #2 and #3 are injected during 0.4 seconds at the beginning of the discharge [10]. After that, the plasma is maintained by the NBI#2. During this phase, the power of NBI#2 keeps low as the effect of ICH application can be clearly seen. The line averaged plasma density of $2x10^{19}$ m^{-3}, the central plasma temperature of 2 keV can be observed. ICH pulses are applied at two different timings. The ECH is overlapped at the second ICH pulse in order to obtain high electron heating at the high electron temperature. However the high electron temperature is not enough because the electron resonance region at this combination between the 2nd harmonic frequency of ECH and the magnetic field, is off-axis. Typical stored energy increment due to the ICH application of 1.55 MW, is 50 kJ at Wp=300kJ. Temperature rising is small in hydrogen plasma. Main contribution of Wp increment may come from the density rising at the plasma edge.

We change the gas from the hydrogen to the helium in order to study the electron heating reduction due to the

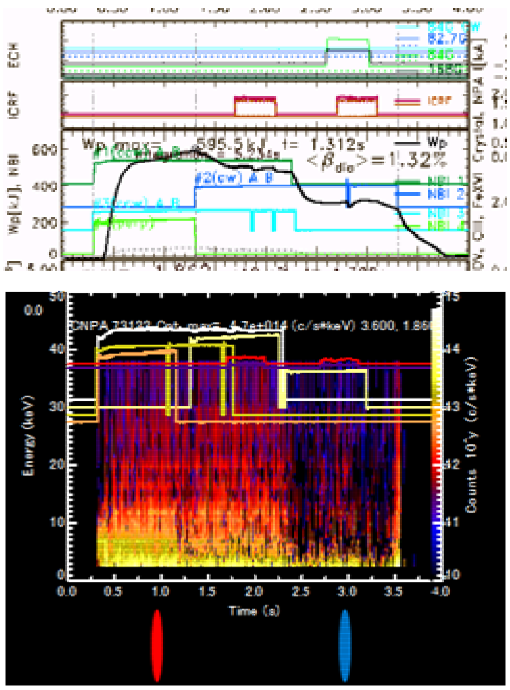

Fig.3(b), The time histories of the plasma parameters and the neutral particle energy spectrum in the voltage setting of helium.

power absorption by the helium ion. The helium resonance layer is around ρ=1/3 at the 3rd harmonics of ICH. As the result, the Wp is obviously reduced by the helium gas puffing. The reduction rate is depended on the amount of the puffing. Therefore the absorption to the electron may be reduced because the injection power of ICH is partially absorbed by the helium ion. The increasing rate of Wp is large at the high electron temperature. This means that effective electron heating by ICH can be obtained in the high temperature, especially at hydrogen plasma. On the contrary, in helium plasma, the temperature dependence of the increasing rate of Wp is not significant. In hydrogen plasma, the ICH power is easily absorbed to plasma electron because there is no resonance region against hydrogen. However, in helium plasma, the power deposition of ICH to the electron is not enough due to the existence of the helium ion resonance layer.

To confirm the helium acceleration, we compare the spectra of the helium and hydrogen by using CNPA with different plate voltages. Figures 3(a) and (b) show the ratio between the signal of He and H in two similar shots. We must remember that most signals are hydrogen even if we set the plate voltage for helium. Therefore the ratio means the ratio between the scattered hydrogen plus helium and the real hydrogen. The large ratios at low and high energy regions are due to the large scattering at the foil and the close trajectory of the hydrogen beams, respectively. The ICH is applied at 3.0 seconds, but not applied at 1.0 second. He/H ratio lower than the helium energy of 5 keV at 3.0 seconds is obviously larger than at 1.0 second. This means the low energy helium ion is accelerated by the higher harmonic ICH.

Higher harmonics heating provides the α particle simulation experiment although it is not effective for the electron heating. There is another candidate of the helium acceleration as He^3/He^4, but it is too difficult due to the hydrogen contamination. By tuning the magnetic field and frequency of ICH, higher acceleration energy of the helium ion over 5 keV can be expected.

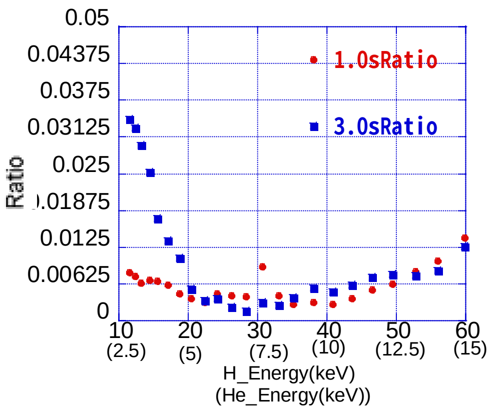

Fig.4. Energy dependence of He/He ratio.

5. Summary

The helium acceleration experiment to study the future α particle measurement has been done. It is very important to establish the α measurement because the helium/α makes a bubble and gives a serious damage on the wall surface. The higher harmonic ICH without the hydrogen resonance is utilized in the electron heating using Landau damping. There is the helium resonance layer at ρ=1/3. In LHD, we can find the helium particle using the charge exchange neutral particle method at this experiment. By the helium acceleration, the electron heating efficiency is reduced. This fact suggests the way of efficient heating. At the same time, we can obtain the useful tool to develop the α particle measurement.

Acknowledgements

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