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

(Received 24 October 2007 / Accepted 24 March 2008)

In higher harmonic ion cyclotron resonance heating using the fast wave, a helium resonance layer appears near the plasma core. It is very important to detect the helium ions to investigate the confinement of α particles, which are produced by a nuclear reaction in ITER or a fusion reactor. In Large Helical Device (LHD), we attempt to observe the charge-exchange helium particles using a compact neutral particle analyzer (CNPA). Helium acceleration below 5 keV can be confirmed by comparing the signal ratio of helium in adjusted plate voltages of the CNPA to that of hydrogen. Successful helium measurement in LHD will lead to the development of α particle measurement.

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

DOI: 10.1585/pfr.3.S1084

1. Introduction

It is very important to investigate α particle heating mechanism in the future fusion reactors because α particles are primarily responsible for heating the fusion plasma. High-energy particles including the α particles are emitted not only by charge exchange but also by MHD instabilities in the fusion reactor [1]. These particles damage the plasma wall in addition to creating a poor plasma confinement. Decelerated α particles (or helium ions) with the energy over 1 keV form bubbles and seriously damage the wall surface unlike hydrogen. In LHD [2], the helium flux is determined to be greater than 10^{19} $\mathrm{m^{-2}s^{-1}}$, with energy more than 1.2 keV using the microscopic measurement of the irradiated material [3]. Therefore, a suitable method for measuring the 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 ions. Helium ions are almost fully ionized except near the peripheral region. A few helium atoms are escaped from plasmas by the double charge-exchange reaction between the background neutral helium and fully ionized helium ions, whose cross section is too small. Therefore, helium ions have not been observed until now by particle measurement. Here we describe the successful observation of helium in higher harmonic ion cyclotron resonance heating (ICH) [4].

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

2. Higher Harmonic Ion Cyclotron Resonance Heating

ICH is one of the most suitable methods for obtaining accelerated helium ions in LHD. We have tried ICH in He^3/He^4 mixture plasma. However, effective heating was not obtained, probably due to contaminated hydrogen acceleration rather than helium acceleration. Here, we propose higher harmonic ICH without using a hydrogen resonance layer. This technique is used for electron heating using Landau damping [5]. For achieving this purpose, ICH should not provide its power to hydrogen ions. If the ions are accelerated, the power is deposited to ions rather than electrons. We selected a suitable combination of magnetic field and ICH frequency so that there is no ion cyclotron resonance layer for hydrogen in the plasma core region. One of the combinations produces the resonance layer for He^4 in the plasma core region. Therefore, two different experiments have been performed at the same combination. One is the experiment with 100% hydrogen gas puffing. Another is the experiment with a mixture gas puffing containing hydrogen and helium in several tens of percentages. In order to obtain efficient electron heating, the hydrogen gas is suitable. However in order to study the mechanism, we use the mixture gas in which helium acceleration is expected.

If we detect helium ions by charge-exchange neutral particle measurement, hydrogen ions are always detected as a noise because their masses and charges are too sim-

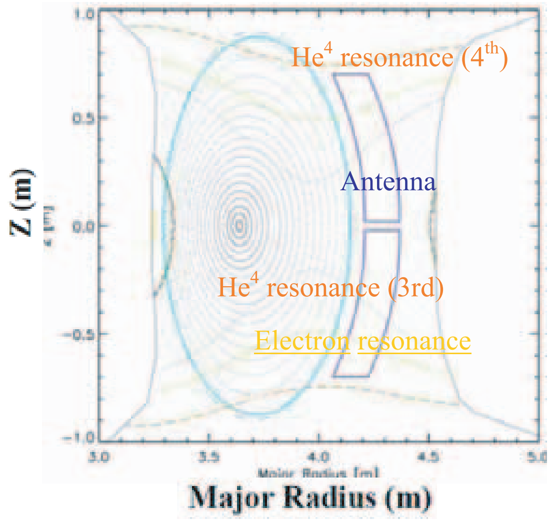

Fig. 1 Magnetic surface, ICH antenna, and resonance layers.

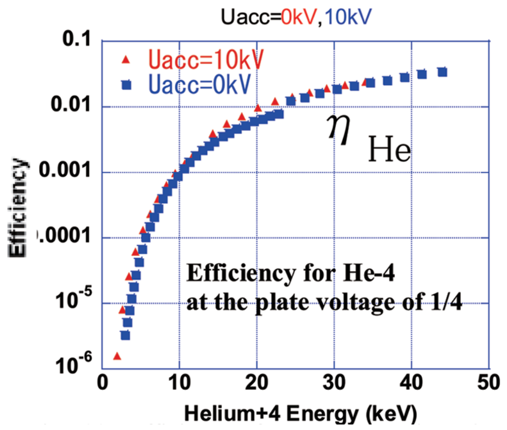

Fig. 2 (a) Efficiency for He^4 at the plate voltage of 1/4.

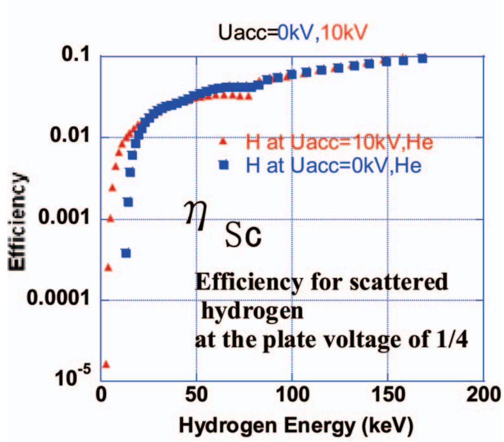

Fig. 2 (b) Efficiency for scattered hydrogen at the plate voltage of 1/4.

ilar to those of helium ions. Fortunately, helium can be observed because hydrogen is not accelerated in this combination. Figure 1 shows the resonance layers at the magnetic field of 1.86 T and ICH frequency of 38.47 MHz, at the vertical cross section of LHD magnetic surfaces [6]. The plasma and ICH antenna are also shown. A He^4 resonance layer appears at $\rho = 1/3$ in the 3rd harmonic of the ICH frequency. Therefore, highly efficient helium acceleration can be expected. On the other hand, hydrogen resonance layers exist only at the peripheral region of the plasma. Unfortunately, electron cyclotron resonance layers exist near the plasma edge in this configuration. The electron heating efficiency and electron heating power deposition to helium ions are expected to be low.

3. Compact Neutral Particle Analyzer

A compact neutral particle analyzer (CNPA) [7] for detecting the charge-exchange neutral particles is installed in the perpendicular direction against LHD plasma nearly at the mid-plane. CNPA is a traditional E//B particle analyzer with a diamond-like carbon film as the stripping foil, a permanent magnet for the energy analysis of particles, and condenser plates for particle mass separation. For precise detection in the low-energy region, there is a particle acceleration tube of 10 keV (= Uacc). Therefore, hydrogen ions with the energy range from 0.8 to 168 keV can be observed using 40 rectangular channeltrons, which are set at the positions for hydrogen measurement.

It is determined that the spatial resolution is 5 cm, using several apertures in the neutral particle flight. Time resolution is set to be 0.1 ms, which can cover the entire plasma duration within the buffer memory of a CAMAC scalar. Data acquisition, data pre-process, and analyzed data display are routinely completed within a 3 min discharge cycle.

If the condenser plate voltage is tuned, the different mass of helium can be observed in principle. According to a simple orbit calculation for the CNPA, the helium beam spot is different from the position of the channeltron array, which is adjusted for hydrogen even if the plate voltage is tuned for helium [8]. Here, we assume that the helium ions are singly ionized after translation through the carbon film. The spot size is assumed to be determined by the aperture size (ϕ = 2 mm), and geometric configuration of the plasma and detector. In the low-energy region, the spot size may be enlarged due to scattering in the foil.

The helium beam spots are not positioned in the detector array for high-energy helium ions when the plate voltage is adjusted to a low-energy channel, because the detector array position is adjusted for protons. We performed accurate calculations for obtaining the helium detector efficiency. The helium energy spectrum must be obtained, because we are interested in low-energy helium spectra in LHD experiments.

The calibration procedures are as follows:

(1) Compare the simulation model [9] including accurate orbit calculation with the experimentally calibrated

value in hydrogen.

(2) Comparison in (1) is nearly perfect. Therefore, we believe the simulation model is accurate, and calculate the efficiency in helium and scattered hydrogen when the plate voltage is set to be 1/4 times that for hydrogen.

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

4. Experimental Results

LHD has a toroidal mode number of $m = 10$ and helical mode number of $l = 2$. The major and minor radii are 3.9 and 0.6 m, respectively. The helical ripple is 0.25, and the maximum magnetic field is 3 T. Although the standard magnetic axis is 3.75 m, it can be changed from 3.4 to 4.1 m by applying a vertical magnetic field. There are three different heating systems: electron cyclotron resonance heating (ECH, 2 MW), neutral beam injection heating (NBI, 15 MW), and ICH (3 MW). A maximum electron temperature of 10 keV is observed using Thomson scattering and 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.

Figures 3 (a) and (b) show the time histories of the hydrogen and helium energy spectra with plasma parameter waveforms in two similar shots. In order to obtain a high–electron-temperature plasma, NBI#1, #2, and #3 are injected during 0.4 s at the beginning of the discharge [10]. After that, the plasma is maintained by NBI#2. During this phase, the power of NBI#2 is maintained low, as the effect of ICH application can be clearly seen. A line averaged plasma density of 2×10^{19} m^{-3} and central plasma temperature of 2 keV can be observed. ICH pulses are applied at two different timings. ECH is overlapped at the second ICH pulse in order to achieve highly efficient electron heating at the high electron temperature. However, the high electron temperature is not sufficiently high because the electron resonance region at this combination of the 2$^{\text{nd}}$ harmonic frequency of ECH and magnetic field is off-axis. Typical stored energy increment due to the ICH application of 1.55 MW and ECH is 20-60 kJ around $W_p = 300$ kJ. Temperature increase is small in hydrogen plasma. Main contribution to W_p increment may come from the density increase at the plasma edge.

We change the gas from hydrogen to helium in order to study the electron heating reduction due to power absorption by helium ions. The helium resonance layer is around $\rho = 1/3$ at the 3rd harmonic of ICH. As a result, W_p is obviously reduced by helium gas puffing [10]. The reduction rate depends on the amount of puffing. Therefore, the absorption due to electrons may be reduced because the injection power of ICH is partially absorbed by helium ions. The rate of increase of W_p is large at the high electron temperature. This means that effective electron heating by

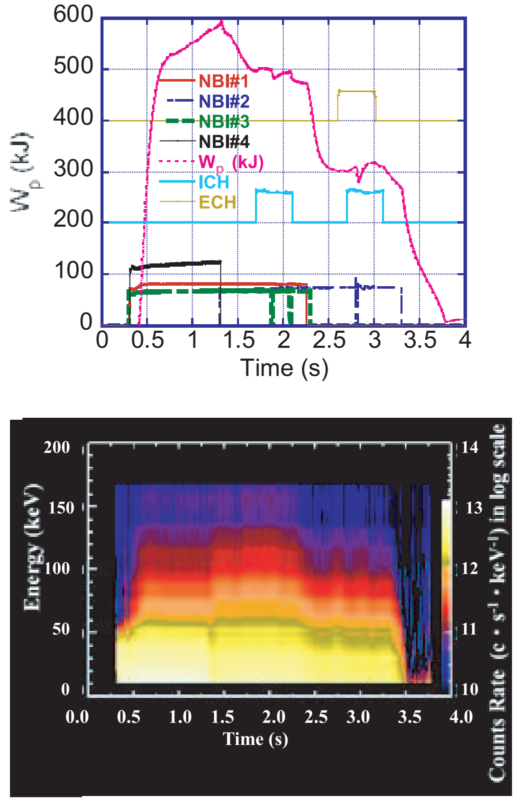

Fig. 3 (a) Time histories of plasma parameters and neutral particle energy spectrum in the voltage setting for hydrogen. The mixture gas of He/H is used.

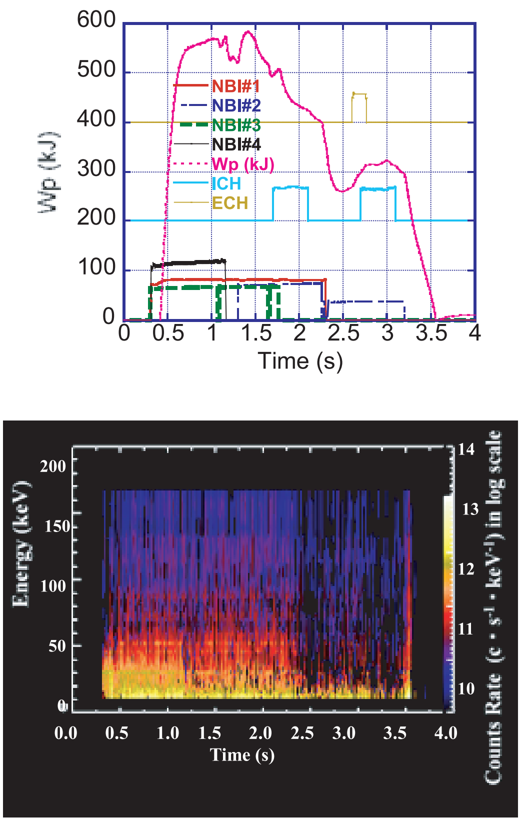

Fig. 3 (b) Time histories of plasma parameters and neutral particle energy spectrum in the voltage setting for helium. The mixture gas of He/H is used.

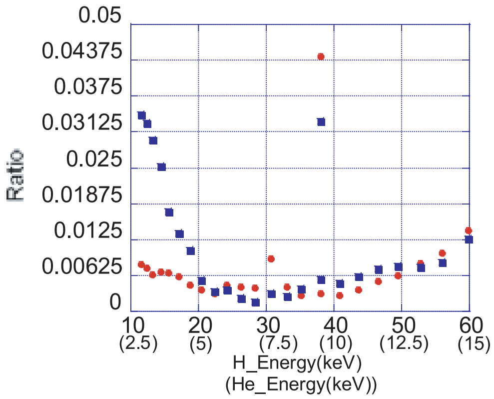

Fig. 4 Energy dependence of He/H ratio.

ICH can be obtained at the high temperature, especially in hydrogen plasma. On the contrary, in helium plasma, the temperature dependence of the rate of increase of W_p is not significant. In hydrogen plasma, the ICH power is easily absorbed by plasma electrons because there is no hydrogen resonance region. However, in helium plasma, the power deposition of ICH to electrons is not enough due to the existence of the helium ion resonance layer.

To confirm helium acceleration, we compared helium and hydrogen spectra using the CNPA with different plate voltages. Figure 4 shows the ratio of He and H signals in two similar shots. We must remember that most signals are due to hydrogen even if we set the plate voltage for helium. Therefore, the ratio indicates the ratio between the scattered hydrogen plus helium and actual hydrogen. The large ratios at the low- and high-energy regions are due to the large scattering at the foil and close trajectory of the hydrogen beams, respectively. ICH is applied at 3.0 s, but not at 1.0 s. He/H ratio lower than the helium energy of 5 keV at 3.0 s is obviously larger than at 1.0 s. This suggests that the low-energy helium ions are accelerated by the higher harmonic ICH.

Higher harmonic heating can be applied to simulation of α particle heating although it is not effective for electron heating. There is another candidate for helium acceleration as He^3/He^4, but it is too difficult because of hydrogen contamination. By tuning the magnetic field and frequency of ICH, higher acceleration energy of helium ions over 5 keV can be expected. To obtain accurate helium measurement, a mass-resolution analyzer should be utilized. However, scattering of protons in the analyzer should still be considered.

5. Summary

A helium acceleration experiment to study the future α particle measurement was conducted. It is very important to establish the α particle measurement because helium/α particles form a bubble and damage the wall surface seriously. Higher harmonic ICH without the hydrogen resonance layer is used for electron heating using Landau damping. A helium resonance layer is present at $\rho = 1/3$. In LHD, we can find helium particles using the charge-exchange neutral particle method in this experiment. By helium acceleration, the electron heating efficiency is reduced. This suggests the approach to obtain efficient heating. The detailed results will be reported elsewhere. Furthermore, we have obtained a useful tool for developing α particle measurement.

Acknowledgments

This work was performed under NIFS-ULBB509, the grants aid of No. 17540475 and 18035013.

[1] L. Chen, Phys. Plasmas **1**, 1519 (1994).
[2] O. Motojima *et al.*, Fusion Eng. Des. **20**, 3 (1993).
[3] Y. Kubota *et al.*, , J. Nucl. Mater., **313-316**, 239 (2003).
[4] T. Mutoh *et al.*, Phys. Rev. Lett. **85**, 4530 (2000).
[5] H.Kasahara *et al.*, 5th Asia Plasma Fusion Association, Jeju, Korea, Aug., (2005).
[6] T. Seki, private communication.
[7] T. Ozaki *et al.*, Rev. Sci. Instrum. **77**, 10E917 (2006).
[8] T. Ozaki *et al.*, JPFR Series, (to be published).
[9] T. Ozaki *et al.*, proc. of Burning Plasma Diagnostics in Varenna (2007) (to be published).
[10] Y. Takase, private communication.