Third Harmonic ICRF Heating in LHD High Beta Experiments

S. Kamio[1], R. Seki[12], T. Seki[12], K. Saito[1], H. Kasahara[12], S. Sakakibara[12], T. Mutoh[3], and LHD experiment Group[1]

[1]*National Institutes of Natural Science, National Institute for Fusion Science, Toki, Gifu, 509-5292, Japan*

[2]*SOKENDAI (The Graduate University for Advanced Studies), Toki, Gifu, 509-5292, Japan*

[3]*Chubu University, Kasugai, Aichi 487-8501, Japan*

The ICRF power injection in the high beta experiment in LHD was demonstrated after recent upgrade of ICRF antennas. The ICRF wave couples and accelerates the energetic particles which are provided by perpendicular-NBIs with 40 keV. The simulation by the MORH code shows the existence of the energetic particles around the ICRF third harmonic resonance layer. As the result of ICRF heating power deposition, the beta value clearly increased and achieved the value of up to 4.1%. The increase of the ion and the electron temperature were not observed, however, the increase of the high energy ions was observed and the ICRF heating efficiency is estimated approximately 30-50%, estimated by the break in slope at the turning off timing of ICRF power. The heating efficiency increase with the density increase.

I. INTRODUCTION

In order to investigate the physics of the high beta confinement, the low magnetic field experiments are demonstrating in the Large Helical Device (LHD). To realize a commercial fusion reactor, high beta confinement is required for reducing the initial cost of the reactor. The ion cyclotron range of frequencies (ICRF) heating is studied in this low magnetic field condition using ICRF higher harmonic wave heating [1]. From the viewpoint of the fusion reactor, the research of the ICRF higher harmonic wave is important in considering the shape of antenna that can be used in a fusion reactor, such as an option of wave guide antenna. The ICRF third harmonic experiments demonstrate for validation of the ICRF wave coupling with fast ions and increasing the energetic particles. In tokamak case, JET and ASDEX-U demonstrated the ICRF third harmonic heating in deuterium plasma [2,3]. In their experiments, the neutron generated by the D-D fusion count rate was increased with ICRF heating. The third harmonic ICRF wave accelerated the energetic particles produced by neutral beam injection (NBI). This ICRF and NBI heating operation showed high neutron generation efficiency.

In the recent LHD experimental campaign, the FAIT antenna was installed [4], the faraday shield on PA antenna was removed [5], and the ICRF control system was upgraded [6], by these updates, high ICRF power up to 4.5 MW can be injected [7]. This is the same level with the JET and the ASDEX-U third harmonic experiments. With this ICRF heating system on LHD, the third harmonic experiments has been demonstrated for investigating the ICRF third harmonic characteristics and achieving higher beta value.

II. Experimental Setup

Figure 1 shows the schematic top view of the LHD and the heating devices. The arrows show the directions of #1-5 NBIs. The LHD has three negative NBI systems #1-3 for tangential direction with 180 keV and two positive NBI systems #4,5 for perpendicular direction with 40 keV. Three ICRF antennas, HAS, FAIT, and PA antenna, are shown with green rectangle. HAS is a toroidal array antenna, FAIT and PA is poloidal array antennas. By recent installing of the impedance transformer, which are optimized at the frequency of 38.5 MHz, the VSWR was decreased and the total ICRF heating power increased [8].

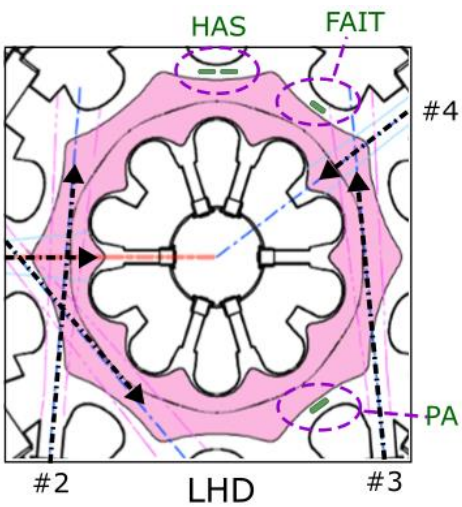

FIG. 1. Schematic top view of the LHD and the heating devises. The arrows show the #1-5 neutral beam directions. The ICRF antennas, HAS, FAIT, PA antenna, are shown with green color.

Figure 2 shows the lines of calculated magnetic flux and magnetic field contours, right hand cutoff, and the hydrogen resonance layer of the ICRF heating in the condition of 100% hydrogen, magnetic field of 1.0 T, and the ICRF parallel wave number k//=5.0 m^{-1}. By decreasing the magnetic field to 1.0 T, the ICRF heating is considered to be third harmonic heating. In Fig. 2, the second harmonic lines seems to be overlapping on the plasma flux surface, however, in actual shape of flux surface is concentrated in high beta experiment. Therefore the ICRF resonance of the second harmonic is outside of the last closed flux surface. The energetic particle calculation by MORH code [9] shows that the fast ion density injected by the perpendicular-NBIs are accumulated on the third harmonic resonance layer as shown in Fig. 2 blue color contour. In the calculation, the electron density is assumed 3x10^{19} m^{-3} hollow distribution. The upper and lower asymmetry derives from the history of the inside and the outside of the NBI port. In the high density plasma, energetic particles from the NBIs deposit outside the horizontal cross section. The high density side of the energetic particles rotates along the helical structure, and reaches the upper side or the lower side at the vertical cross section. In order to inject the ICRF power to the high beta plasma, we intend to utilize the third harmonic heating.

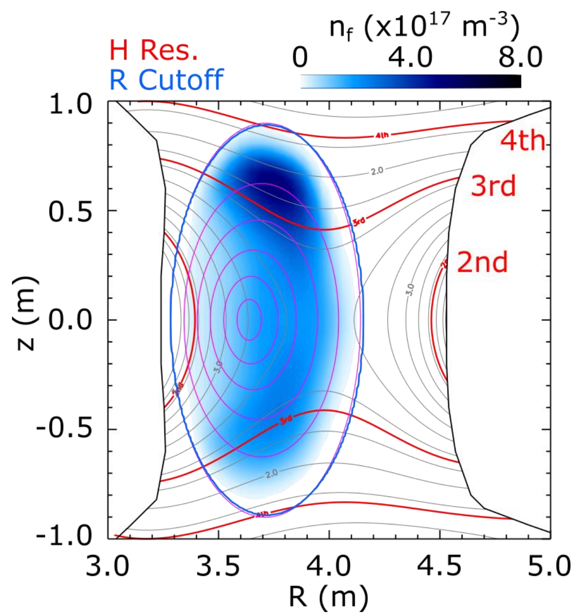

FIG. 2. The lines are calculated flux and magnetic field contour, right hand cutoff, and the hydrogen resonance layer of the ICRF heating in the condition of 100% hydrogen, magnetic field of 1 T and k//=5.0 m^{-1}. The blue color contour is energetic particle flux density supplied by 40 kV radial NBIs. This flux density is calculated by MORH code.

III. Results and Discussions

As the condition of the LHD high beta experiment, the magnetic field is 0.5-1.0 T, magnetic axis is around 3.60 m, and the heating powers are tangential-NBIs 15 MW and perpendicular-NBIs 10 MW. As a result of the ICRF injection, the maximum beta value is increased as shown in Fig. 3 [10]. The 2-4 MW ICRF heating clearly contributed to the increase of the beta value more than 0.2%. In this ICRF third harmonic experiments with NBI, the ICRF wave well absorbed and the stored energy increased. The typical waveforms of these experiments are shown in Fig. 4. In these experiments, the gas of the NBI

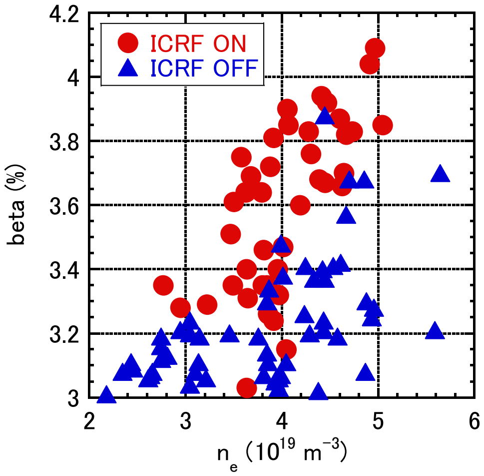

FIG. 3. The achieved beta value of all the discharges of high beta experiment in LHD 18th campaign in 2014-15. The ICRF heating clearly contributed to the increase of beta value.

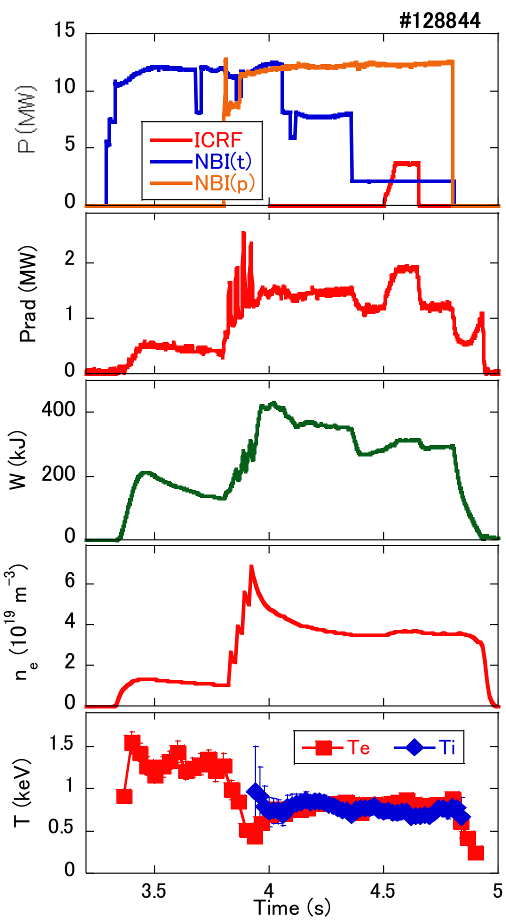

FIG. 4. The typical waveforms of the NBI and ICRF heating power, the radiation loss power, the stored energy measured by diamagnetic loops, the electron density, and the ion and electron temperatures in the high beta experiments. The energy of tangential-NBIs are 180 keV, perpendicular-NBIs are 40 keV. The beams and the target plasma is hydrogen, and the toroidal magnetic field is 1 T at the magnetic axis.

and target plasma are 100% hydrogen, and the toroidal magnetic field is 1.0 T at R=3.56 m which is magnetic axis at vacuum. The ICRF power is 1.9-3.9 MW, the 40 keV perpendicular-NBIs power is 11-12 MW, and tangential-NBIs is 2-3 MW. In this discharge, the radiation loss power is 0.7 MW during the 3.7 MW ICRF heating. This ratio is less than 20% of the net injected power. The stored energy is slightly increased approximately 20 kJ during the ICRF heating on timing. The density of the electron and the temperatures of the ion and the electron are almost constant with and without ICRF injection.

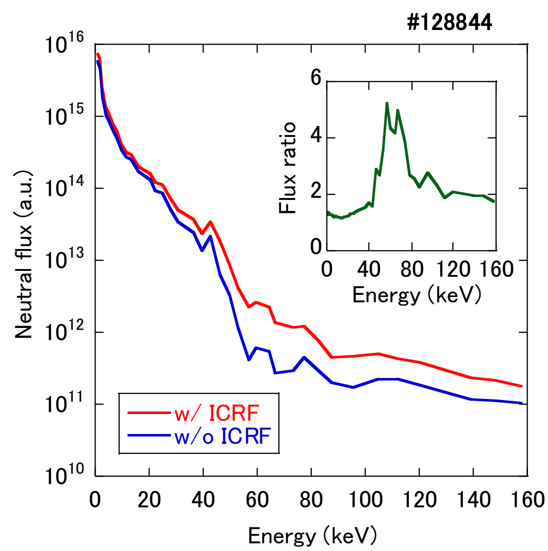

FIG. 5. The energy distributions of neutral flux with and without ICRF heating, measured by CNPA. The green line shows the flux ratio of with and without ICRF heating.

Figure 5 shows the energy distributions of neutral flux measured by compact neutral particle analyzer (CNPA) [11]. Similar with the results of other devices, the count of energetic particles increased with ICRF heating especially more than 40 keV, which is the injection energy of perpendicular-NBIs. The increasing flux ratio strikingly increase at the energy of 40-80 keV. This means the ICRF wave accelerate the 40 keV particles produced by perpendicular-NBIs. However, the distributions of the electron density and the electron temperature measured by

Thomson scattering are almost the same as shown in Fig. 6. In this low magnetic field experiments, the relatively large Larmor radius causes the orbital loss of energetic particles [12]. This energy loss is considered to be the one of the reason of small contribution to the electron temperature. The component which increase the stored energy can be considered to be the accelerated particles.

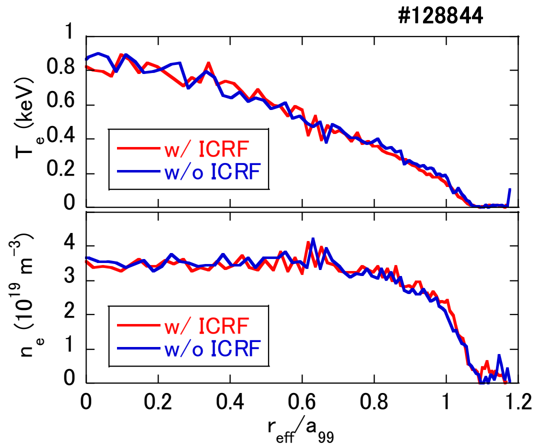

FIG. 6. The distributions of electron temperature and density. There are no clearly difference observed between with and without ICRF heating.

When the electron density and temperature are almost the same value, using the decreasing of the stored energy at the ICRF power turning off timing, the heating efficiency η can be evaluated by the following equation.

$$\frac{\mathrm{d}W}{\mathrm{d}t} = \eta P$$

The differential value dW/dt of this discharge is approximately -1.6 MJ/s, and the heating efficiency η is 44%. The electron density dependence of η is shown in Fig. 8. The ICRF heating efficiency is estimated approximately 30-50% by the break in slope at the ICRF turning off timing. The heating efficiency increase with the density increase. This values of efficiency and increasing tendency are the similar results of former researches in ICRF second harmonic heating experiments [13]. The ICRF perpendicular wave number $k_\perp$ increase with the density increasing. The increase of the η is considered to be the result of $k_\perp$ increase.

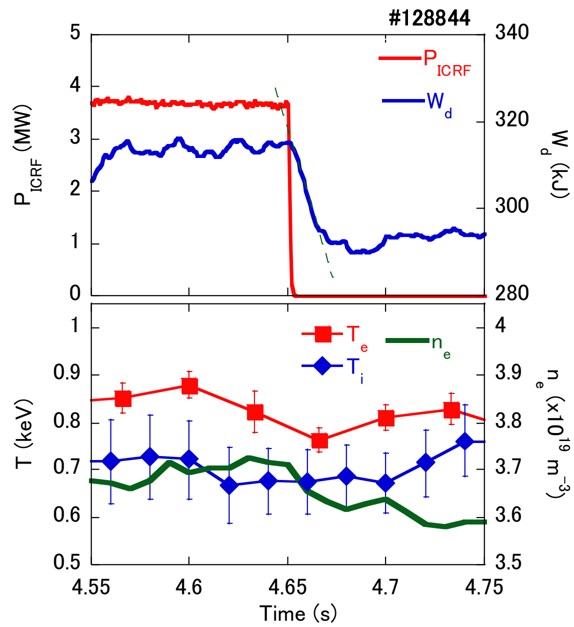

FIG. 7. The time evolution of W_d decreasing after turning off the ICRF heating power, and the density and temperatures.

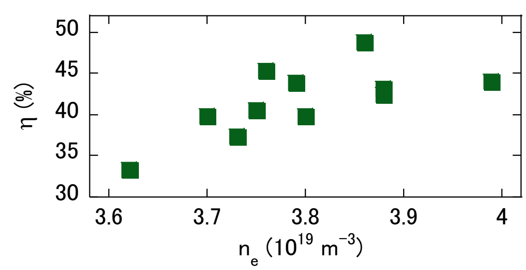

FIG. 8. The electron density dependence of the heating efficiency using similar discharge #128803-844.

IV. Conclusion

The ICRF injection in the high beta experiment in LHD was demonstrated. ICRF wave couples and accelerates the energetic particles which are provided by perpendicular-NBIs with 40 keV. The simulation by the MORH code shows the existence of the energetic particles around the ICRF third harmonic resonance layer. As the results of ICRF heating power deposition, the plasma stored energy increased during the ICRF injection, the beta value clearly increased, and achieved the value of up to 4.1%. The increase of the ion and the electron temperature were not observed, however, the increase of the high energy ion tail was observed. The ICRF heating efficiency is estimated approximately 30-50%, and the radiation loss is less than 20%. The heating efficiency increase with the electron density increase. These results indicate the effectiveness of the ICRF third harmonic heating under the higher density and good confinement.

ACKNOWLEDGMENTS

This work was supported by NIFS Grant No. ULRR702 and ULRR703.

REFERENCES

[1]K. Saito, *et al*., Plasma Fusion Res. (2009).
[2]C. Hellesen, *et al*., Nucl. Fusion **53**, 113009 (2013).
[3]MJ. Mantsinen, *et al*., 43rd EPS Proc. P1.035 (2016).
[4]K. Saito, *et al*., Fusion Eng. Des. **96-97**, (2015) 583-588.
[5]T. Seki, *et al*., 2014 Proc. IAEA Fusion Energy Conf. FIP/P5-3
[6]S. Kamio, *et al*., Fusion Eng. Des. **101**, (2015) 226-230.
[7]T. Mutoh, *et al*., Nucl. Fusion **53**, 063017 (2013).
[8]K. Saito, *et al*., J. Phys. Conf. Ser. 823 (2017) 012007.
[9]R. Seki, *et al*., Plasma Fusion Res. **5** (2010) 027.
[10]S. Sakakibara, *et al*., Nucl. Fusion **57**, 066007 (2017).
[11]T. Ozaki, *et al*., AIP Conf. Proc. 812, 399 (2006).
[12]K. Saito, *et al*., 2006 Proc. IAEA Fusion Energy Conf. EX/P6-17.
[13]K. Saito, *et al*., Plasma Phys. Control. Fusion **44** (2002) 103-119.