Third harmonic ICRF heating in LHD hydrogen experiments

S. Kamio\textsuperscript{1}, R. Seki\textsuperscript{1,2}, T. Seki\textsuperscript{1}, K. Saito\textsuperscript{1}, H. Kasahara\textsuperscript{1}, S. Sakakibara\textsuperscript{1,2}, G. Nomura\textsuperscript{1}, T. Mutoh\textsuperscript{3} and The LHD Experiment Group\textsuperscript{1}

\textsuperscript{1} National Institute for Fusion Science, National Institutes of Natural Science, Toki, Gifu, 509-5292, Japan
\textsuperscript{2} SOKENDAI (The Graduate University for Advanced Studies), Toki, Gifu, 509-5292, Japan
\textsuperscript{3} Chubu University, Kasugai, Aichi 487-8501, Japan

E-mail: kamio@nifs.ac.jp

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Abstract
The ion cyclotron range of frequencies (ICRF) heating power injection in the hydrogen experiment in LHD was demonstrated after the upgrade of ICRF antennas. The ICRF wave couples and accelerates the energetic particles injected by perpendicular-NBIs with 40 keV. The simulation by the MORH code shows the existence of energetic particles around the ICRF third harmonic resonance layers. As the result of ICRF heating power deposition, the beta value increased by 0.2% in absolute beta mainly due to the increased energetic particle content. The increase of energetic ions particularly around 60 keV, which should be accelerated by the ICRF heating, is observed. The ICRF heating efficiency was approximately 30\%–50\%, estimated from the break-in-slope analysis at the turn off timing of ICRF power from the stored energy measured by diamagnetic loops. This increase of the stored energy is mostly the contribution of the increased energetic particles. The heating efficiency increases as the density increases.

Keywords: ICRF, LHD, high beta, third harmonic

(Some figures may appear in colour only in the online journal)
problem was removed and the PA antenna continued to perform soundly [7]; further, the ICRF control system was upgraded [8]. After these upgrades, ICRF power that radiated to the plasma increased up to 4.5 MW [9]. This is the same power level with the JET and ASDEX-Upgrade third harmonic experiments. With this ICRF heating system on LHD, several experiments have been performed for the investigation of ICRF third harmonic characteristics and achieving a higher beta value. These experiments can demonstrate the synergistic effects of the energetic particles injected by NBI and accelerated by the third harmonic ICRF wave.

2. Experimental setup

Figure 1 shows the schematic equatorial plane cross section of the LHD and heating system configuration. The arrows show the #1–5 neutral beam directions. The ICRF antennas, HAS, FAIT, and PA antenna are shown by the green color. The line of sight of the CNPA is shown with the blue colored arrow.

Figure 1. Schematic top view of the LHD and heating configuration. The arrows show the #1–5 neutral beam directions. The ICRF antennas, HAS, FAIT, and PA antenna are shown by the green color. The line of sight of the CNPA is shown with the blue colored arrow.

Figure 2. The poloidal cross section view of the LHD. The lines are calculated flux surface and magnetic field strength contour, right hand cut-off, and the hydrogen resonance layers for 38.5 MHz with the condition of 100% hydrogen, magnetic field of 1 T and \( k_{\parallel} = 5.0 \, m^{-1} \). The blue color contour is the energetic particle flux density \( n_f \) supplied by 40kV p-NBIs. This flux density is calculated by the MORH code.

In order to evaluate the pressure of the fast ions in the LHD, the MORH code [11] is used. This code is a drift kinetic orbit-following the Monte Carlo code. The finite beta equilibrium is calculated by HINT2 [12, 13]. The birth profiles of fast ions injected by NBI, which are used as the fast ion source of the MORH code, are calculated by FIT3D code [14]. The result shows that the fast ion density \( n_f \) injected by the perpendicular-NBIs (p-NBIs) is accumulated close to the third harmonic resonance layer as shown in figure 2, by the blue color contour. The higher \( n_f \) can be seen at the upper and the lower regions. In LHD, the low magnetic field regions are located in the upper side and in the lower side in the cross-section shown in figure 2, and fast ions are trapped in the ripple. The upper and lower asymmetry is derived from the deposition profile of the NBI injected from the outer side of the vacuum chamber. In order to inject the ICRF power to achieve a high beta plasma, we utilize the third harmonic ICRF heating. In this condition, the ICRF heating power is considered to be absorbed by the energetic ions from the p-NBIs at the third harmonic resonance layers.
3. Experimental results

For the investigation of the LHD high beta experiment with ICRF heating, the gas of the NBI and target plasma are 100% hydrogen, the toroidal magnetic field is 1.0 T at the vacuum magnetic axis, $R = 3.56$ m, and the NBI injection powers are 2 MW by the tangential-NBIs (t-NBIs) and 12 MW by the p-NBIs. The initial plasma was generated by using only NBIs [15]. The increasing beta value by ICRF heating can be evaluated by comparison with and without ICRF injection shown in figure 3. The 4 MW ICRF heating clearly contributed to the increase of the beta value from 2.4% to 2.6%. In this ICRF third harmonic experiments with NBI, the ICRF wave was absorbed and the stored energy was increased. The increase of 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 by 20 kJ during the ICRF heating on timing. The electron density and the temperatures of the ions and electrons are almost constant with and without ICRF injection.

Figure 4(a) shows the energy distribution functions of neutral flux measured by CNPA. The vertical axis indicates the measured count rate of the neutral particles at the energy range of more than 80 keV. At the energy range of less than 80 keV, the data is measured using the count rate together with the calibration factor of the detector size. The solid lines indicate the case with p-NBI, and the dotted lines indicate the case without p-NBI. In both cases, the ICRF injection increases the count of neutral flux from the blue lines to the red lines. The neutral flux ratio, which is the energy distribution function with ICRF injection divided by the distribution function without ICRF injection, is strongly increased at the energy of 40–80 keV shown by the solid line in figure 4(b) when p-NBI injection is present. In the case of p-NBI, the neutral flux count is increased up to more than five times at around 60 keV. These results indicate that the ICRF wave accelerates the 40 keV particles injected by p-NBIs. However, the distributions of the electron density and the electron temperature measured by Thomson scattering are almost the same as shown in figure 5. In this low magnetic field experiment, the relatively large Larmor radius causes the orbital loss of energetic particles [3, 16]. This energy loss is attributed to one of the reasons for the small contribution to the electron temperature. Almost all of the increase of the stored energy of the diamagnetic signal should be considered to be the accelerated particles. When the electron density and temperature are almost constant, using the changing of the stored energy at the ICRF power turning off timing as shown in figure 6, the heating efficiency $\eta$ can be evaluated by the following equation [17].
where $\Delta P$ is the step in ICRF power. In the case of figure 6, the differential value $dW/dt$ of this discharge is approximately $-1.6$ MJ s$^{-1}$, and the heating efficiency $\eta$ is 44%. The dependence of the heating efficiency on the electron density is shown in figure 7 in the range $n_e$ at $\rho = 0.7$–0.9. Here, the energetic particles injected by p-NBIs and the ICRF third harmonic resonance are located. All of the results in figure 7 are discharges with p-NBIs, because in the case without p-NBIs, $dW/dt$ and the heating efficiency are small. The ICRF heating efficiency is approximately 30%–50% estimated by the break-in-slope at the ICRF turn off timing. This value of the efficiency and increasing tendency when the density is increased are similar results of previous research in second harmonic ICRF heating experiments [20]. One reason for this increasing tendency is that the ICRF perpendicular wave number $k_\perp$ increases with the density increasing [21].

As a result of the ICRF injection, the maximum beta value is increased up to 4.1% [18]. As the experimental condition of the highest beta discharge, the magnetic field is 0.5–1.0 T, vacuum magnetic axis is around 3.60 m, and the heating power is 15 MW by the t-NBIs and 10 MW by the p-NBIs.

4. Conclusion

The ICRF injection in the high beta experiment in LHD was performed. ICRF wave couples and accelerates the energetic particles provided by p-NBIs with 40 keV to approximately 60 keV when 3.7 MW of ICRF is applied. The simulation by the MORH code shows the presence 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, and the beta value clearly increased. The increase of the ion and electron temperatures were not observed. However, the increase of the high energy ion tail was observed. The increase of the beta value is mostly due to the contribution of the increased energetic particles. The ICRF heating efficiency is estimated to be approximately 30%–50%, and the radiation loss is less than 20%. The heating efficiency increases with the electron density increase. These results indicate the effectiveness of the ICRF third harmonic hydrogen heating under higher density and good confinement.

Acknowledgments

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References

[1] Saito K. et al 2010 Plasma Fusion Res. 5 S1030
[2] Kasahara H. et al 2006 J. Korean Phys. Soc. 49 S192–6
[3] Saito K. et al 2006 Proc. 21st Int. Conf. (Chengdu, 2006) EX/P6-17 CD-ROM (Vienna: IAEA) (www-naweb.iaea.org/napc/physics/FEC/FEC2006/papers/ex_p6-17.pdf)
[4] Hellesen C. et al 2013 Nucl. Fusion 53 113009
[5] Mantsinen M.J. et al 2016 43rd EPS Proc. p P1.035 (https://upcommons.upc.edu/bitstream/handle/2117/89375/Third%20harmonic%20ICRF%20heating%20of%20deuterium%20beam%20ions%20on%20ASDEX%20Upgrade.pdf)
[6] Saito K. et al 2015 Fusion Eng. Des. 96–7 583–8
[7] Seki T. et al 2014 Paper presented at 25th IAEA Int. Conf. on Fusion Energy (St Petersburg 2014) FIP/P5-3
[8] Kamio S. et al 2015 Fusion Eng. Des. 101 226–30
[9] Mutoh T. et al 2013 Nucl. Fusion 53 063017
[10] Saito K. et al 2017 J. Phys.: Conf. Ser. 823 012007
[11] Seki R. et al 2010 Plasma Fusion Res. 5 027
[12] Harafuji K. et al 1989 J. Comput. Phys. 81 169
[13] Suzuki Y. et al 2006 Nucl. Fusion 46 L19
[14] Murakami S. et al 1995 Trans. Fusion Technol. 27 256
[15] Kaneko O. et al 1999 Nucl. Fusion 39 1087
[16] Seki R. et al 2008 Plasma Fusion Res. 3 016
[17] Lerche E. et al 2008 Plasma Phys. Control. Fusion 50 035003
[18] Sakakibara K. et al 2017 Nucl. Fusion 57 066007
[19] Ozaki T. et al 2006 AIP Conf. Proc. 812 399
[20] Saito K. et al 2002 Plasma Phys. Control. Fusion 44 103–19
[21] Stix H. 1975 Nucl. Fusion 15 737