RF Wave Detection with High-Frequency Magnetic Probes in LHD*)

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The study of radio frequency (RF) waves was accelerated by the start of deuterium experiments in the Large Helical Device (LHD) and the introduction of wide-band and long-time data acquisition system. The mass dependency of Ion Cyclotron Emissions (ICEs) driven by perpendicular Neutral Beam Injection (NBI) was clarified by the injection of deuterium beams. Another type of ICE by the tangential beam injection was found in the LHD. Although the details of this type of ICE have not yet been elucidated, a clear linear dependency of its frequency on the magnetic field strength divided by the mass of beam species was found. Non-localized RF waves in the Lower Hybrid Wave (LHW) frequency region were also detected during the injection of a perpendicular beam. It is shown that the frequency increases with the electron density.

Keywords: radio frequency wave, ion cyclotron emission, lower hybrid wave, magnetic probe, large helical device, neutral beam injection

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1. Introduction

In the Large Helical Device (LHD) [1], Radio Frequency (RF) waves in the ion cyclotron frequency region have been investigated with high-frequency magnetic probes and Ion Cyclotron Range of Frequencies (ICRF) heating antennas as receivers [2–5]. Ion Cyclotron Emissions (ICEs) are excited by the non-Maxwellian velocity-space distribution of energetic ions [6]. There are many harmonics in ICEs, and the fundamental frequency is approximately equal to the ion cyclotron frequency at the excitation position. Therefore, measurement of ICEs can be a tool for understanding the behavior of energetic ions. In large tokamaks, ICEs excited at the plasma edge by fusion-born particles have been reported [7, 8]. ICEs excited by fusion-born particles have not yet been recognized in the LHD. However, in the LHD, ICEs excited at the edge of the plasma near the injection port of a perpendicular Neutral Beam Injection (NBI) are confirmed [2, 3]. At the plasma edge, particles supplied by the NBI are ionized to some extent and are lost immediately before the thermalization. Therefore, it is thought that a ring-shaped distribution in velocity space with the pitch angle of 90° is formed and ICEs are excited. Another type of ICE and wide-band RF wave were detected at the time of the MHD bursts of the Toroidicity-induced Alfvén Eigenmodes (TAE) or the Energetic ion driven resistive InterChange mode (EIC) [3, 5]. It is thought that the bursts lead to the transport of the energetic ions which is fast enough to form the non-thermal distribution. Additionally, RF waves were excited.

Although these experimental results were obtained with hydrogen beam injections, the investigation of RF waves excited by deuterium beams began with the start of deuterium experiments in the LHD. Moreover, the detectable frequency up to the Lower Hybrid Wave (LHW) region was enabled by the wide-band data acquisition system. This paper reports newly obtained results on the RF study with magnetic probes. In section 2, experimental devices are explained. The variation of the frequency of ICE driven by perpendicular NBI by changing the beam species is described in section 3. Another type of ICE driven by tangential NBI is described in section 4. Density-dependent RF waves in LHW region were also detected, and the results are shown in section 5. Section 6 is the summary section.

2. Experimental Devices

Port numbers in the LHD are allocated from 1 to 10.5 in clockwise fashion. There are two perpendicular NBIs at the 1-O and 5-O ports, where "O" means outer. Tangential NBIs are also found in the 1-T, 7-T, and 10-T ports, where "T" means tangential. Beam species are hydrogen or deuterium. These NBIs excite various RF waves.

Antennas for ICRF heating that are presently removed were once used as magnetic probes in 4.5-U and 4.5-L ports [2], where "U" and "L" indicate upper and lower. Two pairs of magnetic probes are attached at the 5.5-U and 6.5-U ports [3]; these probes are called 5.5U(a), 5.5U(b),

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6.5U(c), and 6.5U(d). Four probes are connected to the high-speed digitizer NI PXIe-5160 with the −3 dB bandwidth of 300 MHz and data are routinely acquired with typical sampling of 250 MS/s for 5 seconds continuously with the resolution of 8 bits. Four signals are split at the ports of the probes and the two signals of probes 5.5U(b) and 6.5U(d) are transmitted to NI PXIe-5162 with the −3 dB bandwidth of 1.5 GHz through low-attenuation cables for the detection of waves with the frequency in the LHW range of several hundred MHz. Typically, the sampling rate is 2.5 GS/s and the resolution is 10 bits. Data are typically acquired for 20 µs followed by a gap of 980 µs, which is then followed by a second data acquisition time of 20 µs. This pattern is repeated for 5 s. Continuous data acquisition for 200 ms is also possible.

3. Ion Cyclotron Emission Driven by Perpendicular Neutral Beam Injection

Figure 1 (a) shows the NBI power, the stored energy W_p, the line-averaged electron density $\bar{n}_e$, and the spectrogram of the signal of the probe 5.5U(b). The magnetic axis is located at $R = 3.6$ m, and the magnetic field strength on the axis B_{ax} is −2.75 T, where a plus or minus signs of B_{ax} indicates that the magnetic field direction is clockwise or counter-clockwise, respectively. ICEs were excited only during the injection of perpendicular hydrogen beams. The averaged power spectral density (PSD) from 5.3 s to 7.3 s has peaks at 24.0, 48.2, 73.6 MHz, etc. By changing species of perpendicular beams from hydrogen to deuterium, the peak frequency changed as shown in Fig. 1 (b). The averaged PSD from 5.3 s to 5.8 s has peaks at 12.4, 24.6, 37.1 MHz, etc. These frequencies are approximately one-half that of the hydrogen injection. The ion cyclotron frequency Ω is written as $\Omega = qB/m$, where q, B, and m are the charge of ions, the absolute value of magnetic field strength, and the mass of ions, respectively. It is thought that by exchanging the beam species from hydrogen to deuterium, the mass doubled, and as a result the frequency was halved. The linear magnetic field dependency of the frequency has been previously described [2]. Although charge dependency was not confirmed, this mass dependency clearly verified that the detected RFs were ICEs. This experimental result also means that the excitation area was almost fixed at the plasma edge even if beam species was changed. In this plasma edge region near the perpendicular NBI ports, the distribution function is thought to be distorted though the measurement has not been conducted yet.

4. Ion Cyclotron Emission Driven by Tangential Neutral Beam Injection

Another type of ICEs is often observed during the injection of the tangential NBI into a vacuum without gas-puffing for the calibration of the port-through power of NBI which depends on the configuration of the magnetic field. Figure 2 shows the power of tangential hydrogen NBIs, the line-averaged electron density, and the spectrogram of the detected signal with the ICRF antenna at the 4.5-L port in a calibration shot. The line-averaged electron density slightly increased during injections of NBIs, but the density was less than 1×10^{17} m^{-3}, and ICEs were then observed. The time-averaged PSD from 0 to 3 s had peaks at the frequencies of 20.7, 43.6, 66.9, and 89.4 MHz. In general, the PSD of a fundamental ICE is small, but those of second and third harmonics are large. When those ICEs shown in Fig. 2 were observed, energetic particles with the pitch angle of approximately 90° and with the energy approximately the injection energy of NBIs were also observed as shown in Fig. 3. In this measurement, a silicon-diode-based fast neutral analyzer [9] with a line-of-sight almost perpendicular to the magnetic field lines was used. There is a possibility that this population inversion may excite ICEs. ICE frequencies at various magnetic field strengths with the two different beam species were investigated. Figure 4 shows the relationship between frequency

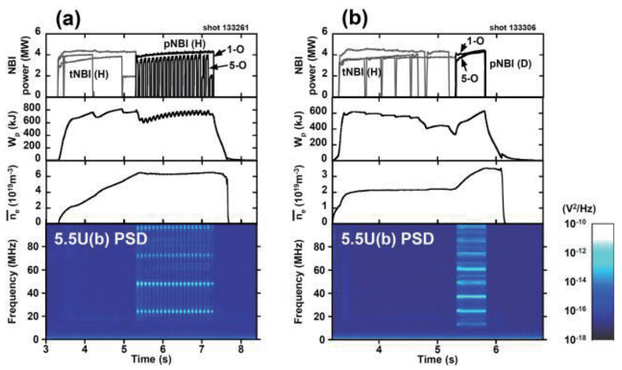

Fig. 1 The emergence of ICEs at the timing of perpendicular injection in the cases of (a) hydrogen beam into hydrogen plasma and (b) deuterium beam into the mixed plasma of hydrogen and deuterium.

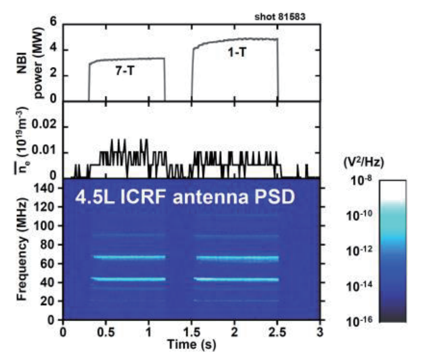

Fig. 2 The emergence of ICEs at the time of tangential beam injections into an extremely low-density plasma. The major radius of the magnetic axis was 3.6 m and the magnetic field strength on the axis was +1.5 T.

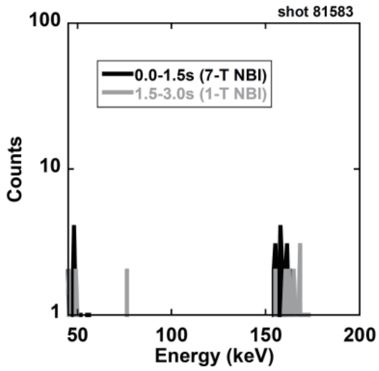

Fig. 3 The energy spectrum of energeticparticles. The line-of-sight is approximately perpendicular to the magnetic field lines.

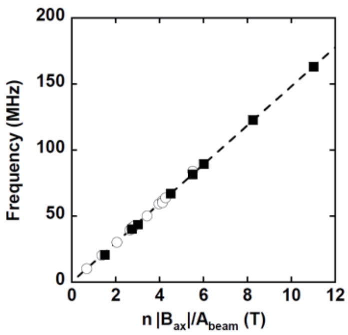

Fig. 4 The relation between the frequency of ICEs excited by tangential NBIs in extremely low density plasmas and the value of $n|B_{ax}|/A_{beam}$. The symbols ■ and ○ mean hydrogen and deuterium beams, respectively.

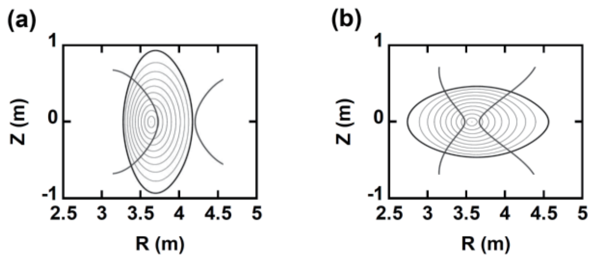

Fig. 5 Flux surfaces and the layers where the fundamental ICE frequency corresponds to the ion cyclotron frequency in (a) vertically and (b) horizontally elongated toroidal cross sections.

and $n|B_{ax}|/A_{beam}$, where n is the harmonic number, $|B_{ax}|$ is the absolute value of magnetic field strength on the axis located in the major radius of 3.6 m, and A_{beam} is the mass number of beam ions. It was clarified that the frequency is proportional to the ion cyclotron frequency. Therefore, this type of emission is also thought to be an ICE. Figures 5 (a) and (b) show the layers where the cyclotron frequency of the beam ions is the same as the fundamental ICE frequency estimated from the linear relationship of the frequency = $14.8n|B_{ax}|/A_{beam}$ obtained from Fig. 4. The position of the layers depends on the coefficient of 14.8. ICEs are thought to be excited somewhere on the layers. The particles that excite ICEs were not well confined because the ICEs immediately disappeared within 1 ms after turn-off of the NBIs. Normally, this type of ICE is observed when the electron density is extremely low. However, even in the high-density plasma of more than $1 \times 10^{19}\ m^{-3}$, ICEs with almost the same frequencies were sometimes observed as shown in Fig. 6. The excitation mechanism of this type of ICEs is presently unknown.

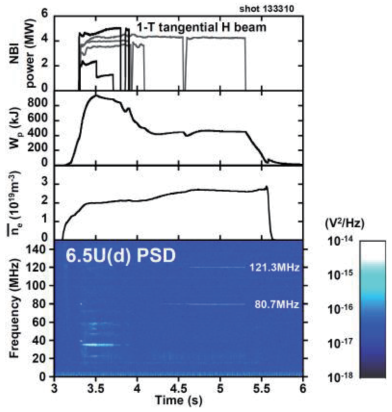

Fig. 6 ICEs excited by a tangential hydrogen beam in high-density plasma. The major radius of the magnetic axis was 3.6 m and the magnetic field strength on the axis was −2.75 T.

5. RF Wave with the Frequency of LHW Range

The LHW frequency region of several hundred MHz was also investigated with the magnetic probes. Figure 7 shows the discharge where perpendicular deuterium beams were injected. The major radius of the magnetic axis was 3.6 m and the magnetic field strength on the axis was −2.75 T. Then, the wave with a varying frequency of from 200 MHz to 400 MHz was clearly detected with the 5.5U(b) probe and the 6.5U(d) probe at the two different ports even in the timing of 1-O NBI alone on the opposite side of the probes, though the square coherence between the two signals was small ($coh^2 < 0.1$). Among the shown parameters of the stored energy W_p, the center electron temperature T_{e0}, the center ion temperature T_{i0}, and the line-averaged electron density $\bar{n}_e$, it seems that the frequency is dependent only on the line-averaged electron density. This density dependent RF wave is thought to be the wave in the frequency region of LHW detected with the collective Thomson scattering diagnostic in LHD [10]. Another feature of this type of RF wave is that the wave is not localized. Figure 8 shows the averaged PSD detected with the two probes 5.5U(b) and 6.5U(d) in different ports during the injection of the 5-O beam. The structure of ICEs driven by perpendicular NBI is seen in the low-frequency region of PSDs. In Ref. 3 it was clarified that ICEs with the

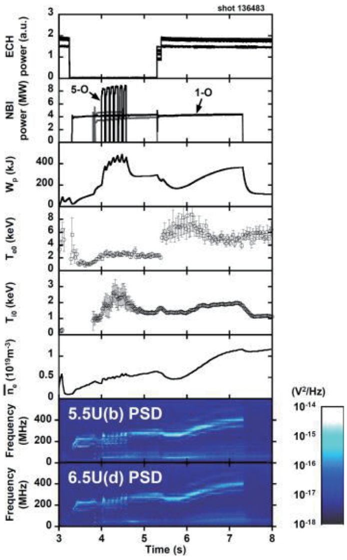

Fig. 7 The LHW range RF excited by perpendicular beam injections.

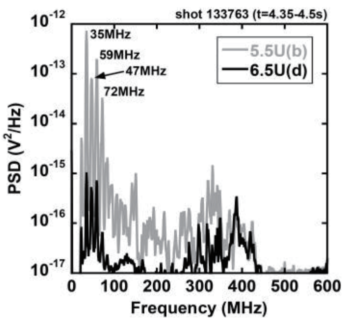

Fig. 8 Power spectra of RFs measured with two different ports at the time of the 5-O NBI without 1-O NBI.

frequency of several ten MHz are localized around the port of a perpendicular NBI. By comparison of the two PSDs in Fig. 8, it was found that the frequency region of the localized wave is extended up to 350 MHz because of the large difference of intensities. On the other hand, the RF with the frequency around 400 MHz is not localized because the intensities are almost the same. The clear detection of RF excited by 1-O NBI with the opposite side probes as shown in Fig. 7 is attributable to this non-localization of the wave. Moreover, it was found that the signal immediately decreases and disappears by the turn-off of the NBI within 100 μs. This means that excitation particles are not well confined. In order to investigate the dependency of the frequency on the line-averaged electron density in detail, the frequency at which the maximum PSD occurred was searched for in various density plasmas. The obtained frequencies and line-averaged electron densities were time-averaged with the span of 0.1 s. The signal of the probe 6.5U(d) was used because contamination of the localized RF wave, which generally increases with density, could be avoided by using the probe farthest from the

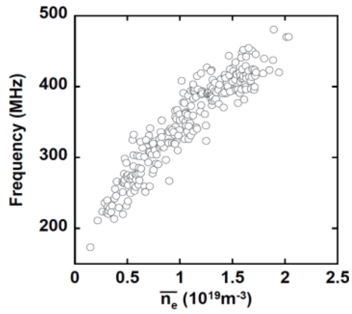

Fig. 9 The relation between the peak frequency of the LHW range RF and the line-averaged electron density.

injection port of 5-O NBI. Figure 9 shows the obtained relation between the peak frequency and the line-averaged electron density. In this data set, the perpendicular beam species was deuterium and the magnetic axis was fixed at $R = 3.6$ m. The absolute value of magnetic field strength on axis was between 2.705 and 2.85 T. The frequency increases with the line-averaged electron density. In order to simulate RF waves excited by energetic ions, Particle In Cell (PIC) simulation was conducted with the following assumptions [11].

- Excitation position is the same with that of ICEs driven by perpendicular NBIs.
- Density and magnetic field are homogeneous.
- High-energy beam ions have the ring-shaped distribution function with the pitch angle of 90°.
- Direction of wave is perpendicular to the magnetic field.

An RF wave with the frequency of several hundred MHz as well as low-frequency ICEs were generated in the simulation. As mentioned in Ref. 11, the tendency that the frequency increases with the electron density is the same with that of the simulation. However, there is a discrepancy in electron density between experiment and simulation. Therefore, the excitation position should be reviewed.

6. Summary

By injecting hydrogen and deuterium beams, a study of mass dependency of ICE frequencies was conducted. The frequency of ICEs obtained at the time of a perpendicular NBI showed a dependency on the mass of beam species as well as the magnetic field strength. It was also found that tangential NBI excites RF waves normally in extremely low-density plasma. The linear dependency of frequency on magnetic field strength divided by mass of beam was demonstrated. Therefore, this type of RF wave is also an ICE. The ICE disappears immediately after the turn-off of NBI, suggesting that the source ions are not well confined and, as a result, the distribution function is deformed enough to excite the ICEs. RF waves with the frequency of the LHW range were detected by magnetic probes at the time of a perpendicular NBI. It was also found that this wave is not localized and that the frequency of this wave increases with electron density as in the PIC simulation.

Acknowledgments

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