Measurement of Ion Cyclotron Emissions by Using High-Frequency Magnetic Probes in the LHD*

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Abstract Two pairs of high-frequency magnetic probes were installed in the Large Helical Device (LHD). During the injection of a perpendicular neutral beam, ion cyclotron emissions (ICEs) with the fundamental frequency corresponding to the ion cyclotron frequency at the plasma edge were detected, which are the same type of ICE as measured with the former spare ion cyclotron range of frequencies (ICRF) heating antennas. This type of ICE was further investigated with regard to the phase and intensity of signals. Another type of ICE was found in the LHD, and these ICEs were synchronized with bursts of toroidicity induced Alfvén eigenmodes (TAE) and the rise of intensity of lost ion flux. Therefore the source of these ICEs was thought to be the particles transferred from the core to the outer region of plasma by the TAE bursts. The frequency of ICEs induced by the TAE bursts increases linearly with the magnetic field strength, since the ion cyclotron frequency increases with the magnetic field strength.

Keywords: LHD, ICE, TAE, lost particle, high-frequency magnetic probe

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1 Introduction

Two pairs of high-frequency magnetic probes were installed in the Large Helical Device (LHD) [1,2]. One purpose of these probes is the detection of the waves produced by ion cyclotron range of frequencies (ICRF) heating antennas as part of the search for an efficient plasma heating method. The other purpose is the measurement of ion cyclotron emissions (ICEs), which is the subject of this paper. ICEs are excited when the distribution function of ions increases with the perpendicular velocity. They are detected in tokamaks [3–6], where core high-energy particles with some pitch angle excurse to the cold edge region in the lower magnetic field side of the plasma. ICE measurement is utilized for the detection of fusion products in large tokamaks, since the excited frequencies are multiples of the ion cyclotron frequency at the excited point. ICEs related to the burst of toroidicity induced Alfvén eigenmodes (TAE) are also reported [7].

In the LHD, during the injection of a perpendicular neutral beam, ICEs with a frequency corresponding to a multiple of the ion cyclotron frequency at the plasma edge were detected by using spare ICRF heating antennas [8]. The fundamental ICE frequency was proportional to the strength of the magnetic field and corresponded to the ion cyclotron frequency of hydrogen ions at the plasma edge, which are supplied with the perpendicular neutral beam injection (NBI). The decay time of ICEs was less than 0.1 ms, therefore the source of ICEs is the lost particles not confined in plasma, as described in Ref. [8]. This type of ICE was investigated further by analyzing the phase and intensity of signals detected with the newly installed high-frequency magnetic probes. Another type of ICE related to the TAE bursts was also investigated in the LHD by use of these magnetic probes.

In section 2, the detail of the newly installed high-frequency magnetic probes is described. In section 3 the new findings of ICEs excited at the time of perpendicular NBI are discussed. In section 4 these results are summarized, and a future study plan is given in section 5.

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2 High-frequency magnetic probes and the data acquisition system

Fig. 1 shows a pair of high-frequency magnetic probes comprising two one-turn loops. The Faraday shields are attached to reduce the electrostatic component, because ICEs as well as the fast waves excited with ICRF heating antennas are thought to be electromagnetic waves. In addition, the direction of the turn of the loops is opposite, to cancel the electrostatic component of signals and the noise on transmission lines by combining two signals with 0-π phasing. The loops are large, 15 cm × 15 cm, for the picking up of small magnetic fluctuation. They were designed using a simulation code, the High Frequency Structure Simulator (HFSS, ANSYS), to reduce the self-inductance for the large signal intensity and to check the effect of the Faraday shields. Two pairs of probes were installed at the toroidally adjacent upper 5.5 and 6.5 ports in the LHD, where the plasma is vertically elongated. The port numbers correspond to the toroidal section numbers from 1 to 10.5. The positions of probes are almost the same in the two ports. The toroidal flux of magnetic fluctuation penetrates the loops of the probes. Each probe is positioned far from plasma to avoid heat load from the plasma. The signal is transferred to an oscilloscope (LeCroy WR6051A), which has a maximum memory length of 12 MW/channel and a maximum sampling rate of 5 GHz. The transmission lines between the probes and the oscilloscope were adjusted to be of the same electric length for the determination of phases. The acquired signals were analyzed by using the fast Fourier transform (FFT) method.

3 ICEs related to the injection of perpendicular neutral beams

The same result as that obtained with the spare ICRF antennas at 4.5-U (upper) and 4.5-L (lower) ports was obtained by using the high-frequency magnetic probe in the 5.5-U port at the timing of the perpendicular neutral beam (hydrogen of 40 keV) from the 5-O (outer) port into hydrogen plasma, as shown in Fig. 2(a). Tangential neutral beams (hydrogen of 180 keV) were also injected to the plasma, but ICEs were observed only at the timing of perpendicular neutral beam. The magnetic field strength on the magnetic axis of 3.75 m is 2.64 T, and the peak fundamental ICE frequency of 23.3 MHz corresponds to the ion cyclotron frequency of hydrogen at the plasma edge on the mid-plane in the horizontally elongated plasma cross-section in front of the perpendicular NBI port. The ICEs excited with the perpendicular neutral beam injection at the 1-O port, which is the opposite side in torus with magnetic probes, were small compared to those excited with the neutral beam injection at the 5-O port, as shown in Fig. 2(a) and (b), where the neutral beam power from each port was 5 MW. The comparison of signal intensity between the 5.5-U and 6.5-U probes revealed that the intensity decreases with the distance from NBI at the 5-O port, as shown in Fig. 2(a) and (c). These results suggest that the excitation sources are localized near the ports of perpendicular NBIs. Fig. 2 also shows that the damping of fundamental ICE is stronger than the second harmonic one.

Fig. 1 A pair of high-frequency magnetic probes installed in the upper port of the LHD. The turn directions of the loops in the Faraday shield are opposite to each other.

Fig. 2 Power spectral density (PSD) of ICEs measured at the timing of perpendicular NBIs

(a) ICEs excited by 5-O NBI and measured with the 5.5-U probe, (b) ICEs excited by 1-O NBI and measured with the 5.5-U probe, (c) ICEs excited by 5-O NBI and measured with the 6.5-U probe, (d) ICEs excited by 1-O NBI and measured with the 6.5-U probe.

It was also found that the phase difference of signals measured by a pair of probes with the different turn direction was 180°, which means that the signals originated from electromagnetic perturbation.
4 ICEs induced by TAE bursts

ICEs of another type were found in the LHD, i.e., ICEs synchronizing with the bursts of TAE. Fig. 3 shows a plasma discharge of hydrogen heated with three tangential NBIs of 14 MW. The magnetic axis was set to 3.8 m, and the magnetic field strength on the axis was 0.75 T. The line averaged electron density at the timing of the hatched region was $1 \times 10^{19}$ m$^{-3}$, and the electron temperature on the magnetic axis was 0.7 keV. The stored energy of the plasma was 40 kJ.

At these plasma parameters, TAE bursts are often observed with Mirnov coils. Fig. 4 is the contour map of the power spectral density of the magnetic fluctuation detected with the high-frequency magnetic probe in the 5.5-U port at the timing of the hatched region in Fig. 3. ICEs with the fundamental frequency around 10 MHz were detected. The power spectral density at the time of 3.704 s is shown in Fig. 5. Although the ICEs are seen clearly up to the third harmonic frequency, the power spectral density is not so peaked compared to that of ICEs excited with the injection of the perpendicular neutral beams shown in Fig. 2. The fundamental ICE frequency ranges from 8 MHz to 12 MHz approximately. Fig. 6 shows the timing of ICEs, TAE bursts with the frequency of approximate 70 kHz, and the intensity of the lost ion flux measured with the scintillator-based lost fast-ion probe (SLIP) [9,10], which shows that they are synchronizing. Therefore, the cause of this type of ICE is thought to be the deformation of the distribution function due to the particle-transfer from the core to the outer region of plasma by TAE bursts.
The dependency of ICE frequency on the magnetic field strength was also investigated. Although the measured frequencies of the fundamental and second harmonic ICEs do not depend on electron density, the frequencies increase linearly with the magnetic field strength, as shown in Fig. 7, where the electron density ranges from $0.3 \times 10^{19} \text{ m}^{-3}$ to $1.9 \times 10^{19} \text{ m}^{-3}$. The reason for this dependency on the magnetic field strength is that the ion cyclotron frequency, which is the fundamental ICE frequency, increases with the magnetic field strength. Fig. 8 shows the region in the vertically elongated plasma cross section as an example where the fundamental ICE frequency of $8\sim12$ MHz in Fig. 5 corresponds to the ion cyclotron resonance frequency of hydrogen ions in the same magnetic configuration of the discharge shown in Fig. 3. Although the area without resonance exists in the high field side, a wide region is covered by the resonance layers. Therefore, the fundamental ICE frequency of $8\sim12$ MHz in Fig. 5 is reasonable, since ICEs originate in plasma.

**Fig. 7** Dependency of fundamental and second harmonic ICE frequencies on the magnetic field strength at the major radius of 3.6 m, $B_0$

**Fig. 8** Region where the fundamental ICE frequency from 8 MHz to 12 MHz corresponds to the ion cyclotron frequency of hydrogen ions in the vertically elongated toroidal section, where ICEs are thought to be excited. The major radius of the magnetic axis is 3.8 m, and the strength of the magnetic field on the axis is 0.75 T

5 Summary and future plans

High-frequency magnetic probes were installed in two toroidal sections of the LHD. They detected two types of ICEs. One type is that excited by the lost hydrogen ions at the timing of perpendicular NBI. It was found that the ICE sources were localized at the perpendicular NBI ports and that the detected waves were electromagnetic. The other type is ICE synchronizing with TAE bursts and the rise of lost ion flux. The ICE frequencies have linear dependency on the magnetic field strength, since the ion cyclotron resonance layer of the fundamental ICE frequency crosses the plasma.

The ICE frequency depends not only on the magnetic field strength but also on the mass of ion species, since the fundamental frequency is the ion cyclotron frequency at the excited point. Therefore, ICEs measured with the high-frequency magnetic probes will be utilized as a diagnostic tool for the fusion products in D-D fusion experiments planned in the LHD.

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