Observation of Ion Cyclotron Emission Owing to DD Fusion Product H Ions in JT-60U

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High-frequency fluctuations in the ion cyclotron range of frequency (ICRF) are excited in magnetically confined plasmas because of the distortion of velocity distribution. In deuterium plasma experiments in JT-60U, ion cyclotron emission (ICE) detected as magnetic fluctuations is observed using ICRF antennas as pickup loops. The toroidal wave-numbers can be estimated using the phase differences between the signals from antenna elements arrayed in the toroidal direction. In this manuscript, ICE due to fusion product (FP) H ions, ICE(H), which is identified separately from the second-harmonic ICE caused by D ions, is newly reported. ICE is considered to result from spontaneous excitation of magnetosonic waves associated with FP high-energy ions. ICE caused by ^{3}He ions and T ions has already been identified and confirmed to have finite toroidal wave-numbers. In contrast, ICE caused by ions originating in neutral beam injection has no toroidal wave-numbers. It is suggested that the appearance of ICE(H) depends strongly on the plasma density, and weak magnetic shear operation is one of the possible conditions for the observation of ICE(H).

Keywords: ion cyclotron emission, ICRF antenna, H ion, DD fusion, JT-60U

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1. Introduction

Fluctuations in the ion cyclotron range of frequency (ICRF) are excited in magnetically confined plasmas because of the distortion of velocity distribution. One of these fluctuations has been reported as ion cyclotron emission (ICE) in DT plasma experiments in JET and TFTR [1, 2] and in deuterium (D) plasma experiments in JT-60U [3,4]. ICE is considered to be a spontaneously excited wave in plasmas with strong anisotropy in the velocity distribution. In JT-60U, magnetic fluctuations are detected with ICRF antennas as pickup loops, and their toroidal wave-numbers are estimated from the phase difference between two antenna elements arrayed in the toroidal direction [5]. So far, ICE caused by fusion product (FP) ^{3}He ions, T ions, and ions originating in neutral beam (NB) injection have been reported. Recently, ICE caused by FP H ions is newly identified separately from the second-harmonic ICE that is caused by D ions. In this manuscript, we study the excitation conditions for ICE caused by H ions.

2. Experimental Setup

JT-60U is a large tokamak at which DD fusion plasma experiments are performed. High-performance plasmas are produced with high-power NB injection, and the emission of DD fusion neutrons is observed. Both positive- and negative-ion based NBs (P-NBs and N-NBs) as well as both perpendicular and tangential injections are used. The temporal evolution of plasma parameters and the power of the injected NBs are shown in Fig. 1. In the discharge (shot #47989), the plasma current is $I_p = 0.8$ MA, and the magnetic field strength is 2.3 T at a major radius of R = 3.4 m. The observation of ICEs in JT-60U has been reported to depend on NB injection; that is, ICE caused by ^{3}He ions is observed with tangential P-NB injection, and ICE caused by T ions is observed with tangential N-NB injection [5]. ICRF antennas are used as pickup loops for detecting electromagnetic and electrostatic fluctuations. A schematic drawing of ICRF antennas is shown in Fig. 2. Two current straps are arrayed in the toroidal direction. Each strap is grounded at the center, and both ends of the strap are connected to signal cables that go directly to the JT-60U control room. The signals are recorded by an oscilloscope with a sampling rate of 500 Ms/s (mega samples per second) and a maximum memory length of 12 MW/ch

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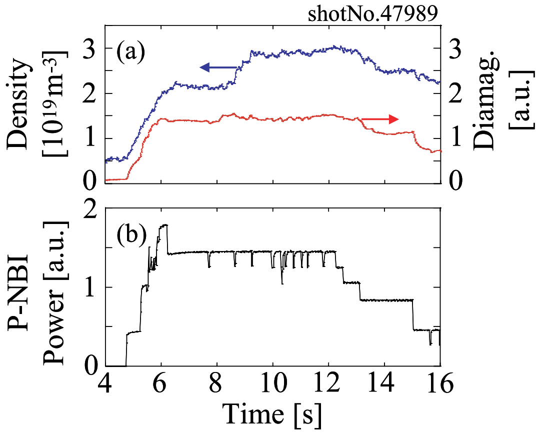

Fig. 1 Temporal evolution of (a) the plasma density and diamagnetism and (b) the power of positive-ion based-NBs (P-NBs).

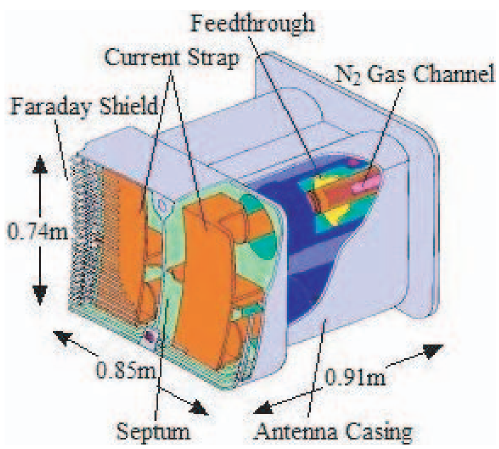

Fig. 2 Schematic drawing of ICRF antenna. Two current straps are separated toward the toroidal direction.

(mega words per channel). In general, signals are sampled for 100 µs every 50 ms, and the behavior of the fluctuations can be analyzed for durations of more than 10 s by using this discrete sampling method. Two antenna units are arrayed in the toroidal direction. We can determine the toroidal wave-number of the excited waves by using this antenna array. The phase differences between more than two antenna elements are detected at the same time.

3. Observations of ICE Caused by H Ions

Figure 3 shows a raw fluctuation signal detected by ICRF antennas and an intensity plot of the temporal evolution of the frequency spectrum obtained by the conventional fast Fourier transform (FFT) method. The intensity of fluctuations in the frequency spectrum is represented by the brightness level, and fluctuations caused by ICE are indicated by bright lines. As shown in Fig. 3 (b), three fairly broad peaks of the fundamental, second-harmonic,

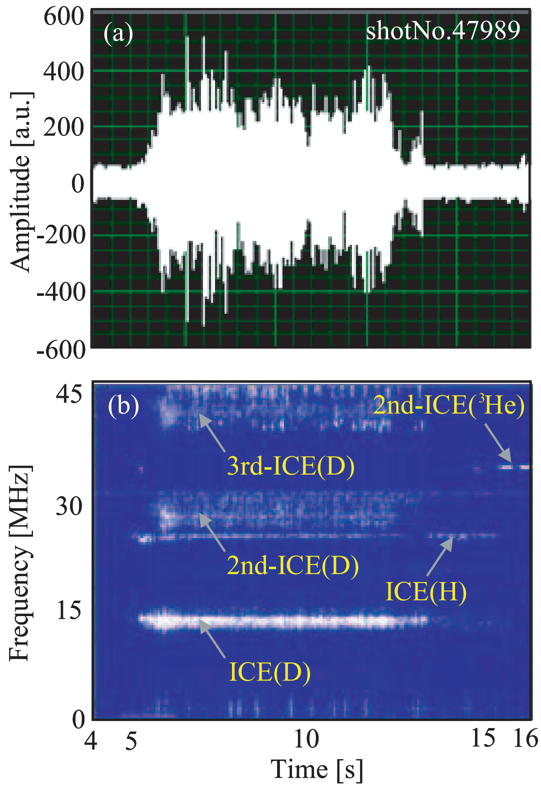

Fig. 3 (a) Raw signal detected by ICRF antennas and (b) intensity plot of temporal evolution of the frequency spectrum.

and third-harmonic ICE caused by D ions [ICE(D), 2nd-ICE(D), and 3rd-ICE(D)] are represented. A sharp peak in the second-harmonic ICE caused by ^{3}He ions [2nd-ICE(^{3}He)] is observed. In Fig. 3 (b), another sharp peak just below 2nd-ICE(D) is clearly observed. In a previous report [5], the differences between ICE caused by FP ions and that caused by injected NBs were precisely discussed. One of the differences is the toroidal wave-number; ICE caused by FP ions has finite toroidal wave-numbers, and ICE caused by injected NBs has no toroidal wave-number. The other difference is the location of the magnetic field strength corresponding to the cyclotron frequencies of ions; the observed frequencies of ICE caused by FP ions correspond to the cyclotron frequencies of the magnetic field strength outside the outermost magnetic surface, and those of ICE caused by injected NBs correspond to the magnetic field strength just at the outermost magnetic surface. Because of the long distance (more than 400 m) between the ICRF antenna and the oscilloscope, precise calibration of the electric length of the cables is needed for evaluation of the phase differences. Figure 4 shows the calibrated phase differences of signals between two antenna elements arrayed in the toroidal direction. As predicted, ICE caused by FP ions has finite toroidal wave-numbers, and that caused by injected NBs has no toroidal wave-number. Figure 4 shows the plot of 2nd-ICE(^{3}He) with finite phase differences and frequencies of ICE caused

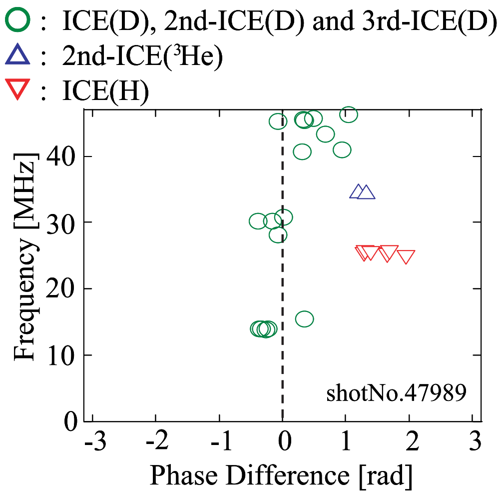

Fig. 4 Calibrated phase differences in ICE caused by ions measured using ICRF antennas; ICE caused by FP ions has finite toroidal wave-numbers, and that caused by injected NBs has no toroidal wave-numbers.

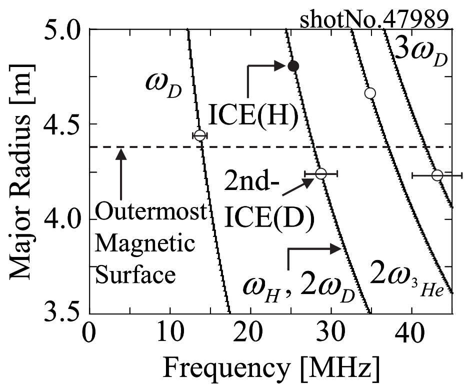

Fig. 5 Location of cyclotron resonance frequency for D, ^{3}He, and H ions (solid lines) and location of observed frequency using ICRF antennas (open and closed circles). Toroidal magnetic fields at the center and at the outermost magnetic surface (R = 4.38 m) are B_t = 2.32 T and B_t = 1.82 T, respectively.

by injected NBs in almost zero region. Frequency peaks just below 2nd-ICE(D) are plotted in the region of finite phase differences. Figure 5 shows the observed frequencies as open and closed circles as well as locations of the cyclotron resonance frequency for D, ^{3}He, and H ions as solid lines. As indicated previously, the frequency of ICE caused by FP ions correspond to the cyclotron frequency of the magnetic field strength in the outer region of the outermost magnetic surface. On the outermost magnetic surface, ICE(D), 2nd-ICE(D), and 3rd-ICE(D) are plotted as open circles and have a fairly broad range. In the outer region, 2nd-ICE(^{3}He) is plotted as open circles. The sharp peak observed just below 2nd-ICE(D) is plotted by a closed circle. From Figs. 4 and 5, this sharp peak is considered to be ICE caused by FP H ions. Therefore, ICE(H) is identified separately from 2nd-ICE(D) from the wave-

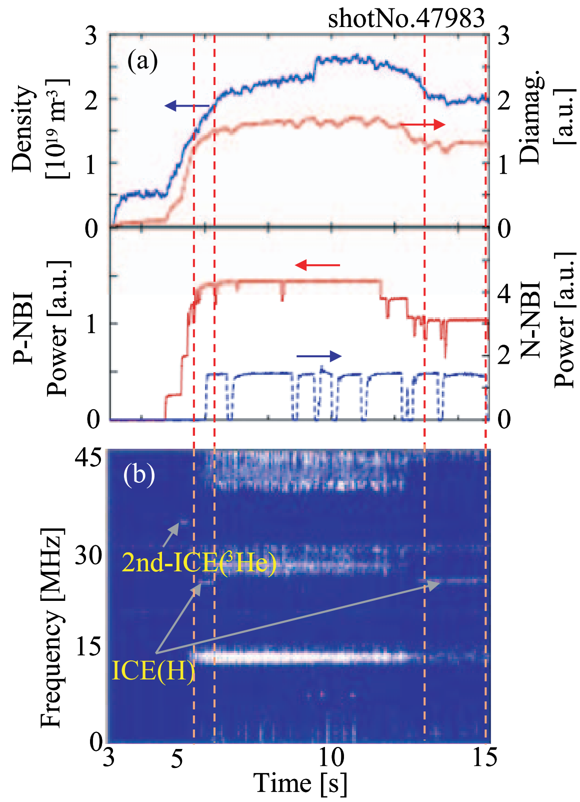

Fig. 6 Temporal evolution of (a) the intensities of the plasma density and diamagnetism and the power of positive-ion based NBs (P-NBs) and negative-ion based NBs (N-NBs) and (b) the frequency spectrum obtained from raw signals using the FFT method. Density range from 1.5 to 2×10^{19} m^{-3} is indicated by dashed lines.

numbers and the locations of magnetic field strength corresponding to the cyclotron frequency.

Figure 6 shows the temporal evolution of the plasma parameters and the frequency spectrum of the discharge in which ICE(H) is observed in the density range from 1.5 to 2×10^{19} m^{-3}, as indicated by dashed lines. This is high-β_p ELMy discharge with weak magnetic shear [3]. It is suggested that the observation of ICE(H) is related to the density. As indicated in Fig. 6, a short period of 2nd-ICE(^{3}He) is observed in the initial phase before the appearance of ICE(H); 2nd-ICE(^{3}He) disappears quickly and ICE(H) appears. Weak magnetic shear operation is a possible condition for the observation of ICE(H), since ICE(H) is generally observed in this operation.

4. Summary

ICE caused by DD fusion product ions has been observed in JT-60U using ICRF antennas as pickup loops. The toroidal wave-numbers can be determined using the phase differences between signals from antenna elements arrayed in the toroidal direction. ICE(H) is newly identified separately from the second-harmonic ICE(D) by measuring the phase difference. The appearance of ICE(H) depends strongly on the density, and weak magnetic shear operation is one of its possible conditions. More detailed analysis is needed to determine the mechanism for the excitation of ICE(H).

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