Observation of Spontaneously Excited Waves near the Ion Cyclotron Range of Frequency on JT-60U

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Abstract. In this paper, experimental observations of spontaneously excited waves in the ion cyclotron range of frequency (ICRF) on JT-60U are described. The fluctuations in ICRF are driven by the presence of non-thermal ion distribution in magnetic confinement plasmas. Two types of magnetic fluctuations are detected: one is due to high energy D ions from neutral beam injections and the other is due to fusion products (FPs) of ^{3}He and T ions. These fluctuations have been reported as ion cyclotron emissions (ICEs) in the burning plasma experiments on large tokamaks. This paper describes the first measurement of the spatial structures of the excited modes in the poloidal and toroidal directions. It is confirmed by using ICRF antennas as magnetic probes that all modes excited spontaneously have magnetic components and couple to the antenna straps. The modes due to D ions have small toroidal wave number $k_{//}$ and will behave as electrostatic waves. On the while, the measurement of finite $k_{//}$ in the modes due to FP ions supports the excitation of the Alfvén waves is the possible origin of FP-ICEs. It is also confirmed that the excited modes due to FP ions have different wave structures and are suggested to be in the different branch of the Alfvén waves, that is, the fast Alfvén wave and the slow Alfvén wave. Frequency peaks due to FP ions are sometimes split into doublet shape as observed in JET experiments. The phase differences of both peaks are measured and indicate that two waves are traveling in both toroidal directions. Both beam-driven ICEs and FP-ICEs are observed and those spatial structures are obtained on JT-60U.

1. Introduction

In magnetically confined plasmas, fluctuations in the ion cyclotron range of frequency (ICRF) would be driven by the presence of non-thermal ion distribution. On the GAMMA 10 tandem mirror [1], ICRF heating is used not only for producing an initial plasma but also for sustaining the MHD stability [2] and heating the central cell ions [3]. Plasmas with a strong temperature anisotropy have been formed when the fundamental ion cyclotron resonance layer exists near the midplane of the central cell mirror field. In a typical discharge, Alfvén-ion-cyclotron (AIC) modes [4] are spontaneously excited due to such a strong temperature anisotropy [5]. The AIC mode is one of the micro-instabilities and is formed as an eigenmode in the direction of the magnetic field line [6]. The frequency of the AIC mode is around 0.9 times ion cyclotron frequency of the local magnetic mirror field. On the while, in fusion-oriented devices with a toroidal configuration, neutral beams (NBs) are commonly used to create high performance plasmas. Resultant high-energy ions are trapped in the local mirror configuration and will form the velocity distribution with the strong anisotropy. Beam-driven ion cyclotron instabilities have been reported in many basic plasma experiments and fusion plasma experiments. In burning plasma experiments on JET and TFTR, ion cyclotron emissions (ICEs) have been observed in the ion cyclotron frequency and its higher harmonic regions [7,8]. The possible mechanism for ICE is considered to be the magnetoacoustic cyclotron instability [9]. The experimental results related to ICEs in the burning plasmas have been reviewed in Ref. 10.

The observations of the electrostatic wave excitation in ICRF have been reported in JT-60 [11] and also ICEs in JT-60U [12]. In this manuscript, experimental observations of spontaneously excited waves in NB-heated deuterium plasmas on JT-60U are described. The spatial structures of the excited modes are measured by using ICRF antennas in the poloidal and toroidal directions. To study the relation among the AIC modes, beam-driven electrostatic ion cyclotron instabilities and ICEs in ICRF, and the basic physics in the magnetically confined plasmas with non-thermal energy distribution is the main motivation of this work. In GAMMA 10, the effects of the AIC modes to plasma parameters have been studied [13-15]. In the toroidal configuration, these spontaneously excited waves will have the different influence on the particle transport and confinement. And also, the measurement of ICEs due to fusion product (FP) ions will become a significant diagnostic tool for the fusion reactivity. The precise study of the excitation mechanism is important for future burning plasma experiments.

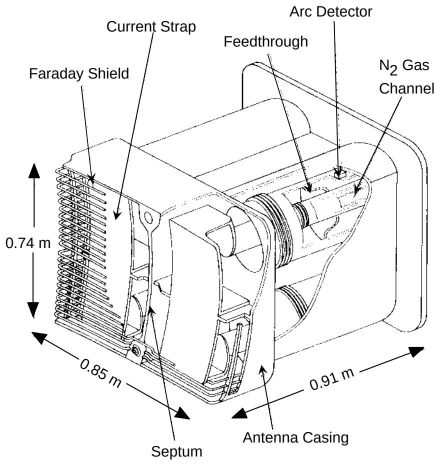

FIG.1. Schematic drawing of ICRF antenna; four current straps are arrayed in two columns and two rows.

2. Experimental setup

On JT-60U, conventional positive-ion-based neutral beams (P-NBs, injection both in perpendicular and tangential directions) and a negative-ion-based neutral beam (N-NB, injection in the tangential direction) are used to realize the high performance operation [16]. ICRF antennas are used as pick up loops for detecting electrostatic and/or electromagnetic fluctuations. A structure of antennas installed in equatorial ports is shown in Fig.1 [17]. Four current loop straps are arrayed in two columns (separated with 0.44 m in the toroidal direction) and two rows in the poloidal direction. The width of each strap is 0.19 m. One end of both straps arrayed in the poloidal direction is connected and grounded at the center of the antenna. Another end is connected to the output of rf generators through the vacuum feed-through, the matching components and the transmission lines. Single layer Faraday shield is used and a good transparency of the rf field is expected. Under these conditions, the antennas can couple to the rf field of the plasma electro-statically and/or electro-magnetically. Two sets of ICRF antennas, which are installed with the distance of 1.67 m, are used in this experiment.

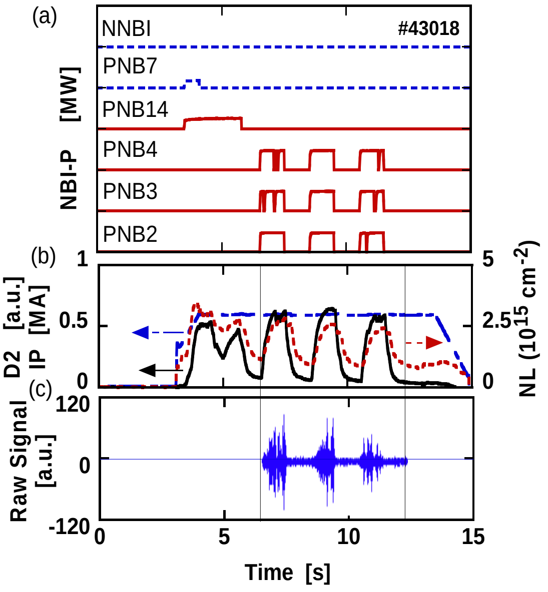

FIG.2. Observation of the fluctuations in the case of perpendicular P-NBs from 6.5 s to 11.5 s; (a) time sequence of NBs, (b) temporal evolution of plasma current, line-integrated density and diamagnetic signal and (c) raw signal of the induced voltage on the antenna strap.

Signal cables are connected to the transmission line between the antenna and the stub tuner via a DC-break element. Detected signals are transmitted to the data acquisition system located in JT-60U control room. Because the measurement of the spatial structure of the excited modes is one of the main purposes of this experiment, the phase differences between two antenna straps should be determined correctly. The signal cables, of which total length is more than 400 m, are used and their effective electrical lengths including coaxial lines, coaxial cables and DC-break elements are calibrated precisely by measuring the propagation time of the incident and reflected pulses. Those signals are recorded with an oscilloscope of which maximum sampling rate is 500 Ms/s and maximum memory length is 12 MW/channel. Typically, signals are sampled during 100 μs in every 50 ms and the temporal behavior of the fluctuations can be analyzed in the duration of more than 10 s by using such a discrete sampling method. Wave numbers in both poloidal and toroidal directions are determined with two straps.

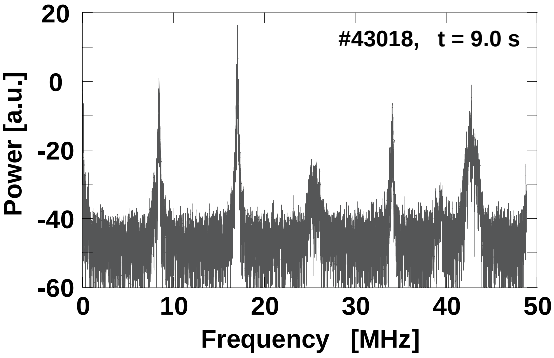

FIG.3. Frequency spectrum of the detected fluctuations during perpendicular P-NB injections at 9 s in FIG.2. Relatively shape peaks and the excitation of high harmonics are observed.

3. Observations of spontaneously excited waves

Figure 2 shows (a) the time sequence of NBs and (b) plasma parameters (plasma current, line-integrated density and diamagnetic signals). A raw signal from the pick up loop (ICRF antenna strap) is indicated in Fig.2(c). As shown in the figure, P-NBs (#2, #3 and #4) which are the positive-ion-based and perpendicular NBs are injected during 1 s in every 1 s from 6.5 s. Both of line density and diamagnetic signals increase clearly with NBs and strong fluctuations appear in the raw signal as shown in Fig.2(c). The frequency spectrum of the detected signal at 9 s is obtained by using the fast Fourier transform method as shown in Fig.3. The modes of which frequency peaks are relatively sharp are observed. The multiple higher harmonic modes are clearly detected. The fundamental frequency (the lowest frequency) is always lower than the ion cyclotron frequency at the outer midplane of the outermost magnetic surface, that is, the lowest ion cyclotron frequency of the confined plasma. In this discharge, the toroidal magnetic field strength has been arranged to increase gradually from 1.2 T to 1.8 T during the time from 6.5 s to 12.5 s. Almost no changes are seen in the plasma parameters. Figure 4 shows the intensity plot of the amplitude of excited modes as a function of time and frequency. As shown in the figure, frequencies are increasing with time, because the magnetic field strength is increasing during the discharge. The amplitude of the mode is represented by the shade of brightness. It is seen that there are complicated structures in the temporal evolution of the amplitude, that is, the plasma parameter and the harmonic number of the modes. For example, the modes with odd harmonic numbers are excited strongly in the initial phase of NB injections and those with even numbers are excited strongly in the latter phase. In Fig.5, frequencies of the modes are plotted (closed

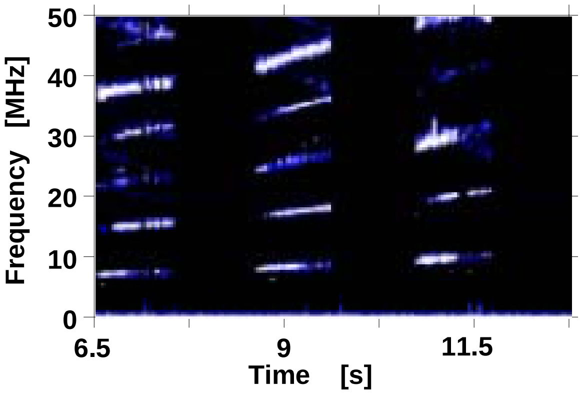

FIG.4. Intensity plot of the amplitude of the fluctuations as a function of time and frequency. The amplitude is represented by the shade of brightness.

circles) as a function of time. The temporal evolution of the fundamental ion cyclotron frequency at the outer (Rout) and inner (Rin) midplane of the outermost magnetic surface, that is, the lowest and highest ion cyclotron frequencies of the confined plasma are also indicated as solid lines. A hatched area in the figure indicates the fundamental cyclotron frequency of D ions within the outermost magnetic surface. The detected frequencies exist just below the minimum cyclotron frequencies. The higher harmonic frequencies at the outer midplane of the outermost magnetic surface are also indicated in Fig.5. (dotted lines) Frequencies of all modes are just lower than the cyclotron higher harmonic frequencies. The same fluctuations have been observed in the case of hydrogen NB in the hydrogen plasma.

Figure 6 shows a typical intensity plot of the fluctuation amplitude in the case of the tangential P-NB and N-NB injections in addition to the perpendicular P-NBs as a function of time and frequency. The time sequence of NBs is indicated at the top of the figure. Figure 7 shows the temporal evolution of plasma parameters ((a) line-integrated density and (b) Diamagnetism) and a neutron emission (c) in the same discharge. As shown in Fig.6, two sharp peaks, of which frequencies are corresponding to the fundamental and 2nd harmonic cyclotron frequencies of fully ionized FP-^{3}He ions near the outer midplane edge of the plasma, appear when the tangential P-NBs (80keV, 4MW) are injected. After perpendicular P-NBs (80keV, 8MW) are injected, modes with relatively broad frequency peaks due to D ions are detected as described in former

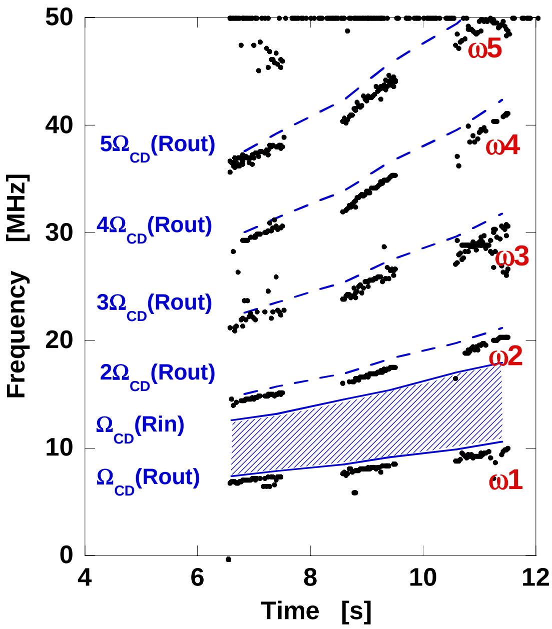

FIG.5. Temporal evolution of the fundamental ion cyclotron frequency and higher harmonic frequencies at the outermost magnetic surface. A hatched area indicates the fundamental cyclotron frequencies of D ions in the confined region. Observed frequencies are plotted in the figure (closed circles).

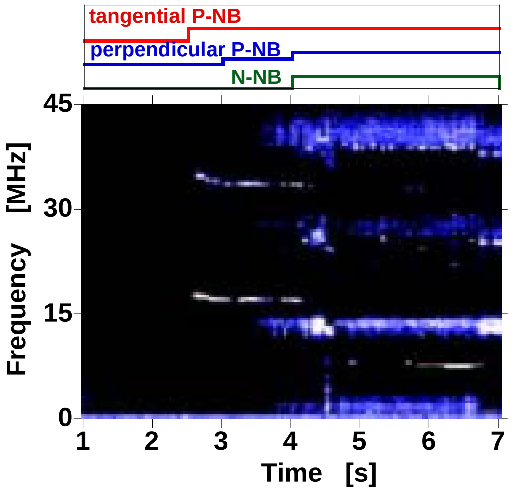

FIG.6. Typical intensity plot of the fluctuations in the case of tangential NBs in addition to the perpendicular NBs. Three types of fluctuations are observed.

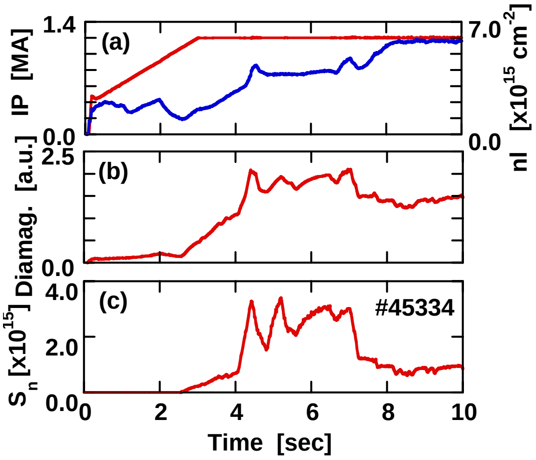

FIG.7. Time evolution of plasma parameters in the same discharge of FIG.6. (a) plasma current and line-integrated density, (b) diamagnetism and (c) a neutron emission. In the discharge, the toroidal magnetic field strength is 2.3 T and effective q-value is 4.7.

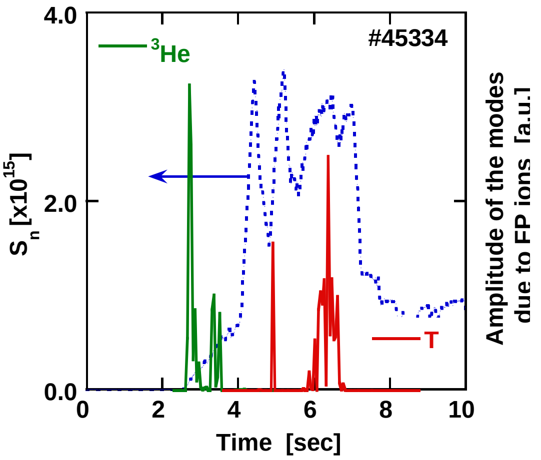

FIG.8. Time evolution of the amplitude of the excited modes due to FP ions. (The Neutron emission signal is indicated as the reference)

section of this Chapter. Then, the modes due to ^{3}He disappear or the amplitude becomes weak. A mode with the lowest frequency below 10 MHz appears after a tangential N-NB (450keV, 3MW) is injected, which is considered to be due to FP-T ions. As indicated in Fig.7, this peak appears when the emission of fusion neutrons becomes large enough. The amplitude of the modes due to ^{3}He ions becomes small when the density increases and the neutron emission becomes large. The temporal evolution of the amplitude of the modes due to ^{3}He and T ions is plotted in Fig.8. The time evolution of the neutron emission is also written in the figure. As clearly shown in the figure, the amplitude of the modes due to ^{3}He becomes rapidly small before the neutron emission becomes large. It is observed that the frequencies of the modes due to ^{3}He ions are changing with time as shown in Fig.6. These frequency changes correspond to the change of the location of the outermost magnetic surface. These experimental observations indicate the mechanism of the mode excitation will be related not only to the fusion reaction but also to the plasma parameters. And also it is suggested that there are different mechanism of the mode excitation between ICEs due to ^{3}He and T ions.

4. Measurements of the wave structures

As described in Chapter 2, one end of each strap is grounded at the center of the antenna. When electromagnetic waves are detected, the phase between signals from two straps arrayed in the poloidal direction should become π because of the polarity of the electric field induced by the time derivative of the magnetic field component. On the while, those signals are detected in phase when the plasma and antenna couples electrostatically. The effective electrical length of the signal cables has been calibrated carefully because the phase difference of the cable of which length is 1 m is about 1 radian at 50 MHz in this experiment. Figure 9 shows the measured phase differences (open circles) of the modes due to D ions. The difference of the effective electrical length between two cables used in this experiment is 3.1 m and the phase difference is calculated as a function of the frequency. The solid line indicates the calculated phase difference when both signals are in the opposite phase. Because data points are somewhat scattered around 1 radian, there is a possibility that the excited modes have fine structures in the poloidal direction with high mode numbers depending on plasma parameters. However, it is clearly shown

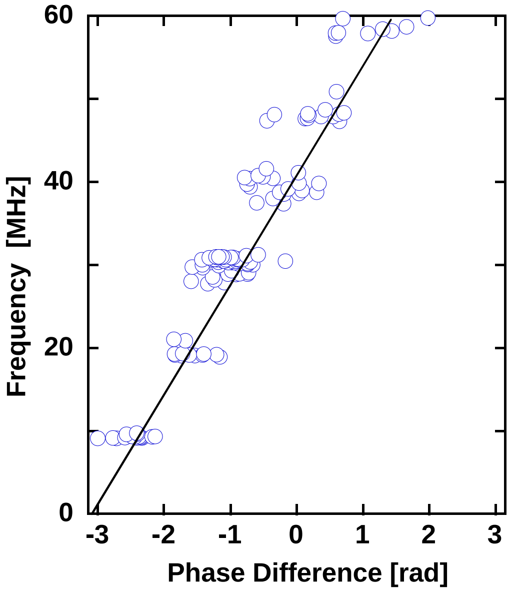

FIG.9. Phase differences between antenna straps arrayed in the poloidal direction. Solid line indicates the calibrated line for the phase difference of π.

the detected modes have the out of phase relation and the excited modes from fundamental to higher harmonics are all electromagnetic waves. It is also confirmed that modes due to FP ions have the same poloidal structure as due to D ions.

By using two antenna straps arrayed in the toroidal direction, the toroidal mode structure can be determined. Two straps of which separation is 0.44 m are used. Figure 10 shows the corrected phase differences of modes in the discharge shown in Fig.6. As indicated in the figure, modes due to D ions have almost no phase differences in the toroidal direction, that is, small $k_{//}$ and will behave as electrostatic waves. On the while, modes due to FP ions have finite phase differences and can propagate in the toroidal direction. The wave numbers of the modes due to ^{3}He and T ions in this discharge are estimated to be around 3 and 10 m^{-1}, respectively. The wave number is determined from the measurement of phase differences among three different antenna straps.

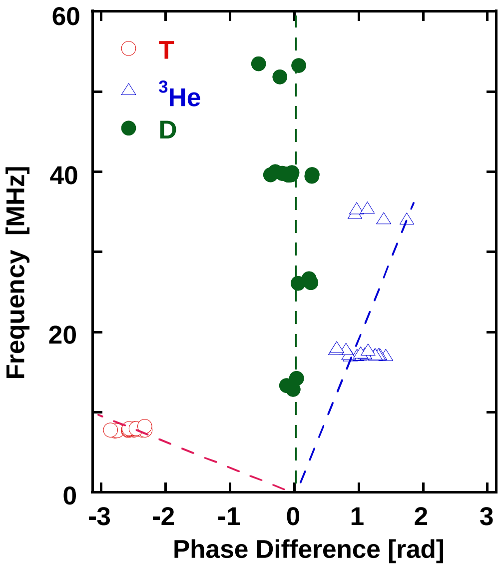

FIG.10. Calibrated phase differences in the toroidal direction. It is clearly shown that waves due to D ions have $k_{//}$~0 and waves due to FP ions have finite $k_{//}$.

It has been reported in JET burning experiments [7] that frequency peaks of excited waves due to FP ions are sometimes split into doublet shape. The phase differences of doublet peaks are also measured and indicate that the two waves are traveling in both toroidal directions.

5. Discussions and Summary

Fluctuations in the ion cyclotron frequency range are clearly observed in NB-heated plasmas on JT-60U. ICRF antennas installed in equatorial outside ports are used as pick up loops for detecting electrostatic and/or electromagnetic fluctuations. It is confirmed that all of observed modes couple to the ICRF antenna magnetically. Two types of fluctuations are identified: One is the mode excited due to high-energy D ions when the perpendicular NBs are injected. The other is the mode excited due to FP-^{3}He and T ions when tangential NBs are injected. The frequencies of the excited modes are always lower than the ion cyclotron frequency and its higher harmonic frequencies at the outer midplane of the outermost magnetic surface. The magneto-acoustic cyclotron instability in the bulk D-plasma is the most probable origin of FP-^{3}He ions [9]. The toroidal wave numbers $k_{//}$ of the excited modes are measured in this experiment. The

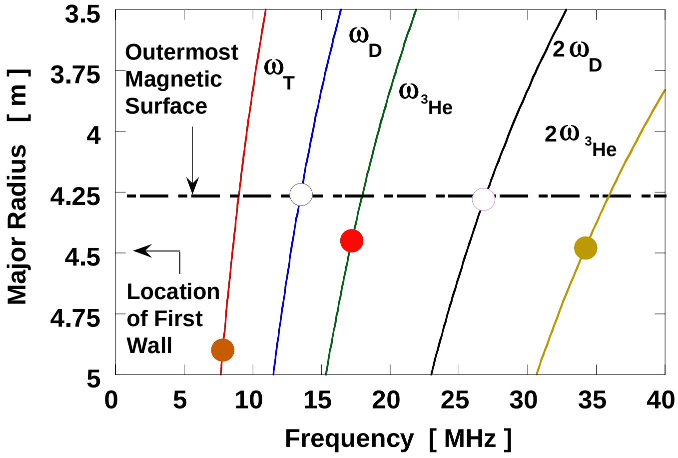

FIG.11. The cyclotron resonance locations of the beam ions and FP ions near the outer midplane of the outermost magnetic surface. The locations of observed frequencies are also plotted in the figure (open and closed circles)

modes due to D ions have small $k_{//}$ and will behave as the electrostatic waves. The modes due to FP ions have finite $k_{//}$ and will support the oblique propagating Alfvén waves in the bulk plasmas are destabilized by FP ions. The excitation mechanism of FP-ICEs by not perpendicular NBs but only by tangential NBs is still unknown.

As shown in Fig.6, ICEs due to FP ions are excited with the sharp frequency peaks in comparison with the ICEs due to D ions. These observations will indicate the eigenmode formation in the local narrow region near the outermost magnetic surface. In Fig.11, the locations of cyclotron resonances near the outer midplane of the outermost magnetic surface are presented. The frequencies of observed modes due to D ions (open circles) and FP ions (closed circles) are also indicated. As mentioned in Ref. 18, the frequencies of the beam driven ICEs correspond just at the plasma edge and those driven FP ions slightly beyond plasma edge. Specially, the frequency of the mode due to FP-T ions is quite low. Because the first wall of the vacuum vessel is located at 4.5 m, the mode due to FP-T ions must have the frequency of less than 0.9 times its fundamental cyclotron frequency at the plasma edge.

Two types of FP-ICEs are also suggested. The modes due to FP-^{3}He ions are excited by the tangential P-NBs and are observed mainly in the initial phase of the plasma buildup. The amplitude of the modes has no relation of the fusion reaction rate (neutron emission). The higher harmonic modes due to FP-^{3}He ions are always excited with the fundamental mode. The detected wave numbers in the toroidal direction are smaller than those due to FP-T ions. On the while, the modes due to FP-T ions are only excited when the tangential N-NB is injected. Only a fundamental mode is excited and the amplitude of the mode has almost linear relation to the fusion reaction rate. The detected wave numbers in the toroidal direction are larger than those due to FP-^{3}He ions. Generally, it is known that fusion reactions of D-D to ^{3}He and neutrons, and D-D to T and protons, have the same cross sections. As indicated in this experiment, both ICEs due to ^{3}He and T ions have different dependences of plasma parameters. From these experimental observations, it is suggested that the fast Alfvén wave branch is destabilized due to FP-^{3}He ions and the slow Alfvén wave branch due to FP-T ions. ICEs due to D ions are suggested to behave as the electrostatic ion cyclotron instability,

Acknowledgments

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