J. Plasma Fusion Res. SERIES, Vol. 8 (2009)

Parametric Excitation of Low Frequency Waves in ICRF-Produced Plasmas on GAMMA 10

Makoto ICHIMURA, Yuusuke YAMAGUCHI, Yukimi MOTEGI, Hiroshi MURO, Toshiaki OUCHI, Shoichi SATO, Tatsuya MURAKAMI, Yusuke SEKIHARA and Tsuyoshi IMAI

Plasma Research Center, University of Tsukuba, Tsukuba 305-8577, JAPAN

(Received: 6 September 2008 / Accepted: 30 January 2009)

In high power ICRF experiments on the GAMMA 10 tandem mirror, plasmas with a strong temperature anisotropy are produced when the cyclotron resonance layer exists near the midplane of the central cell. Saturation of the diamagnetism is sometimes observed when the heating ICRF power is increased. In the plasmas with the strong temperature anisotropy, Alfvén-ion-cyclotron (AIC) modes are spontaneously excited. Low frequency (LF) waves which have differential frequencies between the heating ICRF waves (6.36 MHz) and the AIC modes (5.5 – 6.0 MHz) are also detected. At the midplane of the central cell, azimuthal mode structures are measured and the heating ICRF waves of m = +2, the AIC modes of m = -1 or 0 and the LF modes from m = -2 to m = +2 are detected. These experimental observations suggest the heating ICRF waves with several azimuthal mode numbers branch into the AIC modes and the LF waves. Although axial mode structures are also measured, it has not yet been confirmed that they satisfy the matching conditions. A possibility of the parametric decay of the heating ICRF waves to the AIC modes and the LF waves is discussed.

Keywords: Alfvén-ion-cyclotron mode, anisotropy, azimuthal mode structure, axial mode structure, parametric decay, ICRF heating, GAMMA 10, low frequency wave

1. Introduction

High-power ion-cyclotron range of frequency (ICRF) experiments have successfully demonstrated efficient coupling of the rf power to fusion plasmas. When the ICRF power and consequent wave energy levels increase, various nonlinear phenomena can occur in plasmas. For example, the parametric decay of the heating waves is one of the famous wave-wave interactions observed in many fusion experiments.

In the GAMMA 10 tandem mirror, the ICRF waves have been used for the plasma production, heating and sustaining MHD stability [1]. In a high power ICRF heating experiment, plasmas with a strong temperature anisotropy have been formed due to the existence of fundamental cyclotron resonance layers near the midplane of the central cell. Maximum ion temperature has reached 10 keV and the temperature anisotropy (which is defined as the temperature ratio of perpendicular to parallel to the magnetic field line) becomes more than 10 [2]. Alfvén-ion-cyclotron (AIC) modes are spontaneously excited due to such a strong temperature anisotropy. The AIC modes have several discrete peaks in the frequency spectrum just below the ion cyclotron frequency. These peaks are considered to be eigenmodes in the axial direction [3]. When the power of heating ICRF is increased, it will be expected that the diamagnetism increases and the anisotropy becomes strong. However, the saturation of the diamagnetism is sometimes observed in experiments. Naturally, the degradation of the confinement is a possible candidate for the saturation. The excitation of the AIC modes, which can scatter the hot ions confined in the magnetic mirror field into the loss cone of the velocity space in the central cell, is one of the possible mechanisms [4,5]. In this manuscript, the parametric decay of the heating ICRF waves is discussed for the saturation mechanism of the diamagnetism. Low-frequency magnetic fluctuations with beat frequencies between the heating ICRF waves and discrete peaks of the AIC modes are clearly detected in GAMMA 10.

2. Experimental Setup

GAMMA 10 is a minimum-B anchored tandem mirror with axisymmetric plug/barrier cells at both ends. The central cell, where main plasmas are confined, has an axisymmetric mirror field and is 5.6m in length with the field strength of 0.4T at the midplane. The mirror ratio is 5. For the initial plasma production, an ICRF source

---

ichimura@prc.tsukuba.ac.jp

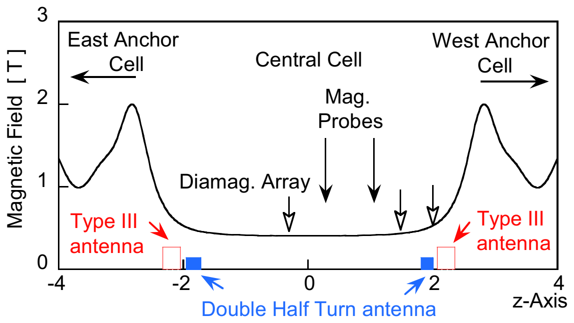

Fig.1 Magnetic field profile of the central cell and the locations of ICRF antennas and diagnostics

(RF1) with so-called Nagoya Type-III antennas on both east and west sides of the central cell is used in combination with short-pulse gun-produced plasmas and hydrogen gas puffing. Fast Alfvén waves are excited in the central cell and propagate to the anchor cell. The MHD stability of GAMMA 10 is kept by the averaged minimum-B configuration due to the anchor heating [6]. To avoid the strong interference between the east and west antennas, the frequency of the west RF1 (10.3 MHz) is slightly higher than the frequency of the east (9.9 MHz). Another ICRF source (RF2) with conventional double half-turn (DHT) antennas also installed on both sides is applied for the main plasma heating. Slow Alfvén waves excited by RF2 (6.36MHz) propagate to the midplane of the central cell and heat ions because the fundamental ion cyclotron resonance layer exists near the midplane. The magnetic field profile in the central cell and the locations of antennas and diagnostics are shown in Fig.1. RF1 and RF2 have two final outputs for both sides of antennas. The total radiated powers from Type III and DHT are typically 200 kW with duration of 200 ms, respectively.

The typical plasma parameters are the density of 2 x 10^{18} m^{-3}, the ion temperature of 5 keV and the temperature anisotropy of more than 10. The temperature anisotropy is estimated from signals of the diamagnetic loop array in the axial direction indicated in the figure. Three magnetic probes, which have larger cross section than the conventional pick-up loop of several mm in diameter, have been installed for detecting low-frequency magnetic fluctuations in the central cell. Magnetic fluctuations are detected by using two probes arrayed both in the azimuthal and axial directions. With a conventional fast Fourier transform (FFT) method, signals of magnetic probes are converted into the frequency spectrum.

3. Observation of Low-frequency Waves

3.1 Alfvén-Ion-Cyclotron Modes

Figure 2(a) shows the frequency spectrum of the magnetic probe signal in the range from 5.5 to 6.5 MHz. A frequency of 6.36MHz in the figure is an applied RF2 frequency and magnetic fluctuations with frequencies just below RF2 are spontaneously excited AIC modes. The AIC modes have several discrete peaks as shown in Fig.2. The spatial mode structures of each discrete peak in radial and azimuthal directions have been measured by magnetic probes and confirmed to be the same structure [3]. Thus, the AIC modes are excited as eigenmodes in the axial direction. The profiles of the excited modes are consistent with the waves in the shear Alfvén branch. Figure 2(b) is the intensity plot of the time evolution of frequency spectrum of the AIC modes. The intensity of the mode is represented by the shade of brightness. It is clearly seen that frequencies of the spontaneously excited waves change depending on the plasma parameters. When the ion temperature increases and the anisotropy becomes stronger, the frequency of the AIC modes becomes higher.

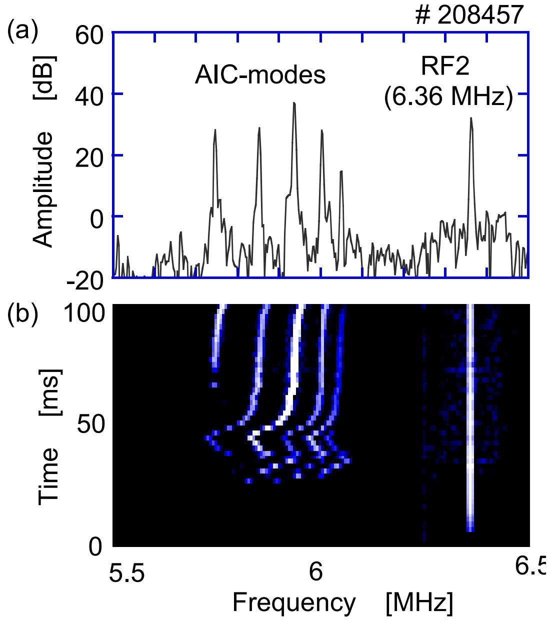

Fig.2 (a) Frequency spectrum of the signal of a magnetic probe and (b) intensity plot of the temporal evolution of the frequency spectrum. The intensity of the mode is represented by the shade of brightness

3.2 Low-frequency Waves

When the power of heating ICRF is increased, the diamagnetism increases and the anisotropy becomes strong. The excitation of low-frequency (LF) magnetic fluctuations has been also detected in such high temperature plasmas. Frequencies of the excited mode, f_{LF}, are less than 1 MHz and satisfy the relation of $f_{LF} = f_{ICRF} - f_{AIC}$, where f_{ICRF} is the frequency of the heating ICRF (RF2) wave and f_{AIC} the frequency of the AIC modes. Figure 3 shows an example of the temporal evolution of the frequency spectrum of (a) the AIC modes and (b) the LF magnetic fluctuations. These fluctuations are detected with the same magnetic probe in the same discharge. A intense peak at 400 kHz in Fig.3(b) corresponds to the differential frequency of RF1, which uses two frequencies of 9.9 and 10.3 MHz on both east and west Type-III antennas, respectively. It is observed that the intensity of the LF waves becomes strong when the diamagnetism becomes large. Here, the possibility of the parametric decay of RF2 waves to the AIC modes and the LF waves is considered. The frequencies of the LF waves are confirmed to be strictly same as the differential frequencies between the RF2 wave and the AIC modes. In the next section, the spatial structures of the excited modes are discussed from the viewpoint of the matching condition for the parametric decay of the heating ICRF waves.

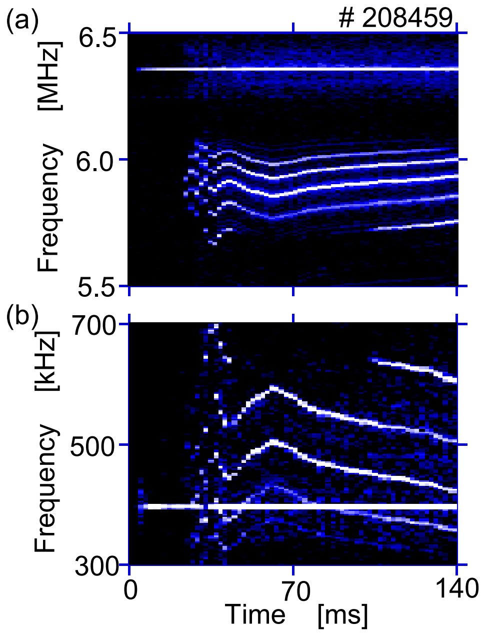

Fig.3 Intensity plots of the frequency spectra of (a) the AIC modes and (b) the low-frequency beat waves

4. Spatial Structures of Excited Modes

4.1 In Azimuthal Direction

To verify the parametric decay for the excitation of the LF waves, spatial structures are investigated by using two magnetic probes arrayed in the azimuthal and axial directions. Figure 4 shows the frequency versus the estimated azimuthal mode number of the heating ICRF waves, the AIC modes and the LF waves. Two magnetic probes are set with an angle of 45 degrees to each other at near the midplane of the central cell (z = 0.33 m). The resolution of the angle is 19 degrees. The mode numbers are estimated from the phase differences between both probes. Figure 4(a) shows the estimated mode number of the heating ICRF waves and the AIC modes. The heating ICRF wave with frequency of 6.36 MHz is detected as m = +2 and the AIC modes are detected between m = -1 and 0. Figure 4(b) shows the estimated mode number of the LF waves with frequencies of several hundred kHz. As indicated in the figure, the estimated mode numbers are not constant and shift to different mode numbers. For example, the mode number indicated by symbols of 'cross' in Fig.4(b) shifts from m = 0 to m = -2 during the discharge. These shifts are considered to be superposition of two or three waves with different mode numbers existing at the same time and changing their relative amplitude. The phase difference will be detected as intermediate values between two azimuthal mode numbers.

Because the excited slow waves with azimuthal mode numbers of m = -1 and/or m = 0 are damped due to the cyclotron resonance layer located between RF2 antennas and magnetic probes, only fast waves, which are not absorbed at the cyclotron resonance layer, can propagate to the probe location. RF2 waves detected near the midplane are fast waves with m = +2. In another discharge, fast waves with m = +1 are also detected. Each discrete peak of the AIC modes has been detected between m = -1 and m = 0 and is almost constant, independent of the plasma parameters. On the other hand, the mode number of each peak of the LF waves is different and changes depending on the plasma parameters.

From these experimental observations, the mode matching of the parametric decay is discussed as followings. If the pump wave (RF2) with m = -1 is excited, the LF waves with m = 0 and m = -1 are excited (symbol of 'cross' in Fig.4), because the AIC modes have mode

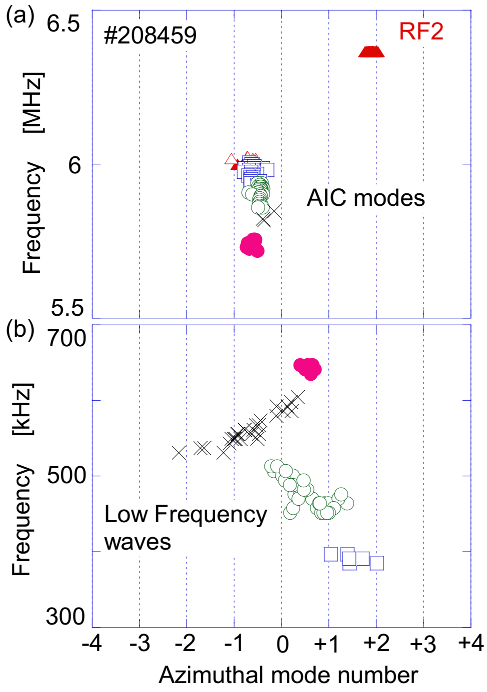

Fig.4 Azimuthal mode structures of (a) RF2 and the AIC modes and (b) the LF waves. Symbols of AIC modes and LF waves in the figure indicate discrete peaks and correspond to each other. It is clearly shown that the mode of the LF waves shifts to different modes depending on the plasma parameters.

numbers of m = -1 and 0. If the pump wave with m = 0 is excited, the LF waves with m = +1 and m = 0 (symbol of 'open circle' in Fig.4) are excited. And also, if the pump wave with m = +1 is excited, the LF waves with m = +2 and m = +1 are excited (symbol of 'square' in Fig.4).

4.2 In Axial Direction

In the axial direction, the mode structure of the excited waves is also measured. The third magnetic probe is located at the position of 0.78 m from the azimuthal probe array (z = 1.11 m). By using two probes arrayed on the same magnetic field line, the axial structure of the excited modes is evaluated. Figure 5 shows frequencies of detected waves as a function of the phase difference between two probes. In Fig. 5(a), measured phase differences of RF2 and the AIC modes are indicated. It is noted that the phase difference of RF2 is almost π. Because the same frequency of 6.36 MHz is used to both east and west DHT antennas, fast waves which can propagate in the central cell have interference with each other and form the standing waves. The phase difference between two probes in the standing wave region is considered to be detected as π or 0. Then, the phase difference of π on RF2 is consistent with the standing wave formation. In the previous paper [3], it is reported that the AIC modes are formed as standing waves near the midplane of the central cell and propagate outside the standing wave region. As shown in Fig.5(a), the phase differences of the AIC modes are almost π or 0, except for a peak with the highest frequency. The AIC mode with the highest frequency is excited in the initial phase with narrow standing wave region. The finite phase difference indicates that the axial probes at z = 1.11 m are located outside the standing wave region. Figure 5(b) shows the phase differences for the LF waves. The shift of the phase differences is again observed and it is difficult to understand precise axial structures of the LF waves. Now, the parameter dependences of the phase difference between two probes are under investigation and no conclusions for the axial structure of the LF waves have been obtained yet.

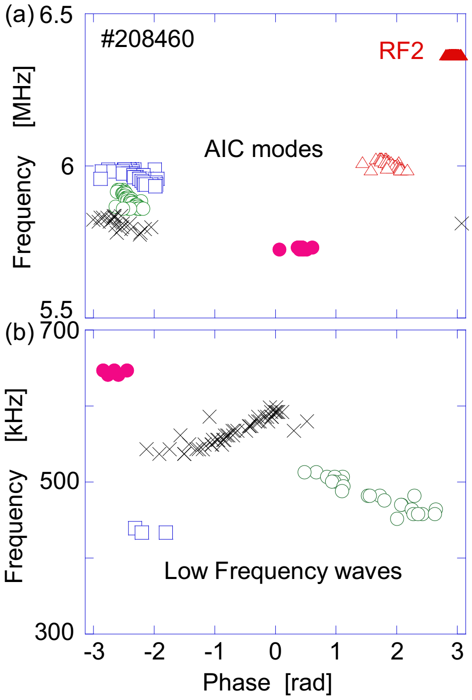

Fig.5 Axial mode structures of (a) RF2 and the AIC modes and (b) the LF waves. Symbols of AIC modes and LF waves in the figure indicate discrete peaks and correspond to each other. The symbols also correspond to those in Fig.4.

5. Summary

In high power ICRF experiments on the GAMMA 10 tandem mirror, plasmas with a strong temperature anisotropy are produced. In such high temperature plasmas, the AIC modes are spontaneously excited. The LF waves which have differential frequencies between the heating ICRF waves and the AIC modes are also detected. The spatial structures of these modes are evaluated for discussing the parametric decay of the heating ICRF waves to the AIC modes and the LF waves. It is suggested from the structure in the azimuthal direction that the RF2 waves with different mode numbers are excited and branch into the AIC modes and the LF waves. Up to now, the structure of the LF waves in the axial direction is not confirmed to be the parametric decay of the heating ICRF waves.

ACKNOWLEDGMENTS

The authors acknowledge the GAMMA 10 group at the University of Tsukuba for their collaboration. This work is partly supported by Grant-in-Aid for Scientific Research under the Ministry of Education, Culture, Sports, Science and Technology, Japan (No.20026002) and also partly supported by the bidirectional collaborative research program of National Institute for Fusion Science, Japan (NIFS06KUGM014).

REFERENCES

[1] Ichimura, M., *et al*., Nuclear Fusion **28**, 799 (1988).

[2] Tamano, T., *et al*., Proceedings of 15th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Seville, 1994, (IAEA, Vienna), Vol.2 p.399 (1995).

[3] Katsumata, R., *et al*., Phys. Plasmas **3**, 4485 (1996).

[4] Ichimura, M., *et al*., Phys. Rev. Lett. **70**, 2734 (1993).

[5] Ichimura, M., *et al*., Nuclear Fusion, **39,** 1995 (1999).

[6] Inutake, M., *et al*., Plasma Physics and Controlled Nuclear Fusion Research, Vol.II, IAEA, Vienna (1993) 651-658