J. Plasma Fusion Res. SERIES, Vol. 6 (2004) 741–744

Excitation of the Alfvén Ion Cyclotron Mode due to Anisotropic Heating

KAKIMOTO Shingo, INOUE Daisuke, ICHIMURA Makoto, HIGAKI Hiroyuki, HORINOUCHI Kentarou, IDE Kouhei, YAMAGUCHI Yuusuke, NAGAI Hirohisa, NAKAGOME Kenichirou, WATANABE Tsuguhiro[1] and CHO Teruji

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

[1]National Institute for Fusion Science, Toki 509-5292, Japan

(Received: 9 December 2003 / Accepted: 6 May 2004)

Abstract

Alfvén ion cyclotron (AIC) mode is studied in the plasmas with two ion temperature components. In the GAMMA 10 tandem mirror, plasmas with the strong temperature anisotropy are produced by ICRF heating. The plasma with two ion temperature components has been observed under the application of ICRF heating. To evaluate the AIC mode in GAMMA 10, the dispersion relation in a hot plasma which has two ion temperature components was solved. The frequency region of the AIC mode excited in the plasma with two ion components is expanded and the growth rate becomes large.

Keywords:

GAMMA 10, AIC mode, anisotropic plasma, two ion components

1. Introduction

The production of the high β (the ratio of ion pressure to magnetic-field pressure) plasmas is one of the most important themes in the GAMMA 10 tandem mirror. Fundamental ion cyclotron resonance heating produces hot ion plasmas in GAMMA 10 [1]. Because ions are accelerated to the perpendicular direction to the magnetic field line in the ion cyclotron resonance layer, plasmas with the strong temperature anisotropy ($T_\perp/T_\parallel > 10$) are formed. Where the $\perp$ subscript indicates the component perpendicular to the magnetic field line and the $\parallel$ subscript indicates the component along the magnetic field line. When the temperature anisotropy became large, the magnetic field fluctuation has been clearly observed with the signals of magnetic probes. This instability has been identified as spontaneously excited Alfvén Ion Cyclotron (AIC) mode [2]. Because the AIC mode relaxes the anisotropy of the velocity distribution, suppression of the AIC mode is important for the improvement of the particle confinement because the axial particle loss is enhanced when the AIC mode is excited. Recently, the high harmonic fast waves (HHFW) are used for the high density plasma production in GAMMA 10. High-energy ions are accelerated when HHFW are applied in addition to conventional ion cyclotron range of frequency (ICRF) heating [3]. This suggests that the plasma has high-energy ion temperature component. It is commonly observed that plasmas consist of multiple ion temperature components and species. The AIC mode will be strongly affected by the composition of the ions and their velocity distributions.

Up to now, the AIC mode in the plasmas which have one component in the ion species and temperature has been studied. In this report, the AIC mode in the plasmas which have two ion temperature components is analyzed by solving hot plasma dispersion relation.

2. Experimental setup and observation of the AIC mode

The GAMMA 10 tandem mirror consists of a central-cell, two anchor-cells, two plug/barrier-cells and end-cells aligned axially. The length of the central-cell is 6 m and both ends of the central-cell are connected to the anchor-cells through the mirror throat regions. The schematic of GAMMA 10 is shown in Fig.1 [(a) the configuration of the magnetic coils, (b) the magnetic field lines and (c) the strength of the magnetic field]. The main plasma is built up with ICRF waves together with gas puffing in the central cell. One of the ICRF system (RF1) is used for plasma production at the central-cell and (magnetohydrodynamic) MHD stabilization of the whole plasma at the anchor-cell. So-called Nagoya type-III antennas, which are installed near both ends of the central cell ($z = \pm 2.2$ m), are used for RF1 antennas. The other RF system (RF2) is used for ion heating at the central-cell mid-plane. Conventional double half-turn (DHT) antennas, which

Corresponding author's e-mail: kakimoto@prc.tsukuba.ac.jp

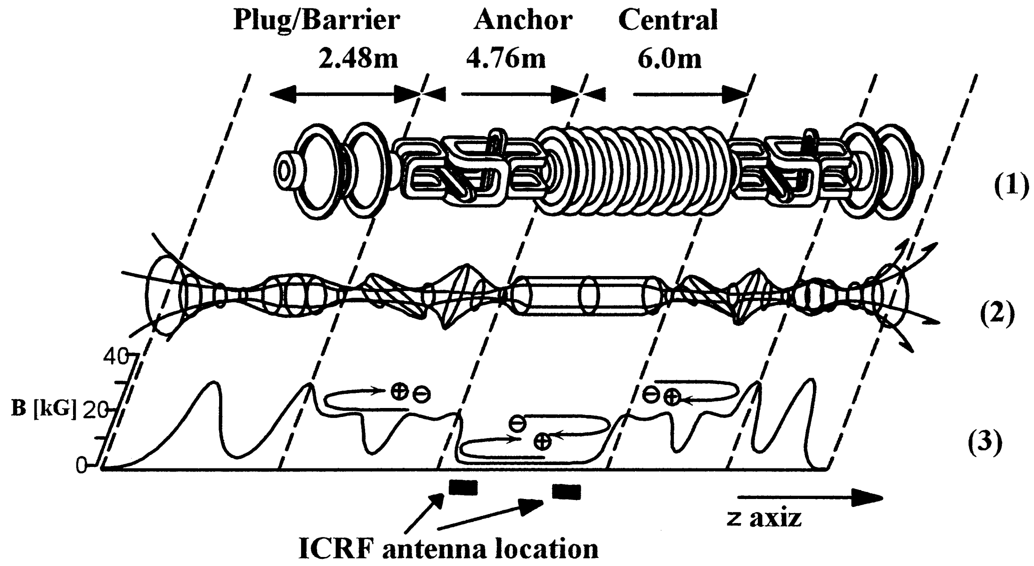

Fig. 1 Schematic illustration of the GAMMA 10 tandem mirror.
(a) The configuration of the magnetic coils. (b) The magnetic field lines. (c) The strength of the magnetic field. RF antennas are located in the both side of the central cell.

are installed at $z = \pm\ 1.7$ m, are used for RF2 antennas.

A new ICRF wave system (RF3) with high harmonic frequency has been introduced for production of high density plasma. The frequency of the RF3 is variable (36–76MHz) which corresponds to the range of 6–12 times of ion cyclotron frequency at the central-cell mid-plane. The oscillator power is 200 kW at maximum. The west side of the DHT antenna is used for the RF3 system. In standard hot-ion-mode operations, RF3 pulse is applied moderately after 50 ms of the discharge initiation using RF1 and RF2 and then the power is increased gradually to the constant power level within 20 ms. Semiconductor detector which can only detect over 10 keV ions has been installed on the central cell in GAMMA 10 [3]. High energy ions have strongly detected just after applying RF3. In this time, there are no increase in the diamagnetic signal. It suggests that the high energy ion tail is formed with RF3. It is observed that a small part of high energy ions are accelerated by applying RF3.

The fluctuations excited inside the plasma are measured with conventional magnetic probes, which are aligned in both axial and azimuthal directions to identify the wave length in the corresponding direction. Figure 2 shows the frequency spectrum of the probe signal. The frequency of the RF2 system is adjusted to the ion cyclotron frequency near the mid-plane of the central-cell. The AIC waves are excited slightly under the frequency of RF2. The experimental observation of the AIC mode in GAMMA 10 has been reported in a ref. [4].

In the following section, the effect of the high energy tail formation on the AIC mode is discussed.

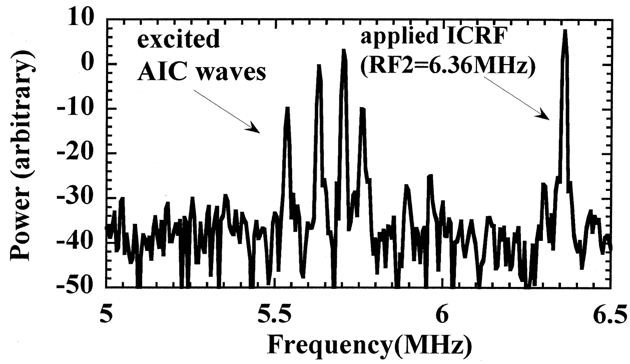

Fig. 2 Frequency spectrum of the magnetic probe signal.

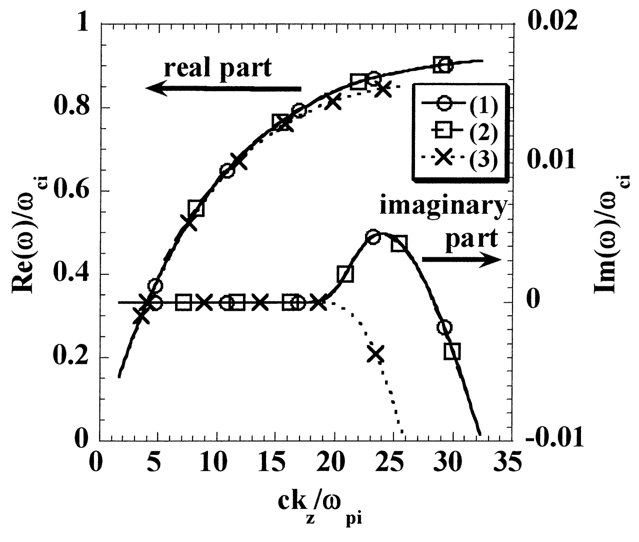

Fig. 3 Slow waves were calculated by following condition.
(1) $T_\perp$ = 2 keV, $T_\perp/T_\parallel$ = 10, $n_e = 2\times10^{18}$ m^{-3}; Solid line.
(2) $T_\perp$ = 20 keV, $T_\perp/T_\parallel$ = 10, $n_e = 2\times10^{17}$ m^{-3}; Broken line.
(3) $T_\perp$ = 0.2 keV, $T_\perp/T_\parallel$ = 1, $n_e = 2\times10^{18}$ m^{-3}; Dotted line.

3. Analysis of the AIC mode in the calculation

3.1 Calculation results of the slow wave with one temperature component

The hot plasma dispersion equation with complex frequency is solved [5]. This hydrogen plasma is assumed to have anisotropic Maxwellian velocity distribution. The used parameters are the typical plasma parameters in the central cell mid-plane of GAMMA 10, a density of $n_e = 2\times10^{18}$ m^{-3}, an electron temperature of $T_e = 100$ eV, an ion temperature of $T_\perp = 2$ keV, an ion temperature anisotropy of $T_\perp/T_\parallel = 10$ and the magnetic strength of $B = 0.4$ T. Small perpendicular wave number of $k_x = 0.5$ m^{-1} is assumed. Figure 3 shows the dispersion relations of the slow waves with the complex frequency. Im(ω)/ω_{ci} indicates instability growth rate. Where ω_{ci} is the ion cyclotron frequency. When the instability growth rate is positive, the plasma is unstable. This instability is called the AIC mode. It is theoretically known well that the AIC mode propagates mainly along the magnetic field line. In this report, it is assumed that the high energy ion component has $T_\perp = 20$ keV and $n_e = 2\times10^{17}$ m^{-3} in order to compare with different two ion temperatures which have same plasma β. A solid line shows the dispersion relation of the AIC mode in the plasma with $T_\perp = 2$ keV and $n_e = 2\times10^{18}$ m^{-3} and a broken line shows the dispersion relation of the AIC mode in the plasma with $T_\perp = 20$ keV, $n_e = 2\times10^{17}$ m^{-3}. In both cases, the plasmas have the same ion $\beta_\perp$ and temperature anisotropy. Because the solid line overlaps on the broken line, it is indicated that the excitation region of the AIC mode in the plasma with one temperature component is determined by the ion $\beta_\perp$ and the temperature anisotropy. The dotted line shows the dispersion relation in the plasma with the isotropic temperature of 0.2 keV. Negative Im(ω)/ω_{ci} indicates the wave damping.

3.2 Calculation of the AIC mode with two ion temperature components

To evaluate the effect of such a tail component to the frequency spectrum of the AIC mode, the dispersion relation in plasmas with two ion-temperature components is calculated.

A solid line in Fig. 4 shows the dispersion relation of the AIC mode in the plasma with bulk component ($n_e = 2\times10^{18}$ m^{-3}, $T_\perp = 2$ keV, $T_\perp/T_\parallel = 10$) and the tail component ($n_e = 2\times10^{17}$ m^{-3}, $T_\perp = 20$ keV, $T_\perp/T_\parallel = 10$). Other parameters are fixed on the same values as indicated in Fig. 3. Both components have the same $\beta_\perp$-values and the AIC modes in the plasmas with each parameters are excited in the same frequency region as predicted in Sec. **3.1**. It is clearly shown in line (1) (solid line) in Fig. 4 that the frequency region of the AIC modes expands to the lower frequency region. It is considered that the AIC mode is superposition of the AIC modes with the bulk components and with the tail component. As shown in Fig. 3, the AIC modes are excited in the same frequency region in the plasmas. However, the solid line in Fig. 4 shows the high-energy ion component expands the frequency region of the excitation of the AIC mode. A broken line in Fig. 4 shows the dispersion relation in the plasma with bulk component. A dotted line in Fig. 4 shows the dispersion relation in the plasma with the tail component and the isotropic bulk component of $T_i = 0.2$ keV. The dotted line indicates the AIC mode with the tail component is excited lower frequency region and more strongly due to the low temperature bulk component.

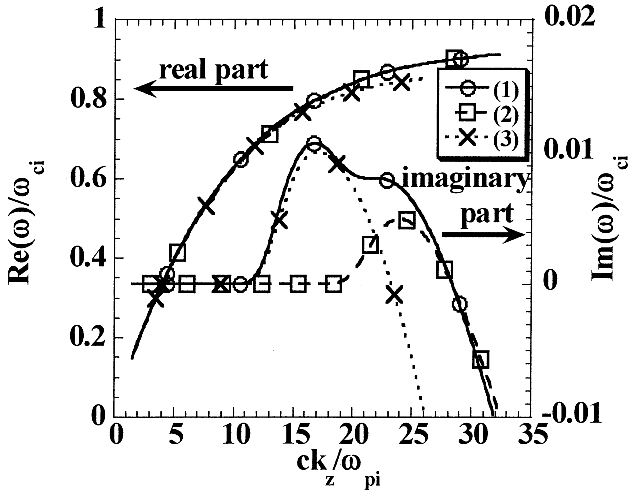

Fig. 4 Comparison with different AIC mode.
(1) Plasma has two ion temperature components. Each ion temperatures are anisotropic; Solid line.
(2) Plasma has one ion component. The parameters of this component are $T_\perp = 20$ keV, $T_\perp/T_\parallel = 10$, $n_e = 2\times10^{17}$ m^{-3}; Broken line.
(3) Plasma has two ion components. Bulk ion has isotropic temperature with $T_i = 0.2$ keV and high-energy ion has anisotropic temperature with $T_\perp = 20$ keV, $T_\perp/T_\parallel = 10$, $n_e = 2\times10^{17}$ m^{-3}; Dotted line.

Because the AIC mode with bulk ion component and high energy tail component superposes on the AIC mode with high-energy tail component and isotropic bulk component, the excitation of the AIC modes in the experiment will be strongly affected by the high-energy tail component. Since this calculation is able to apply to all plasmas with such a high energy tail component, the AIC modes in the minority heating in D-H plasma and on the perpendicular injection of neutral beams can be evaluated. The spectrum of the AIC modes observed in the experiments will be strongly affected from the composition of the ion velocity distributions.

4. Summary

The AIC modes with two ion temperature components plasma are evaluated. The frequency region on which the AIC mode with two ion components is excited expands to lower frequency side. The growth rate becomes higher than the AIC mode in the plasmas with one temperature component.

References

[1] T. Tamano *et al.*, *Plasma Phys. and Controlled Nuclear Fusion Research 1994*, Vol. 2 (IAEA, Vienna, 1995),

p. 399.
[2] M. Ichimura *et al.*, Phys. Rev. Lett. **70**, 2734 (1993).
[3] S. Kakimoto *et al.*, *Transactions of Fusion Science and Technology* Vol. 43, JAN. 2003, 86.
[4] R. Katsumata *et al.*, Phys. Plasmas **3**, 4489 (1996).
[5] H. Ikegami, *Nuclear Fusion Research I*, (Nagoya university publication, Nagoya, 1996), p. 831 (in Japanese).