Coupling of ICRF Waves and Axial Transport of High-Energy Ions Owing to Spontaneously Excited Waves in the GAMMA 10 Tandem Mirror

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Abstract. Plasmas with high ion-temperature of several keV and strong temperature anisotropy of more than 10 have been produced by using ion-cyclotron range of frequency (ICRF) heating in the GAMMA 10 tandem mirror. In such high performance plasmas with strong anisotropy, high-frequency fluctuations, so-called Alfvén-Ion-Cyclotron (AIC) waves, are spontaneously excited. The AIC waves have several discrete peaks in the frequency spectrum. Couplings between ICRF waves for heating and excited AIC waves are clearly observed in the central cell of GAMMA 10. Low frequency waves which have differential frequencies between discrete peaks of the AIC waves are also observed. Parametric decay of ICRF waves are discussed and pitch angle scattering of high-energy ions owing to those low-frequency waves are clearly detected. Energy transport along the magnetic field line is one of the important subjects when the ICRF power is injected in the perpendicular direction to magnetic field line.

1. Introduction

Ion cyclotron range of frequency (ICRF) heating is one of most promising schemes for heating fusion plasmas. When the ICRF power and consequent wave energy levels increase, it will become important to understand the detailed physics of wave-wave and wave-particle interactions. It is required to consider both linear and nonlinear processes for deposition of ICRF powers, for example, parametric decay of the heating ICRF waves has been observed in many fusion experiments [1]. In the GAMMA 10 tandem mirror, the ICRF waves have been used for plasma production, heating and sustaining MHD stability [2]. 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. Alfvén-Ion-cyclotron (AIC) waves are spontaneously excited owing to such strong temperature anisotropy [3]. When the power of heating ICRF is increased, it will be expected the diamagnetism increases and the anisotropy becomes strong. However, saturation of the diamagnetism is sometimes observed in the experiments. The degradation of the confinement will be possible candidate for the saturation. The excitation of the AIC modes, which can scatter the hot ions confined in the magnetic mirror field into loss cone of the velocity space in the central cell, is one of the possible mechanisms. On the other hand, the parametric decay of the heating ICRF waves is discussed for the saturation mechanism of the diamagnetism [4]. Low-frequency (LF) magnetic fluctuations with beat frequencies between the heating ICRF waves and discrete peaks of the AIC modes are clearly detected in GAMMA 10. 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.
High energy ions of which energy is more than 50 keV have been observed in the end-loss ions [5]. The axial transport of high-energy ions due to loss processes other than the classical Coulomb scattering has been suggested. Considerable energy transport along the magnetic field line due to the AIC waves is suggested theoretically [6]. Recently, a divertor simulation study using end loss ions has been started in the GAMMA 10 tandem mirror [7]. Mirror-confined hot plasmas with ion temperature around 0.5 keV are transported along the magnetic field line in the standard operation. The wave-particle interactions between spontaneously excited AIC waves and high energy ions are possible to be important process. In this manuscript, the quasi-linear relaxation process is also discussed.

2. Experimental Setup

2.1. GAMMA 10 Device

GAMMA 10 is a minimum-B anchored tandem mirror with axisymmetric plug/barrier cells at both ends. The central cell has an axisymmetric mirror field and is 5.6 m in length with the magnetic field strength of 0.4 T at the midplane. The mirror ratio of the central cell is 5. The segmented-limiter of which diameter is 0.36 m is set near the midplane. The plasma is produced by applying RF power (RF1) in combination with short-pulse gun-produced plasmas from both ends and hydrogen gas injections near RF-antennas. The plasma is also heated by applying RF power (RF2) with the fundamental ion-cyclotron resonance layer near midplane of the central cell. In addition to the plasma production, RF1 is used for heating ions in minimum-B anchor cells [2]. The frequency of RF1 is selected to be a fundamental ion-cyclotron resonance frequency near the midplane of the anchor cell. Two types of antennas are installed in both (east and west) ends of the central cell. So-called Nagoya Type III antennas (driven by RF1) and conventional double half turn (DHT) antennas with single layer Faraday shield (driven by RF2) are used. Figure 1 shows a schematic drawing of the GAMMA 10 coil system and the magnetic field profile in the axial direction. The locations of heating systems and diagnostics for fluctuations and high-energy ions are shown in the figure. Recently, new ICRF antennas (driven by RF3) are installed in both anchor cells. A bare antenna which is a double-arc-type (DAT) shape without Faraday shield is used. The purpose of the anchor heating is to enhance the anchor stabilization for the operation flexibility.

![FIG.1 Schematic drawing of the GAMMA 10 coil system, axial profile of the magnetic field strength. The locations of the heating system and diagnostics are indicated.](image-url)
Figure 2 shows the temporal evolution of (a) ICRF pulses (RF1, RF2), (b) line density of the central cell and (c) three diamagnetic signals located at the three different positions along the magnetic field line on the typical discharge. As shown in the figure, there are large differences between diamagnetic signals near the midplane (z = -0.33 m) and off-midplane (z = 1.5 m and z = 1.9 m). These differences show the pressure profile along magnetic field line and also indicate the pressure anisotropy. The pressure anisotropy in the axial direction can be estimated from these three diamagnetic signals and indicated in Fig. 2(d). Plasmas with strong pressure anisotropy of more than 10 are formed in the central cell. The AIC waves are excited spontaneously owing to such strong pressure anisotropy.

![Image](image.png)

**FIG. 2** Temporal evolution of (a) ICRF pulses, (b) line density, (c) diamagnetic signals, and (d) estimated anisotropy are indicated.

### 2.2. Diagnostics

To measure high-energy ions, two semiconductor detectors are installed in GAMMA 10. One is an east-end high energy-ion detector, eeHED, of which configuration has been described in Ref. 5 and another is a central-cell high energy-ion detector, ccHED, of which configuration has been described in Ref. 8. A silicon surface barrier (SSB) detector (nominal depletion depth of 300 μm) is used in this experiment. The minimum detectable energy is limited to about 6 keV. The sensitivity of the detector for protons has been indicated in Ref. 5. The eeHED can measure the hot ions transported along the magnetic field line at the east end. The ccHED has co-axial geometry and a fixed pin-hole aperture of 0.5 mm diameters is set in front of the SSB detector on an inner pipe. By rotating ccHED against the magnetic field line, a pitch angle distribution of hot ions can be measured. The ccHED is located just outside of the limiter radius (18 cm) and can detect high-energy ions transported across the magnetic field line. Magnetic probes (MP) and electrostatic probes (ESP) have been installed to measure magnetic fluctuations and density fluctuations in both azimuthal and axial directions in the peripheral region of the central cell.

We have developed a two-channel microwave reflectometer (RM) to study the high frequency fluctuations in the plasma core region. The diagram of the reflectometer system is shown in Fig. 3. This system is composed of two simple heterodyne reflectometers. Each reflectometer uses one antenna for both launching and receiving microwave by using a circulator, which is useful to reduce the number of antennas. As predicted in Fig. 3, the transmitting line of microwave between the antenna and circulator of one reflectometer has two lines. The switching of those paths is made by re-connecting the transmitting line in a
simple way. When we use the line-1 in Fig. 3, simultaneous two-point measurement at two different positions, where the antennas are located, is allowed. This character enables us to investigate the axial structure of the ICRF waves by appropriately locating the antennas at axially separated positions. On the other hand, when we use the line-2, the same antenna is used by two reflectometers. In this case, one cannot select the same frequency for two transmitting microwaves due to cross talk of the system. By appropriately selecting the two frequencies in relation to the density profile, two-point measurement of density fluctuations in the same cross section is allowed. This measurement is the same as so-called correlation reflectometer.

The advantage is that in this system, one can arbitrarily choose two measuring radial positions owing to application of two independent frequency-variable oscillators, which is in contrast to common correlation reflectometers having one main frequency-variable oscillator and several frequency-fixed oscillators for up- or down-converting the main frequency.

The locations of these diagnostic systems are also indicated in Fig. 1.

3. Observation of Wave-Wave Coupling with a Microwave Reflectometer

When the power of heating ICRF is increased, the diamagnetism increases and the temperature anisotropy becomes strong. In addition to magnetic probes installed in the peripheral region, a microwave reflectometer system is introduced for measurement of the spatial structure of density fluctuations in the core region [9]. Density fluctuations of electromagnetic waves in ICRF have been discussed [10] and detected in GAMMA 10 [11]. An axial structure is measured with horn antenna array installed in the vacuum chamber and a radial structure is measured by changing the frequency of injecting microwave. Figure 4(a) shows the temporal evolution of the frequency spectrum of the reflectometer signal in the typical discharge. Intensity plot in the frequency range up to 12.5 MHz is indicated. Figure 4(b) shows plasma parameters and Fig.4(c)-(e) show intensity plots of frequency spectrum of the inner density fluctuations in each frequency range. As indicated in the figure, $f_{RF1E}$, $f_{RF1W}$, $f_{RF2}$ and $f_{AIC}$ are frequencies of the ICRF waves for plasma production (RF1-East and RF1-West of 9.9 and 10.3 MHz), the ICRF wave for heating (RF2 of 6.36 MHz) and excited AIC waves (just below that of RF2), respectively. Several wave-wave couplings between injected ICRF waves and the AIC waves are observed from low frequency to high frequency regions. Couplings in the range more than 20 MHz are identified. Parametric decay from the heating ICRF waves (RF2) to the AIC waves and low-frequency (LF) waves, of which frequencies are $f_{RF2} - f_{AIC}$, has been observed. Continuous density fluctuations are detected in the range lower than 0.1 MHz as shown in Fig.4(e). In the region around 0.1 MHz, low-frequency fluctuations, of which frequencies are differential frequencies between discrete peaks of the AIC waves (indicated as $f_{AICn} - f_{AICn-1}$), are excited. These low-frequency waves around 0.1 MHz are also detected with magnetic probes and electrostatic probes.
installed in the periphery region of the central cell. In the previous experiments, it was observed that appearance of the LF modes \((f_{RF2} - f_{AIC})\) was related to the saturation of the diamagnetism and the intensity of the LF waves becomes strong with diamagnetism.

4. Axial Transport of High-Energy Ions Owing to the AIC Wave

Low-frequency magnetic fluctuations around 0.1 MHz, of which frequencies are differential frequencies between discrete peaks of the AIC waves, are clearly detected with magnetic probes installed in the central cell. These fluctuations are also detected in the ion saturation current signal measured with electrostatic probes. As reported in the previous manuscript [12], the radial transport of high-energy ions due to drift-type fluctuations is observed with ccHED in the central cell. Figure 5 shows (a) the raw signal of eeHED and (b) the intensity plot of the frequency spectrum of the eeHED signal. The fluctuations around 0.1 MHz are clearly detected. Figure 6 shows the raw eeHED signal in the same time scale as indicated in Fig.5 and in the extended time scale of 0.2

FIG.4 (a) Intensity plot of the temporal evolution of the reflectometer signal and temporal evolution of (b) plasma parameters, (c)-(e) intensity plots of the frequency spectra in each frequency range.

FIG.5 Temporal evolution of (a) raw signal of high-energy ions (eeHED) along the magnetic field line and (b) a intensity plot of frequency spectrum of eeHED.
ms. As shown in the figure, high-energy ions are detected as burst-like signals. Each signal peak is considered to contain several tens particles. The period of these bursts corresponds to the frequency of the fluctuations indicated in Fig.5(b). These fluctuations are not observed in the ccHED signals. Then, pitch angle scattering of high-energy ions in the velocity space owing to spontaneously excited Alfvén wave are clearly indicated. If the transport of these high-energy ions along the magnetic field line is mainly caused by the collisional process, the continuous signal of eeHED will be expected and also high-energy ions are detected in ccHED.

In GAMMA10, plasmas with the same beta-value and same anisotropy as in the central cell are formed in the anchor cell. However, the AIC waves in the anchor cells have not been observed until now. Recently, new ICRF antennas have been installed in the anchor cell and additional heating experiments have been performed. The main purpose is to enhance the anchor stabilization for the flexible operation. The increase of the densities in both central and anchor cells and the enhancement of MHD stabilization effect have been already confirmed in the experiment. Figure 7 shows typical plasma parameters when additional anchor ICRF waves (RF3) are applied. When RF3 is applied, the line density in the west anchor cell increases and the raw signal of eeHED increases significantly. In this discharge, the AIC wave in the anchor cell is firstly observed in the GAMMA 10 tandem mirror. Figure 7(d) shows the intensity plot of the frequency spectrum obtained by the reflectometer installed in the west anchor cell. The density fluctuation, of which frequency is around 9 MHz, is clearly observed just below the frequency of the heating ICRF waves. It is suggested that the axial transport of high-energy ions is remarkably enhanced owing to the AIC wave in the anchor cell.

5. Summary

In the GAMMA 10 tandem mirror, fluctuations in ICRF are measured in the core region by using a microwave reflectometer. Wave-wave coupling between injected ICRF waves and spontaneously excited waves is clearly observed. Wave-particle interactions
between spontaneously excited waves and high energy ions (more than 6 keV) are also clearly detected. The axial transport of the high-energy ions that are heated in the perpendicular direction in the central cell are enhanced owing to the AIC waves.

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