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Nonlinear coupling of ICRF waves in the GAMMA 10 central cell
GAMMA 10セントラル部におけるICRF波動間の非線形結合

Ryuya Ikezoe, Takuya Okada, Makoto Ichimura, Mafumi Hirata, Takuro Yokoyama, Yoshiaki Iwamoto, Shuhei Sumida, Kohei Takeyama, Seowon Jang, Masayuki Yoshikawa, Junko Kohagura, Yoriko Shima
池添竜也，岡田拓也，市村　真，平田真史，横山拓郎，岩本嘉章，隅田脩平，竹山紘平，ジャン　ソウォン，吉川正志，小波蔵純子，嶋頼子

Plasma Research Center, University of Tsukuba
1-1-1 Tennodai, Tsukuba 305-8577, Japan
筑波大学プラズマ研究センター　〒305-8577　つくば市天王台1-1-1

Several ion-cyclotron range of frequencies (ICRF) waves simultaneously exists in the GAMMA 10 central cell, which are those externally excited for heating and those spontaneously excited owing to the anisotropy of ion temperature (AIC waves). Bispectral analysis applied to internal density fluctuation measured by a microwave reflectometer clearly shows the occurrence of fruitful wave-wave couplings among the ICRF waves. Nonlinearly excited waves which have difference frequencies of the AIC waves are considered to be important for the axial transport of energetic ions in GAMMA 10. Radial dependence of the calculated bicoherences shows that they are excited especially in the core region.

1. Introduction
Magnetized plasmas in fusion experiments are representative example of the system where many types of nonlinear phenomena exist. They sometimes play critical role on, such as, sustainment of the whole system, self-organization of some unique structure, some kinds of relaxation and saturation mechanism and so on.

In the GAMMA 10 tandem mirror, several ion-cyclotron range of frequencies (ICRF) waves are used for production and heating of plasma. Furthermore, as a unique mode in magnetized plasma with high anisotropy of ion-temperature like in GAMMA 10, Alfvén-ion-cyclotron (AIC) waves emerge just below the ion cyclotron frequency. The AIC waves are considered to cause the relaxation of the anisotropy since the diamagnetism saturates when the AIC waves are spontaneously excited owing to formed anisotropic distribution of ion velocities. To investigate the relaxation mechanism, precise measurement of the ICRF waves in the inner region of hot plasma and the evaluation of nonlinear coupling are needed. It is theoretically shown that ICRF waves are accompanied by density fluctuation and, therefore, they can be detected by a reflectometer. A reflectometer detects local density fluctuation on the cutoff layer of the probing microwave. This spatial resolution is appropriate for the precise measurement of ICRF waves. We have developed a microwave reflectometer and evaluated the nonlinear coupling among ICRF waves in GAMM 10.

2. Density fluctuations of ICRF waves
Figure 1 shows an example of density fluctuation spectrum measured by the developed reflectometer in the GAMMA 10 central cell. In addition to the ICRF waves externally applied for heating, which are denoted by E-RF1, W-RF1 and RF2, spontaneously excited AIC waves can be seen. At the sum and difference frequencies of RF2 and the AIC waves, density fluctuations clearly appear. They are considered to be nonlinearly excited waves.

3. Application of bispectral analysis
For nonlinear wave-wave interaction, the wave frequencies and wavenumbers must satisfy the resonance condition; $f_1 + f_2 = f_3$ and $k_1 + k_2 = k_3$. And also the particular phase relation must be held among these three interacting waves otherwise they are independently excited waves even if the waves satisfy the resonance condition. To distinguish such relation, independent or nonlinearly coupled, bicoherence is helpful and used for many research areas (see such as [1,2]).

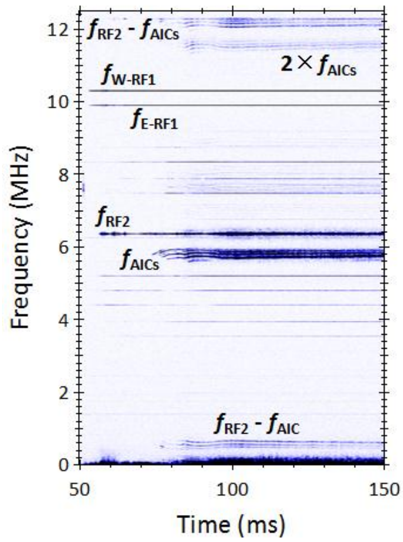

Fig. 1. Density fluctuation spectrum measured by a reflectometer in the GAMMA 10 central cell.

Bicoherence is defined by

$$b^2(k,l) = \frac{E[X_k X_l X_{k+l}^*]}{E[|X_k X_l|^2]E[|X_{k+l}|^2]} ,$$

where E is expectation operator and X_k is the complex Fourier amplitude of the frequency or the wavenumber of k. Statistically meaningful calculation of bicoherence needs proper treatment of expectation operator. The variance is reduced by the factor $1/M$, where M is averaging number. We collect each ensemble in the steady state from three identical discharges. For example, in Fig. 1, the data between 110 – 140 ms is used. The total M is about 900. Here we evaluate only the phase relation in frequency space. The detection of proper wavenumbers with a two-channel reflectometer is now being tried.

An example of the bicoherence is shown in Fig. 2 with concentration on the wave-wave interaction between the AIC waves and the 6.36-MHz ICRF wave (RF2). As clearly shown in Figs. 2(b) and 2(c), $b^2(-f_{\mathrm{AICs}}, f_{\mathrm{RF2}})$ and $b^2(f_{\mathrm{AICs}}, f_{\mathrm{RF2}})$ remain high after enough number of ensemble averaging. These produce the waves at the difference and sum frequencies seen in Fig. 1. In addition, bicoherences of the difference and sum between the AIC waves also remain high. Density fluctuations are seen at the frequencies of $2\times f_{\mathrm{AICs}}$ in Fig. 1. The difference frequencies between f_{AICs} also exist while they are not clear in Fig. 1. Radial dependence of the calculated bicoherences indicates that the difference frequencies are excited especially in the core region.

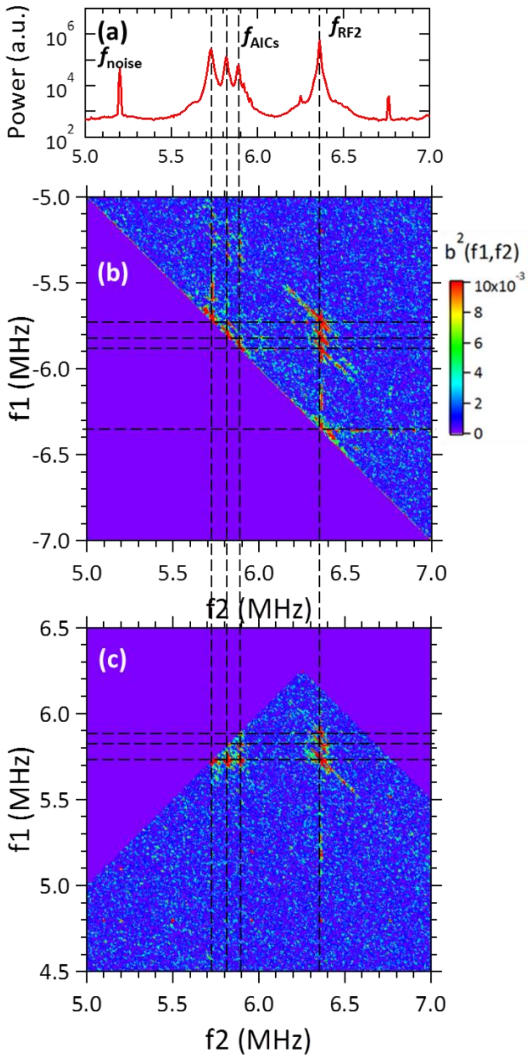

Fig. 2. (a) Ensemble averaged power spectrum of the density fluctuation measured by a reflectometer and (b), (c) its bicoherences.

4. Discussions and Summary

Bispectrum analysis clearly shows the emergence of wave-wave coupling between the ICRF waves in GAMMA 10. The wave-wave coupling could be important for the global parameters of GAMMA 10 for two reasons. As reported in [3], the enhancement of wave-wave coupling suddenly occurs in accordance with the saturation of the diamagnetism in the central cell. One reason deduced from the observation is the possibility of the loss of heating power. ICRF heating power of RF2 is delivered to nonlinearly excited waves through nonlinear coupling with the AIC waves and the heating power is reduced, which might contribute to the saturation of the confined energy.

The second reason is also related to nonlinear coupling. We have observed that the temporal evolution of the axially transported energetic-ions flux measured at the machine end exhibits periodic burst-like behavior rather than the continuous one. If the axial transport is caused mainly by collisions, it should show continuous behavior. Ions which are dropped into the loss cone region in velocity space due to pitch-angle scattering in random phase immediately escape from mirror trapped region along the field lines. The measured periodicity of the burst-like loss of energetic ions is in absolute agreement with the difference frequencies of the AIC waves, which are nonlinearly excited as shown in Fig.2. The enhancement of axial transport of energetic ions through some wave-particle interaction with those nonlinearly excited waves are indicated, which should contribute to the saturation of the confined energy to some extent. An energy balance calculation applied to the hot-ion mode in GAMMA 10/PDX also indicates the existence of anomalous energy flow channel for the perpendicular ion temperature to be lost. The quantitative evaluation of this effect is under investigation.

Acknowledgments

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