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Measurement of ICRF waves in the GAMMA10 tandem mirror using reflectometers

A. Mase, T. Tokuzawa, N. Oyama, Y. Ito, A. Itakura, H. Hojo, M. Ichimura, M. Inutake,[a] and T. Tamano
Plasma Research Center, University of Tsukuba, Tsukuba, Ibaraki 305, Japan

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Microwave reflectometry has been applied to the central cell of the GAMMA 10 tandem mirror for measurements of fluctuations in the ion cyclotron range of frequency (ICRF). The instability with frequency $\omega<\omega_{ci}$ is identified as the Alfvén ion cyclotron wave driven by plasma β and ion pressure anisotropy. Internal magnetic fluctuations with $\delta B/B\sim 10^{-4}$ as well as density fluctuations of the same level for this wave are determined by a combination of X- and O-mode reflectometers. The fluctuations associated with the ICRF heating wave ($\omega=\omega_{ci}$) are also observed by three separated X/O mode reflectometers to study the physics of wave excitation and propagation. The radial profile of the fluctuation level is expected to give an estimation of the deposition profile of the heating power. The results will be applied in order to achieve efficient ion heating and to help the power balance study of central-cell plasma.

I. INTRODUCTION

In magnetically confined plasmas, the application of radio frequency (rf) waves near the ion cyclotron frequency is considered to be one of the most promising methods for additional heating and a necessity for future thermonuclear fusion experiments. The physics of wave excitation and propagation in the ion cyclotron range of frequency (ICRF) is under intensive experimental and theoretical investigation for efficient heating.

In the GAMMA 10 tandem mirror, high-energy plasmas with hot ions are produced by ICRF power. Energy containment of the ions may be dominated by charge-exchange loss and electron drag in tandem mirror plasmas. During the increase of the hot ions, the saturation of the energy containment has often been observed in the strong heated plasmas, which cannot be explained by charge-exchange loss and electron drag. The instabilities relevant to the rf heating may play an important role for this saturation. We report here the observation of waves in ICRF by microwave reflectometers installed in the central cell of GAMMA 10. The reflectometer has good spatial resolution while lacking wave-number resolution, and is ideally suited to study radial distribution of waves relevant to the ion heating.

II. EXPERIMENTAL SYSTEM

The GAMMA 10 is a tandem mirror consisting of a central cell, anchor cells attached to both sides of the central cell for MHD stabilization, plug cells for potential formation, and end cells. It is 27 m in total length, with the central-cell vessel 6 m in length and 1 m in diameter. The magnetic-field strength at the midplane of the central cell is $B_c=0.405$ T, and the mirror ratio is 4.9. The ICRF power with frequencies of 9.9 and 6.3 MHz is employed to build up a plasma and heat ions, following the gun-produced plasma injection. It is fed by double half turn and NAGOYA type-3 antennas located near the mirror throats of the central cell. The frequency of 6.3 MHz corresponds to the ion cyclotron frequency at the midplane of the central cell and 9.9 MHz corresponds to that of the anchor cells. Four gyrotrons providing electron cyclotron resonance heating with a frequency of 28 GHz are then applied to the plug/barrier cells in order to produce confining potentials. The plasma parameters in the central cell are as follows. The density $n_e\cong 2\times 10^{12}$ cm^{-3}, the electron temperature $T_e=60-80$ eV, and the averaged ion temperature $T_i=2-3$ keV.

The reflectometers as shown in Fig. 1 are located at the midplane ($z=0$ m) and at the west side ($z=-1.8$ m) of the central cell that is close to the rf heating antenna. At $z=0$ m, two systems are installed to observe the horizontal and vertical chords in one shot. The system utilizes a 7–18 GHz and/or 18–26 GHz, ~100-mW output of a yttrium-iron-garnet (YIG) oscillator as a source. The YIG oscillator is operated in a fixed frequency mode for the fluctuation measurements. A pyramidal horn with an ellipsoidal reflector is used as both transmitter and receiver. By switching between X- and O-mode, the fluctuations of the whole density region of the radial profile can be observed in the standard operational mode of GAMMA 10. The reflected wave is separated from the incident wave by a circulator, and is mixed with the unperturbed local oscillator wave in a mixer. The homodyne-detected intermediate frequency signals are amplified by low noise amplifiers and then fed to the data processing system.

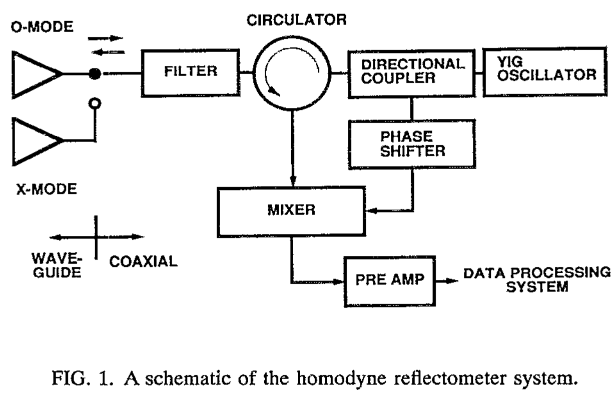

FIG. 1. A schematic of the homodyne reflectometer system.

[a]Present address: Faculty of Engineering, Tohoku University, Sendai 980, Japan.

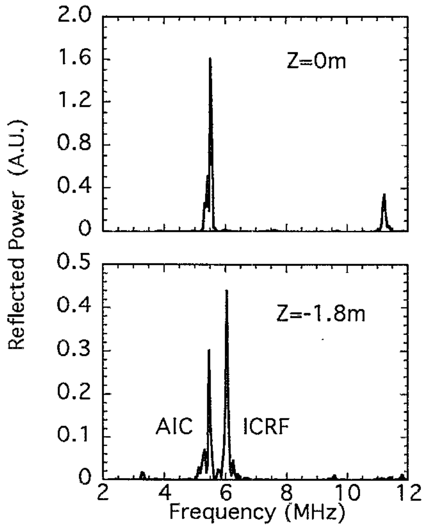

FIG. 2. Frequency spectra of ICRF waves observed at two different positions.

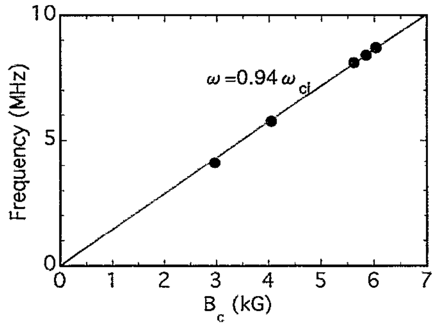

FIG. 3. Frequency of the AIC mode as a function of the central-cell magnetic field.

For measurements of density profiles, a fast-swept reflectometer using a 12–18 GHz hyperabrupt varactor-tuned oscillator is being applied, which can be swept full band in less than 4 μs. The high-frequency fringes due to the change of cutoff layer can be distinguished from those due to the fluctuations, since the fluctuation level with frequency >10 MHz ($\omega>\omega_{ci}$) is much smaller than the average density.

III. EXPERIMENTAL RESULTS

The frequency spectra of the reflectometer signals at two different positions are shown in Fig. 2. The frequency of each YIG oscillator, 18 GHz ($z=-1.8$ m) and 16.5 GHz ($z=0$ m), corresponds to the same critical density of 1.1×10^{12} cm^{-3} for the X-mode propagation. A large peak is seen at the frequency below the applied rf of 6.3 MHz at $z=0$ m, although two peaks are observed at $z=-1.8$ m. The peak frequency of 5.7 MHz coincides with that observed with magnetic probes installed at the periphery of the plasma.[1]

Figure 3 shows that the frequency of this mode depends on the strength of the central-cell magnetic field. The peak frequencies are slightly below the ion cyclotron frequency at the midplane, $\omega=0.94\ \omega_{ci}$. This dependence agrees well with the prediction from the dispersion relation of the Alfvén ion cyclotron (AIC) mode.[2] The AIC mode is driven by plasma pressure and pressure anisotropy. Shear Alfvén wave couples with free energy derived from the relaxation of an anisotropic population of the ion energy state and becomes unstable. We have confirmed that the Fourier amplitude of the reflectometer signals strongly depends on the AIC driving term, $\beta_\perp(T_{i\perp}/T_{i\parallel})^2$, where $\beta_\perp$ is the average plasma pressure and $(T_{i\perp}/T_{i\parallel})$ is the anisotropy of ion temperature defined as the ratio of the perpendicular to the parallel component to the magnetic field.[3] It has also been noted that the amplitude of the X-mode signal is three to five times larger than that of the O-mode signal. Since the time varying component of the mixer output is directly proportional to the small phase change due to the fluctuation components, the ratio of the O-mode signal to the X-mode one is simplified to[4]

$$\frac{\delta\Phi_O}{\delta\Phi_X}\approx\frac{k_O(\tilde{n}_e/n_e)}{k_X[\tilde{n}_e/n_e+(\omega_{ce}\omega_X/\omega_{pe}^2)\tilde{B}/B]}, \tag{1}$$

assuming a one-dimensional approximation in a mirror plasma, and where k_O and k_X are the wave number of the O- and X-mode incident waves, $\tilde{n}_e$ and $\tilde{B}$ the density and magnetic fluctuations, ω_{ce} and ω_{pe} the electron cyclotron frequency and the electron plasma frequency, and ω_X the frequency of the X-mode incident wave. The expression of Eq. (1) can be applied to the present experiment, since the wavelength of the AIC mode, ~60 cm, is much longer than the spot size of the incident waves, 5–8 cm, and the characteristic scale length, $(\lambda_0^2L_n)^{1/3}$=3.5–5 cm, where L_n is the density scale length and λ_0 is the incident wavelength. The typical value of phase fluctuation for the X-mode propagation gives $\tilde{n}_e/n_e+1.6\ \tilde{B}/B\sim0.8\times10^{-3}$ at $r=10$ cm. Also, $\tilde{n}_e/n_e\approx(0.7\sim1.5)\tilde{B}/B$ is obtained from the ratio of the O-mode signal to the X-mode one. Thus, the level of magnetic fluctuation is estimated to be $\sim3\times10^{-4}$.

A radial profile of this mode is obtained for two axial and azimuthal positions, as shown in Fig. 4. It is seen that the instability is small at the edge, and is stronger in the core plasma region with higher β. Also, an almost axisymmetric profile is obtained at the midplane.

In the present experiment, hot ions with several keV produced by ICRF power lose most of their energy to cold electrons with 60–100 eV. The diamagnetic signal increases almost linearly with the ICRF power radiated from the antennas for the low power operation. When the power is further increased the diamagnetic signals cease to increase, as shown in Fig. 5. The reflectometers near the antenna are used to monitor the rf wave in the plasma. The example of frequency spectrum is shown in the lower trace of Fig. 2. In Fig. 5, the reflectometer signals at two radial positions are plotted as a function of time. It is noted that the ICRF wave is detected in the core plasma in the early stage of the discharge; however, it is detected more in the edge during the saturation of the diamagnetic pressure. The change in the rf-wave distribution for two different times is clearly shown in Fig. 6. This figure is obtained by scanning the incident frequencies. The profile of the AIC mode is also observed in

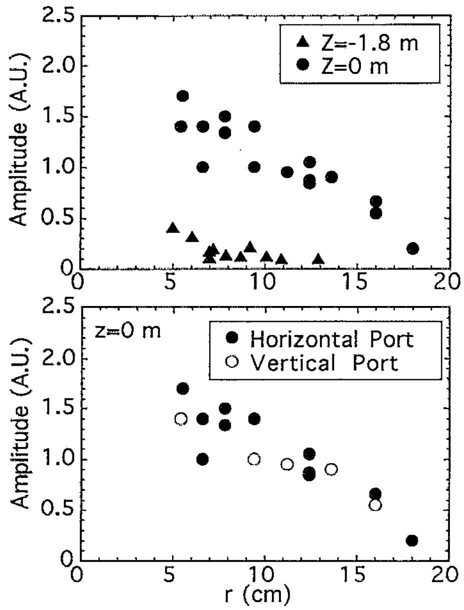

FIG. 4. Radial distribution of the AIC mode at two different positions.

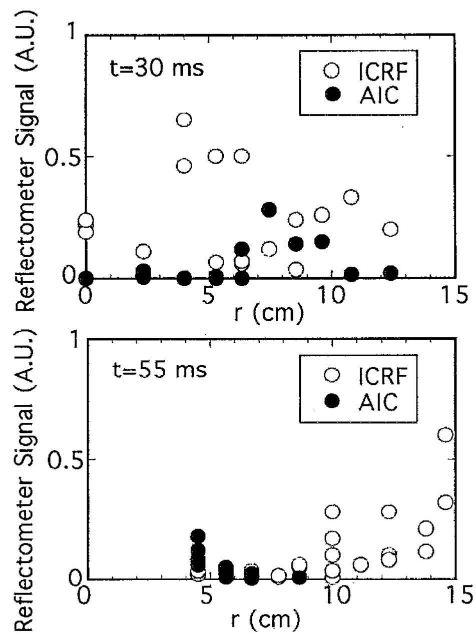

FIG. 6. Radial profiles of the reflectometer signal for a given time.

the same plasma shot at $z=0$ m. The AIC mode starts to grow mainly in the edge region at $t=30$ ms. On the other hand, at $t=55$ ms, the AIC mode enhances and strongly localizes in the core region due to the increase in the plasma β and the temperature anisotropy. The change in the distribution due to the high ion pressure and the pressure anisotropy may cause the saturation of the plasma energy.

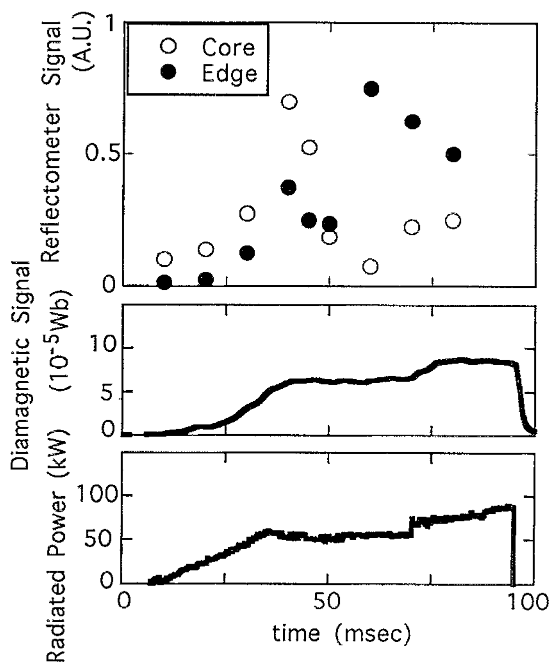

FIG. 5. Time evolution of the reflectometer signals at two radial positions (top), central-cell diamagnetic loop signal (middle), and ICRF radiated power (bottom).

IV. SUMMARY

In summary, 7–18 and 18–26 GHz reflectometers have been applied to the central-cell plasma of the GAMMA 10 tandem mirror. Fluctuations with frequencies of $\omega \leqslant \omega_{ci}$ are identified as the Alfvén ion cyclotron mode from the dispersion relation. The amplitude of the wave strongly depends on the plasma β and the ion temperature anisotropy, and is stronger in the core plasma region at the midplane with higher β value. The level of the magnetic fluctuations $\sim 3\times 10^{-4}$ and the similar level of the density fluctuations are evaluated using both X- and O-mode reflectometers.

The fluctuations associated with the ICRF wave, $\omega=\omega_{ci}$, are also observed by two X/O mode reflectometers to study the physics of wave excitation and propagation. The radial profile of the fluctuation level is expected to give an estimation of deposition profile of the heating power. The change in the ICRF-wave distribution due to the high ion pressure and the pressure anisotropy may cause the saturation of the plasma energy.

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