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Measurement of Alfvén ion-cyclotron wave using both X- and O-mode reflectometers

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Alfvén ion-cyclotron wave excited in the central-cell plasma of the GAMMA 10 tandem mirror is investigated by a reflectometer system. The Fourier amplitude of the instability strongly depends on the anisotropy of the ion velocity distribution function and the plasma β value. The ratio 0.2–0.3 between O-mode and X-mode reflectometer signals suggests that a magnetic fluctuation level similar to the density fluctuation level is excited in the plasma due to the instability.

This Letter describes the first observation of an electromagnetic instability using a nonperturbing reflectometry method. 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 frequencies (ICRF) is under intensive experimental and theoretical investigation for efficient heating. Specifically, Alfvén wave studies are important for understanding mechanisms of Alfvén wave current drive,[1] rf-induced radial transport,[2] rf stabilization of plasmas,[3] as well as plasma heating. In the GAMMA 10 tandem mirror, a slow Alfvén wave is excited and propagates toward the ion cyclotron resonance layer located near the midplane of the central-cell mirror field. Because ions are accelerated in the direction perpendicular to the magnetic-field line at the resonance layer, pitch angles of the heated ions approach a right angle and the perpendicular plasma pressure becomes high near the midplane and low at the off-midplane. Therefore, the ion velocity distribution function at the midplane tends to be anisotropic. As the plasma beta β, the ratio of ion pressure to magnetic-field pressure, increases, an instability due to the anisotropy of the distribution function is expected to be excited and plays an important role in relaxing the anisotropy.[4,5]

In this paper we report an observation of the Alfvén ion-cyclotron (AIC) instability by a reflectometer system installed in the central cell of GAMMA 10. The AIC instability has been observed in several tandem mirrors[6–8] all by using magnetic probes. The reflectometer is a nonperturbing diagnostic method[9,10] of measuring plasma fluctuations and complements the conventional Thomson scattering method since it has good spatial resolution while lacking wave number resolution. The AIC mode is an electromagnetic instability, and this is the first time, to our knowledge, that magnetic fluctuations have been measured by a reflectometer system.

Detailed descriptions of the GAMMA 10 device are shown elsewhere.[11] 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 0.405 T, and the mirror ratio is 4.9. In the present experiment, a plasma is produced and heated by ICRF power with frequencies of 9.9 and 6.3 MHz. They are fed by two types of antennas, a double half-turn antenna and a Nagoya type-3 antenna. The frequency of 6.3 MHz corresponds to the ion cyclotron frequency at the midplane of the central cell, and is required for ion heating by the slow Alfvén wave. The plasma parameters in the central cell are as follows. The line density $n_c l_c \cong 5\times 10^{13}$ cm^{-2} with the effective diameter of $l_c = 20$–25 cm, the electron temperature $T_e = 50$–100 eV, and the averaged ion temperature $T_i \cong 2.2$ keV.

The reflectometer is located at the midplane ($z=0$ m) of the central cell. A 7–18 GHz, 150 mW output of a yttrium–iron–garnet (YIG) oscillator is used as a source. The YIG oscillator can sweep full band in 5 msec using a 12-bit digital driver. However, it 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. The X-mode system sees the vertical chord, while the O-mode system sees the horizontal one. Fluctuations at densities up to 1.5×10^{12} cm^{-3} are measured with the X-mode system. By switching between X mode 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 (central-cell density $n_c \leqslant 4\times 10^{12}$ cm^{-3}). The reflected wave is separated from

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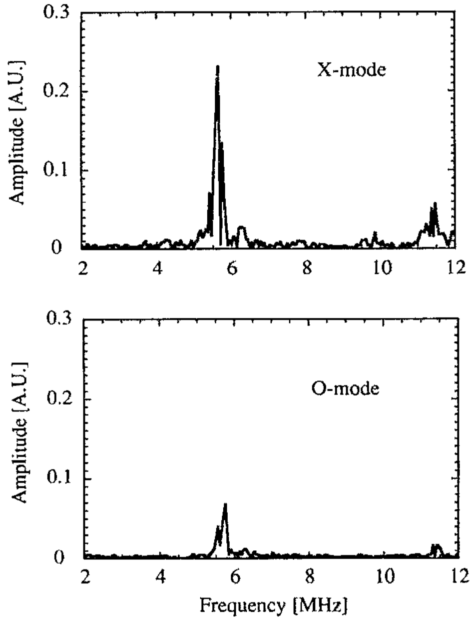

FIG. 1. Frequency spectra of the AIC mode observed by the X-mode reflectometer (upper trace) and the O-mode reflectometer (lower trace).

the incident wave by a circulator, and is mixed with the unperturbed local oscillator (LO) wave in a mixer. The homodyne-detected intermediate frequency (i.f.) signals are amplified by low noise amplifiers and then fed to the data processing system. A phase shifter is inserted into the LO branch in order to adjust a phase offset. Diamagnetic loops are installed at the locations of $z=-0.33$, ±1.5, and 1.95 m, where the mirror ratios are 1.008, 1.077, and 1.264, respectively. The anisotropy of ion temperature defined as the ratio of perpendicular to parallel component to the magnetic-field line, $T_{i\perp}/T_{i\parallel}$ is determined from the diamagnetic loops.[8]

The frequency spectra of the reflectometer signals at $t=70$ msec are shown in Fig. 1 for two propagation modes (X and O). The frequencies of the YIG oscillator, 18 and 11 GHz correspond to the same critical density of 1.5×10^{12} cm^{-3} for the X-mode and O-mode propagations, respectively. A large peak is seen at the frequency below the applied rf of 6.3 MHz. The peak frequency 5.6–5.7 MHz coincides with that observed with magnetic probes installed at the periphery of the central-cell plasma.[8] It is noted that the Fourier amplitude of the X-mode signal is three to five times larger than that of the O-mode signal. Observed low-frequency fluctuations in the range of ~10 kHz are the same level for the two modes.

The refractive indexes of the O-mode and X-mode propagations are given by

$$N_{\rm O}=[1-(\omega_{pe}^2/\omega_{\rm O}^2)]^{1/2}, \qquad (1)$$

$$N_{\rm X}=[1-(\omega_{pe}^2/\omega_{\rm X}^2)\cdot(\omega_{\rm X}^2-\omega_{pe}^2/\omega_{\rm X}^2-\omega_{pe}^2-\omega_{ce}^2)]^{1/2} \qquad (2)$$

in the cold plasma approximation, where ω_{pe} and ω_{ce} are the electron plasma frequency and the electron cyclotron frequency, and $\omega_{\rm O}$ and $\omega_{\rm X}$ are the frequency of the O-mode and the X-mode incident waves, respectively.

In a simple one-dimensional model, the phase changes in the O-mode and X-mode propagations due to the small perturbations of the density and the magnetic field, $\tilde{n}_e$ and $\tilde{B}$ at the critical density layer are given by[12]

$$\delta\Phi_{\rm O}\approx 2k_{\rm O}L_n(\tilde{n}_e/n_e) \qquad (3)$$

$$\delta\Phi_{\rm X}\approx\frac{2k_{\rm X}[\tilde{n}_e/n_e+(\omega_{ce}\omega_{\rm X}/\omega_{pe}^2)\tilde{B}/B]}{1/L_n+(\omega_{ce}\omega_{\rm X}/\omega_{pe}^2)/L_B}, \qquad (4)$$

respectively, where $k_{\rm O}$ and $k_{\rm X}$ are the wave number of the O-mode and X-mode incident waves, and L_n and L_B are the scale length of the density and the magnetic field, respectively. The phase of the reflected extraordinary mode will be sensitive to fluctuations in the magnitude of the magnetic field. The ratio of the phase changes is simplified to

$$\frac{\delta\Phi_{\rm O}}{\delta\Phi_{\rm X}}\approx\frac{k_{\rm O}(\tilde{n}_e/n_e)}{k_{\rm X}[\tilde{n}_e/n_e+(\omega_{ce}\omega_{\rm X}/\omega_{pe}^2)\tilde{B}/B]} \qquad (5)$$

for the case of $L_B\gg L_n$.

The effectiveness using the one-dimensional model may be explained by the following discussion. In GAMMA 10, the perpendicular components of the magnetic field are much smaller than the axial one, that is, B_x, $B_y\leqslant 10^{-4}B_z$ near the midplane of the central cell. Therefore, the magnitude of the magnetic field is written by

$$\begin{aligned}B&\cong[(B_z+\tilde{B}_z)^2+\tilde{B}_x^2+\tilde{B}_y^2]^{1/2}\\&\approx B_z+\tilde{B}_z+\tfrac{1}{2}[(\tilde{B}_x^2+\tilde{B}_y^2)/B_z]\approx B_z+\tilde{B}_z, \qquad (6)\end{aligned}$$

assuming $B\gg\tilde{B}$ even when the perturbation component $\tilde{B}_z$ is one or two orders of magnitude smaller than $\tilde{B}_x$ and $\tilde{B}_y$, which is derived from the analysis of slow Alfvén waves. Also the expressions for the phase shown in Eqs. (3) and (4) are possibly applied to the present experiment, since the wavelength of the observed wave, ~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.

The time varying component of the mixer output is expressed as

$$\begin{aligned}E_m&=E_0\cos(\Phi+\delta\Phi)-\overline{E_0\cos(\Phi+\delta\Phi)}\\&\cong -E_0\delta\Phi\sin\Phi, \qquad (7)\end{aligned}$$

assuming $\delta\Phi\ll 1$, where E_0 is the amplitude depending on the reference and reflected wave, and the bar denotes the time average. Therefore, the amplitude of the mixer output is directly proportional to the small phase change due to the fluctuation components, however, it also depends on the amplitude of the reflected wave and the point around which the phase is oscillating, that is, the phase offset $\sin\Phi$. The amplitude of the reflected waves for the O-mode and X-mode propagations is measured to be similar level by using a detector connected to the circulator directly. Since the value of $\omega_{ce}\omega_{\rm X}/\omega_{pe}^2$ nearly equals 1.6 at $\omega_{\rm X}/2\pi=18$ GHz, we obtain $\tilde{n}_e/n_e/\tilde{B}/B\approx 0.7$–1.5 from the ratio of the O-mode signal to the X-mode one.

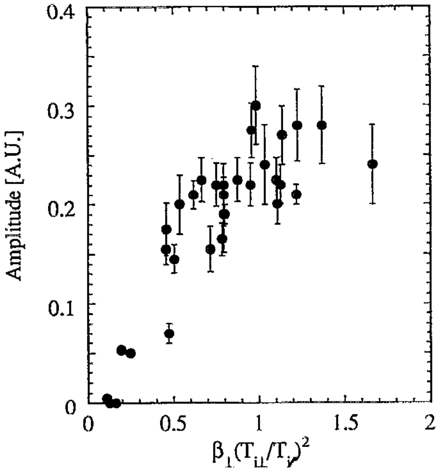

FIG. 2. Fourier amplitude as a function of the AIC driving term $\beta_\perp\,(T_{i\perp}/T_{i\parallel})^2$.

In Fig. 2, the Fourier amplitude of the X-mode signal at $\omega_X/2\pi=18$ GHz is plotted as a function of $\beta_\perp$, the average plasma beta perpendicular to the magnetic-field line, and $(T_{i\perp}/T_{i\parallel})^2$. The density profile is kept almost constant during the plots, and the effect of the phase offset is neglected. It is seen that the amplitude strongly depends on the AIC driving term, $\beta_\perp\,(T_{i\perp}/T_{i\parallel})^2$. The dependence is consistent with theoretical predictions of a convectively unstable AIC mode.[5] Similar dependence has been obtained by the magnetic probes.

A radial profile of the amplitude of this mode is obtained by scanning the frequency of the YIG oscillator, as shown in Fig. 3. The density profile measured with an interferometer is used for determination of the radial position of the reflecting layer. It is seen that the instability is small at the edge, and is stronger in the high β core plasma. The contamination of the mode is small in the radial position where the two modes overlap, since the O mode is not cutoff at the X-mode frequency corresponding to $r=10$–16 cm, and the X mode is not cutoff at the O-mode frequency corresponding to $r=9.5$–14 cm.

These results indicate that the instability is the AIC mode. It is noted that the identification of the AIC mode is also confirmed by the magnetic probes.[8] Knowing the value of E_0 and $E_0\delta\Phi$, we can estimate the fluctuation level $\tilde{n}_e/n_e$ and $\tilde{B}/B$ from Eq. (5). The typical values of $\delta\Phi$ for the X-mode propagation give $\tilde{n}_e/n_e+1.6\tilde{B}/B\sim 0.8\times 10^{-3}$ at $r=10$ cm. Also, $\tilde{n}_e/n_e\approx(0.7\sim 1.5)\tilde{B}/B$ is obtained from the ratio 0.2–0.3 between the O-mode signal and the X-mode signal. The amplitude of the wave magnetic field $\sim 3\times 10^{-4}$ is evaluated from the X-mode reflectometer.

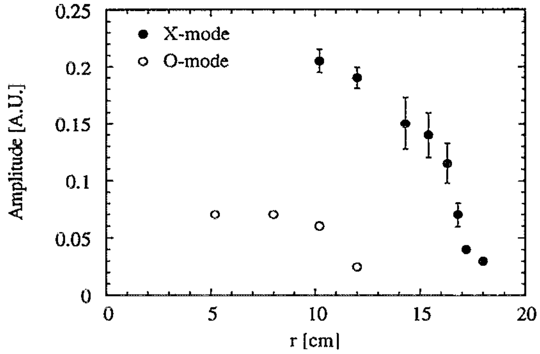

FIG. 3. Radial distribution of the AIC instability.

The density fluctuation and the magnetic fluctuation levels of the AIC mode may be estimated in the following way.[13] The density fluctuation of electromagnetic waves can be obtained by integrating the perturbed electron distribution function $\tilde{f}_e$ (Ref. 14) as $\tilde{f}_e=\int \tilde{f}_e\, d^3v$. Assuming that the unperturbed distribution function is Maxwellian, and using Maxwell's equation $\partial \mathbf{B}/\partial t=-\nabla\times E$ the normalized density fluctuation is calculated as

$$\frac{\tilde{n}_e}{n_e}\approx-\frac{\tilde{B}_z}{B}\frac{\omega}{k_z v_{te}}Z\left(\frac{\omega}{k_z v_{te}}\right), \tag{8}$$

where k_z is the axial component of k, v_{te} is the electron thermal velocity, and Z is the plasma dispersion function. Assuming that $\omega\ll k_z v_{te}$, one obtains

$$|\tilde{n}_e/n_e|\approx\sqrt{\pi}\,(\omega/k_z v_{te})\,|\tilde{B}_z/B|, \tag{9}$$

where k_z is proportional to $n_e^{1/2}$ through ω_{pi}, the ion plasma frequency. Inserting the experimental parameters into Eq. (9), $\tilde{n}_e/n_e/\tilde{B}/B=0.7$–1.0 is obtained. This value reasonably agrees with that evaluated from the reflectometer signals.

In summary, a 7–18 GHz reflectometer has been applied to the central cell plasma of the GAMMA 10 tandem mirror. Fluctuations with frequencies of $\omega<\omega_{ci}$ have been observed by the X-mode and O-mode systems. The instability is identified as the Alfvén ion cyclotron (AIC) mode by using magnetic probes. The Fourier amplitude of the instability strongly depends on the plasma β value and the ion-temperature anisotropy, and is stronger in the core plasma region 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 from the X-mode signal and the ratio of the X-mode to the O-mode signals.

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