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BY A FAST WAVE ANTENNA IN THE ION CYCLOTRON
FREQUENCY RANGE

By

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ABSTRACT

Parametric excitation of ion Bernstein waves is observed with an ICRF fast wave induction loop antenna in the ion cyclotron frequency range ($\omega_0 \sim 2\Omega_i - 4\Omega_i$). Important features of the decay process are investigated and discussed.

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Fast wave heating in the ion cyclotron frequency range is one of the most promising schemes for heating fusion plasmas to ignition temperatures. As the input power and consequent rf energy levels employed in plasma heating increase, it will become increasingly important to understand the detailed physics of the heating process. For example, to answer the important questions of where and how rf energy is deposited in a plasma requires the consideration of both linear and nonlinear processes.

In this Letter we present the first experimental verification of a decay instability in which an ion Bernstein wave (IBW) and an ion quasimode (IQM) are parametrically excited by the near-field electric field of an ICRF antenna. Onset of this decay is observed with a low-threshold electric field in a warm-ion hydrogen plasma over a wide range of parameters. Since the IBW propagates for $\omega < \omega_{pi}$, the decay is allowed in high density regions, and essentially complements the parameter space of the previously reported decay into electron plasma waves (EPW) and ion quasimodes.¹ Decay into ion Bernstein waves may have an important effect on the deposition of rf energy during second-harmonic (or higher) fast-wave heating where the waves are launched from the low-field side with $\omega_o > 2\Omega_i$.

In the context of uniform-pump theory the magnetosonic fast wave and the IBW can be parametrically coupled (with the fast wave acting as pump) when the relative particle drift excursions in the pump field divided by the decay wave wavelength exceed a threshold value. This threshold is determined by the linear damping of the IBW. In the ion cyclotron frequency range the ion and electron drift excursions (in the E x B direction) are comparable and oppositely directed. Ion motion, therefore, can enhance parametric coupling in this

frequency range.¹ The parametric dispersion relation relevant to our experiment can be written²

$$\gamma = -\gamma_2 + \sum_{\sigma, \eta} \frac{|\mu_{\sigma} - \mu_{\eta}|}{8|\partial \epsilon / \partial \omega_2|} \cdot \text{Im} \frac{\chi_{\sigma}(\omega_1) \chi_{\eta}(\omega_1)}{\epsilon(\omega_1)}$$

with

$$\mu_{\sigma} = \left(\frac{q}{m} \right)_{\sigma} \left[\left(\frac{E_{0\parallel} k_{\parallel}}{\omega_0^2} + \frac{\vec{E}_{0\perp} \cdot \vec{k}_{\perp}}{\omega_0^2 - \omega_{\sigma}^2} \right)^2 + \frac{(\vec{E}_{0\perp} \times \vec{k}_{\perp} \cdot \hat{z})^2 \omega_{\sigma}^2}{(\omega_0^2 - \omega_{\sigma}^2)^2 \omega_0^2} \right]^{1/2}, \quad (1)$$

where μ_{σ} is the ratio of drift excursion of species σ in the pump field $\vec{E}_0$ to the decay wave wavelength $2\pi/k$, and $\vec{\epsilon} = \vec{1} + \sum_{\sigma} \vec{\chi}_{\sigma}$ is the hot plasma dielectric response, $\epsilon = \hat{k} \cdot \vec{\epsilon} \cdot \hat{k}$, $\chi_{\sigma} = \hat{k} \cdot \vec{\chi}_{\sigma} \cdot \hat{k}$, $\hat{k} = \vec{k}/k$, and $\vec{\chi}_{\sigma}$ is the contribution to the plasma susceptibility of σ -type particles. The subscripts σ, η refer to all particle species, and the subscripts 0,1,2 refer to pump, low frequency wave (IQM), and lower sideband (LSB), respectively. It is evident from Eq. (1) that the threshold is determined by the damping (γ_2) of the LSB wave. A distinctive feature of this decay is that it involves a finite ion Larmor radius wave (IBW). The dispersion relation for this wave is given by³

$$k_x^2 \epsilon_{xx} + k_z^2 \epsilon_{zz} = 0$$

in the electrostatic approximation, where,

$$\epsilon_{xx} = 1 + \sum_{\sigma} \frac{\omega_p^2}{\omega^2} b_{\sigma}^{-1} \exp(-b_{\sigma}) \sum_{n=-\infty}^{\infty} I_n(b_{\sigma}) 2n^2 (n^2 \Omega_{\sigma}^2 - \omega^2)^{-1},$$

$$\epsilon_{zz} = 1 + 2 \frac{\omega_p^2}{\omega^2} y^2 [1 + \gamma Z(y)], \text{ and } b_{\sigma} = \left(\frac{k_{\perp}^2 v_{T\sigma}^2}{\Omega_{\sigma}^2 m_{\sigma}} \right)^2, \quad y = \omega / k_{\parallel} v_e. \quad (2)$$

The IBW is weakly electron Landau damped but strongly damped at ion cyclotron harmonic resonances. The linear dispersion of the IBW in ACT-1 has been examined earlier [Fig. 1(a); also Refs. 5 and 6]. And of course the three interacting waves should also obey the relations.

$$\omega_0 = \omega_1 + \omega_2 \text{ and } \bar{k}_1 + \bar{k}_2 = 0. \quad (3)$$

Figure 1(b) shows the growth rate calculated by uniform-pump theory [Eqs. (1)-(3)]. When this growth rate is maximized with respect to the decay wave frequencies and wavenumbers [subject to Eq. (3)] the low-frequency daughter wave turns out to be a quasimode at the cyclotron fundamental of H_1^+ , while the lower sideband is found to be a harmonic ion Bernstein wave. The quasimode contribution to the growth rate in Eq. (1), $I_m(\chi_e \chi_i / \epsilon)$, is strongly peaked when the quasimode frequency equals a cyclotron harmonic frequency. Although decay into a quasimode at a minority harmonic is possible, the largest growth rate occurs when the quasimode frequency is at the cyclotron fundamental of H_1^+ . Moreover, since the sideband frequency is constrained by $\omega_2 = \omega_0 - \omega_1$, damping of the sideband wave at the various cyclotron harmonics

is responsible for a periodic sharp increase in the decay threshold as the magnetic field is increased. Excitation of the upper sideband is negligible provided that linear damping on the lower sideband remains weak $\gamma_2 < \omega - \omega_2$. The calculated threshold for the most unstable decay, which is decay into a second-harmonic IBW ($\omega_2 = 1.8 \Omega_{H_1}^+$), is 0.18 volt/cm.

Experimental investigation of this decay process was performed on the ACT-1 research torus.⁴ ACT-1 has a 59 cm major radius, 10 cm minor radius, and a toroidal field adjustable from 1-5 kG on the minor axis. The hydrogen plasma with density $10^9 - 10^{11}$ was produced by an electron beam from a biased hot filament source⁵ and plasma temperatures of $T_e \sim T_i \sim 2$ eV, and low collisionalities of $\nu_i/\Omega < 10^{-3} - 10^{-4}$ were typical. Substantial amounts of molecular H_2^+ and H_3^+ persist in the plasma because of the moderate electron temperature. These minorities simulate D^+ and T^+ , respectively, and their concentrations (typically 20%) were measured earlier through the study of linear wave dispersion relations.^{5,6}

The experimental setup is shown in Fig. 2. A single poloidal ICRF fast wave antenna is excited at 18 MHz. Decay waves are detected by a spectrum analyzer connected to double-tip rf probes capable of scanning the entire minor cross section. To measure wavenumbers, the signals of a fixed and scanning probe in the same r, θ plane are filtered and then compared using either a lock-in amplifier or a mixer.

Parametric instability set in suddenly as the antenna power level was raised above 0.3 watts. A typical decay spectrum is shown in Fig. 3(a). The observed peaks satisfy the relation $\omega_0 = \omega_2 + \omega_1$ within the experimental uncertainties. The upper sideband is evident, but always with less amplitude than the lower sideband. Contours of the ISB wave amplitude, shown in Fig.

3(b), indicate that the decay region is in the antenna near field. As the magnetic field is varied the low frequency quasimode follows the fundamental cyclotron frequency of H_1^+ [Fig. 3(c)]. Figure 4(a) shows the variation of LSB wave amplitude with increasing toroidal magnetic field (decreasing ω_2/Ω_1). In accord with the theoretical prediction (cf. Fig. 1) the decay is strongly suppressed whenever a cyclotron harmonic layer for the LSB wave lies in the decay region and is strongest when the LSB wave frequency lies below the second harmonic of H_1^+ , although decay into higher harmonic ion Bernstein waves (as high as the tenth harmonic of H_1^+) has been observed. Linear excitation experiments involving mode transformation also demonstrate a preference for the second harmonic IBW.⁵ The smoothed appearance of Fig. 4(a) compared to Fig. 1 can be expected since the actual experimental decay region contains a range of pump and toroidal field strengths and densities.

Interferograms of the decay waves [Fig. 4(b)] confirm the identification of the LSB wave as an ion Bernstein wave and the low-frequency wave as an ion cyclotron quasimode. A linearly excited wave is shown for comparison in Fig. 4(c). From the interferograms it is also apparent that the decay waves have wavenumbers of approximately equal magnitude indicating that the pump wave for this decay is nearly "uniform," since $k_0 = k_1 + k_2 \approx 0$. $k_0 \approx 0$ is consistent with the pump wave being the evanescent fast wave which exists near the antenna.

When the density in the decay region was reduced such that $\omega_2 > \omega_{LH}$ (lower hybrid frequency falls below the LSB frequency), then the measured amplitude of the decay waves was observed to fall abruptly. Although decay into an electron plasma wave is allowed at low density, collisional damping (electron-neutral) of the sideband wave increases the threshold in our experiment. Also, in the high density regime, due to the low T_i (1-2 eV) of

the ACT-1 plasma, ion-ion collisional damping limits the growth. These features are shown in Fig. 4(d). Collisional damping will be less important, of course, in higher temperature fully ionized plasmas.

Measurements of the antenna current at the threshold antenna power indicate a threshold electric field of approximately 0.2 volt/cm, in close agreement with the prediction. Saturation becomes important for power levels a factor of 100 above threshold. At this higher power level (~30 W) several new factors appear, including plasma loss and ponderomotive effects, which preclude a simple identification of the saturation mechanism.

In summary, we have presented data from an experimental investigation of parametric instabilities for a pump wave in the ion cyclotron frequency range in a multi-ion-species plasma. Significant coupling to harmonic ion Bernstein waves was observed. The results are in good agreement with the predictions of uniform-pump theory. In a high temperature plasma, where collisions are less important, one would expect decay into an IBW to be allowed over a wide density range, in contrast to decay into an EPW. This process may become important for fast-wave heating schemes where the condition $\omega_0 > 2\omega_i$ occurs in some region of the plasma.

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FIGURE CAPTIONS

FIG. 1. (a) Dispersion relation for the IBW in ACT-1 with an illustration of the decay process. The wavenumbers of the LSB and QM actually have an opposite sign.

(b) Calculated growth rate vs ω_2/Ω_i (toroidal field).

FIG. 2. The experimental setup on ACT-1 for doing ICRF wave studies.

FIG. 3. (a) The decay spectrum. The pump at $f_0 = 18$ MHz, the quasimode at f_{ci} (4-6 MHz), the lower sideband at $f_0 - f_{ci}$, and the upper sideband at $f_0 + f_{ci}$.

(b) Contours of lower sideband amplitude.

(c) Quasimode frequency vs toroidal magnetic field. The line indicates $f = f_{ci}(H_1^+)$.

FIG. 4 (a) Decay wave amplitude vs ω_2/Ω_i . Toroidal field increases to the left. The ion cyclotron harmonics of the LSB wave for H_1^+ , H_2^+ and H_3^+ are indicated.

(b) Interferometry of the decay waves where the LSE is an IBW and the low frequency wave is an IQM.

(c) Linearly excited IBW.

(d) Solid curve is measured LSB amplitude-vs-density. Dashed curve is calculated damping on LSB due to electron-neutral and ion-ion collisions.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

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