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EFFECT OF CONVECTIVE LOSS ON THE
PARAMETRIC DECAY OF COLD ELECTRON
PLASMA WAVES

BY

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ABSTRACT

The resonant decay of cold electron plasma waves was investigated in the Princeton L-2 device in an argon plasma with $n = 10^{10} - 10^{11} \text{ cm}^{-3}$, $B = 900 \text{ G} \approx 2kG$, $f_{pe} = 50 - 80 \text{ MHz}$ ($\omega = 10 - 15 \omega_{UH}$). The decay waves were identified to be ion-acoustic waves and cold electron plasma waves. Because of convective losses in the finite extent pump field, the threshold for parametric decay is considerably higher than the collisional threshold for the dominant $\bar{E}_{O1} \cdot \bar{E}$ coupling. Coupling due to $\bar{E}_{O1}$ can be important in low density high magnetic field plasmas. At high densities ($n \sim 10^{10} \text{ cm}^{-3}$), $\bar{E}_{O1} \cdot \bar{E}$ coupling becomes dominant. The $\bar{E}_{O1} \cdot \bar{E}$ decay convective threshold was measured at various antenna lengths; magnetic field strengths and plasma densities. The experimental results are in good agreement with theory. Indication of pump depletion and enhanced Landau heating of electrons were observed in the parametric decay process.

subject

Plasma Physics
Parametric Decay
Cold Electron Plasma Waves
Ion-Acoustic Waves
Convective Losses
Magnetic Field
Plasma Density
Antenna Length
Pump Depletion
Landau Heating

I. Introduction

The possibility of heating magnetized plasma by lower hybrid waves¹ has been demonstrated recently in tokamak experiments,^{2,3} but the heating mechanism is still not well understood. It is now understood that near the lower hybrid layer where the wave frequency $1 \leq \omega_c/\omega_{lh} \leq 3$, decay into quasi-modes should take place.⁴⁻⁸ Since the slow waves are usually launched by an external slow wave structure, they must propagate through a low density region near the edge of the plasma column where $\omega_o \gg \omega_{LH}$, and here decay into ion-acoustic (or ion cyclotron) waves may occur.^{4,6} To understand the physics of wave propagation in this regime is important since pump depletion due to such processes may seriously limit the energy which can be transmitted to the central region of a fusion plasma column. If the plasma column were uniform, the threshold for parametric decay of the slow wave is much lower than practical power levels needed for the supplementary heating of tokamaks.⁴ Thus, one may expect that three wave processes would lead to unwanted surface heating and pump depletion. Fortunately, the inevitable density gradient near the plasma surface, and the finite spatial extent of the pump wave will significantly raise this threshold. In this paper we study the second of these, namely the effect of the finite extent of the pump wave region upon parametric decay in a nearly uniform plasma. It is well known that a slow wave launched by a finite size source propagates only in a restricted region which is bounded by resonance cones emanating

from the ends of the slow-wave structure.^{9,10} Because of convective losses, it is expected that the finite extent of the pump wave will significantly raise the threshold for the parametric decay processes.^{6, 11-14} It is the purpose of this paper to investigate this effect for slow waves with a pump frequency $\omega_c \gtrsim 10\omega_{lh}$. Preliminary results of this work have been published recently.¹⁵ Here we present further experimental data and a theoretical analysis of this phenomenon. In addition, we also present data showing electron heating associated with this parametric decay. The heating is believed to be due to the electron Landau damping of the sideband waves, which typically have phase velocities one-fifth that of the pump wave, or approximately three times the electron thermal speed. These results are in agreement with the earlier experiments of Porkolab et al.,¹⁶ who observed strong electron heating due to electron Landau damping of the sideband during parametric decay of Trivelpiece-Gould modes in the regime $10 \omega_{pi} \lesssim \omega_o \lesssim \omega_{pe}$, $\omega_o = \omega_{ce}/2$, $\omega_{ce} \gtrsim \omega_{pe}$,¹⁶ and also in the regime $\omega \approx \omega_{pe}$ (O-mode), $\omega \approx \omega_{UH}$ (EO mode)¹⁷ (where ω_{UH} is the upper hybrid frequency).

Finally, we note the work of Bernabei et al.,¹⁸ who also observed parametric decay of the slow wave (launched by a split waveguide). However, in this experiment neither the wavelengths of the decay waves nor the finite pump length effects were measured. Similar arguments hold for the work of others who studied parametric decay in this regime but did not measure the wavelengths of the decay waves.^{19,20}

The plan of the paper is as follows: In section II, we briefly describe the theory of parametric decay taking into account the finite extent of the pump field. In section III we present experimental results obtained in a linear magnetized plasma column and compare them with theory. The conclusions are given in section IV.

II. Theory

In a magnetized plasma with $\omega_{pi} < \omega_o \ll \omega_{pe} < \omega_{ce}$, the parametric coupling coefficient is given by⁴

$$\mu = \frac{e}{m} \left\{ \left(\frac{E_{oz} k_z}{\omega_o^2} - \frac{\bar{E}_{o\perp} \cdot \bar{k}_{\perp}}{\omega_{ce}^2} \right)^2 + \frac{\left[(\bar{E}_{o\perp} \times \bar{k}_{\perp}) \cdot \hat{z} \right]^2}{\omega_o^2 \omega_{ce}^2} \right\}^{1/2}. \quad (1)$$

Where we use the dipole approximation for the pump wave.

The three terms on the RHS of Eq. (1) correspond to electron parallel drift, polarization drift, and $\bar{E} \times \bar{B}$ drift, respectively. When the pump is a slow wave (i.e., electron plasma wave) in the low density region, the polarization drift is smaller than the parallel drift by a factor

$\omega_{pe}^2 / \omega_{ce}^2 \ll 1$, and the parallel drift is smaller than the $\bar{E} \times \bar{B}$ drift by a factor $\alpha^2 = \omega_{ce}^2 \omega_o^2 / \omega_{pe}^4$. Thus, if $\alpha < 1$,

parametric decay occurs at a relatively low threshold

$(U_1 / C_s \ll 1)$ in a homogeneous pump field with daughter waves propagating in the $\bar{E}_o \times \bar{B}$ direction⁴ where $U_1 = cE_{o\perp} / B$, $C_s = (T_e / m_i)^{1/2}$. This process can be significantly modified in a finite extent pump field.^{6-8, 12-14}

Let us first consider the decay driven by the E_{oz} component only. Consider a finite electron plasma wave packet as shown in Fig. 1. The magnetic field $\bar{B}$ is parallel to the $\hat{z}$ -axis, $\bar{E}_o = (E_{oz} \hat{z} + E_{o\perp} \hat{x})$, and the pump wave resonance cone is parallel to the $\hat{\xi}$ -axis (i.e., the group velocity of the pump wave is in the $\hat{\xi}$ -direction). Then, we can use a simple

slab model and denote the amplitude of the decay waves by $a_i(\eta, t)$, where $i = 1, 2$. The parametric instability can be described by the following equations:¹³

$$\frac{\partial a_1}{\partial t} + v_1 \frac{\partial a_1}{\partial \eta} + \Gamma_1 a_1 = \gamma_0 a_2^* \quad , \quad (2)$$

$$\frac{\partial a_2^*}{\partial t} + v_2 \frac{\partial a_2^*}{\partial \eta} + \Gamma_2 a_2^* = \gamma_0 a_1 \quad , \quad (3)$$

where v_1, v_2 are the group velocities in the $\hat{\eta}$ direction, Γ_1, Γ_2 are the linear damping rates, and γ_0 is the growth rate of the parametric instability in a uniform pump field (where $\gamma_0^2 > (\Gamma_1 \Gamma_2)$ is the minimum threshold condition). Here we assumed that the plasma slab is infinitely long in the $\hat{\xi}$ direction. For a pump electric field slightly above this minimum threshold, or for a forward-scattering type of decay,¹¹⁻¹³ only spatial amplification is possible and we can put

$$a_1 = \alpha_1 e^{K\eta} \quad , \quad (4a)$$

$$a_2^* = \alpha_2^* e^{K\eta} \quad , \quad (4b)$$

where $\text{Re } K$ is the spatial growth rate. From Eq. (2) and (3), one can solve for K and get:

$$K = \frac{-v_2 \Gamma_1 - v_1 \Gamma_2 + \sqrt{(v_2 \Gamma_1 + v_1 \Gamma_2)^2 - 4v_1 v_2 (\Gamma_1 \Gamma_2 - \gamma_0^2)}}{2 v_1 v_2} \quad (5)$$

If

$$\frac{\Gamma_1}{V_1} \gg \frac{\Gamma_2}{V_2} , \quad (6a)$$

and

$$\left(\frac{\Gamma_1}{V_1} \right)^2 \gg \frac{\gamma_o^2 - \Gamma_1 \Gamma_2}{V_1 V_2} , \quad (6b)$$

then

$$K = \frac{\gamma_o^2}{V_2 \Gamma_1} - \frac{\Gamma_2}{V_2} ,$$

and the instability condition becomes

$$KL_\eta = \left(\frac{\gamma_o^2}{V_2 \Gamma_1} - \frac{\Gamma_2}{V_2} \right) L_\eta \gg 1 , \quad (7)$$

where $L_\eta \cong L_z \omega_o / \omega_{pe}$ is the width of the wave packet and L_z is the antenna length. It should be noted that in cases where Eq. (6a) and (6b) are not satisfied, Eq. (5) must be used to calculate K.

Now consider the decay of electron plasma waves into ion acoustic waves and electron plasma waves. The sideband satisfies the same dispersion relation as the pump, i.e.,⁴

$$\omega_2 = \frac{k_{2z}}{k_2} \frac{\omega_{pe}}{(1 + \omega_{pe}^2 / \omega_{ce}^2)^{1/2}} . \quad (8)$$

For pure $\vec{E} \times \vec{B}$ coupled decay, the growth rate is:⁴

$$\gamma_o = \frac{1}{4} \frac{U_+}{C_S} \frac{\omega_{lh}}{\omega_o} \sqrt{\omega_1 \omega_2} \left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} \right) . \quad (9)$$

and for pure $E_{O_{||}}$ coupled decay, the growth rate becomes⁴

$$\gamma_0 = \frac{\sqrt{2}}{4} \frac{U_{||}}{v_{Te}} \sqrt{\omega_1 \omega_2} \left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} \right), \quad (10)$$

where $U_{||} = cE_{O_{||}}/B$ is the $\vec{E} \times \vec{B}$ drift velocity, $U_{||} = eE_{Oz}/m\omega_0$ is the parallel electron drift, $\omega_{lh} = \omega_{pi}/(1 + \omega_{pe}^2/\omega_{ce}^2)^{1/2}$, $v_{Te} = (2T_e/m_e)^{1/2}$ is the electron thermal velocity, c is the speed of light, $C_s = (T_e/m_i)^{1/2}$ is the ion acoustic speed, and we assumed $\omega_{pe} \gg \omega_0 \gg \omega_{pi}$, $k_z^2 \ll k_{\lambda}^2$. Since in our experiment $T_i \approx 0$ the low frequency ion acoustic wave is damped by electron Landau damping, namely⁴

$$\frac{\Gamma_1}{\omega_1} = \frac{\sqrt{\pi}}{2} \frac{\omega_1}{k_{1z} v_{Te}} \exp\left(\frac{-\omega_1^2}{k_{1z}^2 v_{Te}^2}\right). \quad (11)$$

The lower sideband is damped by electron-neutral (or ion) collisions and electron Landau damping, and thus⁴

(12)

$$\frac{\Gamma_2}{\omega_2} = \frac{1}{2} \left[\left(\frac{\omega_{pe}^2}{\omega_2^2} \frac{k_{2z}^2}{k_2^2} + \frac{\omega_{pe}^2}{\omega_{ce}^2} \right) \frac{v_e}{\omega_2} + \frac{\sqrt{\pi}}{k_{2\lambda}^2} \frac{\omega_2}{k_{2z} v_{Te}} \exp\left(-\frac{\omega_2^2}{k_{2z}^2 v_{Te}^2}\right) \right] \left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} \right),$$

where $\vec{k}_0 = \vec{k}_1 + \vec{k}_2$, and $k_0 \approx k_1/5$ in our experiment.

(a) Coupling by $E_{O''}$

For pure $E_{O''}$ coupled decay, the components of the group velocities in the η direction (i.e., perpendicular to the resonance cone) are:

$$v_{1\eta} \approx C_s \quad (13a)$$

$$v_{2\eta} = - \frac{\omega_2}{k_{2z}} \frac{\omega_1}{\omega_{pe}} \left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} \right)^{1/2} = -C_s \quad (13b)$$

Using Eqs. (10)-(13), and Eq. (5), one can calculate the spatial growth rate K in the η direction as a function of ω_1 for fixed values of T_e , $n_{O''}$, B , and $E_{O''}$. Figure 2 shows K as a function of ω_1 at various magnetic fields for a set of typical parameters for our experiment. The decay wave should have maximum amplitude at $\omega_1^{(m)}$ where K assumes a maximum value. As one varies the magnetic field B , $\omega_1^{(m)}$ increases with B which agrees qualitatively with the experimental data shown in the next section.

If $\gamma_0^2 \gg \Gamma_1 \Gamma_2$, then from Eqs. (6) and (7) the threshold condition for the parallel coupled decay can be estimated by the relationship

$$\frac{\gamma_0^2}{v_{2\eta} \Gamma_1} L_\eta > \pi \quad (14)$$

We note that the finite length (L_p) of the plasma column in the $\hat{z}$ direction introduces convective losses. Assuming that Eqs. (6a), (6b), and (7) hold in the z direction also, then the threshold becomes

$$\left(\frac{\gamma_o^2}{v_{2z}\Gamma_1} - \frac{\Gamma_2}{v_{2z}} \right) L_p \gg 1 \quad (15)$$

which typically predicts a higher threshold value of E_o than Eq. (14). It should be noted that convective losses due to the finite length of the system in the z direction can be greatly reduced if there are reflections from the ends of the system so that standing waves are set up. Similar phenomena may also occur if in the radial direction two resonance cones cross within the plasma column. Finally, since in the $\hat{z}$ direction $k_{1z} = -k_{2z}$, $v_{1z} = -v_{2z}$, absolute instability may be excited if the condition

$$\left[\frac{\gamma_o^2}{v_{1z}v_{2z}} - \frac{1}{4} \left(\frac{\Gamma_1}{v_{1z}} + \frac{\Gamma_2}{v_{2z}} \right)^2 \right]^{1/2} L_z > \frac{\pi}{2} \quad (16)$$

is satisfied.^{11,12} As we shall see, in our experiments the pump field is never strong enough to satisfy Eq. (16).

b) Coupling by $\vec{E}_{01} \times \vec{B}$

For $\vec{E} \times \vec{B}$ coupled decay, the group velocities of the decay waves and the pump do not lie on the same plane. Exact analysis becomes very complicated¹⁴ and we estimate the threshold for convective decay by splitting the group velocities into components and use the formulae derived for one dimensional decay. In order to simplify the analysis we consider pure $\vec{E}_{01} \times \vec{B}$ decay, namely, we assume that $k_{1r} = k_{2r} = 0$, $v_{1r} = v_{2r} = 0$. Then, if $L_y > L_\eta$, convective loss in the axial (z) direction dominates and the threshold can be estimated by:

$$\frac{\gamma_0^2}{v_{2z} \Gamma_1} L_z \geq \pi, \quad (17)$$

where we assumed that Eqs. (6a), (6b), and (7) hold, and $\gamma_0^2 \gg \Gamma_1 \Gamma_2$. Using Eqs. (9), (10), (14) and (17), it can be easily shown that parallel coupling dominates $\vec{E} \times \vec{B}$ coupling if

$$\frac{\omega_{pe}^2}{\omega_o \omega_{ce}} \left(\frac{\omega_1}{\omega_o} \right)^{1/2} < 1 \quad (18)$$

where we assumed that $(L_z/L_\eta) (\omega_o/\omega_{pe}) \approx 1$ and $\omega_{pe}^2 \ll \omega_{ce}^2$. We have further assumed that for E_{01} coupling there are reflections from the ends of the system so that the condition Eq. (15) is invalidated, whereas for $\vec{E} \times \vec{B}$ coupling the decay waves get out of the pump wave region and damped before arriving at the end of the device so that reflections are ineffective. This is reasonable since in our experiments, the slow wave structure is considerably shorter than the length of the plasma column (by about a factor of 10).

If the wave packet has a finite height L_y (like the lower hybrid waves excited by phased waveguides) and $L_y < L_\eta$, then the convective loss in the y-direction dominates and parallel coupling dominates $E \times B$ coupling if

$$\frac{\omega_{pe}^2}{\omega_o \omega_{ce}} \left(\frac{\omega_i}{\omega_o} \frac{L_y}{L_\eta} \right)^{1/2} < 1. \quad (19)$$

In our experiments Eq. (18) is more relevant. In any case, we see that in general, at low plasma density, high magnetic field and pump frequency, the $E_{o||}$ coupled decay can compete with, or even dominate over the $\vec{E} \times \vec{B}$ coupled decay.

III. Experimental Results

The experiment was performed in the Princeton L-3 device which is shown schematically in Fig. 3. The plasma source is a multi-filament discharge²¹ which converges into a 4-meter-long, 10 cm diameter plasma column. Typical plasma parameters were: density $n \sim 10^{10} - 10^{11} \text{ cm}^{-3}$ argon, magnetic field $B \sim 700 \text{ G} - 2 \text{ kG}$, electron temperature $T_e \sim 1-3 \text{ eV}$, ion temperature $T_i < 0.1 \text{ eV}$. The slow (electron plasma) wave was launched by a slow wave structure consisting of four to sixteen rings driven by an rf oscillator. Details of this set up have been described previously.^{10,15} As shown in Fig. 4, when the rf power was raised above a definite threshold, parametric decay occurred. From the spectrum, it is apparent that the frequency matching condition ($\omega_0 = \omega_1 + \omega_2$) is satisfied. In order to identify the daughter waves, the wavelengths were measured by interferometry using a set up as shown in Fig. 5(a). Different probes capable of scanning in the axial, radial and azimuthal directions were used to measure wavelengths in all directions. At low densities ($n \lesssim 2 \times 10^{10} \text{ cm}^{-3}$) and high magnetic field ($B \sim 1.8 \text{ kG}$) there was no measurable wavelength in the azimuthal direction, and we set a lower bound $\lambda_\theta > 2 \text{ cm}$, while $\lambda_r \approx 0.3 \text{ cm}$. Since the pump wave propagates on the $\hat{z} - \hat{r}$ plane, $k_\theta = 0$ indicates the absence of the $\vec{E}_{0\perp} \times \vec{B}$ coupling. The dipole approximation used in Section II is well justified, since the pump wavelength was about five times longer than the decay waves, and one can see from Eq. (1) that the

parallel coupling dominates over $\vec{E} \times \vec{D}$ coupling.

The directions of the phase velocities were determined by inserting an additional transmission line at the reference side of the interferometer. For measuring the low frequency daughter wave, a boxcar integrator was also used occasionally. As expected, the decay waves propagated nearly in opposite directions and satisfied the $\bar{k}$ -matching condition. The $\bar{k}$ -vector diagram constructed from these measurements is shown in Fig. 5c. From the measured frequencies and wavelengths, the low frequency decay wave was identified to be an ion acoustic wave propagating nearly perpendicularly to the pump resonance cone. The sideband was identified to be an electron plasma wave (slow wave) which obeyed the dispersion given in Eq. (2), and it propagated almost parallel to the pump wave packet. This is apparent from the $\bar{k}$ -vector diagram. Hence, the convective losses of the electron plasma wave should be greatly reduced. In particular, these measurements are in reasonable agreement with Eq. (13b), i.e.,

$$|v_{2\eta}| \approx C_s = |v_{1\eta}| \ll |v_{2\xi}| \approx 4v_{te}.$$

Using Eq. (5), we have calculated numerically the spatial growth rate K as a function of ω_1 for our experimental parameters. We expect that the decay wave frequency as observed in the experiment should be at the maximum of K (assuming that convective losses are absent because the sideband propagates almost along the pump wave). From Fig. 2, one can see that the decay wave frequency should increase with the magnetic field which agrees qualitatively with experimental results shown in Fig. 6. When the pump frequency is varied, one finds that the decay wave frequency and

wavelength also change. The variations are in good agreement with theoretical predictions as shown in Fig. 8. In the present experiment, we could only vary the frequency from 50-80 MHz while maintaining the proper phase shift between the rings.

To determine the threshold electric field, a calibrated double - tip probe was used. It should be noted that the probe was calibrated between two metal plates in vacuum, and the probe response in plasma may be different. Although this is a commonly used technique, we cannot expect the accuracy to be better than a factor of two. If one estimates the electric field from the power radiated by the antenna, one would get a slightly higher value compared with the probe measurement. In our experiment, the pump amplitude varies along its resonance cone trajectory, and it is not perfectly cylindrically symmetric. The threshold electric field measured by the double - tip probe far away from the antenna was about $E_0 \sim 4\text{V/cm}$. It was a factor of two higher near the antenna. Therefore, E_0 is higher than the collisional threshold due to pure parallel coupling ($E_0 \sim 2\text{V/cm}$) and much higher than that due to $\vec{E}_{0\perp} \times \vec{B}$ coupling ($E_0 \sim 0.4\text{V/cm}$). It should be noted that in our experiment the maximum amplification distance in the radial direction is limited by the plasma diameter. If the pump wave were limited to just a single resonance cone, according to Eq. (7) the perpendicular convective losses would yield a threshold field of about $E_0 \approx 20\text{V/cm}$. Because of the cylindrical geometry in our experiment, there is a region where trajectories of the two resonance cones intersect, and here the pump is a standing wave in the radial direction so

that radial convective losses of the decay waves are essentially eliminated. Thus, substantial growth is expected only in such regions, and this was in agreement with experimental observations. Although significant reflection at the plasma boundaries have not been observed in our wave propagation experiments, we cannot rule out small reflections which could also reduce convective losses and thus lower the decay threshold toward the uniform plasma values predicted by Eq. (7).

At low plasma densities ($n \leq 2 \times 10^{10} \text{ cm}^{-3}$), the decay spectrum is relatively narrow ($\omega_1 \sim 10^{-2} \omega_2$) and the sideband follows the resonance cone trajectory of the pump. At higher densities, the decay spectrum broadens as shown in Fig. 8; $\vec{E}_{O_1} \times \vec{B}$ coupled decay dominates and the decay waves propagate on the $\theta - \hat{z}$ plane as shown in Fig. 9. Instead of varying the density, one can also vary the magnetic field. Fig. 10 shows that the $\vec{E}_{O_1} \times \vec{B}$ coupled decay becomes dominant as the magnetic field is lowered. All these agree qualitatively with Eq. (18). Since in pure $\vec{E}_{O_1} \times \vec{B}$ coupled decay, the decay threshold is mainly determined by the convective loss parallel to the magnetic field (see Eq. (17)), by varying the length of the antenna one can investigate the $\vec{E}_{O_1} \times \vec{B}$ coupled decay in more detail. In order to vary the antenna length over a wider range, the parallel wavelength of the pump was shortened from 22 cm to 11 cm. A unidirectional wave was launched by imposing a 90° phase shift between adjacent rings. Fig. 11a shows the decay spectrum near the antenna as the pump power was varied. Two sidebands (one at 73.6 MHz and the other at 74.1 MHz) appeared in the spectrum and their trajectories are shown in Fig. 11b. It is apparent that the 73.6 MHz sideband roughly follows the pump resonance cone and the other one does not. As expected, interferometry

measurements indicate that the 74.1 MHz sideband propagates in the $\hat{\theta}$ direction and therefore is driven by $\vec{E}_0 \times \vec{B}$ coupling.

According to Eq. (17), the threshold electric field should be proportional to $B/\sqrt{L_2 n}$. This is verified experimentally in Fig. 12 which shows the variation of decay threshold with antenna length L_2 , magnetic field B and density n . The scaling with L_2 , B and n agrees very well with theory. We see that typically the threshold electric field is in the range $E_{0\perp} \sim 7-20$ V/cm. The growth of $\vec{E}_0 \times \vec{B}$ coupled decay instability takes place within the antenna length L_2 which is short compared with the length of the resonance cone. The variation of the pump electric field strength over L_2 is relatively small compared with the variation along the whole resonance cone trajectory. Therefore, the measured threshold is less ambiguous than that of the $\vec{E}_{0\parallel}$ decay. Although the measured threshold is usually lower than theory, the agreement is within experimental error since the electric field measured by the double - tip probe is only accurate within a factor of two. It should be noted that the collisional threshold for $\vec{E}_{0\perp} \times \vec{B}$ decay is about 0.4 V/cm at $n = 3 \times 10^{10} \text{ cm}^{-3}$, $B = 1.6$ kG. Therefore, the convective loss due to the finite length antenna ($L_2 = 11$ cm) has raised the threshold 30 times higher. This clearly demonstrates the effect of finite length stabilization.

Figure 12 shows the magnitude of the pump and the sideband waves as a function of rf input power. Since $\omega_2 \gg \omega_1$, the decay wave intensity is mainly concentrated at the lower sideband. When the sideband amplitude increases, the pump amplitude levels off which indicates pump depletion due to the parametric decay instability. However, for $P > 2$ watts, the sideband amplitude remains

saturated even though the pump amplitude increases with input power again. A theoretical interpretation of these steady-state results is not clear, especially since ionization and heating of tails could take place. It is apparent that a significant fraction of the pump energy ($> 10\%$) can go to the sideband. Since the wavelengths associated with the sideband were considerably shorter than that of the pump so that $\omega_2/k_{2z} \approx 4v_{te}$, we expect heating of suprathermal electrons via Landau damping. To investigate this possibility, the parallel component of the electron distribution function was measured by a 5-grid retarding potential energy analyzer. Figure 13 shows some raw data of such measurements. When the rf power is below the parametric decay threshold, there is no measureable change in the electron distribution function because the pump has a parallel phase velocity so high that there are very few resonant electrons in the plasma (i.e., $\omega_o/k_{o||} = 15 v_{te}$). Coincident with the parametric decay, an enhanced electron tail appears with energy between 40-100 eV, which is near the energy range where Landau damping of the sideband should occur. These results are qualitatively similar to those obtained by Porkolab et al.^{16,17} in previous experiments with high-power pulsed microwave signals in the regime $\omega_{pi} \ll \omega_o < \omega_{pe} \approx \omega_{ce}$. We note that the strong soft-X-ray production observed in tokamak experiments may also be related to parametric processes² via Landau heating of tail electrons. Finally, we may remark that similar processes may also have occurred in the recent Alcator-A lower hybrid heating experiments.²²

IV. Conclusions

In this paper, we have demonstrated experimentally the effect of convective losses on the resonant decay of electron plasma waves in the regime $\omega_{pi} < \omega_o < \omega_{pe} \lesssim \omega_{ce}$. For a finite extent pump field, the decay threshold is considerably higher than the collisional threshold for a uniform pump field. We also observed for the first time an associated differentiation between $\vec{E}_o \times \vec{B}$ driven decay and $E_{o\parallel}$ driven decay in this regime. In particular, when convective losses are present in a finite size system at low plasma densities ($\omega_{pe}^2/\omega_{ce}^2 \approx 0.1$), the $E_{o\parallel}$ driven instability can have a lower threshold than that due to the $\vec{E}_o \times \vec{B}$ coupling. High magnetic field also favors $E_{o\parallel}$ coupled decay. Therefore, one would expect the $E_{o\parallel}$ driven decay to play a more important role than the $\vec{E}_{o\perp} \times \vec{B}$ coupled decay at the edge of a high field tokamak like Alcator. Associated with the parametric decay, suprathermal electron tail production is observed. The range of particle velocities observed is about 3.5-5 times the electron thermal speed (when E_o is just above threshold) and this range of velocities corresponds to the parallel phase velocity of the sideband. Indication of pump-depletion associated with these parametric processes has been observed in our uniform plasma. It should be noted that near the edge of a tokamak plasma, there is usually a strong density gradient which could modify these results; in particular, steep density gradients are expected to reduce the growth rates⁷ by detuning the resonant nature of the decay instability. This effect has to be examined quantitatively in each case.

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FIGURE CAPTIONS

Fig. 1. Slab-model of a finite extent lower hybrid wave packet with group velocity $\vec{v}_{go}$ parallel to the $\hat{\xi}$ axis. The magnetic field is along the $\hat{z}$ direction and the wave electric field is $\vec{E}_0 = E_{0\perp} \hat{x} + E_{0\parallel} \hat{z}$. The x-y-z coordinate is rotated into the $\eta\gamma\xi$ coordinate. The angle of rotation is the low hybrid resonance cone angle.

Fig. 2. Spatial growth rate of the parametric instability as a function of decay wave frequency for various magnetic fields. The plasma parameters are as follows: $n = 2 \times 10^{10} \text{ cm}^{-3}$, $f_0 = 75 \text{ MHz}$, $E_{0\perp} = 10 \text{ V/cm}$.

Fig. 3. A schematic of the experimental set up.

Fig. 4. Parametric decay threshold and spectrum at $n = 2 \times 10^{10} \text{ cm}^{-3}$, $B = 1.3 \text{ kG}$. (a) Decay wave amplitude as a function of RF input power. (b) Parametric decay spectrum (linear sensitivity).

Fig. 5. Interferometry measurements of the decay waves. (a) Schematic of the interferometer set up. (b) Interferograms of the decay waves and the pump wave. (c) Relative phase velocities and group velocities calculated from the interferometry measurements.

Fig. 6. Decay wave frequency at various magnetic field strength with $n = 2 \times 10^{10} \text{ cm}^{-3}$, $f_0 = 75 \text{ MHz}$.

Fig. 7. Variation of decay wave frequency and wavelength with the pump frequency ($n = 2 \times 10^{10} \text{ cm}^{-3}$, $B = 1.3 \text{ kG}$) at maximum growth rate.

Fig. 8. Parametric decay spectrum at various plasma densities with $B = 1.7$ kG, $f_0 = 75$ MHz. (a) $n = 2 \times 10^{10} \text{ cm}^{-3}$, (b) $n = 4 \times 10^{10} \text{ cm}^{-3}$, (c) $n = 6 \times 10^{10} \text{ cm}^{-3}$.

Fig. 9. Interferograms of the sideband wave at various plasma densities with $B = 1.7$ kG, $f_0 = 75$ MHz. (a) $n = 2 \times 10^{10} \text{ cm}^{-3}$, (b) $n = 6 \times 10^{10} \text{ cm}^{-3}$.

Fig. 10. Interferograms of the sideband wave at various magnetic fields with $n = 3 \times 10^{10} \text{ cm}^{-3}$, $f_0 = 75$ MHz. (a) $B = 1.6$ kG, (b) $B = 0.8$ kG.

Fig. 11. (a) Parametric decay spectra at various power levels. The pump power was raised in steps of 1 db. $f_0 = 75$ MHz, $B = 1.6$ kG, $n = 3 \times 10^{10} \text{ cm}^{-3}$. Spectrum analyzer set at 75 MHz central frequency, 0.5 MHz/div, linear sensitivity. (b) Radial profile of the pump amplitude at various axial locations. (c) Radial profile of the 73.6 MHz sideband amplitude at various axial locations. (d) Radial profile of the 74.1 MHz sideband amplitude at various axial locations.

Fig. 12. Variation of $\vec{E}_{01} \times \vec{B}$ coupled decay threshold with (a) antenna length L_z ($n = 3 \times 10^{10} \text{ cm}^{-3}$, $B = 1.6$ kG) (b) magnetic field B ($n = 3 \times 10^{10} \text{ cm}^{-3}$, $L_z = 11$ cm) (c) plasma density n ($B = 1.6$ kG, $L_z = 11$ cm).

Fig. 13. The pump and the sideband wave amplitude as a function of RF input power ($n = 3 \times 10^{10} \text{ cm}^{-3}$, $B = 1.3$ kG, $f_0 = 75$ MHz).

Fig. 14. Enhancement of energetic electron tail due to the parametric decay.

Fig. 1. 776216

Fig. 2. 776215

Fig. 3. 762321

Fig. 4. 772488

Fig. 5. 783211

Fig. 6. 776220

Fig. 7. 783233

75 k Hr

(a) 1.6 kG

(b) 0.8 kG

Fig. 10. 786390

(a)

75 MHz

(b)

(c)

(d)

Fig. 11. 786387

Fig. 12. 786389

Fig. 13. 776217

Fig. 14. 776224

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