ABSOLUTE TWO PLASMON PARAMETRIC DECAY
OF
OBLIQUELY INCIDENT ELECTROMAGNETIC WAVES
IN AN INHOMOGENEOUS PLASMA

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in an Inhomogeneous Plasma

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ABSTRACT

The parametric decay of an electromagnetic wave into two electron plasma waves is considered. The electromagnetic wave is obliquely incident on the density gradient. The resulting analysis shows that the threshold for absolute instability decreases as the angle of incidence of the electromagnetic wave relative to the density gradient approaches 90° . The importance of this result to laser fusion is discussed.

The parametric decay of electromagnetic waves of frequency and wave number $(\omega_0, \vec{k}_0)$ into plasma waves $(\omega, \vec{k})$ at quarter-critical density in an inhomogeneous plasma has been extensively discussed in the literature. Rosenbluth¹ pointed out that in the WKB approximation this decay process is convective in nature, and requires a minimum gradient length $L > [k_0(V_0/v_e)^2]^{-1}$ for the decay waves to grow to an appreciable level; here, V_0 is the electron velocity due to the pump, and $v_e^2 = T_e/m_e$. Lee and Kaw² studied the relevant equations without using any WKB approximation for the plasma waves and found that this decay can be absolute; this would permit the decay waves to grow until their amplitude is limited by nonlinear saturation effects. However, Lee and Kaw did not include the wave number mismatch introduced by the pump field into the parametric coupling terms. It is precisely this term which forbids an absolute instability in Rosenbluth's paper. Liu and Rosenbluth³ re-examined this decay and found that when the wave number mismatch was included, absolute instability could exist for $|V_0| > \frac{3}{2} k_{\perp} v_e^2 / \omega_p$, where $k_{\perp}$ is the component of the plasmon wave vector perpendicular to the density gradient, and ω_p is the plasma frequency.

In this article the relevant equations for the two plasmon decay are studied for a pump wave obliquely incident on the density gradient. This reduces but does not eliminate the mismatch term, making an absolute instability easier to generate. No WKB assumption is made concerning the plasma waves. The pump field $\vec{E}_0(\vec{x}, t) = \vec{E}_0^*/2 [\exp(i\vec{k}_0 \cdot \vec{x} - i\omega_0 t) + \text{c.c.}]$ is assumed to vary slowly in the region of the instability. For this to be

true, the pump cutoff point must be far from the quarter critical density point.⁴ It can easily be shown that this is equivalent to requiring $\sin^2 \theta \gg \frac{1}{3}(3/k_0 L)^{2/3}$, where $(\pi/2 - \theta)$ is the angle between the density gradient and $\vec{k}_0$ at the quarter critical density point, and L is the density scale length.

We assume $\vec{E}_0 = E_0 [\alpha \hat{y} + (1-\alpha^2)^{1/2} (\hat{z} \cos \theta - \hat{x} \sin \theta)]$ and $\vec{k}_0 = k_0 (\hat{z} \sin \theta + \hat{x} \cos \theta)$ ($\alpha \leq 1$). There are two decay waves present, $\phi(\vec{x}, t) = \phi(z) \exp(i\vec{k} \cdot \vec{x} - i\omega t)$ and $\phi_-(\vec{x}, t) = \phi_-(z) \exp[i(\vec{k} - \vec{k}_0) \cdot \vec{x} - i(\omega - \omega_0)t]$, and $\omega \approx \omega_0/2$. Using the fluid equations, we arrive at an equation similar to that of Lee and

Kaw:

$$\begin{aligned} \nabla \cdot \left[\frac{3v_e^2}{\omega^2} \nabla \nabla \cdot + 1 - \frac{\omega_p^2}{\omega^2} + \frac{2\gamma}{\omega} \right] \nabla \phi \\ = \frac{e}{m\omega_0^2} \nabla \cdot [\nabla (\vec{E}_0 \cdot \nabla \phi_-) - \nabla^2 \phi_- \vec{E}_0] \\ \nabla \cdot \left[\frac{3v_e^2}{(\omega - \omega_0)^2} \nabla \nabla \cdot + 1 - \frac{\omega_p^2}{(\omega - \omega_0)^2} - \frac{2\gamma}{\omega} \right] \nabla \phi_- \\ = \frac{e}{m\omega_0^2} \nabla \cdot [\nabla (\vec{E}_0 \cdot \nabla \phi) - \nabla^2 \phi \vec{E}_0] \end{aligned} \quad (1)$$

Here, $\gamma = \Delta + i\Gamma$, $\omega = \omega_r + \Delta$, ω_r is the plasmon frequency in the absence of a pump, Γ is decay constant of the plasma waves, and $|\Delta| \ll |\omega_r|$. We now let $\vec{k} = k_x \hat{x} + k_y \hat{y} = \vec{k}_\perp$, $\vec{k}_{\perp-} = (k_x - k_{0x}) \hat{x} + k_y \hat{y}$, where $k_{0x} = k_0 \cos \theta$, and $\omega_p^2 = (\omega^2 - 3v_e^2 k_\perp^2) (1 + z/L)$. We then obtain

$$\begin{aligned} \left(\frac{3v_e^2}{\omega^2} \frac{\partial^2}{\partial z^2} - \frac{z}{L} + \frac{2\gamma}{\omega} \right) \left(\frac{\partial^2}{\partial z^2} - k_\perp^2 \right) \phi - \frac{1}{L} \frac{\partial \phi}{\partial z} \\ = \frac{\omega i e k_y E_0}{m\omega_0^2} \exp(ik_{0z} z) \left(2ik_{0z} \frac{\partial \phi_-}{\partial z} - 2k_x k_{0x} \phi_- \right) \end{aligned}$$

$$\begin{aligned}
& + \frac{e}{m\omega_0^2} \frac{E_0}{k_0} (1-\alpha^2)^{1/2} \exp(ik_{oz}z) \left\{ 2ik_{oz}k_{ox} \frac{\partial^2 \phi_-}{\partial z^2} \right. \\
& \left. + \frac{\partial \phi_-}{\partial z} [2k_x(k_{oz}^2 - k_{ox}^2)] + i\phi_- (2k_x^2 k_{ox} k_{oz}) \right\} \\
& \left(\frac{3v_e^2}{\omega^2} \frac{\partial^2}{\partial z^2} - \frac{(z+\Delta z)}{L} - \frac{2\gamma}{\omega} \right) \left(\frac{\partial^2}{\partial z^2} - k_\perp^2 \right) \phi_- - \frac{1}{L} \frac{\partial \phi_-}{\partial z} \\
& = \frac{\alpha i e k_y E_0}{m\omega_0^2} \exp(-ik_{oz}z) \left(-2ik_{oz} \frac{\partial \phi}{\partial z} + 2k_x k_{ox} \phi \right) \\
& + \frac{e}{m\omega_0^2} \frac{E_0}{k_0} (1-\alpha^2)^{1/2} \exp(-ik_{oz}z) \left\{ -2ik_{oz}k_{ox} \frac{\partial^2 \phi}{\partial z^2} \right. \\
& \left. + \frac{\partial \phi}{\partial z} [2k_x(k_{ox}^2 - k_{oz}^2)] - i\phi (2k_x^2 k_{ox} k_{oz}) \right\} . \quad (2)
\end{aligned}$$

Here, $k_{oz} = k_0 \sin\theta$ and $\Delta z \approx (3v_e^2 L/\omega^2) (k_{ox}^2 - 2k_x k_{ox}) + (4\delta L/\omega)$, $\omega = \omega_0/2 + \delta$, $\delta/\omega \ll 1$. k_0 has been neglected relative to $k_\perp$ in the constant terms of Eq. (2), since $k_0 \ll k_\perp \sim 1/\lambda_D$; however, the exponential mismatch term $\exp(ik_{oz}z)$ has been retained.

We may solve Eq. (2) by fourier transforming, with $\phi(z) = \int ds \exp(isz) f(s)$ and $\phi_-(z) = \int ds \exp(isz) f_-(s)$. Letting

$$f(s) = (s^2 + k_\perp^2)^{-1/2} \exp(i\lambda_D^2 s^3 L) g(s)$$

$$f_-(s) = (s^2 + k_\perp^2)^{-1/2} \exp(i\lambda_D^2 s^3 L) g_-(s) , \quad (3)$$

we obtain, after some algebra,

$$\begin{aligned}
& \frac{\partial g(S+k_{oz}/2)}{\partial S} + \frac{2i\gamma L}{\omega} g\left(S + \frac{k_{oz}}{2}\right) = \frac{-L\gamma_0 g_-(S-k_{oz}/2)}{(S+k_{oz}/2)^2 + k_\perp^2} \\
& \cdot \left[\alpha_0 + \left(S - \frac{k_{oz}}{2}\right) \alpha_1 - \left(S - \frac{k_{oz}}{2}\right)^2 \alpha_2 \right] \exp\left[-i\lambda_D^2 L \left(3k_{oz} S^2 + \frac{k_{oz}^3}{4}\right)\right]
\end{aligned}$$

$$\begin{aligned} \frac{\partial g_{-}(S-k_{OZ}/2)}{\partial S} - \left(\frac{2i\gamma L}{\omega} + i\Delta z \right) g_{-}\left(S - \frac{k_{OZ}}{2}\right) = + \frac{L\gamma_O g(S+k_{OZ}/2)}{(S-k_{OZ}/2)^2 + k_1^2} \\ \cdot \left[\alpha_O + \left(S + \frac{k_{OZ}}{2}\right) \alpha_1 - \left(S + \frac{k_{OZ}}{2}\right)^2 \alpha_2 \right] \exp \left[i\lambda_D^2 L \left(3k_{OZ} S^2 + \frac{k_{OZ}^3}{4} \right) \right], \end{aligned} \quad (4)$$

where $\gamma_O = 2eE_O/m\omega_O^2$, $\alpha_O = +\alpha k_Y k_X k_{OX} - (1-\alpha^2)^{1/2} k_X^2 k_{OX} k_{OZ}/k_O$,
 $\alpha_2 = -(1-\alpha^2)^{1/2} k_{OZ} k_{OX}/k_O$, $\alpha_1 = +\alpha k_Y k_{OZ} - (1-\alpha^2)^{1/2} k_X (k_{OZ}^2 - k_{OX}^2)/k_O$,
and where we have let $S = s - k_{OZ}/2$. We have approximated
 $\{[(S+k_{OZ}/2)^2 + k_1^2]/[(S-k_{OZ}/2)^2 + k_1^2]\}^{1/2} \approx 1$. If we further let

$$\begin{aligned} u(S) &= g\left(S + \frac{k_{OZ}}{2}\right) \exp\left(-\frac{3}{2}ik_{OZ} L \lambda_D^2 S^2 - \frac{1}{8}i\lambda_D^2 L k_{OZ}^3\right) \\ u_{-}(S) &= g_{-}\left(S - \frac{k_{OZ}}{2}\right) \exp\left(\frac{3}{2}ik_{OZ} L \lambda_D^2 S^2 + \frac{1}{8}i\lambda_D^2 L k_{OZ}^3\right). \end{aligned} \quad (5)$$

We then obtain

$$\begin{aligned} \frac{\partial u}{\partial S} + u\left(\frac{2i\gamma L}{\omega} - 3ik_{OZ} L \lambda_D^2 S\right) \\ = - \frac{L\gamma_O u_{-}}{(S+k_{OZ}/2)^2 + k_1^2} \left(\alpha_O + \left(S - \frac{k_{OZ}}{2}\right) \alpha_1 - \left(S - \frac{k_{OZ}}{2}\right)^2 \alpha_2 \right) \end{aligned} \quad (6a)$$

$$\begin{aligned} \frac{\partial u_{-}}{\partial S} - u_{-}\left(\frac{2i\gamma L}{\omega} + i\Delta z - 3ik_{OZ} L \lambda_D^2 S\right) \\ = + \frac{L\gamma_O u}{(S-k_{OZ}/2)^2 + k_1^2} \left[\alpha_O + \left(S + \frac{k_{OZ}}{2}\right) \alpha_1 - \left(S + \frac{k_{OZ}}{2}\right)^2 \alpha_2 \right] \end{aligned} \quad (6b)$$

Equation (6a) and Eq. (6b) may be combined into a single second order equation for u by taking the derivative of Equation (6a). If we then let $u(S) = W(S) \exp\left(-\int^S d\zeta h(\zeta)/2\right)$, where

$$h(S) = -i\Delta z + \frac{2(S+k_{OZ}/2)}{(S+k_{OZ}/2)^2+k_1^2} - \frac{\alpha_1 - 2(S-k_{OZ}/2)\alpha_2}{\alpha_0 + (S-k_{OZ}/2)\alpha_1 - (S-k_{OZ}/2)^2\alpha_2}, \quad (7)$$

we can obtain, after much algebra,

$$\frac{\partial^2 W}{\partial S^2} + W(F_0 + F_1 + F_2) = 0, \quad (8)$$

where

$$F_0 = L^2 \left\{ \gamma_0^2 \frac{[\alpha_0 + S\alpha_1 - (S^2 - k_{OZ}^2/4)\alpha_2]^2 - k_{OZ}^2(\alpha_1^2/4 + \alpha_2\alpha_0)}{(S^2 + k_{OZ}^2/4 + k_1^2)^2 - S^2 k_{OZ}^2} + \left(\frac{2\gamma}{\omega} + \frac{\Delta z}{2L} - 3k_{OZ}\lambda_D^2 S \right)^2 \right\}$$

$$F_1 = L \left\{ -3ik_{OZ}\lambda_D^2 + \left(\frac{2\gamma i}{\omega} - 3ik_{OZ}\lambda_D^2 S + \frac{i\Delta z}{2} \right) \cdot \left[\frac{2(S+k_{OZ}/2)}{(S+k_{OZ}/2)^2+k_1^2} - \frac{\alpha_1 - 2(S-k_{OZ}/2)\alpha_2}{\alpha_0 + \alpha_1(S-k_{OZ}/2) - (S-k_{OZ}/2)^2\alpha_2} \right] \right\}$$

$$F_2 = -\frac{h^2}{4} - \frac{1}{2} \frac{\partial h}{\partial S} - \frac{\Delta z^2}{4} - \frac{i\Delta z}{2} \left[\frac{2(S+k_{OZ}/2)}{(S+k_{OZ}/2)^2+k_1^2} - \frac{\alpha_1 - 2(S-k_{OZ}/2)\alpha_2}{\alpha_0 + (S-k_{OZ}/2)\alpha_1 - (S-k_{OZ}/2)^2\alpha_2} \right]$$

We now may solve Eq. (8) in a manner similar to that of Liu and Rosenbluth.³ We find Δ by assuming L large and neglecting F_1 and F_2 in Eq. (8). F_1 is then included as a small perturbation that determines the correction to Δ . We may also simplify F_0 by neglecting k_0^2 relative to k_1^2 . Temporal instability will first occur when $F_0|_{\Delta, S} = (\partial F_0 / \partial S)|_{\Delta, S} = 0$ for some $\text{Im}\Delta > 0$, or equivalently when two turning points of F_0 coalesce for $\text{Im}\Delta > 0$. This is a necessary requirement for

$W(S)$ to be bounded in the S plane, which by the property of Fourier transforms bounds $\phi(z)$ in z . We note that

$$\left. \frac{\partial F_0}{\partial S} \right|_{\Delta} = - \left. \frac{\partial \Delta}{\partial S} \right|_{F_0} \left. \frac{\partial F_0}{\partial \Delta} \right|_S . \quad (9)$$

Since $(\partial F_0 / \partial \Delta)|_S \approx (4/\omega) [(2\gamma/\omega) + \Delta z/2L - 3k_{oz} \lambda_D^2 S] \neq 0$ in general, we need only require $F_0|_{\Delta, S} = (\partial \Delta / \partial S)|_{F_0=0} = 0$. We may first consider the limit of $k_{oz} \ll k_{ox}$. The equations for Δ become

$$\frac{2\Delta}{\omega} = - \frac{2i\Gamma}{\omega} + 3k_{oz} \lambda_D^2 S + i\gamma_0 \frac{\alpha_0 + S\alpha_1}{(S^2 + k_{\perp}^2)} - \frac{\Delta z}{2L} \quad (10a)$$

$$0 = 3k_{oz} \lambda_D^2 (S^2 + k_{\perp}^2)^2 - i\gamma_0 \alpha_1 (S^2 - k_{\perp}^2) - 2iS\gamma_0 \alpha_0, \quad (10b)$$

where $\alpha_0 = +\alpha k_y k_x k_{ox}$, $\alpha_1 = +(1-\alpha^2)^{1/2} k_x k_{ox}^2 / k_o$.

We have chosen the $+$ sign for the last term in Eq. (10a) for instability for $S > 0$. We first let $\alpha_0 = 0$ ($\alpha = 0$) and

$k_{\perp} = k_x$. For $\gamma_0 \alpha_1 / (3k_{oz} \lambda_D^2 k_{\perp}^2) \gg 1$, Eq. (10b) yields

$S^2 \approx k_{\perp}^2$. Equation (10a) then yields ($V_o \equiv eE_o / m\omega_o$)

$$\text{Im}\Delta = \Delta_i = \frac{k_{ox} V_o}{4} - \Gamma, \quad (11)$$

which results in the normal homogeneous plasma threshold $k_{ox} V_o / 4$

$= \Gamma$. The other solution to Eq. (10b) when $\alpha_0 = 0$ is

$S^2 \approx i\alpha_1 \gamma_0 / 3k_{oz} \lambda_D^2$, which yields $\Delta_i + \Gamma \approx k_o V_o (3k_x k_{oz} \lambda_D^2 / 2k_o \gamma_o)^{1/2}$;

we will ignore this solution since the root $S^2 \approx k_{\perp}^2$ clearly

gives the higher growth rate. A numerical analysis of Eq. (10)

shows that $\Delta_i + \Gamma > 0$ for $\gamma_o (\alpha_1 / 3k_{oz} \lambda_D^2 k_{\perp}^2) > 0.86$. This

results in the condition for absolute instability:

$$\theta < 0.775 \frac{V_o}{c} \frac{1}{k_o k_{\perp} \lambda_D^2}. \quad (12)$$

Equation (12) is valid only for $\theta \ll 1$ and $\theta \gg (3/k_o L)^{1/3}$.

We may now find the first order in $1/L$ corrections to Δ_i by letting $\Delta = \Delta_1 + \Delta_2$, $|\Delta_2| \ll |\Delta_1|$, and expanding Eq. (7)

$$\frac{\partial^2 W}{\partial S^2} + W \left[\frac{1}{2} \frac{\partial^2 F_0}{\partial S^2} \Big|_{S_o} (S-S_o)^2 + \frac{\partial F_0}{\partial \Delta} \Big|_{S_o} \Delta_2 + F_1(S_o, \Delta_1) \right] = 0 \quad (13)$$

This is simply the quantum harmonic oscillator problem, which has eigenvalues

$$\Delta_i = -\Gamma + \frac{k_{ox} V_o}{4} - \frac{(n+\frac{1}{2}) \omega_p}{2k_{\perp} L} \quad (14)$$

For our large L expansion to be valid, the last term in Eq. (14) must be a small correction to Δ_i .

We may now apply this method of analysis to the problem of arbitrary angle of incidence. First, we consider $\alpha = 0$. Our coefficients in Eq. (8) are then: $\alpha_0 = -k_x^2 k_{ox} k_{oz} / k_o$, $\alpha_1 = -k_x (k_{oz}^2 - k_{ox}^2) / k_o$ and $\alpha_2 = -k_{oz} k_{ox} / k_o$. Letting $k_x = k_{\perp}$, $(\gamma_o k_o / 3k_{oz} k_{\perp} \lambda_D^2) > 1$, and using the same analysis as before, we obtain after some algebra the growth rate (to lowest order in $1/L$)

$$\Delta_i = -\Gamma + \frac{k_o V_o}{4} \quad (15)$$

For the case of $\alpha = 1$, our coefficients are: $\alpha_0 = +k_x k_y k_{ox}$, $\alpha_1 = k_y k_{oz}$, and $\alpha_2 = 0$. For $(\gamma_o k_o / 2k_{oz} k_{\perp} \lambda_D^2) > 1$, we obtain

$$\Delta_i = -\Gamma + \frac{V_o k_o}{4} \frac{k_y k_x}{k_{\perp}^2} \left[\left(1 + \frac{k_y^2}{k_x^2} \sin^2 \theta \right)^{1/2} + \cos \theta \right] \quad (16)$$

It is easily shown that $\Delta_i + \Gamma$ is greatest for $k_x = k_y \cos \theta$.

We then obtain

$$\Delta_1 = -\Gamma + \frac{k_o V_o}{4} \quad (17)$$

The analysis has thus shown that absolute instability for the two plasmon parametric decay is possible in an infinite inhomogeneous plasma. It also states for the first time the requirement that

$$\frac{V_o}{c} > k_o k_{\perp} \lambda_D^2 \sin\theta \quad (18)$$

for absolute instability. For $\sin\theta = 1$, Eq. (18) agrees with Liu and Rosenbluth.³ For V_o/c much greater than threshold and for $\vec{E}_o$ either in the plane of incidence or perpendicular to the plane of incidence, the instability will grow with the homogeneous plasma growth rate.

Equation (18) results in a far lower threshold for absolute instability than previously stated in the literature. If we let $k_{\perp} \sim 1/\lambda_D$, Eq. (18) requires $\sin\theta < (V_o/c)(k_o \lambda_D)^{-1}$. For these values of θ , we may estimate Δ_2 . It is easy to show that $\partial^2 F_o / \partial S^2 \sim (L^2 k_o^2 V_o^2) / (\omega^2 k_{\perp}^2)$ and $\partial F_o / \partial \Delta \sim 2k_o V_o L^2 / \omega^2$. Equation (13) would then yield $\Delta_2 \sim \omega_p / k_{\perp} L \sim v_e / L$. We must require $|\Delta_2| \ll |\Delta_1|$ for these solutions to be valid. This yields the condition $V_o / v_e \gg (k_o L)^{-1}$ for absolute instability. This is much lower than the $(V_o / v_e)^2 \gg (k_o L)^{-1}$ threshold previously mentioned.^{1,3} Making $\sin\theta < (V_o/c)(k_o \lambda_D)^{-1}$ is equivalent to letting $\sin\theta < (P/8T_e n c)^{1/2}$. For a 10.6μ CO₂ laser emitting 10^{12} W/cm² on a 50 eV quarter critical density plasma, this becomes $\theta < 27^\circ$, a condition easily consistent with the WKB pump approximation for $k_o L \gg 1$.

The main point of this work is the result that it will be easier to excite absolute instabilities for obliquely incident light waves than for normally incident radiation. This result could be of substantial importance in both the laser pellet and laser heated solenoid fusion schemes, in which the laser light should have ample opportunity to be obliquely incident on the density gradient at some point in the plasma.

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