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2.B Advances in the Theory of the Two-Plasmon Decay Instability in an Inhomogeneous Plasma

We report recent calculations of the growth rate of the two-plasmon-decay ($2\omega_p$) instability, in which we show that although previously published thresholds[1-3] are substantially correct, the spectrum of the most unstable modes depends strongly on the laser wavelength. In addition, we have found substantially reduced thresholds when the laser is incident at an oblique angle to the density gradient of the coronal plasma.

The presence of the strong electromagnetic wave of the laser in the corona of a laser-fusion target provides a source of free energy which can be tapped by a number of plasma instabilities. One example of these is the two-plasmon-decay instability in which the pump electromagnetic wave (the laser light) decays into two plasma waves. The pump wave and the two plasma waves have frequencies and wave vectors (ω_o, $\mathbf{k}_o$), (ω, $\mathbf{k}$) and ($\omega_o - \omega$, $\mathbf{k}_o - \mathbf{k}$), respectively. The physical mechanism for instability is that the first plasma wave and the pump produce a ponderomotive force on the plasma at the beat (difference) frequency of $\omega_o - \omega$ which resonantly drives the second wave. In turn, the beating of the second wave with the pump at frequency $\omega_o - (\omega_o - \omega) = \omega$ resonantly drives the first wave. With sufficient coupling, that is, with a sufficiently strong pump, the positive feedback overcomes the losses due to damping and /or convection of the product waves out of the region, and instability occurs. The coupling mechanism is the same as that which gives rise to Brillouin and Raman scattering. The distinguishing feature of the the $2\omega_p$ instability is that both decay waves are plasma waves. The coupling is most effective when the plasma waves are resonantly driven, that is, when the product waves satisfy the free Langmuir dispersion relations:

$$\omega^2 = \omega_p^2 + 3v_T^2 k^2$$

and

$$(\omega_o - \omega)^2 = \omega_p^2 + 3v_T^2 (\mathbf{k}_o - \mathbf{k})^2 \ , \qquad (1)$$

where v_T is the electron thermal velocity and ω_p is the plasma frequency.

Because the thermal corrections are relatively small this requires

$$\omega \approx \omega_o - \omega \approx \omega_p \approx \omega_o/2 \ , \qquad (2)$$

and so the instability occurs in the vicinity of the quarter-critical density. From Eq. (1) one can readily show that the difference between the frequencies of the two coupled waves is given by

$$\Delta\omega = \frac{6v_T^2}{\omega_o} \ \mathbf{k}_o \cdot (\mathbf{k} - \mathbf{k}_o/2).$$

The frequency splitting is thus proportional to the temperature of the plasma, and to a factor that depends on the k-vector of the unstable mode, which is undetermined at this point.

By various mechanisms such as Thomson scattering of the laser radiation or linear conversion, the plasma-wave spectrum from the $2\omega_p$ instability gives rise to radiation at half-odd-integer harmonics (HOIH), that is $\omega_o/2$, $3\omega_o/2$, $5\omega_o/2$, etc. One can thus hope to use this HOIH radiation as a temperature diagnostic if the relevant k-vectors are known. Indeed, as is described elsewhere in this issue (Section 2.A), multi-peaked HOIH spectra have been observed in both 1-μm and 0.35-μm experiments with splittings of various magnitudes.

Apart from its possible use as a diagnostic, the $2\omega_p$ instability is potentially important if it should absorb a substantial fraction of the laser light into plasma waves, which would in turn transfer this energy to the electrons by accelerating them to approximately their phase velocity. A substantial population of hot ($\sim$ 100 keV) electrons from this source would give rise to target-design problems because of the preheat that would be caused in the fuel. In our experiments to date, however, only small ($\lesssim$ 0.1%) hot-electron populations have been observed.[4]

The theory of the $2\omega_p$ instability in a homogeneous plasma was first worked out by Jackson,[5] who found that the most unstable modes have k-vectors lying in the plane of incidence on the hyperbola shown in Fig. 6. Each point of the hyperbola corresponds to a particular density determined by the frequency-matching conditions in Eq. (1). The homogeneous growth rate is independent of density until Landau damping becomes important. This occurs for $k\lambda_D \gtrsim (k\lambda_D)_{max} \equiv p \simeq 0.3$. In an inhomogeneous plasma, as arises in laser-fusion experiments, the $2\omega_p$ instability is excited in

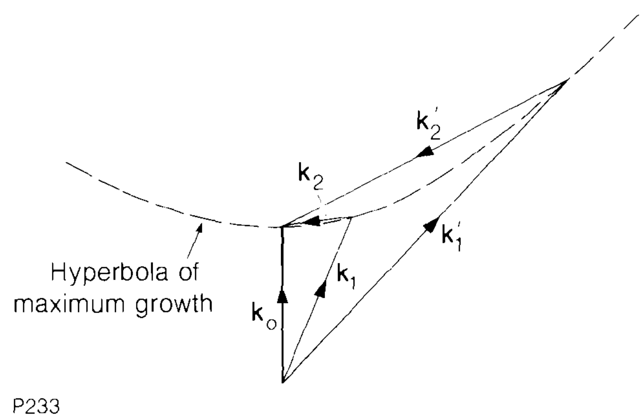

Fig. 6
Decay of photon (k_o) into two plasma waves (k_1, k_2) or (k_1', k_2'). In a homogeneous plasma, these decays are equally unstable. In an inhomogeneous plasma, $\beta << 1$ (as in CO_2 laser experiments) favors the primed decay and $\beta >> 1$ (as in short-wavelength experiments) favors the unprimed.

a small region of density just below quarter-critical, approximately in the range

$$1 - 3p^2 (\simeq 0.18) < n/n_{c/4} < 1 - 9v_T^2/4c^2 \;,$$

the lower limit arising from Landau damping and the upper from frequency matching. As the pump is increased, the instability is first convective, and plasma waves generated thermally (or otherwise) are amplified as they pass through the resonant region. On further increase of the pump the instability becomes absolute. The final level of the plasma-wave amplitudes is then limited only by nonlinear dissipation and not by convective loss from the resonance region, and is independent of the noise level from which the waves grew up.

The theory of the absolute $2\omega_p$ instability in an inhomogeneous plasma was first treated by Lee and Kaw,[1] who restricted their calculation to the case of plasma waves whose wave vector greatly exceeded that of the pump. A more complete theory which included all ranges of plasma-wave wave number was developed by Liu and Rosenbluth.[2] However, in the final stages of their calculation they resorted to various inappropriate approximations, which led to certain anomalies first pointed out by Lasinski and Langdon.[3] We have corrected and extended their calculations[6] to obtain growth rates and thresholds for the absolute $2\omega_p$ instability, for oblique as well as normal incidence of the pump. In the course of these calculations we have identified a new parameter of importance, namely β, defined by

$$\beta = 9v_T^4 k_o^2 / v_o^2 \omega_o^2 = 1.41\ T_{keV}^2 / I_{14} \lambda_\mu^2 \;,$$

where $v_o = eE/m\omega_o$ is the electron "jitter" velocity in the pump field, which provides a qualitative measure of the relative importance of thermal effects and the effect of the pump on the dispersion of the plasma waves. Because the self-consistent variation of electron temperature T_{keV} (in units of keV) with pump power I_{14} (in units of 10^{14} W/cm^2) tends to cancel the explicit dependence of β on pump power, β is determined primarily by the vacuum laser wavelength λ_μ (in microns). Typically $\beta << 1$ for CO_2 laser experiments, while for 1-μm or shorter-wavelength laser experiments, $\beta \gtrsim 1$.

The threshold for absolute instability is found to be a relatively weak function of β given approximately by

$$\left(\frac{V_o}{V_e}\right)^2 k_o L > 3 \ ,$$

or $I_{14} L_\mu \lambda_\mu / T_{keV} > 60$ in practical units. However, the wave number of the most unstable mode is sensitive to p. The perpendicular component of this wave number $k_\perp$ is given approximately by

$$k_\perp \simeq 0.5 \ k_o \beta^{-1/2} .$$

The component of the wave number parallel to the gradient, $k_{||}$, is of course ill-defined because it is a function of position. However, the unstable eigenfunction has its maximum amplitude near the point where $k_{||}$ and $k_\perp$ are related by the hyperbola of Fig. 6, that is where

$$k_{||} (k_{||} - k_o) = k_\perp^2 .$$

Thus, when $\beta << 1, k_{||} \simeq k_\perp >> k_o$, and the most strongly excited plasma waves make an angle of approximately 45° to the pump. This has been directly observed in the Thomson-scattering experiments of Baldis and Walsh[7] who used a CO_2 laser incident on a preformed plasma. In this case ($\beta << 1$), the dependence of $k_{||}$ on β cancels the v_T^2 dependence of $\Delta\omega$ in Eq. (2), and one obtains a frequency splitting given by

$$\Delta\omega / \omega_o = 2.24 \ v_o / c = 4.8 \times 10^{-3} \lambda_\mu I_{14}^{1/2}$$

for the fastest-growing mode. On the other hand, when $\beta \gtrsim 1$, the most unstable $2\omega_p$ mode is into a pair of plasma waves, one with wave vector approximately equal to that of the pump and the other with a wave vector smaller than the pump and approximately perpendicular to it. This second wave typically has a phase velocity greater than the velocity of light and should be relatively ineffective in accelerating electrons. The first wave, however, should generate hot electrons directed up the density gradient. Indications that this is the case arise from a comparison of hard-x-ray spectra and electron-spectrometer data.[8] When short-wavelength probe pulses become available at LLE, Thomson-scattering experiments will permit direct measurements of plasma-wave spectra, and verification of our theoretical conclusions in