

Hot Electron Generation by the Two-Plasmon Decay Instability in the Laser-Plasma Interaction at $10.6\ \mu\text{m}$

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Hot electron generation in a long-density-scale-length ($\sim 300\ \mu\text{m}$) underdense plasma has been studied. For a plasma of maximum electron density of $\frac{1}{4}n_c$ the hot electron emission is localized in the plane of polarization of the incident CO_2 laser and peaked about 45° with respect to the \vec{k} vector of the laser beam, in both forward and backward directions. These observations suggest that the hot electrons are generated by the two-plasmon decay instability at quarter-critical density.

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The problem of laser-plasma coupling has been a central issue in laser fusion studies for a number of years. For high laser intensities, and short-scale-length plasmas, the laser energy is thought to be deposited into a hot-electron distribution at the critical-density surface mainly by resonant absorption. However, in long-pulse-length irradiation experiments ($> 1\ \text{ns}$) which are of current interest, the underdense plasmas become fairly large ($> 300\ \mu\text{m}$) and physical processes which occur at subcritical densities become quite important. In particular, attention has been focused on high-frequency instabilities that occur at or below quarter-critical density, such as two-plasmon ($2\omega_{pe}$) decay instability¹ which is the parametric decay of an incident photon into two electron plasma waves and stimulated Raman scattering (SRS),² where the incident photon decays into a scattered photon and a plasmon. These instabilities are relevant to laser fusion because they are theoretically predicted to generate high-energy electrons which may contribute to preheat and core-corona decoupling.

In this Letter, we present the first experimental demonstration of hot electron generation from two-plasmon decay instability at quarter-critical density in long-scale-length plasmas irradiated by intense nanosecond CO_2 -laser radiation. Since experimentally it is difficult to clearly isolate a specific hot-electron generation mechanism in short-scale-length solid-target plasmas,³ we have used a plasma configuration which, apart from the long scale length, allows a choice of maximum electron density along the CO_2 -laser axis. This has made it possible to isolate hot electrons generated by the two-plasmon decay instability from electrons generated near critical density by resonant absorption or parametric instabilities. Characteristics of the angular distribution of the hot electron emission and its depen-

dence on the plane of polarization of the incident CO_2 -laser beam have then allowed us to identify hot electrons generated in two-plasmon decay from those generated by other processes in the underdense region such as filamentation and stimulated Raman scattering. Direct evidence for the two-plasmon instability in a similar plasma configuration was obtained by Thomson scattering in an earlier study.⁴

The experimental setup is shown in Fig. 1. The plasma was produced by a $1.06\text{-}\mu\text{m}$ laser pulse ($2\text{--}4\ \text{J}$ in $20\ \text{ns}$) focused to a $500\text{-}\mu\text{m}$ spot on a solid carbon target. The $10.6\text{-}\mu\text{m}$ laser pulses in the range $10\text{--}20\ \text{J}$ were focused with a 50-cm -focal-length NaCl lens, giving a focal spot approximately $130\ \mu\text{m}$ in diameter and a maximum power density of $4 \times 10^{14}\ \text{W/cm}^2$. The $10.6\text{-}\mu\text{m}$ beam was incident transverse to the $1.06\text{-}\mu\text{m}$ beam and this permitted a choice of maximum electron densities along the path of the CO_2 -laser beam from below $\frac{1}{10}n_c$ to above n_c . At the peak of the Nd:glass laser pulse, the plasma had a scale length $L = (n^{-1}dn/dx)^{-1}$ along the CO_2 -laser

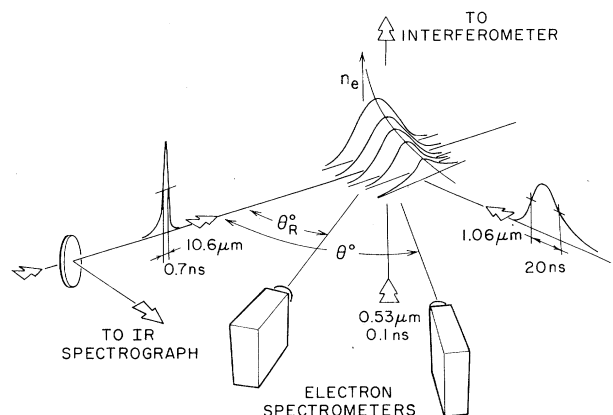


FIG. 1. Schematic diagram of the experimental arrangement.

axis of approximately 300 μm at the electron density of one-quarter critical density ($\frac{1}{4}n_c$). The focal-spot size of the CO₂-laser beam is smaller than the density gradient of the glass-laser-produced plasma target so that the CO₂-laser beam effectively does not see a density gradient across the beam cross section. Electron density and scale length were measured with subnanosecond interferometry for every shot. Furthermore, $\frac{3}{2}\omega_0$ harmonic radiation in the backscattered light was observed with a diffraction grating spectrograph and a 400-MHz-bandwidth HgCdTe detector. Detailed hot-electron distributions were determined with two identical miniature 180° focusing spectrometers in conjunction with surface-barrier detectors. The spectrometer and detector combination were absolutely calibrated against Kodak No-Screen film of known H-D curves using a laser-produced plasma as a hot electron source. The electron energy range of the present measurement is between 35 and 400 keV. The data to be discussed in this Letter represent electron spectra taken during approximately 200 laser shots, with incident laser energy between 16 and 20 J.

Typical hot-electron distributions measured in the plane of polarization of the incident CO₂-laser

beam (*P*) for several different angles with respect to the \vec{k} vector of this beam are shown in Fig. 2. The maximum electron density n_{max} was between $0.25n_c$ and $0.4n_c$. The measured hot electron distributions are well approximated by a Maxwellian distribution of the form

$$f(E) = \pi^{-1/2} [2N_0 E^{1/2} / (kT_e)^{3/2}] \exp(-E/kT_e),$$

where N_0 is the total number of electrons, E is the energy, and kT_e is the effective temperature of the distribution. For the electron spectra at $\theta = 45^\circ$ and 135° this temperature is approximately 60 keV. It should, however, be noted that this is the temperature of hot electrons which have had to overcome a space- and time-dependent plasma potential.

Measurements of the electron spectra (Fig. 2) at various angles show that the hot electron emission is maximum about the 45° directions with respect to the \vec{k} vector of the CO₂-laser beam in both the forward and backward directions, in the plane of polarization of the incident beam. At all other angles ($\theta = 18^\circ, 90^\circ, 170^\circ$) the flux is significantly reduced with lower effective temperatures of the distributions (e.g., $kT_e \sim 15$ keV at $\theta = 170^\circ$). Observations of the electron emission in and out of the plane of polarization of the incident CO₂-laser radiation (Fig. 3) also show

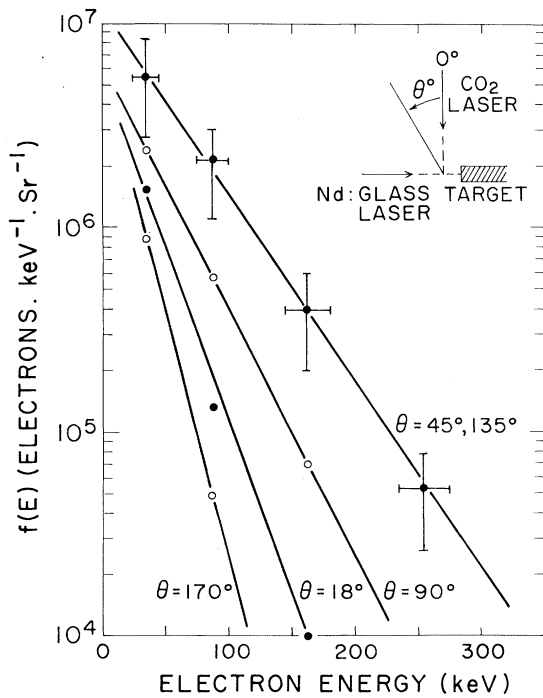


FIG. 2. Heated-electron distributions for *P*-polarized (horizontal plane) light for different angles θ , which is defined in the figure. Error bars denote the standard deviation associated with each average.

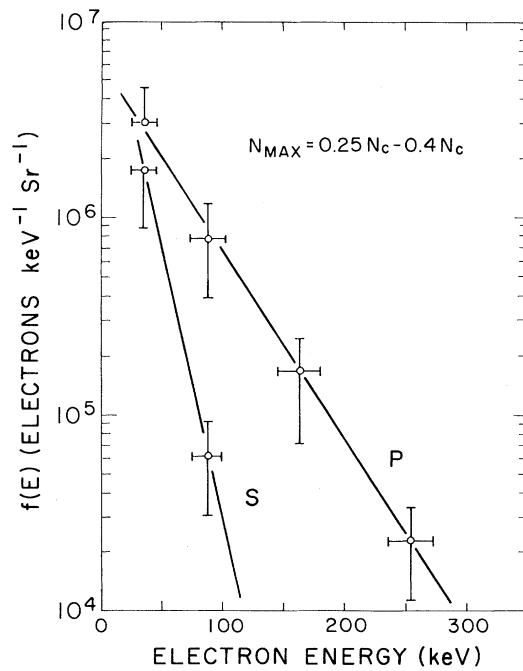


FIG. 3. Hot-electron emission in (*P* polarization) and out (*S* polarization) of the plane of polarization for $\theta = 45^\circ$ and 135° .

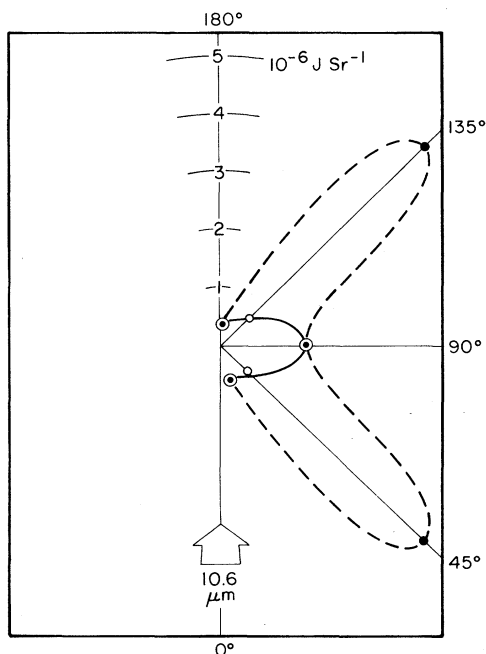


FIG. 4. Polar plot of the energy carried by hot electrons between 35 and 400 keV for P- (closed circles) and S- (open circles) polarized light. Note points common to both polarization at 18° , 90° , and 170° .

that for the two 45° directions the hot electrons are emitted predominantly in the plane of polarization where the emission is strongest and where the highest-energy electrons are observed. The switching of the plane of polarization in these studies was achieved by rotating the polarization vector. At polar angles other than 45° ($\theta = 18^\circ$, 90° , 170°) there is no noticeable change in the electron distribution in and out of the plane of polarization. This strong dependence of the hot electron emission on both the angle with respect to the incident \vec{k} vector of the CO_2 -laser beam and the plane of polarization is clearly evident in the polar plot of the integrated hot-electron energy distribution in Fig. 4, for both S and P polarization. Integrating over the measured distribution, electrons between 35 and 400 keV are found to contain a total energy of $10 \mu\text{J}$. The experimental arrangement did not allow us to measure the hot electrons produced by the damping of the plasmons propagating towards the higher density, thereby enabling us to determine the total fraction of the incident energy going into the hot electrons by $2\omega_{pe}$ decay. In short-scale-length plasmas (L/λ approximately of order unity), where absorption at n_c occurs mainly via resonant absorption, we have previously determined

that up to 1% of the absorbed energy appears as kinetic energy of the fast electrons escaping the target potential under similar irradiance conditions.³

Of the three possible mechanisms in the underdense plasma which are thought to generate heated electron distributions (filamentation, stimulated Raman scattering, and two-plasmon decay instability) the angular distribution observed in these studies can only be generated by the two-plasmon decay instability, since for the ambient plasma temperature in this experiment (of the order of 200 eV)⁵ the maximum growth rate for the two-plasmon instability is along the two 45° directions with respect to the incident \vec{k} vector. Hence, strong electron emission is expected mainly along these two directions. For an axial electron density profile of the form $n(x) = n_0(1 + x/L)$ the threshold for the two-plasmon decay instability is given by the condition $\frac{1}{3}(V_0/V_e)^2 k_0 L > 1$, where V_0 is the electron oscillating velocity ($V_0 = eE_0/m$) and V_e is the electron thermal velocity [$V_e = (2kT_e/m)^{1/2}$]. For a scale length $L = 300 \mu\text{m}$ at $\frac{1}{4}n_c$ and $T_e \sim 200 \text{ eV}$ the two-plasmon decay instability has a threshold of 10^{12} W/cm^2 , which is well within the range of incident laser intensities used in the present studies.

Further evidence for the existence of the two-plasmon decay instability in our plasma configuration results from the direct observations of the decay waves generated by this instability,⁴ and measurements of the $\frac{3}{2}\omega_0$ harmonic in the backscattered light, which was monitored in the present studies. $\frac{3}{2}\omega_0$ light results from a combination of a decay plasma wave and the fundamental wave or higher-order combination (such as three plasma waves) and its observation gives an indication that $2\omega_{pe}$ decay is occurring. In the present study, significant hot electron emission was only observed when measurable levels of $\frac{3}{2}\omega_0$ light (above noise level) were present in the backscattered light.

The strong dependence of the hot electron emission on both the angle with respect to the incident \vec{k} vector of the CO_2 -laser beam and the plane of polarization is localized near $\frac{1}{4}n_c$. When the maximum electron density is increased to $1.1n_c$, instead of the nearly identical emission observed in the two 45° directions at $\frac{1}{4}n_c$ (Fig. 2), the emission is observed predominantly in the backward direction down the density gradient. At this maximum density there is still a contribution from hot electrons generated by the two-plasmon decay instability at quarter-critical density superim-

posed on the electron distribution produced by resonant absorption and/or parametric instabilities near critical density. On the other hand, at maximum densities near $\frac{1}{10}n_c$, the hot-electron emission is neither peaked along the two 45° directions, nor is it sensitive to the plane of polarization of the incident $10.6\text{-}\mu\text{m}$ radiation. The details of electron emission below the quarter-critical density will be published elsewhere. However, the hot electron emission observed near $\frac{1}{10}n_c$ and $\frac{1}{4}n_c$ with S-polarized incident light is tentatively attributed to stimulated Raman scattering. The effective Maxwellian temperature of this distribution $kT_e \sim 10\text{--}15$ keV.

For efficient acceleration of electrons, the phase velocity must be of the order of the thermal velocity. If we assume that the "temperature" of the hot electrons measured here is roughly $\frac{1}{2}M_e V_p^2$, where V_p is the phase velocity of the electron plasma wave, then $V_p \sim 10^{10}$ cm/s. This is about two orders of magnitude higher than the phase velocity of the decay waves in the strong-damping limit ($k\lambda_D \sim 1$, where λ_D is the Debye length) where energy coupling into electrons would be most effective. Thus after trapping and subsequent acceleration by the plasmons, collisional damping, and not Landau damping, pro-

duces the electrons in the tail of the background distribution. Finally, we note that the maximum hot-electron energies and the effective Maxwellian distributions observed in these experiments are in good agreement with those predicted in simulations of the two-plasmon decay instability.⁵

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Collective Microwave Emission from Intense Electron-Beam Interactions: Theory and Experiment

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High-power microwaves are observed in two clear frequency bands when an intense relativistic electron beam passes through an unmagnetized plasma. The high-frequency band has frequency which scales with ω_p and resembles radiation from processes in type-III solar bursts. Theory indicates beam-plasma stabilization may arise from radiative losses. The lower-frequency band, with frequency independent of ω_p , may represent conversion of electrostatic waves near the plasma boundary in inhomogeneities of size ~ 0.3 cm. Experiments in a magnetic field qualitatively agree with our models.

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Though the problem of collective emission from beam-plasma instabilities is old,¹⁻⁶ there is surprisingly little laboratory work.⁷⁻⁹ Most theory has focused on type-III solar radiation bursts.¹⁻⁴ There are both weak-turbulence and strong-turbu-

lence models for emission at the first plasma harmonic and above.¹⁰⁻¹² Though there is some laboratory work on collective emission by intense beams in a strong magnetic field,^{7,8} there are no definitive observations without a field,