ELECTRON ACCELERATION BELOW QUARTER-CRITICAL DENSITY IN CO_2 LASER-PRODUCED PLASMAS

N.A. EBRAHIM
Yale University, Department of Engineering and Applied Science, New Haven, CT 06520, USA

C. JOSHI
University of California, Electrical Sciences and Engineering Department, School of Engineering and Applied Science, Los Angeles, CA 90024, USA

and

H.A. BALDIS
National Research Council, Division of Physics, Ottawa, Canada K1A OR6

Received 22 April 1981

We present detailed characteristics of heated electron distributions in long-scale-length underdense plasmas irradiated by intense nanosecond CO_2 laser radiation. Below $n_c/4$, the heated electron distributions are consistent with heating by Raman instability.

Recently there has been an increased interest in understanding physical processes that lead to high-energy electron generation in laser-produced plasmas of densities less than critical. Several such processes can occur in the large regions of the underdense plasmas of laser fusion targets in use at the present time. One of these, the stimulated Raman scattering (SRS), results from the parametric excitation of an electron plasma wave which coherently scatters-off part of the incident beam [1]. An important feature of the SRS instability, of great consequence to the laser-fusion concept, is its ability to generate high-energy electrons [2] via Landau damping of the plasma waves. Since these electrons could lead to significant fusion-pellet preheat the knowledge of the Raman-heated electron distributions is quite essential to laser-fusion target designs.

In this letter we present for the first time detailed characteristics of the heated electron distributions in long-scale-length underdense plasmas irradiated by intense nanosecond CO_2 laser radiation. The plasma configuration we have used allows us a choice of maximum electron density of the plasma along the CO_2 laser axis. This has enabled us to isolate the Raman-heated electrons in plasmas with maximum densities between the tenth-critical ($n_c/10$) and the quarter-critical ($n_c/4$) density in the weak Landau damping regime ($k_{epw}\lambda_D \ll 1$).

Unlike the $2\omega_{pe}$ decay instability [3] which is localized near $n_c/4$, SRS can occur for $n \leqslant n_c/4$. The frequency matching conditions are $\omega_0 \to \omega_s + \omega_{epw}$, where ω_0, ω_s, and ω_{epw} are the angular frequencies of the incident light, scattered light, and the electron plasma wave, respectively. For densities below $n_c/10$, both the k_{epw} and λ_D become larger and the plasma waves are strongly damped. Near $n_c/4$, SRS has the lowest intensity threshold in an inhomogeneous plasma where the instability becomes absolute. Thus the region of the underdense plasma with densities between $n_c/10$ and $n_c/4$, where SRS is convective and moderately damped, is appropriate for studying the Raman-heated electron distributions.

The experimental set-up is identical to that used in the earlier study of the $2\omega_{pe}$ decay instability [3].

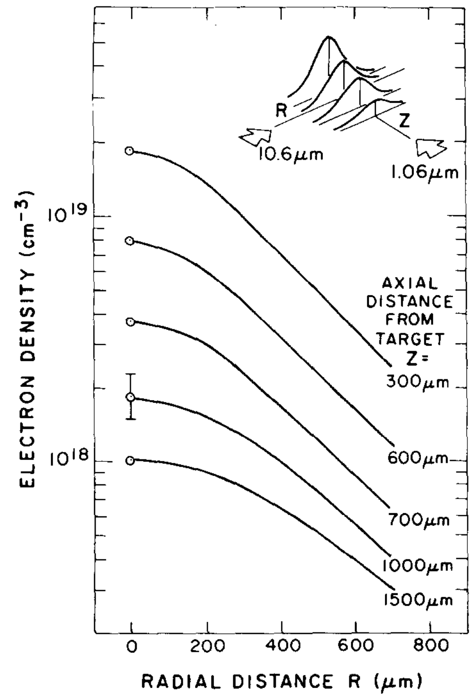

Fig. 1. Typical density profiles for different maximum electron densities along the CO_2 beam axis. R is the distance along the CO_2 axis and Z is the distance from the carbon target surface along the glass laser axis.

The plasma was produced by a 1.06 μm laser pulse (2–4 J in 20 ns) focussed on a solid carbon target to a 500 μm spot. The 10.6 μm laser pulses in the range 5–20 J were focussed with a 50 cm focal length NaCl lens to a half-energy spot of approximately 130 μm and a maximum intensity of approximately 5×10^{14} W cm^{-2}. The CO_2 beam was incident transverse to the glass laser beam permitting a choice of maximum electron densities along the path of the CO_2 beam from below $n_c/10$ to above n_c. Typical density profiles for different maximum electron densities along the CO_2 beam axis are shown in fig. 1. Here, the radial distance is the distance along the CO_2 axis and the axial distance is the distance from the carbon target surface along the glass laser axis. At the peak the 1.06 μm pulse the plasma had a scale length, $L = (n^{-1}\, dn/dx)^{-1}$, along the CO_2 axis of ≈300 μm at $n_c/4$. The temperature of the CO_2-heated plasma volume was estimated [4] to be ≈200 eV corresponding to $k_{epw}\lambda_D$ ≈0.02 at $n_c/10$. Absolute high-energy electron distributions were determined with two identical miniature 180° focussing electron spectrometers [5] in the energy range 35–450 keV. The measurements were made with the spectrometers at various angles with respect to the CO_2 beam but out of the plane of the E vector (s-polarization). This is because we expect enhanced Raman sidescatter in this plane and it also enables us to differentiate between Raman-heated electrons and those heated by the $2\omega_{pe}$ decay instability.

In fig. 2, typical hot electron distributions measured at 170° to the incident CO_2 beam in the forward direction are shown for several maximum electron densities. These distributions are well approximated by maxwellians with characteristic temperatures, T_H, of 12 keV at $n_c/10$, 14 keV at 0.17 n_c and 21 keV at $n_c/4$. Assuming that these electrons are produced by the SRS instability, a comparison of the measured temperatures can be made with simple theoretical estimates [6] of the temperature of the Raman-heated electrons given by $T_H \sim (m_e/2)\, V_\phi^2$, where $V_\phi = \omega_{epw}/k_{epw}$ is the phase velocity of the electron plasma wave. For a background temperature of 200 eV the agreement between experimentally measured T_H of 12 keV at $n_c/10$ and ≈11 keV for the Raman sidescatter given by the simple estimates is excellent. This is not too surprising

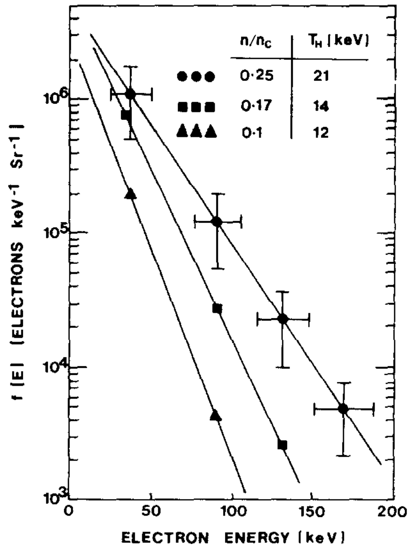

Fig. 2. Hot electron distributions measured at 170° to the incident CO_2 beam in the forward direction (along the incident k vector), for several maximum electron densities (n/n_c). T_H are the maxwellian temperatures of these distributions.

since the electron contribution from densities below $0.1\ n_c$ is not measured, since the kinetic energy of the electrons moving at the phase velocity of the electron plasma waves generated below $n_c/10$ is much less than the lowest energy channel of the electron spectrometer. For higher densities however, the measured temperatures are somewhat lower than those expected from Raman heating. This is to be expected since, as the maximum density is increased beyond $n_c/10$, the hot electrons originate from a range of densities. The observed hot electron distribution is thus a convolution of several distributions corresponding to different densities. Also for densities close to $n_c/4$, shortening of the density scale length [4] due to the ponderomotive force of the plasmons generated by $2\omega_{pe}$ decay instability may be having the effect of making the SRS instability less effective [7]. A crude deconvolution of the hot electron distribution for $n_c/4$ with the distribution at 0.17 n_c for instance shows typically an increase in T_H of about 50% (i.e. $\approx$30 keV) which is in good agreement with the kinetic energy of electrons moving at the phase velocity of the SRS-produced plasmons at 0.2 n_c, consistent with the above interpretation.

Within the range of intensities used in these studies (10^{14}–5×10^{14} W cm^{-2}) the temperature of the hot electrons below $n_c/4$ was found to be nearly independent of the incident intensity. This observation too is consistent with electron heating due to SRS since the phase velocity of the Raman-generated plasma waves depends mainly on the density and the background temperature of the plasma. The angular distribution of the hot electron emission below $n_c/4$ was found to be quite broad with significant hot electron emission in the backward direction. One possible explanation for the backward emission is that the multiple Raman scattering [8] is occurring in the plasma. A simple estimate of Raman reflectivity [6] using $L/\lambda \approx 60$ at $n_{max}/n_c \approx 0.2$ shows that for $v_0/c \approx 0.3$ (likely in the event of filamentation) the Raman-backscattered wave is above threshold for secondary SRS if the initial noise level is taken to be 10^{-5} of the incident. Another possibility is that the space charge potential set-up by the electrons escaping the plasma may be having the effect of scattering some forward emitted electrons in the backward direction. Unfortunately we do not have good statistics to plot the angular distribution of hot electrons below $n_c/4$. It should be noted, however, that the electron spectra measured at 170° and 135° with respect to the CO_2 beam at $n_c/10$ were very similar suggesting that the spectrum of the Raman-generated plasma waves is very broad and both Raman back- and sidescatter are operative. The present experiments were carried out at intensities well above the SRS, back- and sidescatter thresholds [9] of 7×10^{13} W cm^{-2} and 10^{13} W cm^{-2}, respectively.

We have benefited from our discussions with Drs. Kent Estabrook, A.B. Langdon, B. Lasinski, J.M. Kindel and F.F. Chen on many aspects of this work. This work was carried out when C. Joshi and N.A. Ebrahim were with the Division of Physics, National Research Council, Canada.

References

[1] C.S. Liu, M.N. Rosenbluth and R.B. White, Phys. Fluids 17 (1974) 121;
D. Biskamp and H. Welter, Phys. Rev. Lett. 34 (1975) 312;
D.W. Forslund, J.M. Kindel and E. Lindman, Phys. Fluids 18 (1975) 1002.

[2] W.L. Kruer, K. Estabrook, B.F. Lasinski and A.B. Langdon, Phys. Fluids 23 (1980) 7.

[3] N.A. Ebrahim, H. Baldis, C. Joshi and R. Benesch, Phys. Rev. Lett. 45 (1980) 1179.

[4] H.A. Baldis, J.C. Samson and P.B. Corkum, Phys. Rev. Lett. 41 (1978) 1719.

[5] N.A. Ebrahim and C. Joshi, Phys. Fluids 24 (1981) 138.

[6] K. Estabrook, W.L. Kruer and B.F. Lasinski, Phys. Rev. Lett. 45 (1980) 1399.

[7] A.B. Langdon, B.F. Lasinski and W.L. Kruer, Phys. Rev. Lett. 43 (1979) 133.

[8] K. Estabrook, private communication.

[9] C.S. Liu, Advances in plasma physics, Vol. 6, eds. A. Simon and W.B. Thomson (Wiley, New York, 1976) p. 176.