i.e., the pseudowave described by the relation $\omega/k \propto C_e^{2/3}(\omega z)^{1/3}$.[4,5] The dispersion curve in the figure is plotted at a fixed value of z. The corresponding experimental plots are qualitatively in accord with this free-streaming mode, which was easily excited by the mesh excitation, but could not be observed in the beam excitation.

Figure 3(b) shows that the direct coupling due to electrostatic induction is small for the beam excitation, in contrast with the large observed coupling for the mesh excitation. The small direct coupling for the beam excitation may be useful in many experiments.

The experimental result that the wave amplitude changes linearly with the modulation voltage of the beams is in accord with the theoretical results of Eq. (6), because n_b and S_b are considered to be proportional to the modulation voltage. Furthermore, the beam-excited waves which propagate nearly perpendicular to the beams can be also explained by the theoretical results of Eq. (6).

In conclusion, by injecting fast electron sheet beams into plasmas, the electron plasma wave is found to be excited nearly perpendicularly to the sheet beams. The amplitude and frequency of excited waves can be controlled by varying the modulation voltage and frequency of the beams. By comparing the beam-excited waves with the conventional mesh-excited waves, the beam excitation is found to excite the pure electron-plasma mode. That is, the free-streaming mode which is easily excited for the mesh excitation cannot be observed for the beam excitation. Furthermore, the direct coupling due to the electrostatic induction is found to be small for the beam excitation.

The beam excitation can be concluded to be a very useful means for the excitation of pure electron plasma waves.

The authors would like to express their thanks to Professor Y. Hatta for his encouragement in constructing the vacuum chamber at Tohoku University and to Professor T. Itoh, Professor S. Kojima, and Professor T. Morita for their aid in doing experiments at the Institute of Space and Aeronautical Science.

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CO_2-Laser–Beam Absorption by a Dense Plasma

E. Fabre and C. Stenz
Laboratoire de Physique des Milieux Ionisés, Ecole Polytechnique, Paris, France*
(Received 23 April 1973)

We study the absorption of a CO_2-laser beam by an independently produced plasma at approximately the critical density. The measured fractional absorption coefficient agrees with that associated with inverse bremsstrahlung for incident laser intensities below 10^{10} W/cm^2. Above this value, an abrupt increase in absorption is observed.

Plasma production and heating by high-power lasers has been the subject of numerous theoretical and experimental studies for several years. Recently, however, this field of research has acquired a new dimension as a result of the proposal for using laser-imploded DT pellets to demonstrate the feasibility of controlled thermonuclear fusion.[1] One of the main problems to be solved in this context is the coupling of laser energy to the plasma. Indeed, at high incident intensities the temperatures obtained are too high for classical collisional absorption (i.e., inverse bremsstrahlung) to be efficient. Anomalous collisionless mechanisms must then take over the absorption. These mechanisms, generally involving parametric instabilities, have been the subject of several theoretical papers.[2] However, no direct evidence of anomalous absorption in laser-produced–plasma experiments has been reported up to now.[3] One of the possible reasons for this is that in the experiments reported, production and heating of the plasma are performed by the same laser, thus complicating the situation. For example, the presence of large density gradients would result in a considerable increase in the instability thresholds. For a clear interpretation of the experimental results, one would like to have an independently produced plasma as a target for the laser beam. However, anomalous absorption takes place near the critical density n_c, where plasma frequency equals laser frequency. For a CO_2 laser this corresponds to $n_c \sim 10^{19}$ electrons/cm^3 and such plasmas are not easily obtained.

We would like to report in this Letter an experiment in which this problem has been solved,[4] and present what we believe to be the first evidence of anomalous absorption, although the experiment does not allow us to point to the precise nature of the mechanism.

Figure 1 shows the experimental setup. A target plasma is obtained by confining in a spatially uniform magnetic field a dense plasma, which has been created by focusing the output of a 250-MW ruby laser onto a polyethylene foil. The magnitude of the magnetic field is 65 kg and its direction is perpendicular to the foil.[5] This gives good confinement in the directions perpendicular to $\vec{B}$, resulting in a cylindrically shaped target plasma of approximately 2 mm diam. The length of this cylinder increases almost linearly with time as a result of the plasma expansion along the field lines with a front velocity of $\sim 1.5\times10^7$ cm/sec. This target plasma is irradiated transversely by a CO_2-laser beam focused with a 75-mm NaCl lens. The resulting focal spot is $\sim 3.5 \times 10^{-2}$ cm and is located 5 mm from the polyethylene foil. The CO_2 laser used, a Lumonics 103 transverse-excitation atmospheric laser, has a peak power of 40 MW in a pulse with an 80-nsec half-width, thus resulting in power densities incident on the plasma up to 4×10^{10} W/cm^2. The CO_2 laser is delayed by 70 ± 20 nsec with respect to the ruby laser. The incident and transmitted portions of the CO_2-laser beam are monitored by photon-drag detectors.

The electron density of the target plasma was obtained by time-resolved Mach-Zehnder interferometry. Figure 2 shows the radial electron density distribution in the plasma, obtained by Abel inversion at the position where the CO_2 laser is focused. The maximum electron density, on the axis of the plasma, is $(9\pm1)\times10^{18}$ electrons/cm^3, slightly below the critical density at 10.6 μm. The density variation during the interaction time with the CO_2 laser is estimated to be of the order of 5%. This variation is due only to plasma expansion along the field lines, no significant diffusion across the field being observed. The initial electron temperature of the target plasma was estimated from the intensity ratio of two carbon lines, C III at 4070 Å and C IV at 4658 Å. The value of T_e, obtained assuming local thermodynamic equilibrium, is 9 ± 2 eV. It must be noted that this is a spatially averaged value, since the spectroscopic setup does not allow spatial resolution. However, this value is in agreement with the one which is obtained by considering that there is equilibrium between magnetic and plasma kinetic pressure.

Figure 3 shows an example of the experimental

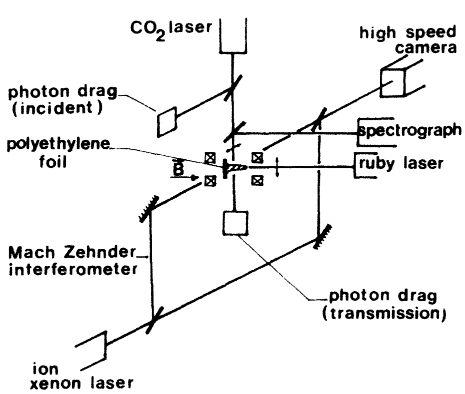

FIG. 1. Experimental setup.

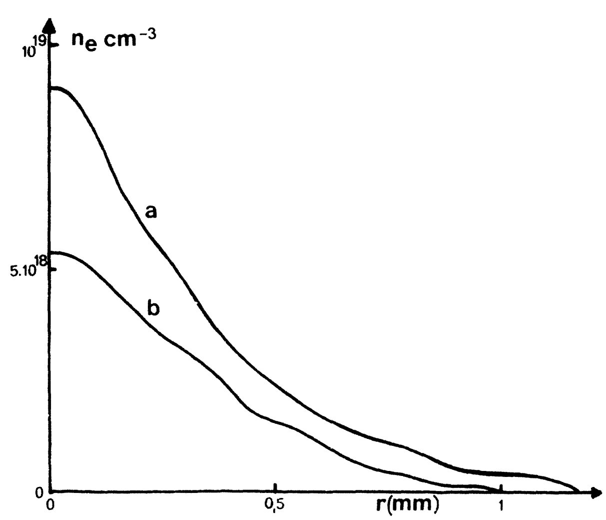

FIG. 2. Electron density in the target plasma 70 nsec (curve a) and 120 nsec (curve b) after plasma production.

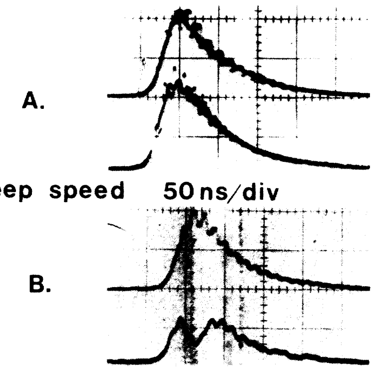

FIG. 3. Oscillograms showing the shape of the incident (upper trace) and the transmitted (lower trace) CO_2-laser pulses: (a) no plasma for calibration, (b) absorption observed when the target plasma is present.

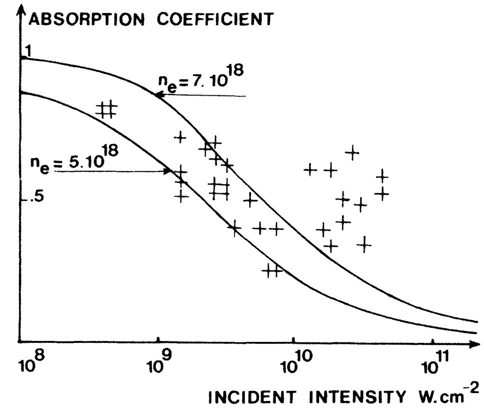

FIG. 4. Comparison between the measured fractional absorption coefficients of the plasma (crosses) and the computed values (solid curves).

results. Significant absorption of the CO_2-laser beam is observed. The time duration of the beam attenuation is from 50 to 100 nsec and corresponds to the lifetime of the target plasma in the CO_2-laser focal region. From these results the maximum fractional absorption has been deduced and is shown in Fig. 4. It varies from 0.85 to 0.2 depending upon the laser intensity in the focal spot. The lines refer to calculations performed assuming classical absorption (see below). It will be seen that the results follow closely the theoretical predictions up to approximately 10^{10} W/cm^2, where an abrupt increase of absorption is observed. It should be mentioned at this point that the spectroscopic measurements gave no definite evidence of plasma heating. However, this is not surprising, since no spatial resolution is available. Moreover, it is possible that local thermodynamic equilibrium is no longer valid under CO_2-laser irradiation, because of the short heating time of 2 to 4 nsec, corresponding to the transit time of plasma particles in the focal spot. As a result of this, thermalization and ionization equilibrium would occur some time after heating and then modification of the spectral emission would be observed only downstream, away from the focal region of the CO_2 laser.

We have analyzed the two most likely effects which could intervene in the beam attenuation as follows:

(a) Beam deflection by the plasma causing the transmitted laser pulse to miss the detector. We have computed the magnitude of this effect taking into account the beam propagation in the plasma density gradient. The maximum beam deflection, which occurs near the boundary of the plasma, is less than 25°. This is considerably less than the aperture of the observation system, which is 40°, half-angle, and we can then confidently conclude that this effect cannot explain the results.

(b) Classical absorption of light by the plasma. The model for the calculation of the absorption coefficient is based upon the following assumptions. Absorption is due to inverse bremsstrahlung and takes place only during the transit time of particles through the focal spot of the CO_2-laser beam. The calculation is self-consistent, in the sense that it takes into account the heating and consequent temperature increase during the absorption. We assume that there is no significant variation of the electron density during the plasma interaction with the CO_2-laser beam due to plasma expansion or additional ionization. It can be easily shown that, if complete ionization of carbon occurs during the interaction, the electron density increases by a factor of 1.33. However, this is an upper value, since the increase in temperature will result in some additional lateral expansion against the magnetic field, thus decreasing the density. We think, therefore, that the assumption of a constant density is justified. However, even the maximum possible increase in density would not explain the experimental results. The initial temperature of the plasma is assumed to be 10 eV, and we have used the experimental density profile in the calculations. The two curves in Fig. 4, calculated for two different values of maximum electron density, serve as good lower and upper limits for the experimental results up to 10^{10} W/cm^2. The fact that the values of n_e used are less than the maximum electron density measured on the axis is not surprising, in view of the difficulty of knowing with good precision the interaction region in the plasma, and also because of the density variation over the focal-spot dimensions. Notwithstanding, there is good agreement between theory and experiment, which is an *a posteriori* confirmation of the validity of the model used.

However, for incident intensities higher than 10^{10} W/cm^2 the absorption coefficient is much larger than the predicted one. As already discussed, no classical mechanism can explain this increase. We think that this is the first evidence of anomalous absorption in laser-irradiated plasmas. Unfortunately, our measurements cannot elucidate the precise nature of the mechanism responsible for the experimental results. Still, the threshold for parametric decay instability, calculated from Nishikawa's theory[6] for our experimental conditions, is of the order of 10^{10} W/cm^2, in good agreement with the intensity value at which the abrupt increase in absorption is observed. Obviously the scatter of data can be due to nonreproducible experimental conditions.

In conclusion, we have observed the absorption of a CO_2-laser beam by a plasma near the critical density. For light intensities less than 10^{10} W/cm^2 the beam attenuation is in agreement with calculations based upon inverse-bremsstrahlung absorption. At intensities higher than this value a large increase in absorption is observed, in agreement with what is expected from the onset of the parametric decay instability.

We thank J. Virmont for his help in computation, B. Thuilier for his valuable technical assistance, and C. de Michelis for his help in setting up the final version of this manuscript.

*Equipe de Recherche associée au Centre National de la Recherche Scientifique.

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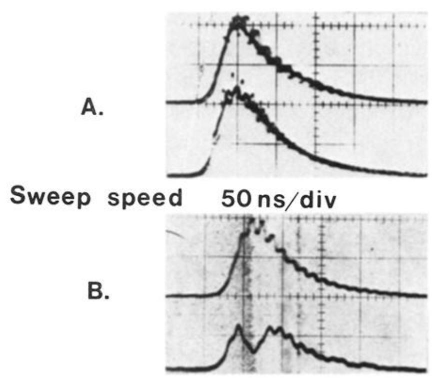
Two-Dimensional Rotons*

Timothy C. Padmore
Department of Physics, Erindale College, University of Toronto, Mississauga, Ontario, Canada
(Received 21 November 1973)

A Monte Carlo calculation of the Feynman-Cohen excitation spectrum is performed for helium confined to two dimensions. No approximations are used. Results for several different areal densities are compared with an exactly similar calculation in three dimensions. Among other results the roton gap is found to be significantly *lower* at corresponding densities in two dimensions, much smaller than previous estimates, and in substantial agreement with experiment.

The careful and ingenious variational calculation by Feynman and Cohen[1] of the excitation spectrum of He II gave the first detailed insight into the structure of the roton, and the idea naturally arises to apply the same methods to other geometries such as films and pores which are the subject of keen current interest.

As a first step I have calculated the Feynman-Cohen (FC) spectrum for helium confined to two dimensions. This is a sensible approximation for submonolayer films because the substrate binding energies far exceed the kinetic and interaction energy per particle. Thus, despite the cost in zero-point energy, the configurations of the atoms will be essentially two-dimensional. One has, of course, to ignore substrate structure which can be very important especially at densities which allow registry with the substrate.



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