can be significantly (12%) below the diamagnetically depressed ion-cyclotron frequency. Magnetic-fluctuation probes show that the mode is nearly left-circularly polarized. These characteristics are all consistent with an Alfvén-like wave generated by the AIC instability. Small m and left-circular polarization are inconsistent with the properties of the DCLC mode.

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Effect of Laser Wavelength and Pulse Duration on Laser-Light Absorption and Back Reflection

C. Garban-Labaune, E. Fabre, C. E. Max,[a] R. Fabbro, F. Amiranoff, J. Virmont, M. Weinfeld, and A. Michard

Equipe du GRECO Interaction Laser-Matière, Laboratoire de Physique des Milieux Ionisés, Groupe de Recherche du Centre National de la Recherche Scientifique, Ecole Polytechnique, F-91128 Palaiseau, France

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Absorption efficiency has been measured in laser-irradiated plane-target experiments with various laser wavelengths (1.06, 0.53, and 0.26 μm), pulse durations (100 ps, 2 ns), and intensities (10^{10}–2×10^{15} W/cm). Results show a strong increase of absorption for long pulses, low intensities, and short wavelengths which favor inverse bremsstrahlung absorption. A one-dimensional Lagrangian hydrocode (FILM) is used to interpret these results.

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High-gain targets for laser fusion applications require favorable performance in two areas of laser-plasma interaction physics: first, obtaining the highest absorption rate, and second, minimizing the generation of suprathermal electrons, especially considering their energy distribution which determines their ability to cause damaging preheat. Both of these areas are predicted to be sensitive to characteristics of the incident laser pulse; we present here experimental results on the influence of wavelength, pulse duration, and laser intensity on absorption efficiency which give experimental evidence that use of short laser wavelength permits larger absorption efficiency by inverse bremsstrahlung.

For this purpose we have used a neodymium-glass laser; using potassium dihydrogen phosphate (KDP) crystals, we can double the frequency with more than 50% efficiency in energy conversion, and quadrupole it with 20% efficiency relative to the fundamental.[1] The available laser energies are 25 J in 100 ps or 100 J in 2.5 ns at 1.06 μm, 12 J in 80 ps or 32 J in 2 ns at 0.53 μm, and 2.5 J in 60 ps or 4.5 J in 170 ns at 0.26 μm.

We have irradiated plane terphane foils, under normal incidence, using a large-aperture ($f/1.3$) focusing lens, in order to be as close as possible to spherical-target experimental conditions. The focal spot diameter was kept constant, and determined by measurement of light transmission through variable-diameter pinholes. It was found to be 50-μm full width at half maximum (FWHM). In all the experiments the best focusing position was used, and was determined as the position giving the highest x-ray emission from the plasma, and by careful study of the impacts on burn-paper. We found that the absorption was very reproducible, as long as the target was within ± 75 μm of the position of the best focus. The diameter of the x-ray pinhole pictures of the target at 1–2 keV was typically 50 μm at best focus.

The main diagnostic was the total-absorption measurement, evaluated by separately measuring the energy reflected back into the focusing lens (including specular reflection and back-reflection) and the energy which is refracted, reflected, or scattered in the remainder of the space not subtended by the lens. For the latter we used an Ulbricht sphere, developed in Garching.[2,3]

Figure 1 shows the variation of total absorption with incident flux, for three wavelengths of the neodymium laser (1.06, 0.53, and 0.26 μm) using short and long pulses. Data collected with a CO_2 laser (10.6 μm), under different conditions (very long focal distance) are also represented for comparison.[4]

The main results are the following: absorption decreases when the laser intensity increases, absorption increases when the pulse duration increases, and absorption increases when the wavelength is decreased.

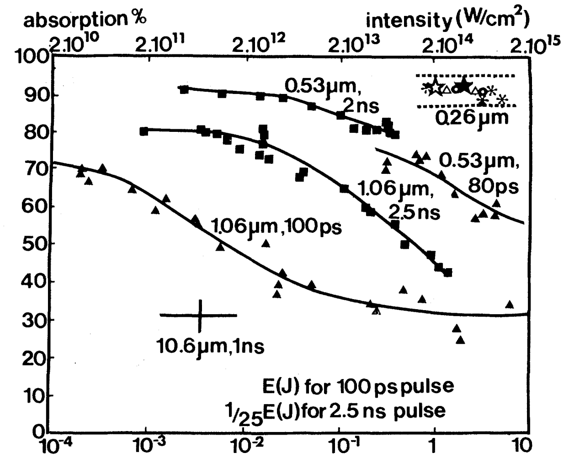

FIG. 1. Fractional absorption of laser light vs incident flux for various experimental conditions: Short and long laser pulses at 1.06 and 0.53 μm on plane $C_{10}H_8O_4$ targets. Typical error bars are represented by dashed lines at 0.26 μm (open star $C_{10}H_8O_4$, 60 ps; closed star Au, 60 ps; asterisks $C_{10}H_8O_4$, 170 ps; open triangles Al, 170 ps; open circles Au, 170 ps).

We first consider the 1.06-μm results: Absorption decreases with increasing flux in the range 10^{11} to 10^{13} W/cm^2, and then stays at a steady level of 30% from 10^{13} to 2×10^{15} W/cm^2. The detailed optical energy balance shows that backscatter is nearly constant at ~22%, when the incident flux varies by more than four orders of magnitude ($2\times10^{10} < I_L < 2\times10^{15}$ W/cm^2). Since we are at normal incidence, this value includes specular reflection and stimulated Brillouin backscattering. We deduce that the Brillouin effect is very weak under these conditions and is probably saturated at a level below 2%. This can be explained by the very steep density gradient due to short pulse illumination.

At low fluxes ($\leq 10^{13}$ W/cm^2) the main absorption mechanism is inverse bremsstrahlung, which decreases when the incident flux is increased because of the increased electron temperature and density gradient steepening. For fluxes between 10^{13} and 2×10^{15} W/cm^2 collisional absorption is weak, and the almost constant absorption level (~30%) is probably due to resonance absorption in a steepened density profile, including possibly ripples and magnetic fields at the critical surface.[5] This result is very similar to absorption measured with high-intensity CO_2 lasers.[4-6]

However, the main result from this experiment is the very important increase in absorption rate,

A, as wavelength is decreased. We have obtained, with short pulses and at 4×10^{14} W/cm^2, absorptions of $(30\pm5)\%$, $(60\pm5)\%$, and $(90\pm5)\%$ at wavelengths of 1.06, 0.53, and 0.26 μm, respectively. These variations can be explained by the increase of inverse bremsstrahlung efficiency with short wavelength, first because the laser light penetrates to higher densities where the plasma is more collisional; and, second, because radiation pressure and flux limitation which produce steepening of the density gradient and which can make the corona hotter must occur at higher fluxes.

The variation of absorption with incident flux at 0.53 μm may be explained, as at 1.06 μm, by a decrease of collisional absorption at high fluxes, mainly caused by a higher electron temperature. In all cases, the backscattering light stays very low ($\leq10\%$) at 0.53 μm.

At 0.26 μm, the losses are shared equally between backscattering and reflection in the sphere, 3 to 5% each. When we used targets made of plastic, aluminum, copper, and gold, the same absorption $[(90\pm5)\%]$ was observed, which confirms the presence of inverse bremsstrahlung at a completely saturated level.

At low flux, the increase of absorption for longer laser pulses (at the same flux) is caused by a better inverse bremsstrahlung efficiency in a longer density gradient.

At high fluxes, for 1.06 μm ($>10^{14}$ W/cm^2), the decrease of absorption with intensity is not only associated with lower inverse bremsstrahlung, but is also and mainly due to increased stimulated Brillouin backscatter. As shown in Fig. 2 for $I_L>10^{14}$ W/cm^2, the energy backscattered in the focusing optics increases very rapidly with the flux, and reaches a level greater than the refraction losses. These results show that the Brillouin backscatter instability may be important in the long-pulse regime at 1.06 μm for high fluxes, and may lead to severely decreased absorption.

This effect is less important at 0.53 μm, where probably our experimental fluxes stay below the threshold of Brillouin backscatter. Thus we confirm the theoretical prediction that Brillouin scatter decreases at short laser wavelengths.[7]

To analyze the short-pulse absorption data, we use a computer hydrodynamics code FILM developed by Virmont *et al.*[8] FILM is a Lagrangian one-dimensional hydrodynamics code. It was used here in planar geometry with a fully ionized, perfect-gas equation of state. The targets were thick plastic ($C_{10}H_8O_4$) foils and inverse-

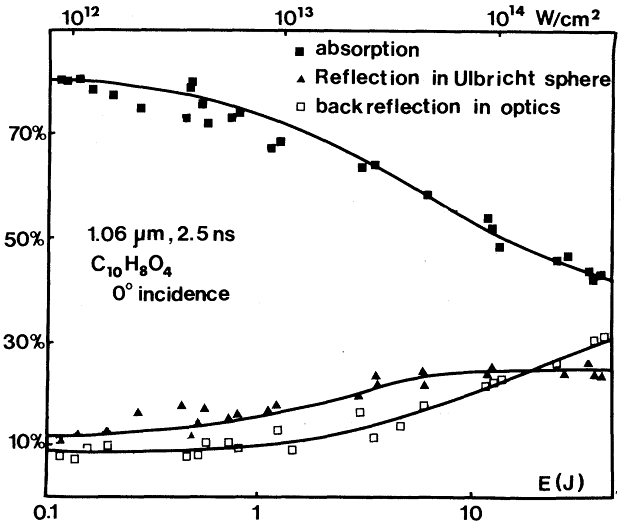

FIG. 2. Detailed optical energy balance at 1.06 μm for the long-pulse regime.

bremsstrahlung absorption[9] was calculated with a mean ion charge defined by $Z_{ib}=\langle Z^2\rangle/\langle Z\rangle=6.2$, where as for the hydrodynamic case $\langle Z\rangle=4.6$. To simulate resonance absorption 20% of the laser energy reaching critical density was put into a hot-electron distribution. The hot-electron temperature T_H was chosen to reproduce the slope of the hard x-ray spectrum.[10] Stimulated Brillouin scattering was not included in the energy balance.

There is a free parameter which is the flux limit applied to thermal electron heat transport. The conductive heat flux was taken to be the minimum of $-K\nabla T$ and $0.6\,f\,n_e m_e(T_e/m_e)^{3/2}$, where K is the classical conductivity,[11] and T_e, m_e, and n_e are the electron temperature, mass, and density. The flux limit f is a phenomenological parametrization of physical processes which may inhibit electron heat flux in laser-produced plasmas.[12]

The experiments carried out at different wavelengths seem to be correctly described by numerical simulations with the following hypothesis: absorption due to inverse bremsstrahlung, ~20% resonance absorption at the critical layer, and noninhibited axial heat transport. This model reproduces experimental variations of absorption with the incident flux and the laser wavelength. Peculiarly the increase of absorption with short wavelengths quantitatively corresponds to the increase of inverse bremsstrahlung efficiency.

If one instead hypothesizes that axial heat transport is inhibited at the value $f=0.05$, as shown by transport experiments,[13] absorption is too small by about 25% for 0.53 and 0.26 μm. The decreased absorption at smaller values of f is due to less efficient inverse bremsstrahlung, since the coronal temperature is increased and the density profile is steepened near the critical density. Then there are two possible ways to account for our absorption data: (1) One can postulate the existence of an additional absorption mechanism such as ion-acoustic turbulence[14] which absorbs an extra 25% of the incident energy. (2) One can explore the hypothesis that some of the absorbed energy is transported laterally out of the laser spot, thus cooling the corona and making efficient inverse bremsstrahlung possible. We suggest that the latter hypothesis deserves further experimental and theoretical attention.

Another point to discuss is the extrapolation of those experiments to larger targets as one expects to use for high-energy fusion experiments. In this case the axial density scale length will be obviously much larger than in our experiments. This will result certainly in very efficient inverse bremsstrahlung even below critical density for short laser wavelength, reducing again the effect of resonance absorption and fast-electron generation by this mechanism. However we probably should be more careful at high intensities with the possibility of occurrence of instabilities such as stimulated Brillouin or Raman scattering and two-plasmon decay, which will need further investigation with larger lasers.

In summary, our experiments have shown that very high absorption rates can be attained at short laser wavelengths. Moreover, because absorption occurs in the subcritical plasma, the influence of mechanisms occurring at the critical layer and generating suprathermal electrons is reduced. This represents the second interest of short wavelengths for which there is a noticeable decrease in hot-electron generation. Detailed observation of the hot-electron temperature deduced from hard x rays will be reported in a separate paper.[10]

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[a]Permanent address: Lawrence Livermore National Laboratory, Livermore, Cal. 94550.

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