Eur. Phys. J. AP **3**, 215–218 (1998)

THE EUROPEAN
PHYSICAL JOURNAL
APPLIED PHYSICS

Experimental study of the transmission of breakdown plasma generated during laser shock processing

L. Berthe[a], R. Fabbro[b], P. Peyre, and E. Bartnicki

Centre Laser Franco-Allemand (CLFA), Laboratoire pour l'Application des Lasers de Puissance (LALP),
16 bis, avenue Prieur de la Côte d'Or, 94114 Arcueil Cedex, France

Received: 6 January 1998 / Revised: 16 April 1998 / Accepted: 30 April 1998

Abstract. Shock wave generation from laser-produced plasma in water confinement regime for an incident 25–30 ns / 40 J / $\lambda = 1.064$ μm laser beam has been studied. Transmitivity measurement of the parasitic plasma breakdown at the surface of water confinement has been performed with a continuous laser probe. Above 6 GW/cm^2 incident laser intensity, the critical electronic density for the laser wavelength is achieved inside the plasma by cascade ionization during the pulse duration. Above 10 GW/cm^2, peak power density transmitted through the plasma saturates. The laser pulse transmitted through the breakdown plasma corresponds to the part of incident laser pulse preceding the transmission cut-off.

PACS. 52.50.Jm Plasma production and heating by laser beams – 62.50.+p High-pressure and shock-wave effects in solids and liquids

1 Introduction

The generation of shock wave from laser-produced plasma in confined regime with water consists in irradiating with high intensity (> 1 GW/cm^2, 10–30 ns pulse duration) pulsed laser, a solid target covered with few millimeters of water. The laser energy is absorbed inside a thin layer at the water-solid target interface and a high pressure plasma is generated. This shock wave is transmitted to the target and its amplitude is high enough to plastify high strength materials [1–3].

These shock waves have been recently studied with a Doppler Velocimeter device in our laboratory [4]. This work shows that above 10 GW/cm^2, peak pressure is saturated and pressure duration is reduced. A plasma breakdown occurring only at the surface of the confining water was supposed to absorb the incident laser energy and to limit the power density reaching the target as the incident power density increases, while the laser pulse duration transmitted to the target is reduced. We report in this article, new investigations on the effect of this plasma which confirm the previous interpretations of reference [4].

2 Experimental set-up

These new experiments consist in measuring, with a laser probe beam, the transmission of the plasma induced at the surface of the water. For these experiments, the high power

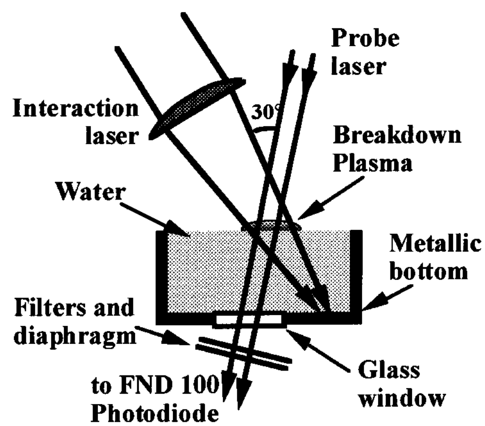

Fig. 1. Experimental set-up for transmission measurements.

Neodymium-glass laser of the CLFA laboratory operating at 1.064 mm wavelength was used. This laser delivers Gaussian pulses of 25–30 ns full width at half maximum (FWHM). The laser output energy is typically 40 J and a 600 mm focal lens allows 3–5 mm diameter spots giving power densities in the 0–25 GW/cm^2 range. The probe is a continuous Argon laser operating at 0.514 μm wavelength and delivering 1.5 W in monomode configuration.

Figure 1 shows the schematic diagram of the experimental set-up. The parallel laser beam probes the interaction spot at the water surface in a direction very close to its perpendicular in order to reduce refraction effects. The two laser beam make a 30 degrees angle so that the probe beam goes across the cell through a glass window

[a] e-mail: berthe@etca.fr
[b] e-mail: fabbro@etca.fr

and the laser interaction beam focuses on the metallic bottom part of the cell. This transmission measurement cannot be disturbed by possible secondary breakdown occurring in water volume along the probe beam and the detection system is protected against the high power interaction beam. The probe laser is selected by a diaphragm and filtered by three interferential filters at 0.514 μm after the glass window. This optical combination is necessary to distinguish laser probe beam from visible plasma emission and from laser interaction diffusion. The laser probe light is collected by FND100 photodiode (with a 1.5 ns rise-time) whose electrical signal is measured by a oscilloscope (Hewlett Packard 54552A). The incident laser interaction pulse is measured at the output of laser chain with a fast photodiode (Hamamatsu R1193U) and synchronized with the laser probe signal. So, the laser probe transmission can be determined as a function of time during the laser interaction pulse. The wavelength of the probe beam (0.514 μm) has been deliberately choosen different from the main laser one (1.06 μm), in order facilitate the transmission measurements due to an easier shielding from stray rays of the main beam. Therefore, it is obvious that the derived plasma transmitivity of the main beam is overestimated for these conditions. However, when a very sharp cut-off transmission occurs (above 6 GW/cm^2, see next paragraph), which lasts typically a few nanoseconds, this difference is not significant because we want mainly determine here a cut-off time t_0. On the other hand, when the transmitivity decreases slowly (for incident intensities lower than 6 GW/cm^2, see next paragraph) this transmission measurement is of course overestimated and has therefore only to be used as an indicative one.

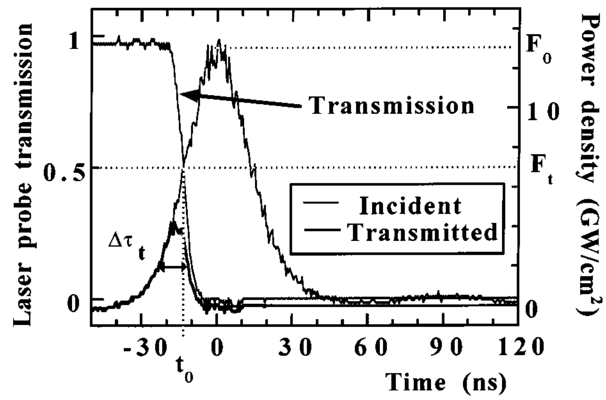

Fig. 2. Results of transmission measurement at 13.5 GW/cm^2: laser probe transmission, incident laser interaction pulse and laser pulse transmitted by the breakdown plasma. Time t_0 corresponds to laser transmission equal to 0.5. F_t is the transmitted peak power density equal to the power density of the incident laser at time t_0 if $t_0 < 0$, or the peak power density of incident if $t_0 > 0$. $\Delta\tau_t$ is the FWHM of the transmitted laser pulse calculated as the product of laser probe transmission with incident laser pulse.

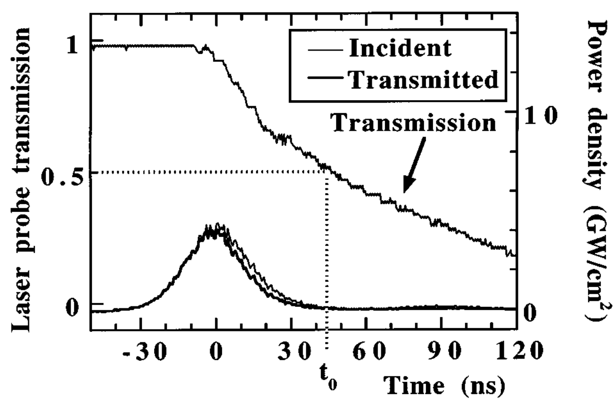

Fig. 3. Same results as in Figure 2 but at 3.5 GW/cm^2.

3 Results and discussion

Figures 2 and 3 show typical transmission measurements. Laser probe signal has been normalized and the incident peak power density is defined as $F_0 = E/(S\,\Delta\tau)$, where E is laser energy, S laser spot surface on the water and $\Delta\tau$ laser FWHM. Zero delay time corresponds to the peak of incident laser pulse. From these data, one can determine: (1) The time t_0 defined when the probe transmission is equal to 0.5; (2) the transmitted peak power density (F_t) as the incident one if $t_0 > 0$ and the power density of incident laser at the time t_0 if $t_0 < 0$; (3) the transmitted laser pulse as the product of laser probe transmission with incident laser interaction pulse. The FWHM of the transmitted pulse can then be estimated and will be defined as $\Delta\tau_t$.

When a high power irradiates a non-absorbing dielectric as water, the fast growth of free electrons by Avalanche Collision Ionization (ACI) (process involving free electrons, neutral or ionized atoms and electrical field of the laser beam *via* absorption by Inverse Bremsstrahlung (IB)) is the main physical mechanism occurring [5]. ACI can be initiated with first free electrons produced either by multiphotoionization absorption process or thermoelectric emission of impurities at the water surface [5]. The electronic density increases by ACI with time and the incoming laser beam is absorbed by IB as this breakdown plasma propagates [6]. This laser absorption is evidenced in Figures 2 and 3 by a transmission decrease which is sharper at 13.5 GW/cm^2 than at 3.5 GW/cm^2 laser intensity.

The cut-off of probe beam observed at 13.5 GW/cm^2 (Fig. 2) implies that the critical electron density for the main beam is reached in the plasma because its critical density (10^{21} cm^{-3}) is 4 times smaller than the critical density at the probe beam wavelength. These electronic densities can be easily obtained, with a water density of 6×10^{22} atoms cm^{-3} and considering a very low plasma ionization degree of about 0.1. These hypothesis and experimental results agree with those obtained in reference [4]. In this article, the vizualisation by a fast camera shows that the plasma at the surface of the solid target is no more sustained when a strong breakdown plasma develops at the water surface. This cut-off is not achieved during the laser pulse at 3.5 GW/cm^2 (Fig. 3) because the laser intensity is not high enough to produce a critical density corresponding to the probe beam wavelength by ACI. This can be obtained only for incident intensities greater than 6 ± 1 GW/cm^2 for our experimental configuration. As the wavelengths of the main and probe beam are different, one can only consider that we have derived here an upper limit for the intensity threshold of the main beam. In this range of laser intensity, one can also see in Figure 3 that the transmission continue to decrease though the laser pulse is no more delivering energy. This effect could result of the thermal energy stored in the water at its surface, which is then partly redelivered during its cooling, to the local air which can be easily heated due to its comparatively very low heat capacity and therefore can be ionized on a greater duration than the laser pulse. This inertial thermal effect cannot be observed at higher irradiance because the breakdown at the water surface decouples very rapidly the laser from the water surface and the air is then strongly and rapidly heated during the laser pulse.

The transmission decrease occurs during the falling part of laser interaction pulse at 3.5 GW/cm^2 ($t_0 = 46$ ns) and during its rising part at 13.5 GW/cm^2 ($t_0 = -14$ ns). The transmitted power density (F_t) is then equal to the incident peak intensity of interaction pulse at 3.5 GW/cm^2, but is smaller at 13.5 GW/cm^2 (F_t = 8 GW/cm^2). We have reported the transmitted power density (Ft) as a function of incident power density F_0 in Figure 4. The experimental curve can be separated in two parts. In the range 0−10 GW/cm^2, the incident peak power density is fully transmitted by the breakdown plasma because the transmission decrease occurs in the falling part of laser interaction pulse ($t_0 > 0$). Above 10 GW/cm^2, F_t saturates and scatters around 10 ± 2 GW/cm^2. The measurements are not very accurate for power densities higher than 15 GW/cm^2 because the transmission cut-off occurs in the very early times of the laser pulse. The threshold of 10 ± 2 GW/cm^2 corresponds to the laser power density for which the cut-off appears at the peak of main pulse ($t_0 = 0 \pm 2$ ns). So, the maximum power density transmitted by the water surface plasma is about 10 GW/cm^2. These results confirm nicely those obtained in reference [4]. In these experiments, the peak pressure levels induced at the surface of the solid target in confined regime are also scattered and limited at 5 GPa, above the 10 GW/cm^2 power density (see Fig. 4).

As the power density increases, the transmitted laser pulse duration is also reduced because the transmission cut-off occurs earlier. The FWHM of the transmitted laser pulse $\Delta\tau_t$ is about 22 ns at 3.5 GW/cm^2 and 14 ns at 13.5 GW/cm^2 (see Fig. 2). We have reported in Fig. 5 the FWHM $\Delta\tau_t$ as a function of incident power density. We have also presented, in this figure, the corresponding effective laser pulse durations that would reproduce, using numerical simulations of shock wave propagation, the experimental induced pressure duration at the solid surface. This method has been described in details in reference [4]. The FWHM transmitted laser pulse measured from transmission experiments strongly decreases above

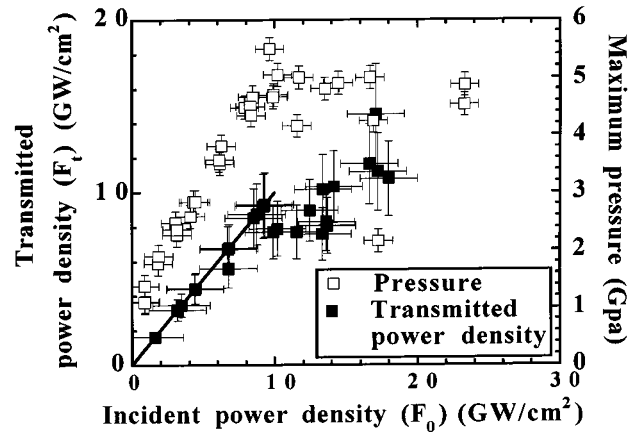

Fig. 4. Peak pressure measurements from reference [4], and transmitted power density F_t as a function of incident power density F_0.

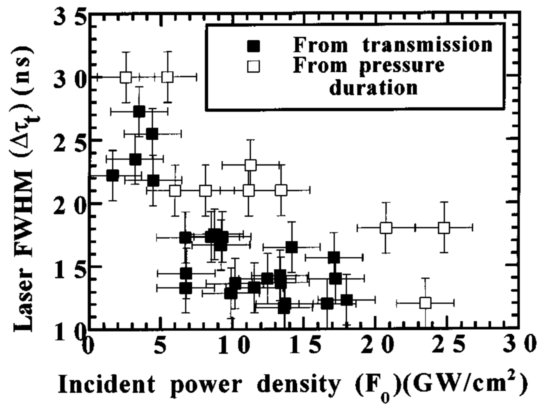

Fig. 5. Transmitted FWHM laser pulse ($\Delta\tau_t$) as a function of incident power density from transmission experiments and determined from the pressure duration measurements (from Ref. [4]).

5–6 GW/cm^2 for increasing incident power density. In the 0–5 GW/cm^2 range, $\Delta\tau_t$ is equal to 25 ± 2 ns whereas it decreases to $\Delta\tau_t = 15 \pm 3$ ns above 6 GW/cm^2. So, This experiment shows that the breakdown plasma at the surface of water transmits a shortened laser pulse when transmission cut-off occurs. For the 0–5 GW/cm^2 power density range, the incident laser pulse does not seem to be very affected by the plasma whose electronic density is rather low (but one must recall that for this intensity range, the rather large uncertainties on the transmission measurements, due to the difference of wavelength between the probe and main beam). Above 6 GW/cm^2, electronic density reaches the critical density and the transmitted laser pulse is then the part of incident laser pulse preceding the transmission cut-off. For the transmitted laser FWHM pulse determined from pressure duration measurements, the behaviour is similar: $\Delta\tau_t$ is equal to 30 ± 2 ns for the 1–6 GW/cm^2 range and decreases to 22 ± 2 ns and 15 ± 2 ns at respectively 10 and 22 GW/cm^2. The agreement is rather satisfactory if one considers the strong difference of the two methods of $\Delta\tau_t$ determination. However, being more direct, the transmission measurements used here are much more sensitive than those using the simulations. Moreover, the pressure duration can be perturbed by the cooling phase of these confined plasma, which is 2-3 times longer than the pulse duration [7]. Nevertheless, the two methods show that the plasma at the water surface absorbs the incident laser pulse and the solid target is then irradiated by a narrower laser pulse. As this parameter defines the thickness of the affected depth during the shock wave propagation, it is important to define it precisely for laser shock processing applications.

4 Conclusion

In conclusion, we have determined the transmission of the breakdown plasma at the surface at the water with a laser probe beam. Above 5–6 GW/cm^2, the critical density at the laser interaction wavelength is achieved during the pulse duration, inside the breakdown plasma by ACI phenomena. Above 10 GW/cm^2, the power density transmitted by the plasma is limited to 10 GW/cm^2 in agreement with saturation threshold previously estimated from pressure measurements. The laser pulse transmitted by the plasma corresponds approximately to the part of the incident laser pulse preceding the transmission cut-off. Therefore, both pressure and transmission measurements allow to explain the current limit of shock wave generation by laser-produced plasma in confined regime. The experimental methodology developed here will be applied to the analysis of the effect of laser pulse duration and wavelength.

This work is a part of a program which has been supported by the CEA (Ministry of Industry), CNRS (Ministry of Education and Research) and the DGA (Ministry of Defense).

References

1. P. Peyre, R. Fabbro, L. Berthe, C. Dubouchet, J. Laser Applications **8**, n° 3 (June 1996).
2. P. Peyre, R. Fabbro, P. Merrien, H.P. Lieurade, Mater. Sci. Engin. A **210**, 102–113 (1996).
3. P. Peyre, R. Fabbro, Opt. Quant. Electron. **27**, 1213–1229 (1995).
4. L. Berthe, R. Fabbro, P. Peyre, L. Tollier, E. Bartnicki, J. Appl. Phys. **82**, 2826–2832 (1997).
5. L.J. Radziemski, D.A. Cremers, in *Laser-induced plasma and applications*, edition Marcel Dekker (INC, N.Y., 1989).
6. Y.P. Raizer, Soviet Physics JETP **21**, n° 6 (November, 1965).
7. R. Fabbro, *et al.*, J. Appl. Phys. **68**, (15 July 1990).