Analysis of the passage of a laser pulse through a hole

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The results of calculations of the transmission of a laser pulse (of length 0.4−1.0 ns) through a hole of diameter 100−500 μm based on a one-dimensional hydrodynamics code are compared with experimental data. The model is based on plasma implosion inside a cylindrical cavity. The hydrodynamic calculations show that the transmission coefficient depends strongly on the diameter of the laser beam as well as of the hole and also on the pulse length. A weak dependence of the transmission coefficient on the laser light intensity is found. The theory agrees well with the results of experiments. [S1063-651X(96)00411-4]

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I. INTRODUCTION

In interaction experiments with direct irradiation of the target it is mainly the laser beam quality that hampers the achievement of a high degree of uniformity in the intensity distribution on the target surface, which is desirable in many applications. To solve the problem the indirect drive scheme was developed with the target in the form of a cavity, inside which a fuel capsule is placed [1,2]. In this case the incident light penetrates through small holes into the cavity, inducing plasma and intense soft-x-ray radiation on the inner surface, which then compresses the fuel more uniformly. The cavity shell is usually made of a high-Z material to enhance the x-ray yield.

One of the major problems of the indirect drive experiments is an efficient deposition of the laser energy into the cavity. The aim is to squeeze a maximum of the laser energy without losses through the hole, the diameter of which is to be as small as possible. The laser beam is usually focused at some point outside the cavity. The passage of the laser light is impeded by the formation of the plasma on the hole periphery if the threshold of ablation $I_0 \sim 10^8 - 10^{10}$ W cm^{-2} is exceeded. The plasma generated on the hole periphery expands inward, and when the critical density is attained across the entire cross section the passage of the light is blocked. The creation of the plasma on the hole periphery and its expansion towards the hole axis result in a shortening of the laser pulse accompanied by a reduction in the transmitted pulse energy. Under such circumstances a small hole (compared to the focal spot) acts as a shutter restraining the laser energy penetrating inside the cavity [3]. A pinhole plasma shutter for optical isolation in high-power lasers also based on the hole blocking by a streaming plasma was described in [4]. On the other hand, plasma closure phenomena in pinholes of the spatial filters embedded in the amplifier chain of the high-energy lasers were explored in [6,5,7]. An interaction of the intense laser radiation with the pinhole perimeter creates a plasma constraining the transmitted radiation and temporally truncating the laser pulse.

The process of hole blocking is intimately connected with hydrodynamics of the high-temperature plasma. To analyze the blocking mechanism a one-dimensional (1D) hydrodynamic code of plasma implosion [8] in a cylindrical symmetry including the absorption of the laser light passing in the axial direction was applied. The computation results are compared with the experiments performed mainly on the laser facility PERUN (the photodissociation iodine laser, located at the Institute of Physics, Prague) or reported in [9,10].

II. PHYSICAL MODEL

A simple model is developed for the evaluation of the fundamental physical processes that are relevant for the dynamics of the laser light passage through a hole. The caustic of the laser focus is certainly much longer than the depth of the hole so that the beam can be considered as having a constant focal radius. The first plasma is formed when the beam periphery hits the entrance. The plasma expanding from the lip is moving radially as well as axially down the hole, where the plasma propagation is aided through a secondary plasma generation by x-ray irradiation of the hole inner wall, though the radiation transport as such is not considered. If the depth of the hole (foil thickness) is much smaller than the hole radius the plasma first covers the inner hole surface before it expands radially.

The smallness of the ratio of foil thickness over the hole diameter immediately raises the question of dimensionality. The problem itself is then clearly 2D, whereas our model is 1D only. As described above, the 2D effects are especially strongly expressed when the laser radiation first hits the hole lip. However, after the plasma has been fully developed, the main heating proceeds near the hole axis. The heat flux determining the dynamics of the plasma expansion is directed along the radius towards the inner wall of the hole. This mechanism thus enforces a quasi-1D geometry and is responsible for the physical relevance of the 1D cylindrical symmetry in our hydrodynamic model.

Clearly, the geometry of the illumination is different from that of a conventional target experiment because the beam path is now perpendicular to the radial density gradient rather than parallel to it. The main energy deposition occurs inside the hole, while the heating of the lip occurs just through the beam periphery exceeding the hole radius. It therefore once again makes sense to assume that during the blocking process the plasma expansion retains the 1D cylindrical symmetry.

Let the intensity distribution across the hole be a function of the form

$$I(r,t)=I_0 f_r\left(\frac{r}{r_0}\right) f_t(t,\tau_0), \tag{1}$$

where I_0 is the maximum intensity on the axis of the hole, f_r, f_t are the functions describing the spatial and temporal shapes of the laser beam, and r_0, τ_0 are the parameters associated with the cross section and duration of the pulse, respectively. The dependence of the pulse on the longitudinal coordinate is ignored in (1) because the foil thickness is much smaller than the length of the focal caustic. If the intensity $I(r_D,t)>10^8-10^{10}$ W cm^{-2} (r_D denotes the radius of the hole), then the rim of the transmitted pulse causes an ablation and creation of the plasma. The plasma expands towards the axis of the hole, thus decreasing the effective radius r_c of the hole. The radius r_c determines the position of the critical surface [$\rho(r_c,t)=\rho_c$, where $\rho(r,t)$ is plasma density and ρ_c critical density]. Neglecting the absorption of the laser light in the region with $\rho<\rho_c$, the expression for the transmission coefficient is

$$k_p=\frac{2\pi I_0}{E_L}\int_0^{t_1} dt f_t \int_0^{r_c(t)} f_r r dr, \tag{2}$$

where t_1 is the time of the total obstruction of the hole [$r_c(t_1)\equiv 0$]. It was assumed that the motion of the critical surface starts at $t=0$.

If the form of the laser pulse is represented by

$$f_t(t,\tau_0)=\begin{cases}1 & \text{if } t\leqslant\tau_0\\ 0 & \text{if } t>\tau_0\end{cases} \tag{3}$$

and

$$f_r(r)=\exp\left[-\left(\frac{r}{r_0}\right)^2\right] \tag{4}$$

then the transmission coefficient k_p from (2) is found to be

$$k_p=\begin{cases}\dfrac{t_1}{\tau_0}\left[1-\dfrac{r_0}{r_D}\mathrm{erf}\left(\dfrac{r_D}{r_0}\right)\right] & \text{for } t_1<\tau_0\\ 1+\dfrac{r_0 t_1}{r_D\tau_0}\mathrm{erf}\left(\dfrac{r_D-v_c\tau_0}{r_0}\right)-\dfrac{r_0 t_1}{r_D\tau_0}\mathrm{erf}\left(\dfrac{r_D}{r_0}\right) & \text{for } t_1\geqslant\tau_0,\end{cases} \tag{5}$$

where $t_1\approx r_D/v_c$ and $E_L=\pi r_0{}^2 I_0\tau_0$. Note that for the derivation of this expression the critical surface motion has been assumed in the form

$$r_c(t)\sim r_D-v_c t, \tag{6}$$

where $v_c\sim$const is the velocity of the critical surface. Under these assumptions the formula (5) renders very revealing information about the basic parameters of the transmission coefficient. It is seen that the coefficient strongly depends on the ratio of the diameters of the beam and of the hole and also on the ratio of the pulse duration and of the blocking time (t_1/τ_0).

On the other hand, from (5) follows a weak dependence of the transmission coefficient on the laser light intensity. It is given by the weak dependence of the time t_1 on I_0. In [11] the velocity of the critical surface was estimated as

$$v_c\approx\alpha c_s, \tag{7}$$

where c_s is sound velocity and α is a parameter of order 1, which depends on the target material. Equating the absorbed intensity I_a to the heat flow due to the thermal conductivity toward the ablation zone we get

$$I_a\approx\frac{\chi_0 T^{7/2}}{c_s\tau_0}, \tag{8}$$

where χ_0 is the thermal conductivity coefficient and T is the plasma temperature. Then the scaling laws for c_s and k_p, considering (7) and (8), can be obtained

$$c_s\propto(I_a\tau_0)^{1/6}\propto(I_0\tau_0)^{1/6}, \tag{9}$$

$$k_p\propto\frac{t_1}{\tau_0}\propto\frac{r_D}{c_s\tau_0}\propto I_0^{-1/6}. \tag{10}$$

Clearly, the dynamics of the critical surface motion determines the passage of the laser light through the hole. If the absorption of the laser light in the underdense plasma is also taken into account it is possible to come to a more general conclusion: the transmission coefficient k_p is determined by the dynamics of motion of the opacity zone r^*, where ρ^* is the density value at which the absorption coefficient $k_a(r^*,t)=1$.

Having in mind the preceding considerations, we formulate a physical model of the absorption based on the following assumptions: the expanding plasma towards the axis has a cylindrical symmetry, the refraction of the laser light inside the plasma is not considered, only the portion of the laser light falling on the plasma with $\rho\leqslant\rho_c$ passes through the hole, and in the region $\rho\geqslant\rho_c$ the laser light is absorbed due to inverse bremsstrahlung with the absorption rate

$$\dot{q}=\rho^{-1}(r,t)I(r,t)k_a(r,t)/d_0. \tag{11}$$

Here ρ is the local mass density, $I(r,t)$ is the radial dependence of the intensity in the focus, and d_0 is the foil thickness; $k_a=1-e^{-\tau}$ is the absorption coefficient, with

$$\tau=\frac{2\pi}{\lambda^2}\frac{d_0 a}{T_e^{3/2}}\langle Z\rangle\ln\Lambda_a(\rho/\rho_c)^2(1-\rho/\rho_c)^{-1/2} \tag{12}$$

being the plasma optical thickness. In (12) λ is the wavelength, a is a numerical constant, $T_e(r,t)$ is the electron temperature (assumed to be the same for electrons and ions), $\ln\Lambda_a$ is the Coulomb logarithm for inverse bremsstrahlung absorption, and $\langle Z\rangle$ is the ionic mean charge state. It follows from (11) that the transmission of the laser light is reduced by both the partial hole blocking due to the critical surface

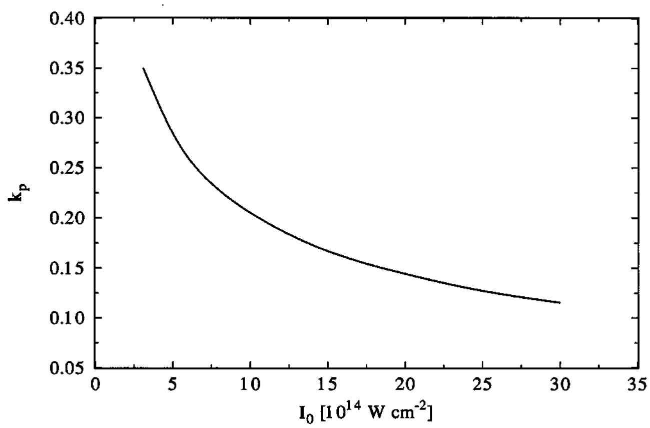

FIG. 1. Calculated dependence of the transmission coefficient of the laser light through a hole in a copper foil on the laser light intensity. The calculation was performed for the radius of the hole $r_D = 75$ μm, beam radius $r_{0.8E} = 75$ μm, and the pulse length $\tau_{0.5} = 0.35$ ns.

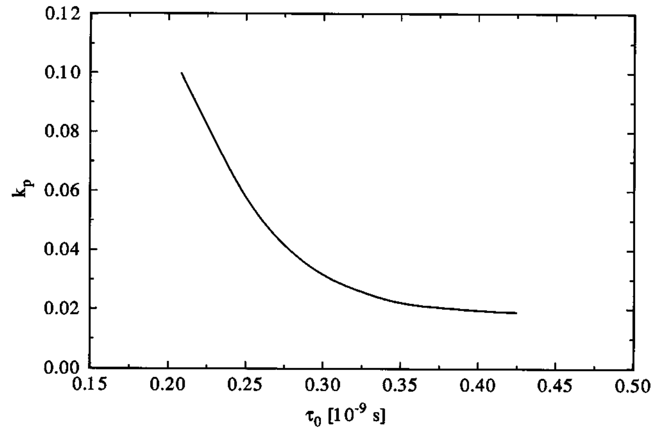

FIG. 2. Transmission coefficient through the hole of a diameter 150 μm (in copper foil) as a function of pulse length. In the calculation the light intensity $I_0 = 3.2 \times 10^{14}$ W cm^{-2} and $r_{0.8E} = 75$ μm was assumed.

motion towards the axis, resulting in the creation of an opaque plasma with $\rho > \rho_c$ and the absorption in the underdense plasma.

An important parameter is the mean charge $\langle Z \rangle$ of the plasma, which determines both the critical density

$$\rho_c = 1.85 \times 10^{-3} \frac{A}{\langle Z \rangle} \lambda^{-2} \tag{13}$$

(A is atomic number of the target material, ρ_c is in g cm^{-3}, and the laser wavelength λ is in μm) and the absorption coefficient. To achieve a reemission, the material of high Z (copper, gold, and lead) is used in *Hohlraum* experiments. Consequently, owing to a large variation in the radiation intensity across the hole radius, different plasma regions are created involving the ions in very different ionized states. To evaluate the mean charge we refer to [12] (Chap. III, Sec. 3), in which the following relation is given:

$$I_z(\langle Z \rangle + 1/2) = k_B T \ln \frac{A_0 T^{3/2}}{\langle Z \rangle \rho}, \tag{14}$$

where A_0 is a constant and k_B is the Boltzmann constant. In derivation of this formula the discrete values of ionization potentials I_z were assumed to be a continuous function of the charge Z.

The two-temperature 1D hydrodynamic code [8], with incorporation of the physical model of the absorption discussed above, was applied to the hole blocking problem. In numerical calculations the space shape (4) and

$$f_t = \exp\left[-\left(\frac{t - t^*}{\tau_0} \right)^2 \right] \tag{15}$$

(where $\tau_0 = \tau_{0.5}/2\sqrt{\ln 2}$, $\tau_{0.5}$ is the pulse duration at half magnitude of the laser pulse, $r_0 = r_{0.8E}/\sqrt{\ln 5}$, $r_{0.8E}$ is the radius of the beam in which the 80% of the energy is contained, and t^* determines the pulse timing) are taken into account.

The resulting dependence of the transmission coefficient on the laser light is displayed in Fig. 1. The choice of the numerical values of the parameters was as follows: $r_{0.8E} = 75$ μm, $r_D = 75$ μm, and $\tau_{0.5} = 0.35$ ns. The calculations show that the dependence of the transmission coefficient on I_0 can be expressed as

$$k_p \approx A + B I_0^{-\gamma}, \tag{16}$$

where A and B are constants.

The dependence appears to be a weak one with the coefficient $\gamma = 0.34$, which is, however, two times greater than the coefficient derived from the simple analytical model; see [3]. Such a result can be expected because of a much more precise evaluation of the crude changes in the plasma heating and, consequently, of the variations of the velocity with which the critical surface approaches the axis of the hole. Note that the velocity of the critical surface was kept constant in the analytical model.

A much more pronounced dependence of k_p on the pulse length (see Fig. 2) was found. The calculations were performed with maximum intensity $I_0 = 3.2 \times 10^{14}$ W/cm^2, radius of the hole $r_D = 75$ μm, and the beam diameter $2r_{0.8E} = 150$ μm. If the pulse length is $\tau_0 = 0.21$ ns the transmission coefficient is $k_p = 10\%$. A two times increase in the pulse length leads to a five times decrease in the transmission coefficient. The overall dependence is qualitatively in accordance with the results of the analytical model.

III. COMPARISON WITH EXPERIMENT

The experimental study of the passage of the laser light through a small hole was performed using the laser facility PERUN (the iodine photodissociation laser system producing subnanosecond pulses at 1.315 μm with the delivered energy up to 50 J [13]) in the energy range 8–10 J. The passage of the light was monitored through measurements of the transmission coefficient and temporal shape of the laser pulse passing through the hole. The transmission coefficient of the hole k_p was determined as the ratio of the energy of the light passed versus the energy of the incident light. Pb foils 50–70 μm thick or/and Cu foils 15 μm thick were used as a target with the hole the diameter ($2r_D$) of which

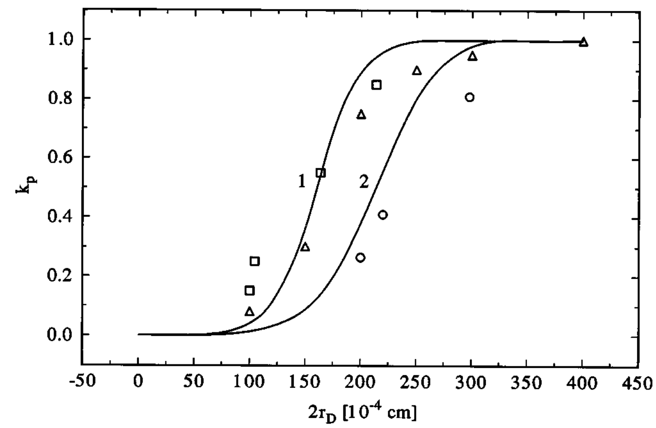

FIG. 3. Comparison of the calculated and experimental dependences of the transmission coefficient on the beam diameter. A copper foil was used as a target. Curve 1: calculation for $r_{0.8E}=100$ μm. $\triangle$, experiment at ASTERIX [10]; $\square$, experiment at PERUN. Curve 2: calculation for $r_{0.8E}=150$ μm. $\bigcirc$, experiment at PERUN.

was varied between 100 and 500 μm. The duration of the laser pulse was $\tau_{0.5}\approx 0.35$ ns, while the laser beam was focused on the target by an $f/2$ focusing aspheric system to produce a focal spot either ≈ 100 μm or ≈ 150 μm.

A comparison of the calculated and the experimental dependence of the transmission coefficient on the hole diameter is shown in Fig. 3 for a Cu foil. Good agreement between the curves over a broad range of radii in the experiment is revealed. In both the experiment and the calculation a decrease in the transparency was observed when the focal spot diameter was increased. Note that the precision of the transversal position of the beam focus with respect to the position of the hole was better than 200 μm and the aiming inaccuracy thus cannot be responsible for the reduction of the energy of the passed light. Analyzing the results, it can be deduced that at a pulse duration of 0.3 ns the transmission coefficient of the hole, the diameter of which is three times larger than the diameter of the focal spot, is equal to 0.8.

In Fig. 4 a similar comparison is shown with the experiment performed in [9], in which a 25-μm-thick gold foil with the hole being varied in the range $70-150$ μm was used. The beam radius was $40-70$ μm and the pulse length $\tau_0=0.3$ ns. Also in this case the theoretical calculation is consistent with the experiment. In [9] the strong dependence of the transmission coefficient on the pulse length is obtained when the light pulse length varied ($\tau_0=0.3$, 0.7, and 1.0 ns) is compared.

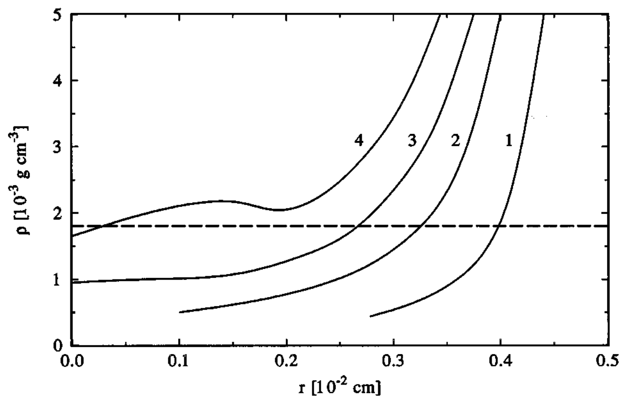

FIG. 5. Plasma density profile across the hole calculated for different times of passing laser pulse. In the calculations $r_D=50$ μm and $r_{0.8E}=50$ μm were used. Curve 1, $t=0.14$ ns, curve 2, $t=0.16$ ns, curve 3, $t=0.18$ ns, curve 4 $t=0.20$ ns. The dashed line marks the critical density.

The radii of the plasma density profiles inside the hole at different stages of the pulse are displayed in Fig. 5. The radius of the focal spot was $r_{0.8E}=50$ μm and the hole radius $r_D=50$ μm. At the beginning ($t=0.14$ ns) the front of the formed plasma still occurs far from the axis of the hole and thus a significant portion of the energy passes freely. The plasma reaches the hole axis at time $t=18$ ns; however, in the region of the radius $r\sim 20$ μm the density of the plasma remains below critical. The total blocking of the hole by plasma comes about at time $t=0.2$ ns. Because of the dynamics of the hole transparency the rear part of the pulse is cut off and, as a consequence, the length of the pulse becomes shorter after the passage through the hole. It is demonstrated in Fig. 6, where the calculated time evolution of

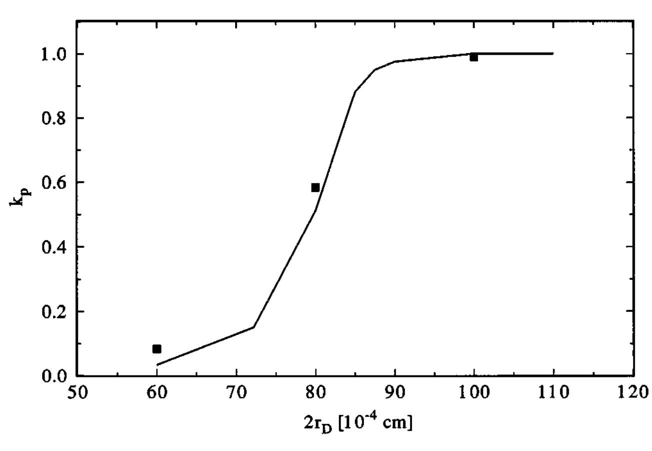

FIG. 4. Calculation (points) and experiment (full line) from [9] of the transmission coefficient as a function of the beam diameter through a hole in a gold foil.

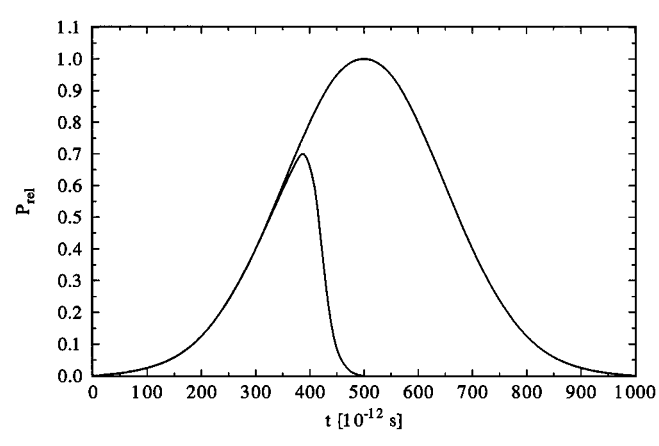

FIG. 6. Calculated shapes of the incoming (curve 1) and passing (curve 2) laser pulses through a hole of a diameter 150 μm, taking into account $r_{0.8E}=75$ μm and $I_0=3.2\times 10^{14}$ W cm^{-2}.

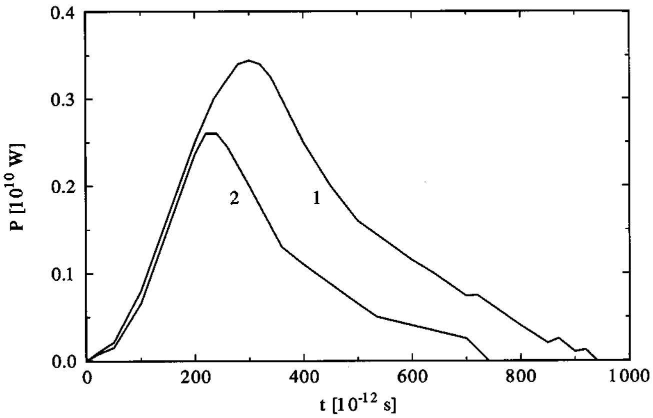

FIG. 7. Shapes of the laser pulse, falling (curve 1) and passing (curve 2) through a hole of diameter 150 μm, which were monitored in the experiment at PERUN.

the pulse before and after the passage is shown. The calculation was performed for laser pulse of the length $\tau = 0.35$ ns, intensity $I_0 = 3.2\times 10^{14}$ W cm^{-2}, and the radius $r_{0.8E} = 50$ μm. Passing through the hole of diameter $2r_D = 100$ μm, the pulse loses approximately 65% of its energy and its length is reduced to 0.16 ns. The numerical result corresponds very well to the experimental time dependence of the pulse in Fig. 7, the parameters of which are approximately the same. In this case the pulse of original length 0.32 ns is reduced down to 0.22 ns.

IV. CONCLUSION

We demonstrated a method of determination of the transmission coefficient of the laser light pulse passing through a small hole. Besides the analytical approach, numerical calculations resulting from an application of a 1D hydrodynamic code with a specific model of the absorption were carried out. It was pointed out that the transmission coefficient depends strongly on the ratio r_D/r_0 and also on the ratio of the pulse length and the blocking time t_1/τ_0. The dependence of the transmission coefficient on the light intensity was found to be a weak one. However, the simple analytical estimate renders the exponent in the power dependence of the transmission coefficient on the intensity two times smaller than the numerical calculations. This is likely due to the constant velocity of the critical surface as assumed in the analytical approach, which represents only a crude zeroth-order description. The changing rate of heating of the expanding plasma towards the axis of the hole causes variations in the critical surface speed and thus the analytical model yields a less accurate prediction for the intensity dependence of the transmission coefficient. Both the analytical approach and the numerical simulations are at least qualitatively consistent with the experimental results.

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