

Laser-Induced Breakdown in a High Pressure Gas Jet

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Laser heating of small gas volumes containing less than 10^{16} particles is investigated experimentally. A freely expanding high pressure gas jet is used as a target. Strong absorption of laser light is observed at gas pressures above 20 atm. The time of light-plasma interaction is measured as a function of light power and number of heated particles. Streak photographs of the laser produced plasma indicate a nearly isotropic expansion. The experimental results agree well with the theoretical predictions based on a spherical model.

I. Introduction

Recently several authors demonstrated the occurrence of nuclear fusion reactions in plasmas generated by laser irradiation of solid targets such as deuterium¹, lithium deuteride² or deuterated polyethylene³. A considerable increase in fusion reaction rate is expected when using (most conveniently gaseous) mixtures of deuterium and tritium⁴.

The heating of dense gases by laser light has been studied by several groups during the past years⁵. The most interesting result of the first experimental studies was that the front of the plasma produced by laser-induced gas breakdown moves with high velocity ($\sim 10^7$ cm/sec) towards the focusing lens⁶. High temperatures are difficult to achieve in such a plasma since the ionized volume and, as a result, the number of heated particles increases rapidly during the laser pulse. Up till now temperature measurements by the soft X-ray method⁷ have been performed in air^{8–10} and neon⁸ at low pressures only, since in high density gases the energy release per particle is too small and the X-ray absorption by the surrounding molecular gas reduces the signal intensity below the detection level⁸.

In a previous letter¹¹ we investigated experimentally the heating by laser light of small volumes of high density gas. A small gas volume was obtained from a freely expanding gas jet¹². In this paper we wish to give a detailed description of further experimental results. First we shall compare different models for the heating of an ambient gas and of a small, well defined gas volume, respectively. After a short presentation of the experimental set up, our experimental results obtained from high speed photography and light absorption studies will be compared with theoretical predictions.

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II. Theoretical Remarks

Let us first consider the case of laser-induced breakdown in an ambient gas. As mentioned above one of the most characteristic phenomena is the expansion of the luminous plasma front towards the focusing lens. Two different mechanisms may account for this phenomenon:

a) The breakdown wave mechanism as suggested by RAIZER¹³. If breakdown occurs in the leading edge of the laser pulse, under certain conditions a breakdown wave moves towards the focusing lens. The ionized volume increases rapidly by multiple breakdown. An estimate of the velocity of the breakdown wave for a laser pulse rising linearly in time gives¹³

$$v \propto (P/\Delta t)^{1/2}/\text{tg } \alpha \quad (1)$$

where P is the maximum power, Δt the risetime, and α the half angle of the focused laser beam. It can be seen from Eq. (1) that in the case of short light pulses (small Δt) and long focal lenses (small α) the initial velocity of the breakdown wave becomes very large. Its absolute value is mainly determined by the development of the electron cascade being a strong function of gas density. Therefore, the velocity of the breakdown wave is expected to increase with increasing gas density.

b) A hydrodynamic expansion mechanism as proposed by RAMSDEN and SAVIC¹⁴. Immediately after breakdown a shock wave travels in all directions. The laser light is preferentially absorbed in that part of the shock wave that moves towards the focusing lens. In the shock wave the gas is heated and ionized, so that the zone of energy release is transported behind the shock front. This hydrodynamic mechanism is similar to a detonation wave in reacting gases and is called the radiation supported shock wave (RSSW) mechanism. Using the Chapman-Jouget theory one gets for the velocity of the detonation front the expression¹³

$$v = [2(\gamma^2 - 1)\Phi/\epsilon_0]^{1/3} \quad (2)$$



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where ϱ_0 is the density in the undisturbed gas, Φ is the incident light flux, and γ the adiabatic coefficient. The front velocity increases with increasing light intensity and decreasing gas density.

A comparison of our experimental results with both expansion mechanisms will be given in Section IV. It should be pointed out that in the experiment the mechanism with the higher expansion velocity will dominate.

The expansion mechanisms in ambient gases discussed above are quasi-stationary processes. On the contrary, the heating of a finite gas volume is time dependent. Theoretical investigations on the heating of isolated, spherical targets were made by DAWSON¹⁵ and FADER¹⁶.

We restrict ourselves to a short summary of Dawson's theory considering the heating of a spherical plasma drop isolated in vacuum. The problem is approximated by assuming an uniform density and temperature distribution within the plasma drop and neglecting radiation losses. During the heating period the plasma is expected to expand isotropically.

A uniform heating of the plasma is possible only if the absorption length for the laser light is of the order of the plasma dimensions. In regions of high density, however, where the electron density exceeds the cut-off density n_{ep} , strong local heating of the plasma may occur. Nevertheless, the energy may be carried away from these hot areas by shock waves or by electronic heat conduction. The validity of these assumptions will be investigated on the basis of our experimental results presented in Section IV.

The heating and expansion of the plasma drop is well described by the set of differential equations for conservation of energy and momentum together with the equation of state. Integration of these equations may be readily done in the case of a spherical symmetry of the plasma. For the temporal development of the plasma radius r and the plasma temperature kT we obtain:

$$r = [r_0^2 + 10 Pt^3/9 N_i m_i]^{1/2}, \quad (3)$$

$$kT = \frac{Pt}{3(N_e + N_i)} \left[\frac{2r_0^2 + 5 Pt^3/9 N_i m_i}{r_0^2 + 10 Pt^3/9 N_i m_i} \right]. \quad (4)$$

P is the constant laser power, r_0 the initial plasma radius, and m_i and N_i are the mass and the total number of heated ions, respectively.

From the conservation of energy we find for the average ion expansion energy

$$E_i = [Pt - (3/2)(N_e + N_i)kT]/N_i. \quad (5)$$

Equations (3–5) are only valid if the total laser energy is absorbed in the plasma. However, as the plasma expands it rapidly becomes transparent to the laser light.

The corresponding time of light plasma interaction t^* may be defined by the condition that the light absorption length equals the plasma diameter, e.g. $2rK = 1$. K is the absorption coefficient of the plasma for the incident laser light¹⁷

$$K = \frac{C Z n_e^2}{(kT)^{3/2}} \left(1 - \frac{n_e}{n_{ep}}\right)^{-1/2} \quad (n_e < n_{ep}). \quad (6)$$

n_e , kT and m are the density, temperature, and mass of the electrons, and Z the charge of the ions. The numerical value of the constant C in CGS units is $C = 2.5 \cdot 10^{-55}$ at the frequency of the ruby laser ($\omega = 2.7 \cdot 10^{15} \text{ sec}^{-1}$). n_{ep} is the cut off density of the plasma, $n_{ep} = m\omega^2/4\pi e^2$.

Making use of Eqs. (3 and 4) we get from the above mentioned condition $2rK = 1$ the following expression for the time of light-plasma interaction:

$$t^* = 1.7 \cdot 10^{-16} N_e^{2/3} A^{5/18} (1 + 1/Z)^{1/6} Z^{-1/6} P^{-4/9} \text{ sec} \quad (7)$$

where P is the light power in Watt and A the atomic mass of the ions.

In order to illustrate the calculations given above, the temperature, expansion energy, and the radius of a nitrogen plasma ($A = 14$, $Z = 5$) are plotted as a function of time in Fig. 1 [see Eqs. (3–5)]. The initial plasma

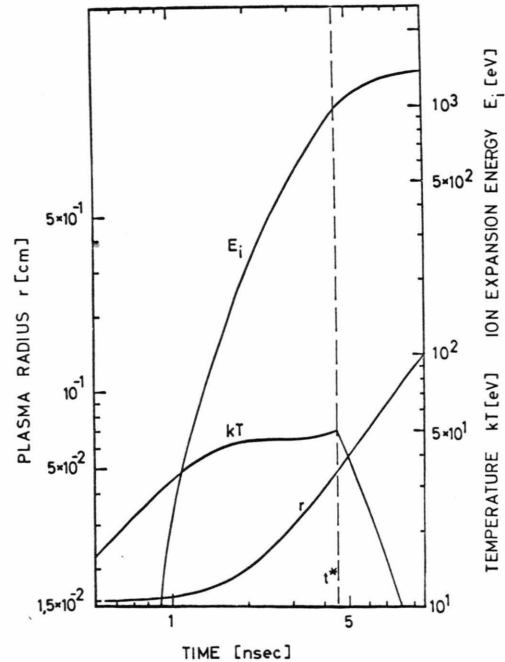


Fig. 1. Temperature, expansion energy, and radius of a nitrogen plasma ($A = 14$, $Z = 5$) with a total number of electrons of $N_e = 2 \cdot 10^{16}$, calculated from Equations (3 to 5). Initial plasma radius $r_0 = 150 \mu$, constant incident light power $P = 200 \text{ MW}$ for times $0 \leq t \leq t^*$. An adiabatic expansion of the plasma is assumed for times $t \geq t^*$.

radius is $150\ \mu$, the total number of electrons $2 \cdot 10^{16}$, and the incident laser power 200 MW. A substantial difference between thermal energy and expansion energy is observed after several nanoseconds. At the time the plasma becomes transparent ($t = t^*$, see vertical line in Fig. 1) 75% of the whole plasma energy is converted into expansion energy. (Comparing the absolute values for kT and E_i in Fig. 1 one has to bear in mind that the thermal energy is shared by all particles in the plasma, whereas the expansion energy is carried exclusively by the ions.) For times $t > t^*$ further heating of the plasma can be neglected and an adiabatic expansion of the plasma is assumed. In this regime the temperature drops rapidly with time and, finally, all the plasma energy is converted to energy of radial expansion.

From Fig. 1 we readily see that the highest temperature is found at the end of the heating process ($t = t^*$). It should be emphasized that the light absorption within the plasma decreases before t^* is reached. As a result, there is no discontinuity of the temperature slopes in the neighborhood of t^* .

III. Experimental

The theoretical results of the preceding section suggest that high plasma temperatures can be achieved with light energies of approximately 1 Joule if the number of heated particles does not exceed 10^{16} . Spherical, solid pellets with a diameter of about $50\ \mu$ contain this number of particles. Experiments with such targets have been performed by a number of investigators¹⁸. Difficulties to produce pellets of reproducible size and shape have been encountered.

In this paper we wish to suggest a new method to produce small volumes with particle numbers smaller than 10^{16} . The target consists of a gas, expanding from a high pressure tank through a small nozzle (radius $R = 80\ \mu$ or $R = 150\ \mu$). The resulting gas jet has strong density gradients along the direction of expansion (z -axis) and perpendicular to this direction (r -axis). The experimentally determined density profiles have been discussed previously¹⁹.

A schematic picture of the target is shown in Figure 2a. The laser light is focused by a lens system L1 (focal length 16 mm, focal spot diameter $150\ \mu$) perpendicular to the z -axis into the gas jet in front of the nozzle at $z \sim 1.5 R$. Because of the strong density gradient in the gas jet along the r -axis, the heated gas volume is much better defined compared to common gas breakdown experiments in an ambient gas. The hatched area in Fig. 2a indicates the gas volume illuminated by the incident laser light (the gas motion of flow velocity $\sim 3 \cdot 10^4$ cm/sec may be neglected during the duration of the laser pulse $\sim 10^{-8}$ sec).

Using the experimentally determined density profiles¹⁹, we can estimate from geometrical considerations the number of molecules N within the illuminated volume as a function of the pressure p_0 in the gas supply.

As an upper limit for N we find

$$N \leq 6.2 \cdot 10^{13} p_0 \quad \text{for } R = 150\ \mu \quad (8a)$$

$$\text{and } N \leq 1.6 \cdot 10^{13} p_0 \quad \text{for } R = 80\ \mu \quad (8b)$$

where R is the radius of the exit of the nozzle and p_0 the reservoir pressure in atm.

Gas target and lens system are situated in a vacuum chamber. The gas jet is initiated by a solenoid valve synchronized to open 40 msec before the laser is fired in order to achieve a stationary gas flow. During that time the pressure in the vacuum chamber rises to less than 1 Torr.

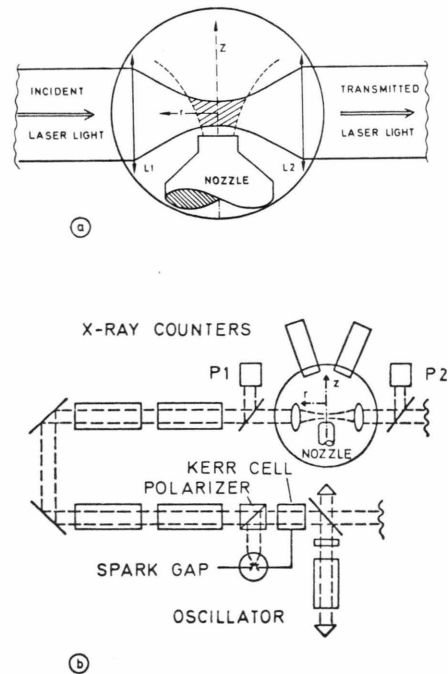


Fig. 2. a) Enlarged schematic of the gas target. L1 and L2 are the focusing and the collimating lens systems, respectively. The broken lines indicate the contours of the gas jet. b) Experimental set up for plasma production in a gas jet.

The complete experimental set up is depicted in Figure 2b. The laser system consists of a passively Q-switched ruby oscillator and four amplifier stages. Its output power is larger than 500 MW. Using a Kerr cell and a laser triggered spark gap for pulse shaping²⁰ we obtain a nearly rectangular laser pulse with a duration of either 8 nsec or 3 nsec and a risetime of less than 1.5 nsec. A rectangular pulse shape is convenient for a direct comparison of the experimental results with the theoretical predictions presented in Section II.

The temporal development of the light absorption in the plasma is investigated by measuring the incident and the transmitted laser light (collimated by lens systems L2) with the fast photodiodes, P1 and P2,

connected to a fast oscilloscope (over-all risetime 0.5 nsec).

Records of the radial growth of plasma luminosity are obtained by an image converter camera viewing the gas jet perpendicular to the plane of Figure 2b. By means of a microscope lens system a magnified image of the plasma is formed at the plane of the recording slit. Scattered laser light is discriminated by a set of filters (8 mm BG 38) in front of the slit. The resolution in time and space of this device was better than 0.2 nsec and 20μ , respectively.

Figure 2b shows two X-ray detectors for measuring the electron temperature. Experimental data have been published previously¹¹; they will be discussed in Section V.

IV. Experimental Results

A) Temporal evolution of the plasma expansion

Taking high speed photographs of the laser-generated plasma we are able to obtain important information about the expansion velocity and, hence, the expansion mechanisms of the plasma. We identify the plasma boundary with the luminous front recorded by the streak camera. We are well aware that a detailed interpretation of the nature of the luminous front is rather complex. However, ALCOCK et al. showed in a recent paper²¹ that the motion of the plasma boundary — deduced from time resolved Schlieren records — agrees fairly well with the motion of the luminous front recorded by streak photography.

First, the main difference between the heating of an ambient gas and of a small gas volume will be discussed.

In Fig. 3 the streak picture of a laser-induced gas breakdown in ambient nitrogen at a pressure of 500 Torr is shown. The picture records the growth of plasma luminosity along the axis of the incident laser beam. The laser light is incident from the left with a peak power of 70 MW. Its pulse shape is nearly rectangular with a duration of 3 nsec and a risetime of 1.5 nsec. For synchronization in time, a small part of the laser light is deflected to the camera giving rise to the bright streak on the left of the photograph.

In Fig. 3 three different regions of plasma development can be distinguished (in agreement with the observations reported by other authors^{10,22}):

1) At the leading edge of the laser pulse there is a rapid increase of light power within 1.5 nsec. This condition favors multiple breakdown within the gas [see Equation (1)]. The diffuse plasma front which expands with a velocity of $6 \cdot 10^7$ cm/sec may be interpreted as a breakdown wave. This velocity is one order of magnitude larger than the velocity of a radiation supported shock wave under similar conditions.

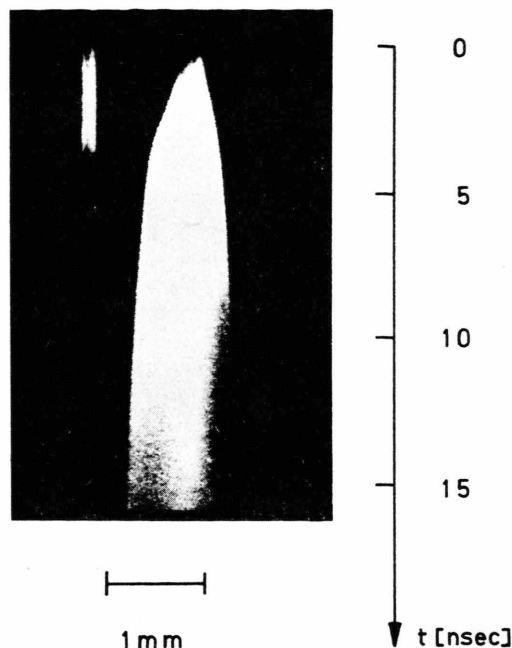


Fig. 3. Streak photograph of gas breakdown in ambient nitrogen at a pressure of 500 Torr. Laser light is incident from the left. Pulse power 70 MW, pulse duration 3 nsec (see time mark).

2) During the maximum of the laser pulse — when the light power is constant — the expansion velocity of a breakdown wave is expected to be small. The expansion mechanism which is suggested to account for the plasma growth during this time is the radiation supported shock wave (RSSW). From Eq. (2) we estimate for a RSSW an expansion velocity of $1.3 \cdot 10^7$ cm/sec (light flux at the shock front $\Phi \sim 8 \cdot 10^{10}$ W/cm², N_2 -density $\rho_0 = 8.2 \cdot 10^{-4}$ g/cm³) which is in good agreement with the experimental value of 10^7 cm/sec deduced from our streak pictures. It is of interest to point out that the rear front of the plasma shows a noticeable expansion. This may be due to an incomplete absorption of laser light within the plasma (gas pressure 500 Torr!) which gives rise to a second RSSW in the direction of propagation of the laser beam. Measurements of the transmitted laser light support this interpretation.

3) After termination of the laser pulse the velocity of the shock front decreases rapidly to $2 \cdot 10^6$ cm/sec. Now, the expansion mechanism is similar to that of a strong explosion in a homogeneous gas²³.

A completely different picture of the plasma expansion is obtained when laser-induced gas breakdown is observed in a gas jet. Figure 4a shows the streak picture recording the expansion of the luminous plasma front

along the axis of the laser beam. The laser light is focused from the left side into a N_2 -gas jet expanding at a pressure of $p_0 = 115$ atm from a nozzle with an exit throat section of a radius of $R = 80 \mu$. The coordinates of the focus are $r = 0$ and $z = 120 \mu$. The laser pulse has a peak power of 22 MW and its pulse shape is nearly rectangular with a duration of 8 nsec. The bright streak on the left of the photograph results from (a small part of) the incident laser light giving a well defined time scale.

Contrary to gas breakdown in an ambient gas we find in the case of breakdown in a gas jet that the expansion of the luminous plasma front towards the focusing lens stops at times when the high power laser light is still incident (compare Fig. 3 and Figure 4a). This fact clearly indicates that the plasma volume, and hence the number of heated particles, is governed by the geometry of the gas jet and not by the duration or power of the incident light pulse.

Now, we wish to analyze the different stages of plasma expansion in detail using the schematic drawing of the streak photograph shown in Figure 4b:

1) First, gas breakdown occurs in the region of highest density, in the center of the gas jet (see point A in Fig. 4b) where the focus is situated. During the strong increase

of light power, the plasma expansion towards the focusing lens ($A \rightarrow A'$) takes place due to a breakdown wave, similar to the case of breakdown in an ambient gas.

2) During the time of constant light power further expansion of the luminous plasma front towards the focusing lens ($A' \rightarrow B$) is due to a RSSW-mechanism. In this shock front all the incident laser light is absorbed. Therefore, the shock wave originating in A' and travelling in the backward direction is not supported by the laser light. Its velocity corresponds to that of a blast wave which is much smaller than the velocity of the RSSW. (Because of less luminosity the blast wave is not visible on the photograph; its assumed front is indicated in the schematic drawing by the dash-dot line.)

3) At B the RSSW is driven back to the center of the gas jet, and a rarefaction wave travels further on into the vacuum. (The rarefaction wave can be seen very clearly on over-exposed photographs.) In order to explain this observation one has to bear in mind that the RSSW is travelling in a medium with decreasing density. At the point B — the "edge" of the gas jet — the density within the shock front decreases to a value where only a fraction of the incoming light is absorbed. The transmitted light supports the shock wave travelling towards the higher density center of the gas jet.

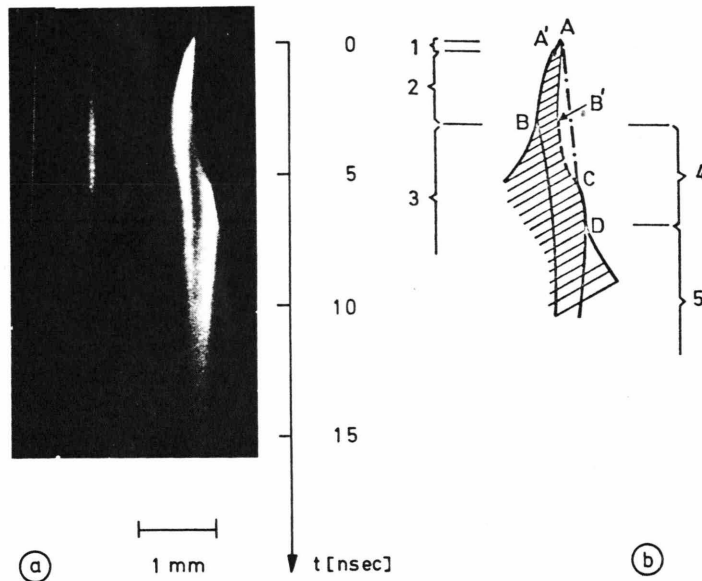


Fig. 4. Streak photograph (a) and the corresponding schematic drawing (b) of gas breakdown in a nitrogen gas jet expanding from a nozzle with a radius of $R = 80 \mu$. Initial gas pressure $p_0 = 115$ atm. Laser light is incident from the left. Pulse power 22 MW, pulse duration 8 nsec (see time mark and Figure 7).

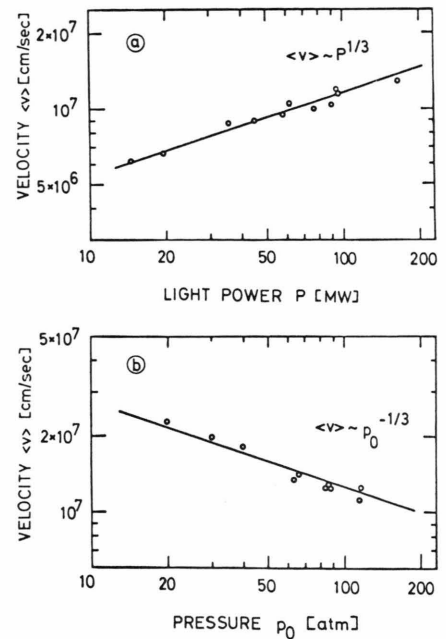


Fig. 5. Measured average expansion velocities of the luminous front a) as a function of light power at constant gas pressure ($p_0 = 115$ atm) and b) as a function of gas pressure at constant light power ($P = 100$ MW).

4) At the same time a pronounced overall decrease in density is noticed because of the plasma expansion. Hence, the light absorption by the shock front is incomplete, and some of the laser light may support a shock wave travelling from the center B' towards the rear edge of the gas jet. This shock front is indicated by the broken line in Fig. 4b. After about 6 nsec this rear shock wave reaches the blast wave at the point C. The high particle density within the blast wave produces the increased luminosity noticed on the picture.

5) When the RSSW reaches the point D — the rear "edge" of the gas jet — the situation is similar to that at point B: a rarefaction wave travels out into the vacuum and a new RSSW travels towards the center of the gas jet.

In order to support the interpretation given above we evaluate from the streak recordings the expansion velocity of the luminous front and investigate its dependence on light power and particle density. Since the situation is rather complex because of the different RSSWs travelling back and forth, we shall define an average velocity $\langle v \rangle$ of the luminous shock front which can be measured quite accurately: $\langle v \rangle$ is defined by the distance the luminous front travels from A' over B and B' to D, divided by the corresponding time. This definition is chosen because the points A' and D are most readily observed.

In Fig. 5a experimental values for $\langle v \rangle$ are given as a function of the incident light power at a constant pressure of 115 atm. Velocities ranging from $6 \cdot 10^6$ up to $1.3 \cdot 10^7$ cm/sec are observed for laser powers between 15 and 200 MW. In Fig. 5b a similar plot of $\langle v \rangle$ is given

for different particle densities at a constant light power of 100 MW. (Note that the particle density within the gas jet is proportional to the pressure p_0 in the gas reservoir.)

Both figures show that the measured shock velocities agree well with the power laws predicted by Eq. (2) for a RSSW. Concerning the absolute values of $\langle v \rangle$, one can show that they are of the correct order of magnitude with respect to Equation (2). An exact quantitative comparison of our experimental values with the theoretical predictions given above is difficult because the shock wave is travelling in an inhomogeneous medium with respect to density. Nevertheless, we think that the good qualitative agreement of experiment and theory indicates that the main expansion mechanism of our plasma is that of a RSSW.

We wish to point out that THOMPSON et al.²⁴ performed similar measurements on a gas jet and interpreted some of their results on the basis of a "deflagration model"²⁵. In this case a similar dependence of the expansion velocity on light flux and gas density exists as in the RSSW model. In our discussion we prefer the RSSW mechanism because in our experiments two conditions, necessary for the development of a deflagration wave, are not satisfied: a) the gas density within our gas jet exceed the cut off density only by a small amount, and b) there is no sharp boundary between the overdense material and the vacuum.

From our streak recordings we learned so far that the expansion of the heated volume along the axis of the incident laser beam — the r -axis — is governed by the

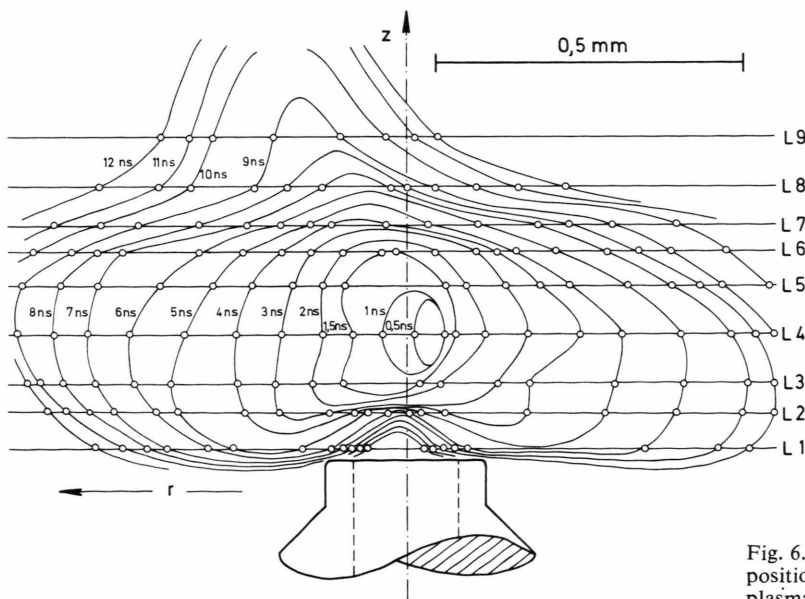


Fig. 6. Two-dimensional picture of the position of the most outward luminous plasma front in the gas jet at different times.

geometry of the gas jet. It is of interest to study the expansion of the plasma in the direction of the nozzle axis — the z -axis. To obtain this information with a high temporal resolution we made a number of streak recordings under identical conditions with respect to light power (30 MW) and gas pressure (20 atm) with the recording slit placed parallel to the r -axis and its position along the z -axis changed from shot to shot. From these pictures the position of the most outward luminous plasma front on both sides of the gas jet (see Fig. 4b) is measured as a function of time.

By this method we are able to evaluate a two-dimensional diagram of the plasma expansion for different times. Such a diagram is shown in Figure 6. At the bottom of Fig. 6 the contours of the nozzle are given. L1 to L9 indicate the different positions of the recording slit along the z -axis. The circles represent the positions of the plasma front as they are found from the streak photographs. Connecting the points which correspond to equal times we get a clear picture of the time history of the plasma expansion along the r -axis and the z -axis.

Two important facts can be deduced from Figure 6:

1) After several nanoseconds the plasma expansion is nearly isotropic; only a slight preference of expansion towards the focusing lens is noticed. The expansion along the focal plane L4 is similar to that shown in Figure 4a. During the first 1.5 nsec the rear side of the plasma does not move, because the laser light is absorbed by the shock front moving towards the focusing lens. After 1.5 nsec this shock front becomes partially transparent to the laser light and a RSSW may develop in the opposite direction, giving rise to a nearly isotropic expansion of the plasma (in Fig. 4a 3.2 nsec are required for the shock front to become transparent because of the higher initial gas pressure of 115 atm.).

2) The expansion velocity of the plasma towards the nozzle is very slow during the time the laser light is incident. For that reason energy dissipation into this region and the resulting enhancement of the number of heated particles may be neglected. This conclusion is also confirmed by theoretical investigations of the similar problem of strong point explosions in an inhomogeneous medium²⁶.

Summarizing our results obtained from the time resolved investigations of the plasma expansion we find the gas jet suitable as a target for laser plasma experiments: the particle number is well defined because of the steep density gradients along the r -axis and the negligible energy dissipation towards the nozzle; the shock waves which travel back and forth along the r -axis provide a good mechanism for the achievement of a uniform density and temperature distribution within the plasma, at least at the end of the laser pulse. However, at the beginning of the laser irradiating strong local heating within the first shock front is expected.

B) Time of Light Absorption

The experimental results derived so far favour the application of the spherical model to our plasma. A characteristic quantity of this model is the time of light-plasma interaction t^* (see Section II). By measuring the temporal development of the light absorption in the plasma — as described in section III — we are able to determine experimentally the value of t^* .

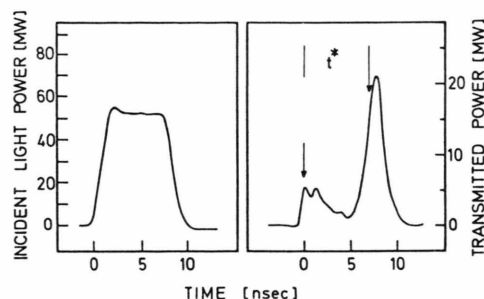


Fig. 7. Time resolved incident (left) and transmitted (right) light pulses. Note the different ordinates. Arrows indicate the time interval t^* between the occurrence of breakdown and beginning transparency of the plasma. Initial gas pressure $p_0 = 40$ atm.

In Fig. 7 an input pulse and a typical transmitted signal are shown. At a power level of 6 MW, breakdown occurs in the N_2 -gas jet, and a strong absorption of the incident light takes place. Only 3% of the incident light is transmitted by the plasma at the time of maximum absorption. Several nanoseconds prior to the end of the laser pulse the transmitted power increases as the plasma becomes transparent. The time interval between the two arrows shown in Fig. 7 gives the time between the occurrence of breakdown and the moment when the plasma transmission has recovered to 37% ($1/e$), i.e. the value of t^* .

In Fig. 8a experimentally determined values for t^* are plotted as a function of light power. The experiments are performed with two different nozzles at a constant pressure $p_0 = 115$ atm with $R = 80 \mu$ (\square) and $p_0 = 40$ atm with $R = 150 \mu$ (\circ), respectively. A similar plot of the dependence of the t^* on initial pressure p_0 (which is proportional to the number of heated particles) at constant light powers ($P = 20$ MW with $R = 80 \mu$ (\square) and $P = 80$ MW with $R = 150 \mu$ (\circ), respectively) is given in Figure 8b. The experimental points represent values averaged over a number of shots. The error bars indicate the maximum deviation from the average value observed in the experiment.

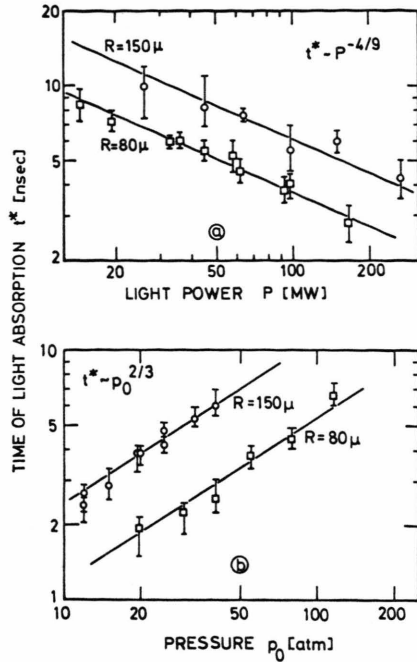


Fig. 8. Measured values for the time of light absorption t^* a) versus incident light power at constant reservoir pressure: (\square) $R = 80 \mu$, $p_0 = 115$ atm and (\circ) $R = 150 \mu$, $p_0 = 40$ atm; and b) versus reservoir pressure at constant incident light power: (\square) $R = 80 \mu$, $P = 20$ MW and (\circ) $R = 150 \mu$, $P = 80$ MW

It is interesting to see that the power law $t^* \propto P^{-4/9} p_0^{2/3}$, predicted by Eq. (7), agrees well with our experimental points. A quantitative comparison with Eq. (7) gives us the number of absorbing electrons $N_e(t^*)$ within the plasma. Table 1 shows a comparison between $N_e(t^*)$ and values of $N_e(p_0)$ estimated from geometrical considerations (Eqs. 8a and 8b). When using Eqs. (8a and 8b) one has to bear in mind that N molecules of nitrogen give rise to $2ZN$ electrons in the plasma, where Z is the degree of ionization of the nitrogen ions. In Tab. 1 we assumed a fivefold ionization which is suggested by our measured temperatures¹¹. The good agreement of $N_e(t^*)$ and $N_e(p_0)$ for the two different nozzles should be noted.

Tab. 1. Total number of heated electrons N_e for two nozzles. $N(t^*)$ is estimated from the measured values for t^* presented in Figure 8. $N(p_0)$ is calculated according to Eq. (8), which was derived from geometrical considerations

$R (\mu)$	$p_0 (\text{atm})$	$N_e (t^*)$	$N_e (p_0)$
80	115	$1.1 \cdot 10^{16}$	$1.8 \cdot 10^{16}$
150	40	$2.1 \cdot 10^{16}$	$2.5 \cdot 10^{16}$

It was thought of interest to investigate the influence of the atomic mass A and the charge Z of the plasma ions on the time of light-plasma interaction t^* . According to Eq. (7) we expect the following dependence (at constant light power and equal number of electrons within the heated plasma volume):

$$t^* \propto A^{5/18} (1 + 1/Z)^{1/6} Z^{-1/6} \equiv f(A, Z). \quad (9)$$

In order to keep the number of electrons constant for various gases we changed the gas pressure p_0 . In Tab. 2 the pressure p_0 and the average charge Z for several gases are listed which give equal numbers of electrons N_e . The values for $f(A, Z)$ and the average atomic mass A are included in Tab. 2.

Tab. 2. Average atomic mass and charge (at $kT = 100$ eV) of various gases. At the indicated pressure p_0 , the total number of heated electrons is equal for all gases cited ($N_e = 10^{16}$ for $R = 150 \mu$). $f(A, Z)$ is given by Equation (9)

gas	A	Z	$p_0 (\text{atm})$	$f(A, Z)$
H ₂	1	1	100	1.12
D ₂	2	1	100	1.355
He	4	2	100	1.39
CH ₄	3.2	1.6	25	1.38
C ₂ H ₄	4.66	2	16.7	1.46
N ₂	14	5	20	1.654

In Fig. 9 the experimentally determined values for t^* (at a light power of $P = 40$ MW) are plotted as a function of $f(A, Z)$. The solid line represents the expected linear dependence according to Equation (9). The good

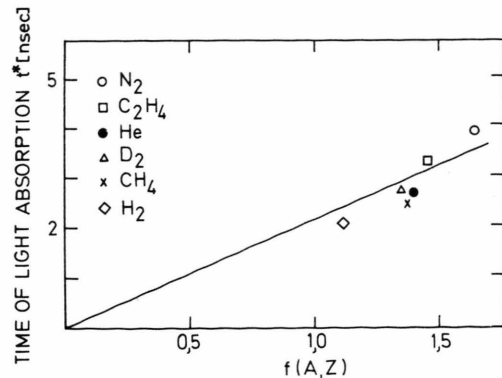


Fig. 9. Mass and charge dependence of the time of light absorption t^* ; $f(A, Z)$ is given by Equation (9). Experimental points were obtained at a constant light power of 40 MW and a total number of electrons of $N_e \approx 10^{16}$

agreement of experiment and theory is an additional support to the spherical model.

V. Concluding Remarks

From our experimental results presented in the preceding section we conclude that the plasma expansion is well described by a spherical model — especially during the final stage of plasma heating. At times comparable to t^* our streak photographs indicate a symmetric plasma expansion, and the measured values for t^* are in good agreement with theory. Hence, at the end of the laser pulse the density and temperature distribution seems to be homogeneous and uniform throughout the plasma to a very good approximation.

Two observations suggest strong local plasma heating at the beginning of the laser pulse: first, our streak photographs clearly show at the beginning an asymmetric expansion of the luminous plasma front, which is attributed to a nearly complete light absorption within the front of a RSSW travelling towards the focusing lens; and second, our experimentally determined temperature values (which have been reported in a previous paper¹¹) are much too high compared to the theoretical numbers computed from the spherical model (140 eV instead of 20 eV, at a laser power of 50 MW).

We wish to discuss the latter point in more detail. The high temperatures observed experimentally suggest that initially a thin, overdense plasma layer is heated, which contains only a fraction of the total number of particles of the plasma. Such a plasma layer of high density may exist within the shock front observed by our streak photography. In this case the plasma heating should be similar to the heating of a solid target²². As a matter of fact, in our previous paper¹¹ we showed that the measured temperature values are close to those observed in solid target heating.

From our streak photographs we know that a high density shock front exists only during the first nanoseconds of the laser pulse. During this time strong local plasma heating may take place. As time goes on, the shock waves travelling back and forth within the plasma will smooth out the temperature gradients, and at the end of the laser pulse one expects a rather homogeneous temperature distribution with an average temperature close to the value predicted by the spherical model. Experimentally it is difficult to record this average temperature, since our X-ray detectors are very sensitive to the maximum plasma temperature²⁷. At the moment careful experimental investigations on this subject are under way. The results will be published in a subsequent paper.

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