Energetic Plasmas Produced by Laser Light on Solid Targets

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Using two parallel simultaneously operating giant pulse lasers light intensities of 3×10^{12} W/cm² were achieved in the focus on a LiD target. Ion energies in the expanding plasma stream of 4.5 keV were observed. Investigations on thin LiH targets showed, that the light pulse interacts only with a target layer several 10^{-4} cm in thickness. The magnitude of the ion flux is estimated and compared with experimental observations.

It has been demonstrated in a number of recent publications that small but very energetic plasmas are being formed, when laser light of high intensity is focused on a solid target [1–12] (placed in vacuum).

A more detailed study of such plasmas showed that the plasma expansion occurs preferentially perpendicular to the target surface [8, 12]. The integrated ion emission in the case of LiH targets was found to be 2×10^{15} ions for a laser intensity at the focus of 3×10^{11} W/cm² [12].

We have continued our investigations and wish to report in this paper on the following two subjects:

a) The dependence of the energy of the expanding ions on the incident laser intensity up to 3×10^{12} W/cm²,

b) the penetration of the plasma into the target during the heating time of the pulse.

I. Experimental

a) The ion energies of the expanding plasma were measured with the experimental system depicted schematically in Fig. 1. In order to achieve large light intensities a laser system was designed which consisted of two simultaneously operating lasers [13]. The switching dyes of laser L1 and L2 were bleached at the same time by means of laser L3 resulting in a simultaneous emission of the laser pulses from L1 and L2 (accuracy better than 3 nsec). This arrangement has the advantage that the light intensity in each laser is smaller than in systems where the ruby crystals are placed in series. The light beams were focused by two lens systems (3 lenses each) with a focal length of 16 mm and an aperture of 0.38. The expanding plasma was analysed using an electrostatic detector placed at a distance of 12.8 cm along the normal to the target surface. An electric field of 200 V/cm was arranged perpendicular to the plasma stream in order to extract the electrons from the expanding neutral plasma. It was shown previously that in this way only positive ions are collected by the detector [12]. The time intervall Δt between the laser pulse ($\sim 10^{-8}$ sec long) and the arrival of the ion stream at the detector was measured with an oscilloscope of a rise time of $6 \cdot 10^{-9}$ sec. The rapid rise of the detector signal, discussed previously, allowed an accurate determination of the arrival of the most energetic ions. The values of Δt turned out to be several 10^{-7} sec, indicating expansion velocities of up to 10^8 cm/sec. Ion energies were calculated assuming an average mass of the ion of 4.5 mass units.

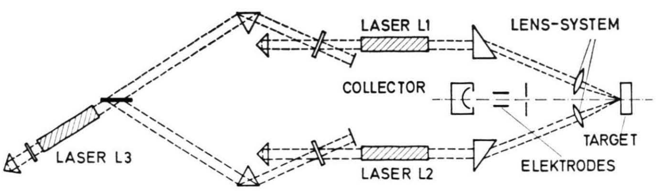

Fig. 1. Experimental system to obtain laser intensities up to 2.5×10^{12} Watt/cm².

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The solid target consisted of pressed LiD pellets. The light intensity in the focal plane was estimated from the energy, the temporal half width of the pulse, the divergence of the laser beam and the aperture of the lens system. Each of the two lasers was operated up to a maximum power of 500 MW (3.5 joule and 7 nsec half width) with a beam divergence of 0.5 degrees. Considering the losses of the optical system of approximately 20%, the combined intensity of the two lasers gave a maximum light intensity of 3×10^{12} Watt/cm^2 at a calculated diameter of the focus of 0.2 mm. This magnitude of the focus diameter agreed with the experimentally determined value. The target and the focusing system was placed in a chamber with a vacuum better than 10^{-5} mm Hg.

b) The penetration of the plasma into thin LiH targets was investigated with an experimental system shown in Fig. 2. The output power of a single ruby laser operating at the power of 150 MW was focused on platelets varying in thickness between 3 and 100 μ. The light intensity at the focus was 3×10^{11} Watt/cm^2. The plane of the target could be positioned in two ways. For the investigation of the penetration of the plasma the plane of the target was held perpendicular to the axis of the light beam. For measurement of the ion energies the target was positioned perpendicular to the axis, connecting the two ion detectors. In this way the plasmas expanding from the back and front side of the target were investigated separately. A fast photocell with an overall time constant of 0.3 nsec was placed 30 cm from the entrance window of the vacuum chamber. Light scattered on the window while the light beam entered the vacuum chamber, gave a direct measure of the incident laser pulse. In those cases where the plasma penetrated the solid target during the time of the light pulse ($\sim 2 \times 10^{-8}$ sec) the transmitted light was directed towards the same entrance window and additional scattered light reached the photocell.

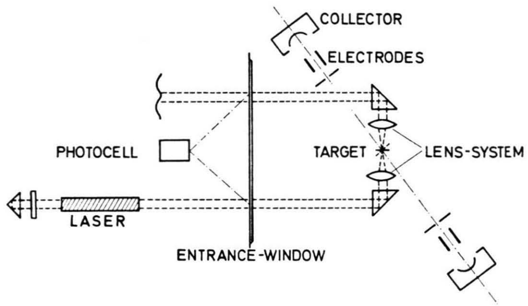

Fig. 2. Experimental system for the investigation of the plasma penetration into thin LiH targets.

II. Experimental Results

a) In Fig. 3 the measured ion energies E_{ion} from a LiD target are plotted versus the incident laser intensity P calculated for the common focus of the two ruby lasers. Ion energies of 4.5 keV were achieved for the maximum laser intensity of 2.5×10^{12} Watt/cm^2 [14]. The small rise of ion energies with light intensity can be represented by the empirical equation $E_{\text{ion}} \sim P^{0.4}$. Extrapolating the straight line of Fig. 3 to higher values indicates that light intensities of approximately 2×10^{13} W/cm^2 are necessary for ion energies of 10 keV. Such light intensities become now experimentally available.

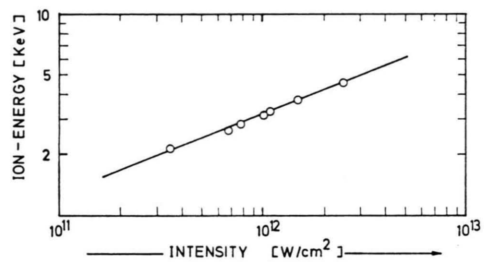

Fig. 3. Measured ion energies versus incident laser intensities (LiD-target).

b) The energetic plasmas produced in the focus of high power laser beams are heated only during the short time of the laser pulse. It is important to know how many ions are present in the plasma at a given time in order to estimate the energy balance between incident energy and the mean energy of each ion. The experimental system discussed above (Fig. 2) allowed an estimate of the number of ions involved during the heating period of the plasma. The oscilloscope traces shown in Fig. 4 were taken with a fast photocell; LiH targets of an approximate thickness of 3 μ (bottom) and of larger than 5 μ (top) were placed in the focus of the light beam. The strong difference between the two patterns stems from the fact that the plasma formed from the 3 μ

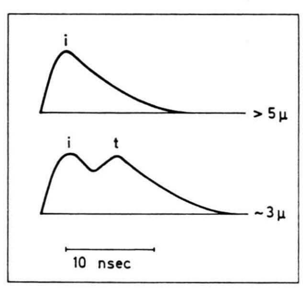

Fig. 4. Oscilloscope traces obtained from LiH-targets of thickness $> 5\ \mu$ (top) and of thickness $\sim 3\ \mu$ (bottom).

[14] Previous data [11] on LiH targets with ligth intensities between 8×10^{10} W/cm^2 and 4×10^{11} W/cm^2 join smoothly into our curve (within experimental accuracy).

target penetrates the whole thickness of the platelet leading to a strong transmission of the laser beam. The first maximum (Fig. 4, i) of the bottom trace corresponds to the signal of the incident beam, while the secondary peak (Fig. 4, t) represents the signal of the transmitted light. Taking into account the time delay due to the optical path in the vacuum chamber, one estimates from Fig. 4 that the 3 μ target becomes highly transparent about 2 nanosec after the maximum of the incoming light pulse. In the case of the thick target ($>5\ \mu$) no transmitted light is observed. The measured signal (Fig. 4 top) comes only from the incident light beam. We wish to conclude from these experiments that the light pulse interacts only with atoms from a thin layer several microns in thickness.

The following observations show that a larger part of the target is involved during the existence of the plasma. In fact the plasma penetrates platelets as thick as 30 μ after the termination of the light pulse. The plasma expanding from the back of these thick targets was less energetic and consisted of a smaller number of ions. This observation was expected since the penetration of the target occurs during the cooling period of the plasma.

The following investigations on targets of 5 μ, 30 μ and 60 μ in thickness are noteworthy:

5 μ: The energy of the ions leaving the back of the target was reduced to 70% and the number of ions was down to 25%.

30 μ: The ion energy was only 40% of that found in the plasma expanding from the front surface of the target. The number of ions were similar to the case of the 5 μ-target.

60 μ: No ions were detected on the back of the target.

The energy and the number of the ions leaving the front surface of the target remained the same in these experiments. The incident light intensity not the target thickness determines the plasma stream (for targets $>5\ \mu$).

It is suggested by these observations that the light pulse heats just a layer several microns in thickness but subsequently the hot plasma interacts with a larger part of the target. The observed craters in the target are no measure of the number of ions heated by the laser pulse.

In recent experiments [4, 6] laser light was focused on suspended solid or liquid particles of approximately 50 μ in diameter. It was reported that the whole particles were evaporated by the laser pulse. We believe, concluding from our experiments, that the major part of the plasmas obtained in this way was formed after the determination of the light pulse. Only a thin layer of the order of several microns interacts directly with the laser light.

III. Discussion

A) Generation of the Plasma

Our solid LiH or LiD targets do not absorb visible light of low intensity. Free electrons are necessary for the absorption of light and for the heating of the plasma. Initially electrons are formed by a multiquantum photoeffect which is possible at the high light intensities in the focus of a laser beam. It has been shown by KELDYSH [15] that the probability for ionization, W, is approximately proportional to P^n, where P is the light intensity and $n = I/\hbar\,\omega$ is the ratio of the ionization energy to the photon energy. For our LiH or LiD targets we make the following rough estimate:

with $I \cong 10$ eV and $\hbar\,\omega = 1.8$ eV (ruby light) we get $n=6$. The probability is now $W \cong 10^{17} [2.5 \times 10^{-15}\,P(\mathrm{W/cm^2})]^6 \mathrm{sec}^{-1}$; i. e. for an average light intensity of $P = 10^{12}$ W/cm^2 we obtain $W \cong 30$ sec^{-1}. Starting with a solid target of $\sim 10^{23}$ atoms per cm^3 approximately 10^{12} atoms will be ionized within a time of 10^{-12} sec. It should be mentioned that the always present impurities in the target provide electronic levels of lower energy; these impurities are more readily ionized increasing the number of electrons still further.

When free electrons are generated, the formation of the plasma proceeds via a more rapid process, the cascade ionization of the target. The development of the cascade is determined by the rate of growth of the electron energy in the radiation field. It was pointed out by RAIZER [16, 17] that the energy gain of an electron can be treated classically for light fields somewhat below 10^8 V/cm. In our experiments the light fields approach values of $F_{\mathrm{exp}} \cong 19 [P_{\mathrm{max}}(\mathrm{W/cm^2})]^{1/2} \cong 3 \times 10^7$ V/cm, which agree with the con-

[15] L. V. KELDYSH, Soviet Phys.-JETP **20**, 1307 [1965].
[16] YA. B. ZELDOVICH and YU. P. RAIZER, Soviet Phys.-JETP **20**, 772 [1965].
[17] YU. P. RAIZER, Soviet Phys.-Usp. **8**, 650 [1966].

dition given above. In an oscillating electric field of frequency ω the mean oscillation energy of the electron is $e^2 F^2/m\,\omega^2$. For our highest light fields this oscillation energy is approximately 0.2 eV. The electron acquires larger energy values from the light waves when it collides elastically with atoms or ions. The rate of growth of the electron energy is approximately given by the equation

$$\mathrm{d}\varepsilon/\mathrm{d}t = e^2 F^2 \nu/m\,\omega^2 \tag{1}$$

where ν represents an effective frequency of collisions with the atoms. The magnitude of ν is estimated by $\nu = n_A\,\sigma\,v$, where n_A is the density of the atoms, σ is an effective scattering cross section of approximately 10^{-17} cm^2 and v is the electron velocity $v = (2\,\varepsilon/m_e)^{1/2}$. Neglecting the energy losses in elastic collisions with the atoms we calculate the time t_i necessary for doubling the electron concentration by integrating Eq. (1) from $\varepsilon = 0$ to $\varepsilon = I$

$$t_i = m_e^{3/2}\cdot\omega^2\sqrt{I}/(e^2 F^2 \sqrt{2}\cdot n_A\,\sigma)\,. \tag{2}$$

Using the experimental values $\omega = 2.7\times10^{15}$; $F = 3\times10^7$ V/cm; $n_A = 6\times10^{22}$ cm^{-3} (LiH target) and $I \cong 10$ eV, the value for t_i comes out to be 10^{-12} sec. This calculation indicates that at the very high electric field of the laser and at the high density of the target the electrons acquire energies of the order of the ionization potential in the short time of 10^{-12} sec.

The number of electrons in the cascade increases rapidly according to $n_e = n_{e0}\,2^{t/t_i}$. Starting with the multiquantum concentration of $n_{e0} \cong 10^{12}$ cm^{-3} a highly ionized plasma of the order of 10^{20} cm^{-3} is formed in the time of less than 10^{-10} sec. As shown in the previous chapter and discussed in details below, the rapid plasma formation occurs in a very thin surface layer of the target [18].

In order to discuss the heating of a dense plasma we require a knowledge of its optical properties. The heating mechanism itself should not be discussed here. The macroscopic optical constants, the absorption coefficient and the index of refraction have been treated by several authors [19–21]. We wish to discuss here only those points which are relevant to the plasmas produced on solid targets.

B) The Optical Constants of a Dense Plasma

The absorption coefficient K and the reflectivity R of a plasma are determined by three parameters: the frequency of the incident light ω, the density n_e and the temperature T_e of the electrons. Strong changes of K and R occur, when n_e approaches a critical value n_{ep}; at this electron concentration n_{ep} the corresponding plasma frequency

$$\omega_P = (4\,\pi\,e^2\,n_{ep}/m_e)^{1/2}$$

is equal to the frequency of the incident light. In our experiments the frequency of the laser light is $\omega = 2.7\times10^{15}$ sec^{-1} and the critical electron concentration is calculated to be $n_{ep} = 2.3\times10^{21}$ cm^{-3}.

For $n_e > n_{ep}$ the absorption coefficient K is independent of T_e:

$$K = (2\,\omega/c)\,(n_e/n_{ep} - 1)^{1/2}, \qquad n_e > n_{ep}\,. \tag{3}$$

It can be seen from Eq. (3) that K is very large with values exceeding 10^4 cm^{-1}; i. e. the penetration depth of light is smaller than the wavelength $1/K < 2\,\pi\,c/\omega$.

For $n_e < n_{ep}$, we have approximately

$$K = \mathrm{const}\,\frac{Z\,n_e^2}{(k\,T_e)^{3/2}}\,(1 - n_e/n_{ep})^{-1/2}, \qquad n_e < n_{ep}\,. \tag{4}$$

Representative values for K calculated for $k\,T_e = 100$ eV are listed in Table 1. The rapid change of K in the neighbourhood of $n_e = n_{ep} = 2.3\times10^{21}$ cm^{-3} is quite apparent.

The amount of light penetrating the plasma, $A = 1 - R$, is again a strong function of the electron concentration. For a sharp boundary R can be calculated from the values of K and n (the index of

n_e	5×10^{22}	10^{22}	5×10^{21}	3×10^{21}	10^{21}	5×10^{20}	2×10^{20}
K	8×10^5	3.3×10^5	2×10^5	1×10^3	4.5×10^2	60	10
A	0.03	0.026	0.025	0.03	1.0	1.0	1.0

Table 1. Absorption coefficient K [cm^{-1}] and amount of light penetrating ($A = 1 - R$) a plasma of various electron densities n_e. A LiD plasma of 100 eV electron energy is assumed.

[18] It should be noted that the energy necessary for the evaporation of a layer of 10^{-4} cm is provided by our laser pulse in approximately 10^{-10} sec.

[19] N. G. Basov and O. N. Krokhin, Soviet Phys.-JETP 19, 123 [1964].

[20] J. M. Dawson and C. Oberman, Phys. Fluids 5, 517 [1962].

[21] H. Hora, Inst. Plasmaphysik Garching, Rep. IPP 6/23 [1965].

refraction) using FRESNEL's equations. It has been shown (for perpendicular incidence) that for $n_e > n_{ep}$ the magnitude of A is quite small (<0.1) because of the high reflectivity of these very dense plasmas. (A is inversely proportional to T_e.) In Table 1, values of A, calculated for a LiD plasma of 100 eV, are listed for various electron concentrations. The change of A near n_{ep} should be noted.

In our investigations we start with plasmas of the high ion density of about 10^{22} cm^{-3}. Initially, a very thin plasma layer will be formed because of the high reflectivity and the small penetration depth of the laser light. The plasma, rapidly expanding into the vacuum, will absorb energy from the light beam according to Eq. (3) or (4), depending upon the local electron concentration. In Fig. 5 the value of

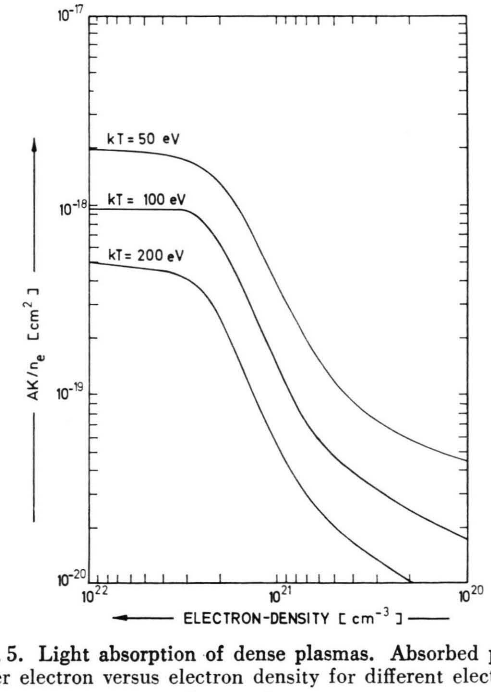

Fig. 5. **Light absorption of dense plasmas.** Absorbed power per electron versus electron density for different electron temperatures.

$A\,K(n_e, T_e)/n_e$, a measure of the absorbed power per electron, is plotted versus electron density n_e. It can be seen that for $n_e \leqq 10^{20}$ cm^{-3} the light absorption is very small and the plasma is highly transparent. Good absorption and resulting heating of the plasma will occur for $2 \cdot 10^{20} < n_e < 2 \times 10^{21}$ cm^{-3} over a depth of approximately $1/K(n_e, T_e)$. It is concluded from Fig. 5 that the absorption depth in our plasmas is approximately several 10^{-2} cm.

C) Energy Gain of the Plasma

In a plasma the absorption of light occurs predominantly by the electrons. A layer of thickness Δx and of unit cross section contains $n_e\,\Delta x$ electrons; these electrons absorb from an incident light beam of intensity P the amount $\Delta P = P\,K\,\Delta x$. If we denote by ε the average energy per electron, then the rate of growth of the electron energy is given by:

$$d\varepsilon/dt = P\,K(n_e, T_e)/n_e\,. \tag{5}$$

As discussed in the last chapter, the absorption coefficient K is a function of the electron concentration and the electron temperature. At an early time of the plasma formation, the high density of the plasma and the large collision rate between the electrons establishes a thermodynamic equilibrium quite rapidly; under these conditions we can speak of an electron temperature T_e.

The ions of the plasma gain energy from the heated electrons in two ways. First, direct electron-ion collisions increase the random motion of the ions leading to an isotropic expansion of the plasma. Second, electrostatic interaction of the more rapidly expanding electrons and the following ions results in a directional expansion of the predominant plasma; the main plasma stream occurs normal to the target surface, since the highly absorbing plasma consists of a thin plasma sheet. Such directional plasma expansion has been observed previously [12].

From energy conservation we obtain:

$$\frac{d\varepsilon_L}{dt} = \frac{d\varepsilon_{ion}}{dt} + \frac{d(k\,T_e)}{dt}\,, \tag{6}$$

i. e. the power absorbed from the light beam is equal to the growth rate of the ion energy plus the temperature rise of the electrons.

DAWSON [22] has solved an equation similar to Eq. (6) making several important assumptions e. g. spherical plasma of constant number of particles, of homogeneous spatial density and of homogeneous particle temperature (resulting from infinite thermal conductivity).

These assumptions are not fulfilled by the plasmas discussed in this paper. The plasma expands predominantly normally to the target surface, there is a large density gradient close to the target surface, and the expanding plasma stream contains large variations in particle energies. Because of this more complicated physical situation the mathematical

[22] J. M. DAWSON, Phys. Fluids 7, 981 [1964].

treatment is very difficult. In the following, only an estimate of the expanding ion stream should be made.

It was shown in the previous chapter that the incident light beam is strongly absorbed within a plasma sheet of the order of 10^{-2} cm. The absorbed light heats the plasma resulting in an expanding plasma stream. The particles leaving this zone are continously replenished by the plasma generated on the target surface.

The energy gain of an electron during a short time τ is given according to Eq. (5):

$$\varepsilon \cong P\, K^{*}(n_e, T_e)\; \tau/n_e \tag{7}$$

where $K^{*}(n_e, T_e)$ is a mean absorption coefficient applicable for the time τ. The energy absorbed by the electrons will be transferred to the ions which we observe as an expanding particle stream. Since losses (heat conduction, radiation) are estimated to be small the expansion energy E_{ion} of the ions (which have lost Z electrons) is

$$E_{ion} = Z\,\varepsilon = Z\,P\,K^{*}\,\tau/n_e\,. \tag{8}$$

We eliminate K^{*} by the following argument. Light is absorbed in the plasma within a depth of approximately $1/K^{*}$. When we denote with τ, the time which the particles require to traverse the length $1/K^{*}$, their velocity is $v \cong 1/K^{*}\,\tau$. The particle flux expanding from the target surface is estimated as:

$$\frac{dN}{F\,dt} = v\,n_{ion} = v\,n_e/Z \cong P/E_{ion}\,. \tag{9}$$

It should be kept in mind that the particle velocities and the concentrations are functions of x, the distance from the target surface. Introducing our experimental values $P_e = 3\times10^{11}$ Watt/cm^2, $E_{ion} =$ 1.8 keV and $F = 3\times10^{-4}$ cm^2, we obtain $dN/dt = 3\times10^{23}$ sec^{-1}; i. e. during a light pulse of approximately 10^{-8} sec, $N = 3\times10^{15}$ ions leave the target. This number should be compared with the number of atoms which interacted with the light beam. The experiments on the thin LiH targets suggested a penetration depth of approximately 3×10^{-4} cm; together with a focus cross section of 3×10^{-4} cm^2, we obtain a LiH volume of 9×10^{-8} cm^3 which contains 5×10^{15} atoms. This particle number agrees well with the number estimated above. It is interesting to note that in a previous investigation the number of expanding ions were measured directly with an electrostatic detector [12]. At similar laser intensities the number of ions were found to be approximately 2×10^{15} in relative good agreement with the values above.

It was shown in the last chapter that the expanding plasma will gain no additional energy from the light wave for low electron concentration, i. e. after a certain expansion, the velocity of the expanding plasma will remain constant. The particle flux will continue to decrease somewhat with distance from the target because of the divergence of the particle stream. If we neglect the latter factor and calculate the particle density in this plasma stream, we obtain using Eq. (8) (with $P = 3\times10^{11}$ Watt/cm^2, $E_{ion} =$ 1.8 keV, and the final particle velocity $v = 2\times10^{7}$ cm/sec) a value for the electron density of $n_e \cong 10^{20}$ cm^{-3}. This value is quite reasonable on account of our knowledge of the electron absorption.