

## INVESTIGATION OF A LASER MICROPLASMA IN THE FOCUS OF TWO LASER BEAMS

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Results are presented of an experimental investigation of the properties of a plasma produced by focusing two opposing laser beams onto small crystalline lithium hydride targets. It is found that development of plasma formation proceeds in a more symmetric manner than in the case of a single laser beam. The velocity rate of expansion of the external plasma layer is measured ( $v \approx 4 \times 10^7$  cm/sec) as well as the velocity of the glowing boundary of the central zone ( $v' \approx 2 \times 10^6$  cm/sec).

### 1. INTRODUCTION

EVAPORATION and ionization of matter at the focus of a powerful pulsed laser, as a method of producing a hot and dense plasma detached from the walls, was investigated in a number of papers.<sup>[1-6]</sup> Haught and Polk<sup>[4, 5]</sup> have shown that lithium-hydride targets with dimensions  $(1-3) \times 10^{-3}$  cm (total number of atoms  $N \sim 3 \times 10^{15}$ ) yield a spherically symmetrical microplasma, in which the particle energy is determined by the peak power  $P$  and by the duration  $\tau$  of the laser pulse:  $\mathcal{E} \sim P^{1/3} \tau^{-1/2}$ . When the target dimensions are increased to  $(2-3) \times 10^{-2}$  cm, the produced microplasma is characterized by an asymmetrical structure, although the target dimensions are still smaller than the diameter of the laser beam at the focus of the lens.<sup>[6]</sup> The reason for it is that at such dimensions the time necessary for the evaporation and ionization of all the target atoms becomes of the order of or larger than the duration of the laser pulse. Such an asymmetrical structure is undesirable in experiments aimed at the study of the capture of plasma by a magnetic field, since it makes the interpretation of the experimental data difficult.

The increase of the power of a laser pulse, using only one beam, is apparently an ineffective means of increasing the rate of transition of the target matter into the plasma state. A theoretical analysis of the process of plasma formation at the focus of a laser, with allowance for the gas dynamic motion of the produced plasma, carried out in<sup>[7, 8]</sup> shows that the rate of evaporation of the target material  $dM/dt$  depends relatively little on the laser radiation flux density  $q_0$ , and decreases with time if the flux is stationary:  $dM/dt \sim q_0^{1/2} t^{-1/4}$ . At the same time, an increase of the radiation power in a giant pulse entails difficulties due to damage of the active material of solid state lasers at fluxes  $10^9-10^{10}$  W/cm<sup>2</sup>.

The difficulties connected with the increase radiation power flux at the focus and with obtaining spatially-symmetrical microplasma with a total number of particles  $N \sim 10^{16}-10^{18}$ , can be overcome in part by using several laser beams focused simultaneously on the targets from several directions. This increases the total radiation power and the rate of transition of the target material into the plasma state in proportion to the num-

ber of beams. We present in this article the results of the investigation of the properties of the plasma produced when targets of lithium hydride are irradiated with two laser beams from opposite directions.

### 2. EXPERIMENT

The experimental setup is shown in Fig. 1. The radiation from neodymium-glass laser 1 is split by a prism 3 into two beams of approximately equal intensity, each of which passes through a system of deflecting prisms 4, amplifier stages 5 and is focused on a lithium-hydride target 8 mounted in the center of vacuum chamber 9. This gives rise to symmetrical irradiation of the targets from both sides with a synchronization accuracy determined by the equality of the geometrical paths in both arms ( $\sim 3 \times 10^{-10}$  sec at an arm-length difference of 10 cm). The intensity of the laser radiation in each beam can be increased by increasing the number of amplifier stages 5 up to the limit imposed by damage of the glass used in the last stages.

Typical values of the energy, the peak power, and the half-width of the radiation pulse under the experimental conditions were 2.5 J, 150 MW, and 15 nsec for each

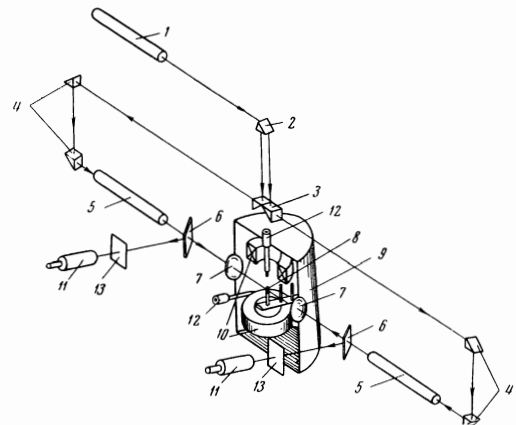


FIG. 1. Experimental setup. 1 - Driving laser, 2 - deflecting prism, 3 - beam-splitting prism, 4 - deflecting prisms, 5 - amplifier stages, 6 - transparent plates, 7 - lenses, 8 - target, 9 - chamber, 10 - magnetic-field coils, 11 - FÉK-14 coaxial photocell, 12 - electric probes, 13 - attenuators.

beam. The focal length of the lenses were 7.5 cm, and the diameter of the focal spot was  $6 \times 10^{-2}$  cm. Targets of crystalline lithium hydride had an approximate form of a parallelepiped with height  $\sim 0.2$  cm and a cross section  $(0.6-2) \times 10^{-3}$  cm<sup>2</sup>, and were mounted in the center of the chamber on a metallic needle. The total number of the target atoms at the focus amounts to  $5 \times 10^{18}-10^{19}$  for the given dimensions. The chamber was evacuated to a pressure  $10^{-5}$  Torr. Two coils can serve for the production of a magnetic field of mirror configuration with amplitude up to 20 kG at the center of the chamber and 45 kG in the "mirror" at a distance 2.5 cm from the center. The experiments were performed at magnetic-field values at the center of the chamber  $B = 0$  and  $B = 12$  kG.

To measure the laser-radiation energy consumed in the production and heating of the plasma, we produced simultaneously oscillograms of the laser pulse at the entrance to the chamber and at exits from the chamber, using coaxial photocells FÉK-14 (11) and two high-speed oscilloscopes. Attenuators 13 at the inputs of the photocells were chosen in such a way that the signals were identical in the absence of the target. The contribution of the second-beam radiation reflected by the target was determined independently using one laser beam. Typical oscillograms are shown in Fig. 2a. The fraction of the absorbed energy of the laser radiation in accordance with the obtained data is  $\sim 50\%$  and does not depend on the magnetic field. The degree of transparency of the focal region for the laser radiation increases monotonically, reaching 100% at the end of the laser pulse. The foregoing is illustrated by the curves of Fig. 2b, obtained by reducing the oscillograms.

To study the dynamics of the behavior of the produced microplasma, we used photographs of the time-scanned glow of the plasma, using an electron optical converter (EOC) camera, registration of the radiation in individual lines of the plasma spectrum with the aid of a spectrograph (ISP-51) and a photomultiplier, and electric probes. The probe measurements of the plasma potential were used to determine the character and rate of expansion of the plasma formation in different directions. The probes were located on top along the radius of the chamber, at a distance 2 cm from the center, at angles 45, 90, and 135° to the laser-beam axis. The obtained oscillograms indicate that in the absence of a magnetic field, in the case of two laser beams, the expansion of the plasma is approximately the same in all directions, whereas when the irradiation is from one side only, the development of the plasma formation proceeds preferably in the region adjacent to the target from the side of the laser beam. Oscillograms of signal from diametrically opposite probes, using one and two laser beams, are shown in Fig. 3.

The average velocity of the plasma boundary was de-

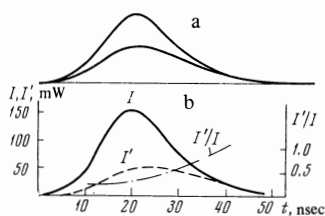


FIG. 2. a – Oscillograms of incident and transmitted radiation of laser pulse, b – plots of the intensity of the incident (I) and transmitted (I') radiation and of the ratio I'/I.



FIG. 3

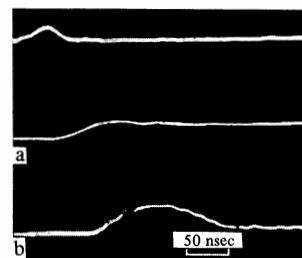


FIG. 4

FIG. 3. Oscillograms of signals from two probes placed along the diameter of the chamber at an angle of 45° to the laser beam axis: a – two laser beams, b – one laser beam.

FIG. 4. Oscillograms of laser pulse (top) and of signal from the probe at magnetic-field values  $B = 0$  (a) and  $B = 12$  kG (b).

termined with an S1-14 oscilloscope from the time interval between the laser pulse and the signal from the probe (Fig. 4). The sweep was triggered by the laser-pulse signal. The obtained value of the velocity is  $4 \times 10^7$  cm/sec. Superposition of an external magnetic field of 12 kG leads to an increase of the transit time by approximately two times.

The symmetry of the plasma expansion when two laser beams are used is confirmed by photographs taken with the electron optical converter camera. The motion of the glowing boundary along the laser axis and in two directions in the perpendicular plane was registered. The overall view of the obtained photographs is the



FIG. 5. Photographs of the expansion of the glowing boundary of a plasma along the laser beam (top) and in the perpendicular plane (bottom),  $B = 0$ .

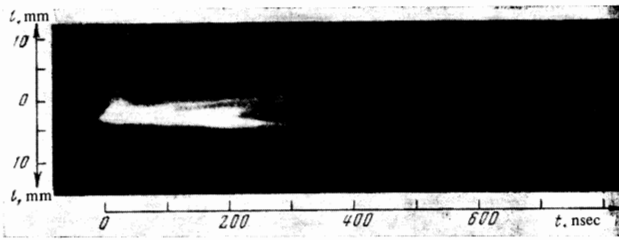


FIG. 6. Expansion of glowing boundary across the magnetic field,  $B = 12$  kG.

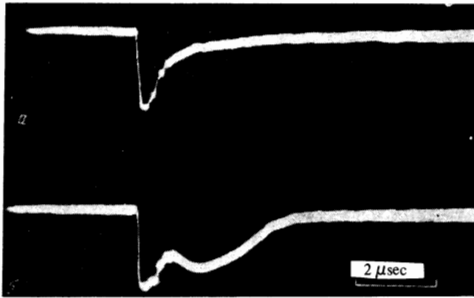


FIG. 7. Emission in the Li II line (5484.7 Å) at  $B = 0$  (a) and at  $B = 12$  kG (b).

same for all three projections (Fig. 5). The photograph of the motion of the glow boundary perpendicular to the magnetic field  $B = 12$  kG and the signals showing the glow of the Li II line (5484.7 Å) of the plasma are shown in Figs. 6 and 7.

### 3. DISCUSSION OF RESULTS

The obtained photographs of the glow of the plasma show that there are two distinct stages in the development of the laser plasma. In the first stage, plasma production takes place with simultaneous heating of the outer layers of the plasma as the result of absorption of the laser radiation. The absorption of the radiation by the surface layers of the target, at fluxes  $\approx 10^9$  W/cm<sup>2</sup>, can lead to a direct transformation of the matter into a vapor having a density of the same order as the solid; the gasdynamic expansion of the produced vapor displaces the absorption and ionization boundary.<sup>[9]</sup> Intense absorption of the laser radiation in the thin layer on the boundary of the nontransparency zone produces large temperature and density gradients; these were experimentally investigated by Basov and co-workers.<sup>[10, 11]</sup>

In accordance with the foregoing, in this stage the photographs show the formation of a brightly glowing central zone with a sharp boundary, expanding with a velocity  $v' \approx 2 \times 10^6$  cm/sec. The outer layers of this zone, after absorbing the laser radiation, form a flux of a weakly-glowing plasma, expanding at a rate of  $\approx 4 \times 10^7$  cm/sec. The external magnetic field  $B = 12$  kG

does not exert a noticeable influence on the dynamics of the behavior of the plasma of the central zone in this stage, since the gasdynamic pressure of the outer layers  $p$  greatly exceeds the magnetic field:  $p \approx mnv^2 \gg B^2/8\pi$ . For example, for an expansion velocity  $v = 10^7$  cm/sec, a density  $n = 10^{18}$  cm<sup>-3</sup>, and an average atom (ion) mass  $m = 6 \times 10^{-24}$  g, we obtain  $p \approx 10^8 \gg B^2/8\pi \approx 6 \times 10^6$  dyne/cm<sup>2</sup>.

The second stage is gasdynamic expansion of the central zone after the termination of the laser pulse. The boundary of the glowing region becomes less sharp and moves with a radial velocity  $\approx 6 \times 10^6$  cm/sec in the absence of a magnetic field. Application of an external magnetic field  $B = 12$  kG leads to an appreciable decrease (by an approximate factor of 10) of the rate of transverse expansion of the glow boundary after the end of the laser pulse. The duration of the emission in the plasma spectral lines increases by a factor 2–3.

For a detailed analysis of the behavior of a laser plasma in a magnetic field, it is necessary to carry out additional measurements of the temperature and plasma density in the central zone and in the outer layers. The results show that simultaneous focusing of several laser beams on a solid target makes it possible to obtain symmetrical plasma formations, greatly facilitating the problem of investigating their behavior in a magnetic field.

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