In conclusion, the authors thank S.M. Ryvkin for a useful discussion of the problems involved, B.I. Shklovskii for a preprint of [7], and A.G. Zabrodskii for help with the experiment.

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SELF FOCUSING OF LIGHT IN A PLASMA AND SUPERSONIC IONIZATION WAVE IN A LASER BEAM

V.A. Batanov, F.V. Bunkin, A.M. Prokhorov, and V.B. Fedorov
P.N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 21 August 1972
ZhETF Pis. Red. 16, No. 7, 378 - 382 (5 October 1972)

With developed evaporation of a bismuth target in a helium atmosphere of pressure $P_0 = 2.5 - 5$ atm by a laser beam ($\lambda = 1.06\ \mu$) of intensity $I_0 \approx 10^7$ W/cm^2 in a millisecond pulse, we obtained a plasma flare regime that is new for metals (in comparison with [1]), with almost complete absorption of the laser radiation passing through the flare.

The presence of strong absorption in the flare was demonstrated by passing through it a beam inclined 5° to its axis. It was found that at $P_0 = 4$ atm, a light energy $E = 2.3 - 3.6$ kJ in a pulse of $\tau = 0.8$ msec, at a focusing-region dimension $d_0 \approx 0.8$ cm on the target, and a traversed flare length $\ell = 4 - 6$ cm, the beam was attenuated by a factor 5 - 10. This corresponds to an absorption coefficient averaged over time and length $\alpha = 0.4 - 0.6$ cm^{-1}.

The figure shows a time scan of the flare. At the start of the process (Nos. 3 and 11), a detachment and drift of the flare from the target is observed [2]. The detachment of the plasma from the target indicates by itself that the target is strongly screened from the incident radiation by the flare[1]. From the fact that the transverse dimension of the flare becomes stable in time it follows that a pressure P, equal to the external pressure P_0, is established in it as a result of expansion.

The condition $P = P_0$ is the key to the understanding of the investigated processes. It enables us to estimate the temperature T and the electron density n_e of the plasma from the measured bremsstrahlung absorption coefficient $\alpha \approx 0.4$ cm^{-1}. A calculation at $P_0 = 4$ atm yields a value of T in the interval $(1.7 - 2.3) \times 10^4$ °K and $n_e \approx 10^{18}$ cm^{-3}. The degree of the first ionization of bismuth is equal to unity in this case, and the degree of second ionization ranges from 0.09 to 0.75.

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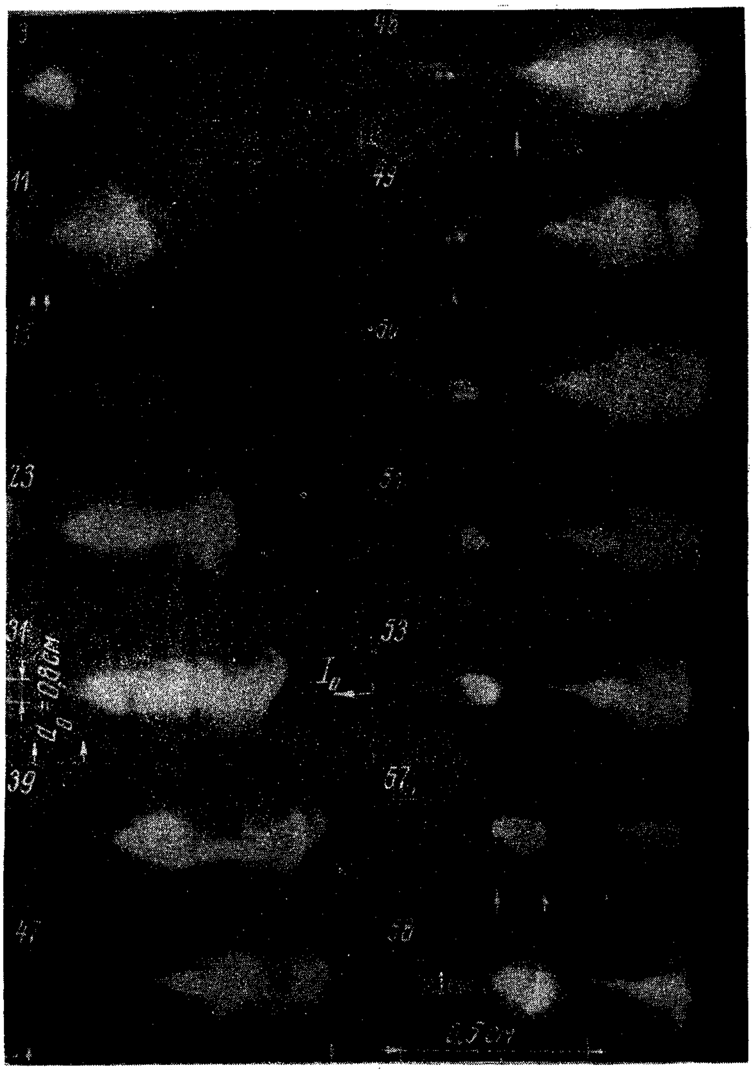
[1] The detachment of the plasma from the target and its connection with the screening of the target by the flare was reported by us in 1969 to the First All-union Conference on the Physics of the Effect of Optical Radiation on Condensed Media, at the Vavilov State Optical Institute. This was the first communication of the possibility of obtaining an absorbing plasma in the vapor of a solid target.



Frame-by-frame time scan of plasma flare from a bismuth target (side view; the beam is perpendicular to the target). Experimental conditions: $P_0 = 4.6$ atm, $E = 3.7$ kJ, $d_0 = 0.8$ cm, $\tau = 0.8$ msec (duration at half the maximum intensity). The background of the spike modulation lies within 30% of the average amplitude. The length of the cylindrical part of the caustic of the focusing lens ($f = 100$ cm) is about 10 cm. The intensity of the incident light in the caustic is $I_0 \simeq 0.9 \times 10^7$ W/cm^2. The frame numbers and the linear scale are shown (60 frames corresponds to a time interval of 1 msec). The arrows mark the surface of the target, the limit of the field of view of the camera (No. 47), the direction of the beam, and the characteristic details of the picture, which are discussed in the text.

Frames 23 and 31 correspond to maintenance of the plasma, which expands to the external pressure P_0, by the beam via the "slow evaporation" mechanism [3]. The plasma cloud drifts from the target in the laser beam along the caustic of the lens. The rear boundary of the cloud is the ionization front, on which a stream of cold vapor is incident. The length of the cloud is increased by the motion of the ionization front through the cold gas in the beam direction.

The condition for maintaining the plasma in the beam is $\alpha I = Q$, where Q is the loss to recombination radiation[2]. Since α and Q are proportional to P^2, the temperature is determined by the intensity, $T(°K) \approx 2.1 \times 10^{-2} Z^{-2} I$ (W/cm^2), where $I = I_0 \exp(-\alpha \ell)$. For $I_0 = 0.9 \times 10^7$ W/cm^2, $\alpha = 0.4$ cm^{-1}, and $\ell = 6$ cm (No. 31) we obtain near the ionization front $I = 0.8 \times 10^6$ W/cm^2 and $T = 1.7 \times 10^4$ °K at an ionization multiplicity $Z = 1$, corresponding to the already mentioned interval $T = (1.7 - 2.3) \times 10^4$ °K.

This is followed, at $P = P_0$, by development of self-focusing instability in the plasma cloud (Nos. 39 - 58). The focusing light cone of the plasma lens produced by the beam is revealed by the sharper plasma glow in the beam direction (Nos. 39, 47). Behind the focus of this lens, the beam diverges, as seen from the weak glow of the cold vapor. The self-focusing takes place slowly and the plasma "follows" the laser beam. The characteristic time of the process, $t_{sf} \sim 10^{-4}$ sec (Nos. 39 - 47), is apparently determined by recombination of the plasma outside the beam. The self-focusing mechanism is such that at $P = P_0$ the laser beam, by virtue of $n_e \sim P_0/T \sim P_0/I$, produces in the plasma cross section a profile $\varepsilon = 1 - \mathrm{const} \cdot n_e$ similar to the profile of I, with a maximum on the beam axis, and is itself focused on this profile. This is made possible by the low thermal conductivity of the plasma: the time required for the thermal conductivity to smooth out the T and n_e profiles produced by the beam over a diameter $d_0 = 0.8$ cm is large, $t_T \sim d_0^2/\chi_e \approx 3$ msec $\gg t_{sf}$ ($\chi_e \sim P_0^{-1} T^{7/2}$ is the electronic thermal conductivity). At the same time, the thermal conductivity limits the maximum self-focusing, since t_T decreases rapidly with decreasing beam diameter d. The experimental ratio (No. 47) is $d_0/d = 4.3$. When account is taken of the attenuation of the beam in the plasma, this yields an estimate $I_{sf} \gtrsim 1.5 \times 10^7$ (W/cm^2) for the intensity in the focus of the plasma lens.[3]

Self-focusing produces a plasmoid in the cold vapor (No. 48). As time goes on, the transverse dimension of the glow from the plasmoid ceases to increase. This indicates that the plasma has expanded to the external pressure. The rate of lateral expansion depends on the pressure P_0. In the figure it is equal to 125 m/sec. In another experiment at $P_0 = 2.7$ atm, $I_0 = 0.55 \times 10^7$ W/cm^2, in which six plasmoids were observed in an interval of 1 msec after the detachment of the plasma from the target, this rate amounts on the average to 220 m/sec. The plasmoid formation mechanism, a flash of absorption in the cold vapor, is analogous to that considered in [5] and is connected with the relation $\alpha \sim \exp(-\Delta/kT)$ (Δ is close to the ionization potential; in the region of weak ionization of the vapor, $\Delta \gg kT$).[4]. The main symptoms of the absorption flash are the following: a) $I_{sf} \gtrsim 1.5 \times 10^7$ W/cm^2 and is lower than the threshold of optical breakdown; b) the plasmoid is produced closer to the target, not

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[2] In this experiment, the loss to heat conduction in the plasma is negligible.

[3] Self-focusing was first discussed theoretically in [4], using plasma as an example, but for a different physical mechanism.

[4] The absorption flash in cold vapor will be analyzed theoretically and experimentally in greater detail in a separate paper.

at the focus of the plasma lens; c) the time of development of the flash (the distance from the plasmoid to the target on No. 48, divided by the vapor velocity) is large in comparison with the time of development of cascade ionization in breakdown, and equals $\sim(10^{-4} - 10^{-5})$ sec. At the start of the pulse, the flash time is shorter (No. 15) and increases towards the end of the pulse (Nos. 48 - 58), owing to the increased absorption of the beam in the plasma cloud at $P - P_0$ as its length increases to the dimension of the cylindrical part of the focusing-lens caustic.

Since the velocity of the flashing part of the glow as it moves opposite to the beam exceeds the drift velocity of the plasma cloud from the target (the plasmoid catches up with the drifting plasma, Nos. 48 - 50), it follows that the plasmoid motion is an ionization wave traveling through the cold vapor between the target and the drifting plasma. One-dimensional wave propagation is maintained by the laser-beam energy absorbed in the wave. The velocity of the leading front of the wave in the figure is 220 - 240 m/sec, and that of the trailing edge is about 100 m/sec. With increasing intensity I and with decreasing pressure $P = P_0$, the wave velocity increases. In the experiment, at $d_0 = 0.8$ cm, $P_0 = 2.7$ atm, and $I_0 = 0.55 \times 10^7$ W/cm^2, the estimated value of $I = I_0 \exp(-\alpha\ell)$ is $\lesssim 2.4 \times 10^6$ W/cm^2, since the bremsstrahlung absorption for Bi under the conditions of this experiment depends little on $T \sim I$ and is determined mainly by the pressure, $\alpha \sim P_0^2$. The indicated value is higher than $I \approx 0.8 \times 10^6$ W/cm^2 on No. 31 of the figure. Accordingly, the velocities of the leading and trailing edges of the ionization wave averaged over the six observed plasmoids, 550 ± 40 m/sec and 360 ± 70 m/sec, exceed the values obtained from the figure. Since the cold-vapor temperature does not exceed the target temperature, and the latter according to Fig. 2 of [6] is $T = 2.4 \times 10^3$ °K at an intensity 2×10^6 W/cm^2 at the target, the speed of sound in the cold bismuth vapor does not exceed 400 m/sec under the conditions of this experiment. Consequently, the observed ionization wave is supersonic[5].

The self-focusing instability cycle terminates when the ionization wave (plasmoid) overtakes the plasma cloud. The process then repeats. The duration of the cycle decreases when I_0 increases and P_0 decreases. As already noted, in the experiment, at $P_0 = 2.7$ atm and $I_0 = 0.55 \times 10^7$ W/cm^2, six cycles of self-focusing instability were observed in the central part of the laser-pulse oscillogram, in a time interval $\tau = 0.8$ msec after the termination of the transient process; the periods of the later cycles were longer than those of the earlier ones.

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