CREATION OF LASER-PLASMA SPHERICAL CLOUDS BY MEANS OF BILATERAL RADIATION

A. A. Avdyeva, Yu. P. Zakharov, V. V. Maksimov,
A. M. Orishich, A. G. Ponomarenko, V. G. Posukh,
V. N. Snytnikov, and A. S. Yatsenko

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The extensive utilization of laser plasma in scientific research (laboratory modeling of nonsteady astrophysical processes [1], the filling of plasma traps [2], etc.) has stimulated much work on the development of plasma streams of various configurations, including those that are most important, and namely, spherical clouds.

We are aware of the fact that it is not possible to create a symmetrically expanding stream, even when subjecting an easily vaporizable deuterium tablet to radiation [3]. The method employed in laser technology to produce a spherically symmetrical plasma through uniform exposure to radiation of a circular target is complex from the technical standpoint. It involves the utilization of a special chamber and a large number of rays ($\gtrsim 9$), which makes considerably more difficult its utilization in large-scale plasma installations intended for special purposes.

It is the goal of the present study to examine the possibilities of using spherically expanding clouds in the presence of simple bilateral radiation of the tablet, and to study the influence of target geometry, i.e., plane, cylindrical, and spherical, on the structure of the plasma corona.

The experiments were conducted on a KI-1 stand, intended for the laboratory modeling of nonsteady astrophysical phenomena [4], in which a laser plasma is used, for example, in experiments to study the mechanisms of collision-free deceleration of the shells of supernovae by the ambient medium [5]. The stand is made up of a vacuum chamber 1.2 m in diameter, 5 m in length, with a residual pressure of 10^{-4} Pa and a laser-beam source, the duration of whose pulse, $\lambda = 10.6$ μm and energy $Q_r \simeq 1$ kJ, can be regulated in the range $\tau_r = 0.05$-1.0 μsec.

Three types of targets were used in the experiments: a spherical target with $\phi = 1$-3 mm, a cylindrical target in the form of a filament with $\phi \simeq 0.3$ mm, and a plane target in the form of a plate with a thickness of 5 mm. All of the targets were fabricated from Caprolon $(C_6H_{11}ON)_n$ [6]. The radiation from the laser source was divided into two identical bundles which were focused in opposite radial directions onto a tablet located at the center of the chamber. The axes of the bundles were inclined to a plane perpendicular to the axis of the chamber at an angle of 10°. The spherical target was suspended on a thin ~0.1 mm metallic strand, while the cylindrical target moved along the axis of the chamber. The plane target was positioned at the same point, but irradiated from one side only, at an angle of $\alpha = 30°$ to the normal to the surface. The cross section of the bundle in the area of the target was $S = d^2 = 16$ mm². In these experiments we used a bell-shaped pulse with a duration of 0.5 μsec at the midpoint of the altitude. The average power of the stream to the target was $J_r \simeq 3 \cdot 10^9$ W/cm².

The diagnostic complex included electric probes [7], j_r ion flux collectors [8], a Mach-Zehnder interferometer at $\lambda = 0.694$ μm with field visualization covering 50 × 50 mm, a time resolution of ~30 nsec, an electron-optical converter, and a device to analyze the mass and charge composition [8]. A large number (~10) of special leads, as well as movable probes, made it possible simultaneously to carry out measurement at various angles (θ, φ) and at various distances (R = 20-60 cm) from the target. The interferometric measurements were monitored by means of the plasma concentration at $R \lesssim 1.0$ cm. The number of particles in the cloud and their total energy is determined by the method described in [9].

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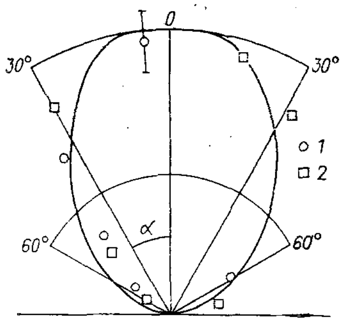

Fig. 1

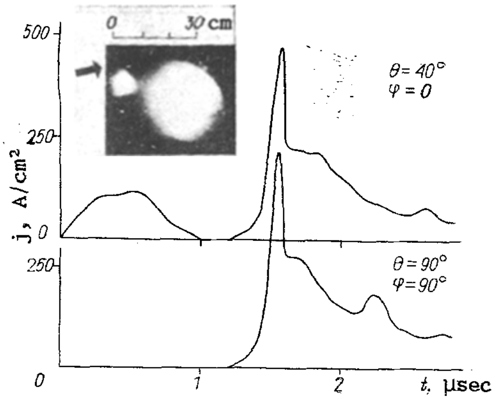

Fig. 2

The measurements showed that the distribution of the number of particles in the cloud, propagated per unit of solid angle $\left(dN/d\Omega = R^2\int\limits_0^\infty j_r\,dt\right)$, is governed by the geometry of the target. Thus, for a plane target we observed a certain distribution $dN/d\Omega \approx \cos^k\alpha$ [10], where $k = 2\text{-}3$; α is the angle calculated from the normal to the surface. The cylindrical target, where its length exceeds that of the diameter, is characterized by a similar distribution in a plane corresponding with the axis of the filament $dN/d\Omega \sim j_r \sim \sin^k\theta$ ($\theta = \pi/2 - \alpha$ is the angle relative to the axis). Figure 1 shows the data for the plane target and these are identified with the numeral 1, while the data for the filament are identified with the numeral 2; the solid line represents the function $\cos^2\alpha$. In the plane perpendicular to the filament we find that the flow relative to the axis of the target exhibits axial symmetry. The deviation of the parameters measured at various angles φ does not exceed ±15% with respect to the number of particles and it does not exceed ±10% with respect to the average velocity.

The use of a circular target enabled us to develop a virtually spherical cloud. Figure 2 shows a diagram of the electron-optical illumination of the cloud as well as the density of the j_r ion flux at various angles θ and φ at $R = 21$ cm. We find good agreement between these flows. Here we also note the shape of the radiation pulse, and the arrow points to the plasma burst in the mirror of the focusing system. With a tablet diameter of 3 mm we have $3 \cdot 10^{18}$ ions with a total energy of ~125 J (an efficiency of ~0.25).

Thus, under the conditions of our experiment, with relatively low power ($J_r \sim 3 \cdot 10^9$ W/cm^2) the distribution of the plasma flow in some spatial plane is determined by the geometry of the target cross section in that plane. In particular, in the irradiation of the filament certain properties of the flow become apparent, such as those that are characteristic of a sphere, and namely, axial symmetry, as well as those that are characteristic of a plane, i.e., the distribution of the plasma along the filament. Significant is that circumstance that spherical (or axial) symmetry is satisfied not only for the integral parameters of the plasma (the number of particles $dN/d\Omega$, the average velocity V), but also for the structure of the flow. Thus, when a circular target is subjected to a radiation pulse of considerable duration ($\tau_r \gtrsim 0.5$ μsec) we observe the formation of a thin ($\Delta R/R \lesssim 0.1$) spherical shell of elevated concentration at the leading front of the cloud, corresponding to the flow maximum seen in Fig. 2. The mechanism for the generation of this shell, studied experimentally in [4] and by the methods of numerical modeling [11], is associated with the nonsteadiness of the process of plasma formation near the target, governed by the finite magnitude of the pulse front τ_φ, exceeding the hydrodynamic scale of ion acceleration ($\tau_\varphi \gg d/c_s$, c_s is the speed of sound). As a result of the increase in power during the time τ_φ a plasma stream is generated with a continuously increasing velocity and its interaction with the leading layers of the plasma leads to the formation of a discontinuity whose disintegration is accompanied by the appearance of a compression zone which moves in the form of a shell to the edge of the cloud with a vacuum. In the case of a cylindrical target the axial-symmetrical shell appears basically quasiperpendicular to the axis at angles of $\theta = 60\text{-}120°$.

The existence of spherical symmetry in the cloud with a circular tablet shows that the process of forming the flow at various angles proceeds identically in the case of a clearly

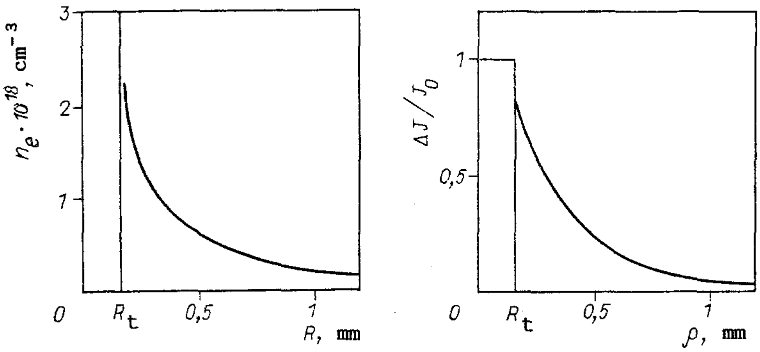

Fig. 3

nonuniform exposure of the surface to radiation. This circumstance provides a basis for the assumption that in this case a process of equalization of the absorbed energy over the target surface is found to occur within the plasma corona. Let us examine the possible mechanism responsible for the uniform heating of the tablet. A typical distribution of plasma concentration along the radius is $n_e(R)$ near the target filament with $\phi = 0.3$ mm when $J_r \simeq 2 \cdot 10^9$ W/cm^2, $\tau_r = 0.52$ μsec and Fig. 3 shows the corresponding calculation results for the fraction of the absorbed power flux moving through the plasma together with the target, i.e., $\Delta J_r/J_r$, in dependence on the directional parameter ρ of the ray for $T_e = 20$ eV [10]. With consideration of the limited convergence (<0.1) the laser bundle near the target is assumed to be parallel. The effect of refraction when $n_e < 2.5 \cdot 10^{18}$ cm^{-3} is insignificant. In determining $\Delta J_r/J_r$ we took into consideration only the absorption that occurred along the path of the ray to the plane of the target as a consequence of the reverse deceleration mechanism having the local coefficient [12]

$$K = \omega^2{}_p/[c\omega\tau(\omega^2 - \omega^2{}_p)^{1/2}],$$

where τ^{-1} is the frequency of the electron—ion collisions; $\tau = 2.4 \cdot 10^4 T_e{}^{3/2}/n_e z$; T_e is the electron temperature, eV; z is the ion charge; $\omega_p = (4\pi n e^2/m)^{1/2}$ is the plasma frequency; ω is the radiation frequency.

Figure 3 shows that fraction of the symmetry absorbed in the cross section of the target when $\rho \leq R_t$ ($R_t = \phi/2$) and it is comparable to the energy absorbed when $\rho > R_t$. The characteristic dimension of the absorption layer increases as the surface curvature decreases from $\delta \sim 0.3$ mm for $\phi = 0.3$ mm to $\delta \sim 4$ mm for a plane surface. Estimates show that the absorption of the energy in the layer occurs with a comparable efficiency both in the case of normal incidence of the ray and in the case of tangential incidence.

Additional experiments were carried out to study the unique features involved in the absorption of laser-plasma radiation for a cylindrical target with $\phi < d$ in the case of unilateral radiation. We measured the energy of the laser bundle passing the filament in two regimes: 1) in the absence of a plasma, with $J_r \simeq 10^6$ W/cm^2; 2) in the presence of a plasma with $J_r \simeq 3 \cdot 10^9$ W/cm^2. The aperture of the measurement system allowed us to record the signal, with consideration of the possible refraction deflection. Measurements showed that the fraction of the radiation retained by the target and by the surrounding plasma in regime 2 exceeds by a factor of approximately 2 the corresponding losses in regime 1. Further experimentation confirms the presence of a layer with $\delta \sim R_t$ in which the energy of the laser radiation is effectively absorbed.

Let us examine the conditions under which the radiation may be absorbed in the corona. Estimates analogous to those in [12] show that the integral coefficient of absorption

$$K_t = \xi L/(c\tau_*).$$

Here $L = [(1/n_e)dn_e/dR]^{-1}$ is the characteristic dimension of plasma nonuniformity; τ_* is the time for the collisions, determined for the critical density; ξ is a parameter which takes into consideration the specific density distribution. According to $T_e \simeq 1 \cdot 10^{-3} J_r{}^{4/9}$ [10, 13], from the condition $K_t \gtrsim 1$ we obtain an estimate for the power flux at which the radiation will be absorbed in a layer of thickness L: $J_r \lesssim 9 \cdot 10^{12}(\xi z L)^{3/2}$. Thus, for $L \simeq R_t = 0.015$ cm, $z = 3$, $\xi \sim 1$ we have $J_r \lesssim 10^{11}$ W/cm^2.

Let us take note of the fact that the found relationship actually determines the condition of energy absorption due to the inverse deceleration mechanism in the laser plasma regardless of target configuration. Analogous results of calculations can be found in [14] for the case of a plane target.

Thus, we have examined the influence exerted by the geometry of a target on the configuration of the plasma corona and for the first time we have experimentally demonstrated the possibility and evaluated the condition for the formation of spherical plasma clouds in simple bilateral irradiation of circular tablets.

In conclusion, we note that in reconstructing the spatial distribution of the concentration of n_e electrons, in this particular study we used the "TOPAS" collection of computer tomography programs [15]. The authors would like to express their gratitude to V. V. Pikalov for his assistance and consultation on this portion of the project.

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