Investigation of the dynamics of expansion of the near-surface light erosion plasma formed during the evaporation of a material by broadband high-brightness radiation

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Abstract. The dynamics of the vapor-plasma flows formed at impact of erosion type magnetoplasma compressor (MPC) discharge radiation on Ti, Al and PTFE targets with use of methods of a holographic interferometry and schlieren photos (Toepler’s scheme in the light field mode) is investigated. In the schlieren and interferogram photos, zones characteristic of the studied process of radiation interaction with matter are well visible: the gas-dynamic evaporation mode is realized (plasma piston mode), there is a shock wave in the gas, the contact boundary between the shock-compressed gas and the vapor plasma. The interferograms analysis indicates that the regime of developed evaporation is preceded by a regime of diffusion evaporation. On the interferograms above the targets at different distances from the radiation source (from the MPC), we observe 3 types of gas-dynamic perturbations: an acoustic wave, a simple wave (Riemann wave), and a shock wave. Qualitative and quantitative description of processes in these zones is discussed in the report. The effect of the radiation spectral composition (we use the method of gas spectral selection), the targets materials, and the degree of surface treatment on the evaporation is shown experimentally.

1. Introduction
Light erosion gas-plasma flows (LEF) are generated by high-intensity optical effects on the surface of condensed media. The study of such flows seems relevant both for solving the problems of modern physics of nonequilibrium spatially inhomogeneous plasma and in connection with numerous technical problems. For example, the erosion of an insulator and electrodes under the action of radiation actually determines the mode of operation of some plasma accelerators and electrodynamic devices [1–3], the use of ablative and light-erosion methods for generating and accelerating gas-plasma flows in plasma-laser accelerators and injectors [4–7], the ablation of heat-shielding layers when a body enters the atmosphere is largely determined by the action of the light flux on the wall [8].

2. Experimental condition
In the present work, the dynamics of the expansion of a near-surface light erosion plasma were investigated. The samples, bars of Al, Ti, and PTFE (30 mm by 50 mm and 10 mm thick), were irradiated with intense pulsed broadband radiation with controlled spectral composition. The radiation source was the erosion type magnetoplasma compressor (MPC) discharge in gas (Ne, Ar, a mixture of Ne with 5% air; $p_{Ar} = 200$ Torr, $p_{Ne} = 400$ Torr), described in [9, 10]. The samples were mounted by
the long side at a distance of 45 mm along the MPC axis (figure 1). Due to this geometry, the radiation flux density at the near and far ends of the sample from the discharge differed by 2–2.5 times. This made it possible to observe different modes of evaporation and transitions between them in one experiment (see below).

The radiation of the erosion type MPC discharge in gas is characterized by high spectral brightness characteristics in the UV and near-vacuum UV (VUV) spectral regions [15]. The light efficiency of this type of device is 40–60% of the energy invested in the plasma [10, 15].

For visualization of shock waves (SW) and other expansion zones of vapor-plasma flow in external gas with large concentration gradients, two-exposure laser holographic interferometry [11, 12] with visualization of large optical fields and the Toeppler method in the light field mode [12] were used. The diagnostic circuit is described in [9, 14]. The second harmonic of a Solar LQ-115 Nd:YAG laser operating in the modulated Q-factor ($\lambda_{sh} = 532$ nm; $W_{sh} = 40$ mJ, $\tau = 7$ ns) was used as a probing radiation source.

![Figure 1](image.png)

**Figure 1.** The scheme of the experiment (a), photo of the targets installation in the discharge chamber (b) and the type of targets from Ti – (c) and Al – (d).

At the two-exposure holographic interferometry the first exposure became before to the beginning of the studied process; the second – was synchronized with the point of interest of the studied process. To obtain interferograms in bands of a finite width [16], which makes it possible to obtain the absolute values of the change in the refractive index, it is necessary to change the angle between the objective and reference beams between exposures. This is achieved by placing a wedge of quartz glass KU-1 with a refracting angle $\gamma = 5^\circ$ in the object beam. Between the two exposures, the wedge was rotated around the beam axis through an angle of $\alpha \sim 3^\circ$. The frequency of the bands, in this case, turned out to be 12–13 cm$^{-1}$.

It is known that the requirements for the spatial and temporal coherence of the light used to reconstruct the image can be significantly reduced if the object was focused on it when receiving the hologram. Each point of the hologram here corresponds to its specific point of the object. Almost a hologram of the focused image was obtained by focusing the object (in our case, the near-surface gas-plasma flow) using a lens system on a holographic film of VRP-M sensitive to the green spectrum. As for the holograms of the focused image, the spectral composition of the restoring source is unimportant [17], the restoration of the hologram was carried out in the white light of a conventional presentation projector and was recorded with a digital SLR camera.

The experimental setup was implemented on the base of the unique scientific installation "Beam-M" (http://ckp-rf.ru/usu/200975) and allows you to reconfigure the circuit for different pulse experiments [18, 19].
3. The results discussion

3.1. Schlieren pictures

1. On recorded Toeplergrams, it can be seen that both the state and roughness of the target surface and the state of the gaseous medium affect the intensity of the LEF. So, consistently comparing the shadows in figure 2a, 2b, 2c, we see that after four discharges, evaporation of the titanium target (red arrow) is almost absent. The 20 Torr of air additive to argon leads to the same result (figure 2d).

![Figure 2](image)

**Figure 2.** Toeplergrams of LEF evolution from targets (the top one is PTFE, the bottom one is titanium) in the field of radiation of the MPC discharge in argon at $p_{Ar} = 200$ Torr ($N_0$ – immediately after pumping out and letting in fresh gas, $N_n$ – without changing the gas $n$ times), $U_c = 20$ kV, time of registration $t = 12 \ \mu$s from the beginning of the discharge.

2. The occurrence of SW over the target, while the piston (target pairs and the vapour-gas contact boundary (CB)) still does not exist there is observed on figure 3. Probably the vapour diffuses first into the surrounding gas (for example, aluminium vapor into argon); then the vapor-gas mixture (Al-Ar) is heated by the incident radiation; at the next stage, this heated mixture expands to form SW. At the same time (when the processes described in the gas-vapor mixture proceed), the increase of target’s surface temperature continues and, consequently, the vapor pressure increases. When the pressure in the vapor reaches the pressure in the gas-vapor mixture the contact boundary (CB) is formed. In this case, it is the boundary between the layer where there are only metal vapors, and on the other side, there is a gas-vapor mixture (aluminum-argon, for example).

![Figure 3](image)

**Figure 3.** Toeplergrams of LEF evolution from an aluminum target ($Ar, p_{Ar} = 200$ Torr; $U_c = 20$ kV; $t = 12 \ \mu$s).

3. There is a band between the SW and the CB in figure 4. This band was not always fixed. We assume that this is the boundary between the vapor-gas mixture and the compressed background gas.

![Figure 4](image)

**Figure 4.** Toeplergrams of LEF evolution from a fluoroplastic target ($Ar, p_{Ar} = 200$ Torr; $U_c = 20$ kV; $t = 12 \ \mu$s).
4. Resistance to non-uniform contact boundaries is also detected. The pattern of primary inhomogeneities in the form of wheat protruding on the aluminum surface with milling processing with a step of 0.5–1 mm is repeated on the contact border without smoothing (figure 5b1, 5c1), on a smooth surface a similar pattern is not observed (figure 5b2, 5c2).

5. The mirror coating of titanium with a thickness of 70 nm did not evaporate under the action of the light from the discharge and even under the action of a plasma stream in 4 shots (figure 6). The formation of a transparency region (figure 6b, 6c, region 2) from exposure to light was monitored before the arrival of the plasma. This allows us to estimate the average flux absorbed by the sprayed film. This flow did not exceed 1.8 MW·cm⁻².

6. The estimates of the velocity of SW and CB over metal targets and fluoroplastic in figure 7 were obtained. These results can be used to estimate the radiation coming from the discharge.
Figure 7. Graphs of the maximum coordinates and the corresponding average velocity of the SW and CB for PTFE targets in argon (a) and aluminum in neon (b).

3.2. Holographic interferometry
The visualization of large optical fields and the resolution of the VRP-M film (ca. 1500 pieces/mm) in figure 8 allows observing and analyzing both the processes in the discharge and on the targets. For a clearer visualization of the interesting regions, it is enough to slightly change the angle of photography at recovery of the hologram, as we can see in figure 9c, 9d, 9e).

The holographic interferogram of a titanic target evaporation in argon is shown in the figure 9.

Figure 8. Holographic interferogram of the discharge of the MPC in argon ($p_{Ar} = 200$ Torr) for 10 µs and evaporation of the titanium target (top) and the fluoroplastic target (bottom) at $U_c = 19$ kV (a) and the aluminum target (top) and fluoroplastic (bottom) at $U_c = 20$ kV (b). On holograms, the region (1) is a defect in optics.
Figure 9. Holographic interferograms of titanium (a) and fluoroplastic (b) targets’ evaporation in the argon gas ($p_{Ar} = 200$ Torr; $U_c = 15$ kV; $t = 10 \mu$s) restored in white light and recorded by a camera (Sony α7). The areas (a – 1, 2, 3) correspond to gas-dynamic perturbation such as – shock wave (c), simple Riemann wave (d) and acoustic disturbance (e).

As already noted, the targets in our experiments were long (50 mm), end the target end closest to the radiation source was 2–2.5 times more energy than the far end. In this case, the deviation of the interference bands was recorded over the entire length of the target, but the shift of the bands differed noticeably when moving from one edge of the target to the other. Above the target, at different distances from the source of radiation (from the MPC) we distinguish three types of gas-dynamic perturbations: an acoustic wave, a simple wave, and a weak shock wave.

At the far (from the MPC) edge of the target (figure 9e, lane 12) an acoustic wave is recorded. Its distinctive features are that there is a disturbance at the leading edge, but behind this front, the interference fringe follows without deviation, i.e. pressure and density are almost the same as background gas. The shift of the interference band is less than $\Delta k \leq 0.1$, which corresponds to a change in the concentration of not more than $\Delta N_{Ar} \leq 0.17 \times 10^{18}$ cm$^{-3}$. Then the gas density jump is $\Delta N/N_0 = 0.024$ (here $N_0 = 7.1 \times 10^{18}$ cm$^{-3}$ – is the concentration of argon at a pressure of 200 Torr). A perturbation with such a small density difference spreads with a sound speed ($v = 350$ m·s$^{-1}$ for argon at $T = 20$ °C). The distance from the disturbance front to the target is $h = 2$ mm. From these data, we can determine the point in time when this disturbance arose: $t = h/v = 6 \mu$s.

The interference band No. 27 in figure 9d corresponds to a simple wave (Riemann wave) created by the plasma piston moving with acceleration. The density jump at the leading edge is small ($\Delta k = 0.2–0.3$, and $\Delta N/N_0 = 0.04–0.05$ – is small), and the disturbance front moves with the speed of sound. At the section AB, the density increases and a shock wave will be formed here later. After the maximum deviation (point B), the density decreases – the BC section. If the piston moved all the time with the same acceleration, then behind the leading edge, as the piston approaches, the gas density
should increase [20]. The density decrease, in our case, means that after the initial acceleration the piston slows down its movement by the time of receiving the interferogram (perhaps even the acceleration has changed its sign).

At the closest to the radiation source edge of the target a shock wave was observed – the third type of gas-dynamic perturbation. There is a steep leading edge (figure 9c, band №41). We get $\Delta N_{Ar} = 1.7 \times 10^{18}$ cm$^{-3}$ when $\Delta k = 1$. To such difference of density ($\rho/\rho_0 = (\Delta N_{Ar} + N_0)/N_0 = 1.24$) there corresponds the Mach number $M = 1.15$ ($\gamma = 5/3$).

Since the deviation of interference fringes above the target is proportional to the change in the gas density, the gas compression behind the shock wave can be estimated using two methods. For the case shown in figure 9b (PTFE, Ar, $x = 0.5$ cm from the target edge), the distance from the shock to the surface of the target is 2 times greater than from the SW to the CB. The gas that occupied the SW – the target’s surface (TS) interval before discharge – now occupies the SW – CB interval. Thus, the compression ratio here is $\rho/\rho_0 = 2.2$. On the other hand, the shift of the bands at this point is $\Delta k = 4$ (figure 9а). This shift corresponds to the compression $\rho/\rho_0 = (\Delta N_{Ar} + N_0)/N_0 = 2$. It turns out the correspondence between the two methods. We add that the compression $\rho/\rho_0 = 2.2$ corresponds to the Mach number $M = 2$.

The interference pattern (figure 9) shows that the distance from the target surface to the boundary of the perturbation is practically independent of the distance from the radiation source.

Since the speed of these disturbances is approximately the same (the speed of sound in the background gas), they arose at once time from the beginning of the discharge. And for different materials this moment is about at 6–7 $\mu$s until obtaining the image or in 3.5–4.5 $\mu$s after the discharge beginning, what approximately corresponds to current’s first maximum. Thus, there is an approximately simultaneous occurrence of disturbances along the entire length of the target, while the absorbed energy is significantly different: as noted above, the absorbed energy at the end of the target close to the MPC is 2–2.5 times greater than at the far end. This result has the following explanation. At the first stage, at the beginning of the discharge, relatively soft radiation heats the surface and the target vapor diffuses into the surrounding gas. During the diffusion of vapors into the gas, an acoustic disturbance does not occur. The second stage begins when hard radiation with a sharp leading edge comes from the discharge, which corresponds to a moment in time close to the maximum current. Vapors diffused into the gas absorb hard radiation, ionize, heat up and, expanding, cause an acoustic disturbance. At this point, the vapor appeared over the entire surface, but in different quantities, therefore the intensity of the resulting wave is different. Further heating of the surface leads to the fact that the pressure in the vapor reaches the pressure of the surrounding gas. There is contact boundary between the vapor and the gas, the developed evaporation regime is realized [21]. The mode when a diffusion mixture of target vapor and ambient gas arises was studied under the influence of laser radiation on matter experimentally [22] and theoretically [23].

4. Conclusion

Using two-exposure laser holographic interferometry and Toepler schlieren-schemes in the light field mode, the dynamics and macrostructure of near-surface vapor-plasma flows arising from the evaporation of condensed substances in the field of broadband radiation of the UV–VUV range of the spectrum are investigated.

We observe the stability of the contact boundary inhomogeneities arisen from the target surface inhomogeneities (an order of a fraction of a millimeter) is observed (i.e. primary surfaces inhomogeneities were shown in the form of contact border).

On the schlieren-pictures and interferograms, the zones characteristic of the studied type of radiation effect on materials are recorded: the gas-dynamic evaporation mode is realized (plasma piston mode), there is a shock wave in the gas, the contact boundary between the shock-compressed gas and the vapor plasma. The analysis of interferograms indicates that the regime of developed evaporation is preceded by a regime of diffusion evaporation. On interferograms above the target at
different distances from the source of radiation (from the MPC), we observe 3 types of gas-dynamic perturbations: acoustic wave, simple wave (Riemann wave), and shock wave.

Acknowledgements
Research has been performed at “Beam-M” facility, following the government task by the Russian Ministry of Education and Science (13.6918.2017/8.9).

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