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Experimental investigation of powerful wide band radiation interaction with the condensed matters

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Abstract. We present the results of powerful (i.e. ionizing) wide band (with photon energy from visible to VUV) radiation interaction with the condensed matters. We used a source with a power up to $10^7$ W/cm² and processes duration $10^{-6}$-$10^{-5}$ s. At schlieren and interferograph photos it is visible that the gasdynamic evaporation mode (the mode of the plasma piston) is implemented: there is a shock wave in gas, contact border between gas and vapors plasma. There is received thermodynamic parameters distribution on height in vapours over the target. The maximum temperature is reached not at contact border (from a radiation source), but in “plasma piston”.

1. Introduction
The interaction of wide band radiation with matter is of considerable scientific and practical interest. Thus, erosion of insulators and electrodes under the influence of radiation actually determines the operating mode of some plasma accelerators and electrodynamic devices [1-5], when a body enters the Earth’s atmosphere the ablation of heat-shield layers is largely determined by the action of light flux to a wall [6, 7], which can lead not only to a change in the thermal protection characteristics of structure, but also to a change in the flow regime. Under specific conditions, in the shock tubes an evaporation of the walls by leading radiation result in a changing of the propagation regime of the shock wave [8]. The interaction of ionizing wide band radiation with matter accompanies processes on the walls of fusion reactors [9, 10], in technological (photolithography, radiation hardening of the surface) and photochemical processes [11-16]. Interaction processes of wide band radiation with matter occur also under the action of high-power laser radiation with matter at the stage when the plasma torch at the target becomes not transparent to laser radiation, and itself is a powerful source of wide band radiation [17-20].

Nowadays, there are a huge amount of experimental and theoretical materials on the interaction of a powerful (changing aggregate state of the target) laser radiation with matter. Mostly, these are lasers of the visible and infrared spectral range, with photon energy being lower than the ionization potential of the target's atoms. There are practically no works on ionizing (with photon energy there is higher than the target atoms ionization potential) laser radiation interaction with the condensed matters. However, the interaction of powerful UV and VUV radiation with condensed matter can be investigated not only by means of laser sources. Wide band radiation sources that have considerable share of the light flux falls on the short-wavelength spectrum region can be used to solve this problem [2, 5, 21].
2. Experimental setup

This paper presents the results of studying the interaction of hard (i.e., ionizing), wide band (the quantum energy from visible to VUV) radiation with a power of up to $10^7 \text{ W/cm}^2$ and duration of $10^{-6}$ to $10^{-5}$ s with matter.

The radiation source was radiating plasmodynamic discharge (RPD) in a gas formed in the erosive type pulse electromagnetic plasma accelerator with coaxial-end geometry electrodes (diameter 6 and 20 mm) and ablative PTFE plasma-forming sleeve, which described in detail in [5]. Laser diagnostics of the gas-plasma flow above the target was performed with application of light field mode of Toepler’s schlieren scheme and two-frame holographic interferometry (these techniques are also described in [5]). We also used a piezoelectric low-inertia sensor that allowed us to measure the pressure on the irradiated samples.

The accelerator was installed in a vacuum chamber with a volume of $1.5 \times 10^{-2}$ m$^3$. This chamber was pumped out before each discharge up to the pressure $p_0 \leq 1$ Pa and filled with gas (Ne, Ar, air, mixture Ne with 2% air) up to pressure $p_{g0} = 2 \times 10^3 - 10^5$ Pa. The capacitor storage device (battery of low-inductance capacitors with a maximum capacity of 36 µF, 25 kV) charged up to the voltage of 15-25 kV was switched with accelerator electrodes a controlled discharger (thyratron). The stored electrical energy maximum was 11.3 kJ.

Rectangular samples with a thickness of 8-10 mm were used as irradiated targets. The width of the targets was 30 mm, and their length varied depending on the conditions of the particular experiment from 10 to 70 mm. Targets individually or several at once were installed parallel to the axis of the RPD at distances of 30-40 mm. Plates of Al, Ti, Cu, PTFE were used as targets.

Usually, there aren’t difficulties in determining the radiation energy and power that hits the target in laser radiation interaction with matter experiments. In our experiments, the determination of these quantities presents considerable difficulties. The discharge radiation properties in the quantum energy range of up to 20 eV (the neon ionisation potential) were studied using calibrated photocells, a pyroelectric sensor in the energy measurement mode. Standard light filters, filters from glass, quartz, LiF were used to cut the spectral intervals. The measurements’ results of the total energy’s spectral distribution of the discharge radiation in neon and neon with air additive are shown in tables 1 and 2 ($E/\Delta h\nu$ – is the energy density averaged over the spectrum, that is, the ratio of the total energy measured in the given interval to the width of this interval), the estimates of the maximum power density at the irradiated target $q_{\text{max}}$ (at $\tau_{1/2} = 10^{-5}$ s and the area of the irradiated surface $S = 113 \pm 5$ cm$^2$) are also given there. The addition of air to the noble gas slightly reduces the total luminous flux, although the spectral range is significantly reduced. The VUV radiation ($h\nu > 6$ eV) is ≈50% of the light energy for a discharge in a pure noble gas. The density of the radiation flux produced by the RPD luminous surface on the targets was calculated similarly to [22]. In the first approximation, the luminous zone was approximated by a hemisphere, the radius of which increased with time. The law of the hemisphere radius increasing was determined from the series of schlieren photographs.

**Table 1.** The spectral distribution of the radiation energy from the RPD $h\nu = 0-20$ eV (Ne, $p$=550 Torr, $q_{\text{max}}$=4.2 MW/cm$^2$).

| Range        | $\Delta h\nu$, eV | $E_{av}$, J | %  | $E_{av}/\Delta h\nu$, J/eV |
|--------------|-------------------|-------------|----|--------------------------|
| 0–20 eV      | 20                | 1190        | 100| 59.4                     |
| 0.5–6.2 eV   | 5.7               | 600         | 50.5| 105                      |
| 0.5–3.1 eV   | 2.6               | 333         | 28.1| 128                      |
| 0.5–11.2 eV  | 10.7              | 817         | 68.8| 76.4                     |
| 4.35–5.0 eV  | 0.65              | 52          | 4.4 | 80                       |
| 2.3–3.16 eV  | 0.86              | 70          | 5.9 | 81.4                     |

The radiation pulse shape in the near UV range was determined by a photocell ($\Delta \lambda$=284-247 nm).
We can assume that the time dependence of the discharge radiation emission approximately coincides with the shape of the light pulse in the region 250-290 nm (oscillograms at figures 1a and 2a).

### Table 2. The spectral distribution of the radiation energy from the RPD $h\nu=0–6.7$ eV (Ne with air ($p=550$ Torr $+11$ Torr), $q_{\text{max}}=3.6$ MW/cm$^2$).

| Range               | $\Delta h\nu$, eV | $E_{av}$, J | %  | $E_{av}/\Delta h\nu$, J/eV |
|---------------------|-------------------|--------------|----|-----------------------------|
| 0-6.7 eV            | 6.7               | 995          | 100| 149                         |
| 0.5-6.2 eV          | 5.7               | 896          | 90 | 157                         |
| 0.5-3.1 eV          | 2.6               | 301          | 30 | 116                         |
| 0.5-6.7 eV          | 6.2               | 822          | 83 | 133                         |
| 4.35-5.0 eV         | 0.86              | 62           | 6  | 72                          |
| 2.3-3.16 eV         | 0.65              | 50           | 5  | 72                          |

3. Experimental results

Figures 1 and 2 show the shadow photographs of the discharge and the corresponding oscillograms of the current, voltage and signal from the photocell, and show positions of the targets relative to the discharge. The second harmonic of the Nd:YAG-laser (532 nm, 7 ns, SOLAR LQ-115) was used as the source of the probe radiation.

*Figure 1. Schlieren photo (CCD camera Videoscan-V2-285TS) of discharge in argon (a) after 6 $\mu$s from the discharge beginning (13300 Pa, 20 kV, 3.6 kJ). Lower target material – Ti (surface after cutting), top target – PTFE. Corresponding oscillogram (b): CH4 – discharge current 1:10, CH2 – signal from the photodiode (peak matches to shooting moment).*

Schlieren photographs (figure 3) show that all the studied materials (Al, Ti, Cu, PTFE) evaporate under the effect of the discharge radiation in Ne and Ar, meanwhile two zones above the target are distinguished: the zone of shock-compressed gas (separated from the background gas by a shock wave (SW)) and the target vapor zone (separated from the shock-compressed gas by the contact boundary (CB)). Thus, the regime of the plasma piston is realized - the material of the target evaporates, the vapors heat up, ionize and push the surrounding gas like a piston, creating SW in it.

The parameters of the near-surface plasma were determined by interferograms (figure 4a). In plasma with an electron density $N_e$, the change in the refractive index ($n-1$) is approximately described by the expression [23]:

$$n - 1 = \frac{N_e}{n_0}$$
\[ n - 1 = -\frac{1}{2} \frac{\omega_p^2}{\omega^2} = -\frac{e^2 \lambda^2}{2\pi mc^2} N_e = 4.49 \cdot 10^{-14} \lambda^2 N_e \]  \(1\)

**Figure 2.** Schlieren photo (scan from 3000 lines/mm VRP-M golographic film) of discharge in argon (a) after 8 \(\mu\)s from the beginning (6862 Pa, 20 kV, 3.6 kJ). Lower target material – beech (type of wood), top target (left to right) – brushed aluminum, polished aluminum, polished copper. Corresponding oscillogram (b): CH4 – discharge current 1:10, CH2 – signal from the photodiode (peak matches to shooting moment).

**Figure 3.** Targets group evaporation under action of controlled spectral content radiation.

In the local thermodynamic equilibrium approximation with respect to the refractive index and some thermodynamic parameter (for instance, pressure), all the other thermodynamic parameters of the plasma can be calculated (a system of equations including the equations of quasineutrality, the equation of state, Saha equation and equation (1) for the refractive index, is solved). In practice, the data [24, 25] were used with the use of expression (1). The analysis shows that the maximum temperature of the plasma \((T \approx 0.7 \text{ eV})\) is reached not at the contact boundary (from the radiation source side), but inside the plasma piston (figure 4b).

A qualitative explanation of this phenomenon is due to the fact that the photoionization cross section decreases with a frequency proportionally to \(\nu^{-3}\), so with the advance deep into the vapors the...
fraction of high-energy ionizing quanta increases, but the average energy transferred during the photoionization also increases, which leads to an increase in temperature, since during the times under consideration the thermal conductivity will certainly not be able to equalize the resulting temperature drop.

In this case, a photoionization wave is registered, but now it is a wave moving in vapors, and one can also identify the macrostructure of the front of this wave. Estimated from the speed of the photoionization wave, the incident radiation flux on the target (in the absorption band of the vapor) is ~ 0.2 MW/cm² for aluminum in the spectral range from 6 to 7 eV.

![Interferograms’ part of zone (a) with radiation and Al target interaction (\(p_{Ar}=73\) kPa, \(t=7\) µs, \(U_{\text{charge}}=25\) kV, \(W_{\text{bat}}=11.3\) kJ) and plasma parameters distribution (b) in height above the target (\(T\) – electron temperature, \(N_e\) – electron concentration)](image)

**Figure 4.** Interferograms’ part of zone (a) with radiation and Al target interaction (\(p_{Ar}=73\) kPa, \(t=7\) µs, \(U_{\text{charge}}=25\) kV, \(W_{\text{bat}}=11.3\) kJ) and plasma parameters distribution (b) in height above the target (\(T\) – electron temperature, \(N_e\) – electron concentration)

Thus, the presence of a hard radiation component of a wide band radiation source results in the maximum of the plasma temperature being inside the layer. If the vapor pressure varies little in height, then at a variable temperature the electronic plasma concentration varies in height. As a consequence, dark bands-zones (zones of the largest gradients of the electron plasma density) inside the plasma layer are observed in Schlieren photographs of the evaporating targets in pure neon and argon discharges. These zones are determined by presence of quanta in the radiation source spectrum that have energy exceeding the ionization potential. When VUV is cut off, the distribution of the plasma parameters over the height will be uniform and the bands inside the layer will not be recorded. This picture is observed for a discharge in neon with the additive of 2% air, figure 3b, where there is no dark band in the target vapors, in contrast to figure 3a (pure neon).

Let us analyze the vaporization mechanism for typical experimental conditions. Vapor passes phases from diffuse motion mode to gas – dynamic during the heating process of condensed material [26, 27]. Condition for that transition is when the surface achieve the temperature which corresponds to vapor pressure higher than backgrounds’ gas. Appearance of hitting wave over the target in our experiments (contact border between vapor and background gas registered after it) can be considered as a moment of transition to gas – dynamics evaporation mode. Meanwhile the abnormally low transition threshold is registered. For example, a shock wave above the Al-target (25 kV, 11.3 kJ, Ne) appeared 2 µs from the beginning of the discharge. At this point in time, the luminous flux to the target reaches 1.4 MW/cm², and the incident energy density on the target is about 1.4 J/cm². Estimations by the method [27] show that to achieve an evaporation temperature by a solid surface in 2 µs, the incident energy density on the surface should reach 5.6 J/cm² (it is assumed that all the incident energy on the target is absorbed). This can be explained, similarly to [26, 27], by the presence of the thermally insulated surface microinhomogeneities, which facilitates their heating up to the evaporation temperature.
4. Conclusion
Under the action of a powerful broad-band UV-VUV radiation (>1 MW/cm²), the condensed matter is subjected to the gas-dynamic evaporation regime (plasma piston mode): there is a shock wave in gas, contact border between gas and vapors plasma. A photoionization wave was observed in the vapor plasma. The maximum temperature is reached not at contact border (from a radiation source), but in "plasma piston". An abnormally low vapor deposition threshold is established upon exposure to such radiation.

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