Shadow streak methods for studying the interaction of relativistic electron beams with polymer targets in the high-current generator diode

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Abstract. When a high-current relativistic electron beam interacts with the polymer surface, plasma forms. The results of a plasma dynamics study in vacuum diode using laser shadow photography, including the effect of atypically rapid propagation of the glow, are presented. Experiments were carried out on the high current generator «Calamary». Series of the experiments to study the plasma propagation along the diode axis and in the transverse direction in different cross sections were performed. The results were discussed and possible ways to continue research were considered.

1. Introduction

Although high-current relativistic electron beam (REB) generators have long lost the status of a "possible version of an inertial fusion driver", they find a number of applications in modern science, technical fields (plasma physics, various aspects of materials science, plasma technologies, electronics, etc.) and some other areas. The processes occurring in a vacuum diode when anode made from metal foils is exposed to REB were widely studied in the second half of the 20th century.

At present, it is of great interest to study the effect [1] and processes occurring with various nonmetallic under high power impact [2-4]. Investigations of polymeric and composite anode targets behavior in vacuum diode [5-7] are of particular interest, because the electron beam provides volume energy release in the sample. This can be different glasses, resins, plastics, and many others materials that are planned for use as components of structural composites in aerospace engineering, or compounds for filling electronic components, instrument cases, and other applications.

2. Experimental setup
To implement the planned research, a shadow streak scheme was developed and created. Pulsed solid-state laser based on yttrium orthoaluminate with neodymium and a nonlinear KTP crystal (potassium titanyl phosphate) was used as the source of probing radiation. The second harmonic radiation with $\lambda=540$ nm generated by KTP was formed and directed using suitable optics to the diagnostic window of the generator’s chamber (12 in figure 1). The duration of a smoothed pulse at the second harmonic is 300 $\mu$s at the base, the pulse energy is up to 100 MJ.

The high current generator «Calamary» ($I \leq 45$ kA, $U \leq 350$ kV) consists of a double forming line powered by a high voltage Marx generator.

The current through the vacuum diode was measured using low-inductive foil shunt (2 in the figure 1); and the voltage was measured by the capacitive divider located close to the output of the coaxial transformer of «Calamary», after that the resistive voltage was calculated taking into account the inductive component. The area of anode interaction with the REB was registered by a pinhole camera (11 in figure 1), in which, if necessary, a second x-ray film was placed behind the amplifier layer to expand the sensitivity range.

The vacuum diode assembly consist of a shell made of stainless steel, an anode target (10 in the figure 1) mounted flush with the surface of the unit, and the cathode (9 in the figure 1). The probing beam gets inside it through the diagnostic window (13 in the figure 1).

The cathodes in the most cases were made of brass in the form of a truncated conoid with a conical hole in a smaller base.

After passing through the cathode-anode gap, the probing beam was directed and focused on the time-analyzing slit of streak camera using a lens (16 in the figure 1) with a diaphragm (15 in the figure 1).
1) and rotary mirror. At the first stage of the work, the time-analyzing slit unfolded in time the image of the axial section of the vacuum diode; during the subsequent stages, to obtain additional data about diode plasma dynamics, the slit was rotated 90° relative to the original position (see the figure 2).

**Figure 2.** Observed regions: 1 is the region located at a distance of ≈ 2 mm from the anode; 2 is the region in the middle of the diode gap and 3 is the region located at a distance of ≈ 2 mm from the cathode.

3. Results and discussion
The images with effect of atypical plasma motion are very uneven in brightness: the first (left) half of each image is relatively dark, and the second half is strongly illuminated by its own glow, which is more intense than the probing radiation. We partially suppressed own plasma glow with selective filters. It was not completely suppressed in order to register both (the shadow pattern and the presence of an atypical motion effect) on the same streak camera (on figure 3).

**Figure 3.** Waveforms of the current and voltage and the shadow streak picture with own plasma glow.

A few words should be said about possible mechanisms for the formation of shadows. The first one is the plasma cutting off of probing beam, when the frequency of probing beam is compared to the plasma frequency. The second one is absorption of the probing beam (free-free and bound-free transitions). The third one is deflexion of the probing beam in areas with density gradients (seems like 14 in figure 1). Our estimates showed that the second and the third mechanisms play an important role in the shadow formation.
In figure 3 we can see that after a moment of 100 ns from the beginning of the current the movement of the substance with the velocity equal to $V = (1.4–3.0) \cdot 10^6$ cm/s from the electrodes is clearly visible. After that we can see the stage of propagation of the glow wave from the diode center to the electrodes with average velocity equal to $V \sim (8–9) \cdot 10^6$ cm/s. After the glow wave, the shadow region and narrow stripes of the plasma self-radiation are visible. At the last stage, we can see a diffuse glow that fills the diode gap almost completely.

During the second stage of experimental series (90° rotated slit), three regions were studied: near the anode (figure 4), near the cathode (figure 5), and in the middle of the gap (figure 6).

![Figure 4](image)

**Figure 4.** The shadow streak picture obtained near the anode region.

In the figure 4 we can see that the area near the anode is gradually filled ($V \sim 3\cdot10^6$ cm/s) with dense opaque matter, and at first the shadow region is symmetric according to the beam axis, but later has some asymmetry. Then we can see a region of diffuse glow lasting about 100 ns, after that we can see the shadow.
Figure 5. The shadow streak picture obtained near the cathode region.

At first in the figure 5 we can see glowing jets which outlined a cone, and later against the cone center is appeared diffusive glow propagating with the same velocity equal to $V \sim 3 \cdot 10^6$ cm/s. Perhaps in this image we do not see a shadow due to the low intensity of the laser beam.

Figure 6. The shadow streak picture obtained in the middle of the gap.

Most of streak pictures obtained at the middle of the diode gap show similar symmetrical pattern which starts from a small central area with a size of 1–2 mm (see figure 6). We can assume that at some moment cylindrical plasma torch is sprouted to the middle plane and then spread further; its radial velocity is equal $V \sim 3 \cdot 10^6$ cm/s. We can also see some shadow region occupied by dense opaque matter, as well as plasma glow regions, which are located slightly asymmetrically.

4. Conclusion
The laser shadow diagnostic in chronographic mode was created on the high current generator «Calamary». Shadow streak pictures where obtained which allow us to study the dynamics of filling a vacuum diode with a matter.

We think that the cylindrical plasma torch is sprouted from anode plane into the diode gap with an average velocity equal to $V \sim 3 \cdot 10^6$ cm/s. After a some stagnation stage corresponding to the stage of maximum compression of the diode plasma we can see the stage of propagation of the glow wave from the diode center to the electrodes with an average velocity equal to $V \sim (8–9) \cdot 10^6$ cm/s. Presumably this glow is due to the thermalization of colliding plasma clots. We also observed some asymmetries of the picture relative to the axis of the electron beam, which are most likely caused by the development of instabilities.

For further study, it is planned to realize methods of Schlieren streak pictures and frame pictures.

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