Experimental Study of a Dense and Current-Conducting Matter Distribution in the Discharge Channel upon Wire Explosion[1]

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Abstract – Experimental results on electrical explosion of wires in vacuum with current density $j \sim 10^{12}$ A/m^2, current rise rate (dI/dt) ~ 50 A/ns and current pulse with amplitude ~ 10 kA are presented. The structure of the discharge channels in vacuum has been studied using laser shadow and schlieren imaging with 7 ns frames, UV pinhole images with 5 ns frames and X pinch x-ray backlighting. The information on the dense core material and the conducting plasma distributions was obtained in our experiments by analyzing and comparing the results obtained from all diagnostics.

1. Introduction

Physical processes taking place at the initial stage of explosion of thin wires play an important role when forming plasma load in fast X-pinch experiments. Therefore, experimental information on time and spatial distribution of conducting, rarefied and dense layers of plasma, which are generated in the process of electrical explosion of wires in vacuum as well as in media, is of great interest.

The stage at which the wire material is transformed from a condensed state to a conducting plasma load is very difficult to study. As a rule, it is necessary to analyze indirect data since direct measurements of the structure of exploding wire distribution of currents and thermodynamic parameters are difficult to perform because of the small spatial and temporal scales. This applies not only to experiments with wire arrays on large machines but also to experiments with single wires of micron dimensions on relatively low-power installations. In the present work, it was attempted to reach a new level of experimental investigation of the discharge channel upon explosion of wires.

2. Diagnostic Means

The scheme of the installation is shown in Fig. 1, *a*; for a detailed description see [1, 2]. The investigations were performed for various conditions of the discharge using electrical, optical, UV and XR diagnostics.

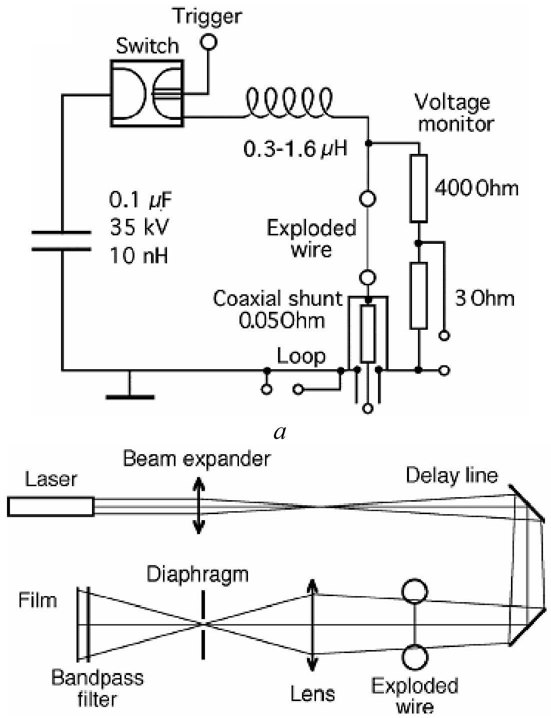

Fig. 1. Experimental setup: electrical circuit (*a*); optical diagnostic (*b*)

A vacuum X-ray diode without filter and with an aluminum cathode was used to study the time characteristics of wire luminescence in the ultraviolet range. The diode was placed 30 cm from the wire. To plot the image of the exploding wire, there was also used a four-frame micro channel camera with 5-ns explosion duration, 10-ns interval between frames and maximum sensitivity in the ultraviolet range (> 10 eV quantum energy). The image was plotted with 1:2 magnification using a 4-pinhole of rather large diameter 400 μm. The spatial resolution in this case was not very good, but using a pinhole of large diameter provided the needed optical efficiency. This, in the final analysis, permitted to register luminescence of low-density explosion products of single wires. In the case when one of the pinholes was covered by a 2-μm mylar filter, transparent for optical radiation and hard

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ultraviolet radiation with > 200 eV quantum energy, a discharge image was absent in this channel. Therefore, it can be concluded that in our experiments there are no quanta with energy > 200 eV.

Figure 1, *b* shows the scheme of laser probing on the basis of YAG:Nd^{+3}, with transformation of the radiation frequency to the second harmonic ($\lambda = 532$ nm, pulse length 10 ns and energy 0.035 J), to obtain optical images of the discharge channel. Photographing the wire in each shot was performed in a multiframe scheme in three separates channels, with the two succeeding the first frame delayed 30 and 70 ns, respectively (not shown in the figure). In one of them (the middle one), the lower half of the diaphragm and the focus of the lens were masked. As a result, this channel gave a schlieren image in the classical "knife" scheme. This permitted to judge the sign of the refraction of the object under investigation and make certain conclusions about the state and distribution of matter in the discharge channel. High-quality photographic lenses with high resolution digital cameras to record the images yielded high quality shadow images of loads with spatial resolution estimated to be 20 μm.

3. Experimental Results

In Fig. 2 there are presented shadow images of the discharge channel in the visible region, and x-ray radiation, upon electrical explosion of titanium wire in vacuum. A core (pointed to by arrows 1) can be seen on the optical images, practically nontransparent for probing of laser radiation. The dimensions of the core during observation (from ~ 360 to 1125 ns) were practically doubled. The diameter of the region pointed to by arrows 2 increased approximately three times and by instant ~ 1 μs peculiarities appear on the image that look like jets of matter (pointed to by arrows 3). The appearance of these jets can be explained as follows: by instant ~ 800 ns the magnitude of the current in the circuit is reduced more than an order of magnitude relative to the maximum value (I_{max} is ~ 12 kA when t is ~ 400 ns; see Fig. 3). Correspondingly, magnetic pressure, directed toward the axis, decreases significantly, which leads to the hotter low-density matter to begin flying apart with high velocity (~ $3 \cdot 10^3$ m/s). The expansion velocities of the core and region occupied by metal vapors also noticeably increase: from $6 \cdot 10^3$ to $4 \cdot 10^4$ cm/s and from $5 \cdot 10^4$ to $1.2 \cdot 10^5$ cm/s, respectively.

The finer internal structure relative to the distribution of dense matter can be examined by means of x-ray radiography with X-pinch as a point source of probing radiation [3]. An image of the discharge channel was obtained in soft x-ray radiation (2–5 keV quantum energy) of the hot point of four-wire molybdenum X-pinch (Fig. 2, *c*). It is clearly seen that there are tow regions of discharge. The inner one corresponds to the part pointed to by arrows 1 on the shadow laser image (Fig. 2, *b*). It should be noted that while the structure of the region pointed to by arrows 2 on the laser and x-ray images are very similar (with the difference that on the laser images the longitudinal formations are significantly thicker), the inner region, nontransparent for laser radiation, has a distinct lateral structure on the x-ray images.

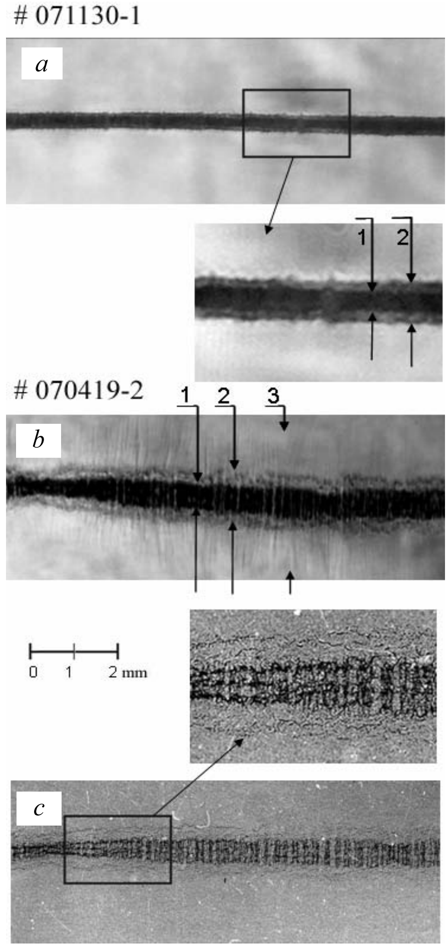

Fig. 2. Optical ($t = 365$ and 1095 ns) (*a* and *b*) and x-ray ($t = 1125$ ns) (*c*) shadow images of part of the discharge channel upon explosion of titanium wire in vacuum ($U_0 = 20$ kV, $l = 12$ mm, $d = 25$ μm)

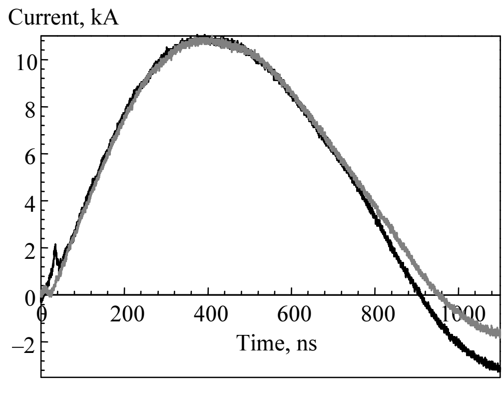

Fig. 3. Time dependences of current upon explosion of silver and titanium (black and grey lines correspondingly) wires in vacuum ($U_0 = 20$ kV, $l = 12$ mm, $d = 25$ μm)

In Fig. 4, there are presented images of part of the discharge channel upon explosion of a silver wire in vacuum. In both images, the lateral structure of the same spatial scale can be distinctly seen. Moreover, one can say that the explosion products of silver wire at instant 260 ns are expanded significantly more than upon explosion of titanium wire. Expansion velocity of their outer boundary by this instant is $\sim 2.5 \cdot 10^5$ cm/s and significantly exceeds even the low density velocity of a titanium plasma jet at a later time. This occurs because, as contrasted to the case of explosion of titanium wire, a significant part of the current continues to flow through the products of silver wire explosion after breakdown. Hence, the energy introduced supports their subsequent intense expansion.

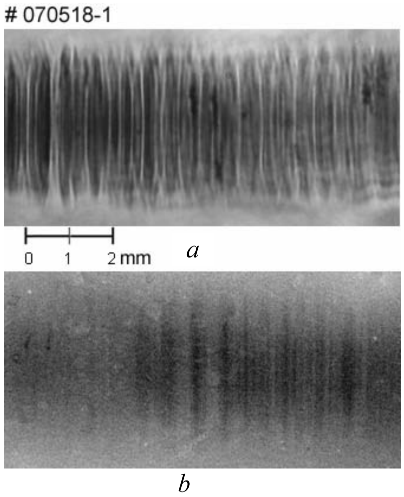

Fig. 4. Optical ($t = 245$ ns) (a) and x-ray shadow-images ($t = 280$ ns) (b) of part of the discharge channel upon explosion of silver wire in vacuum ($U_0 = 20$ kV, $l = 12$ mm, $d = 25$ μm)

Figure 5 shows optical shadow and schlieren images as well as an ultraviolet image of own luminescence of the discharge channel upon explosion of aluminum wire in vacuum. It can be seen that the size of the luminous region (Fig. 5, a) significantly exceeds the size of the dense part of wire explosion products. It is reasonable to suppose that this rare luminous plasma carries a part of the current, thanks to which it is heated and radiates. The luminous region has a distinctly expressed tubular structure and the size of the inner nonluminous part is of the order of that of the dense explosion products' region.

The expansion velocities of the luminous part are determined by means of four frames. In this experiment it is $2.8 \cdot 10^6$ cm/s. The expansion velocities of the near-axial region of dense explosion products (they, most likely, are in a liquid-vapor two-phase state) and quite dense layers of the corona were determined from the optical shadow images ($\sim 2.8 \cdot 10^5$ cm/s). On the basis of these data, it can be stated that rare luminous plasma in the ultraviolet range, transparent for optical probing radiation ($n_e < 7 \cdot 10^{18}$ cm^{-3}), expands with high velocity, exceeding by an order of magnitude the expansion velocity of the dense core.

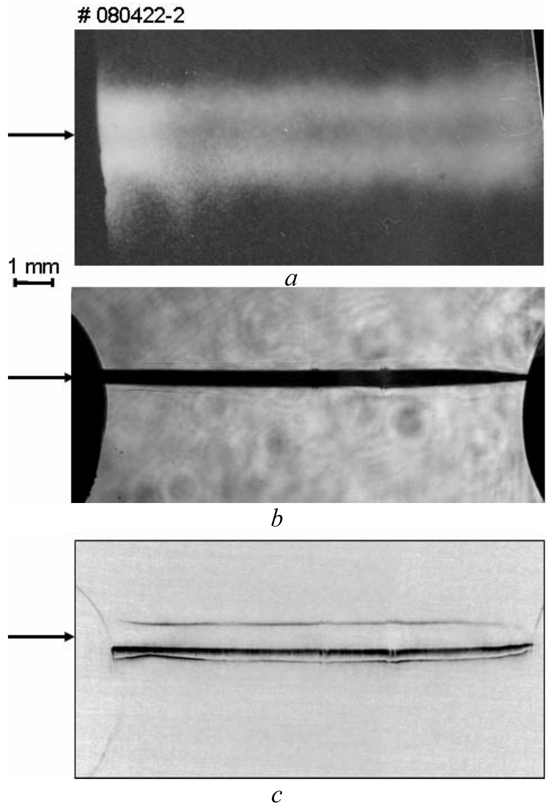

Fig. 5. Own luminescence in UV range ($t = 155$ ns) (a), shadow ($t = 155$ ns) (b), and schlieren ($t = 185$ ns) (c) optical images of the discharge channel upon explosion of aluminum wire in vacuum ($U_0 = 20$ kV, $l = 12$ mm, $d = 25$ μm). Horizontal arrows indicate the initial position of the wire

On the schlieren image (Fig. 5, b) there can be seen a thin almost symmetrical region relative to the inertial position of the wire. However it can be seen with large magnification that they have different structures, one can conclude that they have different nature. Since refraction in neutral (for example, metal vapor) and in plasma has different signs, it can be concluded that neutral as well as charged particles are present in this region, separated by some distance. The outer layers of the corona in view of their low density insufficiently deflect the probing laser beams. As a result, their image is absent on the schlieren photograph. And a broader nonsymmetrical region relative to the discharge axis corresponds to the refraction of matter containing only neutral particles (for example, weak or completely nonionized vapor or liquid). The position of this region corresponds to the boundary of dense explosion products seen on the shadow image. Thus, it can be stated that the dense core, being a two-phase, neutral, liquid-vapor mixture, has an inner structure with a rather sharp gradient of density.

Figure 6 shows optical and ultraviolet images of the discharge channel upon explosion of tungsten wire in vacuum. It can be seen that in this case the size of the luminous region also exceeds the size of the dense region of wire explosion products by more than an order of magnitude. The luminous region in the ultraviolet range does not have a distinct differentiated tubular structure as in the case of explosion of aluminum wire. However, it should be noted that at a later instant such a tubular structure begins to appear. The values of expansion velocities of the luminous region and regions occupied by dense explosion products are presented in the table.

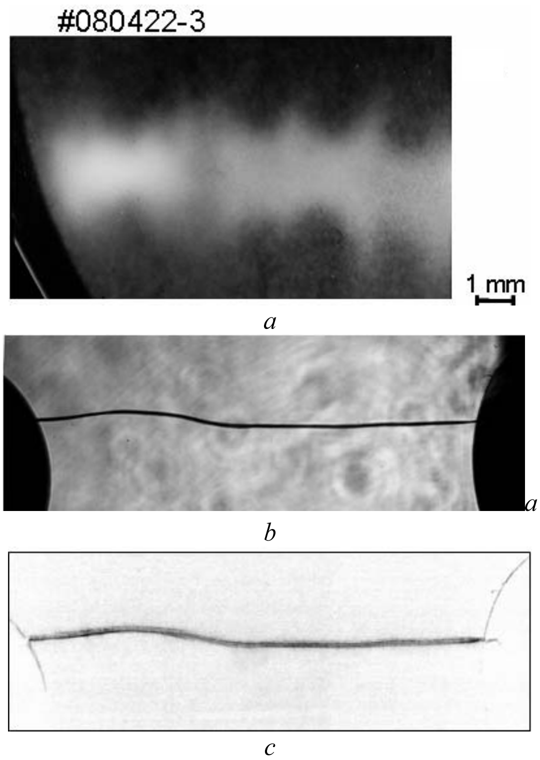

Fig. 6. Own luminosity in UV range ($t = 120$ ns) (*a*), shadow ($t = 180$ ns) (*b*), and schlieren ($t = 210$ ns) (*c*) optical images of discharge channel upon explosion of tungsten wire in vacuum ($U_0 = 20$ kV, $l = 12$ mm, $d = 25$ μm)

In paper [2] there are presented data on development scenarios of discharge-gap breakdown upon electrical explosion of micron wires of various materials in air and vacuum. In accordance with these data, one can say that upon exploding tungsten and aluminum wires breakdown proceeds by different scenarios. In the former case, it is of a shunting nature while in the latter it is internal. When the shunting breakdown develops, practically all the current flows through the external rare plasma, consisting of desorbed gases, metal vapors and light elements contaminating the surface of the wire. In this case, the expansion of the main mass of explosion products occurs at the expense of the energy that deposited into the wire by the instant of breakdown. When the breakdown is internal, even after its completion, a significant part of the current continues to flow within the quite dense explosion products. Precisely because of this, a considerably more intense expansion of wire matter can be observed in this case. This explains the different spatial structures of the luminous region in the ultraviolet range upon explosion of aluminum and tungsten wires. Since expansion of dense explosion products of tungsten wire is considerably less, the narrow (~ 200 μm) region of dense nonluminous explosion products is not seen on the back ground of the broad (~ 2000 μm) luminous region, for its dimensions are beyond the spatial resolution of the system.

It can also be noted that instabilities develop in the luminous region. On sight, they are reminiscent of the ordinary sausage-type instability in plasma, characteristic for regimes with pinching in installations with large currents. In tungsten plasma the instability is developed considerably faster than in aluminum plasma (compare Figs. 5, *a* and 6, *a*). This can also be explained by the difference in scenarios of breakdown development. In shunting breakdown (in the case of explosion of tungsten wire), this rare plasma carries practically all the current. Therefore, forces (directed toward the axis of magnetic pressure and also gasodynamic having the opposite direction) acting on the matter are considerably greater; therefore, the instabilities develop faster. On the other hand, in inner breakdown (in the case of aluminum wire explosion) a considerable portion of the current flows within quite dense explosion products. Consequently, pressures are less and, accordingly, slower development of instability is observed.

The schlieren image obtained upon explosion of tungsten wire is to a large degree symmetrical (Fig. 6, *c*). A symmetrical image in the scheme with "knife" mask would be obtained when in the indicated region there are small uniform scattering centers – e.g., submicron droplets in vapor. However, in large scale there can be noticed that external to the upper boundary there stretches a broad region of eroded structure.

References

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