Investigation of the near-surface matter density radial distribution in the skin explosion of cylindrical conductors

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Abstract. Investigations of the near-surface plasma formation process during skin explosion of cylindrical duralumin and copper conductors in rapidly increasing magnetic fields with their induction up to 500 T were carried out. The formation of plasma on the conductor surface was recorded by its glow in the visible range using a four-frame optical camera with an exposure time of each frame of 3 ns. The internal structure of the surface plasma, the assessment of the density of matter in it and its radial distribution were investigated using radiography pictures obtained by X-ray transmission with $h\nu > 0.8$ keV, which is formed at the "hot point" of the X-pinch. The dependences of the load substance density on its radius were determined and constructed from the obtained X-ray diffraction patterns at different points in time from the beginning of the current. So at 216 ns at a radius of 1.8 mm of a duralumin conductor with an initial radius of 1.485 mm, the density of the substance is estimated to be $0.0068$ g/cm$^3$.

1. Introduction
Plasma formation on the conductors surface as a result of a skin explosion is one of the key issues in the efficiency of energy transportation through vacuum lines of powerful terawatt-level pulsed generators. Nonthermal processes, such as gas-discharge phenomena in desorbed gas or metal vapors, can significantly reduce the magnitude of the magnetic field at which a low-temperature plasma is formed on the surface of the conductor. Its formation is important from the point of view of the energy introduced into the metal substance. In a skin explosion, the time of energy input into the conductor is less or comparable to the time of magnetic field diffusion in it, the current flow and, accordingly, the Joule heat release occurs in the surface layer of the conductor with a size of the skin layer thickness order $[1, 2]$. The main processes that characterize the electrical explosion of conductors (EEC) in the skin mode are the spreading of a shock wave and a nonlinear diffusion wave of a magnetic field in the conductor material, as well as the formation of low-temperature plasma on the conductor surface and the development of overheating instabilities $[3-7]$. The plasma formation on the conductor surface due to a skin explosion, which occurs when the thermal energy density reaches the value of the energy density of sublimation of a substance, is one of the restrictions on the maximum induction of the magnetic field on the electrodes surface of the vacuum transmission line of high-current pulse generators. To correctly determine the role of the near-surface substance in the current transfer, it is necessary to know the distribution of its density on the surface. The aim of this work was to study the dynamics of plasma and the density of matter on the metals surface at values of magnetic induction 300-500 T and the rate of its rise 2-5 T/ns.
2. Experimental setup

Experiments on the study of plasma formation on the surface of Al and Cu conductors in rapidly increasing magnetic fields were carried out on a high-current MIG generator [8] at a current level up to 2.5 MA with a rise time of 100 ns. The use of cylindrical metal conductors with a diameter of 2-3 mm as a load makes it possible to reach peak values of the induction of the azimuthal magnetic field on the surface of the conductor 300-500 T. The current pulse in the load has a prepulse, which starts approximately 250 ns before the start of the main pulse, increases approximately linearly and reaches values of 3% of the amplitude of the main pulse. When the MIG generator operates with such loads, approximately at the maximum of the reverse voltage half-wave on them, the vacuum surface of the water-vacuum bushing is overlapped. Due to the "capture" of the magnetic flux in the vacuum transmission line, the load current at (130th÷150th) ns takes the form of a weakly decreasing exponential with a characteristic decay time of several microseconds.

As diagnostics, we used Rogowski coils, magnetic probes, voltage dividers, a four-frame HSFC-Pro optical camera with an exposure duration of 3 ns, and vacuum X-ray photoemission diodes (XRDs). The location of the diagnostic equipment is shown in figure 1. The plasma formation on the conductor surface was recorded by its own glow in the visible range using a four-frame optical camera with an exposure time of each frame of 3 ns. In addition, vacuum X-ray photoemission diodes (XRDs) recorded the surface plasma reaching a temperature of more than 1 eV in the blackbody approximation. A plasma column with a surface temperature of more than 1 eV emits well in the visible range of the spectrum, which makes it possible to obtain its images with a sufficiently high magnification and an exposure time of 3 ns.

![Figure 1. Photo of the load unit of the MIG generator. 1 - load node (chamber) of the X-pinch; 2 – XRD of X-pinch; 3 - load with a return conductor of the; 4 - unit of diaphragms; 5 - photographic film; 6 - flexible low-inductance multi-cable line; 7 - XPG-3 X-pinch generator; 8 - XRD of the MIG generator load.](image-url)

To study the internal structure of the surface plasma, a synchronized generator with a load in the form of an X-pinch developed in IHCE SB RAS was used [9]. Investigations were carried out on the basis of X-ray diffraction patterns obtained by scanning the plasma column with X-rays with $h\nu > 0.8$ keV, formed at the “hot point” of the X-pinch. The load unit, in which the X-pinch was stationed, was located directly in the vacuum chamber of the MIG generator. The X-pinch was pulsed from a separate compact high-current pulse generator XPG-3 located at a short distance (outside) from the vacuum chamber of the MIG generator. The generator provided a current flow through the X-pinch with an amplitude of up to 250 kA and a rise time of 150–200 ns. This made it possible to obtain a short X-ray pulse ($h\nu > 0.8$ keV) with a duration at half height of less than 2 ns. The current flowing through the X-pinch was measured with a Rogowski coil located in close proximity to the load. The time dependence of X-ray emission from the X-pinch was recorded using a vacuum X-ray diode with an Al cathode (XRD) behind a filter, which determines the measurement in the spectral range...
$h\nu > 0.8$ keV. The size of the radiation source was controlled by a pinhole camera. To transmit the current pulse to the X-pincher load node, a flexible low-inductance transmission line was used, consisting of 82 RK50 cables with a diameter of 3 mm each. Figure 1 shows the external view of the vacuum chamber with the load of the MIG generator together with the installed compact pulse high-current generator XPG and its load unit, connected by a flexible transmission line.

The XPG-3 generator was started by a signal from a magnetic probe installed in the viewing window in the area of the second water line of the MIG generator. Such a synchronization system for the MIG and XPG generators made it possible to ensure the appearance of a probing X-ray pulse with an accuracy of 10 ns. The optimization of the X-pincher configuration in order to realize no more than two emitting hot spots made it possible to obtain sufficiently clear images of radiography pictures with a magnification factor of more than three. The fact is that in the region of the X-pincher waist, depending on different conditions, several hot spots can be realized, spaced by tens of microns in space. Because of this, the image on the film may be blurred due to the superposition of several shadows. In experiments on X-ray sounding on the MIG generator, an X-pincher was used, consisting of two or four molybdenum wires 25 μm in diameter, since such an X-pincher configuration is the most optimal for a given pulsed generator from the point of view of the generated soft X-ray source characteristics [10]. The angle of rotation of one electrode relative to the other when twisting the wires in the X-pincher ($\varphi \approx 220^\circ-225^\circ$), the interelectrode gap (7 mm) and the angle of inclination of the conductors relative to the vertical axis ($40^\circ-45^\circ$) were optimized.

![Figure 2](image)

**Figure 2.** Scheme of X-ray shadow probing of the exploded conductor (a) and the total transmission curve of the entire set of used filters (b).

In addition to obtaining shadow images of the exploded conductor, the density of the expanding surface plasma was estimated using step attenuators made from the materials of the conductor being investigated [11]. In the experiment, two shadow images were simultaneously recorded on one image: the exploded conductor itself and a step attenuator made of the same material as the conductor. Since the density of blackening of the film D is proportional to the intensity of radiation I transmitted through a layer of the investigated substance with a thickness of h, then at those points where the densities of blackening of the image of the plasma and one of the stages of the attenuator coincide, their linear mass along the line of sight will also coincide. A stepped filter was applied to a polypropylene film 6 μm thick. To deposit thin layers of Al or Cu on a PP film, we used a magnetron sputtering system with an Al or Cu target 100 mm in diameter, respectively. The X-ray radiography diagram of the exploding conductor is shown in figure 2. The magnification factor of the diagram was 3.5. The image was recorded on photographic films Mikrat ORTO and RF-3, located one after another, which made it possible to register shadow images in two spectral ranges. To protect photographic films from the visible part of the X-pincher radiation spectrum and the plasma object under study, a composite filter was installed in front of them, consisting of a polyethylene film with a thickness of 2 μm with aluminum sputtering with a thickness of 0.2 μm and a polypropylene film with a thickness of 6 μm with an aluminum layer of 0.2 μm deposited on it. A stepped attenuator made of copper or duralumin was applied to the upper part of the same polypropylene filter [12]. Apertures
were placed in front of the camera to protect it from the explosion products of the conductor. The total filter determined the energy of the probing radiation quanta of more than 2.5 keV at a transmission level of more than 0.2 (figure 2 (b)).

3. Results and discussion
In the course of the experiments, the electrical explosion of cylindrical conductors made of duralumin and copper with different diameters was studied, which made it possible to study the formation of plasma at different rates of increase in the magnetic field induction 2-5 T/ns. Figure 3 shows typical images in the visible range of the self-radiation of the plasma column formed during the explosion of copper and duralumin conductors with a diameter of 2 mm at different times from the beginning of the current flowing through them. Comparing the images in figure 3, we can note several features of the explosion of conductors made of different metals in a field of up to 500 T.

![Figure 3. Pictures of self-glow in the visible range during the explosion of copper and duralumin conductors with a diameter of 2 mm at different times from the beginning of the current flowing through them.](image)

Continuous glow of the surface of duralumin conductors was observed starting from 55-60 ns, while copper even at 70 ns the surface glows with separate spots, i.e. at this time, it has only the beginning of the formation of plasma on the surface. In the region of three hundred nanoseconds, a greater expansion of the diameter of the duralumin column was observed in comparison with the copper one. After a hundredth of a nanosecond, all loads began to develop instabilities. Figure 4 shows the images of the luminescence in the visible range of an Al conductor with a diameter of 1.9 mm at various points in time, obtained using a more high-aperture recording scheme with a magnification factor of 37. There are also X-ray diffraction patterns obtained at 108 ns when the conductor is transmitted by X-pinch radiation.

It can be seen that already at the 40th nanosecond from the beginning of the current transmission through the aluminum conductor, a weak glow of its near-cathode part appears. And by the 70th nanosecond, a uniform glow of the entire surface of the conductor is observed. At the same time, an increase in the XRD signal began, signaling that the plasma on the surface reached a brightness temperature of more than 1 eV in the blackbody approximation. X-ray diffraction patterns of the explosion of an Al conductor, obtained at 108th ns from the beginning of the current in two ranges of photon energies ($h\nu > 2.5$ keV - (b) and $h\nu > 3.5$ keV - (c)), showed a weak expansion of matter from the surface, significantly inhomogeneous in all coordinates. When comparing the degree of transmission of the surface substance and step filters on some X-ray diffraction patterns, we can say that the mass of the substance per unit surface area along the line of sight is identical to the mass of Al filters with a thickness of 0.5-1 μm.
Figure 4. Pictures of self-glow in the visible range of an Al conductor 1.9 mm in diameter at various times at the initial stage of the explosion (a) and X-ray diffraction patterns obtained at 108th ns when it is transmitted by X-pinch radiation (b – $h\nu > 2.5$ keV, c – $h\nu > 3.5$ keV).

For a more correct determination of the near-surface matter role in the current transfer in the conductors skin explosion, it is necessary to know the distribution of its density along the radius of the plasma column. Such a distribution from the obtained X-ray patterns can be obtained using the inverse Abel transform. For the numerical solution of the reconstructing problem the distribution profile of a substance from the data of X-ray studies of the conductors electric explosion in a vacuum, a calculation code was developed that allows using the X-ray diffraction patterns of its explosion as initial data. The problem of reconstructing the substance distribution profile from X-ray diffraction patterns belongs to the category of inverse problems of X-ray optics. In the process of radiation interaction with matter, the characteristics of the probing radiation flux change. The main thing is that the absorption coefficient of the exploded conductor material in the source spectral range does not change significantly during the probing time. To find the substance distribution profile, it is sufficient to have changes in the intensity of the incident radiation flux $I_0(r, \nu)$ due to its absorption by the object under study (the Beer–Lambert–Bouguer law):

$$ I(r, l, \nu) = I_0(r, \nu) \cdot \exp\left[-\int \mu(l, \nu) \rho(l) dl\right]. $$

(1)
Here: $\nu$ is the frequency of the probing radiation; $\mu(l, \nu)$ - specific absorption coefficient; $\rho(l)$ - local density of the investigated substance; $l$ is the path traversed along the sounding beam.

To solve the problem of reconstructing the substance distribution profile, a system of equations with variable coefficients $I_0/I(r)$ was used. The spatial characteristics $\mu \cdot \rho(r)$ of a conductor of a given cylindrical geometry were determined in the selected section by measuring the integral ratios $I_0/I(r)$ directly from the X-ray diffraction patterns. Additionally, the code implements the possibility of calibrating the absorption coefficient $\mu(l, \nu)$ according to the data of attenuation measurements of the probing radiation flux intensity using a step attenuator. In this case, the calibration results can be used as normalization directly when calculating the dependence $\rho(r)$.

In the experiments, the image of the exploding conductor was recorded on Mikrat ORTO and RF-3 films. Then the films were scanned, and the resulting image was inverted and processed in accordance with the requirements of the numerical code for the original image. Figure 5 shows the explosion X-ray diffraction pattern of a cylindrical duralumin load with a diameter of 2.97 mm, obtained at 216 ns from the beginning of the current flow, processed in accordance with the requirements of the numerical code. The calculation was carried out in the selected section (highlighted rectangle in the figure). The result of processing is the distribution $\mu \cdot \rho(r)$.

Figure 6 (a) shows the dependences $\mu \cdot \rho(r)$ on the radius of the conductor in the selected section of the X-ray diffraction pattern shown in Figure 5. The dependences of the product $\mu \cdot \rho(r)$ corresponding to the left and right edges of the conductor are shown in blue and pink colors; dark blue indicates the initial radius $r_0$ of the "cold" conductor before the current starts to pass through it. Due to the strong absorption of the probing radiation by the substance of the central core of the load, the central part of the image is outside the dynamic range of the source-detector system.

As can be seen from figure 6, during 216 ns the conductor expanded by at least 400 $\mu$m along the radius, and the expansion was quite symmetric. To assess directly the substance density and its dependence on the radius, it is necessary to choose the value of the mass absorption coefficient of radiation $\mu$. The values of the coefficient $\mu$ obtained from the estimates of the blackening density corresponding to the thicknesses of the aluminum step attenuator are $\sim 560 \text{ cm}^2/\text{g}$, which corresponds to radiation with an average quantum energy of 3.4 keV. Using such a calibration of the coefficient $\mu$ for the transmission of step filters, the dependences of the density of the conductor substance on its radius were obtained. These dependencies are shown in figure 7. It can be seen from them that, for example, for a radius of 1.8 mm (that is, for a substance that has expanded by 315 $\mu$m relative to the initial radius), the density of the substance is 0.0068 $\text{g/cm}^3$ for values of the coefficient $\mu = 560 \text{ cm}^2/\text{g}$. Thus, if we use its value obtained during calibration (using the transmission of step filters) as the effective value of $\mu$, then for 216 ns of explosion of a duralumin conductor with an initial diameter of 2.97 mm at a diameter of 3.5 mm, the density of the substance is only 0.02 $\text{g/cm}^3$. 

Figure 5. Inverted X-ray diffraction pattern of the explosion of a cylindrical duralumin conductor with a diameter of 2.97 mm, obtained at 216 ns from the beginning of the current flow, prepared for use in numerical calculations. The calculation was carried out in a selected rectangular section.
Figure 6. Dependences $\mu \cdot \rho (r)$ for a cylindrical duralumin load with a diameter of 2.97 mm (shot 2181). a) - curves correspond to the left and right boundaries of the conductor, b) the same dependences on an enlarged scale (the distribution corresponding to the left boundary of the conductor is shown in mirror image). The dark blue straight lines indicate the initial position of the conductor boundary before the explosion.

The density of a substance measured by this method depends on the absorption coefficient of the probe radiation, and the accuracy of the density measurement will increase with a decrease in the energy range of the quanta of the probe source.

Figure 7. Dependences of the substance density on the radius $\rho (r)$ for a cylindrical duralumin load with a diameter of 2.97 mm, corresponding to the left (blue curve) and right (pink curve) boundaries of the conductor.

4. Conclusion
The process of formation of near-surface plasma during skin explosion of cylindrical duralumin and copper conductors in rapidly increasing magnetic fields on a high-current MIG generator with a current amplitude of up to 2.5 MA and a rise time of 100 ns is investigated. The internal structure of the surface plasma, the assessment of the density of matter in it and its radial distribution were investigated using radiography pictures obtained by X-ray transmission, which is formed at the “hot point” of the X-pinioh. The dependences of the density of the load substance on its radius were determined and constructed from the obtained X-ray diffraction patterns at different points in time from the beginning of the current. So for 216 ns of explosion of a duralumin conductor with an initial diameter of 2.97 mm at a diameter of 3.5 mm, the density of the substance is only 0.02 g/cm$^3$. 
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