Surface discharge during electrical explosion of conductors in strong magnetic fields

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Abstract. In experiments on the electrical explosion of conductors in rapidly growing mega-Gaussian magnetic fields, it was found that at the initial stage of the explosion, “hot spots” up to 500 pieces/mm² were recorded on the surface. At a later stage, a plasma layer was formed on the surface of the conductor, in which filaments, that is, current channels, were formed. In this work, on the basis of the ecton theory, a model of the development of a surface discharge is constructed. The model makes it possible to estimate, firstly, the magnitude of the current flowing through the surface plasma, and secondly, the thickness of the plasma layer.

1. Introduction

Interest in the electrical explosion of conductors (EEC) in the current skinning mode is associated with various applications. Let’s note some of them. First, the generation of strong magnetic fields, both by compression of metal shells [1, 2], and by the explosion of single-turn solenoids [3, 4]. Second, compression in the Z-pinch geometry of heavy metal liners, inside which extreme states with pressures of 1-100 Mbar can be realized [5]. Third, the electromagnetic acceleration of bodies [6, 7], in particular, the acceleration of flat metal plates in experiments on the study of shock waves (see, for example, [8, 9]). And finally, the transportation of electromagnetic energy through vacuum transmission lines on the currently developed multi-terawatt generators with a current level of 30-50 MA [10, 11], which are supposed to be used to implement controlled thermonuclear fusion schemes based on Z-pinchs.

The main processes that characterize the EEC in the skin mode are the propagation of a shock wave and a nonlinear diffusion wave of a magnetic field in the conductor material [2, 12], as well as the formation of low-temperature plasma on the conductor surface [13, 14] and the development it has flute-like instabilities [15]. Nonlinear diffusion is characterized by an anomalously high rate of penetration of the electromagnetic field into the conductor compared to ordinary diffusion. An increase in the diffusion rate is associated with a decrease in the conductivity of the metal due to the heating of the metal by the current flowing through it. In [16], the initial stage of the explosion was studied, that is, the processes preceding both the appearance of a nonlinear diffusion wave and the development of flute-like instabilities. In this work, the explosion of aluminum rods 1 mm in diameter with a current of about 1 MA was investigated. The photographs obtained by the authors of [16] indicate that in the initial stage of the surface explosion, brightly glowing spots appear on it. The size
of these luminous spots was about 5 μm (the minimum size was determined by the resolution of the recording equipment), and their number reached 500 pieces/mm² [16]. The expanding spots form a plasma layer on the cathode surface. After the formation of a plasma layer, filaments are formed in it - layers parallel to the direction of current flow. That is, apparently, current channels. A similar situation is observed in the experiments on the MIG facility, carried out by I M Datsko and N A Labetskaya.

From our point of view, the most probable reason for the appearance of brightly glowing spots on the cathode is the formation of ectons on the surface of the conductor [17]. Ectons are centers of plasma formation, formed in the process of explosive emission and arising during the explosion of metal micro tip [17, 18]. This work is devoted to the analysis of the parameters of the plasma layer arising from the electric explosion of conductors in the current skinning mode, from the point of view of the theory of ectons.

2. Simulation of the explosion of a microtip on the cathode surface

Explosive emission of electrons occurs on the cathode surface at high electric field strengths and is accompanied by an explosion of metal microvolumes [17, 18]. A large concentration of energy in small volumes is achieved due to Joule heating caused by autoelectron emission from microtips. As shown in [19], the emission of electrons occurs in the form of separate portions - ectons. The emergence of an ecton is associated with overheating of the metal during a microexplosion, and the termination of its functioning is due to the cooling of the emission zone [17, 19]. The functioning of an ecton is a complex and multifactorial process, the details of which are still clearly insufficiently studied. In addition to the emission of electrons, the functioning of an ecton is accompanied by the generation of multiply charged ions, droplets of liquid metal, etc. After the termination of the functioning of an ecton, micron-sized craters may remain on the cathode surface [17, 19].

To simulate the explosion of a microtip, we used the magnetohydrodynamic (MHD) program [20-23], based on the “particles in cells” method and allowing one to simulate the explosion of conductors in a two-dimensional approximation. The system of MHD equations implemented in this program consists of hydrodynamic equations reflecting the laws of conservation of mass, momentum, and energy:

\[
\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{v}) = 0; \tag{1}
\]

\[
\rho \frac{\partial \mathbf{v}}{\partial t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla p + \frac{1}{c} \mathbf{j} \times \mathbf{H}; \tag{2}
\]

\[
\frac{\partial \rho c}{\partial t} + \nabla (\rho c \mathbf{v}) = -p \nabla \mathbf{v} + \frac{j^2}{\sigma} + \nabla (\kappa \nabla T). \tag{3}
\]

Maxwell's equations written in the quasi-stationary approximation (disregarding the displacement currents):

\[
\frac{1}{c} \frac{\partial \mathbf{H}}{\partial t} = -\nabla \times \mathbf{E}; \quad \nabla \times \mathbf{H} = \frac{4\pi}{c} \mathbf{j}; \tag{4}
\]

and Ohm's law:

\[
\mathbf{j} = \sigma (\mathbf{E} - \frac{1}{c} \mathbf{v} \times \mathbf{H}), \tag{5}
\]

where \( \rho \) is the density of the substance; \( \mathbf{v} \) is its speed; \( p, \varepsilon \) and \( T \) are pressure, internal energy and temperature of the substance; \( \mathbf{H} \) is the magnetic field strength; \( \mathbf{E} \) is the strength of the electric field in a fixed coordinate system; \( \mathbf{j} \) is the current density; \( \kappa \) and \( \sigma \) are coefficients of thermal conductivity and conductivity, respectively.
The system of equations (1-5) was solved in a cylindrical coordinate system, in \((r, z)\) geometry. The following algorithm was used for the numerical solution of the system of equations (1-5). The equation of motion (2) was solved for each of the particles, then, by summing over all particles in each of the cells, the average mass velocities and density of the substance were found. The continuity equation (1) in this method is fulfilled automatically due to the Lagrangian nature of the particles. The equations of energy change (3) and Maxwell's equations (4) were solved on an Eulerian fixed grid, which was constructed at the beginning of the calculation and did not change during the numerical solution.

The program used wide-range semiempirical equations of state [24], which takes into account the effects of high-temperature melting and evaporation. When calculating the electrical characteristics of the metal and the coefficient of thermal conductivity, we used the tables of the conductivity of copper [25], compiled using the calculation and experimental technique [26].

![Figure 1. Initial density distribution in a microtip on the surface of a copper cathode.](image)

The problem was solved in the following formulation. It was assumed that on the surface of a flat copper cathode there is a microtip, which has the shape of a cylinder, with a radius of 0.3 \(\mu m\) and a length of 1.5 \(\mu m\) (see figure 1). The microtip was exploded with a constant current of 3.2 A, the value of which was chosen from the following considerations. It is known [17] that for a copper cathode the minimum current value at which a single ecton can function is approximately 1.6 A, and when the current is doubled, a second ecton is formed on the cathode surface. Accordingly, 3.2 A is the maximum current flowing through a single ecton. The radial size of the microtip was chosen so that the current density through the microtip would be approximately equal to \(10^9\) A/cm\(^2\), that is, it would be close to the limiting current density of auto-electron emission [27].

The results of modeling the explosion of a micropoint are shown in figure 2. This figure shows the spatial distribution of density (figure 2 (a)) and temperature (figure 2 (b)) at the moment of the explosion of the microtip, that is, at the moment close to the maximum voltage. When a microtip explodes near the cathode surface, the substance transforms into a plasma state. In this case, a region of increased pressure is formed near the cathode, the value of which can reach several tens of kilobars. As a result, a crater with a radius of several microns is formed on the cathode surface (figure 2). The crater formation process is most intense in the first nanoseconds of the discharge.

Thus, magnetohydrodynamic calculations show that an electric explosion of a microtip with parameters typical for a single ecton leads, first, to the formation of a crater with a radius of several microns on the cathode surface, which is consistent with experimental data. Secondly, during the explosion, the metal passes into a plasma state, and the volume of the exploded substance is 1–2 \(\mu m^3\).
3. Surface discharge development model

Let us analyze the process of formation of a plasma layer on the surface of a conductor in a rapidly growing magnetic field. We will consider a cylindrical metal rod of radius $R_{rod}$ and length $l$, surrounded by a return current conductor with radius $R_{rc}$. A current increasing in time flows along the rod along the $z$ direction, the rate of current rise is $dI/dt$.

Let us estimate the possibility of the development of explosive emission on the surface of conductors with a rapid increase of the magnetic field induction. In this case, the electric field strength on the cathode surface should reach values of several hundred kV/cm \[28\]. In our situation, an electric field arises between the metal rod and the return current conductor, that is, along the $r$ direction. The potential difference between the rod and the return current conductor can be estimated as

$$U \approx \frac{1}{c^2} \int \frac{dI}{dt}$$ \hspace{1cm} (6)

where $L = 2\ln R_{rc}/R_{rod}$ is the inductance of the rod - return current conductor system; $c$ is speed of light in vacuum. Then the electric field strength on the surface of the metal rod in the radial direction will be equal to

$$E_r \approx \frac{2l}{c^2 R_{rod}} \frac{dI}{dt}$$ \hspace{1cm} (7)

For the experimental conditions described in \[16\], the $dI/dt$ value is approximately equal to $10^{13}$ A/s. Then at $l/R_{rod} \approx 10$ the electric field strength in the radial direction should be approximately 200 kV/cm. With such a value of the electric field strength, explosive electron emission should occur on the surface of the rod. That is, explosive emission centers should form on the cathode surface, the formation scenario of which is described in the previous section.

Next, let us estimate the parameters of the plasma layer formed during the operation of explosive emission centers. According to the calculations, the results of which are presented in the previous section, with the explosion of one microtip into a plasma state with a temperature of several eV, approximately 1-2 $\mu$m$^3$ of an initially solid metal passes over, that is, one ecton produces approximately $(1-2) \cdot 10^{11}$ metal ions. Since the number of ectons is $200-500$ pieces/mm$^2$, the total number of ions formed in the process of explosive emission can be estimated as $N_i \approx (0.5 - 1) \cdot 10^{16}$. In addition to these ions, molecules of gases desorbed from the surface of the conductor should exist in
the surface layer. The number of these molecules is approximately \(10^{15}\) molecules/cm\(^2\) [29], that is, comparable to the number of ions formed in the process of explosive emission.

Apparently, the formation of a current sheet on the surface of a conductor does not occur immediately after the explosion of microtips, since the plasma formed during the explosion of individual ectons should combine to form connected regions. The distance between ectons is \((N_{\text{ect}})^{0.5} \approx 40 \text{–} 70 \mu\text{m}\). Expanding with a thermal velocity of about \(10^6 \text{ cm/s}\), the plasma must cover this distance in 5-10 ns. However, in a magnetic field, the plasma can freely expand only along the magnetic field lines, that is, along the azimuthal direction, which is observed in [16]. Plasma expansion across the magnetic field lines, along the \(z\) and \(r\) directions, is hindered; therefore, the formation time of a connected region is delayed.

Let us estimate the magnitude of the current that flows in the surface plasma layer. We will assume that, firstly, almost all of the generator current flows through the metal rod. Secondly, the current flowing in the rod is skinned, and in the plasma layer, due to its small thickness, skinning effects are absent. Then the axial component of the electric field strength in the surface layer will be determined by the field created by the current flowing through the rod, \(I\), the resistivity of the metal conductor \(\delta_{\text{met}}\), and the skin layer thickness \(\Delta_{sk}\):

\[
E_z \approx I \frac{\delta_{\text{met}}}{2\pi R_{\text{rod}}\Delta_{sk}} = \frac{\delta_{\text{met}}}{\pi c^2} \frac{l}{R_{\text{rod}}} \frac{dl}{dt}.
\]

(8)

Taking the conductivity of the metal under normal conditions (for copper it is equal to \(\delta_{\text{met}} = 1.55 \times 10^{-6} \text{ Ohm}\cdot\text{cm}\), and for aluminum \(\delta_{\text{met}} = 2.5 \times 10^{-6} \text{ Ohm}\cdot\text{cm}\)), we obtain the typical values of the axial component of the electric field strength \(E_z \approx 1\text{–}2 \text{ kV/cm}\).

Further, since the surface layer is held by the pressure of the magnetic field, it can be assumed that the rate of change in its thickness is small in comparison with the thermal velocity of the plasma. In this case, the following equilibrium condition can be written for the plasma layer

\[
\frac{\partial p}{\partial r} \approx \frac{1}{c} j_{pl} B_{\phi}.
\]

(9)

where \( p = (1 + Z)kTN_j / \Delta_{pl} \) is the thermal pressure in the surface plasma layer of thickness \(\Delta_{pl}\); \(Z\) is the average charge of the ions; \(T\) is the temperature in the plasma sheet; \(k\) is the Boltzmann constant; \(j_{pl} \approx I_{pl} / (2\pi R_{\text{rod}}\Delta_{pl})\) is current density in the plasma layer; \(I_{pl}\) is the current flowing through the plasma layer; \(B_{\phi} \approx (2I) / (cR_{\text{rod}})\) is the value of the magnetic induction in the plasma layer; \(I\) is the current flowing through the metal rod (it is assumed that \(I_{pl} \ll I\)).

Then equilibrium condition (9) will have the form:

\[
(1 + Z)kTN_j \approx \frac{1}{c^2} \frac{\Delta_{pl}}{\pi R_{\text{rod}}^2} I_{pl} I.
\]

(10)

On the other hand, for a plasma layer, Ohm's law can be written in the form:

\[
E_z = \frac{l}{2\pi R_{\text{rod}}\Delta_{pl}} \frac{\delta_{pl}}{I_{pl}} I.
\]

(11)

where \(E_z\) is the electric field strength determined by expression (8); \(\delta_{pl}\) is the resistivity in the plasma layer. The latter value is determined by the expression [30]:

\[
\delta_{pl} = \frac{\Delta_{pl}}{l} \frac{\delta_{\text{met}}}{\pi c^2}.
\]
\[
\delta_{pl} = \frac{4\sqrt{2}\pi e^2 \sqrt{m_e Z}}{3 (kT)^{3/2}},
\]
(12)

where \(e\) and \(m_e\) are the charge and mass of the electron; \(\Lambda\) is the Coulomb logarithm.

At a plasma temperature of 3-5 eV, an average charge of 3-5, the resistivity of the plasma layer can be estimated as \(\delta_{pl} \approx 0.02 - 0.04\) Ohm cm.

As a result, from (10) and (11) we obtain expressions that determine the current through the plasma layer and its thickness:

\[
I_{pl} \approx \sqrt{2\pi^2 e^2 (1 + Z) kT N} \frac{E \cdot R_{rod}}{I \delta_{pl} \cdot l};
\]
(13)

\[
\Delta_{pl} \approx \sqrt{0.5 \pi^2 (1 + Z) kT N} \frac{R_{rod} \delta_{pl}}{E \cdot I}.
\]
(14)

Substituting the values of quantities in (13) and (14), we obtain that, in experiments [16], a current of about 100–150 A runs through the plasma layer, and the thickness of the plasma layer is 15–30 μm.

4. Conclusion

Thus, in this work, a model of the development of a surface discharge during the explosion of conductors in strong magnetic fields is built, based on the theory of ectons. This model shows that at the initial stage of the electrical explosion of conductors in the current skinning mode, a plasma layer several tens of micrometers thick is formed on the metal surface. Only a small (hundredths of a percent) part of the total current flowing through the load flows through this layer.

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References

[1] Fowler C, Garn W and Caird R 1960 J. Appl. Phys. 31 588–94
[2] Knoepfel H 1970 Pulsed high magnetic fields: Physical effects and generation methods concerning pulsed fields up to the megaessted level (Amsterdam-London: North-Holland publishing company)
[3] Bocharov Y N, Krivosheev S and Shneerson G 1982 Pisma Zh. Tekh. Fiz. [in Russian] 8 212–6
[4] Krivosheev S, Titkov V and Shneerson G 1997 Tech. Phys. 42 352–66
[5] Oreshkin V I, Chaikovskii S A, Labetskaya N A, Ivanova Y F, Khishchenko K V, Levashov P R, Kuskova N I and Rud A D 2012 Tech. Phys. 57 198–202
[6] Kinslow R 1970 High-velocity impact phenomena (New York: Academic Press)
[7] Rashleigh S and Marshall R 1978 J. Appl. Phys. 49 2540–2
[8] Fortov V E 2007 Phys.-Usp. 50 333–53
[9] Nash T et al 2004 Phys. Plasmas 11 L65–8
[10] Slutz S, Olson C and Peterson P 2003 Phys. Plasmas 10 429–37
[11] Azizov E et al 2004 Plasma Devices Oper. 12 123–32
[12] Oreshkin V I and Chaikovsky S 2012 Phys. Plasmas 19 022706
[13] Chaikovsky S, Oreshkin V I, Mesyats G, Ratakhin N A, Datsko I and Kablambaev B 2009 Phys. Plasmas 16 042701
[14] Awe T, Bauer B, Fuelling S, Lindemuth I and Siemon R 2010 Phys. Plasmas 17 102507
[15] Oreshkin V, Chaikovsky S, Datsko I, Labetskaya N, Mesyats G, Oreshkin E, Ratakhin N and Rybka D 2016 Phys. Plasmas 23 122107
[16] Awe T, Yu E, Yates K, Yelton W, Bauer B, Hutchinson T, Fuelling S and Mckenzie B 2017 IEEE T. Plasma Sci. 45 584–9
[17] Mesyats G 2000 Cathode Phenomena in a Vacuum Discharge (Moscow: Nauka)
[18] Mesyats G and Proskurovskii D 1971 Zh. Eksp. Teor. Fiz. [in Russian] 13 7
[19] Mesyats G A 1995 Phys.-Usp. 38 567
[20] Oreshkin E, Barengolts S, Mesyats G, Oreshkin V and Khishchenko K 2016 J. Phys.: Conf. Ser. 774 012191
[21] Barengolts S A, Mesyats V G, Oreshkin V I, Oreshkin E V, Khishchenko K V, Uimanov I V and Tsventoukh M M 2018 Phys. Rev. Spec. Top.-Ac. 21 061004
[22] Barengolts S, Uimanov I, Oreshkin V, Khishchenko K and Oreshkin E 2021 J. Appl. Phys. 129 133301
[23] Barengolts S A, Oreshkin E V, Oreshkin V I and Khishchenko K V 2019 IEEE T. Plasma Sci. 47 3406–11
[24] Fortov V, Khishchenko K, Levashov P and Lomonosov I 1998 Nucl. Instrum. Meth. A 415 604–8
[25] Oreshkin V I, Baksht R, Labetsky A Y, Rousskikh A, Shishlov A V, Levashov P, Khishchenko K and Glazyrin I 2004 Tech. Phys. 49 843–8
[26] Bakulin I D, Kuropatenko V and Luchinskii A 1976 Zh. Tekh. Fiz. [in Russian] 46 1963–9
[27] Fursey G, Zhukov V and Baskin I 1984 Limiting Densities of FEE Currents and Pre-Explosive Effects (Novosibirsk: Nauka) pp 21–41
[28] Samokhin A 2010 Plasma Phys. Rep. 36 149–63
[29] Oreshkin V I and Baksht R B 2020 IEEE T. Plasma Sci. 48 1214–48
[30] Braginskii S 1965 Transport processes in a plasma. Reviews of plasma physics vol 1, ed M A Leontovich (New York: Consultants Bureau)