Electric explosion of flat copper conductors in asymmetric and symmetric configurations in the current skinning mode

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Abstract. Plasma formation on the surface of conductors as a result of a skin explosion is one of the key issues of the efficiency of energy transportation along the vacuum lines of terawatt-level pulsed generators. Experimental studies of plasma formation on the surface of flat conductors were carried out on the MIG generator (current level ~ 2.5 MA, rise time ~ 100 ns). The magnitude of the magnetic field induction exceeded the values required for the explosion of the conductor surface facing the magnetic field in an asymmetric configuration or both surfaces of the conductor in a symmetric configuration. It was shown that in both configurations, a plasma channel is formed on the surface of a copper foil with a thickness of 100 microns along its longitudinal axis. Experimental data on the dynamics of plasma formation at the edges of a flat conductor have been obtained. A magnetohydrodynam simulation of an explosion in strong magnetic fields of flat conductors whose width is much greater than their thickness showed that: the expansion of the plasma along the width of the conductor is suppressed, and the plasma expands mainly along its thickness. The simulation results are in good agreement with the experimental ones.

1. Introduction

Studies of the electric explosion of conductors (EEC) in the current skin mode are one of the key issues of the efficiency of energy transportation along vacuum lines of high-power pulse generators of the terawatt level. Such generators are supposed to be used for various technical applications, one of which is, for example, the implementation of controlled thermonuclear fusion schemes based on Z-pinch schemes (see, for example, [1]). The main problem that needs to be taken into account when designing such generators is possible electrical explosion of the surface of the electrodes of the transmission lines. One of the consequences of such an explosion is the formation of plasma in the interelectrode gap, which can significantly reduce the efficiency of electromagnetic energy delivery to the load.

During EEC in the current scanning mode, a dense low-temperature plasma is formed on the surface of the conductor, and a shock wave and a wave of nonlinear diffusion (WND) of the magnetic field propagate in the conductor substance [2, 3]. The rate of penetration of the electromagnetic field
into the conductor in the case of nonlinear diffusion is significantly higher compared to the linear stage, which is explained by an increase in the resistivity of the conductor substance (metal in our case) due to its heating when an electric current flows through it. Depending on the explosion mode, both Rayleigh-Taylor instabilities (RT) caused by high magnetic field pressure and overheating instabilities can develop in the metal, the structure of which is determined by the dependence of the resistivity of the substance on temperature.

In our previous works [3, 4], cylindrical conductors (solid or hollow) were studied. From the point of view of studying nonlinear diffusion and surface plasma formation, it is of interest to study flat conductors designed in such a way that the induction of the magnetic field on their surface is approximately equal to the induction of the magnetic fields reached on the surface of cylindrical conductors. To solve this problem, the width of a flat conductor should be approximately \( D = 2\pi R \), where \( D \) is the width of a flat conductor, \( R \) is the radius of a cylindrical conductor. Hence, according to estimates, the parameters should be: width of 5 mm, length of 10 mm and thickness of 100-200 microns (which corresponded to the wall thickness of the tubes used in early experiments).

A characteristic feature of a flat conductor, on the surface of which a current pulse flows, is a significant enhancement in the magnetic field at the edges of the plate compared to the magnetic field in the center of the plate. Nonlinear diffusion and field amplification at the edges of a flat conductor can significantly affect both plasma formation and the development of instabilities.

2. Experimental procedure and results

Experimental studies of plasma formation on the surface of flat conductors were carried out on a MIG generator at a current level of up to 2.5 MA and a rise time of 100 ns. The load of the generator in these experiments was a flat conductor (a copper plate) with a thickness of about 100 microns.

The diagnostic setup of the MIG generator includes magnetic probes, Rogowski coils, and a four-frame HSFC Pro optical camera with a minimum frame exposure of 3 ns, which is used to register the plasma formed on the surface of the conductor by its self-emission in the visible range of the spectrum. Previously, we conducted experiments with a flat copper conductor in the so-called asymmetric electrode system [5, 6]. The asymmetric configuration consisted of two flat conductors of different widths: a copper plate (width 5-10 mm, thickness ~ 100 microns) was located at a distance of 1.5-2 mm parallel to a massive wide stainless steel conductor that plays the role of a current return path.

![Figure 1](image_url)

**Figure 1.** The load unit design: a) front view – a flat conductor is installed with the wide side to the HSFC Pro camera; b) side view – a flat conductor is installed with the narrow side to the HSFC Pro camera.
Such a configuration of the electrodes has certain disadvantages, such as the impossibility of pulse X-ray backlighting of the plate, a high probability of uncontrolled shorting of the gap by expanding plasma, a significant complication of modeling of the magnetic field distribution. A symmetrical configuration in which a flat conductor is located on the axis of a cylindrical current return electrode with diagnostic windows is more promising. This paper presents the results of experiments with flat conductors in an axisymmetric configuration of electrodes.

Figure 1 schematically shows a load unit design: a) front view – a flat conductor is installed with the wide side to the HSFC Pro camera; b) side view – a flat conductor is installed with the narrow side to the HSFC Pro camera. In figure 1, the following abbreviations are used: C – cathode, A – anode, MITL – magnetically insulated transmission line.

Using the HSFC Pro optical four-frame camera, both frontal (conductor width) and side on (conductor thickness) images of the load were obtained (see figure 2). Images of the conductor explosion process (figure 2 (a) and figure 2 (b)) were recorded in different shots.

The dimensions of the conductors were as follows: width – 5 mm, length – 10 mm, thickness – 90 microns. It should be noted that a hole with a diameter of 200 microns was drilled in the copper plate (figure 2 (a)) at a distance of about 0.5 mm from the axis, which is clearly visible in the images. Also should be pointed that when installing the copper plate for registering the side images (figure 2 (b)), the plate was slightly bent when pumping out the vacuum.

![Figure 2](image)

As can be seen from figure 2, at 61-65 ns from the beginning of the current flow, a weak glow of the edges of the copper plate is observed. A relatively uniform glow of the entire width of the plate is observed only at 80 ns, and the edges still glow more intensely, and weakly expressed instabilities begin to form already at 65 ns and become more noticeable at 80 ns (frontal images) and clearly visible at 96 ns (side images). As in the asymmetric configuration, the appearance of a plasma channel ("strip") near the axis of symmetry of the conductor should be noted on the frontal images of the load. The weak glow of the plasma channel is observed at 70-75 ns from the beginning of the current flow,
at 80 ns it becomes much more pronounced and bends around the hole drilled in the plate. Also the processes of the appearance and development of instabilities on the edges of a flat conductor are clearly seen.

3. MHD program description
A two-dimensional magnetohydrodynamic (MHD) program was used to simulate the explosion of flat conductors. In this program, the simulation of the explosion process is performed in \((x, y)\) geometry, that is, in a plane perpendicular to the flow of current (current flows in the direction of the \(z\) axis). The new program is based on the algorithms previously used by the authors in the two-dimensional MHD program JULIA [7, 8], based on the "particles in cells" method. The system of hydrodynamic equations implemented in the program consists of equations reflecting the laws of conservation of mass, momentum and energy:

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

\[
\rho \frac{\partial \mathbf{v}}{\partial t} + p \mathbf{v} \nabla \mathbf{v} = -\nabla p + \frac{1}{c^2} \mathbf{j} \times \mathbf{B}. \tag{2}
\]

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

where \(v\), \(p\), \(\epsilon\) and \(T\) are the velocity, the pressure, the internal energy and the temperature of the substance, respectively; \(j\) is the current density; \(k\) is the heat conductivity; \(\sigma\) is the electrical conductivity.

The magnetic field induction was calculated using the Biot-Savart law:

\[
\mathbf{B} = \frac{1}{c^2} \int \frac{\mathbf{j} \times \mathbf{R}}{R^3} \, dV, \tag{4}
\]

where \(R\) is the radius vector, \(c\) is the light velocity in a vacuum. It was assumed that the current density in the substance is distributed in proportion to the conductivity \(j \sim \sigma\).

The system of equations (1-4) was solved in a flat coordinate system, in \((x, y)\) geometry. The following algorithm for the numerical solution of the system of equations (1-4) was used. The equation of motion (2) was solved for each of the particles, then by summing all the particles in each of the cells, the average mass velocities and density of matter were found. The continuity equation (1) in this method is satisfied automatically due to the Lagrangian nature of the particles. The energy equation (3) and equation (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 boundary conditions for the equations of motion (2) can be imposed either by setting the velocity or by setting the pressure at the boundary. When integrating equation (2) on a free boundary (the boundary with a vacuum), the boundary conditions were chosen in the form \(p = 0\). In the center, at \(x = 0\) and \(y = 0\), the boundary conditions corresponded to the symmetry condition with respect to the axes.

The boundary conditions for the energy equation (3), including the heat conduction equation, were imposed by specifying the heat flow at the boundaries. Everywhere at the borders, the heat flow was assumed to be zero, which corresponds to the absence of external sources and heat deflux.

The simulations used wide-range semi-empirical equations of state [9]. When calculating the electrical characteristics of the metal and the thermal conductivity coefficient, copper conductivity tables were used, compiled using the computational and experimental methodology [10, 11].

4. Results of the MHD simulations
The results of two-dimensional MHD simulation of an electric explosion of flat copper conductors at a current pulse with amplitude of 2 MA and rising time of 100 ns are presented below. During the
simulation, the real dependence of the current on time, taken from the experiment, was used. The explosion of a foil with width of 5 mm and thickness of 100 microns was simulated. The initial conditions were chosen as follows. The temperature of the substance was 3000 K, the density was equal to 8.9 g/cm\(^3\). The calculated grid had a size of 250×150 (x, y), that is, it consisted of 3.75×10\(^4\) cells, the number of large particles was 10\(^7\).

The initial density distribution, which reflects the geometry of the problem, is shown in figure 3.

Figures 4 and 5 show the distributions of the density and temperature of the substance at time \(t = 135\) ns, that is, 35 ns after the generator current reaches its maximum value.
As can be seen from figure 5, by this time the temperature of the main mass of the conductor is 20-30 eV. At this temperature, the thermal velocity of the ions \( v_{Ti} \sim (T / m_i)^{1/2} \), where \( m_i \) is the mass of the ion, is about \( 10^6 \) cm/s. Expansion of plasma usually occurs at a speed close to ion thermal velocity. In our case, as can be seen from figures 4 and 5, the conductor expansion occurs only along with the y axis. Along with the x axis, the size of the conductor is approximately equal to its original value. A similar pattern can be observed in the experiments, the results of which are presented in the previous section (see figure 2 (a)). In the experiments, as well as in the simulations, the size of the conductor along the x axis, that is, in the direction parallel to the width of the conductor, practically does not change during the electric explosion.

![Figure 5. Spatial distributions of the temperature of the substance at time \( t = 135 \) ns from the current start.](image)

The explanation of this phenomenon is related to the topology of the magnetic field that occurs when a current flows through a flat conductor, namely, with the magnetic field enhancement at the edge of the flat conductor [12]. Let us consider a flat plate with the following dimensions: the width of the plate (x axis) is equal to \( D \); the thickness (y axis) is equal to \( d \); the length of the plate (z axis) is infinite; the current flows along the plate along the z-axis. Then the enhancement factor at the edge of the plate is equal to:

\[
\beta \approx \frac{1 + \ln 2\chi}{\pi},
\]

where \( \chi = D/d \). The expression (5) is valid for \( \chi \gg 1 \). Having in mind that in our case the width of the plate \( D = 0.5 \) cm, and its thickness \( d = 100 \) microns, we get that the magnetic field enhancement factor is equal to \( \beta \approx 1.8 \). This means that the magnetic pressure on the edge of the conductor is approximately 3.2 times greater than on the surface in the center of the conductor.

According to estimates, in experiments, the uniform current distribution in the flat conductor is established several nanoseconds after the passage of a nonlinear diffusion wave through the conductor [13]. In our case, the wave of nonlinear diffusion propagates along the y axis from the edge of the conductor to its center.

The simulated enhancement of the magnetic field at the edge of the conductor is shown in figure 6, which shows the spatial distribution of the magnetic field at time \( t = 30 \) ns.
Since the enhancement of the magnetic field leads to the fact that the magnetic pressure at the edge of the conductor significantly exceeds the value of the magnetic pressure in the center of the conductor, as a result, the plasma expansion along the $x$ axis is suppressed and the conductor expands mainly along the $y$ axis.

![Figure 6. The simulated enhancement of the magnetic field at the edge of the conductor at time $t = 30$ ns.](image)

5. Conclusion
Experiments with electrically exploded flat conductors in asymmetric and symmetric electrode configurations were carried out on the MIG generator (current up to 2.5 MA, rising time of 100 ns). In both configurations of the electrodes, the appearance of a plasma channel in the axial region of a flat conductor, as well as the appearance and development of instabilities on its surface, was recorded.

A specially developed two-dimensional magnetohydrodynamic program was used to simulate the explosion of flat conductors in symmetric electrode configuration. In this program, the simulation of the explosion process is performed in $(x, y)$ geometry, that is, in a plane perpendicular to the flow of current (current flows in the direction of the $z$ axis). A magnetohydrodynamic simulation showed that during an explosion in strong magnetic fields of flat conductors whose width (along the $x$ axis) is much greater than their thickness (along the $y$ axis), the plasma expansion along the $x$ axis is suppressed, and the conductor expands mainly along the $y$ axis. This is due to the enhancement of the magnetic field at the edge of the plate, which provides higher magnetic pressure at the edge of the plate as compared to the magnetic pressure in its center. The simulation results are in good agreement with the experimental results obtained.

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