Determination of the conductor resistance during their explosion in vacuum under conditions of skinning the current

A G Rousskikh, A S Zhigalin and V I Oreshkin

Institute of High Current Electronics of the Siberian Branch of the Russian Academy of Sciences, Akademichesky Avenue 2/3, Tomsk 634055, Russia

E-mail: russ@ovpe2.hcei.tsc.ru

Abstract. The work is devoted to the investigation of the features of the conductor explosion in a vacuum under the conditions of skinning the current, and specifically, the effect of the magnetic field nonlinear diffusion wave spreading over the exploded conductor on its electrical properties. Experiments on the explosion of conductors were carried out on the IMRI-5 pulse power generator. The exploded conductor was soldered to the cathode and mechanically clamped between the plates on the anode. In the experiments, we used two types of conductors, cylindrical and flat (foils). Cylindrical conductors were of two types: copper (0.5 mm in diameter) and aluminum (0.44 mm in diameter). Foils were also of two types: copper with a thickness of 300 microns and aluminum with a thickness of 200 microns. The foil width varied from 1 to 3 mm. The length always remained 30 mm. To calculate the circuit inductance and calculate the corrections for the real conductor inductance, we used a load that was either a copper foil 600 μm thick and 1 cm wide, or a copper conductor with a diameter of 2 mm (short circuit mode).

1. Introduction

Interest in investigations of conductor’s electrical explosion (CEE) in the current skinning mode is associated with the solution of a number of practical problems. One of the problems is the electromagnetic energy transportation in magnetically isolated transmission lines on multi-terawatt generators being developed at present [1] with a current level of 30-50 MA and a rise time of less than 100 ns. Such generators are supposed to be used to implement controlled thermonuclear fusion schemes based on Z-pinchess [2, 3]. At a generator current level of several megaamperes, the magnetic energy density in the load area is high enough to explode the transmission lines electrodes surface, which will lead to the plasma formation in the interelectrode gap. The presence of plasma in the interelectrode gap, in turn, will lead to a decrease in the efficiency of transporting electromagnetic energy from the source to the load. Another task is to study CEE within the framework of the concepts MAGO/MTF (Magnetized Target Fusion [3]) and MagLIF (Magnetized Liner Inertial Fusion [4, 5]). In these concepts, compression of the initially heated deuterium-tritium mixture with a metal liner is assumed. Other problems should be noted, such as the generation of superstrong magnetic fields, both by compression of metal shells [6-8] and during the explosion of single-turn solenoids [9], as well as the electromagnetic acceleration of bodies [10], in particular, the acceleration of flat metal plates in experiments on the shock waves study [11, 12].
The main processes occurring during CEE in the current skinning mode are the joint propagation of a shock wave, a nonlinear diffusion wave (IRD) of a magnetic field in the conductor material [12, 13] and, as a consequence, the formation of a dense low-temperature plasma on the conductor surface. Nonlinear diffusion of a magnetic field is characterized by an abnormally high penetration rate of an electromagnetic field into a conductor (compared to ordinary diffusion). The increase in the rate of diffusion of the magnetic field is associated with an increase in the resistivity of the metal due to its heating by the flowing current. For most metals, the resistivity increases with increasing temperature $T$, so the following approximate expression can be written for the resistivity:

$$\delta(Q) = \delta_0 \cdot (1 + \beta \cdot Q),$$

(1)

where $Q = \rho \cdot c_v \cdot T$ is the thermal energy density, $\beta = (\delta_0, \rho_0, c_v)^{-1} \cdot \partial \delta / \partial T$, $\delta_0, \rho_0$ is the resistivity and density of the metal at 2730 K, $c_v$ is the heat capacity at constant volume, $\partial \delta / \partial T$ is the derivative of the resistivity of the metal on temperature.

With magnetic field diffusion penetration into a substance, the thermal energy density is approximately equal to the energy density of the magnetic field [7], that is:

$$Q \approx \frac{B^2}{2 \mu_0}.$$  

(2)

The process of nonlinear diffusion can be realized only in a sufficiently strong magnetic field [8], in which the metal resistivity increases approximately twofold, which corresponds to the value of induction:

$$B_0 = \left(\frac{2 \mu_0}{\beta}\right)^{0.5}.$$  

(3)

The value of the magnetic field induction $B_0$ for most metals is several tens of tesla (for copper, 45 T and aluminum, 30 T). The magnitude of the magnetic induction of several tens of T corresponds to a magnetic pressure on the conductor surface of several tens of kbar. Therefore, the wave of nonlinear diffusion spreads through the substance together with the shock wave caused by the magnetic field pressure on the conductor surface.

When a wave of nonlinear diffusion spreads through a substance, the depth of magnetic field penetration into a conductor can be estimated as [8, 14]:

$$\Delta_h \approx 0.75 \frac{B(t)}{B_0} \left(\frac{\delta \cdot (t - t_0)}{\mu_0}\right)^{0.5},$$  

(4)

where $t_0$ is the moment in time at which the magnetic field induction at the conductor boundary reaches a value equal to $B_0$.

The aim of this work was to experimentally study the spreading of a magnetic field nonlinear diffusion wave that occurs during an electric explosion of flat and cylindrical conductors in the current skinning mode, when the magnetic field induction value significantly exceeds the value of $B_0$, which is typical for CEE modes implemented in the MagLIF concept [4, 5]. The paper analyzes the results of experiments on the explosion of flat copper conductors at a current level through the conductor of 300 kA and a rise time of the current pulse of 700 ns.

2. Experimental setup

Experiments on the explosion of conductors in the current skinning mode were carried out on the IMRI-5 pulser setup [15], which consists of a capacitor bank with total capacitance $C_0 = 3.23 \mu F$ that was charged to voltage $U_0 = 70$ kV. The inductance of the electrical circuit was 62 nH, and the inner resistance of the pulser was 0.15 Ohm. The energy stored in the bank is transferred to the load unit.
with a controlled multigap switch. The short-circuited pulser can switch current pulses of amplitude 0.5 MA with a rise time of 450 ns. The geometry of the load node is shown in figure 1.

![Load geometry](image)

**Figure 1.** Load geometry.

To exclude the effect of sparking at the contacts of the conductor with the electrodes of the IMRI-5 generator, the conductor was soldered to the high-voltage cathode (the soldering height was 4 mm) and crimped with brass contacts from the side of the grounded anode. In addition, rubber washers 2 mm thick and 20 mm in diameter were put on this conductor on both sides of the attachment of the exploded conductor. The length of the conductor was 30 mm.

3. Electrophysical diagnostics

To measure the voltage drop on conductor $U_c(t)$, the current $I_c(t)$, and the derivative of the current $dI_c(t)/dt$, we used an active divider, a Rogowski coil, and an inductive loop, respectively. The inductive loop was calibrated according to the Rogowski coil indications, while the loop sensitivity was determined from the equation:

$$K_{\text{loop}} = I_c(t_1) \int_0^{t_1} U_{\text{loop}}(t) \, dt,$$

where $t_1$ is the time at which the current derivative value is zero, $I_c(t_1)$ is the current value determined from the readings of the Rogowski coil at time $t_1$, $U_{\text{loop}}(t)$ is the signal from the inductive loop. The voltage division factor of the active divider was $K_{\text{div}} = 1892$, the Rogowski coil contained $N = 1040$ turns loaded on a shunt with a resistance $r_{sh} = 0.196$ Ohm. Thus, the inductive loop had a sensitivity of $K_{\text{loop}} = 88 \text{ A/(V·ns)}$. Oscillograms were recorded on a TDS 2024C oscilloscope.

The voltage drop in the circuit section where it is measured is described by the formula:

$$U_c(t) = d(L_{\text{circ}} \cdot L_c(t)) / dt + I_c(t) \cdot r_{\text{circ}}(t),$$

where $L_{\text{circ}}$ and $r_{\text{circ}}(t)$ are, respectively, the inductance and resistance of the circuit section where the voltage drop is measured. The resistance $r_{\text{circ}}(t)$ should be the sum of the electrode resistance $r_0$ and the conductor resistance $r_c(t)$ ($r_{\text{circ}}(t) = r_0 + r_c(t)$). The induction $L_{\text{circ}}$ should be the sum of the electrode induction $L_0$ and the conductor induction $L_c$ ($L_{\text{circ}} = L_0 + L_c$).

4. Explosion of cylindrical conductors

In the experiments, we used two types of cylindrical conductors (wires): copper 0.5 mm in diameter and aluminum 0.44 mm in diameter. The magnitude of the magnetic induction on the surface of the exploded conductor can be estimated as:

$$B_y \approx \frac{\mu \cdot \mu_0 \cdot 2 \cdot I}{4 \cdot \pi \cdot r_0},$$
where \( \mu_0 = 4 \pi \cdot 10^{-7} \text{H/m} \), \( \mu = 1 \), \( I \) is the current flowing through the conductor, \( r_0 \) is the radius of the conductor.

With a current amplitude of 300 kA and a conductor radius of 0.22 mm, the magnetic field induction on its surface will be about 270 T, which is significantly higher than \( B_0 \). The thickness of the skin layer for a copper conductor in the conditions of the IMRI-5 installation is:

\[
\delta = 5.03 / (\sigma f)^{0.5} = 116 \mu\text{m},
\]

at \( \sigma = 5.88 \cdot 10^5 \text{Ohm}^{-1} \cdot \text{cm}^{-1} \), \( f = 0.32 \text{ MHz} \).

To calibrate the electrical measurements and calculate the inductance corrections for such conductors, we used a load that was a copper conductor with a diameter of 2 mm. From the condition that in the short-circuit mode (SC) the following equation must be used:

\[
U_c(t) = L_0 \cdot \frac{dI_c(t)}{dt} + I_c(t) \cdot r_0,
\]

it was found that \( L_0 = 27.5 \text{ nH} \), and \( r_0 = 3 \text{ m\Omega} \). Similar calculations were carried out for a circuit with an exploding conductor load. Calculation of the inductance of the circuit section on which the conductor is located (based on the geometric dimensions) shows that the inductance of a copper conductor with a diameter of 2 mm is \( L_{Cu2} = 11.5 \text{ nH} \); the inductance of a copper conductor with a diameter of 0.5 mm is \( L_{Cu0.5} = 15.7 \text{ nH} \); the inductance of an aluminum conductor with a diameter of 0.44 mm is \( L_{Al0.44} = 16.1 \text{ nH} \). These inductance values were used to calculate the voltage drop across the exploded conductor.

The best agreement between the readings of electrophysical measurements is obtained if the inductance of the circuit section on which the voltage is measured is \( L_{kz} = 43.2 \text{ nH} \). The active resistance of the copper conductor changes insignificantly (within the experimental error) and amounts to 1.03 m\( \Omega \). With a tabular specific resistance of a copper conductor of \( 1.7 \cdot 10^{-6} \text{ Ohm} \cdot \text{cm} \), this resistance corresponds to a conductive layer with a thickness of 86 microns, which is close in value to the thickness of the skin layer. Upon transition to the explosion of conductors with a diameter of 0.5 mm, the load inductance should increase by \( \Delta L_{0.5} = 4.15 \text{ nH} \). When switching to conductors with a diameter of 0.44 mm, the load inductance should increase by \( \Delta L_{0.44} = 4.54 \text{ nH} \). This correction was taken into account when processing oscillograms obtained during the explosion of these conductors.

4.1. Explosion of copper cylindrical conductors with a diameter of 0.5 mm

Figure 2 shows an oscillogram of the current, time dependences of the resistive voltage drop across the conductor and the conductor resistance, obtained in a shot with a copper conductor 0.5 mm in diameter (Shot#17). The inductance of the section of the circuit where the voltage is measured (based on the calibration shots and the correction for the geometric parameters of the conductor) is \( L = 47.35 \text{ nH} \).
4.2. Explosion of aluminum cylindrical conductors with a diameter of 0.44 mm

Figure 3 shows an oscillogram of the current, time dependences of the resistive voltage drop across the conductor and the resistance of an aluminum conductor with a diameter of 0.44 mm (Shot#16). The inductance of the circuit section on which the voltage drop is measured was taken equal to \( L = 47.74 \, \text{nH} \). In figure 2 and figure 3, the dotted vertical line shows the instant of breakdown along the exploded conductor. The calculation of the resistance of the conductor was made until the breakdown occurred. As can be seen from figure 3 and 4, the resistance of the conductors’ changes over time. At the beginning, the resistance decreases, and then begins to grow, which indicates the heating of the surface of the conductors and the appearance of a wave of diffusion of the magnetic field, propagating deep into the conductors.

![Figure 3. 0.44 mm diameter aluminium conductor (Shot#16). Oscillogram of the current, time dependences of the resistive voltage drop across the conductor and the resistance of the conductor.](image)

5. Explosion of foils

In the experiments, we exploded copper foils 300 µm thick and aluminum foils 200 µm thick. The foil width varied from 1 to 3 mm. The length has always been 3 cm. To calculate the inductance of the circuit in which the exploded conductors were installed, we used a load that was a copper foil 600 µm thick, 1 cm wide and 3 cm long (Short circuit mode). Based on the calibration shots, the inductance of the circuit section where the voltage drop is measured is \( L_{\text{dc}} = 41 \, \text{nH} \). In order to estimate how much the short-circuit inductance is less than the inductance of real foils, a coaxial geometry with cylindrical conductors whose perimeter was equal to the perimeter of the foils was considered.

Based on this approximation, corrections to the inductances were obtained, which must be added to the short-circuit inductance for real conductors are shown in table 1.

| Foil width (mm) | Foil thickness (mm) | Adjustment for inductance (nH) |
|-----------------|---------------------|-------------------------------|
| 1               | 0.3                 | 6.3                           |
| 2               | 0.3                 | 4.56                          |
| 3               | 0.3                 | 3.46                          |
| 1               | 0.2                 | 6.54                          |
| 2               | 0.2                 | 4.72                          |
| 3               | 0.2                 | 3.6                           |
5.1. Explosion of aluminum foil 200 microns thick
Figure 4 shows the current oscillogram, the time dependences of the resistive voltage drop along the conductor and the resistance obtained in shots with aluminum foil whose width was 0.96, 1.87, and 3.2 mm, respectively (File Shot#12, Shot#14, Shot#15).

![Figure 4. Aluminium foil with a thickness of 200 μm, the widths of which were 0.96, 1.87, and 3.2 mm, respectively (Shot#12, Shot#14, Shot#15). Oscillogram of the current, time dependences of the resistive voltage drop across the conductor and the resistance of the conductor.](image)

5.2. Explosion of copper foil 300 microns thick
Figure 5 shows the current oscillogram, the time dependences of the resistive voltage drop along the conductor and the resistance obtained in shots with copper foil, the widths of which were 1.17, 1.89, and 2.97 mm, respectively (Shot#09, Shot#11, Shot#07).

![Figure 5. Copper foil 300 μm thick, the widths of which were 1.17, 1.89 and 2.97 mm, respectively (Shot#09, Shot#11, Shot#07). Oscillogram of the current, time dependences of the resistive voltage drop along the conductor and the conductor resistance, at a value of the magnetic field induction significantly exceeding the value of $B_0$.](image)

6. Conclusion
As a result of the research carried out, a significant amount of experimental data was obtained on the explosion of conductors under conditions of skinning current. The obtained experimental data will serve as the basis for the spreading processes analysis of the magnetic field nonlinear diffusion waves into the conductor, based on numerical modeling in the magnetohydrodynamic approximation.
Acknowledgment
The work was carried out within the framework of the state assignment of the Ministry of Science and Higher Education of the Russian Federation on the topic No. FWRM-2021-0001. The work was supported by RFBR and ROSATOM according to the research project No. 20-21-00036.

References
[1] Slutz S, Olson C and Peterson P 2003 *Phys. Plasmas* **10** 429–37
[2] Mitrofanov K N, Grabovsky E V, Alexandrov V V, Oleinik G M and Frolov I N 2013 *IEEE Pulsed Power and Plasma Science Conference* (New Jersey: IEEE) pp 16–21
[3] Lindemuth I R 2015 *Phys. Plasmas* **22** 122712
[4] Slutz S, Herrmann M, Vesey R, Sefkow A, Sinars D, Rovang D, Peterson K and Cuneo M 2010 *Phys. Plasmas* **17** 056303
[5] Gomez M R et al 2014 *Phys. Rev. Lett.* **113** 155003
[6] Fowler C, Garn W and Caird R 1960 *J. Appl. Phys.* **31** 588–94
[7] Saharov A D 1966 *Phys.-Usp.* **8** 725–34
[8] Knopfel G 1972 *Superstrong pulsed magnetic fields* (Moscow: Mir)
[9] Bocharov Y N, Krivosheev S I and Shneerson G A 1982 *Pis’ma v Zhurnal Tekhnicheskoj Fiziki* [in Russian] **8** 212
[10] Kinslow R 1970 *High-velocity impact phenomena* (New York: Academic Press)
[11] Fortov V E 2007 *Phys.-Usp.* **50** 333–53
[12] Lemke R, Knudson M, Hall C, Haill T, Desjarlais P, Asay J and Mehlhorn T 2003 *Phys. Plasmas* **10** 1092–9
[13] Oreshkin V I and Chaikovsky S A 2012 *Phys. Plasmas* **19** 022706
[14] Chaikovsky S A, Oreshkin V I, Datsko I M, Labetskaya N A and Ratakhin N A 2014 *Phys. Plasmas* **21** 042706
[15] Rousskikh A G, Oreshkin V I, Labetsky A Yu, Chaikovsky S A and Shishlov A V 2007 *Tech. Phys. Plasmas* **52** 571–6