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Electrical explosion of plane conductors in megagauss magnetic fields

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Abstract

Experiments with electrically exploding copper foils of thickness 100 μm and width 5 mm were performed on a MIG generator at a current of amplitude up to 2.5 MA and rise time 100 ns. Using a four-frame optical camera with an exposure time of 3 ns, the intrinsic luminescence of the foil outer surface was imaged. The images showed different stages of plasma generation and instability development, in particular, the formation of a plasma channel along the foil longitudinal axis within about 75 ns from the onset of current flow. The factor of enhancement of the magnetic field at the foil edges was estimated analytically. The estimates have indicated that the magnetic field enhancement may result in the formation of a shock wave propagating from the foil edge to its center.

INTRODUCTION

The studies of the electrical explosion of conductors (EECs) in a skinned current mode are of interest for various technological applications. One of the problems is associated with the transport of electromagnetic energy in the magnetically insulated transmission lines of the multiterawatt generators capable of producing currents of amplitude 30–50 MA and rise time less than 100 ns that are currently being developed [1, 2]. Generators of this type are supposed to be used in systems of controlled thermonuclear fusion based on Z pinches [3, 4]. Other problems are involved in studying the EEC in the framework of the Magnetized Liner Inertial Fusion (MagLIF) concept [4, 5]; in the generation of superstrong magnetic fields, both by compressing metallic shells [6] and by exploding single-turn solenoids [7, 8]; in the electromagnetic acceleration of bodies, such as the acceleration of flat metal plates in shock wave experiments [9, 10], etc.

The main processes that occur in an electrically exploding conductor with a skinned current are the joint propagation of a shock wave and a nonlinear magnetic field diffusion wave in the conductor material [11, 12], the formation of a dense low-temperature plasma at the conductor surface, and the development of large-scale instabilities. The nonlinear magnetic diffusion into the conductor is characterized by an anomalously high, compared with conventional diffusion, penetration rate of the electromagnetic field. The increase in magnetic diffusion rate is due to an increase in the resistivity of the metal heated by the current flowing through it.

EXPERIMENTAL RESULTS

Experiments on the electrical explosion of conductors were carried out on a MIG generator [13, 14] capable of producing terawatt-level pulses at currents of amplitude up to 2.5 MA and rise time 100 ns. The test objects were copper foils of width 5 mm. The diagnostics included electrotechnical current measurements and optical imaging of the conductors with an HSFC Pro four-frame camera providing an exposure time of 3 ns. The optical system of the camera was adjusted so that the dynamics of the intrinsic luminescence of the foil surface could be observed in the z, x plane. The direction of the z axis coincided with that of the current flow. The length of the conductor along this direction, L, was 15 mm, its width along the x direction, D, was 0.5 mm, and its thickness along the y direction, d, was 100 μm. The experimental procedure and results are described in detail in [15]. The aim of the present work was to clarify the interpretation of the results of these experiments.

Figure 1 shows the images of the intrinsic luminescence of a foil obtained using the HSFC Pro optical camera. The first image (see Fig. 1a) was taken 75 ns after the onset of current flow through the conductor. At this time, the current through the conductor was approximately 1.6 MA, that is, the image was taken earlier than the generator current reached a maximum of 2.3 MA. The second image (see Fig. 1b) was taken at the 135th nanosecond (at a current of 2 MA), that is, after the current reached a maximum.

EXPERIMENTAL RESULTS

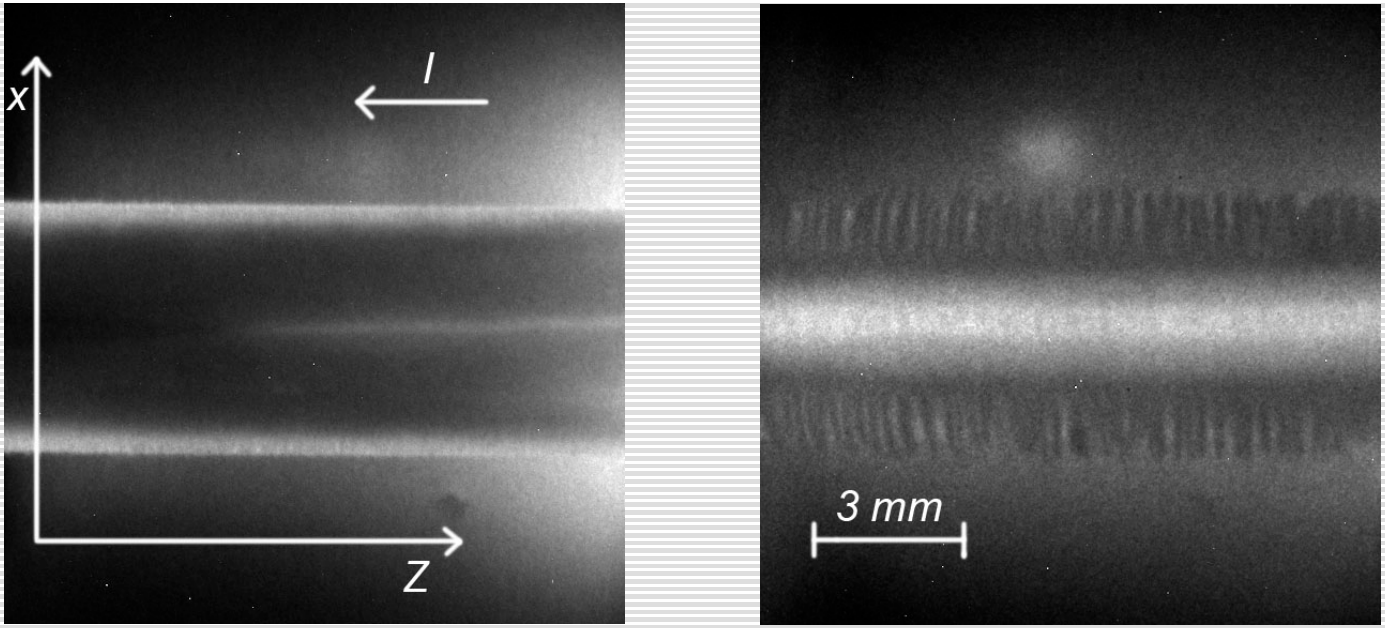

Fig. 1. Images of the surface of a foil taken with the HSFC Pro.

EXPERIMENTAL RESULTS

The initial stage of the foil explosion proceeded in a skinned current mode. At this stage, during the first 40–45 ns, a nonlinear magnetic diffusion wave propagated along the thickness of the conductor (along the y direction) [11]. After the propagation of the nonlinear diffusion wave, a uniform current mode was established [11] with the current density distributed over the cross section of the conductor in direct proportion to its conductivity. This explosion stage is presented by Fig. 1a. As can be seen in Fig. 1b, a shock wave propagated along the x direction from the edges of the foil to its center, after which large-scale instabilities occurred on the foil surface. Most likely, the shock wave was formed due to the pressure of the magnetic field, which can be estimated as

, $$p_m = \frac{B^2}{8\pi} \qquad (1)$$

where B is the magnetic induction. The direction of the shock wave propagation from the edge to the center is determined by the enhancement of the magnetic field at the foil edge. Let us estimate the magnitude of the field enhancement.

DISCUSSION

Consider a flat plate with the following dimensions (see Fig. 2): the width (along the x axis) is D, the thickness (along the y axis) is d, and the length (along the z axis) is infinite. Along the z axis, a current I flows, which is distributed uniformly over the cross section of the plate, so that the current density is determined as

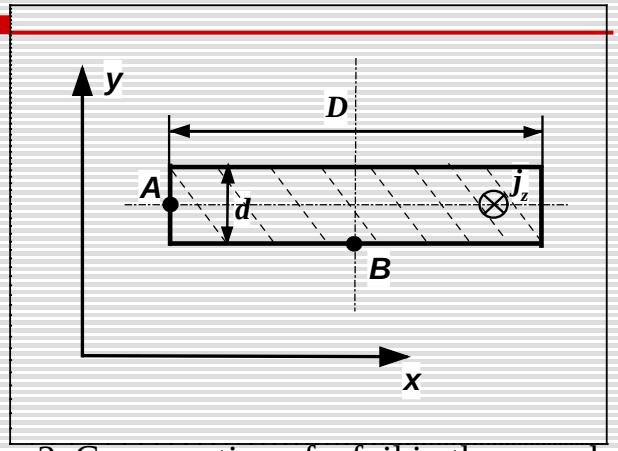

Fig. 2. Cross section of a foil in the x, y plane.

$$j_z = \frac{I}{d \cdot D}$$

The magnetic induction can be calculated from the Biot–Savart law: $\mathbf{B} = \frac{1}{c}\int \frac{\mathbf{j}\times\mathbf{R}}{R^3} dV$,

where **R** is the radius vector of a point and c is the velocity of light in vacuum.

At point A, the magnetic field vector has one component directed along the y axis. By placing the origin at point A, for the y component of the magnetic field at this point, we can write

$$B_A = \frac{I}{cD}\left[\ln\left(1+4\chi^2\right)+4\chi \cdot arctg\left(\frac{1}{2\chi}\right)\right] \approx \frac{2I}{cD}\left(1+\ln 2\chi\right) \qquad (2)$$

At point B, the magnetic field vector has only one x component. By placing the origin at point B, for the x component of the magnetic field at this point, we can write

$$B_B = -\frac{I}{cD}\left[\chi \ln\left(1+\frac{4}{\chi^2}\right)+4 \cdot arctg\left(\frac{\chi}{2}\right)\right] \approx -\frac{2\pi I}{cD} \qquad (3)$$

where $\chi = \frac{D}{d}$. The approximate equalities refer to the case $\chi >> 1$.

Then we can write for the magnetic field enhancement factor $\beta = \left|\frac{B_A}{B_B}\right| \approx \frac{1+\ln 2\chi}{\pi}$ (4)

DISCUSSION

Let us estimate the magnetic fields and magnetic pressure typical of experiments carried out on the MIG facility. Assume that the current flowing through an exploded foil is 2 MA. Then, according to (2,3), the magnetic induction at points A and B is about 4.5 and 2.5 MGs, respectively, and, hence, $\beta \approx 1.8$. The 4.5-MGs magnetic induction, according to (1), corresponds to a magnetic field pressure of 800 kbar. This pressure can initiate a strong shock wave in a material, such as observed in Fig. 1b. During the propagation of such a wave through a foil, the material behind its front should heat up and its conductivity should decrease, resulting in current focusing in the axial region of the foil. In addition, the convergence of the shock wave to the axis should be accompanied by quite strong compression of the material at the foil axis. As the conductivity of the foil material increases on compression, this also contributes to the current flow near the longitudinal axis of the foil.

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