Peculiarities of the magnetic field distribution in the railgun channel

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Abstract. The measurement of the magnetic field induction in the railgun channel was carried out. The influence of the conductivity of the rail material on the efficiency of magnetic field generation using external coils was evaluated. The distribution of the pulsed magnetic field corresponding to the experimental conditions is calculated. The evaluation of the applicability of the used model for the simulation of railgun for various types of boundary conditions in the passive circuit was carried out.

1. Introduction
Railgun is experimental device with a wide range of possible applications: high speed body acceleration [1], generation of strong shock waves [2], deposition of different materials onto a substrate [3]. One of the main parameters determining the dynamics of acceleration is the maximum induction and the form of the magnetic field pulse in the gap between the rails. The simplest and most effective way to increase induction in the channel is to use external coils [4, 5]. The actual problem is the optimization of the rail accelerator design and the power supply system in terms of the most efficient acceleration.

Figure 1. The appearance of the rails, the plate of polycarbonate and one of the external magnetic field coils and magnetic field sensor. The arrows indicate the measurement points of the magnetic field in the channel.
2. Experimental facility
The railgun consists of two copper rails 160 mm long, located one above the other (figure 1) [6]. Polycarbonate plates are fixed on the sides of the rails, on which copper coils are located, creating an external magnetic field. The channel cross-section is 2 × 2 mm. The rails and coils were connected to independent pulsed power supplies, which made it possible to determine the contribution of each of them to the total magnetic field.

At the initial moment, the first power supply initiates electric breakdown behind the accelerated body and a current begins to flow through the gas gap between the rails in the rail-to-rail circuit. At the selected moment of time, the second power supply delivers current pulse through the external coils. The magnetic field acts on the gas discharge, forcing it to move and push the body in front of itself. In the simplest model of acceleration [5], the discharge thickness between the rails is zero. It is affected by the Ampere force, determined by the expression \( F_A = \frac{1}{2} L I_R^2 \). Here \( I_R \) – total current through the rail–discharge–rail circuit, \( L' \) – is the inductance of this circuit per unit of its length (linear inductance), \( L'I_R = B_R h \), where \( B_R \) – is the magnetic induction in the channel generated by the current \( I_R \), \( h \) – the height of the gap. Also, a magnetic field \( B_M \) from external coils acts on the discharge. Thus, the total accelerating force is determined by the expression \( F_A = \frac{1}{2} L'I_R^2 + B_M I_R h \). Let us introduce the parameter \( M' \) – linear mutual inductance of the coils and the rail circuit, defining it by the expression \( M'I_M = B_M h \), where \( I_M \) – current through the coil. In this case, the expression for the Ampere force will take the form \( F_A = \frac{1}{2} L'I_R^2 + M'I_M I_R \). \( I_R \) and \( I_M \) are set by the configuration and initial charge of the power sources of the respective circuits and recorded during the experiment. The parameters \( L' \) and \( M' \), due to the geometry and material of the electrodes, can be determined in advance.

To measure the magnetic field, the railgun is assembled without a projectile body and without a breakdown initiator, the muzzle ends of the rails are short-circuited with a copper bridge. Holes were made in the side plates of polycarbonate through which magnetic field sensors are placed in the channel. Holes are located at a distance \( x_1 = -5 \text{ mm}; x_2 = 40 \text{ mm}; x_3 = 90 \text{ mm}; x_4 = 135 \text{ mm} \) from the position of the projectile body (figure 1). The magnetic field sensor is a coil of copper wire with a length of 2 mm and a diameter of 1.4 mm, filled with epoxy compound. The leads are twisted between themselves and connected to a coaxial cable. The sensor signal is recorded by an oscilloscope, then integrated numerically to produce a profile proportional to the magnitude of the induction of the measured magnetic field. Measurements in each section are repeated with two opposite orientations of the sensor. This eliminates the parasitic component of the signal, which remains unchanged in both cases, while the useful signal is inverted. Sensors were calibrated by placing them in a known field generated by a specially made high-current Helmholtz coil.

3. Mathematical model
The main task of the numerical simulation was to determine the applicability of the model for the optimization tasks of the railgun design. For this reason, a two-dimensional geometry was chosen (figure 2), since the calculation of the full three-dimensional problem for these purposes is redundant and requires significant computational resources. The model was implemented in the COMSOL Multiphysics. At the boundaries of the computational domain, the insulation condition was specified. In the experiment, the current supply was connected either through rails or through coils (figure 3). In the active circuit, a current pulse measured in the experiment was set. Two variants of the boundary conditions for the
passive circuit were considered in the calculation – the possibility of current induction in it and the forced equating it to zero.

4. Results

In figure 3 solid lines show the currents that are set as the boundary conditions of the active circuit for the rails (red curve) and for the coils (black curve). The dashed line shows the induced currents in the passive rail and coil circuit, obtained in the calculation.

At all measurement points, the magnetic field induction along the channel is almost unchanged. Figure 4 shows the measurement results at $x_1$ point and the calculated data. It can be seen that the two-dimensional model adequately reproduces the features of the generation of a magnetic field, but the calculated values slightly exceed the experimental ones. Since the dimensions of the sensors are comparable to the size of the channel, and the magnetic field is maximal in the center of the channel and quickly falls to its walls, an experiment is recorded in the experiment. Similar measurements by the same sensors, but in a channel with a cross section of $6 \times 6 \text{ mm}$, showed a decrease in the own field of the rails from the center of the channel to the wall by more than 12%. This inhomogeneity is apparently more pronounced in the case of a magnetic field from external coils compared to the intrinsic field of the rails.

![Figure 3](image_url)

**Figure 3.** Current through rails (red curve) and coils (black curve). The solid line is the boundary condition for the active circuit, the dotted line is the induced currents in the passive circuit, obtained in the calculation.

![Figure 4](image_url)

**Figure 4.** The magnetic field of the rails (a) and coils (b) measured in the experiment (red curve) and calculated under different boundary conditions in the passive circuit (black curves): given zero current (solid curve) and induced current (dashed curve).

The effect of a decrease in the magnetic field shown by calculations when the passive circuit is “closed” is explained by the induction of a current in it (figure 3), which prevents a change in the magnetic flux through it. Due to the large difference in area, the effect is manifested with a different force depending on the variant active circuit – passive circuit. The closure of the passive turns of the
outer coil has little effect on the flow in the active rail – discharge – rail circuit, since its changes make up a small part of the total magnetic flux.

In the experiment, the ends of the rails and the outer coil on the side of the breech are connected to current sources with high internal resistance, and the "circuit" of the circuits does not occur. However, if in the process of acceleration a separation of the plasma piston occurs, we can expect a weakening of the field in the region between the layers and, as a result, a decrease in the accelerating effect on the leading layer.

Figure 5 shows the experimental inductance of the rail – discharge – rail circuit and the linear mutual inductance of the coil and rail – discharge – rail circuit at various points. Figure 6 shows the influence of the electrode material on the magnetic induction in the center of the channel. It can be seen that the rail material has a strong influence on the pulse shape.

![Graph](image1.png)

**Figure 5.** The linear inductance of the rail – discharge – rail circuit (left) and the linear mutual inductance of the coil and the rail – discharge – rail circuit (right) at various points.

![Graph](image2.png)

**Figure 6.** The influence of the electrode material on the magnetic induction in the center of the channel. Red curve – current profile, black – induction of copper coils, green – from duralumin, blue – from titanium.

5. Conclusion
The paper presents the results of measurements of the magnetic field induction in the railgun channel. The influence of the conductivity of the rail material on the efficiency of magnetic field generation using external coils was evaluated. The distribution of the pulsed magnetic field corresponding to the
experimental conditions is calculated. The evaluation of the applicability of the used model for the calculations of railgun for various types of boundary conditions in the passive circuit was carried out.

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