Rationalization of plasma piston’s particles parameters in a coaxial railgun

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Abstract. This article is devoted to collisionless plasma particle motion in a coaxial railgun bore. Numerical modeling results showed that 2 types of motion can be realized in this system. Plasma particle parameters such as mass and charge were rationalized according to the types of motion and their roles in throwing body acceleration. The most effective parameters of the whole system were obtained.

1. Introduction
A railgun accelerators efficiency mostly depends on the choice of rational parameters and optimization of the plasma piston’s particles flow in the railgun bore. There are railguns of various types and configurations, that affects solving optimization problems. The most well-known and efficient models are coaxial and plane-parallel railguns. Also, it is necessary to consider the application of accelerators. For example, they are used in high energy density physics [1], shock wave generators [2], materials science [3], in outer space [4], etc. Nowadays, the efficiency of such systems does not usually exceed 30-40%.

The most common reasons for railgun’s losses of efficiency are: speed skin-effect [5], the electron escape effect [6] (emission crisis), unpredictable interactions of current carriers’ particles in a plasma piston with a throwing body and railgun channel [7].

The collisionless plasma model is widely used to describe the processes in these plasma formations [6]. This model, with strong external fields, describes certain types of particle motion, the most well-known of which is the cycloidal trajectory. The railgun accelerator’s plasma parameters and composition are optimized by using author’s [7] and collisionless plasma models. The criterion of optimization was the most complete energy transfer of particles of the accelerator chemical composition to the throwing body, taking into account the free path. It increases the overall efficiency of the plasma formation acceleration [7]. However, in comparison with plane-parallel systems, a different type of particle trajectory can be realized in a coaxial railgun. The trajectory type changes allow to increase the longitudinal velocity of the particles in comparison with plane-parallel ones, especially nearby the axis of symmetry (cumulative effect).

The relevance of the article is to create the rational model for the plasma formation behavior in the railgun bore. Thus, the objective of this article is to rationalize the behavior of plasma formation particles throughout its movement in the channel of a coaxial railgun in order to increase the effectiveness of the action of the entire railgun system.
2. Physical and mathematical model

The model of plasma formation acceleration process is shown in the figure 1a. The inner electrode (Electrode 1) is powered by the capacitor $C$, the outer electrode (Electrode 2) is grounded. The electric field of intensity $E$ is directed along the radius $r$, as shown in the Figure 1a. The current $J$ flowing through the central electrode via the plasma formation reaches the external electrode and creates a magnetic field $B$; its direction is also shown in the Figure 1a. The resistance in the circuit is $R$, the initial voltage on the capacitor is $U_0$, the radii of the external and internal electrodes are $r_1$ and $r_2$, respectively.

![Figure 1a. The scheme of plasma formation acceleration in the railgun bore.](image1.png)

![Figure 1b. The scheme of a current carrier particles motion in the plasma formation.](image2.png)

The plasma piston’s distance from the edge of the bore during the piston’s movement is greater than the radius of the external electrode. Thus, edge effects along the $z$ axis can be ignored, so the
electromagnetic field is uniform. Then the distribution of the electric field along the \( r \) axis is similar to the case of the cylindrical capacitor:

\[
E = \frac{U}{r(t) \cdot \ln \left( \frac{r_2}{r_1} \right)},
\]

where:

- \( U \) – the capacitor’s voltage,
- \( r_1 \) – inner electrode radius,
- \( r_2 \) – outer electrode radius,
- \( r \) – the distance from the cylinder axis.

The magnetic field is similar to the case of a straight conductor of constant circular cross-section. The influence of the transverse currents is neglected [6]:

\[
B = \frac{\mu_0 U}{2\pi r(t) R},
\]

where:

- \( \mu_0 \) – magnetic constant.

The dependence of the voltage between the electrodes on the essential acceleration time, that is described by the equation \( U = U_0 \cdot e^{-\alpha t} \), is shown in the figure 2 [7].

![Figure 2. Graph of voltage change vs time for a collisionless plasma.](image)

In this paper the model of a collisionless plasma is used, without taking the azimuthal motion of the particles into consideration. The motion of the current carrier particles in the plasma formation is shown in Figure 1b. Similar to Figure 1a, the following items are shown: \( \vec{E} \) and \( \vec{B} \) vectors, the outer and inner radii of the railgun channel \( r_2, r_1 \) and also the directions of velocity vectors of the plasma particle along the axial and radial axes \( v_z, v_r \); \( F_L \) is the Lorentz force.

So as the system is symmetric, it is possible to consider the half of it. The initial velocities of the particle correspond to the Maxwell distribution with the temperature of 11000 K [1]. As it can be noticed, the direction of the Lorentz force is positive both along the \( r \) and \( z \) axes for a wide range of velocities, therefore positive initial velocities are chosen.

The system of equations describing the motion of a particle with initial conditions is written as follows:
\[
\begin{align*}
\dot{m} \cdot r(t) &= q \cdot \left( \frac{U_0 \cdot e^{-\frac{t}{\tau}}}{r(t) \cdot \ln \left( \frac{r_a}{r_0} \right)} - \frac{\mu_0 \cdot U_0 \cdot e^{-\frac{t}{\tau}} \cdot z(t)}{2 \cdot \pi \cdot r(t) \cdot R} \right) \\
m \cdot \dot{z}(t) &= q \cdot \frac{\mu_0 \cdot U_0 \cdot e^{-\frac{t}{\tau}} \cdot r(t)}{2 \cdot \pi \cdot r(t) \cdot R} \\
r(0) &= r_0 \\
r'(0) &= \sqrt{\frac{3R_0 T}{N}} \\
z(0) &= 0 \\
\dot{z}(0) &= \sqrt{\frac{3R_0 T}{N}}
\end{align*}
\]

where:

\( m \) – the mass of particles [kg], \( z(t) \) – the coordinate along the channel of a railgun [m], \( \dot{r}(t) \) – the velocity of particle along the vertical axis [m/s], \( \dot{z}(t) \) – the velocity of particle along the channel of the railgun [m/s], \( \ddot{r}(t) \) – the acceleration along the vertical axis [m/s²], \( \ddot{z}(t) \) – the acceleration along the channel of a railgun [m/s²], \( q \) – the charge of plasma particle [C], \( U_0 \) – the initial voltage on the capacitor [V], \( \tau \) – the discharge time of the capacitor [s].

3. **Numerical experiment**

Numerical simulation of the equation system of charged particles motion in a plasma formation was carried out using Maple. Parameters changed in their ranges with the corresponding values of steps.

Table 1. The variability intervals of parameters.

| Parameter name       | The lower limit | The upper limit | Increment |
|----------------------|-----------------|-----------------|-----------|
| Voltage, V           | 1,000           | 10,000          | 1,000     |
| Resistance, Ohm      | 0.1             | 1               | 0.1       |
| External electrode radius, cm | 7               | 12              | 1         |
| Internal electrode radius, mm   | 1               | 2               | 1         |
| Mass, u              | 1               | 42              | 1         |
| Charge, 1.6·10⁻¹⁹ C  | 1               | 8               | 1         |
| Capacity, µF         | 200             | 1,000           | 100       |
The results of the simulation show that two types of particle motion are realized at times of cyclotron period in the coaxial railgun: cycloidal and aperiodic (figure 3a, b). The different types of motion are useful for various particles. This can help to solve the rationalization problems of the interaction of plasma formation with accelerated body, inner and outer electrodes and other environments. For example, electrons should better have the cycloidal type of motion, because it allows the maximum number of electrons to remain in the region of the internal electrode, so that they do not leave the system, what can partially solve the problem of an emission crisis. In addition, electrons have small sizes but at the same time huge energies of about 2500 eV; their interaction with the throwing body is undesirable, because instead of an elastic collision, electrons are introduced into the surface layers of the material with the formation of radiation porosity (Schottky and Frenkel lattice defects). As alternative for electrons, the ions can be used for transmitting the impulse to the body, since they are large and heavier. Respectively, the aperiodic type of trajectory is more useful, because the acceleration of ions is constantly positive, therefore, their kinetic energy is much higher than in the case of cycloidal motion trajectories.

For each specific configuration it is necessary to find the charge and mass of the ion that can solve the rationalization problem of plasma formation parameters in a coaxial railgun. The parameters should be chosen so that during the half the cycloidal period the aperiodic trajectory changes to the cycloidal one and the maximum of kinetic energy is achieved. The transition from an aperiodic motion type to a cycloid one occurs in case of change in the sign of the radial component of the particle acceleration. It can be noticed from the system of equations (1):

\[
\dot{r}(t) = \frac{U_0 e^{-\mu t}}{r(t) \cdot \ln \frac{r_2}{r_1}} \left( \frac{\mu_0 \cdot U_0 e^{-\mu t} \cdot z(t)}{2\pi \cdot r(t) \cdot R} \right) \quad m \geq 0
\]

It is obvious that the change in the sign of the acceleration occurs when the axial component of the velocity exceeds the characteristic value \( v_{z,\text{lim}} \):
4. Conclusion

According to the results of the calculation, a number of particles that satisfy the necessary criterion were obtained. From the whole number of particles, the argon isotope ($^{42\text{Ar}}$) turn out to be the most practical one. The following parameters of the railgun are necessary to ensure the movement of such a particle along the needed trajectory:

$$V_{\text{lim}} = \frac{2\pi R}{\mu_0\ln \frac{r_2}{r_1}}$$

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