Estimating the railgun plasma piston rational parameters for the nanosatellite acceleration

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Abstract. The article examines the problem of finding rational parameters and composition of particles as well as optimizing plasma piston interaction with the launched object such as nanosatellite. Optimization of plasma formation parameters is necessary for solving the following problems: implementation of particles into the launched object’s surface with the formation of radiation porosity, increasing the object’s specific volume, heating the object’s construction materials up to the phase changing, heating the materials of the railgun, increasing the object’s mass etc. These measures will increase the efficiency of the perspective rail systems for the nanosatellite acceleration. We introduce an algorithm for determining the rational parameters of plasma formation which allows perpendicular fall of plasma particles onto the surface in order to increase the nanosatellite speed.

1. Introduction

Currently, there are many orbital satellites and clusters of satellites in use. They support systems of communication and Earth remote sensing. It helps to research processes in atmosphere and other important science-oriented problems. Satellite launching by means of modern rockets is extremely expensive and often causes heavy damage to the environment. That is why systems of pulse launch are being developed at present. Pulse systems design highly depends on the parameters of the projectile. In this article we use the parameters and the view of the nanosatellite from the article [1].

Electromagnetic launch using a rail accelerating system (railgun) holds much promise [2]. However, in case of launching nanosatellites the common practice of using conductor materials for the projectile has a number of weak points.

This problem can be solved by using different types of conductor armature, which accelerates the projectile. Usually metals such as cuprum and aluminium are used. But for various reasons it is not rational for the nanosatellites launching. Firstly, the efficiency of the railgun modern constructions is near 30%, so more than 60% of energy is wasted for the heating of the construction. Secondly, the efficiency of the systems is reduced due to the projectile mass increase. In addition, such systems have low reliability.

In our opinion, using a plasma piston for accelerating the nanosatellite is the most efficient way of launching, but there are various problems inherent to any interactions between the plasma and the solid. They are:

1. Implementation of plasma piston particles into the nanosatellite body and the launcher rail surface. That causes radiation-induced defects.
2. Increase of the nanosatellite body specific volume.
3. Heating of the nanosatellite materials up to the phase transition, heating of the launcher materials.
These effects efficiently reduce the plasma piston interaction with the nanosatellite. The level of such effects highly depends on plasma piston particles composition [4]. The equations of plasma piston state and rails metal are described in the articles [5-18].

Let us consider the multicomponent plasma formation in close volume interacting with the electromagnetic field to define the rational parameters of particles in the plasma piston. The trajectory of movement is close to the trajectory of a particle in the exponentially decreasing electromagnetic field, which is described in the article [19]. In this work we solve the problem of defining the rational parameters of the multicomponent plasma formation. The parameters rationalized in this article are the particle mass and charge. All other parameters are equal to the parameters in the process of a projectile electromagnetic acceleration by railgun for model and real experiments. Nevertheless, this problem appears in any interaction of plasma with a surface. Such optimization may be carried out for several reasons. Let us consider the extreme number of particles normal incidence onto the surface of the object, as a first approximation. It is equal to the parallelism of a particle’s velocity vector to x axis. It occurs in different time for different types of trajectories. Let us analyse the problem of rationalisation in case of permanent electromagnetic field.

2. Rational parameters of plasma formation particles in case of permanent electromagnetic field

As it is well known, the particle’s trajectory represents the following equations in case of permanent electromagnetic field:

\[
\begin{align*}
    x(t) &= -\frac{1}{2} U_0 md \cos \left( \frac{q k U_0 t}{md} \right) k_u + 2 \sin \left( \frac{q k U_0 t}{md} \right) md q Rn S - 2 t q^2 U_0 Rn S k_u - m d U_0 k_u, \\
    z(t) &= \frac{1}{2} md U_0 \sin \left( \frac{q k U_0 t}{md} \right) k_u - 2 \cos \left( \frac{q k U_0 t}{md} \right) q Rn S + 2 q Rn S \\
    \end{align*}
\]

Hence, the form of the z-component of velocity is the following:

\[
\dot{z} = \frac{1}{2} \frac{U_0 \cos \left( \frac{q k U_0 t}{md} \right) k_u + 2 \sin \left( \frac{q k U_0 t}{md} \right) q Rn S}{q Rn S k_u}
\]

The time up to the normal incidence of a particle onto the surface was found from the equation \( \dot{z} = 0 \). It is equal to

\[
t_{n.s.} = -\frac{\arctg \left( 1 \frac{U_0 k_u}{2 q Rn S} \right) md}{U_0 k_u q}
\]

(1)

Further we have to make a guess for the time of a particle’s falling onto the surface in a real situation. Here we use the approximation expressed as:

\[
t_{n.s.} = t_0 + A v
\]

(2)

\( t_0, A \) – constants.

This way:
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\[
t_0 + Av = -\frac{\arctg \left( \frac{1}{2} \frac{U_0 k_w}{q R n S} \right) md}{U_0 k_w q}
\]

And after elementary conversion:

\[
\arctg \left( \frac{1}{2} \frac{U_0 k_w}{q R n S} \right) md + (t_0 + Av) q k_w U_0 = 0
\] (3)

This equation can be solved analytically, but it is possible to determine the particle’s mass and charge with regard to the normal incidence using numerical values of the parameters from this formula.

It is possible to describe this sequence as the following algorithm:

Choosing the type of electromagnetic field variation \(\rightarrow\) Estimating the particle’s trajectory of movement \(\rightarrow\) Calculating the time up to the normal incidence \(\rightarrow\) Using linear approximation \(\rightarrow\) Converting the equation to \(Bq + f(q) = 0\) type. \(B\) – constant, \(f(q)\) – some function \(\rightarrow\) Choosing the particle fulfilling the equation.

3. Rational parameters of plasma formation particles in case of exponentially decreasing electromagnetic field

Let us develop the algorithm in case of exponentially decreasing electromagnetic field.

As shown in [19], the trajectory of the particle in this field is expressed as:

\[
\begin{align*}
x(t) &= \left( \text{Si} \left( \alpha \beta e^{-\frac{t}{RC}} \right) - \text{Si} \left( \alpha \beta \right) \right) \left( \frac{RC}{k_w} \sin(\alpha \beta) + \frac{CU_0}{2 am n S} \cos(\alpha \beta) \right) - \\
&\quad - \left( \text{Ci} \left( \alpha \beta e^{-\frac{t}{RC}} \right) - \text{Ci} \left( \alpha \beta \right) \right) \left( \frac{CU_0}{2 am n S} \sin(\alpha \beta) - \frac{RC}{k_w} \cos(\alpha \beta) \right) + \frac{t}{k_w}, \\
z(t) &= \left( \text{Si} \left( \alpha \beta e^{-\frac{t}{RC}} \right) - \text{Si} \left( \alpha \beta \right) \right) \left( \frac{RC}{k_w} \cos(\alpha \beta) - \frac{CU_0}{2 am n S} \sin(\alpha \beta) \right) - \\
&\quad - \left( \text{Ci} \left( \alpha \beta e^{-\frac{t}{RC}} \right) - \text{Ci} \left( \alpha \beta \right) \right) \left( \frac{RC}{k_w} \sin(\alpha \beta) + \frac{CU_0}{2 am n S} \cos(\alpha \beta) \right)
\end{align*}
\]

\[
\alpha = \frac{q}{m}, \quad \beta = \frac{R C k_w U_0}{d}.
\]

Hence, the form of the velocity z-component is the following:

\[
\dot{z} = -\sqrt{\frac{RC}{k_w}} \left( \frac{RC \cos(\alpha \beta) - \frac{1}{2} \frac{CU_0 \sin(\alpha \beta)}{am n S}}{RC} \right) + \sqrt{\frac{RC}{k_w}} \left( \frac{RC \sin(\alpha \beta) + \frac{1}{2} \frac{CU_0 \cos(\alpha \beta)}{am n S}}{RC} \right)
\]

The time up to the normal incidence of a particle onto the surface was found from the equation \(\dot{z} = 0\). It is equal to
We use the following linear approximation:

\[
t_{u,n} = \ln \left( -\frac{\alpha \beta}{\text{arctg} \left( \frac{2R \text{am} S \tan(\alpha \beta) + U_0 k_u}{-2R \text{am} S + U_0 k_u \tan(\alpha \beta)} \right)} \right) \frac{RC}{RC}
\]

(4)

And after the conversion we get:

\[
\alpha \beta e \left( \frac{U_0}{RC} + \text{arctg} \left( \frac{2R \text{am} S \tan(\alpha \beta) + U_0 k_u}{-2R \text{am} S + U_0 k_u \tan(\alpha \beta)} \right) \right) = 0
\]

(5)

As (3) has no analytical solution for \( q \), the equation (5) has no analytical solution for \( \alpha \), but it is possible to determine the function \( q(m) \) with regard to the normal incidence, using numerical values of the parameters from this formula. Thus the algorithm successfully works in case of generating the electromagnetic field by the high voltage capacitor.

However, the equation (5) has multiple roots, because of the function \( \text{arctg} \left( \frac{2R \text{am} S \tan(\alpha \beta) + U_0 k_u}{-2R \text{am} S + U_0 k_u \tan(\alpha \beta)} \right) \) is quickly oscillating. So it is rational to consider the minimization of the parameter \( \hat{\alpha} = \alpha \beta e \left( \frac{U_0}{RC} + \text{arctg} \left( \frac{2R \text{am} S \tan(\alpha \beta) + U_0 k_u}{-2R \text{am} S + U_0 k_u \tan(\alpha \beta)} \right) \)\)

4. Numerical calculations of rational parameters

In this experiment we use a system with the following parameters:

\[
U_0 = 5 \text{ KV}
\]

\[
C = 8 \text{ } \mu \text{F}
\]

\[
R = 0.1 \text{ Ohm}
\]

\[
d = 30 \text{ mm}
\]

\[
k_u = 4\pi 10^{-6} \frac{\text{S}}{\text{m}}
\]

\[
n = 10^{29} \frac{1}{\text{m}^3}
\]

\[
S = 10^{-6} \text{ m}^2
\]
For choosing the ions with rational parameters the graph of parameter $\kappa$ from the mass of ion was plotted for these experiments.

![Graph of parameter $\kappa$ dependence on the mass of ion with the charge +1.](image)

**Figure 1.** The plot of the parameter $\kappa$ dependence on the mass of ion with the charge +1. Consequently, the heavy ion with the charge +1 is the most effective at the start of acceleration. It is Al+ for example in this experiment.

$\kappa$-parameter depends on the mass of ions in the plasma formation, but it is vanishing with the mass higher than 100 u. So, our model is the most effective in this region. This model is the most useful at the start of nanosatellite accelerating by the plasma formation, if the speeds of the nanosatellite and plasma formation are less than the speed of sound. Also, these examples show that rational parameters are different for different systems.

5. Rational parameters of experimental setup

An electromechanical scheme of the experimental setup is shown on fig. 2. AC current with 220 V and 50 Hz is regulated and transformed by TRESNSTELTRAFO LTS 006 (10) to the battery charger МОЧЕНТГЕН МОХХ ВС-20-10 (9) and controlled by the universal voltmeter В7-22А (11). 6 kV DC voltage from the battery charger is transmitted to the pulse capacitors ИК 5-200 У2 (7). It is controlled by the voltmeter В7-40-4 (12) with the voltage divider ДНВ-1000 (4). The charging time is 15 min. Then the
charging scheme switches off. The gas-discharge arrester ИПТ-6 (8) is used for the process initiation. The speed of the accelerated object and plasma formation is registered by the pair of inductivity coils (3) with the resistance 50 Ohm and inductivity 3 μH connected to the grounded (1) oscilloscope С9-8 (2). The process is filmed by the digital camera and high-speed camera СФР. The rationalization of the plasma formation is considered at the initial stage.

Figure 2. Electromechanical scheme of experimental setup. 1 – ground, 2 – oscilloscope С9-8, 3 – inductivity coils, 4 – voltage divider ІНВ-1000, 5 – wall of vacuum chamber, 6 – railgun, 7 – battery of capacitors ІК 5-200 У2, 8 – gas-discharge arrester ИПТ-6, 9 – battery charger МОСПЕНТГЕН М0ЧХ BC-20-10, 10 – laboratory transformer TRESNSTELLTRAFO LTS 006, 11 – voltmeter B7-22A, 12 – voltmeter B7-40-4.

Because the rational particle for the initial stage is Al⁺ so the plasma piston formative charge consists of chemically pure aluminum and С12H22O11 packed into the aluminum foil. According to the theory and parameters from [20] we can consider resonance of its eigen frequency with plasma frequency:

\[ \omega_p = \sqrt{\frac{e^2}{4\pi \varepsilon_0 m_e}} = \frac{\hbar}{2m} \]  

If the interaction speed is about 2 km/s the Langmuir frequency should be:

\[ \omega_p = 5.711 \times 10^9 \text{ rad/s} \] 

So, the concentration of ionized aluminum particles in the plasma has to be about

\[ n = \frac{4\pi \varepsilon_0 m_e \omega_p^2}{e^2} = 1.4 \times 10^{25} \text{ m}^{-3} \] 

It is possible to estimate the rational aluminum mass in the plasma formative charge with its volume V=5.4 \times 10^{-7} \text{ m}^3 and temperature of plasma formation T=7500 K, using the ionization equation:
The rational mass for other temperatures is shown on the fig. 3.

\[ m_{Al} = \mu_{Al} \left( \frac{nV}{\left( \frac{2m_e k_B T}{\epsilon_0} \right)^{\frac{3}{2}} \left( \frac{e}{2} \left( k_B T \right)^{\frac{1}{2}} \right)} \right) = 0.00015 \ k^2 \]

The rational mass for other temperatures is shown on the fig. 3.

**Figure 3.** Plot of dependence of the rational mass of aluminum on the temperature of plasma formation

Finally, the optimal ratio between Al and C\textsubscript{12}H\textsubscript{22}O\textsubscript{11} is 1:1 for the total mass of the plasma formative charge of 0.32 g.

6. Conclusion
The rationalization model of plasma formation parameters is considered in the article. The main parameters that could be rationalized according to the parameters of the experimental setup and the interaction speed are ions of plasma formation specific charge for different stages and rational initial masses of unionized charge elements.

References

[1] Gerasimov Yu V, Karetnikov G K, Selivanov A B 2013 Nano-satellites Stabilization under Condition of Pulse Launch in the Atmosphere and Space J. Engineering Journal: Science and Innovation 8
[2] Fionov A.S., Gerasimov Yu.V., Fillippenko A.V. 2007 Options for the Development of Mass Acceleration Technology in Space Proceedings of IV all-Russian conference
[3] Lehmann P., Reck B., Vo M.D., Behrens J. 2006 Acceleration of a Suborbital Payload using an Electromagnetic Railgun Proceedings of the 13-th International Symposium on Electromagnetic Launch Technology
[4] Vijayan T., Venkatramani N. 2003 Heating and Transport of Metal Plasma in a Vacuum-Arc Rail Gun IEEE Transactions on Plasma Science
[5] Fortov V.E., Ilkaev R.I., Arinin V.A. et al. 2007 *Phase Transition in a Strongly Nonideal Deuterium Plasma Generated by Quasi-Isentropical Compression at Megabar Pressures* Phys. Rev. Lett. **99** 185001

[6] Filinov V.S., Bonitz M., Fortov V.E. et al. 2005 *Coulomb Crystallization in Two-Component Plasmas* Phys. Rev. Lett. **95** 235006

[7] Eremets M.I., Trojan I.A. *Melting of Hydrogen at Megabar Pressures* 2007 21st AIRAPT and 45th EHPRG International Conference on High Pressure Science and Technology. Book of Abstracts/Eds. Angilella G.G., Pucci R., Siringo F. Catania

[8] Khomkin A., Shumikhin A. 2008 *Electrical Conductivity of Dense Metal Vapor Plasma* High Temperatures -High Pressures **37** 247.

[9] Boriskov G.V., Bykov A.I., Il’kaev R.I et al. 2005 *Shock Compression of Liquid Deuterium up to 109 GPa* Phys. Rev. B. **71** 092104

[10] Milyavskiy V.V., Utkin A.V., Zhuk A.Z. et al. 2005 *Shock Compressibility and Shock-Induced Phase Transitions of C60 Fullerite* Diamond & Related Materials **14** 1920.

[11] Pyalling A.A. 2010 *Semiempirical multiphase equation of state for hydrogen* High temperature **48** 163-169

[12] Kopyshev V.P., Medvedev A.B., Khrustalev V.V. 2006 *Equation of state of explosion products on the basis of a modified Van der Waals model* Combustion, Explosion, and Shock Waves. **42** 76-87.

[13] Verbitskaya O.V., Kuznetsova O.V., Mironova E.E., Sapozhnikov A.T., Sokolov V.P. 2007 *Integrated information and technological environment for development of equations of state* VANT **3-4** 37-45

[14] Khishchenko K.V., Fortov V.E., Lomonosov I.V. 2005 *Multiphase Equation of State for Carbon over Wide Range of Temperatures and Pressures* Int. J. Thermophys **26** 479.

[15] Jean Clérouin, Pierre Noiret. 2008 *Direct measurements and ab initio simulations for expanded fluid aluminium in the metal-nonmetal transition range* Phys. Rev. B. **78** 224203.

[16] Mazevet S., Ze’rah G. Ab 2005 *Initio Simulations of the K-Edge Shift along the Aluminum Hugoniot* Phys. Rev. Lett. **101** 155001.

[17] Gérald Faussurier, Christophe Blancard, Pier Luigi Silvestrelli 2009 *Evaluation of aluminum critical point using an ab initio variational approach* Phys. Rev. B. **79** 134202.

[18] Xianwen Ran, Yuying Yu, Hua Tan, Wenhuai Tang 2008 *Behavior of aluminum shear modulus in solid-liquid mixed phase: Estimation with percolation theory* J. of Appl. Phys. **103** 103539.

[19] A.G. Maslov 2014 *Trajectory of charged particle in exponentially lowing electromagnetic field* Molodezhniy naucho-technicheskiy vestnik **9**

[20] Y V Gerasimov, A G Maslov 2016 JPCS **731** 012006