

Hypersonic Electrodynamic Railguns with Pulse-Dynamic Biasing System

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Abstract: In this paper the simulation results of hypersonic accelerator with pulse dynamic biasing system (PDBS) which provide external magnetic field compensation are given. The nearest analog of PDBS shown is Halbach-Array. Using magnetic compensation provides is shown to increase the magnetic field in inter-rail gap of the railgun up to 270% and to increase traction force up to 310%. Besides the magnetic compensation is shown leads to the suppressing of magnetic field in outside of railgun system and facilitate EMC problem, at the same time weakening of repulsive force between rails provides the increasing of vitality of the system.

Keywords: Electrodynamic Railgun, Pulse Dynamic Biasing System, Halbach-Array, Magnetic Compensation

1. Introduction

Movement of the body influenced by electromagnetic Lorentz force

$$F_{EM} = dIB \quad (1)$$

in the railgun with considering of the resistance forces acting on the rotor, is described by the equation:

$$\frac{d}{dt}(mv) = F_{EM} - F_D, \quad (2)$$

where d – gap between rails (railgun caliber), B – magnetic induction, which is produced in the gap by current I in rails, m – projectile mass, $m = m_B + m_r$, m_B – body mass, m_r – rotor mass, v – instantaneous velocity, F_D – total strength of air resistance and rotor friction strength [1]. Rotor may be either independent element or the component of the body designing. In the classical two-rail electrodynamic railgun (EDRG) electromagnetic strength is expressed through the inductance per unit length of the rails

$$F_{EM} = \frac{1}{2} L_x I^2 \quad (3)$$

Taking into account the limitation on the compression

strength maximum (and, consequently, the limitation on the acceleration) in form

$$\frac{L_x I^2}{2m} + \frac{N}{m} v^2 \leq \frac{\sigma}{\rho l}, \quad (4)$$

so, from (1) we get the expression for instantaneous velocity of the body movement without breaking:

$$v(t) = \xi \frac{1 + \frac{v_0 - \xi}{v_0 + \xi} e^{-\frac{4N\xi}{m}t}}{1 - \frac{v_0 - \xi}{v_0 + \xi} e^{-\frac{4N\xi}{m}t}} \quad (5)$$

Here N – total air resistance and rotor friction factor, v_0 – initial body velocity, σ – body material pressure breaking point, ρ – body density, $\xi = d\sqrt{\sigma / 2N}$.

From (5) it follows that the uniformly accelerated body acceleration regime is optimal that provides the achievement of required velocity on the minimum length of the accelerator. Expression (1) shows that the increase of the force acting on the rotor length d is attained either by increasing the current in the conductor, or by increasing the magnetic field induction in the loop of current flow, or by increasing both components simultaneously. In classical

railgun magnetic field is produced by the current in the rails, so increasing of current is required to increase the forces, but it leads to the survivability of accelerating system decrease. In this paper we consider the railgun, in which in order to eliminate the disadvantages of the classic railgun and to provide survivability requirements, the magnetic field is created by the PDBS [2]. Prospects for the use of the PDBS are shown too.

2. Biasing System Formation

In preliminary investigations, the benefits of throwing planar configuration bodies are shown [2]. When designing the complex, intended to accelerate the relatively small mass to hypersonic velocity special attention should be given to the biasing system effectiveness. The PDBS is based on the separation of functions of forming the current loop and the magnetic field source between the individual structural elements of the accelerator and therefore an independent power supply for each of these elements is provided. Moreover, current sources and fields are optimized in order to realize the most favorable spatial distribution and field amplitude-time mode of operation that provides the greatest value of the accelerating force (1). Optimal spatial magnetic field configuration is created in the area of the interelectrode gap where accelerated body is located at the current time.

Principles of PDBS for the first time were set out in [1, 2]. There was investigated an optimal form of the projectile as well and advantages of the flat body acceleration were analyzed. Further by the same way were followed the authors of [3].

However, the most effective from the point of providing optimal magnetic field distribution, traction force on the rotor and operational features of railgun is the biasing system designing based on Halbach array (HA) principle (Fig. 1), which is characterized with the magnetic field almost completely absent on the one hand due to a special arrangement of the HA elements [4].

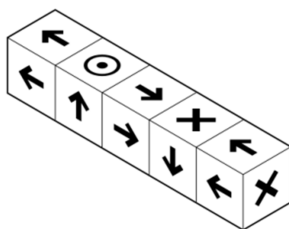


Fig. 1. Linear magnetic Halbach array, consisting of five segments. https://en.wikipedia.org/wiki/Halbach_array.

Magnetic field distribution in HA can be represented by Mallison drawings [5]. This drawings show the configuration of magnetic field caused by a ferromagnetic material having a plane surface with a variable magnetization vector on coordinate X (upper left drawing) and on coordinate Y (upper right drawing). Particular attention should be paid to the fact that the field of the HA in the upper half of both drawings has the same direction,

while in the lower half - the opposite. As a result we get the structure of magnetic field two structures superposition, and its magnetic field is shown in Fig. 2.

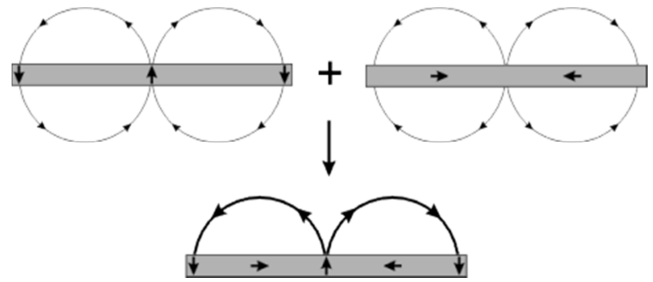


Fig. 2. Magnetic field superposition of two HA: https://en.wikipedia.org/wiki/Halbach_array.

The basic meaning of HA is the compensation of the magnetic flux from one side of the HA that causes it to enhance the other. Thus, it is possible to formulate the two main advantages of the HA as the devices to form the one-sided magnetic flux:

- (1). From one side of HA magnetic flux is twice bigger than the flux, formed by the single HA;
- (2). From the other side of HA magnetic flux is equal of 0.

As a result, electromagnetic analogue of the HA has been developed. It was used as PDBS for which the magnetic field distribution calculation was carried out (Fig. 3). Patent literature search did not show any known development accelerators using this principle, which gives grounds to assume that a similar generating system of pulsed magnetic field is absent today.

The developed biasing system has the next features:

- (1). The average value of the amplitude z -components of the magnetic field (perpendicular to the motion plane of the projectile) in the interelectrode gap (pos. 1 in Fig. 3) has increased by 70% compared to the system without the bias magnetic field compensation.
- (2). Magnetic field in the rail arrangement regions is directed in such a way to compensate the repulsion force of the electrodes and, thus, to provide a more robust sliding contact of the plane projectile with the rails (pos. 2 Fig. 3). Furthermore, the possibility of electrodes repulsion compensation practically does not reduce the average amplitude of z -components of the magnetic field in the interrail gap due to the high spatial gradient of the magnetic field at the boundary of the interrail gap (about 0.5 T/mm). This gradient can be controlled within wide limits through the reallocation of supply currents in the biasing system windings.

(3). It is seen that magnetic field is concentrated into the PDBS and it is practically absent from the outside. This fact can significantly simplify the solution of problems related to the electromagnetic compatibility of the design of the accelerator complex or integrate the accelerator with other electronic systems.

It should be noted that these figures may be improved in the process of solving optimization problems for a particular electrodynamic accelerator with certain parameters.

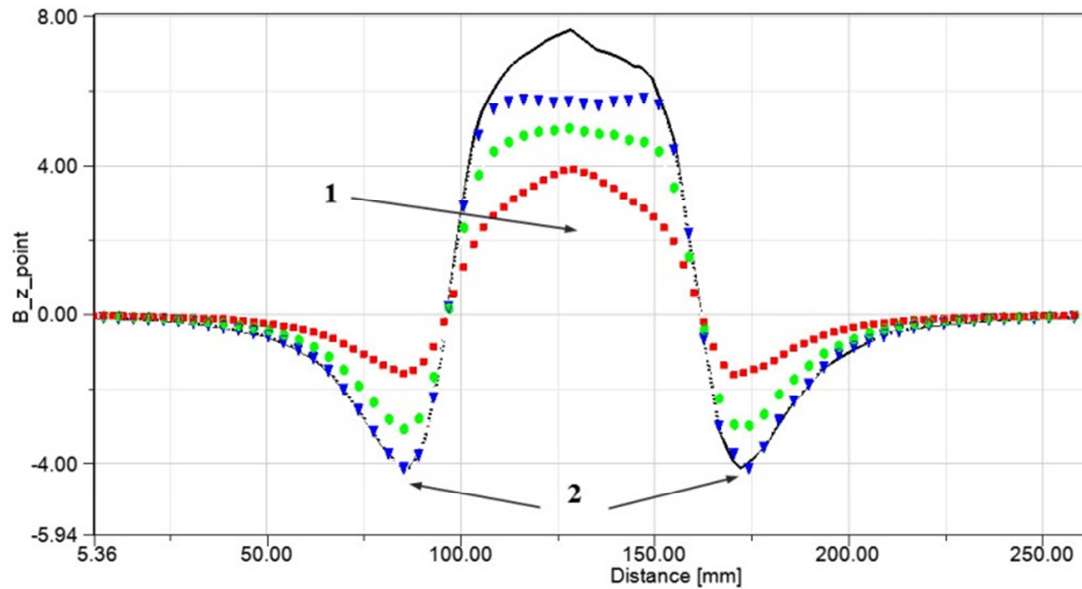


Fig. 3. Magnetic induction z-component distribution at different current in the biasing system windings; 1 - into interrail gap, 2 - in the rail arrangement regions.

One of the problems to ensure the survivability EDRG is to maintain good contact of the projectile with rails [6]. When EDRG is powered by currents of the order of $10^5 \div 10^6$ A, the Ampere force seeks to expand the current loop (Fig. 4) and it leads to deformation of the rails and to the loss of reliable end electrical contact with the projectile.

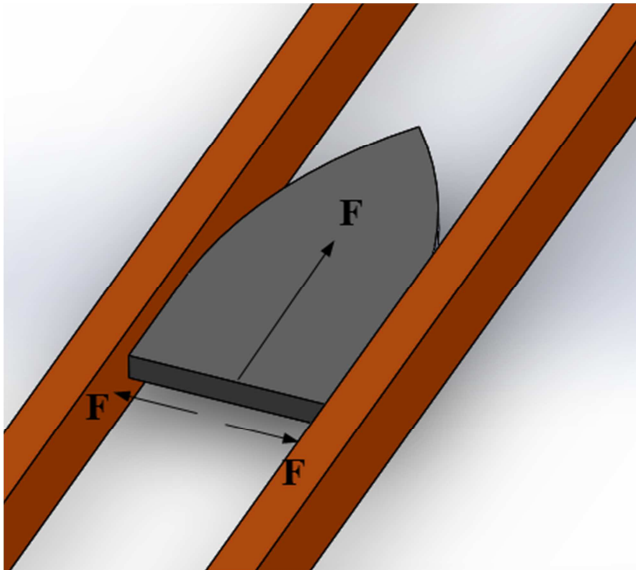


Fig. 4. Electrodynamic forces act on the projectile and on the rails.

In Fig. 5 a designed structure is shown in which each rail is represented by a pair of parallel buses, and the electrical contact is provided as a result of girth of the projectile by buses from the upper and lower sides. When power is applied, the current is divided between the tires in half, and the electrodynamic forces arising in parallel conductors with currents of the same direction, are seeking to reconcile the bus together, providing a reliable contact with the plane

projectile. In such a construction electrodynamic repulsion forces rails do not affect on the reliability of the contact and can displace only along its upper and lower surfaces.

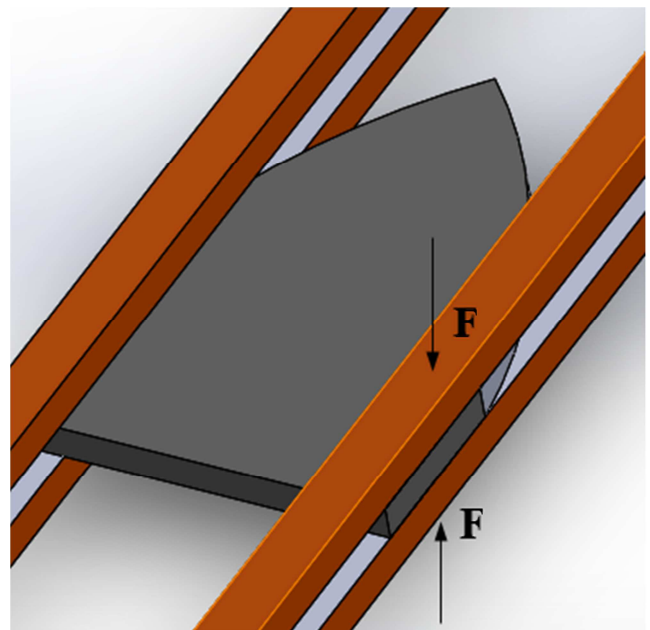


Fig. 5. The electrodynamic forces occurring in parallel conductors with currents of the same direction provide electrical contact.

3. Magnetic Field Distribution Simulation

3.1. Input Data for the Calculation

For a preliminary assessment of the EDRG designing finite element model with the following input data was built:

- Current pair bus of rails - 500 kA;

- The current density in the PDBS winding was selected based on the biasing pulse duration of one section of the order 0.3 ms and overheating of the windings is not higher than 60°C;

- The cosine form of a current pulse that imitates the capacitor bank discharge with the given parameters;

- Interrails gap - 30 mm.

Such extreme current load suggests pulsed-periodic regime to avoid overheating, otherwise it is necessary to introduce compulsory cooling.

The schematic design of the railgun with the PDBS is shown in Fig. 6. The projectile 1 that has the form of a flat tapered plate is located in the interrail gap formed by a pair of directing rails 2 and the PDBS coils 3. To increase the efficiency of use of the PDBS power supply, as well as the efficiency of the railgun overall, PDBS is divided into sections. Power is supplied to the section of the series, as the projectile moves through the channel of accelerating. Such partitioning allows to create a pulsed magnetic field only in the region of the acceleration channel, where the projectile is directed at any given time. Biasing pulse duration should be less than the time of passage of projectile through the section, and since the projectile moves with acceleration, so its interaction with the each subsequent section of the PDBS is reduced. Thus, the length, the inductance and the supply current pulse characteristics of each section are calculated individually depending on the projectile injection into each section and the accelerating process dynamics.

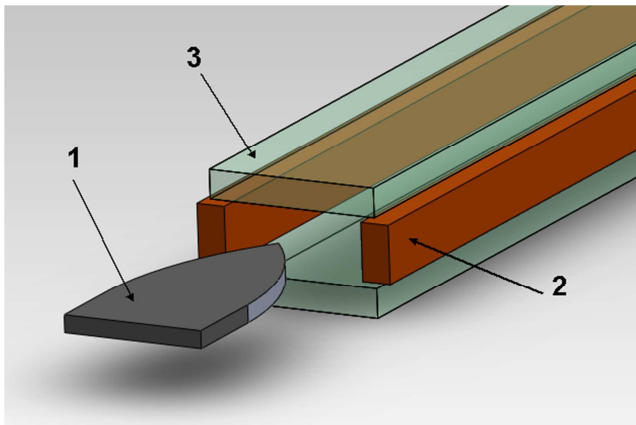


Fig. 6. Railgun with PDBS and rectangular cross-section of the muzzle: 1 – projectile, 2 – rails, 3 – PDBS coils.

The following characteristics were taken into account when designing the railgun construction. To increase the magnetic induction in the acceleration channel, the upper and lower PDBS coil should be as close to each other as possible. On the one hand, this condition will lead to the fact that the acceleration channel will have a low height, and rails will change into flat tire. On the other hand, to prevent excessive electrode heating by the current pulse the rails should have a relatively large cross section, that at its low altitude will detonate geometric centers of currents therein by a distance much larger than an interrail gap.

Thus, the magnetic field generated by the current in the rails will be dispersed, and its contribution to the total field in the accelerating channel will be inefficient. However, because at this stage of investigations the main objective was a simulation of the PDBS with the magnetic field compensation (Fig. 7) in order to analyze the correctness of the structural and technical solutions, the rails shape optimization was not conducted, and their cross section in a pair of square was selected as having the highest inductance per unit length.

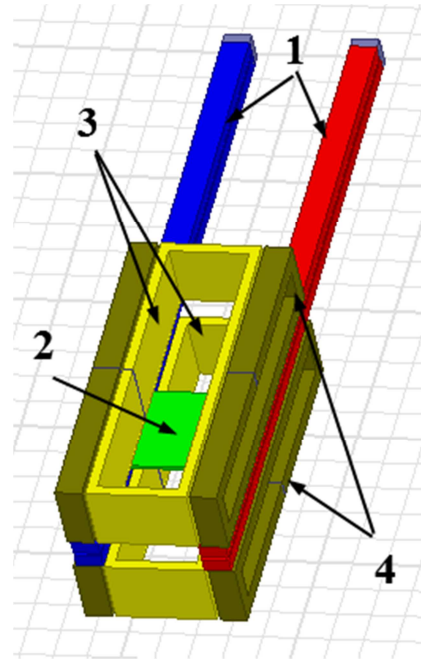


Fig. 7. Railgun with the PDBS and magnetic compensation: 1 – rails, 2 – rotor, 3 – PDBS, 4 – magnetic compensation system.

3.2. PDBS Analysis

To carry out a correct comparative analysis of the efficiency of the PDBS with a bias magnetic field compensation in the first stage the bias system was modeled, similar to that described in [2].

Results of distribution magnetic field are shown on Fig. 8 and Table 1. Advantages of the PDBS with magnetic field compensation that follow on comparative analysis of the results of calculations are the next:

(1). Application of a magnetic field compensation provides a more uniform distribution of the magnetic field in the acceleration channel plane, which allows to distribute the load more evenly on the accelerated body and reduces its deformation. This, in turn, allows for greater overload values that do not lead to the destruction of the projectile.

(2). Using of magnetic field compensation provides increasing of the peak value $B_{z\ max}$ and average value $B_{z\ avg}$ of the magnetic induction in the system for 72.6% and 62.1% respectively compared with the system without compensation. This factor can be further improved due to the complexity of the biasing system design and increase the number of compensating windings.

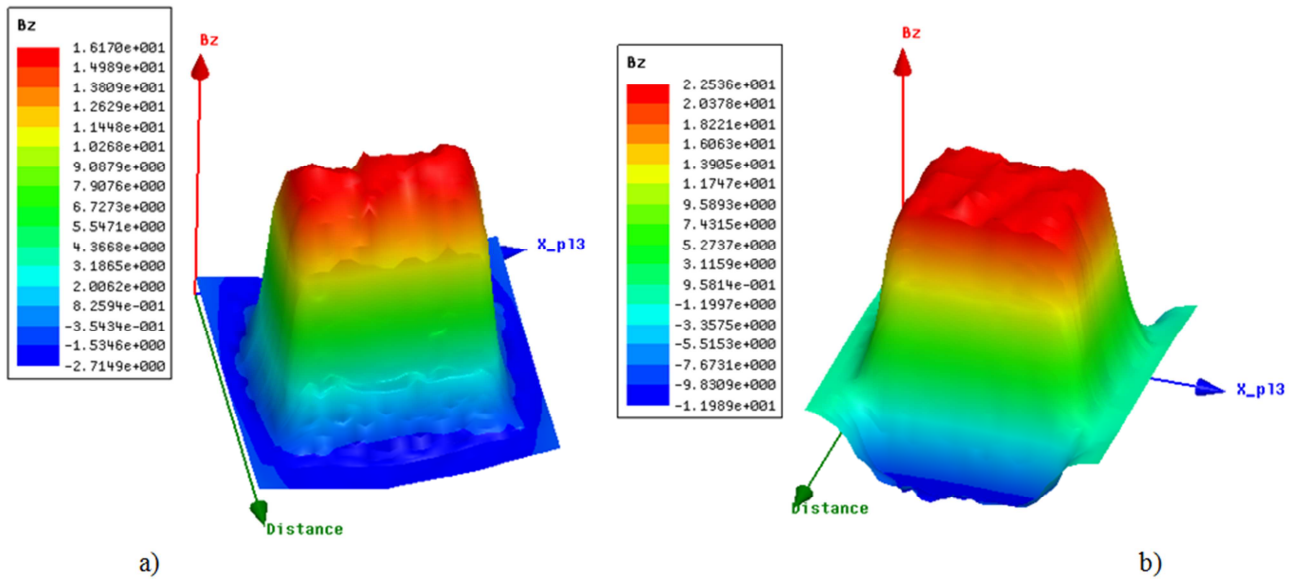


Fig. 8. Spatial distribution of magnetic field of the PDBS in the accelerating channel plane without magnetic field compensation (a), with magnetic field compensation (b).

Table 1. Magnetic field distribution parameters.

PDBS mode	Magnetic induction (z-component), T		$B_{z\text{ avg1}}/B_{z\text{ avg2}} \cdot 100\%$	$B_{z\text{ max1}}/B_{z\text{ max2}} \cdot 100\%$
	$B_{z\text{ max}}$	$B_{z\text{ avg}}$		
1. without magnetic field compensation	15,69	12,49	72,6	62,1
2. with magnetic field compensation	21,62	20,12		

Quite different the spatial distribution of the field seems in the dynamics EMRG action. Interaction of PDBS magnetic field with the projectile moving by acceleration channel is accompanied by induction of eddy currents in the rotor which, in turn, generate magnetic fields that weak the PDBS field in this region of the channel. The result is a picture of the field shown in Fig. 9.

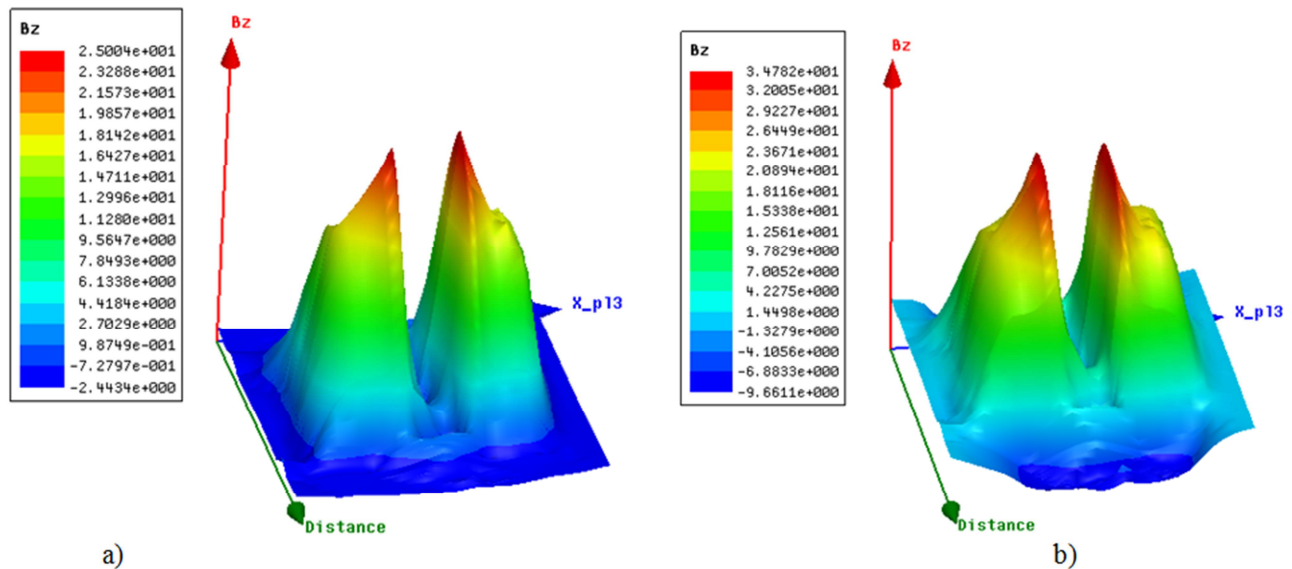


Fig. 9. Spatial distribution of magnetic field of the PDBS in the accelerating channel plane considering the influence of rails and projectile without magnetic field compensation (a), with magnetic field compensation (b).

3.3. Comparative Analyze Results

To realize the comparative analysis of the estimation results the parameters of the magnetic field generated in the acceleration channel and the force acting on the projectile

and on the power bus by the magnetic field have been shown in Table 2. Here are indicated the next:

– $F_{0\text{ max}}$, the peak value of the force acting on the projectile in the interrail channel without biasing;

- $F_{1\max}$, the peak value of the force acting on the projectile in the interrail channel without the magnetic field compensation;
- $F_{2\max}$, the peak value of the force acting on the projectile in the interrail channel with the biasing and the magnetic field compensation;
- $F_{20} = F_{2\max} / F_{0\max}$, parameter that characterize the efficiency of the PDBS with the magnetic field compensation with respect to the accelerator without biasing;
- $F_{21} = F_{2\max} / F_{1\max}$, parameter that characterize the efficiency of the PDBS with the magnetic field compensation with respect to the accelerator without the compensation

Table 2. Components of force acting on the projectile.

Force acting on the projectile in the interrail channel, kN			PDBS efficiency	
$F_{0\max}$	$F_{1\max}$	$F_{2\max}$	F_{21}	F_{20}
98,7	282,6	405,9	1,4	4,1

Tab. 3 shows vector components of the magnetic force action on the rails:

- F_{x0} , the peak value of the force acting on the rail ("recoil") without biasing;
- F_{x1} , the peak value of the force acting on the rail ("recoil") with biasing without field compensation;
- F_{x2} , the peak value of the force acting on the rail ("recoil") with biasing and field compensation;
- F_{y0} , the peak value of the repulsive forces of forward and reverse current distributors without biasing;
- F_{y1} , the peak value of the repulsive forces of forward and reverse current distributors with biasing without field compensation;
- F_{y2} , the peak value of the repulsive forces of forward and reverse current distributors with biasing and field compensation;
- F_{z0} , F_{z1} , F_{z2} , the peak value of the attractive force between current supply buses with biasing and field compensation, with biasing without field compensation, with biasing and field compensation respectively.

Table 3. Components of forces acting on the rails.

Vector components of forces acting on the rails, kN								
$F(x)$ ("recoil force")			$F(y)$ (repulsive force)			$F(z)$ (attractive force)		
F_{x0}	F_{x1}	F_{x2}	F_{y0}	F_{y1}	F_{y2}	F_{z0}	F_{z1}	F_{z2}
2,3	4,2	8,1	-89,6	-66,8	-116	290	258	236

4. Conclusions

An analysis of the calculation results leads to the following conclusions:

- (1). The PDBS with compensation increases the peak and average value of the magnetic field in the interrail gap by 38% and 61%, respectively, compared with the system without the bias field compensation, and 149% and 271% compared to the railgun without PDBS.
- (2). The use of the PDBS with the compensation can

increase the force acting on the projectile by 40% compared with the railgun with PDBS without compensation and by 310% compared to the railgun without PDBS.

(3). A significant increase in the magnetic induction in the interrail gap and increase of the force acting on the projectile is accompanied by a relatively small increase in the repulsive force between the rails, the value of which is increased by only 29%. This became possible due to partial compensation of the forces of repulsion by the magnetic field of opposite polarity generated by PDBS. This parameter can be improved in the process of optimizing, when the designing the PDBS sections under the preset mode acceleration regime, due to the redistribution of current in the PDBS windings.

(4). Monitoring of the magnetic field value inside and outside the PDBS modeling during its working process shows quite effective suppression of the magnetic field outside the system. In the field of local peaks of the magnetic field inside the PDBS, related to the accelerated projectile there is a strong suppression of the external field. Thus, the magnetic field compensation in the PDBS can be used as an effective method of dealing with EMC problems.

(5). Use of the PDBS with magnetic field compensation provides more homogeneous magnetic field in the accelerating channel, that in turn distributes the load evenly in the projectile, preventing it from breaking during acceleration process.

(6). In general, the analysis confirms the operability of the proposed design of the PDBS with compensation of the magnetic field. Despite the relatively high efficiency of the PDBS, its parameters can still be improved in the process of system optimization using a specific operating conditions in real railgun project. Since the velocity and the time of passage of each section are different, the design of each section should be individualized, taking into account the skin-effect caused by the driving of the projectile and the skin-effect caused by the operation of the PDBS.

(7). The existing railgun models are based on quasimagnetostatics views. However, considered in this paper PDBS principle opens up the prospect of designing the railgun, which implements the principle of magnetic cumulation similar devices considered in [7-10]. This mode of railgun authors called as parametric or magnetocumulative railgun. The parametric railgun simultaneously is provided as a dynamic biasing, and the effect of compressing the magnetic field is generated by PDBS. Positive feedback on the magnetic field, which provides the increase of the field and the current in the magnetizing system is implemented using a special configuration of the biasing coils and rotor geometry, as well as the current distribution between the rails and PDBS.

(8). Further development of the electrodynamic acceleration technique with the PDBS consist in applying the biasing magnetic field pumping using magnetoplasmatic compressor in which the magnetocumulative effect is implemented simultaneously. At the same time the authors used the experience gained in the designing and application of magnetoplasmatic compressors [11-13]. These forward-

looking principles of railgun now are objects of scientific interest of the authors.

Acknowledgment

This work performed on authors own initiative and contains results of the personal investigations. Unfortunately, there are nobody whom authors could wish your thanks except themselves. However we are sure that these results may be useful, for instance, at designing of project Mars expedition, artificial meteor, maglevs. Electrodynamic launch systems takeoff-elevating platforms with deck-based aircraft carriers are of authors interest as well and it will be considered in further papers.

References

- [1] V. I. Chumakov, O. V. Stolarchuk, *Pulse processes and systems: Manual for laboratory works*, Sevastopol, Naval Academy by of P. S. Nakhimiv, 2012, 70 p.
- [2] V. I. Chumakov, O. V. Stolarchuk, *Railgun System with Pulse-Dynamic Biasing of the Muzzle*, Proceedings of 16th International Symposium on Electromagnetic Launch Technology (EML 2012) Beijing, China, 15-19 May, 2012, p. 854, DOI: 10.1109/EML.2012.6324994.
- [3] K. I. Sukhachov. *Electromagnetic railgun with external magnetic field*. Bulletin of Saratov State Aerospace University, 2015, Vol. 14, No. 1. P. 177-189.
- [4] K. Halbach. *Design of permanent multipole magnets with oriented rare earth cobalt material*, Nuclear Instruments and Methods, 1980, Vol. 169, No. 1 P. 1-10.
- [5] J. C. Mallinson, H. Shute, D. Wilton. *One-sided fluxes in planar, cylindrical and spherical magnetized structures*, IEEE Transactions on Magnetics, 36, 2, Mar 2000, doi: 10.1109/20.825805
- [6] M. P. Galanin, A. P. Lototski, S. S. Urazov, Yu. A. Khalimullin. *Mathematical simulation of the railgun metallic contacts erosion*. Moskov, RAS, Institute of applied mathematics, 2003, 29 p.
- [7] V. I. Chumakov, A. V. Stolarchuk. *Complexing EMG designing principles* // Proc. of 2-nd International Radio Electronics Forum" Applied Radio Electronics. The State and Prospects of Development." IREF-2005. Vol. VI. – Kharkov, AS ARE, KhNURE, 2005.–P. 92-95. (in Russian)
- [8] V. I. Chumakov, A. V. Stolarchuk. *Parallel cumulation based on multiliner systems* // Problems of atomic science and technology. – 2006.–No 5.–C. 235-239. (in Russian)
- [9] Complexing explosive magnetic generator / Chumakov V. I., Stolarchuk A. V., Koniakhin G. F. / Pat. of Ukraine No 46997, 11.01.2010, H01T 13/00. (in Ukrainian)
- [10] Plane-helical complexing explosive magnetic generator / Chumakov V. I., Stolarchuk A. V., Koniakhin G. F. / Pat. of Ukraine No 74115, H02N 11/00, 2012. (in Ukrainian)
- [11] Yu. Ya. Volkolupov, M. A. Krasnogolovets, M. A. Ostrizhnoi, V. G. Nesterenko, O. I. Kharchenko, V. I. Chumakov. *Results of visual investigations of the magnetoplasma compressor emission in air*. Technical Physics, 2001, Vol. 46, No. 8.-P. 1040-1044.
- [12] Pat. of Ukraine No 97985. Destroying of cumulative stream / V. I. Chumakov, O. V. Stolarchuk, 2015. (in Ukrainian)
- [13] Pat. of Ukraine No 104719. Pulse sterilizer / V. I. Chumakov, M. O. Ostrizhnyi, O. V. Stolarchuk e. a. 2016. (in Ukrainian).