# HALBACH ARRAY LAUNCH SYSTEM

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***Abstract:*** *This paper presents a new design of an electromagnetic launch system which solves the weakness of previous designs. The presented system is based on Halbach array arrangements of permanent magnets. In the first part of paper are presented the railgun and coilgun designs and the weakness are identified. Based on this observation a new design is presented. In order to analyze the interaction between all elements of this design was used an interactive software package based on finite element method (FEM) to analyze, solve 3D electromagnetic field problems, and simulate the movement of Halbach array armature. The interaction between all elements of the design was checked for six values of current in conductors I = {100, 300, 500, 700, 900, 1100} A. All simulation data confirm this new design has a great potential of development.*

***Keywords:*** *railgun, coilgun, Halbach array, Lorentz force*

## 1. INTRODUCTION

In order to accelerate an object of mass *m* a different kind of energy can be used. If we want to obtain also great performance the chemical energy can be used. In time the launch systems based on chemical energy achieved their limits. In order to expand the limits of launch systems electromagnetic energy can be used. During time different electromagnetic launch systems were developed. The most promising systems were based on using Lorentz Force. According to theory the Lorentz force is:

$$\vec{F} = q\vec{v} \times \vec{B} \tag{1}$$

Because in electromagnetic launch systems we don’t use a singular charge but many it is much easy to use the equation of Lorentz force based on current intensity.

$$F = I \cdot l \times B \tag{2}$$

This form of Lorentz force is sometimes presented as Laplace force. Because:

$$F = I \cdot l \cdot B \cdot \sin\alpha \tag{3}$$

where α is the angle between vector *l* and B;

The force has a maximum when $\alpha=90^0$ and a minimum when $\alpha=0^o=180^0$. This is a very important observation because when we create an electromagnetic launch system the magnetic field B must be perpendicular on a current-carrying wire. During time different designs of electromagnetic launch systems was studied. One of the best designs is called railgun.

A railgun consists of two parallel conductors called rails and a sliding conductor between rails called armature. The projectile is mechanically connected with armature.[1]

A very high current *I* flow through rails. The combination between this simple design and very high currents create the condition to obtain a great Lorentz force on armature according with fig. 1.

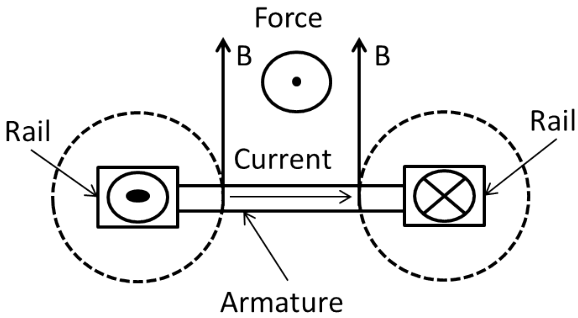


Fig. 1 Railgun

Studying fig 1 we can observe some advantages of this design:

- the magnetic field B is perpendicular on armature;

- the current *I* create the magnetic field around rails and the current on armature. By increasing the current *I* the Lorentz force is also increased;

- the length of rails can be calculated according with the performance of the launcher.

The expression of force acting on armature can be approximate according with equation 4.

$$F = \frac{1}{2} I^2 L' \tag{4}$$

where $L'$ is magnetic gradient inductance.

Because this design uses only straight conductors the value of magnetic gradient inductance is very low. The only way to obtain a high value of force is to increase the current *I* which flow through conductors. Other important advantage of this design is the position between magnetic field and armature. Even the magnetic field created by rails is not so strong compared with a magnetic field created by a coil the armature is touching the rails and use very efficient the magnetic field created [2]. This big advantage comes also with a big disadvantage of this design, sliding contacts between armature and rails. In order to create a great electromagnetic launch design we should preserve the advantages of railgun design and to avoid his great weakens sliding contacts.

The second direction of development of electromagnetic launch systems is induction coilgun. In order to reduce the value of current *I* the rails can be replaced by coils. By using coils we can obtain the same value of magnetic field density *B* created by the rails with less amount of current. The current inside armature can be obtained by using induction instead of sliding contacts.

$$u_i = -\frac{d\phi_B}{dt} \tag{5}$$

$$u_i = -\frac{d}{dt}(BA\cos\theta) = -\left(\frac{dB}{dt}\right)A\cos\theta - B\left(\frac{dA}{dt}\right)\cos\theta + BA\sin\theta\left(\frac{d\theta}{dt}\right) \tag{6}$$

where θ is the angle between $\vec{B}$ and $\vec{n}$ (normal unit of surface area A). We assume the magnetic field is uniform distributed in space.

The coilgun design was developed based on Faraday's law of induction, named induction coilguns where only the magnetic field is variable, the surface *A* and angle *θ* are constant.

The Faraday's law can be writen:

$$u_i = -\left(\frac{dB}{dt}\right)A\cos\theta \tag{7}$$

One design consists of coils which create a barrel and allow a projectile made by aluminum to move inside them.

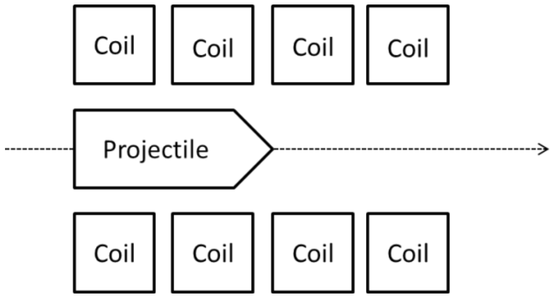


Fig. 2 Induction coilgun

The axial component of magnetic density $\overrightarrow{B_a}$ inside coil creates the induced current inside projectile, which interact with radial component of magnetic field density $\overrightarrow{B_r}$ [3, 4]. The induced current depends by rate of change of the axial magnetic density $\overrightarrow{B_a}$ and the radial magnetic flux density $\overrightarrow{B_r}$ depends by amount of magnetic flux. The magnetic flux is created by the coil and is only one magnetic flux, which induces current in projectile and provide in the same time the radial magnetic field on induced current.

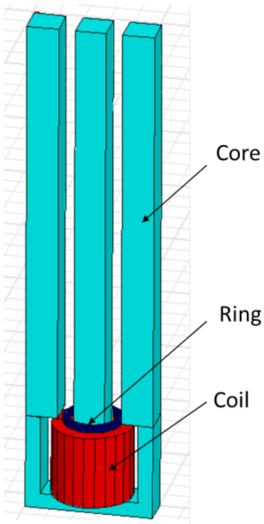


Fig. 3 E shaped coilgun

It is difficult to control in the same time with one coil the rate of change of the axial magnetic density $\overrightarrow{B_a}$ and the radial magnetic flux density$\overrightarrow{B_r}$. Also it is difficult to control the phase of induced current in projectile and the phase of the radial magnetic flux density$\overrightarrow{B_r}$. Compared with railgun the coilgun create a strong magnetic field using only a fraction of current and avoid the sliding contacts. The coilgun design is also much complex than railgun because the position of projectile must be synchronized with powered coil.

Also the coilgun use AC currents instead DC currents and the phase must be tighten controlled.

In order to increase the radial magnetic flux density $\overrightarrow{B_r}$ and to decrease the current inside the coil a design with magnetic circuit made by ferromagnetic materials was proposed. The magnetic circuit creates also a zone where the magnetic field is radial on conductor, in our case a ring. (fig. 3). The E shaped design use the soft magnetic materials and use the Lorentz force to accelerate projectiles but that design does not allow to control the difference of phase between induced current in projectile and the phase of the radial magnetic flux density$\overrightarrow{B_r}$. [5]

At this point we can identify the main aspects which should be taken into consideration when a design of an electromagnetic launch system is created:

- the Lorentz force should be used to accelerate the projectile;
- the magnetic field should be perpendicular on current-carrying conductor;
- for great efficiency the current-carrying conductor should be intersected by the high magnetic field created;
- the contact between the projectile and the accelerator should be avoided.

If is possible the electromagnetic launch system should be simple as a railgun and efficient as a coilgun. A design which obeys all this conditions is presented in the following chapter.

## 2. THE NEW HALBACH ARRAY GUN

Before the presentation of a new electromagnetic launch system let analyze again the equation of Lorentz force:

$$F = I \cdot l \cdot B \cdot \sin\alpha \qquad (3)$$

In order to obtain maximum force the angle must be $\alpha=90^0$. The magnetic flux density *B* with 1 tesla can be easy obtained with permanent magnets. A value of 10 tesla is relatively hard to obtain and the increase in value of force is not justified. In the near future it is possible to obtain permanent magnets with more than 1 tesla magnetic field. The next element is *l*. Apparently the value of *l* cannot be increased but if we use more wires like in a coil we can increase easily the value of force by N times. The value of current *I* can be easily increased.

For this design we use a circular Halbach array with uniform field inside made by 12 permanent magnets like in fig. 4

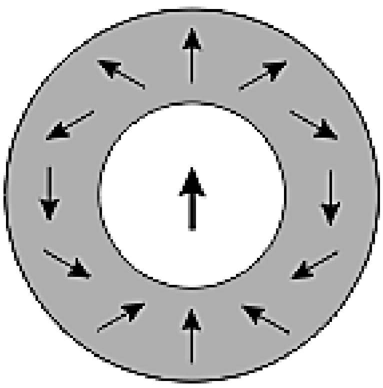

Fig. 4 Cylindrical Halbach array with uniform field inside

The direction of magnetization within the ferromagnetic material, in plane perpendicular to the axis of the cylinder, is given by:

$$H = M_r \ln\left(\frac{R_o}{R_i}\right)\hat{x} \tag{8}$$

where $M_r$ is the ferromagnetic remanence (A/m). If the ratio of outer $R_o$ to inner radius $R_i$ is greater than *e* the flux inside the bore actually exceeds the remanence of the magnetic material used to create the cylinder.

The Maxwell interactive software package that uses the finite element method (FEM) was used to analyze, solve 3D electromagnetic field problems, and simulate the magnetic field created by the circular Halbach array. The result is showed in fig. 5.

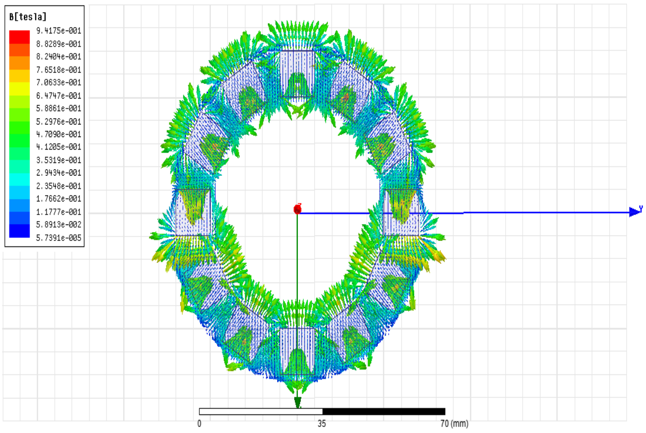

Fig. 5 Magnetic field created by a circular Halbach array

In this design the circular Halbach array is the moving armature and the projectile can by mechanically attached by this armature in order to be accelerated.

The non-moving part of electromagnetic launch system is represented by conductors arranged as displayed in fig. 6.

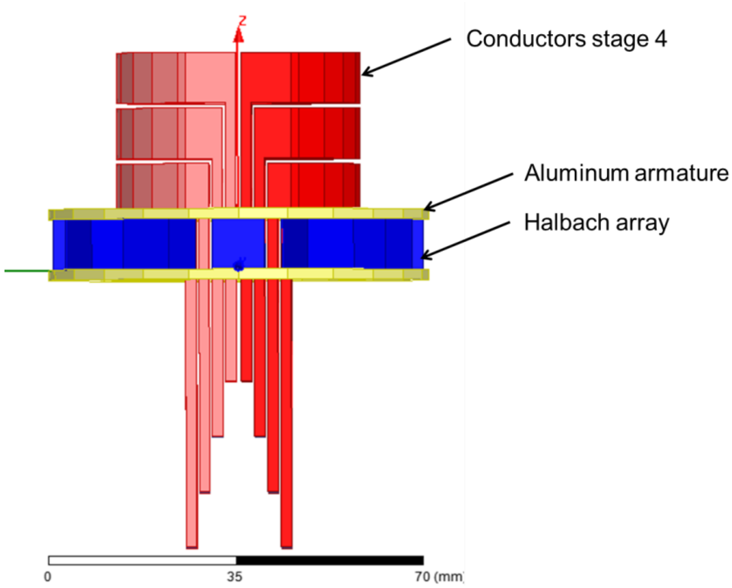

Fig. 6 Halbach Array launch system (side view)

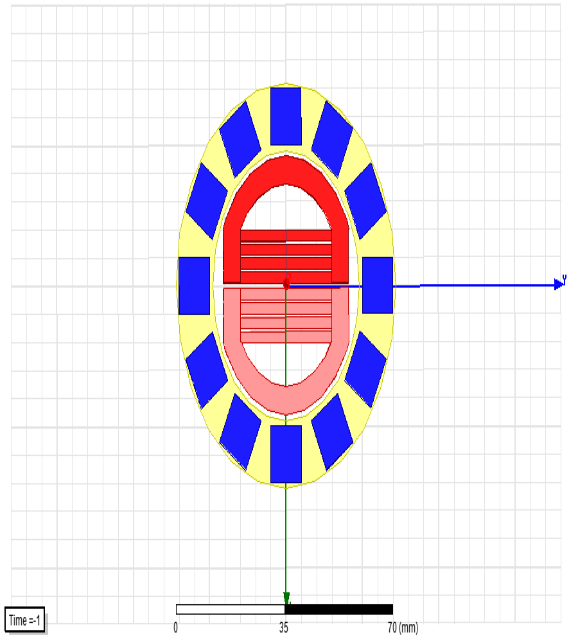


Fig. 7 Halbach Array launch system (top view)

The conductors are placed where the magnetic field has the highest value on x axis of the cylinder and are placed in such a way to obtain many conductors with the same direction of the current inside. The conductors are divided in 4 stages of the length equal with the length of permanent magnets. For each stage we have two sets of conductors in order to obtain the Lorentz force in same direction on both sides of Halbach array cylinder. The magnetic field *B* is perpendicular on conductors and with this configuration we have N conductors of length *l* placed inside magnetic field. The conductors are arranged in such a way to carry the same intensity of current in each conductor. Now we can increase the value of current in order to obtain the desired value of force.

In order to rigidize the Halbach array two aluminum plates are placed in top and bottom of the permanent magnets. The bottom part of the design represents the connection of conductors to sources of direct current. In the following chapter is presented the simulation results of this new design.

## 3. THE SIMULATION RESULTS

The permanent magnets are cube shape with length of 10 mm arranged into cylindrical Halbach array with magnetic field inside in one direction along x axis. The conductors are placed inside cylinder and are divided into four stages. The number of stages depends by the acceleration length necessary to obtain desired muzzle velocity of projectile. Each stage has two sets of conductors in order to control the direction of current inside. In this way the direction of Lorentz force is the same for both sets of conductors of each stage. The conductors are powered with a DC current source. Each set of conductors can accommodate 100 separate conductors. The inner radius of Halbach array is $R_i$=25mm and the outer radius is $R_o$=35mm. The total mass of permanent magnets and aluminum rings is *m*=0,1 kg.

In order to analyze the interaction between all elements of this design was used an interactive software package based on finite element method (FEM) to analyze, solve 3D electromagnetic field problems, and simulate the movement of Halbach array armature. The interaction between all elements of the design was checked for six values of current in conductors *I*={100, 300, 500, 700, 900, 1100} A. The variation of maximum Lorentz force acting on z direction on armature is presented in fig.8

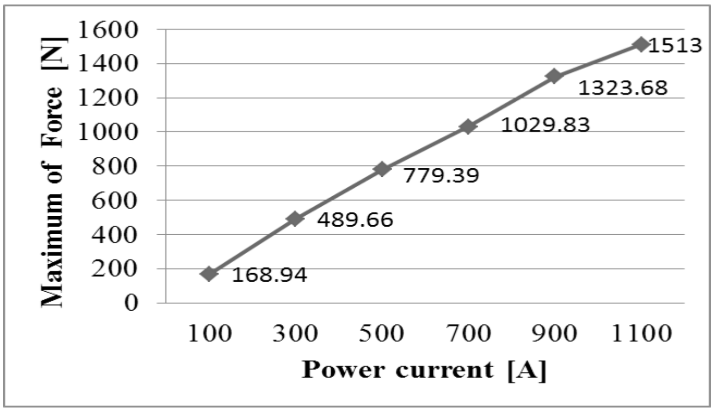


Fig. 8 Maximum Lorentz force acting on armature

Because the magnetic field *B* and the number of conductors N have constant values the value of force depend only by value of current *I.* According with graph the maximum force has a linear growth.

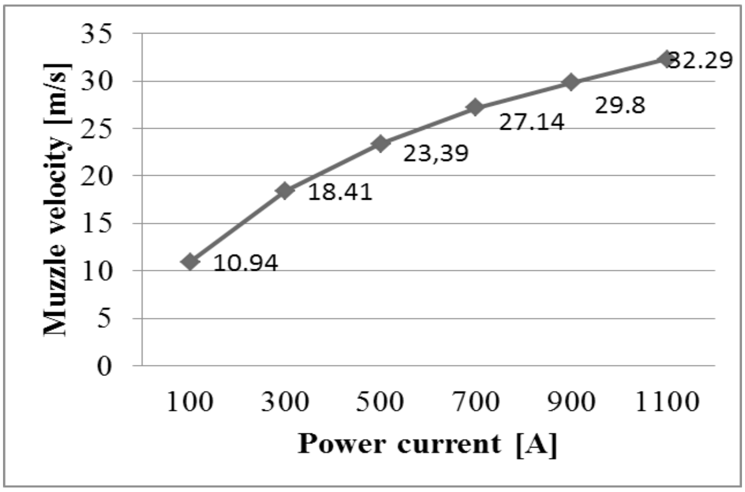


Fig. 9 Muzzle velocity of armature

Based on force acting on armature the muzzle velocity is calculated. The velocity of the armature does not increase in the same way like force because the time of acceleration decreases nonlinear. In the fig 10 is displayed the acceleration time of the armature.

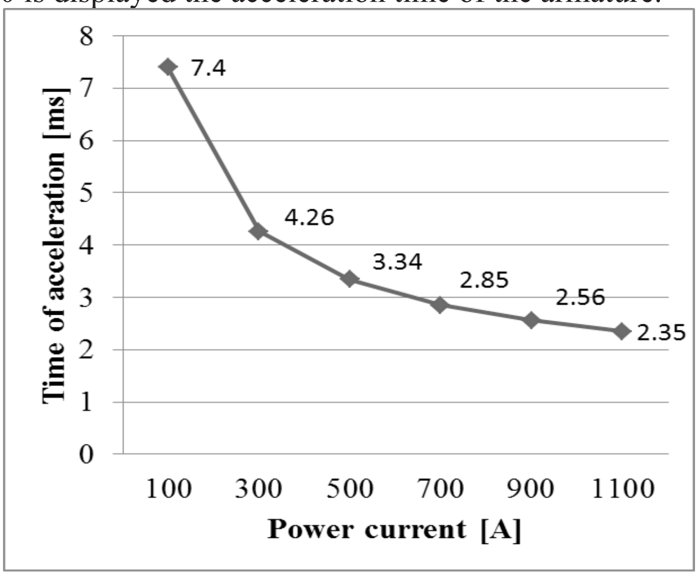


Fig. 10 Time of acceleration

## CONCLUSIONS

This design has great advantages over current electromagnetic launch systems. The static part of accelerator can be easily powered with high currents according with destination of accelerator. The magnetic field is perpendicular on conductors from the design. The number of conductors and the length of acceleration path can be calculated according with destination. For a long length of acceleration different number of stages synchronous powered with the position of armature can be created. Between stator and armature are not any contact, the armature is moving freely during acceleration. The intention of this paper was not to obtain maximum muzzle velocity of armature. The muzzle velocity can be increased if the magnetic field is increased. With a proper design of Halbach array the magnetic field can be increased. If the materials of permanent magnets are improved a higher value of magnetic field can be obtained. Because the time of acceleration is very short for special application the Halbach array can be created using electromagnets powered only during acceleration time.  Taking into consideration all this aspects we can conclude this Halbach array gun has a great potential of development.

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