TWO FLUXES MULTISTAGE INDUCTION COILGUN

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Abstract: *This paper presents a new design of electromagnetic launcher based on induction. This design uses two magnetic fluxes to accelerate a projectile and the configuration allow multiple stages. The two fluxes multistage induction coilgun design offer multiple advantages over single flux designs. First we can control much efficient the induced current in ring and the induced coil current is kept at low values. Second the direction of magnetic field B inside the air gap is perpendicular on ring and the Lorentz force is acting on ring during entire length of magnetic circuit. Because the magnetic field B is created by a different coil we can manage to keep the magnetic circuit unsaturated for a great efficiency.*
Keywords: *Magnetic field, induction, Lorentz force, coilgun*

1. INTRODUCTION

The actual systems to accelerate projectiles based on chemical energy have achieved their limits but our demands are continuous growing. The electromagnetic launch systems (EMLS) are a possible answer to this issue.

This paper present a new design of EMLS based on induction. Before presentation of this design let analyze very short the actual designs.

Based on force used to accelerate the projectiles the EMLS are with attractive and repulsive force. The attractive force EMLS are well known like reluctance coilguns and are made by coils used to accelerate ferromagnetic projectiles.

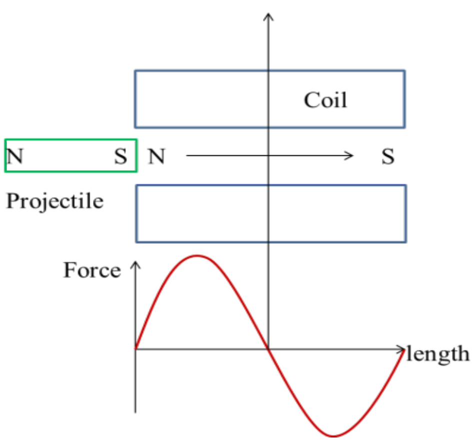

Fig. 1 Reluctance coilgun

When the coil is powered an electromagnet is created.

The flux lines created by coil intersect the ferromagnetic material of projectile and a magnet is created.

The poles between coil and projectile are different and an attractive force is acting on projectile. The projectile is accelerated inside the coil until it reaches the middle of length of coil when the force became repulsive. In that point the power of coil must be switched off in order to allow the projectile to travel further. If multiple coils are synchronized with projectile position, the projectiles can be accelerated with a multistage coilgun. At the end only half length of coils is used to accelerate the projectile. Because the projectile is made by a ferromagnetic material this design is efficient until saturation. This design use ferromagnetic materials but the accelerating force is not Lorentz force.

Other EMLS designs are based on repulsive force. This force is Lorentz force.

$$\vec{F} = I \int d\vec{l} \times \vec{B} \tag{1}$$

The well-known design based on Lorentz force is railgun design. This design consists of two conductors (rails) and an armature made by conducting materials. The armature has an electrical contact with both rails but is able to move alongside the rails. When the rails are powered by a high current the armature is accelerated by Lorentz force alongside the rails.

In this design the projectile is accelerated on the entire length of rails and is not limited by saturation.

In the railgun design (fig. 2) the current *I* can be increased with great impact on Lorentz force. The main advantage of railgun design is the possibility to increase the current inside armature at very high values due to electric contact between armature and rails.

In the same time the sliding electric contact between armature and rails represented the weakness of this design. Because of high currents used that electric contact affects the rails during lunches.

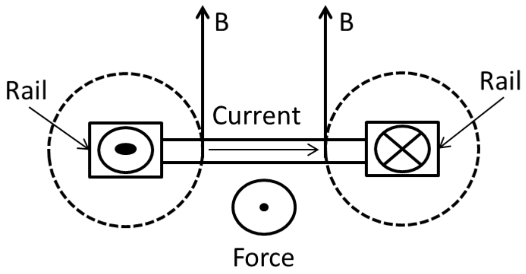

Fig. 2 Railgun

In order to decrease the current and to avoid contact between projectile and accelerator another design was created. The rails were replaced by coils and the armature was allowed to move inside or outside the coils. In this way we can obtain the same value of magnetic field density *B* with less current. In order to replace the sliding contacts the current inside armature $u_i = -\frac{d\Phi_B}{dt}$ined by induction.

$$u_i = -\frac{d\Phi_B}{dt} \tag{2}$$

$$u_i = -\frac{d}{dt}(BA\cos\theta) = -\left(\frac{dB}{dt}\right)A\cos\theta - B\left(\frac{dA}{dt}\right)\cos\theta + BA\sin\theta\left(\frac{d\theta}{dt}\right) \tag{3}$$

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

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

The Faraday's law can be writhed:

$$u_i = -\left(\frac{dB}{dt}\right)A\cos\theta \tag{4}$$

One design consists of coils which allow a projectile made by aluminum to move inside them (fig3) [1]. The axial component of magnetic density $\vec{B_a}$ inside coil creates the induced current inside projectile which interact with radial component of magnetic field density $\vec{B_r}$. The induced current depends by rate of change of the axial magnetic density $\vec{B_a}$ and the radial magnetic flux density depends by amount of magnetic flux. The magnetic flux is created by 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. It is difficult to control in the same time with one coil the rate of change of the axial magnetic density $\vec{B_a}$ and the radial magnetic flux density$\overline{B_r}$.

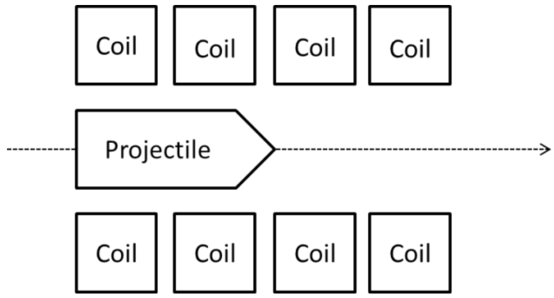

Fig. 3 Induction coilgun

These two designs railgun and coilgun are based on Lorentz force but do not take advantages of ferromagnetic materials.In order to increase the radial magnetic flux density $\overline{B_r}$ and to decrease the current inside 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.4).

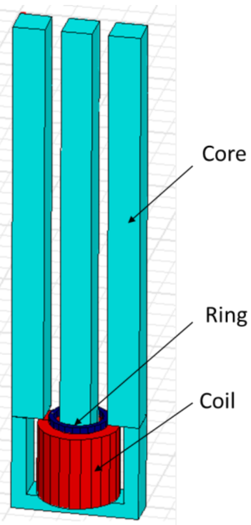

Fig. 4 E shaped coilgun [2]

The E shaped design use the ferromagnetic materials and use the Lorentz force to accelerate projectiles but that design does not allow multiple stages. We need multiple stages because if we increase the current in coil at certain value the ferromagnetic material will reach the saturation point. 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. First we should use the Lorentz force to accelerate the projectile. Second we should avoid the contact between the projectile and the accelerator. This can be achieved if we use the induction. Because of this, coils should be used to induce current into projectile. In order to take advantages of ferromagnetic materials a magnetic circuit should be in place to create a strong magnetic field radial to the path of induced current in projectile.

And in order to keep the ferromagnetic material below saturation point all design should be created with multiple stages. A design which obeys all that conditions is presented in the following section.

2. TWO FLUXES MULTISTAGE INDUCTION COILGUN DESIGN

First we design an air core coil which will induce current into a ring placed outside the coil (fig.5). The coil has an air core in order to obtain a low inductance and give us the possibility to increase the current in coil without saturation problem eq.5. In this design the surface A is constant and the angle $\theta=0^0$ and is not changing.

$$u_i = -\left(\frac{dB}{dt}\right) A\cos\theta = -\left(\frac{dB}{dt}\right) A \quad (5)$$

The power source is a direct current source (DC) because all system will work in transient mode and the time when entire system is powered is less than time constant of induction coil.

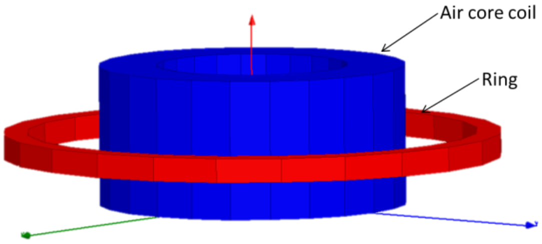

Fig. 5 The induction system

In this way the coil create only an induced current inside the ring. We need another coil which will create the radial magnetic field. Together with this coil we will design a magnetic circuit in order to control the magnetic flux. This coil is connected separately in order to control the saturation of ferromagnetic materials from magnetic circuit. The design is similar with E-shaped design but allow multiple stages of acceleration (fig.6).

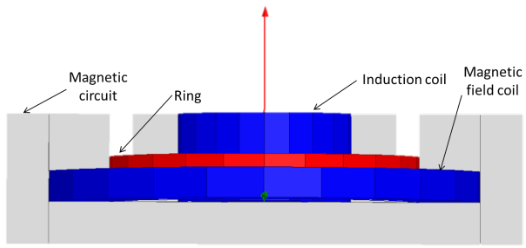

Fig. 6 First stage of two fluxes multistage induction coilgun

In order to find which dimensions should be modified to increase the Lorentz force acting on ring we made the following assumptions. All magnetic field created by induction coil is uniform distributed inside coil. All magnetic field created by magnetic field coil is uniform distributed inside magnetic circuit.

The force acting on ring is Lorentz force:

$$\vec{F} = \vec{F_r} + \vec{F_l} \quad (6)$$

where:

$\vec{F_r}$ is Lorentz force acting on right side of magnetic core; $\vec{F_l}$ is Lorentz force acting on left side of magnetic core.

$$\vec{F_r} = \vec{F_l} \quad (7)$$

$$\vec{F_r} = i_r \int \overrightarrow{dl_r} \times \overrightarrow{B_r} \quad (8)$$

where:

i_r is the induced current in ring; l_r is the arc of ring inside the air gap of right side magnetic core; B_r is the radial magnetic field density inside the air gap of right side of magnetic circuit created by magnetic field coil.

Because the l_r is constant let find i_r and B_r.

$$i_r = i_{ri} - i_{rB} \quad (9)$$

where:

i_{ri} is the induced current in ring by the induction coil; i_{rB} is the induced current in ring by the magnetic field coil.

Because the time constant of induction coil is larger than the time where the coil is powered ($\tau > t_i$) the induction coil will work on the linear part variation of current in coil (fig.7).

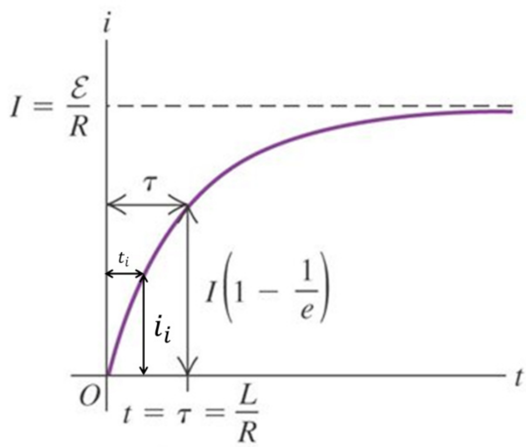

Fig. 7 t_i working time of a stage

The current is induced in ring using the same principle like in a transformer with concentrically windings. Because the ring is moving and the time spent in one stage is very short the induction coil can be powered with DC current and the variation of current is enough to induce a current in the ring.

We wrote the instantaneous currents equations for the time t_s inside the working time $0 \le t_s \le t_i$.

$$i_{rI}(t_s) = -M_{Is}\frac{dI_I/dt}{R_r} = -M_{Is}\frac{\mathcal{E}_{Is} - i_{Is}R_I}{L_{Is}R_r} \quad (10)$$

$$i_{rB}(t_s) = -M_{Bs}\frac{dI_B/dt}{R_r} = -M_{Bs}\frac{\varepsilon_{Bs}-i_{Bs}R_B}{L_{Bs}R_r} \quad (11)$$

$$i_r(t_s) = -\frac{1}{R_r}\left(M_{Is}\frac{\varepsilon_{Is}-i_{Is}R_I}{L_{Is}} - M_{Bs}\frac{\varepsilon_{Bs}-i_{Bs}R_B}{L_{Bs}}\right) \quad (12)$$

where:

R_r is resistance of ring inside the air gap of right side magnetic core; M_I is the mutual inductance between induction coil and ring; ε_I is DC source voltage of induction coil; i_I is current inside induction coil; R_I is resistance of induction coil; L_I is inductance of induction coil; M_B is the mutual inductance between magnetic field coil and ring; ε_B is DC source voltage of magnetic field coil; i_B is current inside magnetic field coil; R_B is resistance of magnetic field coil; L_B is inductance of magnetic field coil.

The mutual inductance between induction coil and ring M_I is constant

$$M_I = \frac{\mu_0 N_I A_I}{l_I} \quad (13)$$

The mutual inductance between magnetic field coil and ring M_B depend by the position z of the ring. When the ring is moving the mutual inductance M_B will decrease because the flux decrease when the distance z between ring and magnetic field coil increase.

$$M_B(z) = \frac{\phi_{rB}(z)}{I_B} \quad (14)$$

As we can see the projectile is the ring made by aluminum for less resistance in order to obtain the maximum induced current. In order to increase the variation speed of magnetic field the value of inductance L_I of induction coil must be keep it at low level. The value of inductance L_B of magnetic field coil must be at high level. This also helps us to obtain a higher value of radial magnetic field B_r inside air gap.

$$B_r(t_s) = \frac{1}{2}B_B(t_s) = \frac{1}{2}L_{Bs}\frac{i_{Bs}}{N_B A_{core}} \quad (15)$$

where:

B_B is all magnetic field created by magnetic field coil; N_B is turns of magnetic field coil; A_{core} is the transversal surface of air core (we assumed all magnetic flux is inside core and cross the air gap).This design was multiplied four times resulting two fluxes multistage induction coilgun presented in fig.8.

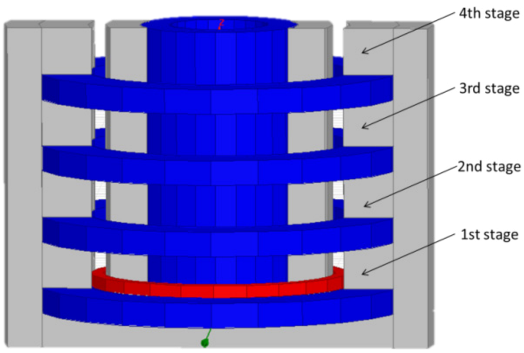

Fig. 8 4th Stages two fluxes induction coilgun

When the ring is reaching the second stage it already has an initial speed and the accelerating time will be shorter than in first stage ($t_1>t_2$).

In order to achieve the same amount of current in the second induction coil in a shorter time we will use a higher voltage. At the end all stages will function at the same amount of current but the voltage will be increased accordingly. The magnetic field B is created by the magnetic field coil. The magnetic circuit created around this coil provides a perpendicular magnetic field on ring inside the air gap where the ring is moving. Both coils induction coil and magnetic field coil are powered at the same time. When the ring reaches next stage the power is switched off in first stage and switched on in the next stage, with increased voltage.

In order to check the validity of this design the following dimensions of this design was calculated. The dimensions were calculated for an experimental model which was built for laboratory measurements for E shape design [2] in order to obtain a great acceleration force. The mass of aluminum ring was calculated at 10 grams. We started from dimensions of device used for E shaped design and during simulation we changed dimensions in order to obtain the maximum speed of ring.

Table 1 Coil parameters

Induction coil	Inner radius	20 mm
	Outer radius	32 mm
	Length	29 mm
	Number of turns	300
Magnetic field coil	Inner radius	53 mm
	Outer radius	73 mm
	Length	10 mm
	Number of turns	300
Ring	Inner radius	47 mm
	Outer radius	52 mm
	Length	5 mm
	Number of turns	1

These dimensions will allow us to build a real model and to make measurements according to our laboratory possibilities. The Maxwell interactive software package that uses the finite element method (FEM) was used to analyze, solve 3D electromagnetic field problems, and simulate two fluxes multistage induction coilgun design. Because the presented equations give us only an image of which dimensions should be modified in order to obtain high speed of projectile we used Maxwell software to simulate the transient interaction between all parts. Through those simulations we fund the right dimensions and calculated the values of all dimensions without the simplified assumptions.

3. SIMULATION RESULTS

The coilgun with dimensions already calculated was build using 3D simulation software.

During the simulation we limited the current inside induction coils at 1600 A in order to protect the real coils. The values of voltages and duration of pulses for every stage are presented in Table 2. In this simulation both coils from the same stage were powered with the same voltage.

Table 2 Stages parameters

Stage 1	Voltage (V1)	3600V
	Time (t1)	1.7 ms
Stage 2	Voltage (V2)	5600V
	Time (t2)	1 ms
Stage 3	Voltage (V3)	9600V
	Time (t3)	0.55 ms
Stage 4	Voltage (V4)	11600V
	Time (t4)	0.4 ms

The variation of induced current inside ring is presented in fig.9.

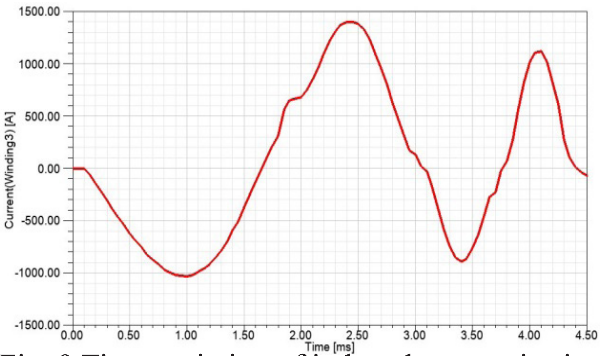

Fig. 9 Time variation of induced current in ring

In order to obtain this variation each stage was powered in opposition with previous stage. The time variation of current in accelerating coils is presented in fig.10. As we can see each stage is powered in opposition with previous stage when the ring is passing a certain position after the previous stage was switched off.

The current inside the induction coils are limited at 1600 A. The current inside the magnetic field coils reach the maximum value at 500A.

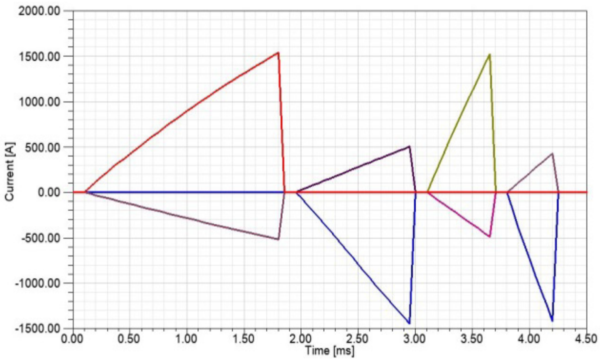

Fig. 10 Time variation of acceleration coil currents

Also the power time of each stage decrease according with values presented in table 2.From the graph in fig. 11 we can see the variation of current in induction coils is higher than variation of current in magnetic field coils.

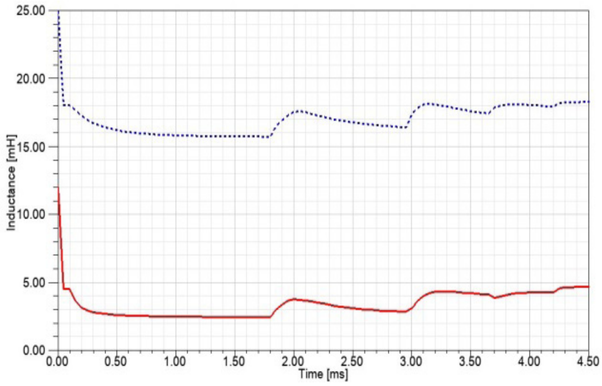

Fig. 11 Time variation of self-inductance L_B and L_I

From the fig.11 we can see the time variation of inductance for induction coil and magnetic field coil from stage 1.

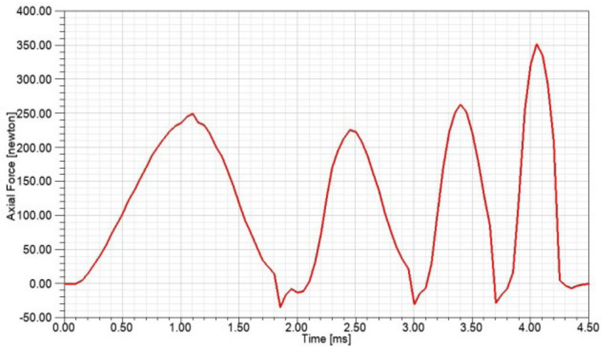

Fig. 12 Time variation of accelerating force acting on ring

From the fig.12 we can see the Lorentz force is acting on ring during entire time when the ring is inside a stage. The time when the Lorentz force is acting on ring is decreased in higher stages but the maximum value of force is around 250 N. This design creates significant forces only on axial direction for ring acceleration. The forces on radial direction are kept at low values as is shoved in fig.13. The maximum force on radial direction is 7.5 N.

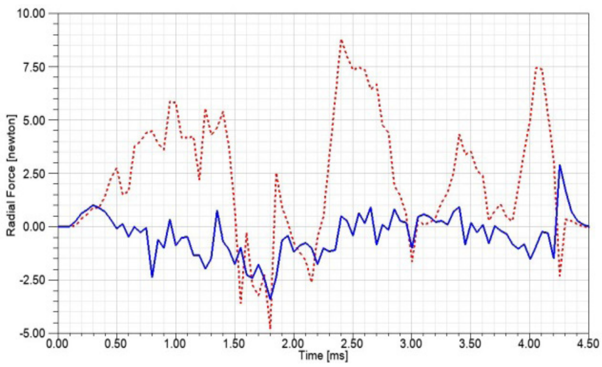

Fig. 13 Time variation of radial forces on ring

At the end the speed of ring was calculated for each stage in order to determine the muzzle velocity.

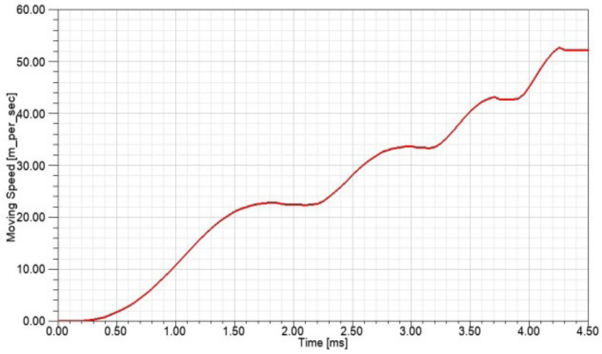

Fig. 14 Time variation of ring velocity

The ring is continuous accelerated from 0 m/s to 53 m/s in 4.3 ms. The value of muzzle velocities of ring is not very important at this time because should be validated in a practical experiment. The important thing is this design can accelerate a projectile using multiple stages without creating strong radial forces and without contact between projectile and coils.

CONCLUSION

The two fluxes multistage induction coilgun design offer multiple advantages over single flux designs. First we can control much efficient the induced current in ring and the induced coil current is kept at low values. Second the direction of magnetic field density *B* inside the air gap is radial on ring and the Lorentz force is acting on ring during entire length of magnetic circuit. Because the magnetic field density *B* is created by a different coil we can manage to keep the magnetic circuit unsaturated for a great efficiency. By using the Faraday's induction law in order to replace the physical contact between projectile and accelerator, the ferromagnetic materials for a strong magnetic field density *B* and a proper timing of switching power on/off we can create a better electromagnetic launch system able to launch a projectile at the desire velocity with less energy.

The next step is to build a laboratory model in order to prove in practice the values obtained through simulation.

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