Projectile Acceleration In Electromagnetic Field

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Abstract: This paper briefly describes the idea to accelerate a conducting projectile to higher velocities using electromagnetics. It presents the basic idea of the accelerator, why they have to be developed and how to implement the physics into a practical prototype which explores the specific implementation issues. The principle is based on Lorentz force which relates current to the force generated. To investigate the feasibility of the concept a 0.3 meter long accelerator powered by a 2.64kJ power source was built.

Keywords: Electromagnetics, Power, Capacitor

INTRODUCTION

Conventional chemical based propellants have a theoretical limit on acceleration, that is, for a given mass to be accelerated to a particular velocity it requires certain mass of fuel. Now if the same mass of projectile to be accelerated to higher velocity, the mass of fuel required also increases and this relation is linear. To resolve this issue one needs to find a method where the projectile shouldn't carry any fuel with it during acceleration. One such method is acceleration using electromagnetism.

Electromagnetic accelerator consists of two parallel metal rails connected to an electrical power supply. When a conductive projectile is inserted between the rails; at the end connected to the power supply, it completes the circuit. Electrons flow from the negative terminal of the power supply up the negative rail, across the projectile, and down the positive rail, back to the power supply. This current makes the accelerator behave as an electromagnet, creating a magnetic field inside the loop formed by the length of the rails up to the position of the armature. The accelerating force is proportional to the current driven in the system. This allows one to control the acceleration by controlling the current waveform [1].

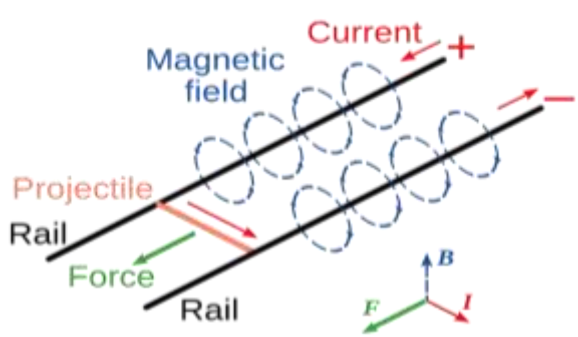

Figure1: Basics of electromagnetic accelerator

A current I, traveling through the rails induces a magnetic field B, between them. The interaction of the armature current with the magnetic field induces an electromagnetic force called the Lorentz force [2] which is given by:

$$F = q\ v_d \times B$$

Where,

q is the charge.

V_d is the drift velocity of that charge through the armature.

B is the magnetic field between the rails.

Calculation of magnetic field between the rails:

Let L be the length of the rails, l is the distance between the rails and y is the half of the distance between the rails. Magnetic flux density due to a straight conductor of finite length at a point is given by [2],

$$B = \frac{\mu_0 I}{4\pi r}\ \sin\theta_2 - \sin\theta_1 \quad Wb\ \ m^2$$

Where,

μ_0 is permeability of free space in $H\ \ m$ whose value is $4\pi \times 10^{-7}\ Wb\ \ m^2$.

r is perpendicular distance from the point P in meters.

θ_2 *is* angle between horizontal plane to the top end of straight conductor.

θ_1 *is* angle between horizontal plane to the bottom end of straight conductor.

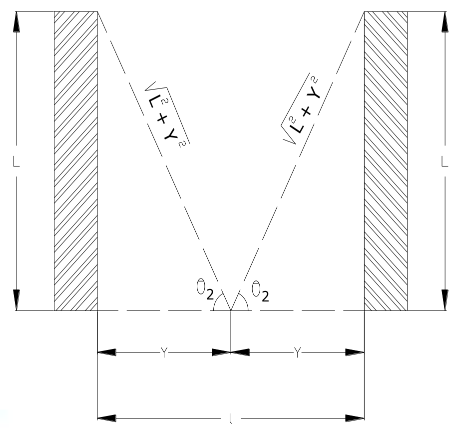

Figure 2: Force at a point considering both rail

$$B_{rail1} = \frac{\mu_0 I}{4\pi y}\ \ \frac{L}{\sqrt{L^2+y^2}} \quad Wb\ \ m^2$$

$$\sin\theta_2 = \frac{L}{\sqrt{L^2+y^2}} \qquad\qquad \sin\theta_1 = 0$$

$$B_{rail2} = \frac{\mu_0 I}{4\pi y}\ \ \frac{L}{\sqrt{L^2+y^2}} \quad Wb\ \ m^2$$

Total Magnetic flux density:

$$B = B_{rail1} + B_{rail2}$$

$$B = \frac{\mu_0 I}{2\pi y}\ \ \frac{L}{\sqrt{L^2+y^2}} \quad Wb\ \ m^2$$

Therefore,

$$F = Il\frac{\mu_0}{2\pi}\frac{I}{y}\ \ \frac{L}{\sqrt{L^2+y^2}}$$

$$F = \frac{I^2}{2}\ \frac{l\mu_0}{\pi y}\ \ \frac{L}{\sqrt{L^2+y^2}}$$

$$F = \frac{L'I^2}{2}\ \text{Newton}$$

Where,

$$L' = \frac{\mu_0}{\pi}\frac{l}{y}\ \ \frac{L}{\sqrt{L^2+y^2}} \quad \text{H / m}$$

L' is the Inductance Gradient.

L is length of the rails in meters.

l is distance between the rails in meters.

y is the midpoint between the rail.

Assuming the rail dimensions as L=0.3m, l=0.01m, and y=0.05m.

$$L' = \frac{4\Pi \times 10^{-7}}{\pi} \frac{0.01}{0.05} * \frac{0.3}{\overline{0.3^2 + 0.05^2}}$$

$$L' = 7.99 \times 10^{-7} \ H/m$$

Assuming a lossless system and neglecting frictional loss and air drag force:

$$F = ma = \frac{L'I^2}{2} \ Newton$$

$$a = \frac{7.99 \times 10^{-7}}{3 \times 10^{-3} \times 2} \ I^2$$

$a = 1.33 \times 10^{-4} I^2$ meter/second^2

From the above equation it is observed that the squared value of current has to be multiplied by a factor of 1.33×10^{-4} to get the acceleration of projectile.

METHODOLOGY

Assume an ideal condition such that the system is completely lossless and there is no air-drag, no frictional losses and electrical losses, and the conversion of electrical energy to mechanical energy happens with negligible losses too. As intended, to attain four times the speed of sound in accelerating a 3 gram particle one has to design a high energy power source. Let us calculate the amount of kinetic energy (KE) required to do this work

KE = 0.5 * m * v^2

Where,

m is mass in kg.

v is velocity in meter/second.

KE=[0.5*0.003*(4*340.29)]=2779.13 joules

As it was assumed that it is a loss less system, potential energy required is equal to the kinetic energy; in another words, completely potential energy (PE) is transferred as kinetic energy.

KE = PE = 2779.13

Potential energy stored in a capacitor rated at 400V is given by:

PE = 0.5 * C * V^2

C = 34739.125 * 10^{-6} farad

Hence, ten numbers of 3300uF capacitors are chosen and each individual capacitor has a 50KOhm, 10W wire wound resistor for charge equalization and also to serve as a bleeder to prevent unwanted charge buildup when power is switched off. The figure 3 shows the block diagram of electromagnetic accelerator system classified in a broader manner.

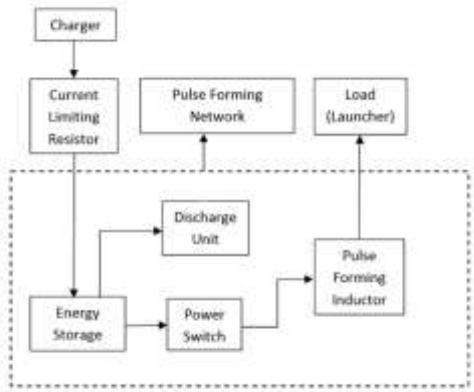

Figure 3: Block diagram of electromagnetic accelerator

CHARGING UNIT

Let us calculate the peak current drawn by the capacitor for charging:

$$I_{charging} = (V/R) * e^{(-t/R*C)}$$

Where,

V is rated voltage of capacitor

R is the value of charging resistance

t is time in seconds

RC is called the Time Constant

At t=0, the charging current will be maximum, and as t increases current drops exponentially. And as R decides the charging current and charging time, we choose an optimum value of 1k ohm.

$$I_{charging\ (peak)} = [\ (400/1000) * e^{0}\ ] = 0.4\ A$$

Power dissipated in resistor during charging is given by:

$$P_{charging} = [(I_{charging})^2 * R] = 160\ watt$$

Therefore

- Transformer rated at 230/400 1A is chosen.
- Wire wound resistor of 1k ohm 200W is chosen.
- Bridge rectifier rated at 600V 30A (market available) is chosen.

Using this unit the capacitor bank can be charged to peak voltage of 400V in 5RC seconds, which is 165 seconds.

PULSE FORMING NETWORK

Capacitor based pulsed power systems can be described using a simple RLC circuit as shown in Figure 4. In which, C is the equivalent capacitance, L is pulse shaping inductance, R is the dynamic resistance of the load.

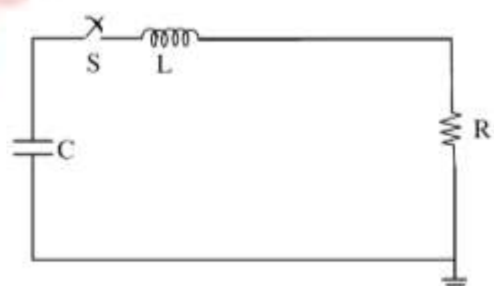

Figure 4: Basic circuit pulse power supply

When the switch S is closed, the capacitor will start to discharge the stored energy into the system. During the discharging time of the capacitor, the energy stored in a capacitor is transferred to the inductor and inductor gets charged. The inductor will be fully charged, when the capacitor is completely discharged and current flowing through the circuit will reach to maximum

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value at this point [3]. To obtain the required pulse, it depends on the values of L, C, and R. If the inductance value increases, the peak current value decreases and the decaying time of the pulse current increases. To produce large value of impulse currents, all the capacitors are charged in parallel and discharged in parallel through a series inductor [3].

If the capacitor is charged to a voltage V and discharged when the switch is closed, the current I is given by [3]:

$$I = [\ (V/\omega L)[e^{(-\alpha t)}]\ \sin(\omega t)\ ]$$

Where,

$\alpha = (R / 2L)$ and $\omega = \sqrt{(1/LC) - (R^2/4L^2)}$

Time taken for current to rise from zero to first peak (100%) is [3]:

$$t_1 = [\ (1/\omega)\ \tan^{-1}(\omega/\alpha)\ ]$$

To calculate R:

$$R = \rho l/A$$

Where,

ρ is resistivity of copper in ohm/meter

l is length in meters.

A is cross sectional area in $meter^2$

Assuming the rail of length * breadth *height as 0.3*0.005*0.02 meters and a distance between rail as 0.01 meters, resistance of rail will be:

$$R=[1.68*10^{-8}*(0.3+0.3+0.01)]/[0.02*0.005]$$

$$R = 1.0248*10^{-4} \text{ ohm}$$

To satisfy condition for critical damping:

$$R = 2*\sqrt{L/C}$$

CAPACITOR

The capacitors used in the system are capable of storing large energy and discharging it momentarily. Peak current per capacitor is:

$$I = V / ESR= 400 / 0.05 = 8kA$$

Where, ESR is Effective Series Resistance

The pulse power supply has to store 2640 joules of energy, hence totally 10 capacitors have been chosen and total theoretical peak current will be 80k A.

INDUCTOR

The pulse forming inductance value is decreased in an effort to generate an increase in peak accelerator current. The inductor used in this pulsed power supply has a simple air core design. According to the equations, it is observed, as the value of inductance increases peak current decreases with an increase in the pulse width time. Due to practical limitations on building a high current inductor, various smaller values are selected on trial and error basis and it was found the inductor value between 1uH to to 5uH to be more economical and practically feasible.

Referring to the table 1, it was found that inductor with 3uH possessed an optimum combination of rise time to peak voltage and henceforth it was chosen.

Calculating peak current at $t = t_1$ for various inductance values:

L (uH)	α	ω	R	t_1 (ms)	I (kA)
1	5500	230.28	0.011	0.18	26.74
3	3166.7	270.614	0.019	0.32	15.47
5	2500	548.27	0.024	0.39	11.68

Table 1: Selection of Inductor

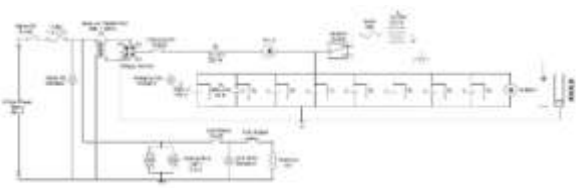


Diagram 1: Circuit of the accelerator

MECHANICAL UNIT

The electromagnetic accelerator will be composed of three main parts the rails, the injection system, and the projectile (armature). The rails and injection system will be mounted on top of the electrical unit. The armature will also function as the projectile, rather than having an armature push a projectile.

ARMATURE

The armature will be the simplest part of the launcher. It will be a single piece of 10mm thick material that will be in the shape of a square with a point in front. The shape will be very important because the armature must have a large surface of contact with the rails to keep them away from welding together. It can be made of either aluminum or graphite because of their high conductivities. Aluminium would be preferred for its low mass and lesser cost.

Specification	Aluminium	Graphite	Copper
Density (gcm^{-3})	2.70	2.23	8.96
Melting Point(°C)	660.32	5,530 °C	1084.62
Electrical resistivity (nΩ·m)	28.2	25	16.8
Thermal expansion ($\mu m \cdot m^{-1} \cdot K^{-1}$)	23.1	22.8	16.5

Table 2: Comparison of various projectile material

RAILS

Copper will be used for the rails for its low resistivity and low thermal expansion. Ultra-pure, oxygen-free, electronic grade copper-101 alloy would be ideal because of its great electrical conductivity and high purity. The two parallel rails will be 300mm long, 5mm thick and 20mm high. These dimensions will maximize the generated magnetic field and, consequently, the Lorentz force on the armature. The optimum geometry for rails is parallel plates where the facing sides are more than twice the plate thickness. The center of the rails will have perpendicular projections out of the sides of the barrel where the rails will be connected into the capacitor bank. The projections will give the rails the shape of an L and will allow for easy electrical connection to the rest of the circuit.

INJECTION SYSTEM

To avoid the problem of the armature melting to the rails, the armature will be injected so that it will already be in motion when the electromagnetic accelerator switches on. This method will reduce the resistance of the circuit by avoiding a physical switch, make the device more efficient and will help to lessen the melting problem. Because the accelerator will activate at the instant anything conductive is injected into the device, safety will be a big consideration in this type of the injection system.

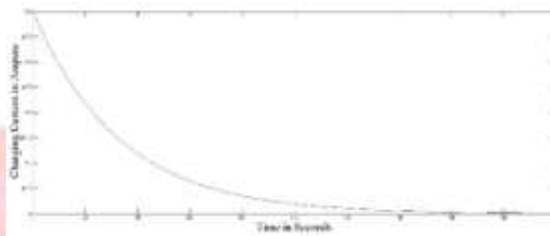
The injection system will be a continuation of the barrel without the copper rails. It will be broken into two main parts: the loading chamber and the pneumatic firing mechanism. The chamber will be simply 150mm empty space before the rails where the armature will reside. The solenoid will then activate the electromagnetic launcher by releasing compressed gas. A 5mm diaphragm 230v AC solenoid valve controls the gas flow and serves as the trigger for the gun. Currently the injector is being operated with CO_2 gas cylinder capable of providing 150 psi of initial force.

Advantages of CO_2 injector system:

- It will allow the armature to travel the longest distance over powered rails and thus minimize localized rail erosion and kinetic friction.
- CO_2 being a dielectric gas will reasonably reduce arcing during projectile entry and exit.
- Due to Joule-Thomson effect, that is cooling of pressurized gases due to sudden expansion helps in cooling the rails and the projectile.

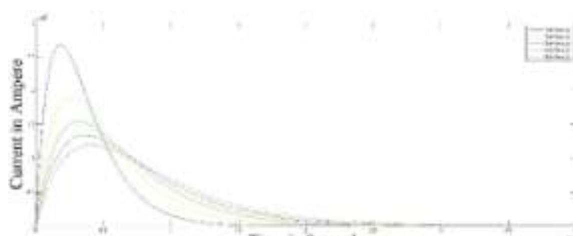
RESULTS AND SIMULATION

It is to be noted that, measuring of impulse wave requires a good research laboratory and facilities. Instead it was found economical to compare the calculated values to the simulation plot and to conclude on the result.



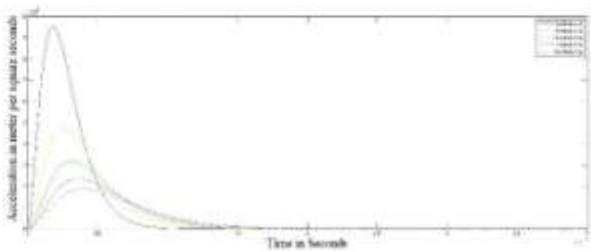
Graph 1: Charging Current Characteristics of Capacitor Bank

The above graph is comparable with the practical values obtained. Multiple charging and discharging sequences were performed and it was found that the design of the charging unit is satisfactory and stable without any heating effect or lag in charging time.



Graph 2: Current vs Time characteristics for various inductor values

As theoretically assumed, from the above graph it was found that as inductor value increases value of peak current drops and at the same point of time pulse with increases which largely affect the value of acceleration. Graph 2 is in accordance with the calculated values of time to peak currents and magnitude of peak currents.



Graph 3: Acceleration vs Time characteristics for various inductor values

Measuring velocity and acceleration with proper facility is nearer to an impossible task. Instead, relating them to currents as per the equations derived earlier is more practical. It is observed in graph 3 that acceleration is maximum when current is maximum. It can also be noted that for inductor of 1uH acceleration has a maximum value but the projectile is accelerated for the shortest duration out of the lot. In contrary for 5uH projectile will be accelerated for longer duration but with a lesser acceleration value. As per the theoretical assumption 3uH inductor provides an optimal combination of peak current and pulse duration.

TESTING RESULTS

A 3 gram 10*10mm aluminium projectile was fired. First four firing was successful whereas as the successive firings had higher arcing problems due to corrosion of the rails, which led to fusing of the projectile with the rails. The rails had to be resurfaced for further firing. Figure 5 shows the comparison of projectile before and after firing. Figure 6 shows the after effect of firing on the rails.

Figure 5: Comparison of projectile

Figure 6: After effects of firing on rails

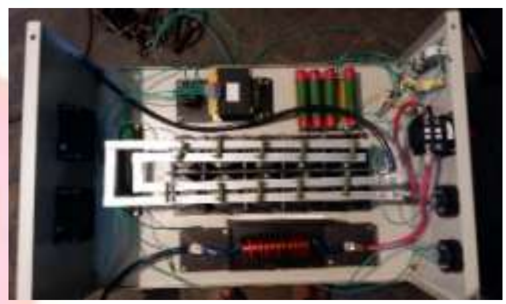


Figure 7: Internal view of the power module

Figure 8: Front view of the complete module

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Figure 9: Rear view of the complete module

Figure 10: Side view of the complete module

Figure 11: Top view of the complete module

APPLICATIONS OF ELECTROMAGNETIC ACCELERATORS

Electromagnetic accelerators have a number of potential practical applications, primarily for the military and research. However, there are other theoretical applications currently being researched.

Launch or launch assist of spacecraft: Electromagnetic assistance to launch rockets and space applications using this technology would likely to be real in coming years involving specially formed electromagnetic accelerators and superconducting magnets [4].

Weaponry: Electromagnetic accelerators are being researched as weapons with projectiles that do not contain explosives or propellants, but are given extremely high velocities. Electromagnetic accelerators by firing smaller projectiles at extremely high velocities can yield kinetic energy impacts equal or superior to the destructive energy of conventional guns with much greater range.

Trigger for fusion reactor: Electromagnetic accelerators may also be miniaturized for inertial confinement nuclear fusion. Fusion is triggered by very high temperature and pressure at the core. Current technology calls for multiple lasers, usually over 100, to concurrently strike a fuel pellet, creating a symmetrical compressive pressure. Electromagnetic accelerators may be able to trigger fusion by firing energetic plasma from multiple directions. The theoretical process developed involves four key steps [5]:

- Plasma is pumped into a chamber.
- When the pressure is great enough, a diaphragm will rupture, sending gas down the rail.
- Shortly afterwards, a sufficient voltage is applied to the rails, creating a conduction path of ionized gas.

- This plasma accelerated down the rail, eventually being ejected at a large velocity.

FUTURE WORK

The major problem with electromagnetic accelerator is handling high currents. Switchgears of higher ratings will be more expensive than the whole accelerator unit. And due to higher order of amperes the projectile fused to the accelerator rails. Hence we need a strong research in the field of materials and switchgears to make electromagnetic accelerators more feasible and economical.

CONCLUSION

The testing of the accelerator was found to be satisfactory with fewer arcing and fusing issues. It was noted that graphite as a armature would have performed better due to the higher melting point and lower coefficient of friction. Simulation of the module proved the concept of linear acceleration using magnetism and if we can handle higher currents safely and effectively, particle acceleration using magnetism is one of the cheapest and most efficient means.

REFERENCE

[1] Scott Harmon, "A Look into Railgun Physics and Design", Senior Honors Thesis, CARROLL COLLEGE, April 2011.

[2] John Krauss and Daniel A Fleisch, "Elctromagnetism with Applications", McGraw-Hill, 5th edition, 1999.

[3] M S Naidu and Kamaraju, "High Voltage India", 4th edition, THM, 2008.

[4] Ian R. McNab, "Launch to Space with an Electromagnetic Railgun", IEEE TRANSACTIONS ON MAGNETICS, VOL. 39, NO. 1, JANUARY 2003.

[5] F.D. Witherspoon, R. Bomgardner, A. Case, S. Messer, S. Brockington, and L. Wu, "Minirailgun Accelerator for Plasma Linear Driven HEDP and Magneto-Inertial Fusion Experiments", 36th ICOPS Meeting, San Diego, CA, June 1, 2009