Design, Fabrication, and Testing of an Electromagnetic Rail Gun for the repeated testing and simulation of Orbital Debris Impacts.

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An Electromagnetic Railgun (EMRG) was designed, built, and tested, capable of firing a projectile a 1 gram projectile at 650 m/s muzzle velocity. The EMRG utilizes an injector, a high voltage power supply, a capacitor bank, inductors and rails. The injector fires 2300 psig Nitrogen gas into the system to provide an initial velocity. The high voltage power supply charges the capacitor bank. The capacitor bank discharge the electric potential built up through the projectile while inside the rails in order to create the EMRG's force. The inductors are used to pulse form the capacitor bank in order to get acceleration in more of the EMRG barrel. The barrel consists of two parallel copper bars encased in Garolite-11, Teflon, and Fiberglass. These subsystems all work together for a remote firing of the EMRG during testing. Testing showed that a 0V test resulted in 70 m/s velocity, a 20V test resulted in 165 m/s and 420V test resulted in a minimum of 650 m/s.

I. Nomenclature

D_w	=	Diameter of wire
f	=	Frequency of current impulse
I_0	=	Initial Current
I_{max}	=	Peak current
I_{RMS}	=	RMS Current
R	=	Resistance
ω	=	Period of current impulse
l_w	=	Length of wire
l_r	=	Length of rails
i	=	Current
$\vec{L}$	=	Length Vector
L'	=	Inductance gradient
$\vec{B}$	=	Magnetic field vector
m	=	Mass of the projectile
c_{pvc}	=	specific heat of PVC
m_{pvc}	=	mass of the PVC
L	=	Inductance
T	=	Pulse time
N	=	Number of Capacitor Banks
C	=	Capacitance
P	=	Power emitted from the EMRG
μ	=	Permittivity of free space
ESR	=	Equivalent Series Resistance
ESL	=	Equivalent Series Inductance
PFN	=	Pulse forming Network

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I. Introduction

Electro Magnetic Rail Guns, EMRGs for short, are systems that use electrical energy to propel particles by converting electric energy into kinetic energy. This allows an EMRG system to accelerate a projectile to extremely high velocities. While this same task can be done with conventional or light gas guns, both are limited by the acceleration of the expanding gas. The projectiles in those systems can never exceed the acceleration of the gas it uses. As EMRGs convert electrical energy into kinetic energy, effectively instantaneously, they are not limited by a maximum acceleration. Though EMRGs themselves tend to only be about 2% efficient, theoretically they have no limit to how much energy can be input to the system and thusly no maximum velocity the system can attain.

A. History of EMRG

Though EMRGs are just starting to be utilized for practical purposes, the technology is nothing new. The first EMRG were developed during the turn of the nineteenth century. In 1901, the "Paten Electric Cannon" was one of the earliest known EMRGs. Indeed, 45 patents were issued for EMRGs before the second world war[1AL]. The first documented major success is attributed to the Australian university for creating the first EMRG to propel a 3 gram particle up to Mach 6 in an evacuated chamber.[1AL]

The United States Military began researching EMRGs as a viable weapons system in the late seventies, when the head of the Propulsion Technology Branch of the Army Research and Development Command in Denver began to inquire about the possibility of using them as weapons platforms. Twenty years later the Center for Electromechanics was formed at the University of Texas which focused the development of EMRGs.[2AL]

Presently EMRGs are being researched for large scale military applications. It is thought that the future of artillery will be moved to EMRG systems, with an ultimate goal of deploying EMRG systems in combat to cover an area of over 200 miles.

B. Overview and definition of subsystems

EMRGs are made up of a few subsystems: an electrical subsystem, an injector, a pair of supported conductive rails, and a projectile.

1. *Electrical Subsystem*

The EMRG electrical subsystem is composed of three subsystems that output a pulse of current: a power source, a storage system; and a delivery system. The power source provides the storage system with electricity that is then stored. When the EMRG is fully charged and ready to fire the storage system sends the electricity as quickly as possible through a delivery system, a system of electrical cabling, and to the conductive rails.

2. *Injector*

The injector subsystem is required to accelerate the projectile before it reaches the electric rails. If the projectile enters the electric rails with no or a low initial velocity, the projectile will weld to the rails. To combat this, an injector system must be used to give the projectile an initial velocity. The more initial velocity obtained using the injector is also energy that the electric rails do not have to impart onto the projectile; ideally an injector that provides as much velocity as possible should be used.

3. *Supported Conductive Rails*

The conductive rails are the most important subsystem in the EMRG. They are the system responsible for converting electrical energy into kinetic energy using Lorentz force. Based on the size and distance between the rails the rate of conversion between electrical and kinetic energy is controlled. This conversion creates a large amount of force on the projectile but also on the rails themselves. To ensure that the rails do not fail due to the induced force, they are supported by a rigid structure.

4. *Projectile*

The projectile itself must be conductive. This allows the current to pass through the projectile and convert the electric energy into a force on the projectile. High melting points will maintain their shape better under firing conditions, but will also tend to do more damage to the barrel when they fragment.

C. Governing Equations

An EMRG is a system that takes large amounts of electrical energy and converts that energy into kinetic energy by means of the Lorentz Force. The Lorentz Force is defined by the equation,

$$\vec{F} = i\vec{L} \; x \; \vec{B} \tag{1}$$

When this law is applied to two parallel rails with a conductive projectile running between, the Lorentz Force vector runs directly down the middle of the rails, allowing for the acceleration of a projectile, as shown in figure 1.

Current flows through the rails, creating a magnetic field about the rail with its direction following the right hand rule. Then the current runs through the projectile, perpendicular to the rails, and finally leaves

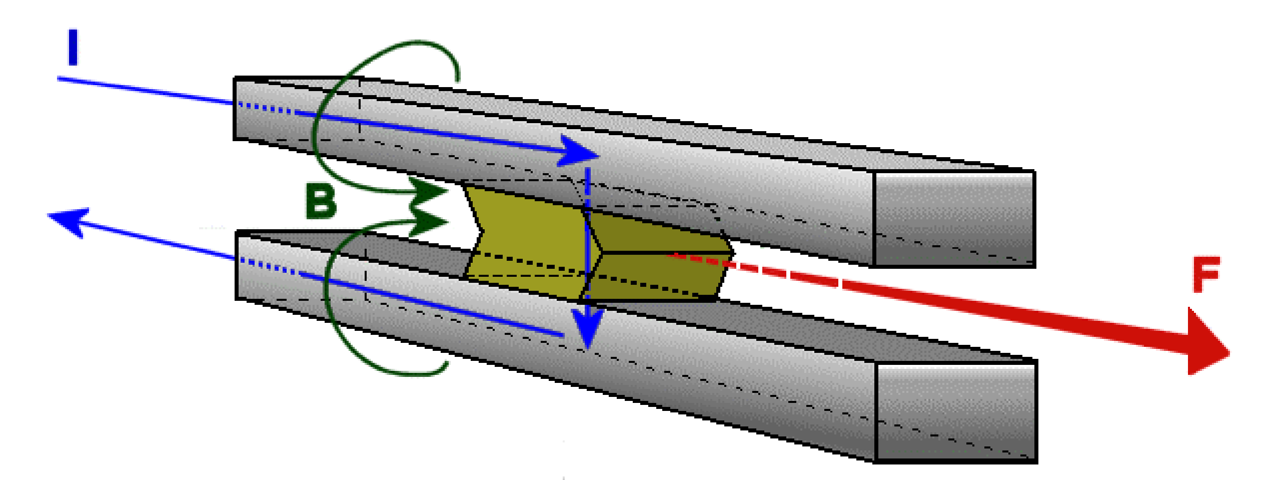


Figure 1: EMRG Demonstration of Lorentz Force[1]

through the other rail. These magnetic fields are combined together in the same direction within the projectile, creating a large Lorentz Force as shown by Eq. 1.

Though the Lorentz equation is the basis of EMRG and geometry, it cannot be directly used, as it is incomplete. The vector $\vec{B}$ is very difficult to accurately calculate analytically, as it is based on the rail current, cross-section, length, position of the projectile. However, once geometry is decided on a characterization of the geometry can be made as a magnetic field factor, L'. The magnetic field factor is also the inductance gradient of the EMRG geometry and is expressed in Henrys per meter. L' allows for a dramatic simplification of Eq. 1 into a scalar force expressed as:

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

From this forcing function we were able to solve for acceleration using Newton 2nd law

$$F = m \cdot a \tag{3}$$

$$a = \frac{L' i^2}{2m} \tag{4}$$

Once acceleration is found, an easy integration provides velocity and position.

II. Objective

A. General Objective

The goal of the EMRG project is to create a cost effective and reliable means to accelerate particulate with a mass of a gram or greater to orbital speeds. Similar systems, such as a Light Gas Gun, use high pressure gasses to accelerate projectiles for hypervelocity testing. These systems are expensive and unwieldy, sometimes occupying an entire building at a cost of millions of dollars. The EMRG is intended to serve the same purpose at a fraction of the space need and price.

Electric acceleration has two distinct advantages over its competitors. First, the EMGR avoids the use of a physical propellant. Without a highly pressurized gas, the test environment can be free of residual gas contamination. A Light Gas Gun can only accelerate objects to its propellant gas' speed of sound, while an EMRG has no such limitation. In addition, there is no need to store highly volatile and dangerous gasses for an EMRG. The second advantageous is the cost. The EMRG can potentially be built on a college budget.

If successful, the EMRG will become a repeatable test bed for the simulation of hypervelocity impacts. The development of a lightweight and durable spacecraft shield is just one possible use for such a device. Other uses include hypersonic simulation and the effects of impact liquefaction. An EMRG has the potential to serve as a test bed multiple aspects of college level research.

D. Specific Objective

The specific objective of the prototype EMRG is twofold. The first goal is to perform a demonstration of concept; prove that the founding theories are not only applicable to rapid acceleration but also attainable with a college undergraduate skill-set. The second goal is to create a model which generates testable results so that measurements can be compared to the mathematical predictions.

These objectives are designed to create a prototype that can serve as a stepping stone towards completing the overall objective. Even after a considerable amount of research, it was deemed risky to dedicate the resources needed to build a full-scale model without first establishing a Railgun manufacturing and performance knowledge base. Railguns are, in a sense, state of the art; the majority of research in this field is unavailable. Without access to sufficient data, the need arose to learn by doing instead of relying on a comprehensive literature review to be successful. The prototype embodies this philosophy of learning firsthand, and will provides critical information to complete the full scale model

III. Prototype

A. Electrical System

1. Capacitor Bank

With the goals we had for the prototype, we deemed it necessary to research and design a pulsed capacitor bank for the system. This pulsed system uses several banks of capacitors separated by large inductors to delay the output of the individual banks. One of the simpler methods is the Rayleigh Line Flow Pulse Forming Network (PFN), shown in Fig. 2. This method of solid state pulsing allows for longer forcing time on the projectile by slowing the output of the charged capacitors. This increases overall acceleration,

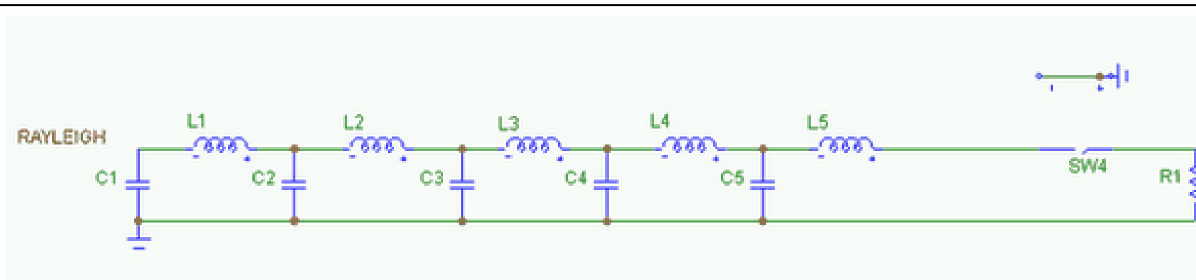


Figure 2. Rayleigh Line Flow Model[2]

allowing the system to operate at a much lower current, and allows for the purchase of much more affordable 450V electrolytic capacitors. Rayleigh Line PFNs use equal inductances and equal capacitances to simulate a square wave with the alternating outputs of the capacitor banks through the capacitors. Ness Engineering suggests the design of these capacitors is based on how many banks are desired, and how long the pulse is using Eq. 4 and 5; where Eq. 4 determines the size of the inductors and Eq. 5 determines the size of the capacitor banks [2JC].

$$L = R \cdot \frac{T}{N} \tag{5}$$

$$C = \frac{T}{(N \cdot R)} \tag{6}$$

This design does a good job of leveling the output of the capacitor banks discharge, and can sustain fairly long pulses with enough capacitance. For the design of our system, we decided to use this Rayleigh Line design as our pulse forming method for its simplicity and its consistent capacitances and inductances. Therefore reducing the overall complexity of our system, allowing us to buy identical capacitors, and build identical inductors within a fairly loose tolerance; tolerance allowance found by investigation of circuit with a sensitivity analysis.

When designing the Capacitor bank it was important to base the design around capacitors that we could afford. Since the cost of capacitors capable of completing our goals were seen upwards of $30K, the main driver to the design of the power supply/capacitor bank needed to be the capacitors themselves. 10 mF, 450V Electrolytic Cornell-Dubilier capacitors were utilized and purchased from a surplus supplier. Getting this allowed for a 16 kJ capacitor bank, totaling 16 capacitors with 4 excess, for under $700. These capacitors were arranged evenly to make 4 banks of capacitors each at a total capacitance of 40mF. This set up was designed to eliminate Equivalent Series Resistance (ESR) and Equivalent Series Inductance (ESL), and maximize overall capacitance.

The arrangement of the capacitor banks, the inductors in between each bank, and the rails fit into the overall capacitor system is shown in Figure 3. In this Rayleigh Line system, the barrel of the EMRG is the electrical load and each capacitor bank acts as a single capacitor. This acted as our baseline design of the power storage system as we moved on in the design process.

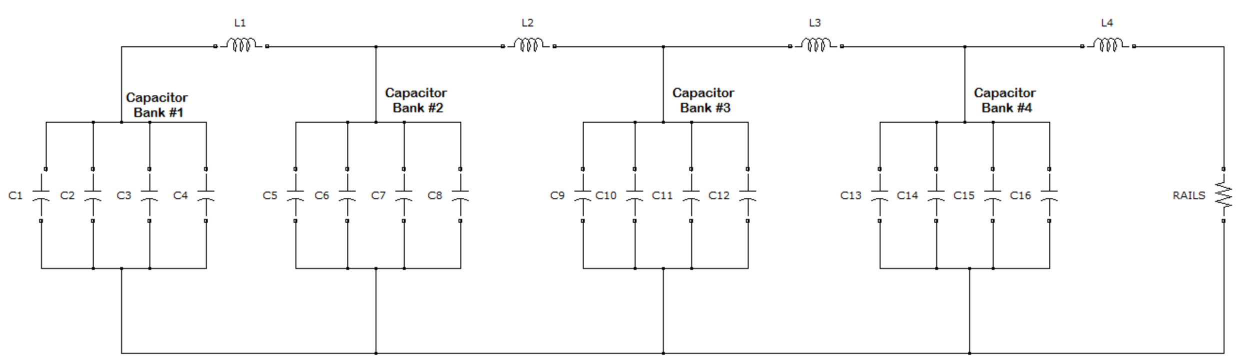


Figure 3: Capacitor Bank Design

With these capacitance values and desired pulses as high as 1.5 milliseconds, the Rayleigh Line PFN design equations became increasingly inaccurate, so we modeled the output and varied parameters. This circuit includes ESL of the capacitors, outputs of currents through each capacitor bank and each inductor, and the voltage and current across the rails; all to be used in the overarching system Simulink model. The model blocks L1, L2, and L3 are the inductors required for pulse forming, along with their inherent resistances. One unique area of design of this system is that the final inductor of the Rayleigh Line PFN is the internal inductance of the copper rails. The inductance of the rails was found to be high enough to replace the final inductor. This system is a smaller subsystem of a greater architecture.

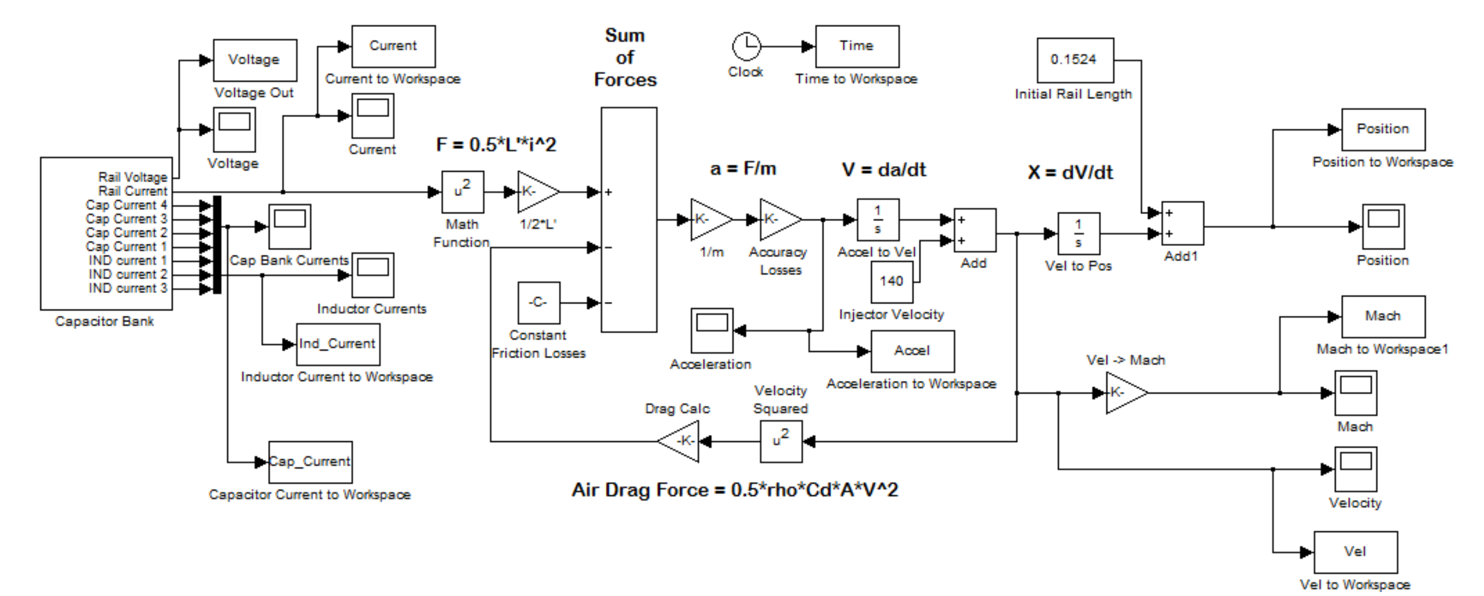


Figure 4: Full EMRG Physical System Model

The diagram in Fig. 4 shows the Simulink diagram that takes all of the electricity in the charged capacitor banks and converts that current output into forces, accelerations, and velocities, and then outputs that data to the MATLAB workspace for further processing. This models the physical rails, projectiles, and capacitor bank. These models allowed us to make the smallest changes anywhere in the design and immediately see their effect on everything else very quickly.

As the design of our system continued it was found that the inductances in the Rayleigh Line equations

Table 1: EMRG Design Parameters

	Parameter	Value
INPUTS	**Capacitor Voltage**	450 Volts
	Capacitor Capacitance	10,000 uF
	L' of rails	0.327 uH/m
	Rail Inductance	0.30 uH
	Rail Resistance	0.38 mΩ
	Inductor Inductance	0.6 uH
	Injector Velocity	~140 m/s
OUTPUTS	**Max Capacitor Current**	~20 kA
	Max System Current	~100 kA
	Max System Frequency	~1 kHz
	Velocity @ barrel exit	~950 m/s

were not giving us the necessary pulses that were required out of such a large system. This led to a varying of the inductances, both up and down, to view the effects on the system as a whole. It was found that a low enough inductance the pulse forming does not work anymore and we are left with a very high current, low pulse time capacitor discharge. With a high enough inductance the output became a very large (under-damped oscillator) going from 100 kA to -100 kA in times of about 2 milliseconds. The final design of the PFN is shown in Table 1.

The final portion of the capacitor system design is to develop a method to discharge the capacitors into resistors instead of the rails.

The final portion of the capacitor system design is to develop a method to safely discharge the capacitors into a bank of resistors instead of the rails. This system is comprised of 3 225W, 100 Ohm resistors capable of discharging the fully charge capacitor bank system in less than 5 minutes were there to be a situation in which the capacitors were fully charged, but they could not be fired.

1. Inductors

Inductors are sequential coils of wire that induce a magnetic field when a change occurs in the flow electricity through the wires. There is a time lag between the moment electricity first enters the inductor and when it leaves. Our inductors exploit this fact. They act like buffers that will delay capacitor bank discharges, as explained in the pulse forming network section.

Inductors "resist" a change in voltage by storing energy as a magnetic field. The magnetic field lines envelope the entire structure of the inductor and become concentrated in the inductor's "core," this is the space inside the coil of the wire. This core can materials are divided into two categories, ferric and non-ferric material. Ferric materials allow for more concentrated magnetic fluxes, smaller inductor sizes, and high Inductances. They require a complicated design process to optimize many variables, exotic core-materials, and tend to have 'iron' or core-losses due to the core's magnetic interactions.[4ALL]

All ferric materials have a magnetic flux limit that, if surpassed due to excessive current, will degrade the inductance of the inductor to a point between 10% and 20% its designed level. That point is said to be the saturation level. Materials with a range of characteristics can be inserted into the core to modify the maximum permeability. [4ALL] Size constraints generally require a small inductor geometry which forces magnetic fields into a smaller area which demand higher permeability than air. This, however, was not a concern for our project...

Our inductors are designed with an 'air core' configuration. Air Core inductors do not have ferric inserts, they are generally bigger and have a number of characteristics that are advantageous to our design. Firstly their inductance is derived from their geometry, not a function of current; and therefore, do not have saturation limit. This makes the design process much simpler. Because inductors do not rely on special types of material in certain geometries further complexity was eliminated. In choosing between air and ferric cores, a tradeoff in losses is made. While the lack of a conducting medium in air core means that air core inductors will not experience hysteresis and eddy current losses, high copper losses tend to develop.[3] (6)

Using an html program created by Martin E Merserve[1ALL] we were able to easily create an inductor based on our inductance needs, wire size, and current. His program then did some fine tuning to allow for easier construction of the inductors. We treated this solver as a black box calculator and then checked it against air-core calculations from a website maintained by the University of Surry[3ALL]. Our inductors required between 0.1 and 0.7 microhenrys with a wire size of 6AWG. Using Meserve's program for .4 microhenrys and a 1 inch PVC pipe as the diameter form inductor specifications were obtained. We created a 4 turn inductor with a coil length of 13/16th of an inch. Adding 2 inches onto each side gave us an inductor wire length of roughly 30 inches. Given our results in attempting to braise the copper connectors together, it would be desirable to have a tab length of 4inches.

In systems that have very high frequency skin effects become a problem[2ALL]. Skin effects occur when high frequencies cause current to only flow on the outer edges of a conducting medium as shown in Eq. (7)

$$Dw = \frac{200}{\sqrt{f}} \tag{7}$$

At a nominal 90,000 amps, our wire would need to be 20 times larger for skin effects to become noticeable.

In calculating the resistance of the inductor it was assumed the inductor acts as a perfect inductor in series with a resistor. Only the resistance of the physical wire itself is taken into account. With 30 inches of wire and a resistance of .3951 ohms per foot we have a resistance of .988 milliohms.

It was known that magnetic interaction in the inductor could cause it to fail by implosion, so a PVC pipe filled with cement was placed inside each inductor.

Because air-core inductors generally have more wire, 'copper losses' become the prominent source of performance loss. Because the magnetic field in an inductor acts as a resistive element inductor losses are not limited to the resistance in the coiled wire[2ALL]. To calculate this loss the diameter of the wire must be taken into account as seen in Eq. 8

$$C_l = .002 \cdot l_w \cdot \left(\frac{I_{rms}}{D_w}\right)$$

(8)

With 100,000 amps going through the system, the inductors will dissipate 10M watts, in the length of time we fire; they will dissipate 7.90 KJ of energy into the inductor form.

As a first order approximation that will be further refined at a later point, we can say that all the energy being dissipated by the inductors will go directly into the PVC pipe in the form of conduction. Taking the assumption that the energy transfers at a steady state, we calculated that the PVC form will increase by 88 degrees Celsius as seen from Eq. 9

$$\Delta T = \frac{C_l}{c_{pvc} m_{pvc}} \tag{9}$$

Where c_{pvc} is the specific heat of PVC taken to be 90 $J/(kgK)$ and m_{pvc} is the mass of the PVC, estimated to be .1 kg. From standard room temperature of 25 degrees Celsius our inductor core is projected to rise to 113 degrees Celsius which is just over the 100 degree melting point of pvc. While these calculations suggest melting will occur, we believe that our over-approximation will keep us below the melting point. For example, energy transfer has been approximated at a steady state heat transfer that conducts only transfers to the pvc pipe. We assumed convection and radiation to the air, which covers more than fifty percent of the surface area, is negligible when it should play a major part in reality. Our EMRG will utilize 3 inductors with 4 turns wrapped around a 1.0 inch diameter pipe. It will dissipate 7.90 KJ of energy during a fire time of 1 millisecond. And it will have a resistance of 0.988 milliohms.

2. Power Supply

The power supply of the system is a commercial off-the-shelf 800 volt capacitor charger. This supply provides a constant power to the capacitor bank, on the order of several mill watts, and the supply can be calibrated to engage a light when load has reached a specific voltage. For operation, the supply is hooked up to control box near the operators, away from the capacitors, because remote operation has yet to be designed. Due to the resistance of the wires connecting components and the resistance of the capacitors to being charged, a full charge of 450 volts can take over 3 hours.

Although a suitable power supply for the prototype was capable of being bought, a much higher voltage power supply can be overly expensive. Over the course of the design of the EMRG, the design criteria for a higher performance power supply was reviewed. The following considerations and decisions are presented as a starting point for the creation of a supply suitable for the full scale model.

In order to discharge a large reservoir of power, it must be stored. However, in order to store power, it must be supplied. A capacitor bank may be a cheap and fast was to store large quantities of electrical power, but it has a challenging design parameter: voltage. The energy stored in a capacitor is proportional to both the capacitance and the square of the voltage across the capacitor. An increase in either parameter increases the amount of the energy stored, yet an extended review of the current market for capacitors showed that high voltage capacitors are generally cheaper than high capacitance. In the interest of designing the EMRG so that it was both affordable and high performing, high voltage capacitors were chosen as the main form of energy storage.

The challenge of designing for high voltage capacitors is twofold; high voltage is both dangerous and sparsely available. The power that runs through most facilities is usually between 110 and 240 volts AC, which is only a small fraction of what would optimally be available. In addition, wall power is potentially lethal, and an improperly designed system runs the risk of exposing its operators to deadly amounts of electrical energy. Increasing this voltage by an order of magnitude only increases the level of danger it presents. Both of these considerations drove the design of the power supply.

The complete power supply design also accounts for additional logistical considerations, beyond the driving requirements. Capacitors charge when exposed to a DC current, yet a standard facility line current is AC. The supply needs to transform this power by means of an AC to DC converter. In addition,

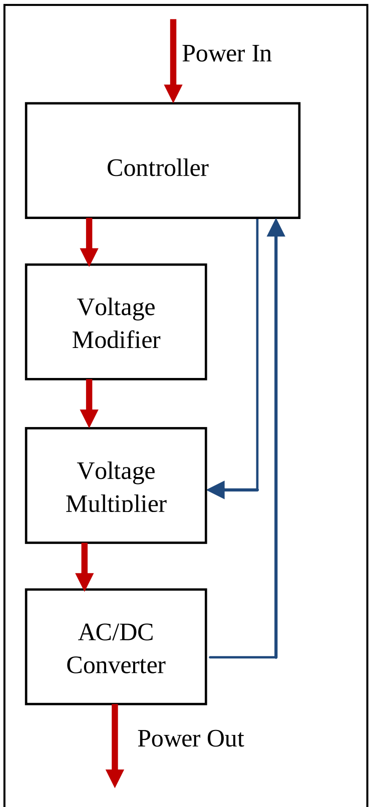


Figure 5: Power Supply Flow from the source to capacitor bank.

the ability to provide varying voltages offers significant testing value. Different voltages lead to different amounts of energy storage, which can serve to help verify initial modeling and fire at different velocities.

In summary, the design consists of four major parts: A control structure, a voltage modifier, a voltage multiplier and an AC to DC convert. Figure 5 is a simple flowchart that highlights a few key relationships between each of the components. The red arrows show the flow of power through the system, while the blue arrows represent a connection between the controller and each subsequent phase.

The power first runs into the controller. The controller is defined as the group of parts that regulate and display the flow of power. The controller encompasses the means to ultimately manage the rest of the components. The controller also includes displays to allow monitoring and measurement recording. The controller does not directly adjust electrical parameters, it simply regulates it. The voltage modifier takes the output of the controller and limits it to the desired value. This stage is essentially prepares to power for the multiplier stage. The voltage multiplier increases the voltage at the expense of amperage. The output of this stage is the intended capacitor voltage. In the interest of safety, the controller must also provide this stage a means to discharge if necessary. The final stage of this design is the AC to DC converter. The sole purpose of the phase is to modulate the current to the form accepted by the storage system. Once the conversion is complete, a display allows the final voltage to be measured.

A simple, cheap design has been developed following this flowchart. Figure 6 shows an inexpensive and simple

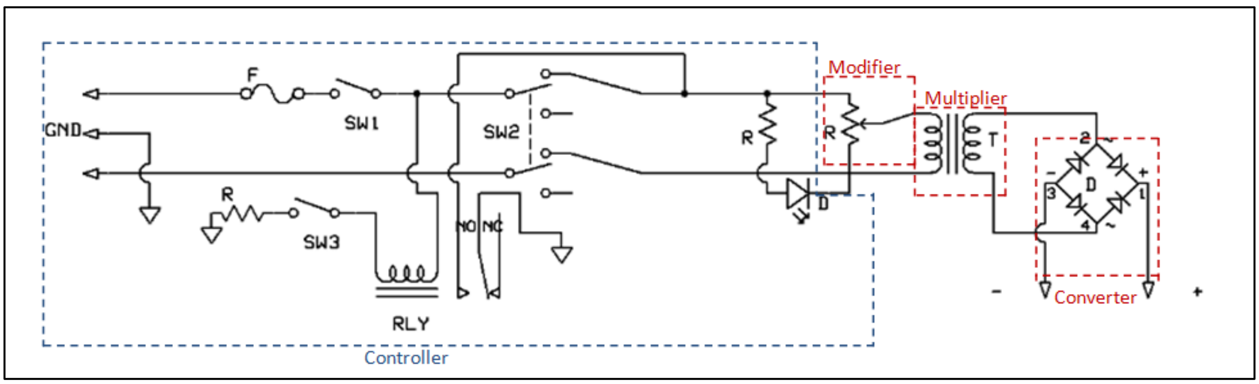


Figure 6: The preliminary power supply design for the EMRG

power supply that can easily generate the required power. The exact output range of the power supply is a function of the transformer, labeled 'T,' which can easily be interchanged for the desired output as long as the following converter is rated at that voltage.

This controller is comprised of three main parts: a power shunt, a discharge relay, and an indicator LED. The shunt includes the initial fuse, as well of switch 1 and switch 2. This section acts as the on-off mechanism, and the dual switches ensure that the supply is not accidently engaged. The relay activates when switch 3 is closed, providing a means to discharge the residual electrical buildup in the transformer after operation. Finally, the diode labeled 'D' simply indicates when the supply is operational and therefore dangerous. The voltmeter has been excluded from Fig. 6, but would bridge the output of the converter.

The modifier, multiplier, and converter stages are all easily purchased electrical components. A variable resistor serves as an ideal modifier, while the multiplier is simply a step up transformer. The exact number of turns would dictate the voltage delivered to the power storage system. A high voltage diode bridge converts the feed from the transformer to direct current.

The exact components needed to build this supply would be determined by the desired output. For this current prototype an off the shelf has been purchased for the 450V system. However, the expense and rarity of the supplies that can produce the voltage needed for a full scale model requires that a custom system be constructed.

E. Structures

The EMRG rails serve two purposes; too act as the electric conducting rails and to ensure that the conducting rails do not fail structurally.

1. Conductive Rails

The conducting rails are required to supply the rated maximum current to the projectile, retain contact with the projectile, and supply a proper magnetic field to create a Lorentz force. The geometry of the conductive rails, as well as the distance between them, dictates the magnetic field. As show in Eq. 2 the magnetic field factor, or inductance gradient is the key in getting the most amount of electric energy converted into kinetic energy. The primary way to determine L' is to use finite elements to determine the magnetic field; however a method was found that uses the height, width, and distance between the rails to approximate L'. It was found that the dimensions of the rails could be varied slightly; without much difference in L' [1GL].

Due to the requirements for the rails 2 36" x ½" x ¼" that are 0.25" apart oxygen free copper rails were selected for the conducting rails. These dimensions were determined without taking L' effects into account, as it was assumed that any L' would be sufficient to attain high enough velocities (for prototype testing). Using the method explained in Kerri's method it was approximated that the L' of our conductive rails is 3.271×10^{-7} H/m.

1. Structural Rails

The structural rails are required to withstand the repeated loads associated with the EMRG operations and to be easily maintained. The conductive rails will be reinforced with Garolite-11, Teflon, and Fiberglass held together with stainless steel bolts. The force pushing against the rails follows

$$F = \frac{\mu_o I^2 L}{2\pi d}$$

(10)[1SGZ]

Where I is the maximum current through the rails, L is the length of the rails in meters, d is the length in meters between the rails. Using this equation and the known yield strength of our materials it was determined that the Fiberglass, Teflon, and Garolite-11 would hold given bolts of sufficient strength and distribution. Using the equation

$$F_{max} = \#bolts \cdot A_{bolts} \cdot YS$$

(11) [1SGZ]

It was determined to have 34 1/2inch bolts distributed down the length of the barrel; with 17 bolts on each side.

2. Schematics and specific design

The rails were designed for simple manufacturability, as well as for a small projectile (1 gram of aluminum) and can be seen in Figure 7 below. The barrel was designed for a 1/4" x 1/4" projectile, and the rails themselves were of

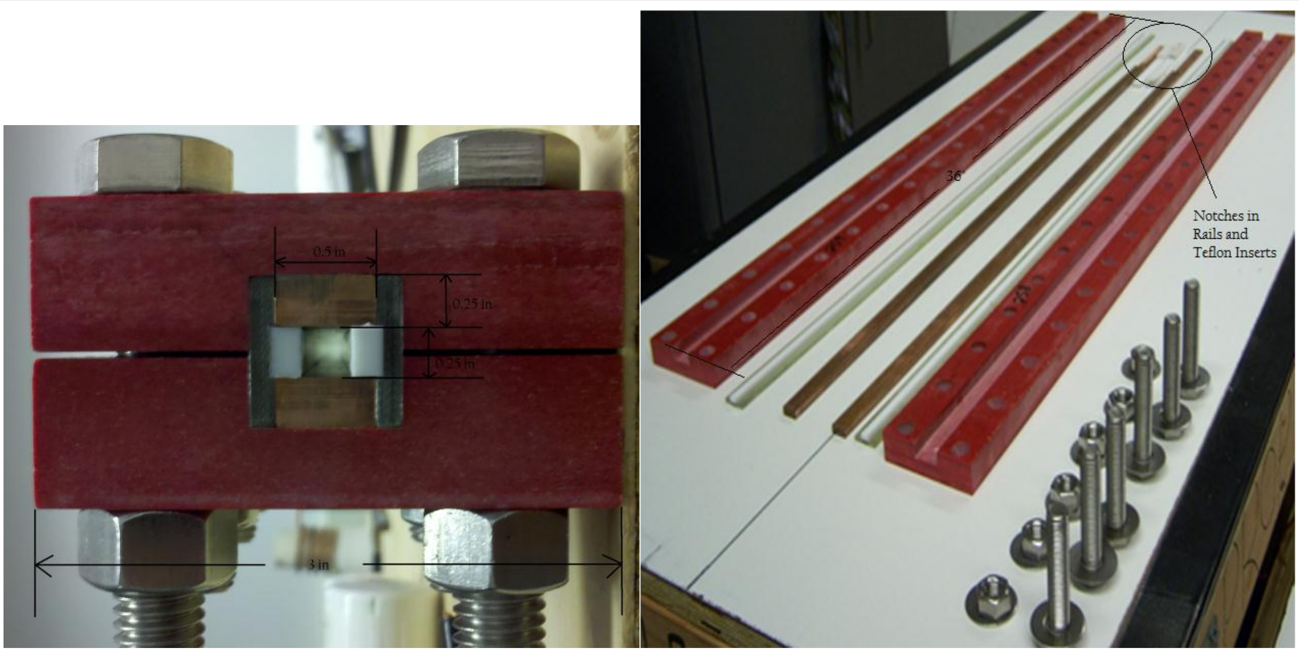


Figure 7. Inner Dimensions (left) and length (right) of finished prototype rails

that same thickness, and were 0.5" tall to best create the magnetic fields to force the projectile down the barrel according to the L' approximations in Kerrick's method. The rails were just about 36" in length, with a notched section at the beginning where the Teflon rails were inserted. Overall this is a very simple and repeatable design. Due to the small thickness of the Garolite and Teflon however the machining was quite a bit more expensive than previously thought, and in future designs these thickness will be increased and other measures will be taken to ensure that the manufacturing costs are mitigated as much as possible.

3. Injector

Some methods of injecting a projectile into the rails include conventional guns, springs, or compressed gas. The most common method used, and the method that our system implement, is the use of compressed gas. We are implementing a high pressure compressed air injector system in order to get the most energy out of the injector, as well as avoid the danger associated with a conventional gun.

The system in the EMRG is composed of 4 main components: a pressure tank, a solenoid valve, a transfer hose, and a rail adapter. The pressure tank is pressurized to a maximum of 3000 psi with compressed nitrogen. The solenoid valve is implemented in order to safely fire the injector system remotely. The solenoid is a critical component because when the projectile enters the conductive rails, it immediately reaches the electric field and begins to accelerate. However, this implies that when EMRG is armed the solenoid is the firing mechanism. Thusly, the solenoid valve allows the operator to fire the EMRG and injector system remotely. Since the capacitor system will be armed before the injector is fired, the solenoid valve acts as the main firing switch for the entire system. Lastly, the rail adapter will connect the injector to the rails and allow the compressed gas to enter between the rails and accelerate the projectile through the non-conductive rails, into the conductive rails.

Because the non-electric portion of the rails is relatively short, the injector system must raise the speed as high as possible. Due to budget constraints a 3000 psi system was selected, which accelerates the projectile to nearly sonic velocities before it reaches the conducting rails. However; due to safety concerns and the availability of 3000 psi nitrogen tank the injector was only set to 2300 psi of nitrogen.

F. Projectile

Railgun utilize electric conduction to propel armatures down the rails. There are two types of systems employed by rail guns to launch a projectile. The simplest is a conducting projectile that forms a circuit with the rails and is propelled down the track. The more complicated version uses an insulated projectile that is pushed by an armature.

Insulated projectile systems (IPS) are what all rail guns above four kilometers per second utilize. Insulated projectiles are preferred for faster systems because they will not deform inside the barrel, they allow for speeds above 4 kilometers per second, and, because there is less deformation in the projectile, more uniform impact results. However; they are more complex, require the addition of slightly more mass.

We chose a simple projectile-only system because we could satisfy our requirements with a less complex system. Above 4 km/s systems will create a plasma armature because of the amounts of energy going through the system; our speed did not require a plasma armature. We also decided to go with a simpler design because future projects will be able to test projectile geometry affects better without variables introduced by a separate projectile-armature system. Because a plasma armature system was undesirable, the mass required to create a solid armature would slow the system down considerably.

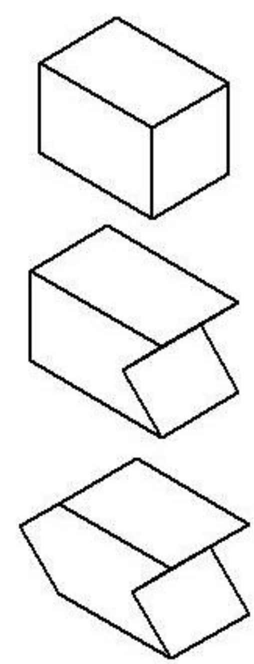


Figure 8. Three projectile geometries to be tested in the EMRG

The projectile material was also design consideration. Research of other rail guns suggested the viability of two materials: aluminum and molybdenum. Aluminum is a good conductor, it has low density, it is inexpensive, easy to machine, and commonly used as the standard material in space impact testing. Aluminum has a low melting temperature which means that more melting will occur and more vaporized projectile material will collect on the rails. A lower melting temperature also meant that we expected to see less destruction to the rails. This is a huge concern in rail gun design as explained in previous sections. Molybdenum on the other hand has a melting point of 2,625 degrees Celsius. Compared to aluminum, it has three times the density, worse conductivity, more difficulty, and is considerably more expensive. While molybdenum is an ideal candidate for high speed rail guns, we chose aluminum because its unit volume is ideal for our dimensions, it was easier to work with, because it was much less expensive, and because aluminum is the material approximation of space debris.

Geometry was the third design constraint. The dimensions of the bore were .25 inches by .25 inches. With aluminum's density of 2.70 g/cm^3 and a projectile target weight of 1g we found a nominal length of .35 inches. As seen in fig. 8, three projectile designs were created to test the impact of projectile geometry. The first design was a simple cube of aluminum with dimensions and clearances of .249 x .249 x .36 in. The second utilized a V tail while maintaining the volume and thus weight of the projectile. V tails theoretically will create a magnetic field that pushes the outer material of the projectile into the conducting rails which will increase the duration of rail connection and minimize arcing. Its dimensions were .249 x .249 x .432 in. our third design utilized both a V tail and a wedge-shaped nose in hopes of reducing drag. Its dimensions were .249 x .249 x .485 in.

We hope that manufacturing these by ourselves would make the process quicker and cheaper, but we found that each projectile took roughly .5 to 2 hours (depending on the design) to machine. Also we had difficulty machining such small parts so we had to file down each projectile to fit into the barrel which destroyed our precision machining and makes it impossible to tell if our V tails and nose wedges were effective. We suggest sending the projectiles out to be precision machined by professionals.

II. Test Results

A. Results and Outcomes

Initial testing of the prototype Railgun went almost flawlessly. Two sets of testing were completed; an impromptu test of individual systems before a scheduled firing date and the test of the components together.

The injector systems was the first tested. The solenoid and piping were connected to the pressurized nitrogen tanks, and solenoid function was tested by quickly energizing and de-energizing the internal coil. Once the injector was demonstrated to work properly, the system was integrated with the rails. The target platform, three quarter inch steel plates suspended in a plywood box, was placed on top of a table several feet in front of the barrel. The projector was loaded into the firing chamber, and large piece of plywood was erected as a temporary blast shield. Once the area was clear, the injector was discharged.

The projectile was eventually located in its final resting place, about half a foot away from the blast shield. The projectile flew too quickly to be observed by the naked eye, but the shape of the post-fired round suggests that the round likely ricocheted several times before eventually coming to rest. Visual inspection revealed two distinct and significant deformations, which were recreated afterwards. With a hammer and an unfired projectile, identical to the one fired, it was determined that the impact required to recreate deformations the size observed in the test required a sizable amount of force compared to output of a normal human arm. Such an impact posed significant health concerns, so this test demonstrated that the projectile catching mechanism needed review.

The electrical system was tested second. Capacitor charging was tested after the resistor bank was integrated by connecting the power supply and allowing the system to charge to slightly more than 300 volts. The test took several hours, and upon completion, the resistor bank was remotely engaged through the relay. Thankfully, the resistor bank also functioned as intended, discharging the capacitors in a matter of minutes.

Once these tests were completed, an official test was schedule. This test was attended by representatives of Cal Poly's Environmental Health and Safety office, to ensure that operations were completed without significant health concerns. Three tests were performed: one to test the injector system, one to test the electrical system, and then a full power test. The first two tests were performed verify that the individual systems were still functioning properly before introducing significant danger when fully charged.

There were three main sources of measurement data; a high speed camera, a voltmeter and data acquisition system. (DAQ) The high speed camera was used in conjunction with a calibrated backboard with equally spaced lines so that footage, with the addition of some simple geometry, could be used to calculate the speed of the projectile. The voltmeter was connected across the leads of the high voltage power supply so that the voltage of the system could be viewed at any given time, and so that the starting and ending voltages could be used to calculate the power dissipated by the EMRG. Finally, a DAQ card was connected to a laptop with the program LABVIEW was only used in the final trial, in an attempt to measure the more intricate transient voltages during discharge.

The first test, a dry firing of the injector without the electrical system, went exactly as intended and propelled the projectile into the redesigned target. The projectile embedded itself into the foam, successfully preventing the significant ricochet problems found in the initial testing. Review of the footage showed that the projectile left the barrel at a speed of about 80 m/s, setting a baseline for the proceeding tests.

Next, the capacitors were charged to 20 volts and the same test was performed. However, unlike the previous tests, the solenoid failed. When used in conjunction of the control circuit, the solenoid refused to energize. Thankfully, a bypass to the control circuit was implemented, allowing the solenoid to be plugged directly into 120V AC power, successfully resolving the issue. To the date of this report, it is still unclear what caused the malfunction. Review of the footage showed that the projectile was accelerated to about 175 m/s, more than doubling the baseline speed, with a final potential of 8 volts.

Finally, the capacitors were charged to 420 volts and the system was once again fired. This time, the firing process included a significantly bright flash and a smoking target, indicating that the projectile achieved significantly greater speeds. Calculations based on the review of the footage shows that the projectile must have been travelling in excess of 650 m/s. The exact speed is impossible to determine because one of the only two frames partially obscures the position of the project, so only an estimation could be developed. Using the end of the barrel, which is inaccurate because the projectile is still within the barrel in the specific frame, as the starting point of reference, it can be said with certainty that the projectile fired faster than 650 m/s, without bound with respect to the maximum possible speed. The mathematical model suggests that the velocity cap is closer to 1000 km/s.

Figure 9. Three select frames from the high sped footage. These chronicle the high power test firing.

Below, figure 9 is three select frames from the high speed footage. The top is the first frame of the projectile after it has left the barrel, which is the bright object that is leading the superheated gas cloud. The bright cloud leaving from the barrel is likely a combination of superheated and plasma-field aluminum and nitrogen, but the exact composition is undetermined. Recovery of the projectile showed that the immense charge density and friction generated during the firing process was enough to melt, and then evaporate, the outside of the aluminum projectile, indicating that barrel internal temperature must have exceeded 4500 ºF. The middle frame was taken just microseconds after the first, and the bright gasses and plasma leaving the EMRG makes it impossible to identify the project. The final frame is after the project has impacted the target, showing that the immense of the impact temporarily ignited the flame resistant foam.

Figure 10. The three projectiles, after being fired from the EMRG. The high powered round is on the right, the 20-V is on the top, and the injector only round is on the bottom.

Figure 10 compares the three recovered projectiles. The round from the injector appears almost entirely un-deformed. The round from the second test is only slightly more damaged that the injector round, with little visible deformation. The third projectile, from the high voltage test, is significantly deformed, with significant mass loss to gasses and contortion due to the significant forces it was exposed to.

B. Test Failures and improvements for further testing

Some of the failures of the test include the destruction of our inductors, some wires coming loose from support, as well as the control box failing as the main means to fire the solenoid.

The inductors used in the firing, as discussed in the previous sections, absorb some of the energy dissipated by the capacitors with the goal of manipulating the pulse output of the capacitor banks. This energy was stored in magnetic fields around the inductors. This same magnetic field, along with the magnetic field created by the conducting rails themselves, interacted with the current running through the inductors and caused them the smash in on themselves along their length. This was an unexpected phenomenon. What was expected was that the inductors would crush their housing due to the magnetic fields, and this was taken into account by filling the PVC pipe supporting the inductors with cement. The future inductors used in our system will be comprised of a solid non-conducting material that will be custom threaded for the specific inductance. This will allow for even more accurate inductances as well as prevent them from failing as shown in Fig. 11.

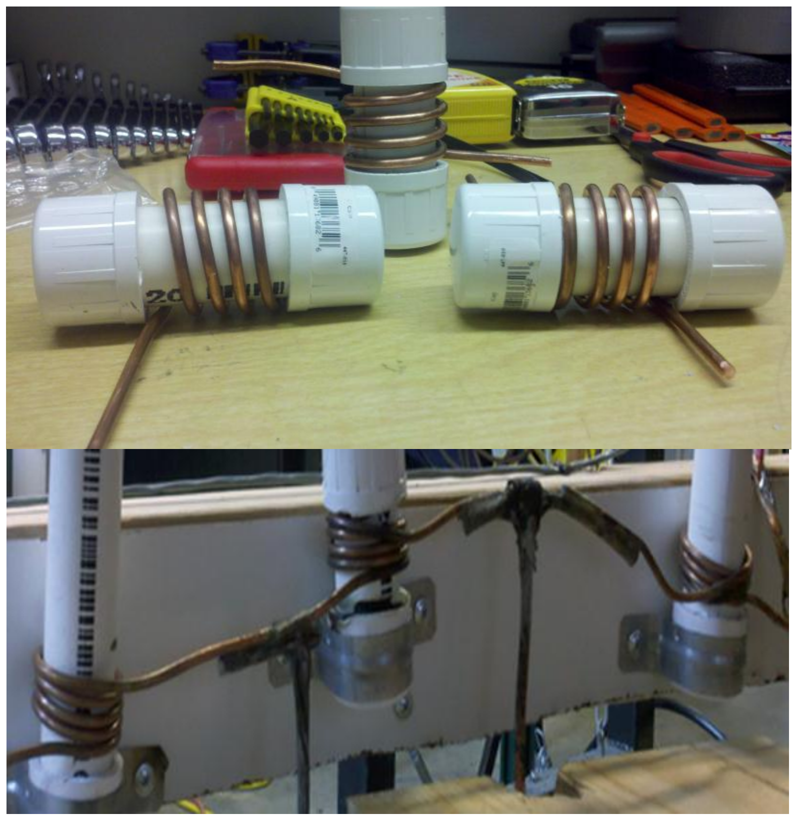


Figure 9. Inductors before firing (top) and inductors after the firing (bottom)

Some of the electrical connections were loosed from their restraints due to the intense magnetic fields and forces induced within the wires during the firing. This will be addressed in the future and will be mitigated by more analysis on possible forces in connection areas, and reinforcements will be made accordingly to allow for the Railgun to be fired repeatedly with as few repairs as possible.

Another failure seen by the test firings was unresponsiveness of our solenoid firing circuit. This prevented us from firing the solenoid effectively, and required us to plug the solenoid cabling directly into wall power for our full 420V firing. This was a tragic, and simple, failure on our part and needs more analysis as of yet. During tests of the system the solenoid would fire every time. On the day of the firing it began to fail; firing 75% of the time during tests, and not firing at all with the capacitors charged. This could be due to the magnetic fields gathering in the system and causing interference, or it could be simply due to bad design/wiring. This will have to be tested further and designed in a more robust way so as to mitigate failures in the future.

IV. Future Work

A. Requirements of EMRG capable to 3+ km/sec

With the results of this test showing us such favorable speeds from the system, as well as a positive concurrence with the proposed speeds predicted by the mathematical analysis, an EMRG capable of speeds greater than 3 km/s is most definitely possible. The current design does not allow for such speeds however, due to the great amount of energy required. So in order to reach the orbital speeds required for the testing of satellite shielding, the Railgun must go through a complete redesign after more extensive testing of the current system to analyze where improvements on efficiency and repeatability, as well as safety, can be implemented.

The first and most important improvement that must be made is an upgrade to the power supply that supplies the current to the rail system. This is by far the largest limiter of the Railguns maximum speed. The capacitor bank of this prototype output a power around 16 kJ and obtained a speed of about 650 m/s. That gives the projectile a kinetic energy of about 200 J. This is a energy output to kinetic energy efficiency of 1.25%. For an equally sized projectile travelling at 3 km/s the projectile kinetic energy is around 4,500 kJ. With the same efficiency the power supply for the Railgun must output greater than 360 kJ. This is a 22.5 times increase in output power. With current capacitor technology this can be accomplished, and has been long outdone by the naval Railgun program, which has a capacitor bank of 32 MJ, and is working on another with an energy of 64 MJ. There is a team at Cal Poly that is currently working on a Compulsator, a form of flywheel energy storage system, to accomplish this goal, which would make the Railgun much safer and much more repeatable, as it would last much longer than a capacitor bank, and can be repaired as well.

Another improvement that will be made will be testing and implementing several different rail augmentation schemes. A large driver of the efficiency of the rail gun is how effectively it creates magnetic fields, and how well those fields are utilized by the projectile during the firing. Several schemes that shall be tested with the current rail system are magnetic field enhancements from the use of solid magnets, dual rails that will improve the full use of the current flowing through the rails, inductor placement with respect to rails, as well as several other rail augmentation techniques demonstrated by Naval Postgraduate Academy Master's Theses, as well as other schemes provided by our own ingenuity and experimentation. All of these improvements increase the efficiency of the Railgun, allowing for a more effective system at a lower cost, at a lower energy.

Finally, future work for the Railgun that will be accomplished first will be making it much safer, and much more repeatable. This may include some improvements to the design to allow for the above tests to be done, as well to allow for possible in house machining to reduce the cost of the testing, as cost is always an important driver in University projects.

V. Special Considerations

A. Safety

1. Design Inhibits

1. Hazardous Operations

The hazardous procedures associated the design, fabrication, and test of the EMRG are straight forward for design and fabrication; however, are extremely unique and critical during testing. During design there will not be any hazardous procedures. During fabrication the HAZOPS associated include basic machining hazards; which will be mitigated by only allowed properly trained personnel to operate machinery.

The main hazards occur during testing of the EMRG. The prototype is estimated to utilize approximately 100kA and 450V which will increase the projectile to approximately 1500 m/s. The hazards associated with this are primarily electrocution and projectile impact, with both being potentially lethal. To ensure a safe operation of the EMRG definitive steps are taken, in conjunction with the Cal Poly Safety Office. To ensure proper safety of other persons around the facility (as well as the operator) a rigorous safety checklist will be used that will include clearing the area, a warning before firing. The firing procedures are included in the appendix.

The primary method of mitigating the testing hazards is to remotely fire the EMRG in one of the Aerospace Departments propulsions bunkers. NOTE: The EMRG will ALWAYS be fired remotely. These facilities are equipped for high energy systems such as rocket motors, jet engines, and supersonic wind tunnels. The use of these facilities will always be implemented with a remote firing capability; which will allow the operator to be behind the blast walls of the facility and operate the EMRG remotely.

To mitigate damage to the facility from the projectile, the firing distance has been minimized to two feet, and is fired into a wooden box that housed three half-inch plates of iron covered in 4 inches of foam to capture the material and prevent ricochet. The projectile travels very short distances, which eliminates the risk of missing the target, and impact a strong barrier that will stop its movement. This will mitigate the danger from a high speed projectile.

In accordance with the Rick Management Office, a number of safety features were added to the rail gun. All exposed electrical junctions were covered with boxes to prevent accidental contact with technicians. The capacitor banks were covered with a sheet of ¾ inch plywood to limit debris from potential, catastrophic capacitor failure.

2. EMP

An electromagnetic pulse, or EMP for short, is a discharge of energy that propagates through earth's magnetic field after a huge release of energy. This shock wave of energy radiates outwardly from the source much the way waves radiate when a stone is thrown into a calm lake. If an EMP wave front interacts with a conducting media currents are induced as free electrons are pushed by electromagnetic forces. Any sensitive equipment in the area subjected to these interactions can be damaged or destroyed. The extent of that damage depends on its proximity to the source of the discharge because amplitudes of electromagnetic waves degrease as the surface area modeling the sphere increases at some rate. Using equations from Attay Kovetz's Electromagnetic Theory[6ALL] and a few simplifying sources that estimated our power output to be a sin wave we derived an equation for power radiated from the rail gun by

$$P = \frac{4(\omega l_r I_0)^2}{12\pi^3 \mu c^3} \tag{12}$$

Table 2. A list Estimated Energy for Degradation of electrical components. The point contact diodes are most easily damaged and therefore used as baseline.

Device type	Energy (μJ)
Point-contact diodes 1N82A–1N69A	0.7–12^a
Integrated circuits μA709	10^a
Low-power transistors 2N930–2N1116A	20–1000^a
High-power transistors 2N1039 (Ge)	1000^a
Switching diodes 1N914–1N933J	70–100^a
Zener diodes 1N702A	1000^a
Rectifiers 1N537	500^a
Relays^b (welded contacts)	2–100 × 10^3
Resistors (0.25 W carbon)	10^4

^{a} Energy required to damage semiconductors having a 1-μs square pulse.
^{b} DNA *EMP Awareness Course Notes.*

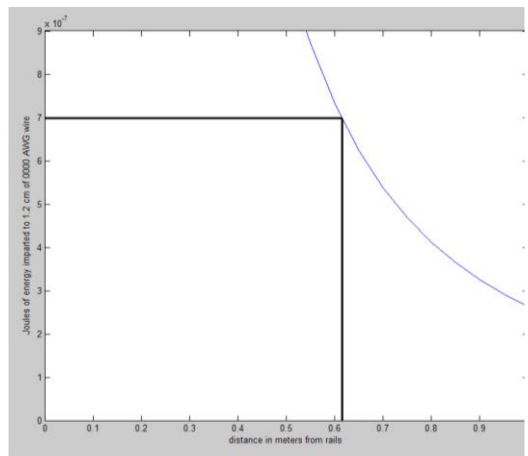


Figure 10. energy absorbed by electrical components at a distance perpendicular to the bore.

Knowing that the wave energy will disperse intensity as a square of its distance, we were able to find energy absorbed by a component at as a function of its distance from the EMRG and its wire size. Giving ourselves a margin of 2 times the expected peak amperage and an absorbing wire surface area of a 0000 AWG wire we arrived at the energy absorbed by electronics as seen in figure 12. Table 2, taken form Ricketts, shows that we should not expect component degradation of any kind unless electronics see a minimum of .7 micro Joules of energy. Our estimates show that we should not expect to see this until electronics get closer than .65 meters from the barrel. As an extra measure of precaution we advise that no electronics are placed less than 1.5 meters from the rail gun.

Using Ricketts table of degradation, it was seen that point-contact diodes were the most sensitive equipment and were therefore chosen as the dangerous energy absorption level for our EMRG.[7ALL]

VI. Conclusion

A. Review and actual conclusion to the work we have done

It was found that with our current configuration the EMRG could fire up to 650 m/s and potentially even more had it been charged to 450 Volts instead of 420V. While this is an exceptionally fast speed, it is not fast enough for orbital debris testing. However; the prototype that was designed, built, and tested served its purpose exactly as intended. It successfully tested all of the EMRG theories that are expected to use in the large scale test. A critical part of the prototype success was in the pulse forming network and the voltage drop before and after the test. By examining the scorching in the rails, it was determined that the inductors succeeded in forming the pulse, which was also confirmed by the voltage drop from 420 to 30 volts across the test.

While there were many testing issue the fundamentals of the design held perfectly and the prototype perfectly positions Cal Poly to create a larger EMRG capable of orbital speeds.

References

Note these references need to be redone to AIAA format.

[1AL] & [1SGZ] –‘ Design and Construction of an expandable series trans-augmented railgun” by Michael R Lockwood, NPS, July 1999

2AL – “Design and Construction of a one meter Electromagnetic Railgun” by Fred Charels Beach, NPS, July 1996

1ALL-http://www.k7mem.150m.com/Electronic_Notebook/inductors/coildsgn.html#Design_Cons

2ALL- http://info.ee.surrey.ac.uk/Workshop/advice/coils/power_loss.html#q

3ALL-http://info.ee.surrey.ac.uk/Workshop/advice/coils/air_coils.html

4ALL- http://www.vishay.com/docs/49782/49782.pdf

6ALL-Kovetz, A. Electromagnetic Theory, Oxford Press. New York, 2000. Chap. 12.

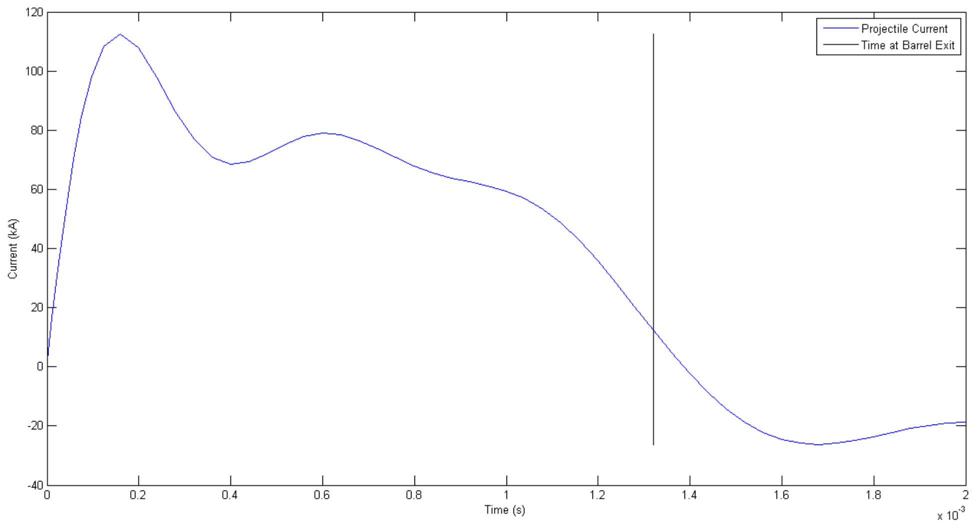
7ALL-Rickets, L. et, all. EMP Radiation and Protective Techniques, Winely-Interscience, 1976. Chap. 3. [1JO] Feliciano, Allan S., “The Design and Optimization of a Power Supply for a One-Meter Electromagnetic Railgun”, Naval Postgraduate School, Monterey, CA, Dec. 2001

[2JC] Ness, Richard M., “Ness Engineering/Technical Data/Pulse Forming Network (PFN) Formulas,” Ness Engineering Inc., URL: http://www.nessengr.com/techdata/pfn/pfn.html#Rayleigh [cited: 8 December 2010

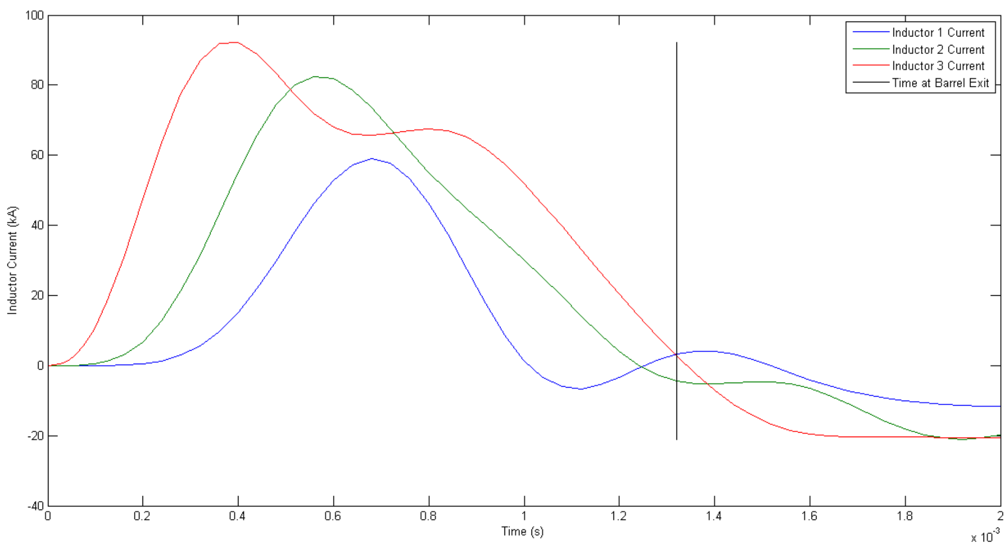
[1GL] Kerrisk, J.F, “Current Distribution and Inductance Calculations for Rail-Gun Conductors”, LA-9092MS, Los Alamos National Laboratory, Los Alamos, NM

[1SGZ]

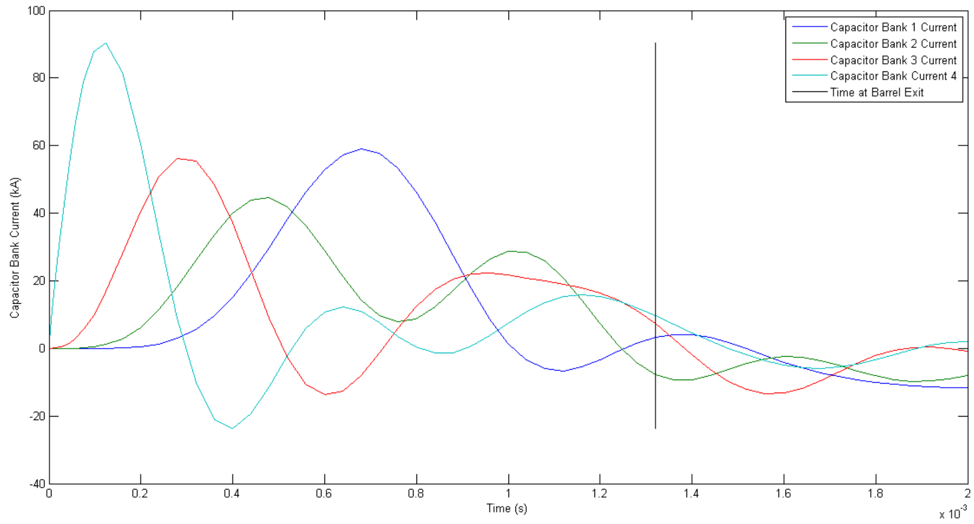
Appendix 1: Capacitor Output Parameters



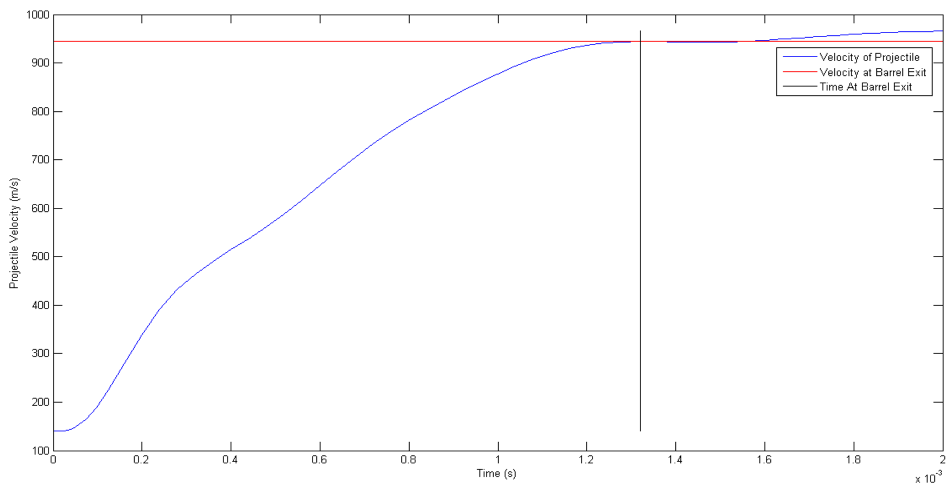
Projectile Current over Time



Inductor Currents over Time



Capacitor Bank Currents over Time



Velocity of Projectile over Time

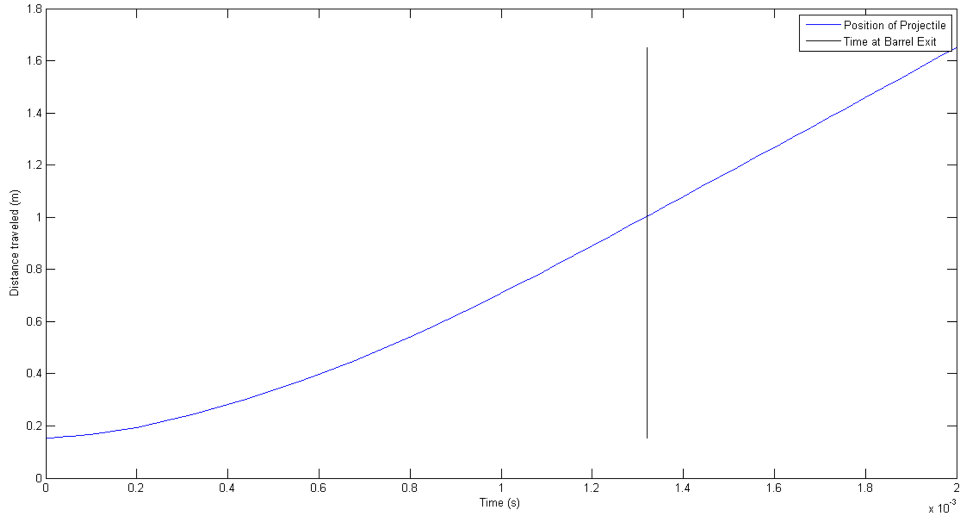


Figure 11 Position of Projectile over Time

Firing Procedures

Prep

Target set up

1. Bolt target lead onto frame at the appropriate length from the muzzle of the EMRG and

Gun set up

1. Check to see that there are no obstructions down the rails.
2. Torque on all bolts along rail to be 10 **foot-pounds**, start from the air-injector end and work from top to bottom back to front in a zig zag pattern.
3. Ensure bleed resistors are functioning properly and are connected to the rails
4. Place full nitrogen injector tank into cradle and latch down with chain.
5. Remove injector and tank caps
6. Assemble injector fittings and tubes
7. Align Barrel with target
8. Engage braking mechanisms on wheels
9. Bolt gun down
10. Cordon off area with the red ‘danger’ tape

Data acquisition set up

1. Set the HSC shield box (HSCSB) in view of barrel profile.
    - i. **The camera must be AT LEAST 1.5 meters from the rails.**
    - ii. Plug power and Ethernet cables through hole in the back of the High Speed Camera Shield and place

b. Projectile loading

i. Insert projectile into bore, from the exit side, such that the front is pointing down range
ii. Using the ramrod, gently push the projectile until its back end reaches the injector plate.
iii. **Remove ramrod**

c. Piping pressurization.
    i. Slowly open the pressure valve until the pressure gauge reads the desired pressure.
    ii. **Caution: a choking hazard now exists due to possible high concentrations of nitrogen in the area around EMRG**
d. Clear area of personnel
    i. All personnel must now clear to the Rail assembly area.
    ii. Remove the safety bypass of the relay to allow charging. And bring it into room
e. Capacitor charging
    i. Ensure Resistor bank is in the 'Off' position
    ii. Ensure that the switch box is properly plugged in
        1. Plug fluke meter into rails at appropriate terminals and set to voltage measurement
        2. Connect power supply cables to exposed screw leads
        3. Cover with blue safety box
        4. Plug Relay into Rail system
        5. Plug wall power cord to wall power outlet
        6. Connect green power supply to capacitor bank cable
    iii. Plug the charger into the wall
    iv. Turn on the power supply with the switch located on the supply
    v. Flip both power supply switches. The capacitors should now be charging.
    vi. **CAUTION: BE SURE TO STOP THE POWER SUPPLY AT 450 VOLTS**
    vii. Switch power supply on the control box to the off position
    viii. Unplug power supply from the wall
    ix. Unplug the power supply from the wall

The EMRG is now EXTREMELY HAZARDOUS. Care should be taken not to enter the area of the EMRG until after capacitor banks are discharged. SERIOUS INJURY OR DEATH CAN OCCUR IF THIS IS NOT FOLLOWED

Pre-firing procedures

1. Visually check to be sure ram rod is removed from barrel.
    i. If the rod is still in the barrel, discharge the capacitors into the bleed resistors, enter the EMRG area and remove the Ram Rod
    ii. Return capacitors to charging position and resume Pre-firing procedures.

2. Begin Collecting data
   i. High speed Camera testing
      1. Open Phantom Camera Control
      2. Plug extension cord powering lights and high speed camera into wall.
      3. When the camera is accessible by the computer open the camera pool window and check that the camera is accessable
      4. Close camera pool
      5. Acquisition>Set up and recording…
      6. In upper left hand corner camera read out should specify camera
      7. Set resolution to 650 x 480
      8. Set sample rate to 9402 pps
      9. Set Exposure to 100 micro seconds
      10. Make sure auto exposure is on
      11. Select 'capture' to arm the camera system
      12. Await fire command. The system will continuously record until the trigger is clicked. At these settings the camera will record 1.8 seconds of data. The goal of the camera operator is to hit the trigger button after the projectile has hit the target but before the event is over written.

Firing

1. Flip down both power supply switches on control box
2. Turn off power supply
3. Unplug power supply
4. Disconnect power supply leads
5. Flip firing switch
6. Begin countdown form 5
7. At 2, flip data acquisition divider box on
8. At 1, run data acquisition in Lab view
9. On fire depress both firing buttons to discharge EMRG.
10. Immediately after firing switch the resistor bank to ON and turn off firing switch
11. Allow for 4 minutes for capacitors to fully discharge
12. Verify discharge with potentiometer before approaching.

Post firing

Safety check

Do not approach the system until after the system voltage drops below 5V!

AFTER CHECKING THE VOLTAGE across the rails, the EMRG is safe to approach.

End data collection