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An Electromagnetic Railgun Design and Realization for an Electrical Engineering Capstone Project

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An Electromagnetic Railgun Design and Realization for an Electrical Engineering Capstone Project

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Abstract: This work reports on how a team of four undergraduate students at the United States Air Force Academy designed, built, and tested a desk-top railgun for a year-long senior design project. The objective of the design was to safely launch a small projectile at a muzzle velocity of 350 meters/second from an approximately 1-meter long barrel using capacitor-based energy storage limited to a maximum of 450 VDC. The projectile needed to be fired into a catch to facilitate demonstrations inside a laboratory environment. The project was also constrained by a $5,000 operating budget and access to parts available in the laboratory. The three electrical engineering students and one systems engineering student self-selected the project and decided how to divide tasks, structured and managed a schedule, planned budget use, and leveraged in-house machine shop capabilities. The paper describes how the cadets decomposed the project into a set of subsystems including: (1) the rail system and supporting barrel, (2) the armature or projectile, (3) an injection system to provide the projectile with an initial velocity along the rails, (4) a mechanical catch system to facilitate safe and convenient firing, (5) an electrical energy storage system, (6) a high-voltage circuit for charging the storage system, (7) a pulse-forming network (PFN) that interfaces the storage system to the rails, (8) timing electronics needed to actuate the PFN, (9) a measurement system to monitor muzzle velocity, rail current, capacitor voltage, and rail temperatures, and (10) safety elements and protocol to minimize the probability of shock, misfire, or accident. The paper then describes how the project evolved from a System Requirements Review to the Preliminary, Critical, and Final Design Reviews. This senior design project was especially notable for three factors: (a) the emphasis on an early implementation which facilitated multiple passes along the design spiral, (b) the close synergy between the evolution of the hardware and the simulation models, and (c) the inter-disciplinary nature of the design which provided opportunities for electrical engineers to consider items such as material properties, forces on the barrel, temperature effects, aerodynamic drag, rail ablation, and velocity measurements. In the process of the design, students were able to leverage their circuit analysis skills and build on their simulation experience in both Multisim and Simulink. The paper concludes with a section on lessons learned and recommendations on strategies for mentoring such a project.

Keywords

Electromagnetic Railgun, Lorentz Force; Electromagnetic Launch

I. Introduction

If you want to quickly attract the attention of the university's safety officer, propose a senior capstone design project to build a desktop Electro-Magnetic Launch (EML) gun, better known as a railgun. But as anxious as it makes administrators and lawyers, any project geared toward launching a projectile by harnessing high currents captures the imagination and excitement of the typical undergraduate engineering student familiar with movies that feature a railgun, like *Eraser* or *Transformers 2*. The following describes how a team of four engineering students moved such a project from concept to specification, critical design, prototype, and a final product.

The concept of a railgun dates back to Fauchon-Villeplee's patent of the electric canon filed in 1919. The basis for the technology is the Lorentz Force which characterizes the interaction of a current and a magnetic field. A basic railgun as shown in Figure 1 consists of two highly conductive rails, a highly conductive armature that contacts each rail and is free to slide, and an energy source capable of delivering
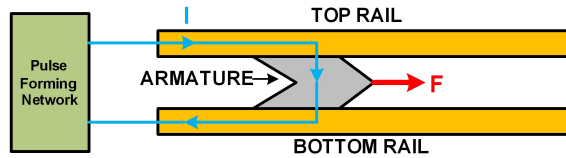
Figure 1: Illustration of Railgun Concept

high currents through the rails and armature. Practical railguns may then include a barrel, current-shaping circuitry, an injection system, muzzle shunts, monitoring equipment, bullet catch, and a slew of safety protocols.

Motivated by the re-emergence of the all-electric ship concept where all installed mechanical power is first converted to electric power, the U.S. Navy has invested heavily in EML-gun technology as an alternative to conventional ordinance that uses explosives. Since a railgun with a designed muzzle energy of 63 MJ can achieve launch velocities of 2.5 km/sec with a projectile range on the order of 200 nautical miles, this weapon destroys its target with kinetic energy, far exceeding the range of current 5-inch guns, while avoiding the logistic hazard of transporting explosive shells. This capstone senior design project seeks to scale back this lethality and focus on engineering a reduced-scale, desktop-size launcher that demonstrates proof-of-concept while providing a reliable platform for follow-on research.

II. System Specifications

The project was constrained by a budget of $5,000 plus any equipment already available in the laboratory and by an over-arching emphasis on safety. This necessarily forced the students to identify the key physical relationships between the subsystems early in the design process so they could complete a back-of-the-envelope design and determine what specifically drove cost. From this exercise coupled with research into desktop EML-guns described in the literature emerged the following specifications:

- Peak muzzle velocity of 350 m/s

- Capacitor-based energy storage that did not require a costly power source

Other attributes that the team viewed as important are:

- Footprint representative of desk-top of 4' by 2.5'

- Set-up time of < 20 minutes (including energy storage charging)

- Remote firing capability to enhance safety

- Bullet trap that could contain rounds from an M4 assault rifle to provide considerable margin

- Means of safely aborting a shot and discharging the energy storage

- Means for avoiding spot welding the armature to the rails

The above were the primary specifications the design team developed at the onset of the project. However, deliverables were fundamentally constrained by the end of the academic year in early May and with all members of the design team scheduled to graduate.

III. Railgun Subsystems

Subsystem	Key Design Metrics
Rails and Armature	Conductivity, melting tempeature, mass density, cost, ease of machining, feasibility
Energy Storage System	Cost, size, feasibility, ease of charging/discharging straightforward monitoring
Pulse-Forming Network	Cost, risk, complexity
Armature Injection System	Cost, performance
Measurement of Speed and Current	Cost, performance, feasibility
Safety protocol	Simplicity, redundancy, design margins, ruggedness, human exposure

Table 1: Function Decomposition of Railgun System

The design broke down functionally into the subsystems listed in Table 1. The team identified the critical figures of merit with cost and feasibility being the dominant factors in a 1-year student project.

IV. Electromagnetic Railgun Basics

With respect to analyzing the railgun system, the team wanted to 1) avoid re-inventing the wheel, 2) stay away from using overly detailed models to explore the preliminary design space, and 3) exploit computer simulation where possible to validate, perform tradeoffs, and introduce more detail. Figure 2 shows a basic railgun topology, while Table 2 defines the abbreviations used in the schematic.
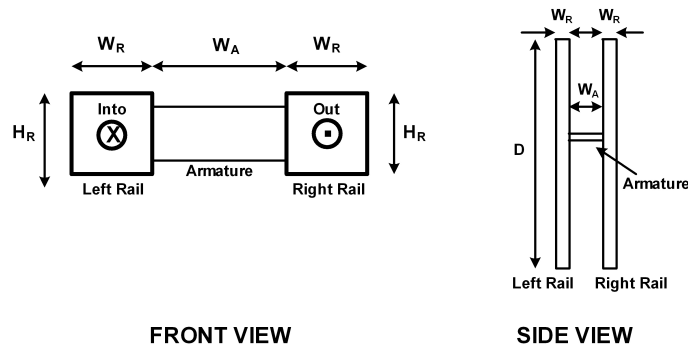

Figure 2: Illustration of Railgun Concept

Abbreviation	Railgun Aspect
W_R	Width of rectangular rails (meters)
H_R	Height of rails (meters)
D	Length of rails (meters)
W_A	Distance separating rails (meters)

Table 2: Railgun Abbreviations

Note, one rail carries current into the page and the other carries out of the page, with an armature fitted in between passing the current from one rail to the other. The team needed to characterize the flux density field that exists along the armature and then compute the average force on the armature. First, it was assumed the rails are much longer than they are wide and the center of the current distribution was at the

center of the rail. If we apply the Biot-Savart Law, the flux density, B, created by a semi-infinite wire carrying current I is:

$$\vec{B} = \frac{\mu_o}{4\pi}\frac{I}{r} \tag{1}$$

The constant, μ_o, is the permeability of free space, and equals $4\pi \times 10^{-7}$ H/m, r is the distance from the center of the rails, and I is the current in the rails. The magnetic field contribution at a point, x, between the two rails, with the center of the rails serving as the $x = 0$ point, is given by

$$\vec{B} = \frac{\mu_o I}{4\pi}\left[\left(\frac{1}{\frac{W_R+W_A}{2}+x}\right)+\left(\frac{1}{\frac{W_R+W_A}{2}-x}\right)\right] \tag{2}$$

The force on the armature can then be found by integrating the differential form of the Lorentz Force Equation along the armature to give

$$F = \frac{\mu_o I^2}{4\pi}\ln\left[\frac{2W_A+W_R}{W_R}\right] \tag{3}$$

Typically in railgun literature, the force expression is rewritten as:

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

The parameter, L', is called the inductance gradient whose value is fixed once the geometry of the system is selected and can be measured by a simple inductance test.

$$L' = \frac{\mu_o}{\pi}\ln\left[\frac{2W_A+W_R}{W_R}\right] = 4\times 10^{-7}\ln\left[\frac{2W_A+W_R}{W_R}\right] \tag{5}$$

As a first cut, if we ignore the uncertain viscous friction between the rails and armature and any aerodynamic drag, the motion of the armature with mass m in terms of the distance along the rails in the y direction is governed by

$$F = \frac{1}{2}L'I^2 = m\frac{d^2y}{dt^2} \tag{6}$$

Equation 6 can be solved for acceleration and, assuming a constant current, integrated to find the velocity:

$$\frac{dy}{dt} = \frac{L'I^2}{2m}\times t \tag{7}$$

The velocity can be integrated to get position and then the expression for position set equal to the length of the rails, D, to solve for the time that the armature is in the barrel, t_b.

$$t_b = \sqrt{\frac{4\times m\times D}{L'\times I^2}} \tag{8}$$

This time can then be substituted back into Equation 7 to find the railgun exit or muzzle velocity, one of the key system design specifications.

$$\frac{dy_{muzz}}{dt} = \sqrt{\frac{L'D}{m}}\times I \tag{9}$$

The kinetic energy at the muzzle is then computed as

4

$$KE_{muzz} = \frac{1}{2}m\left(\frac{dy_{muzz}}{dt}\right)^2 = \frac{1}{2}L'I^2D \qquad (10)$$

Finally, this kinetic energy had to be related back to the required stored electrical energy. Here, the team decided to use an estimated efficiency of 1% as reported for desk-top railguns found in the literature. Full-scale railguns demonstrate efficiencies on the order of 40%. If a capacitor-based energy storage system is assumed with capacitance C and voltage V, it follows that the potential energy is

$$PE = 100KE = 100\left(\frac{1}{2}L'I^2D\right) = \frac{1}{2}CV^2 \qquad (11)$$

Solving Equation 11 for capacitance yields

$$C = \frac{100L'I^2}{V^2} \qquad (12)$$

This result in Equation 12 establishes a relationship for the total amount of required capacitance, a key cost driver, in terms of the inductance gradient, rail current, and stored voltage.

In order to initiate the design, the team made the following preliminary assumptions:

1. The injection system would supply 100 m/s of the desired 350m /s of muzzle exit velocity.

2. The barrel length would be 1 m, with half of that length reserved for building up velocity by the injection system.

3. The preliminary rail layout leads to an inductance gradient on the order of $L' = 300\,nH/m$.

4. Rail layout assumptions plus an initial choice of an aluminum armature results in a projectile mass on the order of 8 g.

5. Capacitor storage voltage of 400 V.

These assumptions lead to a back-of-the-envelope calculation of a rail current on the order of 58 kA, a time in the barrel of around 4 ms, a required stored energy of about 25k J, and 0.3 F of total storage capacitance. The capacitance was found to be the key driver of cost and significantly influenced the team's ability to reach full scale.

V. Design Tradeoffs and Selection

For each subsystem, the team analyzed various alternative courses of action. In many instances, the team used a decision matrix to help guide the best avenue. Prior to starting the subsystem tradeoffs, the team needed to decide between a high-voltage, low-capacitance design and the low-voltage, high-capacitance design. To make the best decision for the project several factors were taken into account. First the power density for the high voltage design was much greater than the low voltage design. However, the low-voltage design was safer overall. One of the biggest factors was the charge time. The high-voltage system charges much faster than the low-voltage design. A decision matrix, seen in Table 3, was made to pick the best system-level design for the railgun. Priority was placed on cost, charge time, and power density as the railgun had to meet budget constraints yet remain feasible enough to charge within a short amount of time for a demonstration.

Based on the results shown in Table 3, the team opted for the high-voltage system. All subsystem decisions are based on this result. The availability of a 500 VDC power supply readily available in our laboratory led to a 400-volt storage voltage, which helped minimize further expense.

	Cost	Power Density	Charge Time	Specialized Charger	Size	Total
Measure Weight	0.5	0.2	0.2	0.05	0.05	1.0
High Voltage	$ 4,636	$1 \times 10^5\ W/kg$	0.125 hr	Yes	0.3113 m^3	0.72
	0.27	0.20	0.20	0	0.05	0.72
Low Voltage	$3,000	$1 \times 10^3\ W/kg$	4 hr	No	0.05 m^3	0.588
	0.5	0.002	0.006	0.05	0.03	0.588

Table 3: Electrical System Decision Matrix

Options for energy storage in a pulse-forming network (PFN) include capacitors, inductors, a rotating mass, or batteries. Batteries are quickly eliminated because of the high current levels under consideration and the associated volume of required batteries. For the remaining capacitor-inductor-rotating machine alternatives, the theoretical energy density of these methods is commonly estimated as 1:10:100, indicating the attractiveness of inertial storage. However, the complexity, cost, and safety-concerns of inertial-based systems (e.g., compulsators) rules them out for a low-cost, desk-top, single-shot railgun. Both capacitor-based and inductive-based storage systems can be made modular. Although the inductive system has a short charging time, the requirement for a high-current opening switch that diverts the current through the rails imposes both high cost and greater complexity. Therefore, the team selected a capacitor-based design.

A. Rails and Armature Material

In addition to cost and ease of machining, the key physical characteristics for candidate materials for both the rails and armature are listed in Table 4. Though Tungsten and Tantalum are considered for practical gun rails and armature due to their superior temperature characteristics, the cost and uncertainty of working with these materials ruled them out. The superior conductivity properties of copper made it an attractive choice for the rails while the lower mass density of aluminum drove the selection for the armature. Both copper and aluminum are commonly worked with in the university's machine shop, thus reducing technical risk.

Material	Melting Temp, T_M (ºC)	Density, ρ (kg/m^3)	Conductivity, σ (Ω−m)$^{-1}$	Specific Heat, C (J/kg−ºC)
Copper	1084	8960	5.8×10^7	385
Aluminum	660	2720	3.82×10^7	900
Tungsten	3410	19,250	1.79×10^7	134
Tantalum	2996	16,600	7.7×10^6	150.62

Table 4: Key Properties for Rail and Armature Candidate Materials

B. Injection System

The injection system provides the initial velocity to the armature and prevents it from being spot welded upon firing the Pulse-Forming Network (PFN). Based on related railgun designs, it was decided that the injection system should contribute 100 m/s of muzzle velocity in addition to the 250 m/s provided from the electromagnetic system. These values provide for a high enough velocity value to study rail ablation while not approaching values that pose increased safety concerns. Design alternatives for the injection system included pneumatic, spring-actuated, or explosive propulsion. The pneumatic solution was chosen for its ease of manufacture, low cost, and high velocities. Common components such as an

automatic sprinkler valve, high pressure valve stem, and PVC pipe and fittings could be used to realize the specifications. A custom interface between the circular PVC and rectangular barrel could be readilty fabricated in the university's machine shop.

C. Pulse-Forming Network (PFN)

The job of the PFN is to synthesize a pulse of current of required duration from the stored electrical energy. Two common modular topologies based on capacitor storage were considered for this project as shown in Figure 3.
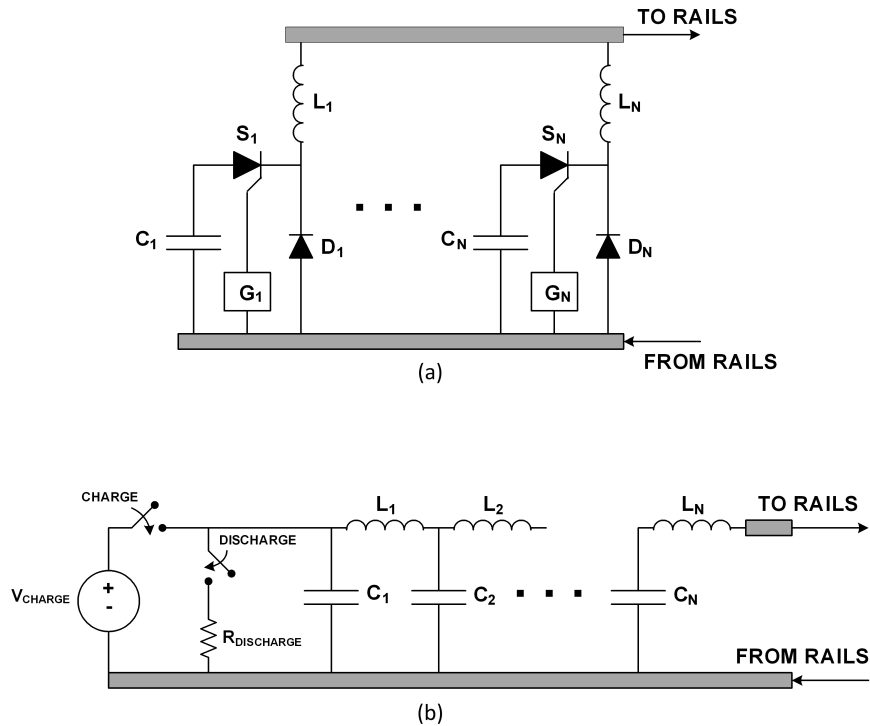

Figure 3: PFN Options: a) Closing-Switch Design; b) Rayleigh Network Design

Each module of the circuit in Figure 3a consists of a capacitor, current shaping inductor, closing switch, and a crowbar diode. The circuit operates by turning on the switch, discharging the capacitor voltage, building up the inductor current, and then after the capacitor has discharged having the inductor current continue to flow through the crowbar diode. Subsequent modules are gated *on* to keep the aggregate current supplied to the rails as constant as possible. In contrast, the Rayleigh network shown in Figure 3b consists of a ladder of LC-stages. The team designed and simulated each in Multisim, but decided on the Rayleigh network because it did not require the expensive closing switches and their associated gating circuitry and pressure clamps. The idea with the Rayleigh network is that the armature contacting the rails will serve as the closing switch which will initiate discharging the network.

D. Barrel Material

The barrel must house the rails, interface electrically with the PFN, and interface mechanically with the injection system. It is important that the barrel be simple to manufacture, requiring no tools or material unfamiliar to a university machine shop. The key metric was all materials had to withstand a full-power shot and not shatter or melt. Grooved or channeled rails were ruled out for difficulty of manufacturing and marginal improvement of armature-rail contact. The proposed barrel design is shown in Figure 4, where the copper rails are the colored rectangular sections at the top and bottom with the air gap in the center.
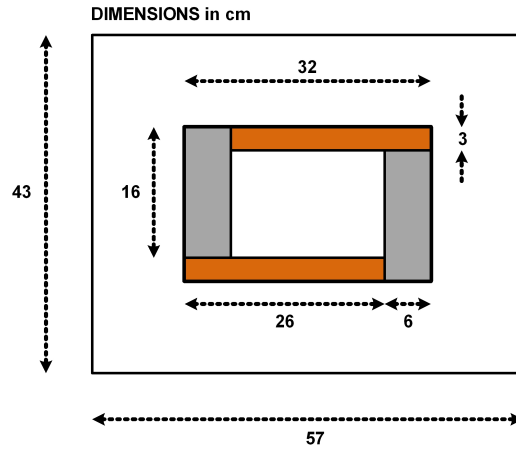
Figure 4: Barrel and Rail Design

G10-FR4 fiberglass-epoxy laminate (Garolite) is chosen for the outside barrel material due to its extremely high strength and high dimensional stability over temperature (tensile strength = 45 kpsi; flexural strength = 70 kpsi). The team decided on using multiple M8 bolts to hold together the barrel as each bolt has a breaking point of 2150lbs. The barrel must withstand the worst case forces produced by the injection system and the rail current.

E. Safety

Safety was given the highest priority in the design and execution of this project. There were two primary areas for safety measures. The first involved the significant electrical energies involved in this system. We will have capacitors on the order of 10 mF charged to 400 volts. Ideally, this energy will be transferred from the capacitors to the projectile. However, we could have situations where we have charged the capacitors but are not able to fire the system. Thus, an effective way to discharge the capacitors is needed. We opted for a simple RC circuit with a bank of high-power resistors.

The second area which requires significant safety measures is the actual firing of the projectile. The design requires an 8-gram projectile reach velocities higher than the speed of sound. We investigated different types of bullet-catches which we would place at the end of the barrel to catch the projectile. However, this caused a few issues. First, it was difficult to design the geometry such that the catch and the measurement system could happily coexist without causing issues to the overall system. Additionally, we were worried about properly aligning the catch with the barrel. Because of this, any high-power test shots would be conducted at the gun range located near the university.

F. Measurement

A critical part of validating the design is to measure and confirm the rail current. This then enables verification of the simulation model and provides confidence in using the model to predict future performance. There are two typical strategies for measuring very-high current pulses of short duration: a current-transformer Pearson Probe or a Rogowski Coil. The Rogowski coil was selected because of the convenient clip-around coil makes it less intrusive to the test setup, it is intrinsically safe since there are no dangers of open circuit secondaries, they have excellent linearity since there are no magnetic materials to saturate, and they can accept large overload currents without damage. A preliminary review also showed a cost advantage for the Rogowski coil.

The critical performance specification is the exit or muzzle velocity of the railgun. Options for measuring

this are bullet chronograph (optical based) and high-speed camera. The team selected the bullet chronograph because of the huge cost savings. The backup plan was to borrow a high-speed camera from the physics department, especially if muzzle flash caused problems with properly triggering the bullet chronograph optical electronics.

VI. Subsystem Design

A. Rails and Armature

The team needed to assess whether the selected rail and armature materials would melt under the specified current. An equation from the *Melt Wear Control of Metals in High-Speed Sliding Contacts* publication by then Doctoral Candidate Edin E. Balic was referenced in order to derive Equation 13, which calculates the maximum temperature rise at the exit of a metal coming in contact with another metal.

$$T = 2qdk\pi P_e\alpha + T_O \tag{13}$$

where d is the half-length of the armature contact path, q is the power per area, k is the thermal conductivity, P_e is the Perclet number, and α is the thermal diffusivity of the rail material. This equation was applied to the armature in order to test if the armature would melt. Due to the very short amount of time the armature would be in contact with the rail, and the short duration of the current, the armature was found to only reach about 78° C, far below the 660° C melting point of aluminum.

B. Injection System

The injector system needs to supply an initial velocity to the projectile in order to prevent the occurrence of spot-welding. We opted for a pressurized system that could be actuated with a simple electric solenoid valve commonly used in sprinkler systems. The completed subsystem is shown below in Figure 5.
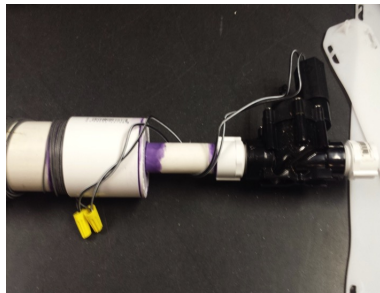

Figure 5: Injector Subsystem

A hole was drilled in a 3"-endcap to slightly smaller than the diameter of the 802 HP valve stem. The stem was fit into place in the whole and sealed with expanding polyurethane glue. The end cap was primed and glued into place on a 3' section of the 3" pipe using standard PVC welding glue. A 3.75" reducing bushing and a 0.75" male-to-female threaded adapter were glued into place on the other end of the pressure vessel. Teflon tape was used to treat the threads of the adapter and then the solenoid was screwed into place. The barrel adapter was then screwed into place on the opposite side of the valve. This completed the construction of the injector. The total cost of the injector system was $36.80; however, this cost does not include the labor provided by the university's machine shop.

C. Pulse-Forming Network

The underlying theory for a pulse-forming network in an electromagnetic railgun was discussed in a previous section. Assuming a constant force and duration, we determined the approximate square current pulse required to achieve the desired velocities. Assuming contact with the rails to be 1 ms and an 8-g projectile, a force of 27.44 N is required to accelerate the projectile to 343 m/s, which is the speed of sound. This results in a 1-ms current pulse with a magnitude of 13.4 kA. Working backwards from the desired current pulse, a PFN was designed. A five subsection PFN was chosen as a tradeoff between the added complexity of more subsections and the ability for a PFN with more subsections to sustain a longer pulse. Figure 6 below shows the circuit diagram for a simple, five subsection Rayleigh line PFN. The component values were determined to be 0.333 μH for the inductors. Ideally, we would have 50 mF capacitors for the capacitors, which we will create with five 10-mF capacitors wired in parallel. However, we were ultimately limited to buying 8.2 mF capacitors, which resulted in a slightly lower capacitance. The PFN, as shown in Figure 3b, was simulated in Multisim, with the results shown in Figure 6. The
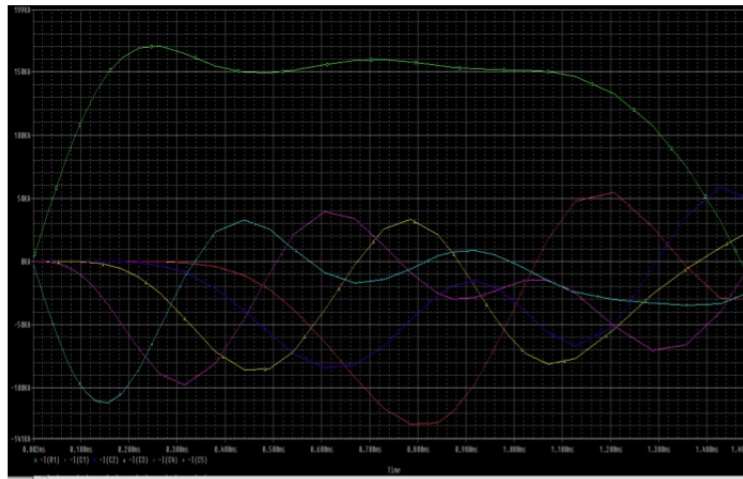

Figure 6: PFN Simulation Results

simulation results for the PFN showed that the average rise time for the PFN was 149 microseconds with an average pulse current of 150 kA. The pulses had an average duration of 1.12 milliseconds. All of these parameters were within our desired values. Obviously the current value is an order of magnitude higher than what we designed for (13.4 kA). We have made some efficiency assumptions as part of our calculations. Ideally we would have time for more theoretical analyses. However, due to time constraints, the team has decided to implement a spiral development, which will build a lower current gun first. The first iteration will be tested, from which we will be able to refine our simulation results.

D. Barrel and Armature

The barrel and armature subsystem is the fundamental interface between the electrical energy and the kinetic energy. The barrel interfaces with the injector subsystem, the PFN, and transfers all energy into the armature. We wanted the barrel to withstand numerous full-power test shots, as many electromagnetic railgun barrels fail after only one shot. The barrel length and system also needed to be small enough to be portable due to the fact the high-voltage testing would be conducted outside of the laboratory. Figure 7 shows the initial design.

The rails of the barrel will exert a significant force on each other due to the opposing currents traveling through them. Thus, it was possible the barrel could rip itself apart if not constructed properly. Therefore,
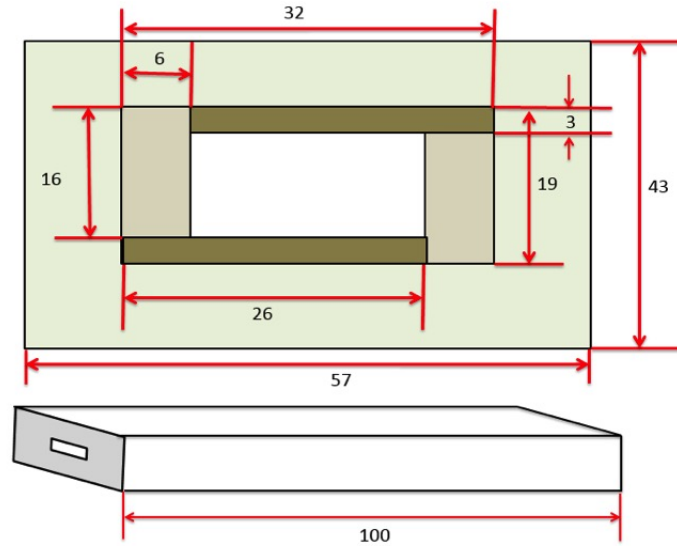
Figure 7: Barrel Design

we needed to calculate the force on the barrels.

$$Barrel\ Force = 31 + (4\pi)(1 \times 10^{-7}) \left(\frac{150,000}{16\pi}\right)^2 \left(\frac{1}{0.13}\right)^2 = 4,357\ lbs \tag{14}$$

We will use 14 bolts to hold the rails in place. Thus, we will need

$$lbs/bolt = \frac{4,357}{14} = 311\ lbs/bolt \tag{15}$$

The breaking point of M8 bolts is 2,150 pounds. Therefore, we believe the rails should withstand the force due to the currents. Figure 8 shows the completed barrel system with three projectiles.
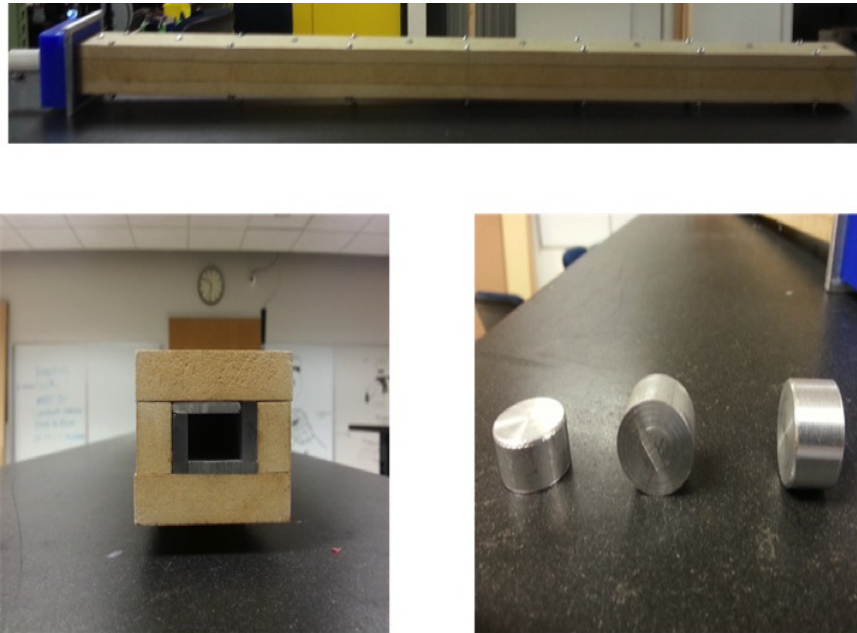

Figure 8: Barrel

E. Safety

A bank of 3-kΩ and 30 Watt power-dissipating resistors is used to discharge the energy storage system, both in the event of a no-fire, and also to ensure all residual energy is discharged from the system. The discharge circuit was simulated in Multisim. A fully charged capacitor bank will discharge in 460
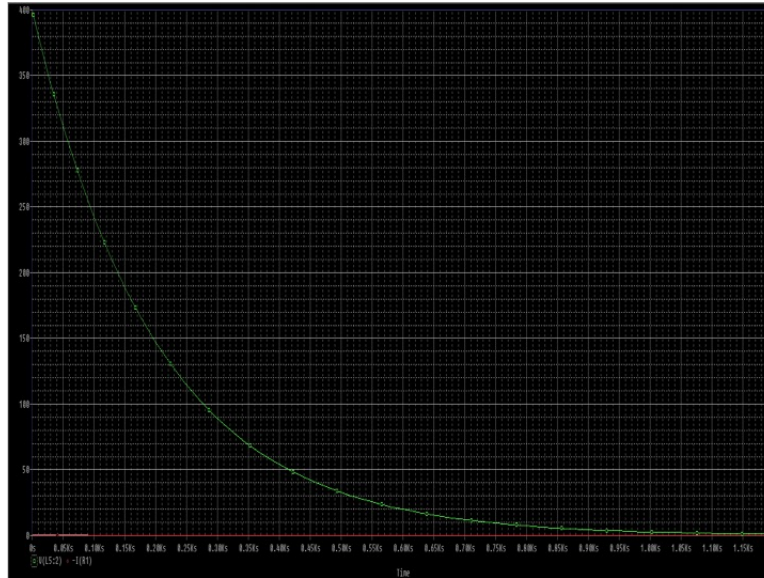

Figure 9: Discharge Safety Circuit

seconds. The peak discharge current was 500 mA with a peak discharge wattage of 200 W.

VIII. Subsystem Testing Results

A. Injector Testing

The pressure vessel was placed in an empty room with all entry points guarded against accidental entry into the test area. The vessel was charged and then discharged through the solenoid in 20 PSI increments starting at 10 PSI and ending at 110 PSI. The test was considered a success as there were no visible weakening of any valves or joints and no catastrophic destruction of the pressure vessel, valve stem, or solenoid diaphragm. In between test points, the integrity of the pressure vessel was carefully observed. At the end of the five high pressure tests, the vessel was charged to 10 PSI and the joints were coated with a soap and water mixture to test for leaks. The test was conducted and considered successful.

B. Pulse-Forming-Network Testing

The PFN was first designed and built on reduced-scale to examine the output current and any internal ringing within the LC-sections. The inductors are constructed as air-core inductors using thick wire gauge. The initial electrical system testing consisted of charging then discharging the Rayleigh circuit capacitors through power resistors at 20V , 150 V, and 400 V to assess heat dissipation issues and to note potential ringing problems in the PFN. As of this writing, testing is on-going. The low-voltage capacitors have been charged to 50 V, and successfully discharged through the armature. No issues were found.

C. Measurement System Testing

The Rogowski coil was first used with a low-power PFN to demonstrate its ability to capture short pulse duration currents. The bullet chronograph will be assessed during integrated system testing. Specifically, the team will establish the ability for the bullet chronograph to function if any muzzle flash in present.

IX. System Integration

System integration occurred in the following order, after subsystem testing was completed. The injection system was merged to the rail/barrel assembly to facilitate testing those two systems without any PFN involvement. The bullet chronograph measurement system could then be integrated to establish the relationship between pressure setting and muzzle velocity. Next as the planned injection system pressure is increased, the bullet catch is put into place to confirm the integrity of the interface and structural integrity of the catch. With preliminary validation of the injection system, barrel, bullet chronograph, and projectile catch, the team can connect up the PFN subsystem. This subsystem consists of the LC-sections of the Rayleigh network, the high-voltage charging power supply, the high-power dump resistors used to bleed down residual energy, the bus-work connecting the network to the rail system, the Rogowski coil current monitoring unit, and the voltmeters used to monitor residual voltage on the capacitors. Once this system is coupled, testing can commence as described in the next section.

X. System Testing

The team has constructed and is currently testing a low-power PFN prototype that consists of five LC-sections of the Rayleigh PFN network. Time and money permitting, more LC-sections will be added to realize the full-power design. The integrated low-power system will be tested first at low-injection-pressure and low current (low storage voltage), then at higher injection pressures and low rail current, and finally at high injection pressures and high currents (high storage voltage). Specifically for PFN testing, the stored capacitor voltage will be gradually stepped up from an initial value of 50 V up to the maximum voltage of 400 V. For each shot, the team will measure and record muzzle velocity, rail current, and residual capacitor voltage, and examine the barrel for wear and mechanical integrity. By gradually bringing up the rail current and resultant system forces, it is hoped that any unexpected results will minimize unintended subsystem damage and facilitate re-engineering.

XI. Results

The team is currently in system testing and system integration. Due to the unforeseen delay in a student dropping the injector system and breaking a critical valve, system testing has been delayed. We fully expect the students to successfully testfire their system, as all subsystems are working correctly. Results will be presented at the conference in June.

XII. Pedagogical Aspects of the Railgun Capstone Experience

ABET requires the inclusion of a capstone design experience in its engineering accredited programs. Therefore, our university has to include a capstone design project in its curriculum. Therefore, we are not doing anything novel by having a capstone project. However, we have been able to compare the electromagnetic railgun capstone project with the execution of other capstone team's within our department. We believe the railgun experience has been more educational for the students for a variety of reasons to include

- Hands-on nature of the project.

- Ability for design iterations.

- Multidisciplinary aspect (CpE, EE, ME, and Physics).

- Nature of the project enhances curiosity and excitement.

This railgun project also follows a very effective pedagogical sequence. The students start with a first-principle analysis that uncovers basic relationships between key subsystem parameters. This analysis permitted the development of simulation models that facilitated rapid exploration of the design space to both shrink the admissible parameter value range and enable "tweaking" of the final design. The students were then placed outside their normal comfort range by having to address mechanical issues of the project and performing a cost analysis. Engineering students at our institution do not have many opportunities to research part availability on the internet, interact with vendors, and formulate and execute a budget. This capstone provided this real-world experience in the context of a tight schedule. By the start of the second semester of the project, the team had an effective spreadsheet approach to how cost and performance scaled. This wisdom coupled with the experience of presenting and defending their conclusions gives the students the closest practical sense of what it is like to formulate a product proposal, something that many of them will experience throughout their careers.

Early prototyping of subsystems like the barrel and pulse-forming network was critical to risk reduction, exposing construction issues that might have caused serious delays if encountered toward the end of the project. It was also critical as a learning experience to calibrate the student's understanding of how long it actually takes to build, instrument, and test something new. Most students only have carefully designed lab experiments to guide them in formulating a schedule. In most instances, this is woefully inadequate and leads to overly optimistic timelines. Early prototyping exposes this and provides for some hope of correction and motivates additional outside-of-class work. The project mentors have found that "starting earlier" is probably the most common lesson learned by students at the end of a capstone project. "If only I had known that X would take that long" is why many projects don't finish or result in many sleepless nights right at the end of the semester. In the execution of the railgun project, this early prototyping brings this awareness to the fore and enabled better forecasting of schedule slip and creating a remediation plan.

Finally, this project facilitated significant subsystem development without overly complicated system integration challenges. Many capstones fail because subsystem interfaces are not well thought through, primarily because students do not have much experience in this area. As the end of the semester nears, students frequently default to rapid integration, hoping that everything will work the first time. Students typically miss methodically and painstakingly testing subsystems together in order to determine what works together properly and what is causing a problem. Many projects fail because the integration is too complicated and not enough time was allocated. For the railgun, the early development of the pneumatic injection system provided the students with a way to test launching projectiles and taking measurements, giving real confidence that further integration would be successful.

XIII. Conclusions and Lessons Learned

Contrasting the effectiveness of one type of senior design experience over another is difficult because it is contentious what metrics should be used, how to establish proper controls, and how to account for normal variations between students and mentors. Should capstones be one or two semesters? Should they be individual, small team, or large interdisciplinary efforts? What makes sense from a faculty manning perspective, financially, and from the perspective of the students? It's the lead author's opinion that there are no easy answers. It comes down to what priorities a program places on the capstone experience and how well mentors are able to initially scope the project. There is no substitute for mentors having completed a similar project to establish whether it is achievable and provide the best technical guidance to keep the students on a path to success. Most institutions do not provide anywhere near the time or

funding for faculty to de-risk senior design projects so the process defaults somewhat to the varied experiences of each faculty member.

The railgun project fits the priorities of our unique institution. Specifically, it is interdisciplinary, it is two-semester, it adheres to ABET guidance, there is a sponsor, and the execution nicely follows the acquisition process that all of our graduating students will encounter. Now there are other benefits of the project, but the starting point must be the institutional priorities. The authors find that having a project sponsor is a very effective means for motivating students. It raises expectations and no student wants to look bad in front of an outside evaluator. The interdisciplinary component is also important because most engineering systems that our graduates operate, manage, and acquire will be just that. Breaking down stove-pipe thinking like "I only do electrical engineering stuff" is an important goal. A two-semester project gives enough time to engage the entire acquisition process going from initial specification and derived requirements (SSR) to the feasibility assessment of a paper design (PDR) to the detailed design of the various subsystems and interfaces (CDR) to the documentation of the subsystem construction, integration, and final testing (FDR). Each phase of this process has the students presenting their work and defending their design decisions in front of multiple faculty members. Though each design review takes the students away from making further progress, they provide invaluable opportunity to improve presentation skills, to feel comfortable in an adversarial process, to make early progress on technical reporting, to receive early technical feedback while course corrections are still manageable, and to experience the practice of engineering.

As mentioned earlier, other benefits of the railgun project include coupling the theoretical development to simulation and early prototyping and cost analysis. This gives the students an early sense of progress and by being able to launch a projectile in the first semester, a sense of fun and excitement. Since the project timeline is artificially constrained by graduation, getting the students to buy in and establish ownership is very important. It is our experience that failure to achieve this ownership lessens the quality of the experience and the probability of project success. Ownership can in part be measured by outside of class time, but most noticeably it can be seen in team dynamics and peer reviews. In both cases the railgun project scored high.

The railgun project mentors also incorporated a site visit for the team to see two actual operational railgun facilities. Such a field trip was important as the students were able to interact with experts and develop contacts for questions or for background information. Again, such field trips may not be practical for most programs, but the concept of connecting the design to something tangible, to something other engineers are dedicating their life to, goes far in terms of motivation and excitement.

The challenges of a railgun project cannot be overlooked. It does require some specialized machining, operating equipment at high voltage, the cost is high relative to typical projects, and the interdisciplinary nature of the problem requires greater coordination and support. In part, the cost is managed by considering outside sponsorship. This sponsorship both defrays the cost and provides an outside customer that changes the typical student/faculty dynamic and better models what goes on in the real world. There are many sources of such donations, including corporations that may also sponsor competitions which can also motivate student interest. The safety aspects of the project are probably the most important challenge because students often like to work late at night and are often rushing to produce results. High voltages, high currents (though on orders of milliseconds), high temperatures, high forces, and projectile speeds that can cause harm must all be accounted for by the mentors and lab technicianss, but in the end analysis, there is nothing here that is unusual in a laboratory environment. Some students are more comfortable with prototyping, and we believe this is the critical part of how students might be recruited for such a project.

Finally, the railgun project is seen as a success because it has generated significant interest among sophomores and juniors in the program. Students want to build a launcher; they want to know how it works. Like robotics, it is very visual and intriguing. This is also helpful for attracting students to the major. It is also good from the perspective of faculty research. The current railgun efforts have opened the door to collaboration between the EE and physics departments. Unlike many senior design projects that might end up on a shelf in a closet, the railgun can continue to be used as future capstone projects and/or independent research to include modifications to increase muzzle energy, the system can be adapted to facilitate research like electromagnet augmentation and different means of taking system measurements, and more detailed simulations can be developed to help better match predictions with actual firing measurements. We are also hopeful that such future projects might provide more quantitative pedagogical data to supplement the more anecdotal conclusions provided here.

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