Final Paper: Railgun

Jay Chiruvolu, John Kim

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Abstract

This paper details the progress of planning, designing, and building an electromagnetic railgun in the ASR Whitaker lab. The railgun is made out of 4 large 450-Volt capacitors, 2 large aluminum-7075 rails, acrylic guiding rails, an aluminum rectangular bullet, and a 100 psi air compressor. The railgun is capable of shooting metal projectiles at approximately 15 m/s when charged at 300 Volts. It reached an acceleration of 145.51 $\frac{m}{s^2}$ and efficiency of 0.04%.

2 Motivation and History

The idea of a railgun stemmed partially from our first semester motor project—using electromagnetism to propel objects. They were depicted in video games (i.e. Halo 3) and movies (i.e. Transformers 2, Ender's game, and Battleship) as futuristic weapons with sparking electricity flowing down the rails. By building a fully working railgun, we hoped to have the opportunity to gain a better understanding of the physics behind electricity and electromagnetism while being hands-on with a project. More generally, undergoing this massive project has taught us that nothing ever goes as planned, and at each hurdle, we needed to analyze and identify the reason behind the problem. Constantly trying new ideas and picking the most optimal method out of all the ones that don't fail ultimately lead to our final railgun and project. This project also exposed us to "mechanical debugging," per se—physical problems are much more of a challenge to solve than digital ones.

The railgun is rapidly beginning to fill a required niche in the sector of projectile launching in the world today. Already we've seen militaries around the world begin to build railguns on their warships to replace conventional missile systems. It seems much of the military community has decided that they are a good investment for the future. Much of this revolves around the cost-effectiveness of the weapon itself. Railgun projectiles are much cheaper than the rockets traditionally used in their place, and trading a railgun slug for an enemy missile is a highly cost-effective trade for any government (China's newest railgun uses projectiles that cost between $25k and $50k, while basic U.S. Tomahawk missiles cost $1.4M each). [1] Additionally, railgun slugs are much safer and easier to store than rockets or chemical weapons, making them a very appealing choice for a warship that would be away from land for a significant period of time. Finally, railguns, while not as powerful as standard Tomahawk cruise missiles (64 MJ vs 3,000 MJ), offer cheaper and more scalable destructive power and have the ability to fire armor-piercing projectiles, an appealing feature in naval combat. Additionally, while many countries have developed defense systems for missiles, there is no known method of defending against railgun shells. For these reasons, the railgun is poised to make a splash in naval warfare in the coming years.

Figure 1: Current railgun prototype for the US Navy by BAE Systems

The railgun itself was first theorized by the Germans during WWII. A man named Joachim Hänsler initially proposed it and designed a spec, but they never ended up building it due to cost and power constraints. In more recent memory, American and Great Britain began research into railgun technology in 1993, which is still in testing today. The landmark railgun designers today are BAE Systems, a British defense contractor, and General Atomics, an American contractor. Tests were done with the BAE design extensively from around 2008-2012, and the contractor is now tasked with designing a multi-purpose projectile for the railgun. Their datasheet claims their design can reach speeds of over Mach 7, firing a 3.2kg projectile over 100 nautical miles. [2, 3, 4, 5]

Unfortunately, the schematics for the BAE and GA designs haven't been released to the public, due to the fact that they're under development and probably still classified. However, they do have some interesting features that seem to mitigate some of the issues, like active cooling inside of the rails to make sure that the gun doesn't heat up too much. They also feature new ways of energy storage, more advanced than just directly hooking up a capacitor bank to the rails. They use a compulsator (basically a modified alternator), which essentially spins a rotor at high speeds with low friction. The electromagnets in the compulsator are built for minimum inductance so it can be released in very quick short bursts, perfect for high energy weapon systems. [6, 7] Obviously, this would be very expensive and complicated for us to build at our scale, but it's an interesting design nonetheless.

Railgun systems are also being designed to launch things into space. Though the heat and electricity would likely be too dangerous for humans, the possibility of shooting resources like food, water, or fuel is being considered. These systems can reach escape velocity and put objects into orbit. Because of the high tangential velocity needed to put an object into space, these systems are generally built up the slopes of mountains and such. [8] We'll see how that pans out over the next ten years.

3 Theory

The physics behind the railgun originates from simple electricity and magnetism. The railgun can be simplified to essentially two parallel metal conducting rods with a projectile connecting them together, as shown in Figure 3.

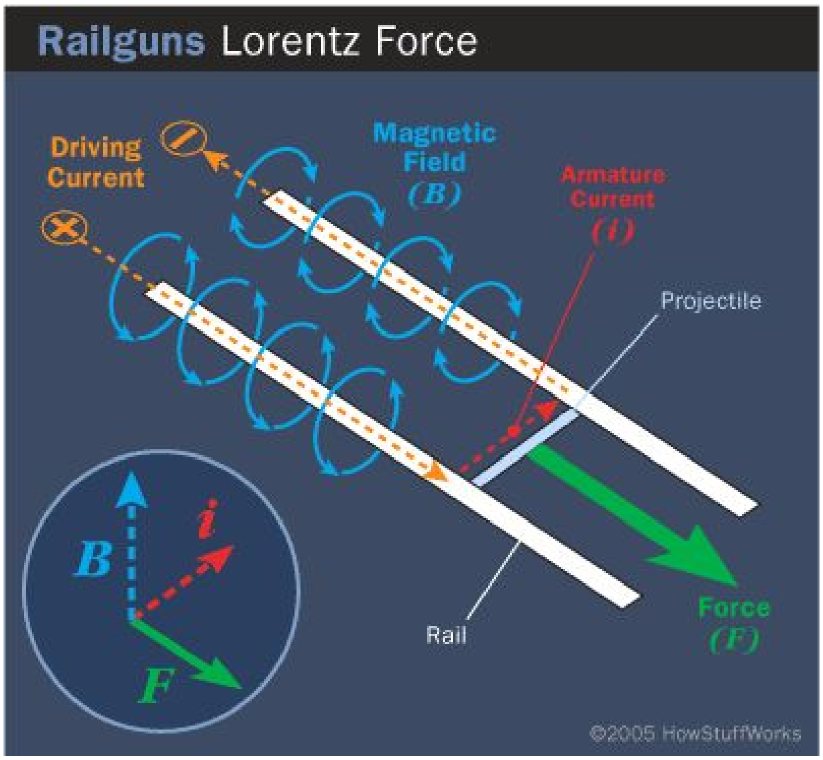

Figure 2: Induced magnetic fields present in a railgun cause the force to launch the projectile forwards.

Current from the capacitor bank flows through both rods thanks to the metal projectile connecting them together. Generally speaking, current flowing through a rod or a stick induces a spiraling magnetic field as shown in blue circular arrows in the diagram above. The direction or orientation can be derived from the right-hand rule, shown in the bottom left. Assuming that the magnetic field in between the rods is constant (or at least the differences are negligible), the magnitude of the magnetic field of a straight current-carrying wire can be calculated using the equation $B = \frac{\mu_0 I}{2\pi R}$ (a version of the Biot-Savart law), where μ_0 is the permeability of free space constant, I is the current, and R is the distance from the wire.

Because the current flow in one rod is opposite of the other rod, the magnetic field lines are symmetrical with respect to the middle, and thus the projectile will experience a magnetic field upwards (or downwards depending on the direction of current flow). Using the equation

$F = i\int B \times dl$, we can estimate the electromagnetic force that acts upon the projectile. Figure 3 below shows how the equation of the magnetic field and force can be used to calculate the acceleration of the projectile. This value can be used even further to estimate the time and velocity at which it leaves the rails using the RC constant, shown in Figure 4.

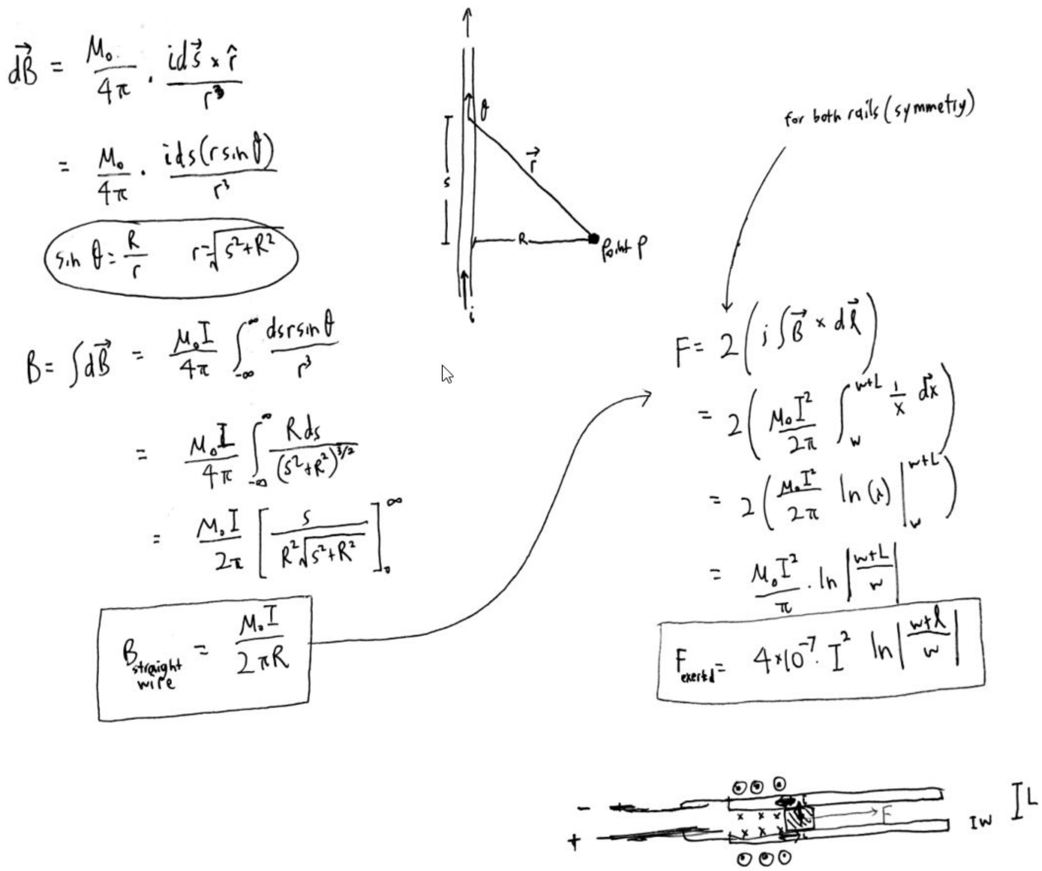

Figure 3: Derivation of the magnetic field of a straight wire (left) and the force exerted by it onto the projectile between the rails (right)

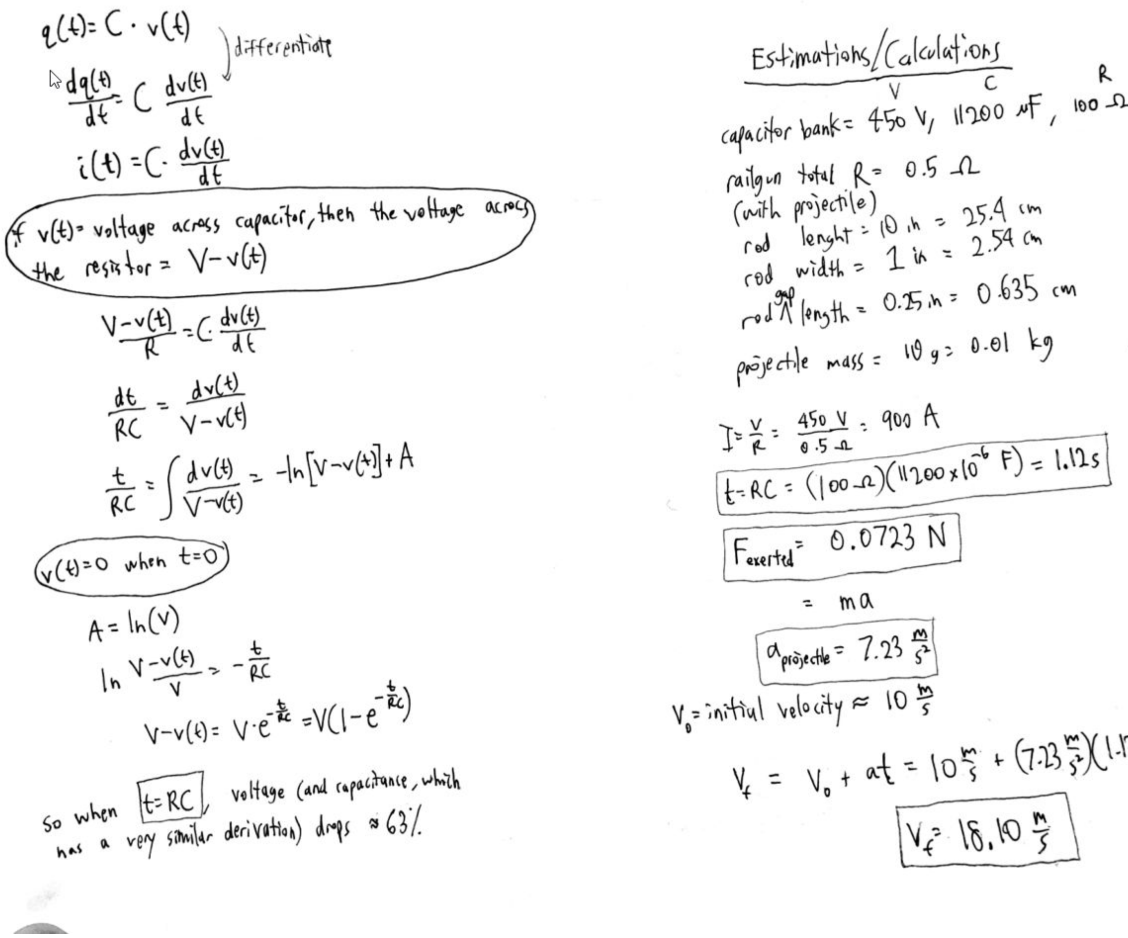

Figure 4: Derivation of the RC time constant (left) and sample calculations given measured values (right)

The electromagnetic force from the railgun, however, is not enough to propel a projectile from standstill to high velocities. The high current creates a lot of heat, which causes the projectile to weld to the rods and stop moving. In order to avoid this issue, the projectile must have some initial velocity going into the rods, which can be achieved by using a spring-loaded mechanism or an air compressor gun. Every metal has a different melting point, but in our case, copper with a thickness of around 0.25 inches has a fusing current of around 1000 Amps. We decided to use copper for its high electrical conductivity, ductility and corrosion resistance, and availability. Our initial design of using a spherical projectile and a straight rod kept resulting in the ball fusing despite an initial velocity most likely because there was only one point of contact between the projectile and the rails, so the resistance was most likely increased significantly. Another problem was the projectile itself, which had a high resistance by itself due to its coating, so using metal sheets of copper as projectile seemed to be an ideal choice.

4 Design

4.1 Circuit

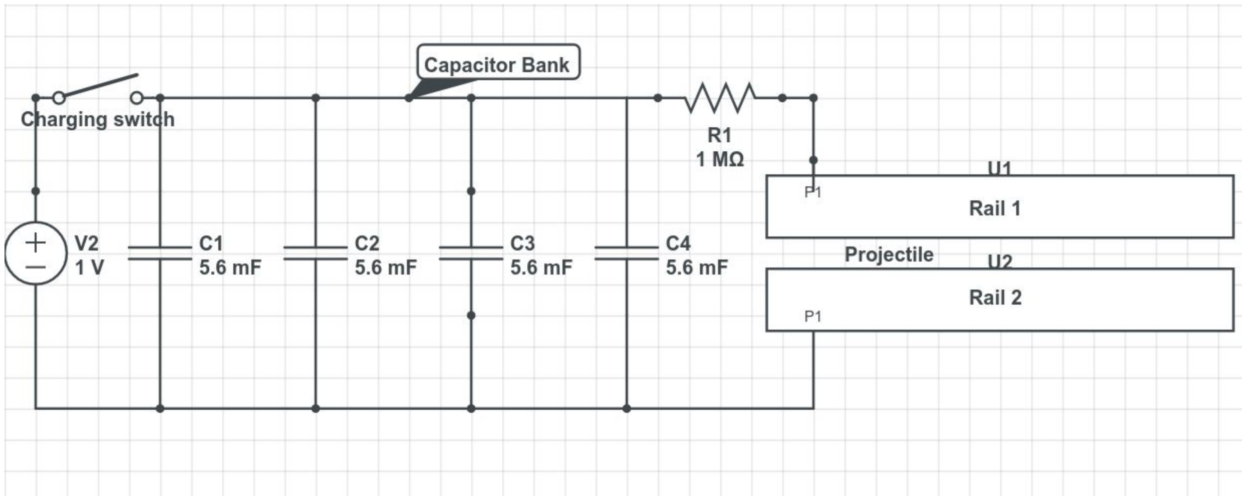

Figure 5: Circuit diagram of the railgun, which consists of the capacitor bank and the rails.

The capacitor bank of our current prototype consist of 4 large capacitors, each one having the potential to hold up to 5600 μF at 450 Volts. Because we only have access to a 500 Volt power supply, they are all connected in parallel so that the capacitances add up but the total voltage of the bank stays the same at 450 V. In addition, the combined capacitances will allow more charge to accumulate and discharge quickly since the amount of charge discharged in a given time is directly proportional to its capacitance (loses approximately 67% of its charge in $\tau = RC$ seconds. Both the positive and negative terminals of the bank are always connected to the rails. Fortunately, this is safe because as long as the metal projectile does not come into contact with the two rails and complete the circuit, charge cannot flow anywhere.

4.2 Prototype #1

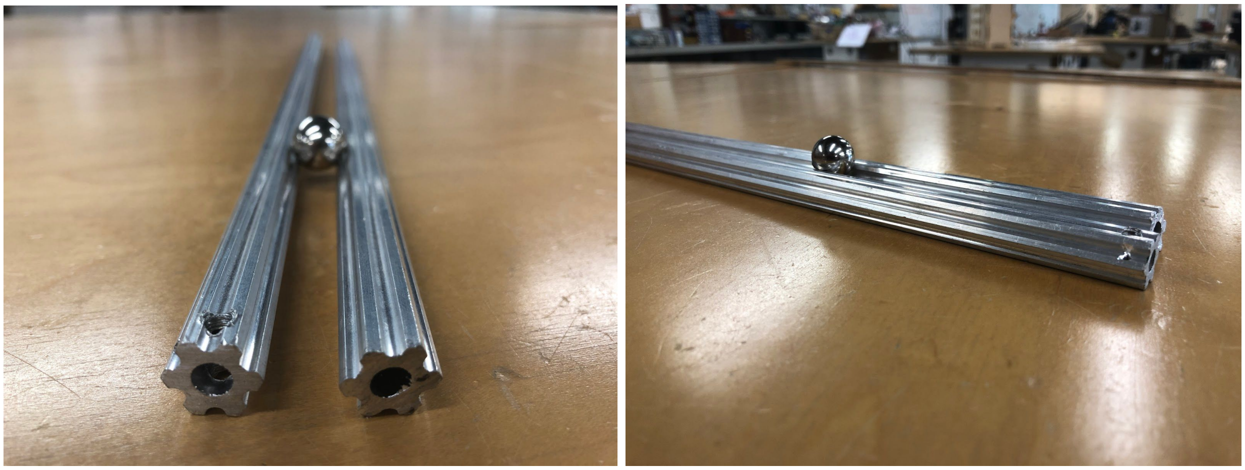

Figure 6: Front and lateral view of the railgun prototype initial design. The aluminum hexagonal rails and spherical projectile were all found in the Whitaker lab.

Figure 7 above depicts the initial design of the railgun. The primary concern before starting the project was friction, as having a lot of friction would slow the projectile down. The idea of having a sphere essentially roll along a rail was proposed because the static friction would allow the ball to roll along the rails and not lose energy in the system. We found rails that had a hexagonal cross-section and a couple metal ball bearings inside the lab. After testing this setup with a spring-loaded solder sucker providing the initial velocity, however, it was clear that this design would not work because the ball continued to weld to the rails. One problem was the lack of electrical contact between the ball/projectile and the rails. Having only one small point of contact on each rail increases the electrical resistance of the system by a significant amount, hence why there was a lot of electricity flowing through the rails but a miniscule force acting upon the ball to propel it forward. Also, the solder sucker didn't seem to provide enough velocity to avoid the welding issue. Additionally, we didn't have a pre-rail runway designed yet, so we had to start the ball with the solder sucker and immediately connect the capacitor bank to the rails (though we were using much smaller capacitors). We also tried rolling the ball down a PVC tube to get it going, which was great, but the resistance issue was too much to overcome.

4.3 Prototype #2

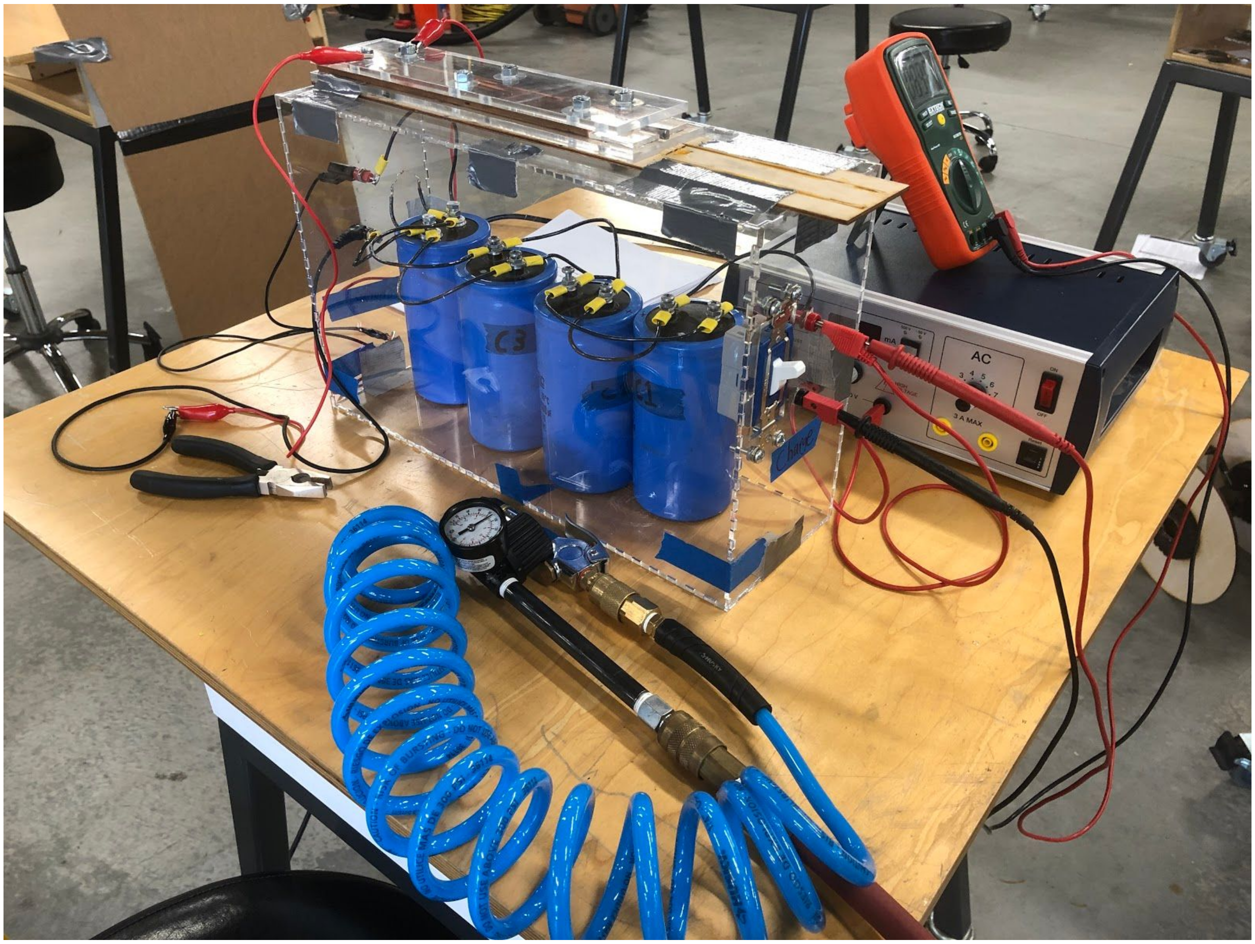

Figure 7: Top/lateral view of the second railgun prototype design. The rails and projectiles are rectangular and made of copper. Other equipment shown are an air compressor (blue curly tubing), a 500-Volt power supply, and a voltmeter to check the real-time charge on the capacitors.

Figure 8 above depicts a CAD diagram of the second design of the railgun. We decided to use thin and flat rectangular blocks of copper as our rails in order to avoid the problem of the projectile not making enough contact with the rails which increases resistance. Copper also has good conductivity compared to other metals. After multiple failed attempts of launching the projectile with a slide and a solder sucker pump, the launch mechanism was changed to the air compressor in the lab; which would supposedly provide more than enough initial velocity for the projectile not to weld to the rails. The projectile, a small rectangular block of copper, was launched from the launch mechanism into the guiding rails, which was laser-cut from acrylic for non-conductivity, for a straight path down the gap between the copper rails.

Multiple days of testing concluded the results of this design. Nearly every time the railgun propelled the projectile forward into the rails, the copper bullet welded almost instantaneously, which can be attributed to two main reasons: the material and launch mechanism. Although copper has excellent conductivity, it also has a low melting point (1981 °F) and is thus easy to weld. The other possible reason for the welding, the air compressor launch mechanism, was also perfectly valid; as the air compressor in the lab only had a pressure rating of around 100 psi. We decided to try working with a new design and more durable metals, so we moved on to the next prototype.

4.4 Prototype #3

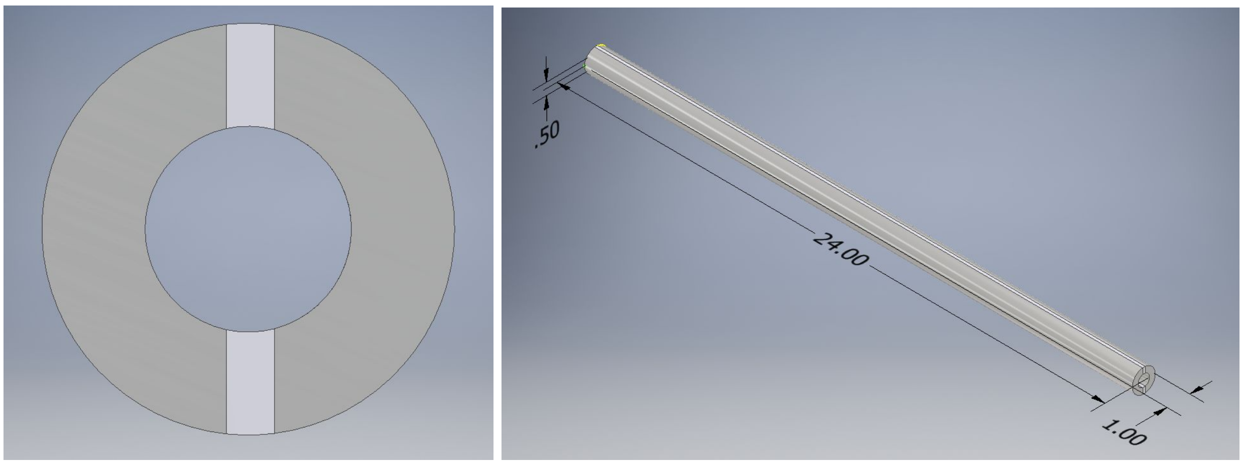

Figure 8: Front (cross-section) and lateral view of a CAD diagram and the railgun prototype's third design. The white material in between the two metal rails is High-Temperature CPVC (plastic) in order to separate the rails apart.

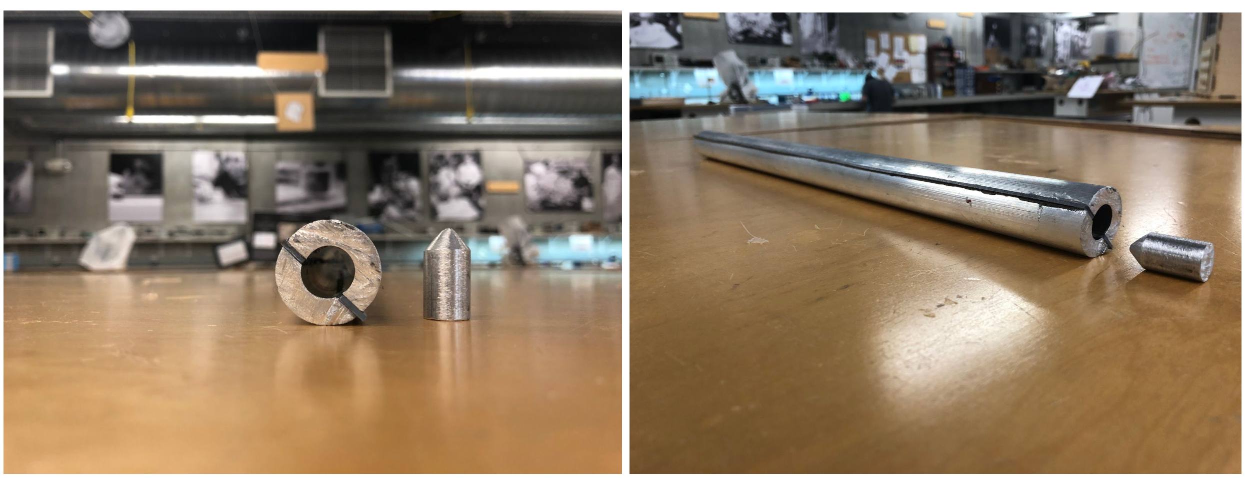

Figure 9: Front and lateral view of the railgun prototype's third design.

Figure 8 depicts a CAD diagram of the third prototype design of the railgun, and Figure 9 above shows the real third prototype design. A major problem with the initial and second prototype's design was the projectile welding to the rails due to the lack of electrical contact, which drastically increases resistance. In order to combat this obstacle, tubes and rods made of aluminum-7075, known for its high strength and heat resistance when compared to other aluminum alloys, were ordered from McMaster. The plan was to saw down the middle of tube, place a thin sheet of plastic in between to separate it into two rails, and propel the projectiles made from the rod down the tube hole.

One obstacle we expected was that by placing a thin sheet of CPVC plastic in between the two halves of the tube, the circular hole down the tube would be widened into an oval. This would cause the projectiles made from the rod not smoothly fit the rails and undermine the electrical contact that this design proposed to maximize. However, it was also expected that sawing the tube in half would remove enough aluminum material off to create a small indent to offset the space the plastic sheet would occupy. Thinner sheets of plastic were near impossible to obtain cheaply and efficiently, so we had to hope that 1/16 in. thickness would be thin enough. This plan did not end up working as well as expected, and as shown in Figure 10, the hole was not circular enough to accomodate the bullet fashioned from the rod—and so we moved onto the final prototype.

4.5 Final Prototype

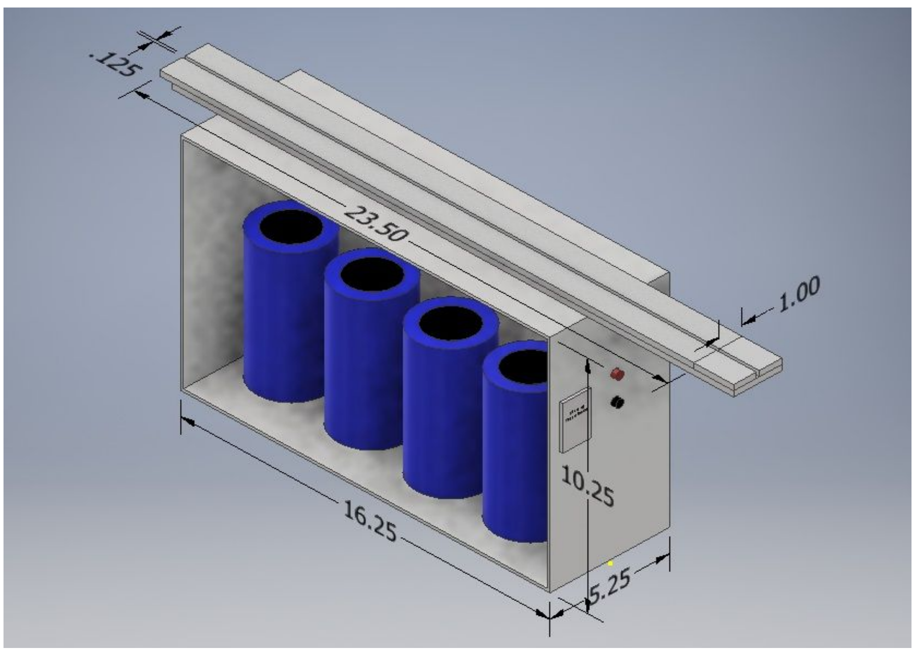

Figure 10: Top/lateral view of a CAD diagram of the final railgun design. The aluminum rails, guiding blocks, and launch mechanism sit on top of the capacitor bank. All of the dimensions are in inches.

Figure 11: Top/lateral view of the final and finished railgun. The rails are made of aluminum-7075, known for its high strength and heat resistance.

Figure 10 and 11 above depicts a CAD diagram and picture, respectively, of the final design of the railgun. As seen from the figures above, the final design closely resembles the second prototype design. The only changes are making the rails and projectile larger and changing the material from copper to aluminum-7075. We also made sure to be much stricter about dimensions, as the first prototype was built to accommodate the bullet we made, rather than the bullet being built to fit the rails. This allowed us to make many bullets, which was helpful in overcoming the fact that the bullets would be severely worn from the welding and high temperatures, making them much less efficient in later testing rounds. This last prototype was also much longer, which allowed for more time in the rails to accelerate.

5 Results

Results from testing all of the prototype designs were taken into account when building the final version. The goals were to maximize electrical contact, have a smooth pathway for the projectile, use rails with good conductivity and high heat resistance, and have a decent launching mechanism to provide strong initial velocity. We believe that the final version reflects these goals and the lessons that were learned from failures with the previous prototypes.

For our final specifications, we measured the velocity and acceleration of our projectile, as well as the energy efficiency we had. Velocity and acceleration were calculated by using a laser-photogate setup connected to an oscilloscope to measure the duration of time our inch-long projectile blocked the laser, thus allowing us to discern how fast it was traveling. Thus, the equation for the velocity of the projectile is $v = \frac{d}{t} = \frac{\text{length of bullet}}{\text{time blocked}}$. As shown in Figure 13 below, the velocity at the beginning and end of the rails was measured to calculate acceleration, and the mass of the bullet was taken to calculate final kinetic energy so we could measure the efficiency of our bullet. We also measured the speed the bullet traveled through uncharged rails to see how much the rails were actually affecting the velocity of the projectile. All charged tests were conducted at 300 V as more would cause the rails and bullets to be seriously damaged from the welding.

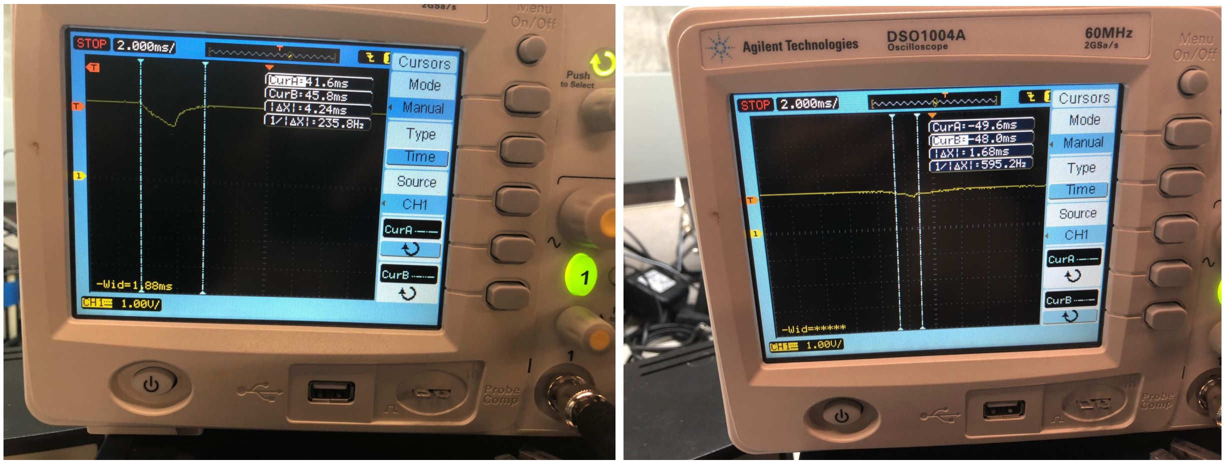

Figure 12: Measurement of time projectile traveled across the photogate at the beginning and end of the rails, respectively (4.24 ms and 1.68 ms) when charged.

Table 1: Listed Measurements

Parameter	**Measurement**
Time at first photogate (charged)	4.24 ms
Time at last photogate (charged)	1.68 ms
Time to traverse rails (charged)	62.745 ms
Time at last photogate (not charged)	3.28 ms
Mass of projectile	2.06 g

We ended up getting a final velocity measurement of 15.1 meters/second, which isn't too bad (although below expectations, given the amount of energy put into the system). The time the bullet traveled through the rails was 62.745 milliseconds.

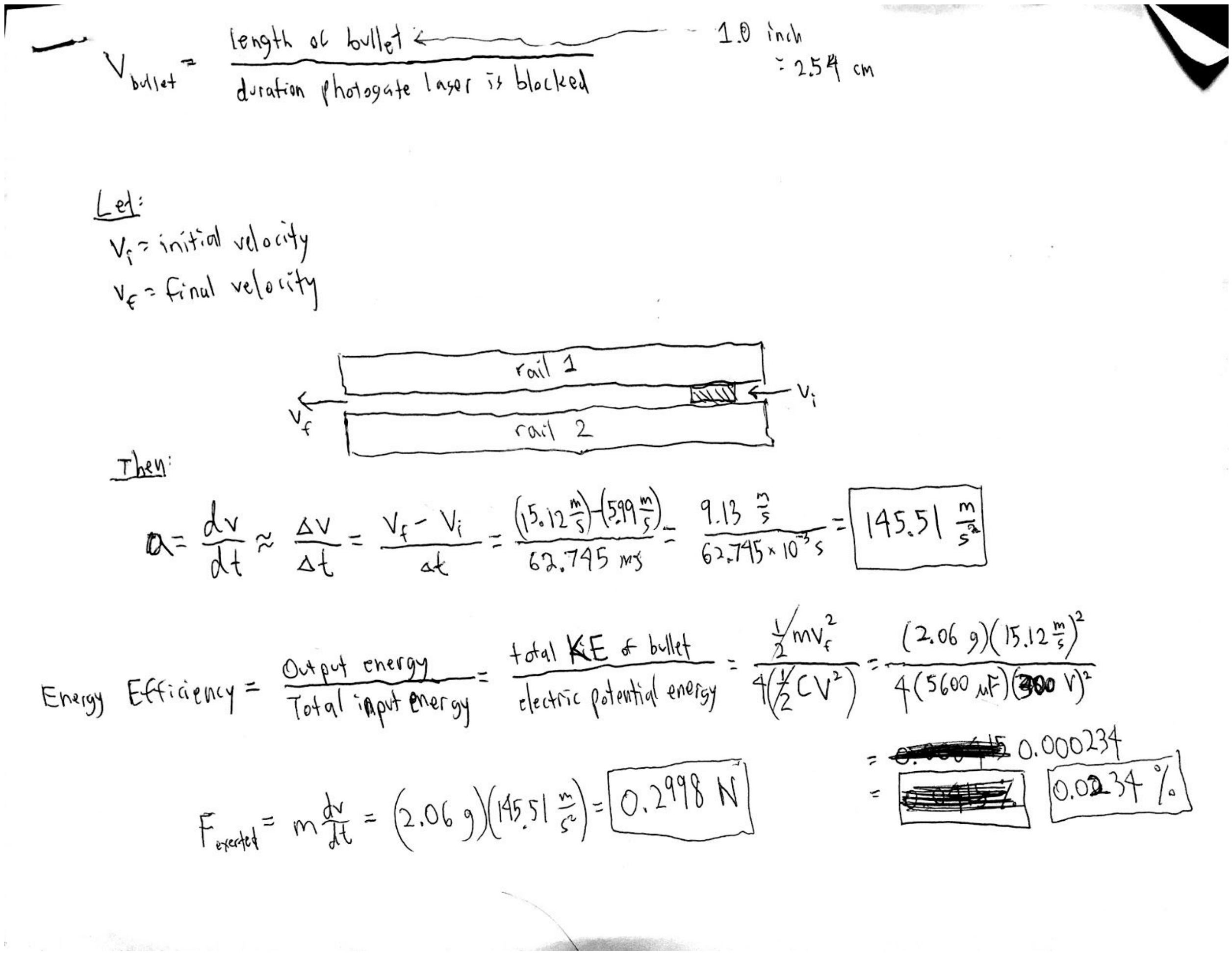

Figure 13: Derivation and sample calculations for the variable acceleration of the projectile and the energy efficiency of the railgun system.

The force on the bullet was calculated by using the relationships between the magnetic field and force in Figure 3. Efficiency of the railgun was measured simply by dividing the output energy the system exerts, which was in the form of the projectile's kinetic energy, by the total input energy inserted into the system, which was in the form of potential electrical energy stored in the capacitors. As shown above in Figure 13, the kinetic energy of the bullet $KE = \frac{1}{2}mv_f^2$, where v_f is the final velocity of the bullet out of a charged railgun, which is included in Table 2 below. The electric potential energy $W = \frac{1}{2}CV^2$, but since there are 4 capacitors, that input energy is multiplied by 4.

Table 2: Calculated Specs

Spec.	**Measurement**
Velocity of bullet (charged)	15.1 m/s
Velocity of bullet (not charged)	7.74 m/s

Acceleration of bullet	145.51 m/s^2
Force on bullet	0.2998 N
Efficiency	0.0234%

6 Conclusion

After spending months prototyping, rebuilding, theorizing, and testing, we ended up with a railgun that works decently well. Our design process was very iterative; the only means we had to test designs we came up with was to fully build it out and run a full test on it, which was both time and resource intensive. I don't believe that our final model ended up working as well as we might have liked, and we never really got over the issue of welding. After testing nearly every other parameter that might have affected why it was welding, I believe we can invoke Occam's Razor and say that it really was just a matter of initial velocity of our projectile as it hit the charged rails. Perhaps if we used a air compressor with a higher psi (the lab hose capped out at around 100, while many paintball launchers can reach over 5,000), we might have been able to dodge the issue of welding completely, but paintball is a dying art and any useful high-compression canister would have been well over our budget of $200 for this project.

As far as measurement errors go, we had some trouble getting the oscilloscope to work with both photogates, so we ended up having to use one gate over multiple trials, possibly making measurements of acceleration and velocity inconsistent. Also, we had little way to control the output of air from the lab hose, so while we did try to keep that relatively constant from one shot to another, there may have been some level of variance in that too.

It is difficult to tell whether, despite how low it (0.0234%) seems, the efficiency of our railgun is actually on par with other railguns. Railguns in theory should be very inefficient due to the sparks flying and welding problems. A ton of energy is put into pushing those sparks out of the rails, and welding consumes a lot of energy as well. There is a large amount of heat required to melt the metal in the first place. However, the energy efficiency of the system could have been increased if the friction between the rails and the projectile was kept low, the overall resistance in the system was decreased, and very highly conductive but strong and durable materials were used.

In the end, I think the building process of this railgun gave us a real sense of why developing these for repeatable use is such a challenge. At the start of this project, both of us found ourselves wondering why R&D into these weapons had been going on for as long as it had with no real signs of adoption or mainstream use, despite the simple concept. Now we know that there are a lot of challenges that need to be tackled, and that this is almost more of a materials science issue than a standard physics/engineering issue. Minimizing heat/rail damage and maximizing efficiency is something that will likely take a long time to do. We, however, very much look forward to the day when railguns rule the seas and we can say goodbye to the inefficiency of missiles in naval combat.

7 Next Steps

If more time was given to continue work on this railgun, our first step would definitely be to figure out a more powerful initial propulsion system. As discussed earlier, a paintball launcher or a scuba tank of some sort would probably be a good way to get the psi we'd like to test. Another thing we didn't get a chance to do was work with conductive graphite. The graphite has a very high melting point and doesn't really weld, which would be a godsend as a projectile. However, the graphite dust is very bad for human lungs and it is very hard to cut safely, so we had to put that plan on hold and go back to using simpler metals. It would also be cool to test other metals, like titanium which we tested briefly but didn't have the proper tools to work with, to see how much better they could perform than the aluminum we ended up using.

8 Acknowledgements

We would like to acknowledge Dr. Dann for the vital safety procedures for charging, discharging, and handling the railgun, Mr. Ward for the help on the lab equipment and general tips, and online videos and articles on the various possible designs. Without being exposed to many different railgun designs, we would not have had the opportunity to build a fully-functional railgun by the end of the semester. We'd also like to thank our trusty sandpaper sheets and metal file for scraping the welded bits off our initial rail prototypes so many times.

9 References

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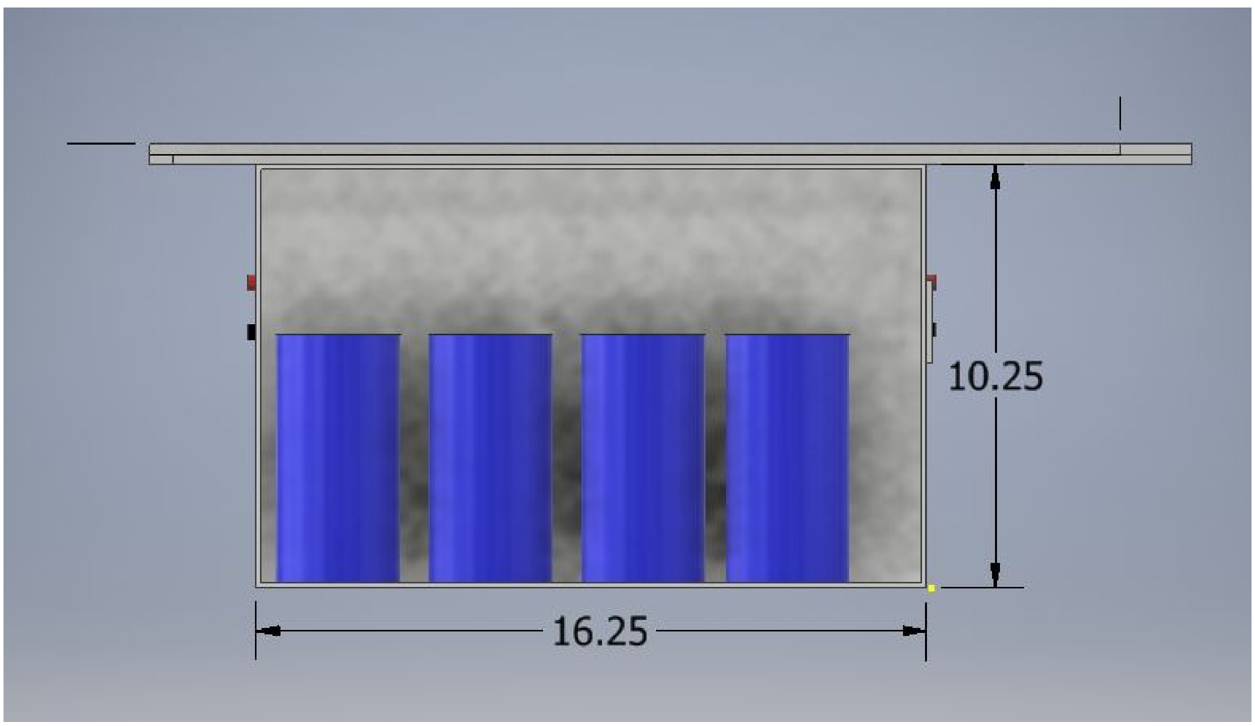
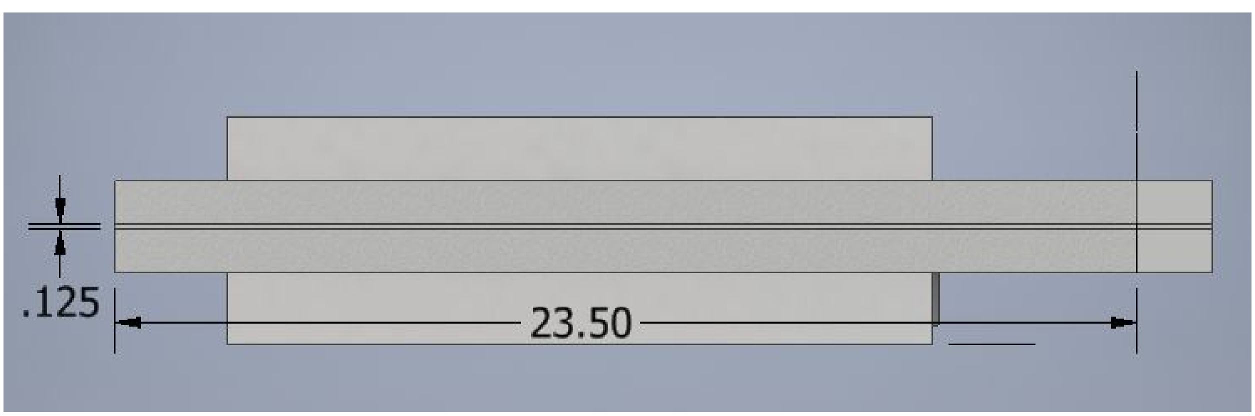
[7] Werst, M., et al. "Fabrication of a Compensated Pulsed Alternator for a Rapid Fire Railgun System." *IEEE Transactions on Magnetics*, vol. 22, no. 6, 1986, pp. 1812–1816.
To be perfectly honest, I'm fuzzy on the details of how exactly these compulsators work. I'll come in and discuss with you at some point to see if you have a simple way of explaining them.

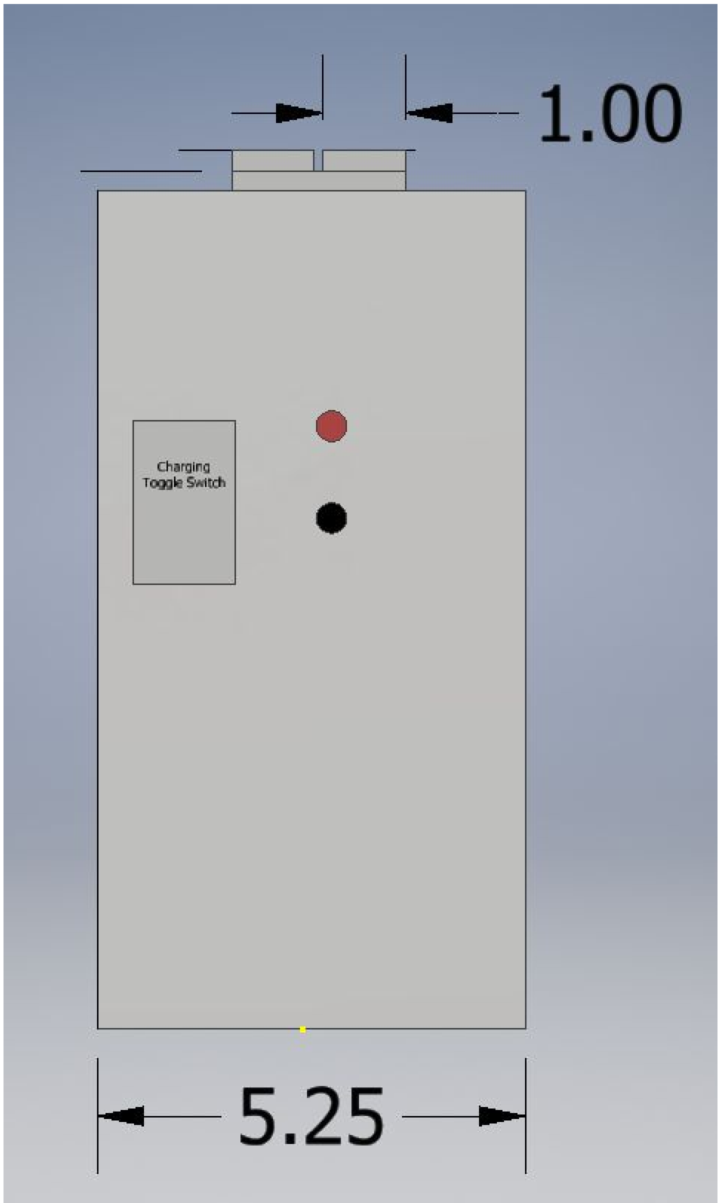
[8] Pearson, Jerome. "Low-Cost Launch System and Orbital Fuel Depot." *Acta Astronautica*, vol. 19, no. 4, 1989, pp. 315–320.

Appendix A

Additional angles of the CAD for our final design



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