Electromagnetic Propulsion

The Conversion of Electromagnetic Fields into Kinetic Energy

Matthew Roy

I. ***Abstract***

The exploration and application of magnetic propulsion is an increasingly important field. To demonstrate magnetic propulsion I am building a coil gun. Also known as a gauss rifle, a coil gun uses magnetic fields to propel a ferrous projectile at high velocities. The coil gun is very similar to the more famous rail gun in that they both use electricity to accelerate projectiles, but the method of acceleration is somewhat different. A coil gun is a solenoid, or a coil of wire that creates a uniform magnetic field within a region (the center). A rail gun uses two rails at a very high voltage difference, with the projectile bridging the gap between them to complete the circuit. While building the coil gun I will gain a deeper understanding of circuits, capacitors and electromagnets. I will do many calculations and explore the concept of efficiency in energy conversion (i.e., how much electrical energy is transferred in kinetic energy). I will also explore potential applications for "mass drivers" and other devices that use electromagnetic fields to propel objects.

II. *The Introduction*

I came up with the idea to build a coil gun after I was saved from the likely third-degree burns and arson on my permanent record when my original idea to build a flamethrower was denied. I had extensively researched flamethrowers, but extenuating circumstances (e.g., conflict with common sense) forced me to pick a new project. Ben London had considered building a coil gun earlier and that reminded me of the possibility. I've always loved magnets and high velocity projectiles, so the logical combination would be to build a coil gun.

I was initially considering building a rail gun. However, after some research I chose to build a coil gun over a rail gun because of issues in durability and practicality. My research showed that coil guns are more forgiving than rail guns. Rail guns are notorious for their rails overheating and welding the projectile to them due to the heat generated by the enormous current. The rails become damaged by this over time, and the armature (projectile) has a very limited lifespan. Furthermore, the current runs through the two rails in opposite directions, creating a significant repulsive force between the two rails that causes serious damage over time. Finally, rail guns rely on the length of their rails to accelerate their projectiles and I would prefer my design to be more compact. [(1)] Therefore I chose to make a coil gun, which does not suffer from the problems associated with the rails. This being said, the force of a coil gun is harder to predict than the relatively straightforward equation of the rail gun because unlike a rail gun, the projectile does not accelerate evenly throughout the coil gun "barrel". This means that the coil gun will require far more tinkering to maximize its efficiency.

The future is bright for magnetic propulsion. Rail guns scale better than coil guns and offer greater efficiency, so much of the research into electromagnetic propulsion is aimed at making rail guns feasible. Both rail guns and coil guns offer immense acceleration at levels higher than were possible with ballistics. The acceleration of a rail gun is far more evenly dispersed than that of a regular gun, as a rail gun does not rely on an explosive charge to propel an object. This smooth acceleration means that people are looking to rail guns as potential launchers for orbital craft and scramjets - Supersonic Compression Ramjets that need to be traveling at high velocities before their engines work. [(2)] There has also been a very serious examination of the feasibility of "mass drivers" to launch matter into orbit. Mass drivers are basically large coil guns that use superconducting coils to accelerate large payloads to extreme velocity. However, the enormous capital investment they entail makes them currently unfeasible. In the future that may change; for example, a mining operation on the moon would probably use mass drivers to efficiently exchange material with earth. (3)

Of course, the military is also seriously interested in the technology, and for more than just weapons. Indeed, the Navy has already used a rail gun to launch fighters into the air from the short runway of an aircraft carrier. [2] But of course, weapons development is also investing heavily in rail guns. Imagine the ability to provide supporting artillery fire from over 200 miles away! The marines in particular are interested in just that capability. [4 p. 8] However, you probably won't be seeing super-guns anytime soon. There are a number of limitations of today's technology that are holding back rail guns, namely the sheer amount of power they require and the enormous wear and tear problems mentioned earlier. The Navy has a semi-functioning 32 megajoule rail gun with an expected muzzle velocity of over 5,800 m/s, but it will probably be a while before we see it on the field. [5]

III. History

The idea behind electromagnetic propulsion is relatively new. In the early 1890's Emile Bachelet demonstrated levitating a metal carriage using magnetic fields. In 1918, Louis Octave Fauchon-Villeplee invented an electric cannon that resembles a modified linear motor. In the 1960's the first linear induction motor was designed by Eric Laithwaite. (6)

The origin of actual coil guns is a bit more obscure, since the basis of a coil gun is a hollow-core electromagnet. However, rail guns use a more specialized design that is a relatively new concept. The first rail guns were tested in the early 1970's at the Australian National University. In the 1980's, research into rail guns increased drastically due to the United States' initiation of the Strategic Defense Initiative, nicknamed "Star Wars." The goal of the initiative was to place advanced weaponry in orbit to knock out enemy missiles from space. While rail guns were initially considered for a land based missile defense system, rail guns were suddenly a topic of heavy research and heavier funding from the "Star Wars" program. Many different defense contractors worked on developing different versions of rail guns, but the degrees of success varied greatly. (5)

IV. SketchUp Drawing

Dimensions: (see Appendix B for circuit diagram)

Coil

Coil Type	Coil Length	Coil total diameter	Coil internal diameter	Coil resistance	Number of windings
12 gauge, multi-stranded copper wire	5 ½ inches	3 inches	¾ inch	0.50 Ohms	Approx. 300
	145 mm	90 mm	20 mm		

Capacitors

Charging Capacitor

Capacitor Height	Capacitor diameter	Capacitance	Max voltage
51 mm	29 mm	1,000 uFarad	250 V

Driving Capacitor

Capacitor Height	Capacitor diameter	Capacitance	Max voltage
115 mm	6.0 mm	22,000 uFarad	100 V

Projectile

Composition	Mass	Length	Diameter
Solid steel bar	80.42 grams	145.00 mm	9.50 mm

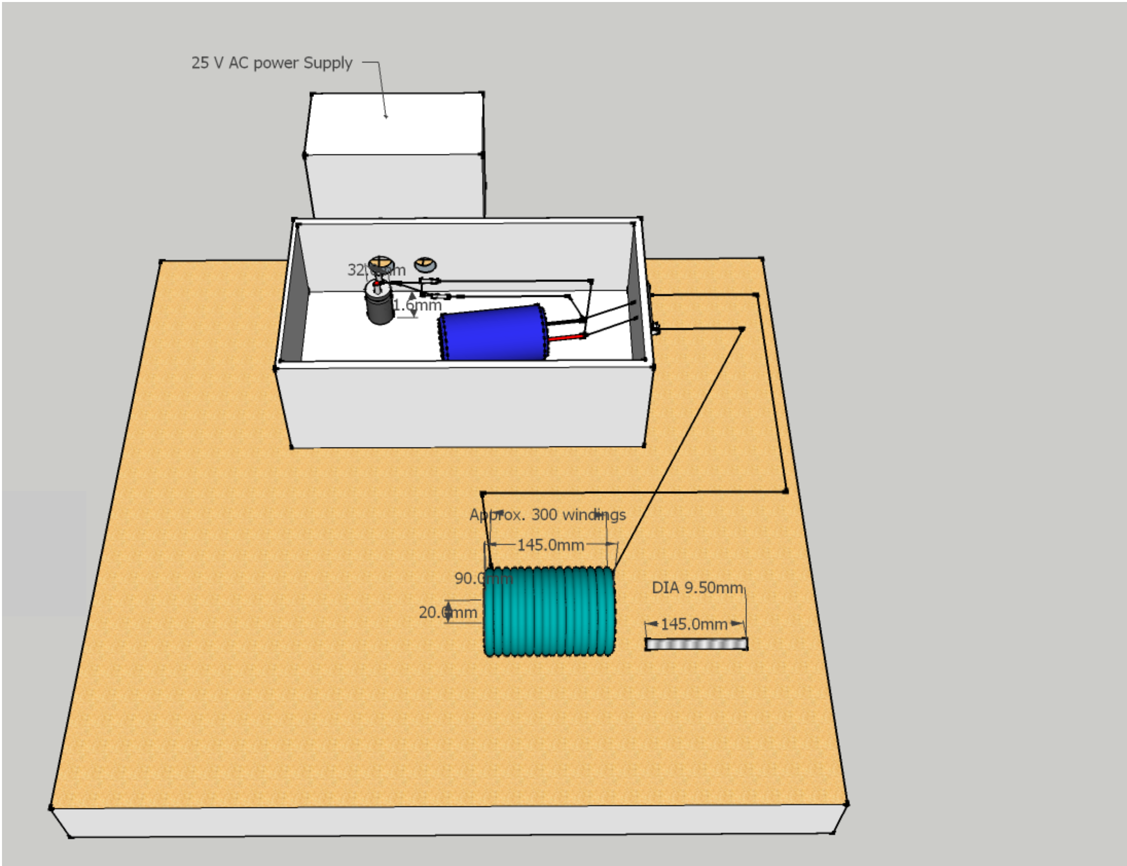


Figure 1: Entire Coil Gun Overview

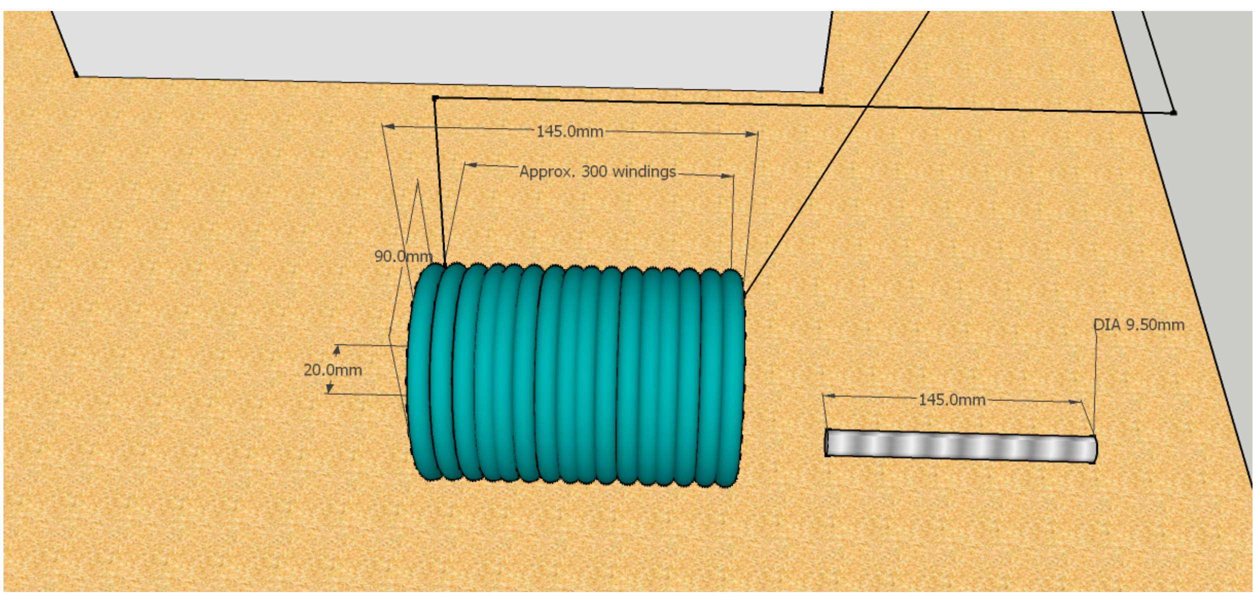


Figure 2: Coil and Projectile

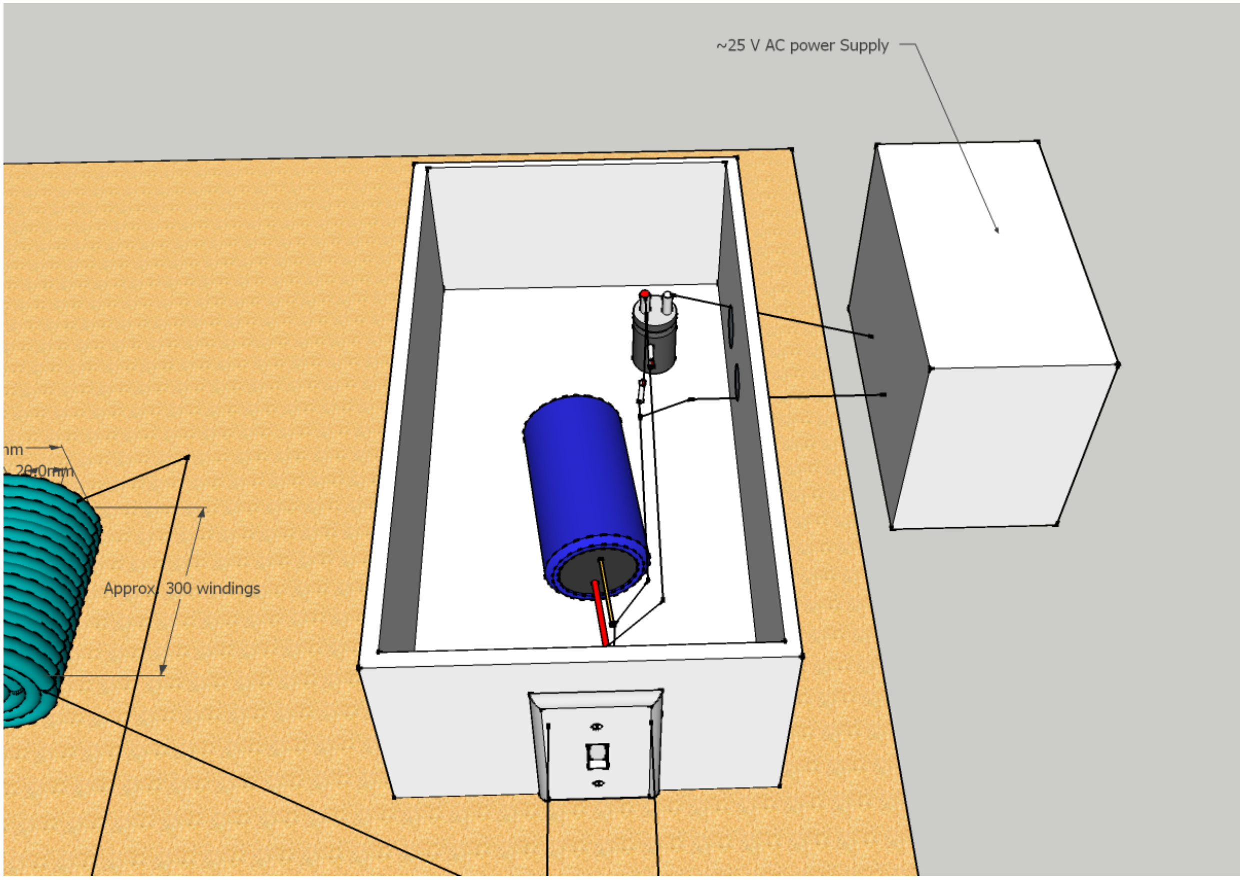


Figure 3: Charging Box Overview (small doubling circuit capacitor and large blue driving capacitor)

Note: Small capacitor is a 250V, 1,000 µF electrolytic capacitor, large is a 100 V, 22,000 uF

V. Theory

A) Capacitors

One of the key components of the coil gun is the capacitor. A capacitor stores electrical energy in the form of static electrical fields, rather than the chemical reactions of a battery. The earliest capacitors were developed in 1745 and called Leyden jars; they were glass jars coated on the inside and out with separate sheets of metal foil. When a potential difference was applied across the two different sheets of foil, a charge was stored that could later be released as a spark.

Capacitors consist of a pair of conductors (such as metal sheets) separated by a dielectric (better known as an insulator, such as the glass jar). When there is a potential difference (voltage) across the conductors, a static electric field develops in the dielectric that stores energy and produces a mechanical force between the conductors. A capacitor is characterized by the capacitance value, measured in farads. This is the ratio of the electric charge on each conductor to the potential difference between them, or C = Q / V. A capacitor can store work in this electric field, with the calculation of $W = ½ C/V^2 = ½ V*Q$.

Capacitors in parallel have the same applied voltage and a cumulative capacitance. This essentially means that multiple capacitors in parallel as equivalent to one capacitor with a larger capacitance, or Ceq = C1 + C2. Capacitors in series act as a smaller capacitor at a higher voltage, or 1/Ceq = 1/C1 + 1/C2.

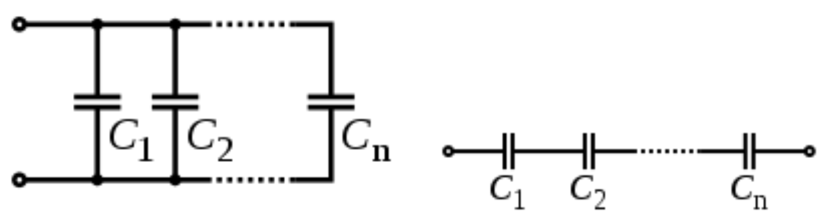


Figure 4: Visual diagram of capacitors in parallel (left) and series (right) [7]

I am using 250 volts, 1,000 microfarad electrolytic capacitors arranged in parallel for easy charging and discharging. I currently have eight capacitors connected, making my capacitor bank the equivalent of one capacitor of 250 volts, 8,000 microfarads.

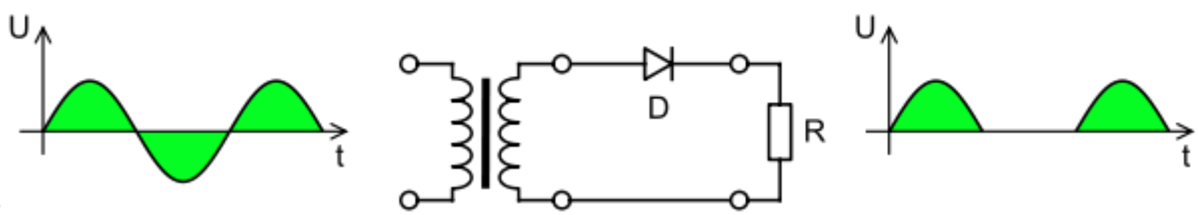
The (electrolytic) capacitors can explode if charged the wrong way or at too high a voltage. Their internal electrolyte liquid boils and the pressure can build up until the capacitor explodes. Charging it in reverse also wrecks the inner coating of the capacitor. Non-polarized capacitors (such as Leyden jars) can be charged both ways without problem, making it the capacitors of choice for AC applications. However, many modern capacitors are polarized because they are cheaper to make than the equivalent non-polarized capacitors and can store more charge. The type of polarized capacitor used in this experiment (electrolytic) uses an aluminum oxide layer held in place by the electric field. [8]

B) Solenoid

A solenoid is a coil of wire wrapped in a spiral about a central core. When an electrical current passes through the solenoid it creates a magnetic field that is uniform in a region of space. My coil gun uses a hollow core solenoid which produces a uniform magnetic field in center of the coil. This uniform magnetic field (B) is equivalent to $B = \mu_0 \frac{Ni}{l}$ where u_0 is the magnetic constant, N refers to number of turns, I to current, and L to length of the wire loop. Using this formula and experimental data points, I calculated that my coil has approximately 300 turns . [9 p. 7] I calculated that my coil has approximately 300 turns using $B = \mu_0 \frac{Ni}{l}$. I measured a magnetic field of 0.0032 T at a current of 1 amp. Therefore N = (0.14 m * 0.0032 T) / (1.00 amps * $1.25664E10^{-6}$) = 296 turns. Testing the coil at 2 amps with a field of 0.00678 T came out with 304 turns, so the approximate number of turns is 300.

C) Rectifier

A rectifier converts AC current into DC output using diodes that only allow current to pass in one direction. The simplest rectifier is a half-wave rectifier that only converts half of the AC wave into DC current, blocking the other half (see figure 5A). I made a full-wave rectifier using four 6-amp 800V diodes, which converts the entire AC current into DC (see figure 5B). [10 p. 6]



A)

B)

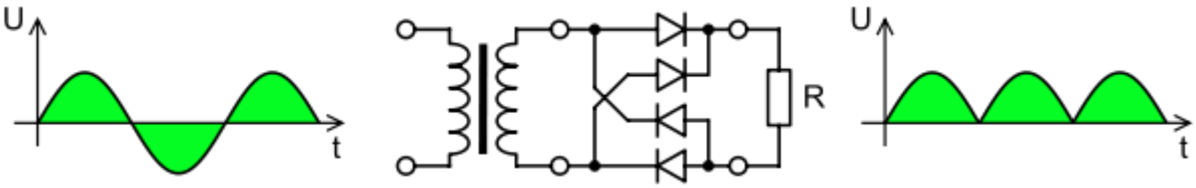


Figure 5: A (top) is half-wave rectification while B (bottom) is full-wave. [10]

D) Voltage Multiplier

A voltage multiplier uses rectifiers and capacitors to multiply an input AC voltage and produce a DC output. The circuit shown in Figure 6 below is a voltage doubler. In this case, the multiplier is being used to charge a capacitor. The AC current is run through a capacitor, which discharges down one of two rectifier pathways depending whether it is a positive or negative charge. During one cycle of the AC current – where the top AC node is negative and the bottom is positive – the doubling capacitor is charged up to current's peak voltage of V. During the next half cycle where the top node is positive and the bottom is negative, the capacitor boosts the AC voltage as it is applied to the load capacitor, creating a voltage difference of 2V across the second capacitor. The cycle then repeats, with the doubler capacitor cyclically applying a voltage of 2V to the load capacitor.

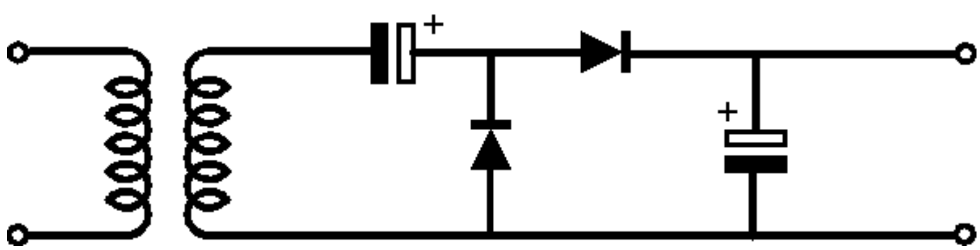


Figure 6: Doubler capacitor is on the left, load is on the right

E) Coil Gun

A coil gun is a solenoid connected via switch to a charged capacitor, with a ferrous projectile placed at the entrance of the coil. When the switch is triggered, the capacitor discharges in a split second into the solenoid coil. This sudden surge of current creates a strong magnetic field that pulls the projectile towards the strongest point of the field, the center of the coil (see figure 7 below). In a perfect design, the current shuts off as the projectile reaches the center (otherwise it would begin drawing the projectile backwards) and the projectile rockets out of the barrel with the momentum imparted during the discharge time. The main issue is optimizing the projectile placement/discharge time so that there is the maximum KE imparted in the projectile. This coil gun uses a long projectile to maximize efficiency, since perfect timing for current shutoff is impractical. The long projectile ensures that even if the capacitor takes a long time to discharge, the projectile will still be dragged forward since there is a ferrous mass behind the coil. For instance, if the projectile was a ball bearing, at the point where the ball bearing crosses the center of the coil it will begin decelerating as it is pulled backward. However, if the projectile is a length of steel rod, at the point where the front of the steel rod crosses the center of the coil and begin being drawn backwards, the rest of the rod's length is still behind the center point and is thus being drawn forward.

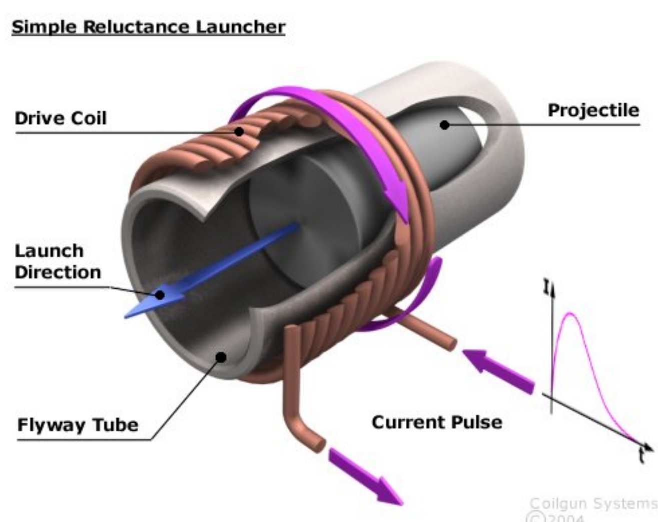


Figure 7: Coil Gun example (11) (12)

VI. *Results*

The coil gun performed very well. A length of solid iron rod was used as the test projectile. It had a mass of 80.42 grams and a length of 145.00 mm. The tests were run with a very useful and efficient setup. The variation tested was the distance from the beginning of the coil to the end of the rod. This is represented by the length of the arrow in the diagrams below (Figure 8). This was measured by placing the rod in the center channel of a ruler, and moving the rod closer to the coil along the ruler placement. All of the launches were conducted with the capacitor charged to 90 volts, with a margin of error of 0.5 volts. The velocity was measured using a photogate with the projectile's length entered as a parameter. It tested the time the gate was blocked for and calculated the speed by dividing the length of the projectile by the time it took to pass through the photogate. Three separate tests were run on each placement of the rod, and the three velocities were averaged and graphed (Figure 9).

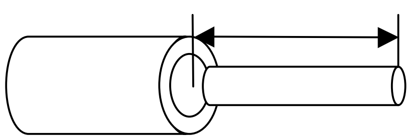


Figure 8A: 150 mm (-5)

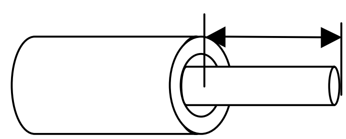


Figure 8B: 100 mm (45)

Rod End (mm)	Initial length inside of coil (mm)	Velocity test 1 (m/s)	V2 (m/s)	V3 (m/s)	V avg (m/s)	Kinetic Energy (joules)
150	-5	3.262	3.436	3.372	3.356667	0.453055
140	5	6.741	6.685	6.564	6.663333	1.785324
135	10	7.621	8.026	7.853	7.833333	2.46733
130	15	7.909	7.86	8.181	7.983333	2.562729
125	20	8.362	8.268	8.251	8.293667	2.765841
120	25	8.31	8.321	8.289	8.306667	2.774519
115	30	8.237	8.211	8.311	8.253	2.738784
110	35	8.222	8.204	8.237	8.221	2.717586
100	45	7.936	7.918	7.89	7.914667	2.518833

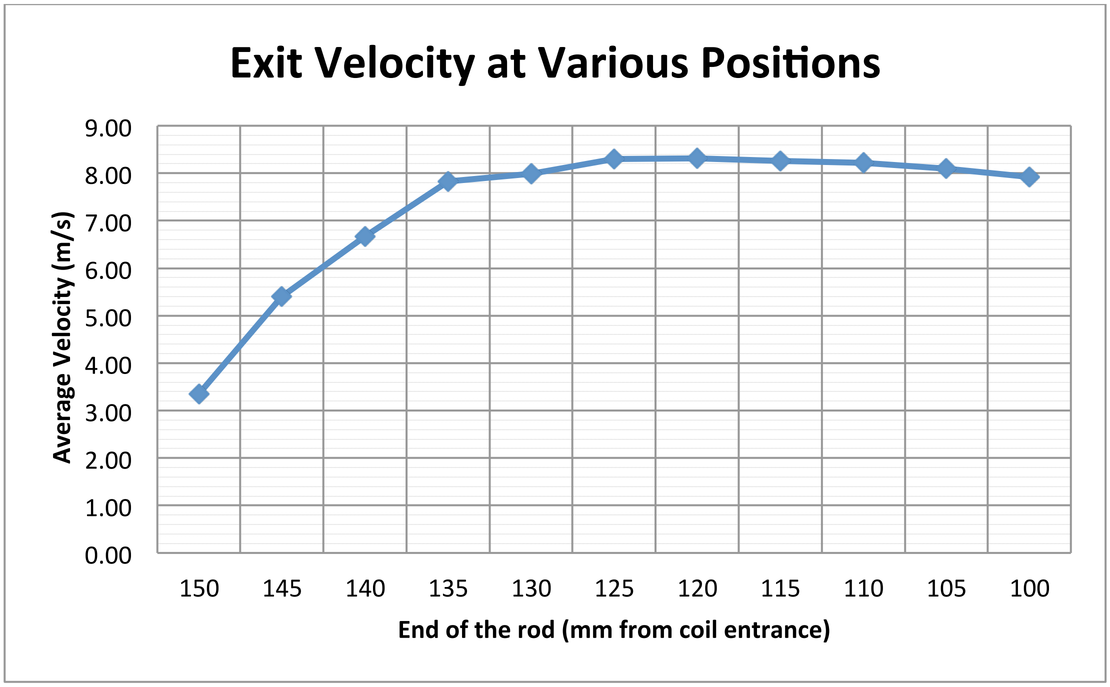


Figure 9A: Speed with distance measured from back of the projectile to the coil

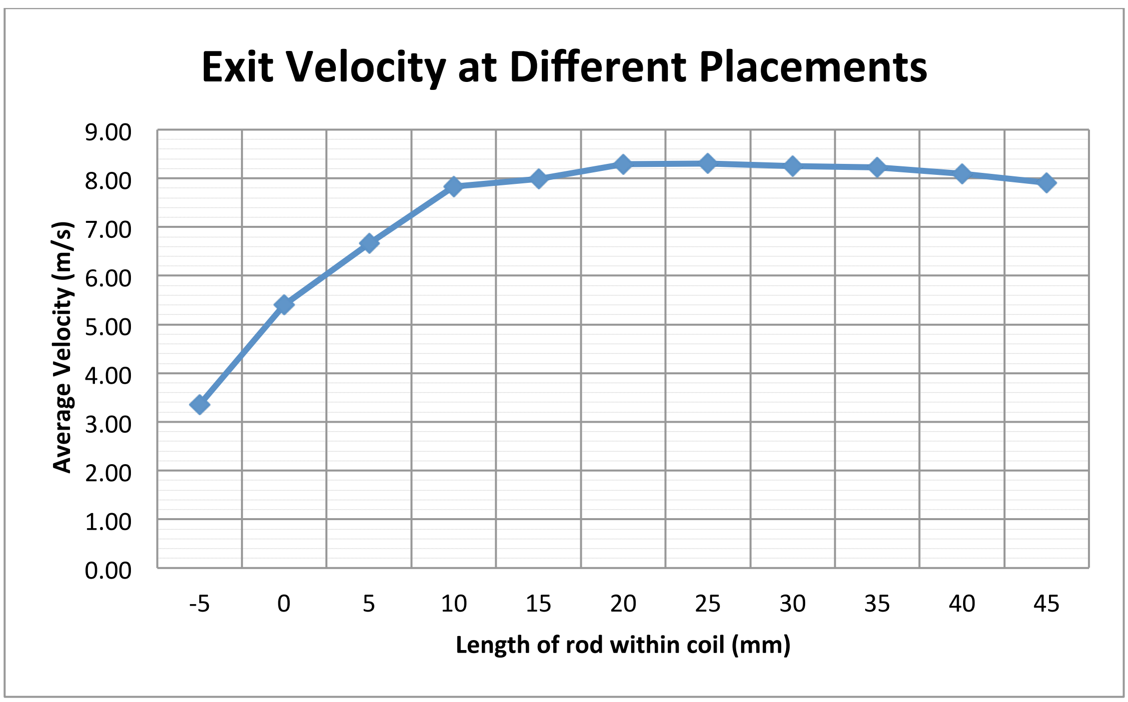


Figure 9B: Speed with distance measured from front of the projectile to the coil

As the results show, the coil gun rapidly gained efficiency as more of the iron rod started within the barrel. The initial velocity more than doubles from moving the head of the iron from 5 mm outside of the barrel (150 mm) to 5 mm within the barrel (140 mm). The max average velocity of 8.307 m/s occurred at 120 mm, or with 25mm of the iron rod starting inside of the coil.

At the peak average velocity, the kinetic energy ($1/2*mv^2$) of the rod was 1/2*(0.08042 kg) * $(8.307\ m/s)^2$ = **2.775 joules**.

The energy stored in a capacitor is calculated by $½*C*V^2$. The capacitor that was used was a 100 volt, 22,000 uF electrolytic capacitor charged to 90 volts. The energy stored inside was ½ * (0.022 F) * $(90\ v)^2$ = **89.1 joules**.

Therefore, the peak efficiency of the coil using the tested projectile was (2.775 / 89.1) * 100 = **3.11% efficiency**. This low efficiency is one of the downsides of coil guns and rail guns. In fact, "coilguns are often below 1% efficient. Coilguns above this are fairly good." (13) An efficiency that is >3% is very good for a coil gun, and the even laboratory precision calibrated coil guns can rarely reach above 10% efficiency. (12)

The 100 V, 22,000 uF capacitor worked very well. With a doubling circuit the capacitor was charged up to 90 volts from the purportedly 25 V AC power supply. Obviously the peak voltage was closer to 45V, rather than the 35 volts that a nice AC curve would have, as calculated by (AC voltage)*sqrt(2). As Figure 10 below shows, the capacitor discharged nicely into the coil, with 90% discharge within 0.02 seconds. An interesting dip below zero occurred shortly after total discharge. This showed that a reverse current was created within the coil. The explanation for this is that the intense magnetic field created by the electromagnet is stored in the surrounding air. This means that the energy is not completely lost, and that a portion of the energy is returned to the circuit. This is somewhat akin to a rebound from dropping an object onto a surface. Part of the energy from the drop is stored in the object – in this case as elastic compression, which then causes a slight rebound. (13)

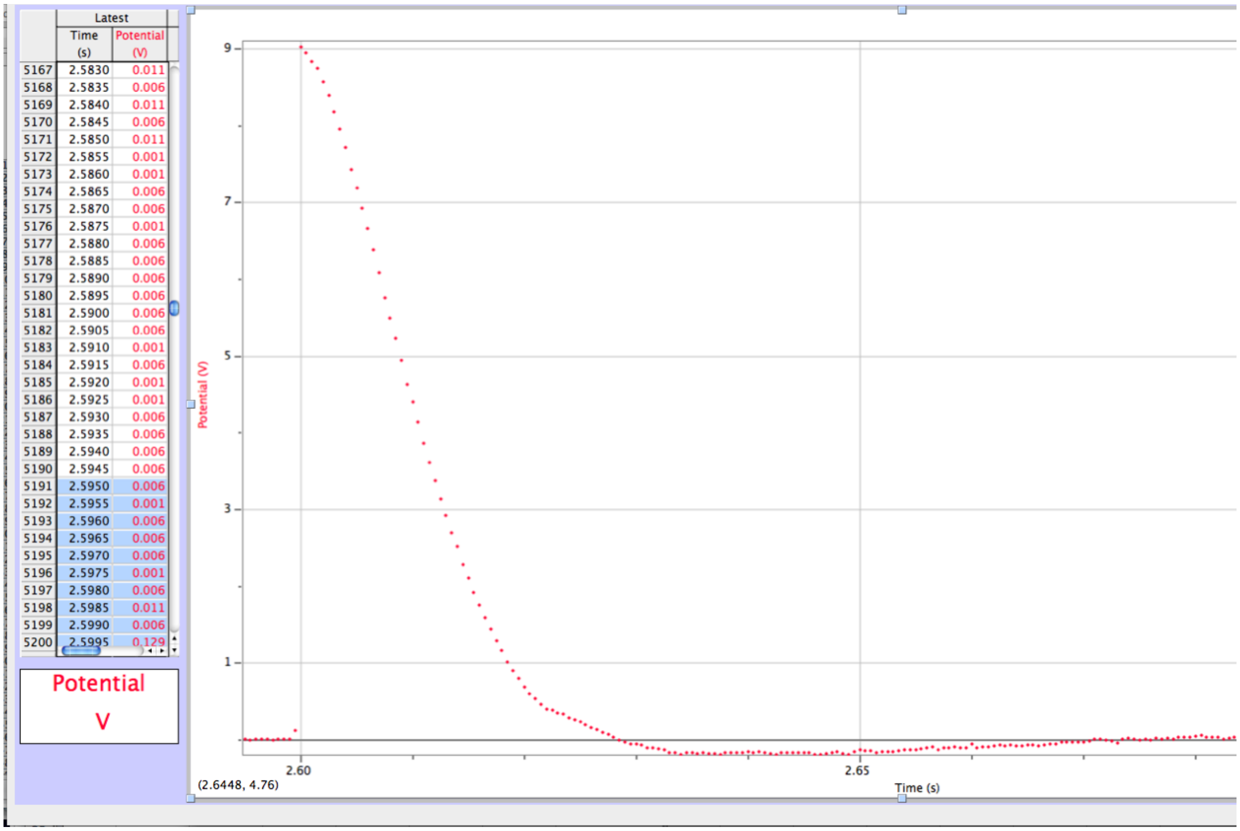


Figure 10: Graph of Capacitor Discharge

The data was taken of the discharge of the capacitor into the wire coil. The voltage was measured by using ten resistors in series and measuring the drop across one of them, so the voltage values in the graph are 1/10 of the actual values. As you can see, there is a negative voltage dip during the time span of 2.63 seconds to 2.67 seconds.

In conclusion, the coil gun is a resounding success. It takes 25 V input and boosts it to over 90 volts to charge a capacitor. It consistently launches a slug of steel at over 8 meters per second with a relatively high efficiency.

VII. *The Next Step*

I have a working coil gun that can launch a piece of solid steel rod over two meters into the air. I fixed the high-voltage power supply and built my own doubling circuit. My coil gun works with over 3% efficiency, a very respectable figure for a coil gun. At this point my next step would be modifications to my design. I would use more capacitors, higher voltages, and different projectiles. Right now my 100 volt, 22,000 uF capacitor works well. However, the high capacitance to voltage ratio means that there is a significant discharge time of just over 0.02 seconds. A higher voltage capacitor could discharge the same amount of energy more quickly, which would increase the efficiency of the coil gun (for an explanation see the section on coil guns). Finally, I would make use of the energy stored in the field to recharge the capacitor bank. With a rectifier circuit and an outer shell I could use the rebound effect to recover some of the energy lost when the capacitor discharges.

VIII. *Acknowledgements*

This project would not have been successful without the help of many individuals. First off, a shout out to the entire classes for helping me locate parts and tools. I would also like to thank Ben and Keegan for helping with my project on numerous occasions. I also owe a debt of gratitude to the nameless individual who first built the wonderful coil I am using. Finally, a huge round of applause for Dr. Dann: thank you for all of the pieces of advice, second chances, and help with my project.

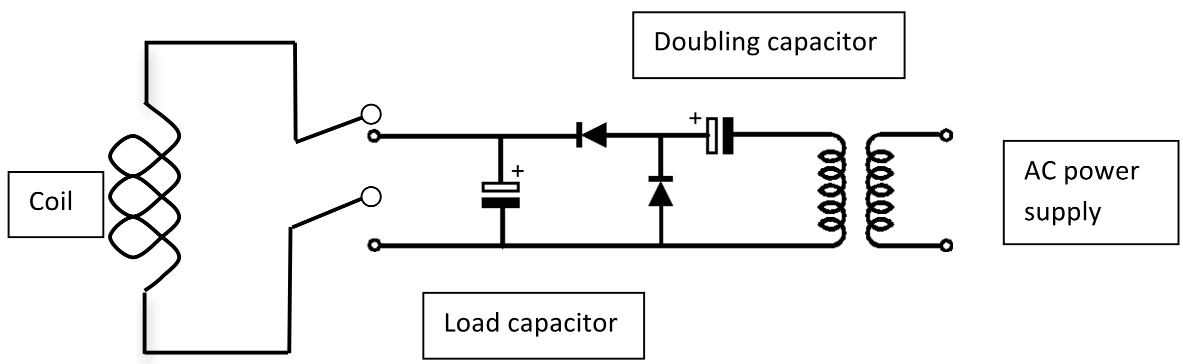
IX. *Appendix A: Parts list*

Please note: The coil is possible (and partially done) with current classroom supplies; this list is what it takes to build a new one. Also, N/A means it is unimportant where it is purchased.

Part Description	**What needed for**	**Cost**	**Purchase at:**
Rectifier Diode 1N4007 (Specs of Vr/1000V Io/1A)	Fixing high-voltage power supply	$0 (free sample pack)	Fairchild-direct.com
Rectifier (6 amps, 800 volts)	Building power supply	4 * $00.50	HSC

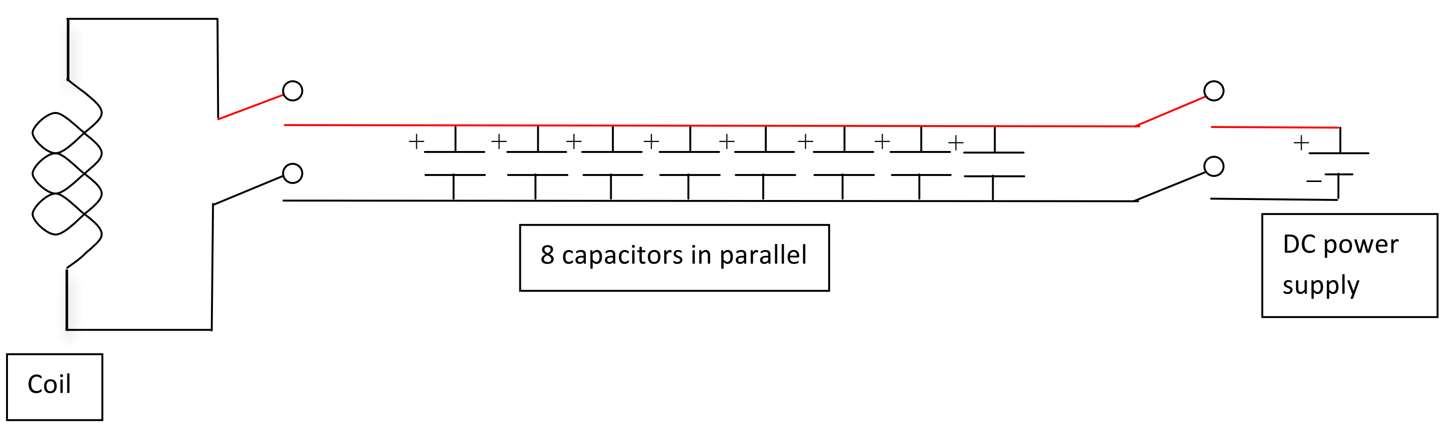
Wire (18-20 Ga)	coil	$7	N/A
PVC Pipe (20 mm diameter)	coil integrity	$5	N/A
Electrolytic Capacitors (250V 1000uF)	Energy storage	$4.75 each	HSC

Appendix B: Circuit Diagram



Appendix D: Archive

Old Circuit Diagram



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