Electromagnetic Acceleration:

Asynchronous Linear Induction Motors

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By
Wilson Wong
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David P. Belanger
Advisor

David P. Belanger
Senior Theses Coordinator

David P. Belanger
Chair, Department of Physics

ABSTRACT

A coil-gun uses pulsed currents of large magnitude to propel ferrous projectiles at high speeds. The various problems associated with high currents and magnetic fields are discussed, as well as the components and design of my experimental coil-gun. I tested the coil-gun at various charge voltages and different projectile sizes, then calculated the efficiency of the coil-gun with measured values of muzzle speed, projectile weight, and discharge energy.

INTRODUCTION

The first projectiles known to mankind were simple rocks thrown by hand. Eventually, devices like the catapult, slingshot, and bow were invented to propel projectiles with pure mechanical forces that were far greater than a man's arm and hand were capable of producing. These mechanical devices that use stored potential energy were limited to the strength of the elastics or springs that store the energy, and were not capable of propelling objects at supersonic speeds. The invention of black powder, and eventually the modern smokeless gunpowder, allow rifles like the Barrett M82 to fire a projectile at about 2.5 times the speed of sound [2]. However, as time progresses, so does the search for technology to propel projectiles at higher speeds.

Electromagnetic accelerators like rail-guns and coil-guns are not limited by the properties of gas expansion, and thus have no theoretical limits on velocity [3]. The US Navy has ongoing research, and even a few operational experimental rail-guns for use on battle ships. The advantages of such high projectile velocities is that effective ranges are greatly increased, to more than 200 nautical miles, with the energy at impact still about equivalent to a Tomahawk missile [4].

Rail-guns are currently more efficient than coil-guns because of the amount of research the US military is putting into them, but coil-guns are still a promising technology. Coil-guns currently run at only 1-4% efficiency, but they do not generate large clouds of plasma out the muzzle like rail-guns do at high powers. They also do not suffer from erosion due to electrical arching, and therefore have lower maintenance and operational costs than rail-guns.

The main idea behind a coil-gun is to generate a magnetic field from a solenoid with high currents to attract a ferrous projectile, then shut down the field and current to let the projectile continue through and out the other end at high velocities. Coil-guns are also known as Gauss guns, named after Carl Friedrich Gauss, who formulated the mathematical descriptions of magnetic effects in magnetic accelerators [5]. The basic components include a power source, a solenoid, a barrel, and a switch. These four components will only work together in very low power and low efficiency applications, because with the high voltages and currents encountered in more powerful guns, there are many complications that can arise. These include power switching, EMP and counter-EMF generation, power loss from resistance, and charging.

POWER

The maximum muzzle velocity of a coil-gun is completely dependant on the current that runs through the gun, since the magnetic field generated inside a solenoid is proportional to the current applied and the number of turns divided by the length [1], as shown in Eq. 1.

$$B=\mu nI/L \quad (1)$$

Capacitors are the perfect power source because they are able to hold large amounts of energy and release all of it in fractions of a second. The energy a capacitor holds is dependant on the square of the voltage at which charge is stored [1], shown in Eq. 2.

$$U=(1/2)CV^2 \quad (2)$$

A basic capacitor consists of two parallel plates separated by a small distance, as shown in Fig. 1.

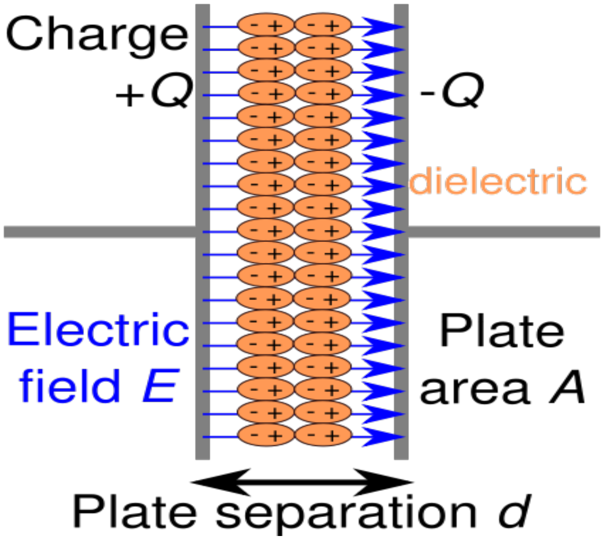

Figure 1: Basic capacitor illustration [6].

The capacitance C of a capacitor can be calculated by dividing the amount of charge on each conductor by the voltage between them. The amount of charge each conductor can hold is dependant on the surface area of each conductor, whereas the maximum voltage is dependant on the capacitor's ability to insulate the two conductors from each other. It is difficult to have a high voltage capacitor that can hold a lot of charge in a small package, since both increased conductor surface area and increase conductor insulation both require larger internals.

In addition to high energy capacity, a good capacitor for use in a coil-gun application must have low ESR and ESL, or equivalent series resistance and inductance. If a multi-meter were to be used to measure the resistance between the anode and cathode of a capacitor, it would read "open" or infinite resistance, because the anode and cathode are not physically connected in a capacitor. However, during discharge, there will be a small amount of resistance from the inherent imperfections in the capacitor material itself. There are also special pulse-rated capacitors that have larger leads and extra heavy duty internals to handle higher currents encountered in pulsed power applications.

The capacitors I used in my coil-gun are three Cornell Dubilier capacitors rated at 450VDC that hold 2,400μF of charge each. Using equation (2), the three capacitors connected in parallel should provide 720 joules of energy. It only takes about 16 joules of energy crossing a human's heart to stop it, and should all 720 joules happen to be released in an uncontrolled manner, such as accidental short circuiting, it could release a bright flash of light and a shockwave similar to that of a stick of dynamite. The prototype rail-guns the Navy have used capacitor banks that store over 9,000,000 joules of energy [3]!

SOLENIOD

The magnetic field generated by a solenoid is given by Eq. 1 above, and the generated field shape is shown in Fig. 2 below.

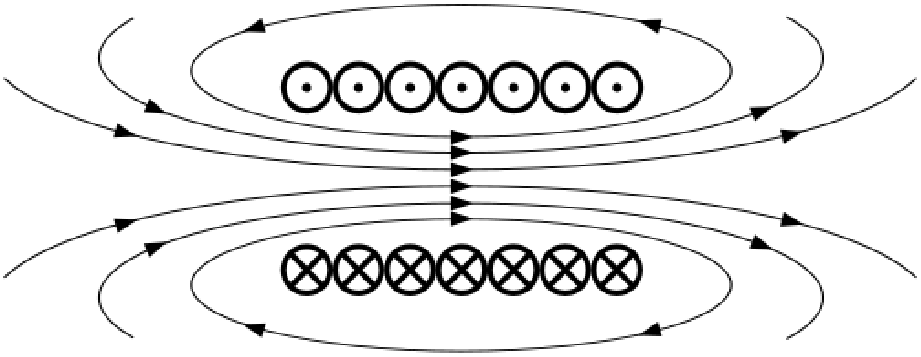

Figure 2: Solenoid cross section with its generated magnetic field [7].

This cross section of a typical one-layer seven-turn solenoid shows the generated magnetic field when current is running through it. The current is coming out of the page in the bottom and into the page at the top.

The solenoid, along with the power source, are the two most important components because they control how much power can be discharged, and with how much efficiency. The resistance of the solenoid is the main source of resistance the coil-gun will have, and is determined by the gauge of wire used. The resistance determines the maximum current pulse that can be generated from the capacitors, since current is voltage divided by resistance [1], given in Eq. 3 below.

$$V=IR \dashrightarrow I=V/R \quad (3)$$

I can now calculate the maximum current that will flow through the solenoid with the known resistance of the coil, which is 0.2 ohms according to my multi-meter, and the charge voltage of the capacitors. The maximum current without considering other sources of resistance should be about 2,250 amperes. If only the resistance of the solenoid is considered, and assuming 100% efficiency, the maximum theoretical magnetic field that my solenoid can generate with fully charged capacitors is about

34,000 Gauss! The typical magnetic field generated inside a magnetic resonance imaging machine is only 15,000-30,000 Gauss [13].

Other sources of resistance include the ESR of the capacitors, and the resistance of the power switch, but two are small in comparison with the solenoid. Solenoids, consisting of multiple turns of wire, also have a significant amount of inductance. An inductor resists changes in current, so the more turns a solenoid has, the more inductance it will have, causing the capacitors to have a longer discharge pulse, and lower peak current.

The length of the solenoid itself does not affect the magnetic field it generates as long as the turns per unit length is constant. However, if the solenoid is too short, there will only be a small timeframe to switch off the current before the projectile crosses the midpoint and begins to get pulled back inside, reducing muzzle velocity, or in extreme cases, firing backwards. Having a coil that is too long, in contrast, will reduce the efficiency of the coil-gun. A projectile in the center of a powered solenoid will experience no force, but if moved towards either end, it will get pulled back to the center. The force is greatest just past the end of a solenoid, and diminishes towards the center. Therefore, even if the capacitor bank was able to provide a high current for the period of time required to pull the projectile from one end into the middle of the solenoid, the projectile is experiencing very little acceleration after entering 1/4 of the solenoid, resulting in wasted energy.

My solenoid is wound with 12AWG solid copper wire, with 90 turns in about three inches length. The resistance of this coil is about 0.2 ohms, as measured by my multi-meter. Considering that there will be minimal resistance from the other components, I should theoretically be seeing maximum current pulses of 2,250 amps without considering the inductance of the solenoid.

POWER SWITCHING

In order to handle the large amount of current that will flow once the circuit is completed by the switch, special solid-state switches are required. Normal switches and contactors can weld together when trying to complete the circuit, because normal switches do not close instantly. There is a point when the tiny imperfections on the contact plates of a contactor touch before the rest of the plate physically closes together, as well as arching that can occur right before full contact. The resistance of these tiny imperfections can generate immense I^2R losses, which can weld the contacts together before the switch actually fully closes.

I use a small silicon controlled rectifier in my coil-gun, rated at 600VDC, and 3500 amps pulse. Silicon controlled rectifiers, also known as thyristors or SCRs, are made of four layers of alternating P and N type semiconductors [8]. A diagram of the basic SCR is shown below in Fig. 3.

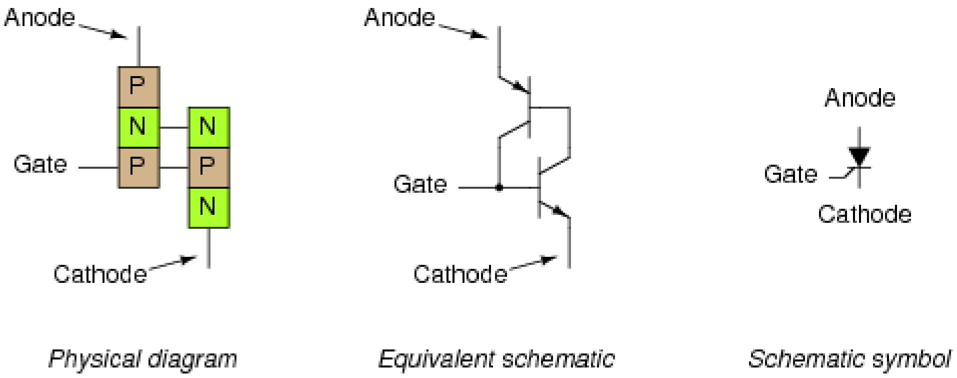

Figure 3: Diagram and schematic of an SCR [8].

By applying a small voltage between gate and cathode, the lower transistor (NPN) will be forced "on" by the resulting base current, which will cause the upper transistor to conduct, which then supplies the lower transistor's base with current so that it no longer needs to be activated by a gate voltage [8]. Once latched "on", there is no way to turn off the SCR until the current flowing through falls below the holding current. This is not a problem in my application, because I want the capacitors to drain fully. If the gate receives a small current pulse but the current through the SCR less than the holding current, the SCR will not turn on.

If used correctly, the SCR is the only logical choice in electromagnetic pulse weapons, with its high pulse current ratings, instant conduction, complete silence, and low (relative to the voltage and current it can pass) trigger pulse requirements. The only downside is that in order to properly conduct and transfer excess heat from the internals, the SCR must be smashed between two heat-sinks with forces in the hundreds of pounds per square inch to several thousand pounds per square inch for larger SCRs. My SCR is held in between four 3/16" aluminum plates, bolted together with nylon bolts, as shown in Fig. 4 below.

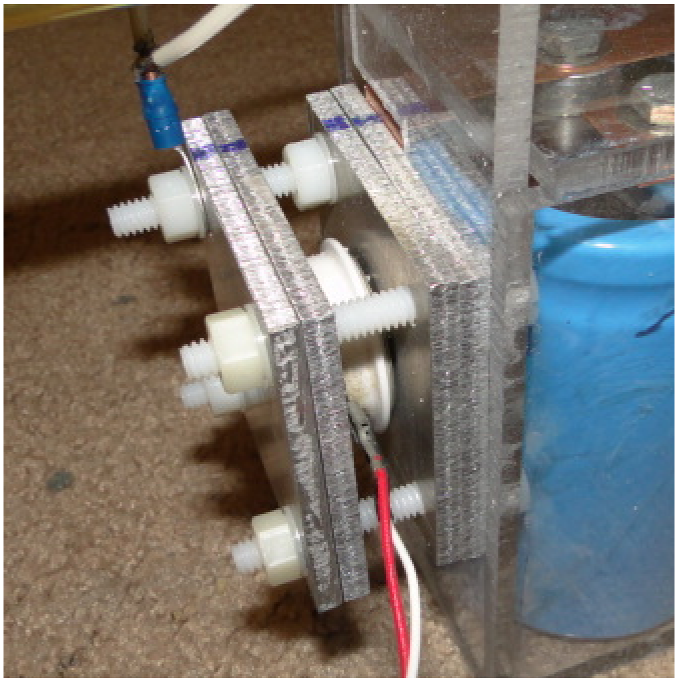

Figure 4: Custom SCR mount to maintain pressure for conduction and heat removal.

I chose to use nylon bolts because I cannot have a path of conduction between each side of the SCR. Using a regular steel bolt would simply let the current bypass the SCR, making the SCR useless and completing the circuit.

PROJECTILE

Kinetic projectiles by definition do not contain any explosive payload, and destroy targets by transferring sheer kinetic energy into shock waves and heat. Projectiles fired by coil-guns and rail-guns fall into this category, since they can be fired at speeds that no conventional weapons can achieve.

There are a few special qualities that projectiles used by electromagnetic weapons must have to be effective, in addition to the standard armor piercing abilities. First, the projectile used in a coil-gun must be of ferrous material so that the generated magnetic field can attract the projectile, but it must also be non-magnetizeable. If the projectile were to become magnetized, energy would be lost in the magnetization process, and result in lower muzzle velocities.

Second, the higher the magnetic permeability, the stronger the magnetic field can pull on the projectile. However, permeability does not help much if the material saturates too easily. The force a magnetic field exerts on a ferrous material is roughly linearly proportional to the field until the material reaches its saturation point. Past this point, increasing the magnetic field will still increase the force exerted, but with diminishing returns. Therefore, having high permeability *and* high saturation is required, but if one needed to choose, having high saturation is slightly more advantageous.

In terms of shape, the worst shape is a sphere, since it concentrates the maximum mass into the least amount of volume, thus achieving little acceleration. I chose to use a cylinder shape, since it is easy to make, and fills the barrel completely, eliminating free space between it and the solenoid and allowing maximum magnetic coupling. I used a 1/2" cold rolled steel bar cut into various lengths. Of the few materials that were available to me in a 1/2" round bar, the cold rolled steel was the best choice. The other two materials, wood and aluminum, are not ferrous at all.

CHARGING

Charging high-capacity capacitors at high voltages can prove to be quite a problem without spending a lot of money. If money was not an issue, the best way to charge by far would be to use an adjustable industrial DC power supply that can provide a voltage of at least the maximum rating of the capacitors to be charged. Industrial power supplies are by no means cheap, so most home-made coil-guns make use of a variac, step-up transformer, and full wave bridge rectifier in series to charge at an acceptable rate. A variac can provide 0-180VAC to a step-up transformer that doubles the variac voltage, and the full-wave rectifier will change the AC to DC.

Industrial power supplies may be able to charge the fastest, but the cheapest way to charge is with the use of a Cockcroft–Walton generator. A Cockcroft-Walton generator, or CW generator, is named after John Douglas Cockcroft and Ernest Thomas Sinton Walton, who in 1932 used this circuit to power a particle accelerator [9]. It converts AC power to high voltage DC power at low currents using a series of diodes and capacitors. The CW generator can easily be made to output ten times the input voltage, in either half-wave or full-wave versions. The full wave version requires almost twice the number of diodes and capacitors, but puts out a much smoother DC voltage. A schematic of a simple two-stage half-wave CW generator is shown below in Fig. 5.

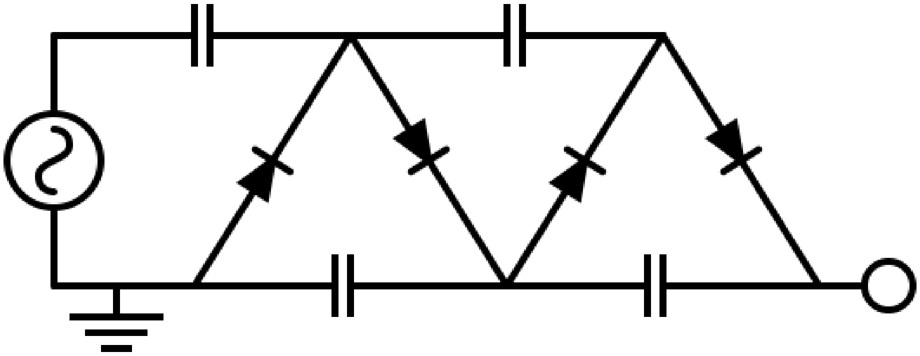

Figure 5: Schematic of a two-stage Cockcroft-Walton generator.

At the time when the AC input reaches its negative peak potential, the leftmost diode is allowing current to flow from the ground into the first capacitor. When the AC signal reverses polarity, the first diode switches off, and the second switches on. Now current flows out of both the AC source *and* the first capacitor, charging the second capacitor to twice the charge held in the first. Every time the AC switches polarity, the capacitors boost the voltage towards the right. The increase in voltage, then, is the number of stages times twice the input voltage.

In my coil-gun I used a three stage half-wave CW generator to achieve 660VDC from a typical 110VAC wall outlet. The output current of my CW voltage multiplier is extremely low, and takes about two hours to fully charge my 720 joule capacitor bank. Because of the way the CW generators are built, I am also able to achieve lower voltages of 440VDC and 220VDC simply by tapping the output in earlier stages, similar to a multi-tapped transformer. My capacitors are rated at 450VDC, so I am forced to only make use of two out of the three stages available on my CW generator. Below in Fig. 6 is a picture of my custom three stage CW generator.

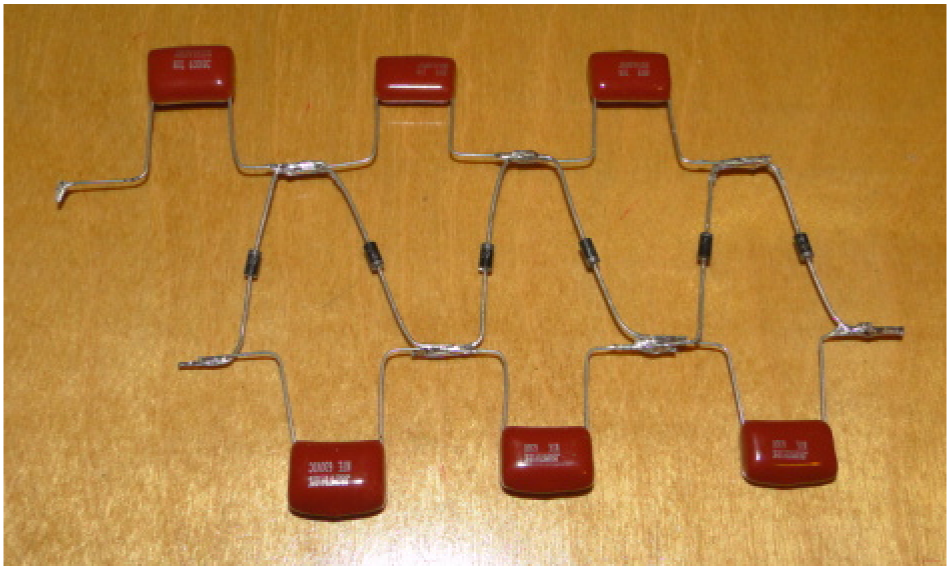

Figure 6: My custom three stage half-wave CW generator.

It contains six IN4007 diodes rated at 1000V, and six NTE capacitors rated at 630V, soldered together in the half-wave version of a CW generator. AC input goes in from the upper left capacitor, and is grounded at the lower left capacitor. For 660VDC output, the positive terminal is located at the far right, and the 440VDC output is in the top mid-section, as indicated in Fig. 5. The DC negative terminal is the same ground as the AC input.

EFFICIENCY

Since the coil-gun technology is currently 1-4% efficient at best, one of my goals is to maximize the efficiency of my coil-gun. The main losses come from I^2R resistive losses, which primarily come from the solenoid. If the resistance of the solenoid were to drop any lower than it currently is at 0.2 ohms, then the maximum current pulse would exceed the capabilities of my SCR switch. The only way to reduce resistive losses, then, is to incorporate multiple stages, each with a smaller current pulse. Multiple stages require a much more complicated set-up, involving photo-sensors to properly time the triggering of subsequent coils, but would be well worth the reduction in resistive losses, since the loss is proportional to the current squared.

The other large source of energy loss comes eddy currents generated in all parts of the coil-gun, but most evident in the barrel and projectile. Eddy currents are generated in conductors to oppose the change in flux that created them [10]. The change in flux would be the magnetic field created by the solenoid during firing, which at 34,000 Gauss is quite large. The eddy currents circulate around the surface of the conductor they are in, and create their own magnetic field that is opposite to the original field. I chose to use a brass barrel because it has a low coefficient of friction and so that I can use the largest possible diameter projectile that will fit into the solenoid. However, brass is a conductor, so in order to minimize the eddy currents, I cut seven alternating 1mm wide slots along the length of the thin barrel. I did not put one single slot that runs the length of the coil because when the coil-gun is fired, the coil contracts. One long slot would allow the coil to contract and squeeze the barrel against the projectile. Figure 7 shows one of these slots that the coil does not cover.

Figure 7: Slot in brass barrel to minimize eddy current generation.

The slots in the thin brass were easy to cut with a Dremel equipped with a cutting blade, but the projectiles were a different story. The 1/2" cold rolled steel projectiles are subject to eddy currents, but they did not give to the cutting blade of the Dremel, so I was not able to put shallow slots into the projectiles. This will lower the overall efficiency of the coil-gun as the projectiles will have an induced magnetic field that opposes the one generated by the solenoid, reducing the effective acceleration.

The last major improvement to the efficiency of the coil-gun would be the application of external iron. External iron would help with the efficiency of the coil-gun by reducing the size of the magnetic field outside of the solenoid. The iron, if used correctly, will guide the magnetic field through itself from one end of the solenoid to the other end, and will prevent the magnetic field from expanding too far outside the solenoid. This will concentrate more of the magnetic field onto the projectile, thus increasing the force exerted. Figure 8 shows an AutoCAD rendering I created to show proper placement of external iron, if it is to be used effectively.

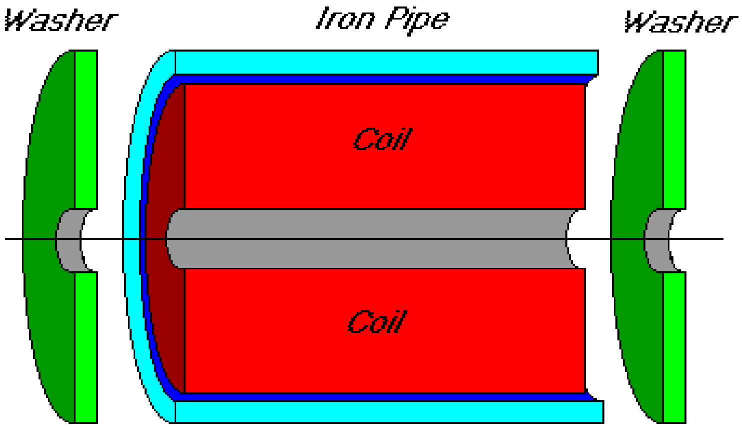

Figure 8: AutoCAD rendering of external iron placement.

The red element is the existing coil, around the empty space inside the barrel. The green elements are iron washers that go on each end of the coil, with and internal diameter equal to that of the barrel. The last element, the light blue element, is the iron pipe that fits around the coil, and is tightly clamped by the two green washers. The thickness of the iron does not affect its ability to redirect magnetic fields because iron has such a high magnetic permeability.

POTENTIAL PROBLEMS

The biggest problem that plagues coil-guns involves the very magnetic field that accelerates the projectile. Thousands of amperes of current run though a sufficient sized solenoid will generate strong magnetic fields, but once the current is shut off, the magnetic field will collapse. This changing magnetic field will induce a current in the solenoid which can be equal or greater in magnitude than the original current pulse, albeit shorter. The direction of this current, unfortunately, is in the opposite direction of the original flux that caused it according to Lenz's Law [1]. This will reverse charge the capacitors and overload the SCR, potentially resulting in catastrophic failure for both components. This is known as a back-EMF, or counter-EMF, and can be avoided or blocked with the addition a simple resistor or diode.

The easiest and most effective method of preventing the back-EMF in the first place is to wire in a resistor in series with the solenoid. With the proper resistance, the coil-gun can be made into a critically damped RLC circuit that resists the back-EMF generated in under-damped systems. This method is often not used, however, because a critically damped system will have a very long discharge pulse with a much lower peak current. This will have a detrimental effect on final projectile velocity since the maximum magnetic field generated is much lower than an un-damped system. Also, since the solenoid will be energized for an extended period of time, the projectile can pass the center of the solenoid before the discharge finishes, and get sucked back into the solenoid.

Another simple method to prevent back-EMF damage is to direct the current back into the coil over and over, to allow the resistance of the solenoid to dissipate the energy. This is the method I am using in my coil-gun. This energy will heat up the solenoid, and allow it to safely cool down slowly. In order to redirect the current, the use of a flyback diode is required. A flyback diode is basically a diode placed in reverse parallel with the solenoid, as seen in Fig. 9 below.

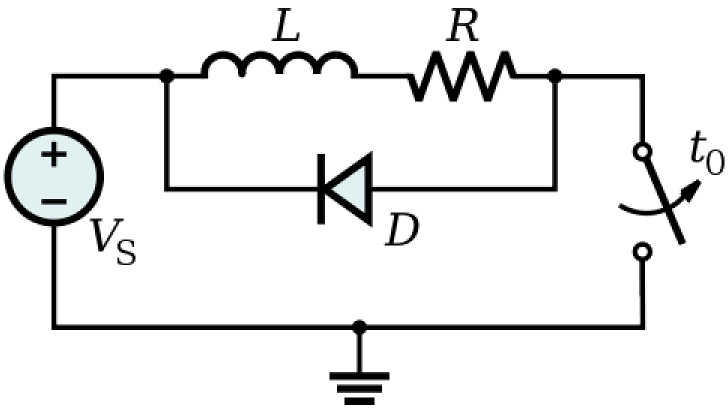

Figure 9: Diagram of a flyback diode in a simple inductive circuit [11].

V_s would be my capacitors, L is the solenoid, D is the flyback diode, R is the resistance of the solenoid, and t_0 is the SCR. When firing, the diode blocks current and forces all of the energy through the solenoid until the capacitors are finished discharging. At this instant, the SCR will turn off and create an open point in the circuit. When the magnetic field collapses, it will generate current in the direction of the original pulse. However, since the SCR is now off, the current goes through the only complete circuit: an infinite loop through the diode and solenoid.

SAFETY

With a capacitor bank that holds 720 joules of energy, any small malfunction could potentially trigger an explosive failure of various components. I designed a trigger box with a 15 feet long cable the fire the coil-gun from a distance. The trigger box contains eight AA batteries in series with two switches to prevent accidental firing. Figure 10 below shows the illuminated safety toggle switch and the push-button fire switch mounted on a galvanized steel box containing the batteries to trigger the SCR.

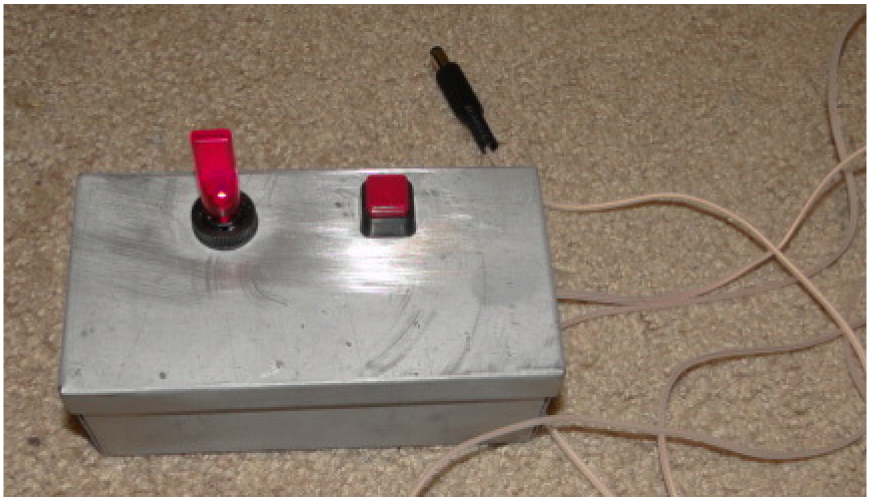

Figure 10: Trigger box with 15 foot cable.

Another subject of concern is the natural charge build-up in the capacitors, and how to safely discharge the coil-gun without firing. To prevent charge from building inside the capacitors over time during storage, a 1,000 ohm bleeder resistor is used that connects the two copper bars of each terminal. The discharge the capacitor bank when fully charged, a 25W ten thousand ohm resistor is connected between the two sides of the capacitor pressure plates. The large resistor can safely discharge all 720 joules in less than five minutes, without overheating.

Finally, during firing, all electronic devices within a ten foot radius of the coil-gun were moved away to avoid the electromagnetic pulse generated by the large change in magnetic field. Electromagnetic pulses, or EMPs, can destroy electronic devices by inducing damaging current and voltage spikes [12].

RESULTS

The finished coil-gun with SCR, flyback diode, discharge resistor, and trigger box are shown in Fig. 11 below.

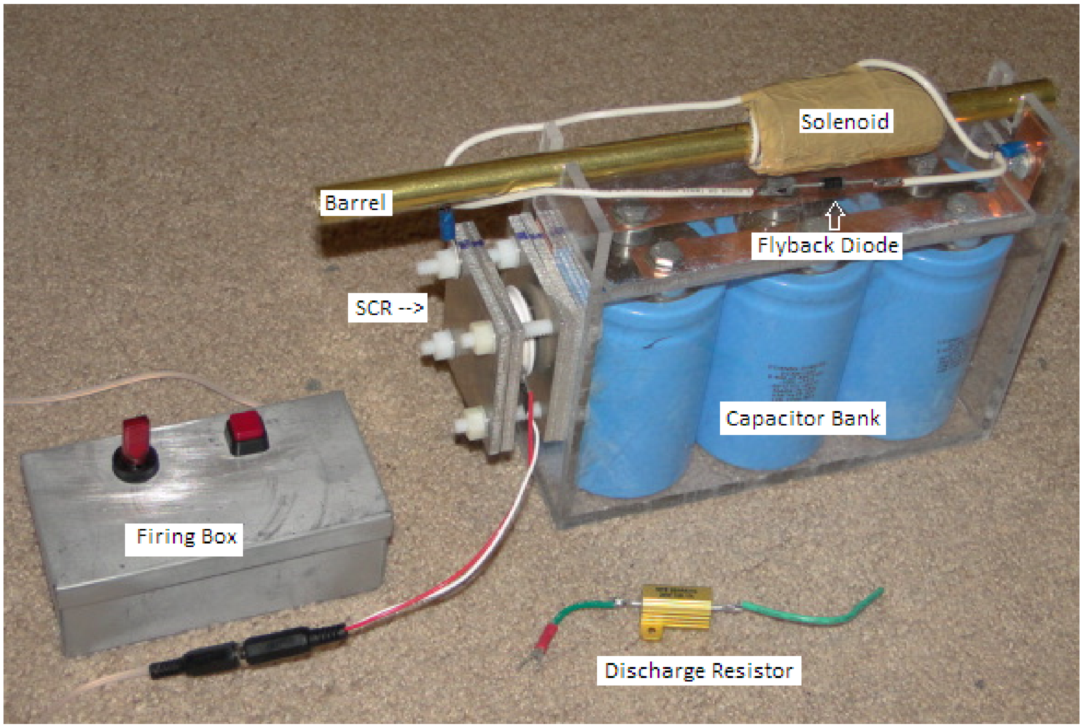

Figure 11: Finished product.

The completed circuit is shown in Fig. 12 below, and includes the trigger box circuit.

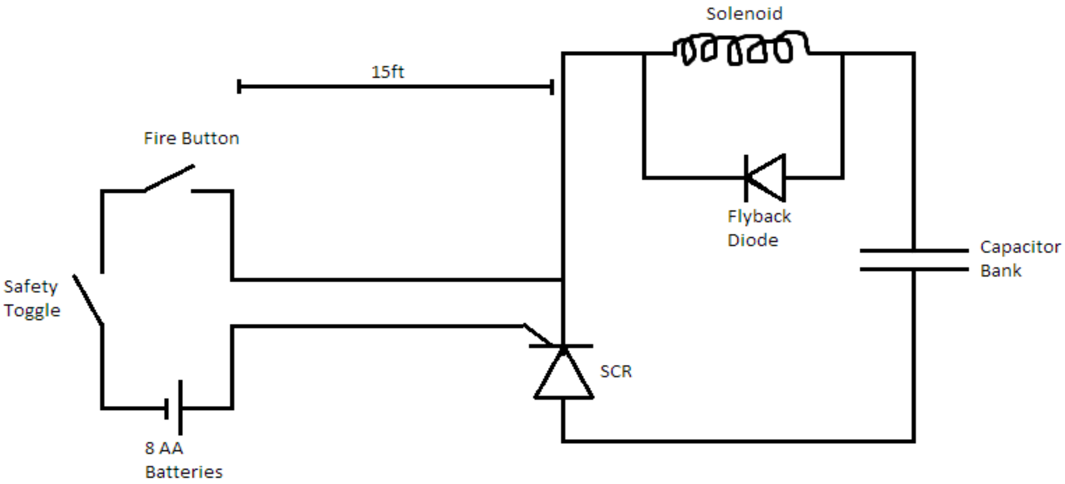

Figure 12: Completed circuit.

I initially started testing the coil-gun at 220VDC so that in case something went wrong, there would not be as much energy involved. The tests went well for the various lengths of projectiles at 220VDC, but when I charged the capacitors to their full capacity of 440VDC, the SCR would not trigger. I still have not figured out why this is the case, since it should be easier to trigger an SCR when it is holding back higher voltages. I checked all connections to make sure there was no open point in the circuit, and made sure the batteries in the trigger box were new, but to no avail. Luckily, I had the discharge resistor to safely discharge the 720 joules.

I recorded the muzzle velocity of each of the successful shots with a friend's chronograph, and was able to calculate the efficiency of each shot by dividing the kinetic energy of each projectile with the known discharge energy. The kinetic energy is given by elementary kinematics in Eq. 4 below.

$$E=1/2mv^2 \quad (4)$$

The mass of each projectile was measured on a digital scale, and the velocity was obtained with the chronograph. Table 1 below shows the statistics of each shot, with the efficiency of each.

Charge Voltage	**Charge Energy**	**Projectile Length**	**Projectile Mass (g)**	**Projectile Speed (m/s)**	**Projectile Energy**	**Final Effeciency**
220VDC	175 J	1.75"	48	11.73	3.33 J	1.9%
220VDC	175 J	2.0"	50	12.68	4.02 J	2.3%
220VDC	175 J	2.25"	58	13.00	4.9 J	2.8%
220VDC	175 J	2.5"	62	12.34	4.72 J	2.7%
220VDC	175 J	2.75"	69	10.56	3.85 J	2.2%
440VDC	720 J	-	-	-	-	-

Table 1: Results of successful shots.

The most efficient shot is the one with a projectile length of about 75% that of the solenoid. The efficiency is just about equal to what coil-guns are capable of today, but I feel that if I was able to get some shots off with 440VDC in the capacitors, the efficiency numbers would not be much better. The higher current from a full charge will increase I^2R losses, and result in more heat.

However, if I incorporated external iron and had the tools to put a shallow slot in each projectile, I can probably squeeze 1-2% more efficiency out of my coil-gun design. If I were to go even further and make two or three more stages to lower the current pulse in each stage, I should be seeing even more improvements in efficiency.

CONCLUSION

Coil-gun technology today is far from practical usage in terms of efficiency, but with more research into this field, there should be promising results, just like the rail-guns. I was able to design and build a fully functional small scale coil-gun with slightly less than 3% efficiency in terms of input/output energy, but with a few modifications and possibly scaled up to multiple stages, the efficiency of my coil-gun could potentially be twice as efficient. With more time and funding, I plan to continue modifying the coil-gun; eventually adding two more stages, slotted projectiles, and external iron to each stage. I would need to incorporate photo-sensors to trigger subsequent stages, and a whole new capacitor, SCR, and flyback diode circuit on each stage.

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