UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Multistage Coilgun Part 2

ECE 445 Final Report

Alejandro Esteban Otero

Parker Li

Theodore Culbertson

TA: Jackson Lenz

Project No. 53

3 May 2017

Abstract

The coilgun is a type of projectile accelerator that uses the electromagnetic field created by a solenoid to propel a bullet. The energy is stored in three different banks of capacitors that will release it to the inductors to accelerate the bullet. Our group was tasked with taking charge of the power component of the project, and we designed and implemented the triggering circuit for a correct and reliable firing of the gun. Furthermore, we incorporated new features in order to make possible the correct charge of the capacitors and added several features to make this device safer.

Table of contents

1. Introduction

1.1 Background

The multistage coilgun is a project originally developed in 2013 by a group of students for their Senior Design Project. It is a type of projectile accelerator in which the driving force is created by the magnetic energy gradient along the axis of the barrel. Current flowing through a coil will induce current to flow in the opposite direction in a conductor within the coil. These opposing currents create a repulsive force between the projectile and the coil, propelling the projectile forwards. The self inductances of the armature and stator coils are independent of position; thus the force is only dependent upon the mutual inductance, which is a function of the relative position between the armature coil and the stator coil [1].

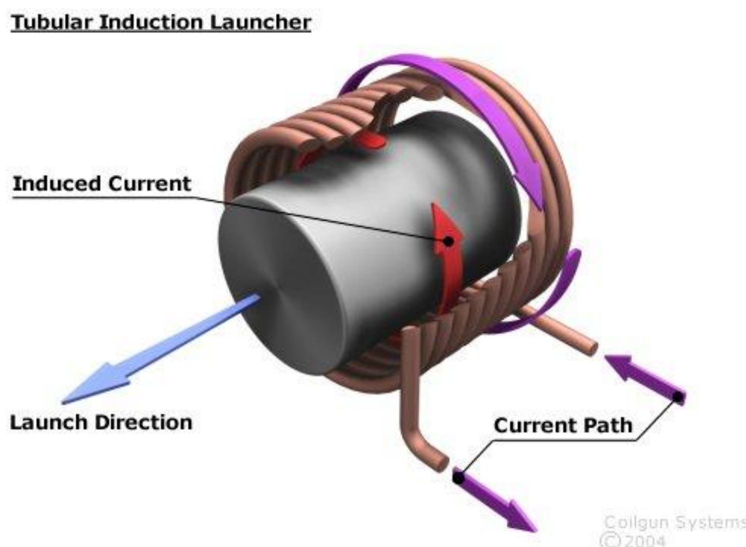


Figure 1: Coilgun theory overview [2]

The coilgun is multistage because it consists of three coils rather than just one. Current is sent through the first coil to accelerate the projectile from standstill, then the other two coils are given current as the projectile passes through them in order to continue accelerating it. If each coil is fired at the optimal time, the projectile will be accelerated much more than if there were only a single coil. However, if a coil is fired at the wrong time, it may slow down or even stop the projectile. We are using multiple position sensors and a microcontroller to locate the projectile and determine the optimal time to fire the second and third coils.

The group from 2013 was successful in firing the gun, but the project still presented some issues to be solved. The main issue was the high failure rate of some components, which were frequently overloaded due to the high current and voltages present in the system [3]. Other issues included accidental discharging of the capacitor bank due to improper use of the charging control. The system lacked a method to guard against user error.

1.2 Objective

The purpose of this project is to be an educational exhibit on the use of electromagnetic force. It is intended to be a permanent exhibit for Engineering Open House (EOH). It has been demonstrated there several times already, always drawing great interest from visitors. Our team has completed and optimized the project such that it can be displayed at EOH every year with minimal setup, difficulty, or need to replace components.

Two groups have been working on this project this semester. Our team was in charge of improving the longevity of components and upgrading the charge controller. We also added extra safety features to several components of the project.

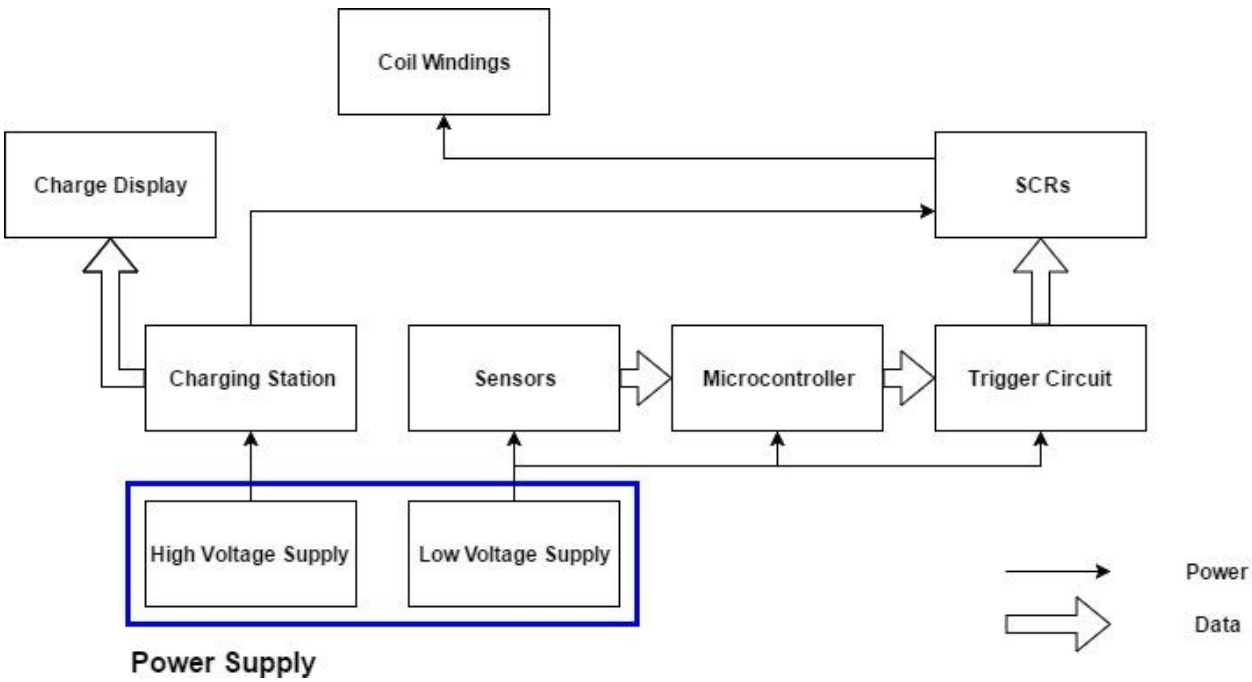


Figure 2: Block Diagram

1.3 Overview

Figure 2 shows the major components of our project. Our team is responsible for all blocks other than the sensors and the microcontroller. The other team, Team 52, was in charge of those two components.

The basic operation of the coilgun begins with the power supply being used to charge the capacitors in the charging station. When the gun is to be fired, a signal is sent from the microcontroller to the triggering circuit which will trigger the SCR to conduct current to the first coil. This accelerates the projectile through the barrel towards the other two coils. As the projectile passes through the second coil, the sensors allow the microcontroller to determine its position and the optimal time to signal the triggering circuit. When it does, the next SCR will conduct current to the second coil, further accelerating the projectile. The process repeats when the projectile passes through the third coil.

2. Design

2.1 High Voltage Power Supply

The high voltage power supply must provide the energy to the capacitors that will later be used to fire the coilgun. It must be able to supply the voltage to which we intend to charge the capacitors. This power supply is meant to be a permanent fixture of the coilgun, so the lab benches are not acceptable.

The group from 2013 obtained six 50 V DC power supplies that could be connected in series, powered by a single wall outlet, and permanently fixed to the same table as the coilgun. We have been charging the capacitors to 200 V, so we connected four of these supplies in series.

There was some concern over whether these smaller supplies connected in series could provide the necessary power. Our primary requirement on them was voltage, and we quickly determined that four supplies in series could provide approximately 197 V, well within our acceptable margin. Since the high voltage supplies would only be used to charge capacitors and would never have to provide continuous power, there was no requirement on the amount of current they could supply. However, we decided that they should be able to charge a single 30,000 µF capacitor bank to within 10% of the target 200 V in less than 10 seconds. The four supplies in series proved adequate to meet this requirement, as shown in Figure 3.

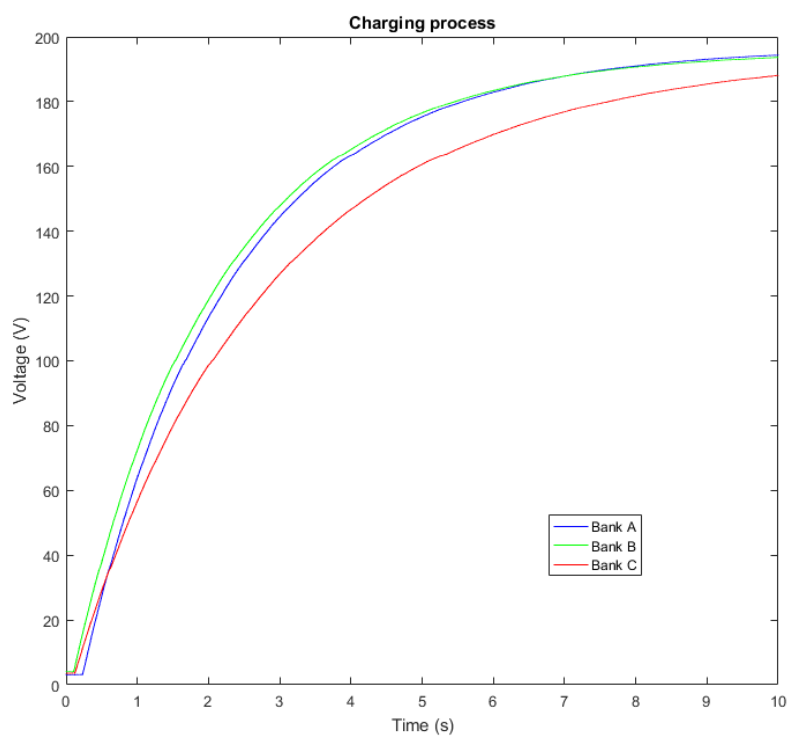


Figure 3: Capacitor Charging Process

2.2 Charging Station

The charging station stores the energy that is used to fire the coilgun. It consists of three banks of capacitors. The first bank contains four 10,000 μF capacitors connected in parallel, while the other two banks contain only three capacitors.

The capacitors purchased by the group from 2013 are rated to 450 V. By the end of their time working on the project, they were firing the coilgun by charging the capacitors to 120 V [3]. We have been charging the capacitors to 200 V, still well within the capacitors' specifications.

Between the size of these capacitors and the danger of the high voltage they would be charged to, it was necessary to design enclosures for them. The group from 2013 built three large boxes that would hold the capacitors. These enclosures have six ports on the front for all of the cables necessary to connect the banks to the rest of the circuit. There are also two ports on the back, but there was nothing that we needed to connect them to, which left them as a way for the user to access high voltage components of the circuit. To remove this danger, we disconnected these ports.

The enclosures also included fiberglass covers on the top that could be removed in order to replace the SCRs or manipulate the connections to their gates. However, removing these covers would allow the user direct access to the capacitors, which could be charged to high voltages. In order to mitigate this danger, the boxes were designed with an aluminum bar that would short the capacitors when the cover was removed. Shorting highly charged capacitors would be dangerous, but we consider it to be a better option than giving the user direct access to metal bars with 200 V across them.

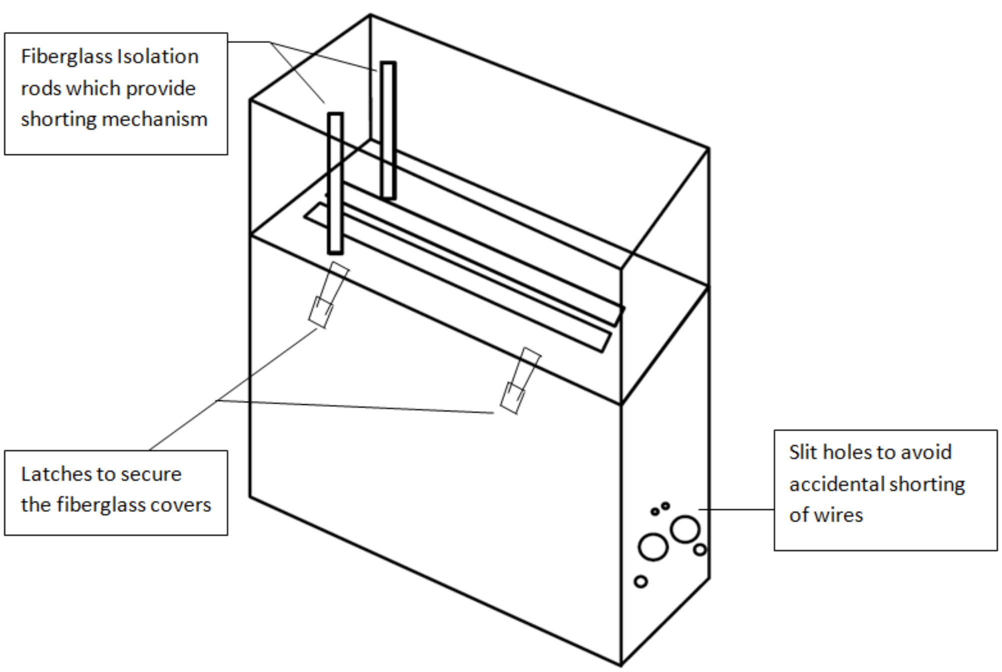


Figure 4: Capacitor Bank Enclosure [4]

2.3 Charge Controller

The charge controller is a box with three buttons, each of which allows current to flow from the high voltage power supply to one of the capacitor banks. The buttons were only rated to receive 10 A of current, so a 20 Ω resistor was included between the power supply and the buttons to protect these components.

However, the design used by the group from 2013 still risked damage to the buttons. If more than one button were pressed at the same time, current could flow from one capacitor to another with only the resistance of the wire impeding it. This created a very high risk that the current through the buttons would exceed 10 A. Previous users of the coilgun complained of frequently having to replace the buttons after making this mistake.

To alleviate this, we included diodes with each of the switches to ensure that current could not flow from one capacitor to another. An alternative solution would have been to include resistors in place of these diodes, but this still would have allowed the capacitors to share charge if two buttons were pressed at the same time. We decided that it would be better to only allow the capacitors to be charged by the power supply, so we used diodes instead of resistors.

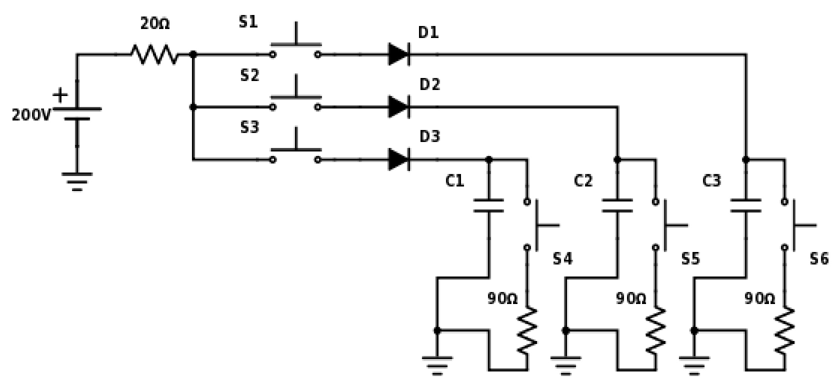


Figure 5: Charge Controller with Diodes

In addition to the charge controller with the diodes, Figure 5 shows the discharge circuits that were attached to each capacitor bank. The capacitors sometimes carried some excess voltage after the gun was fired, and there had to be a way to get rid of this voltage. We connected a switch and a 90 Ω resistor across each capacitor bank so that we could return the capacitor to 0 V after each firing.

2.4 Charge Display

The charge display lights an LED when the voltage of the capacitor bank is above 25 V. There is an identical module for each of the three capacitor banks. This is meant as a safety feature to warn the user that the capacitors have been charged to a potentially dangerous voltage. Voltmeters are used on each of the three capacitor banks during regular operation, but the numbers displayed on them are not easily visible and they turn off after a few minutes. The charge display acts as a more consistent, easily noticeable warning.

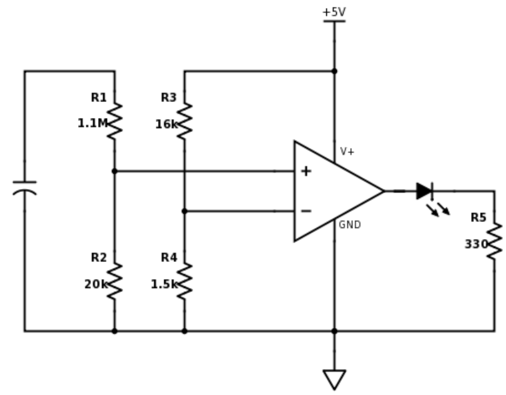


Figure 6: Charge Display Module

Figure 6 shows the design of the charge display, which uses voltage dividers to bring the capacitor voltage to a manageable level and to establish a reference voltage to compare it against. These two signals are compared by a comparator which outputs a logical one only when the non-inverting input is at a higher voltage than the inverting input. The resistor values were chosen with two criteria in mind. Firstly, the non-inverting input could not go above 5 V or it might damage the comparator. Since the capacitor voltage was expected to reach 200 V, the divider had to lower the voltage below 2.5%. Secondly, the non-inverting input had to be at a greater voltage than the inverting input when the capacitor charge had reached the target voltage of 25 V, and at a lower voltage when the capacitor charge was less than 95% of the target voltage.

$$200V\left(\frac{R_2}{R_1+R_2}\right) < 5V$$

$$0.95(25V)\left(\frac{R_2}{R_1+R_2}\right) < 5V\left(\frac{R_4}{R_3+R_4}\right) < 25V\left(\frac{R_2}{R_1+R_2}\right)$$

The above equations express these requirements mathematically. Substituting in available resistor values that satisfied these requirements, R1 was chosen to be 1.1 MΩ, R2 was chosen to be 20 kΩ, R3 was chosen to be 16 kΩ, and R4 was chosen to be 1.5 kΩ. R5 was chosen to be 330 Ω to limit the current through the LED while still allowing it to turn on when it received 5 V.

A charge display circuit was built and tested on a protoboard as a proof of concept. While this initial circuit met all functional requirements, we were unsuccessful in constructing a final version on a PCB. The PCB was designed to use the wrong package for the comparator IC. Stopgap measures to work around this initially appeared to have been successful, but several pins of the comparator quickly became stuck at unexpected voltages. We believe this was a result of the imprecise soldering that was necessary. As such, we were not able to integrate the charge displays into the finished product.

2.5 Trigger Circuit

The coilgun supports a sequence of up to three stage firings. The microcontroller gives the signal to the initial stage to fire, then handles the timing for the subsequent stages to fire. The microcontroller is a digital device that is capable of outputting the 5V necessary to trigger the SCR, but not the current required to trigger the SCR. Thus the triggering circuit was designed to be an intermediary between the firing signal coming from the microcontroller to the triggering signal into the SCR gate. The triggering circuit provides the power to trigger the SCR from a low voltage power supply rather than through the microcontroller. It was also necessary to include a pulse transformer to act as an electrical isolation unit between the low power side and the high power side. This was done to avoid damage to the microcontroller should a fault or error occur on the high power side.

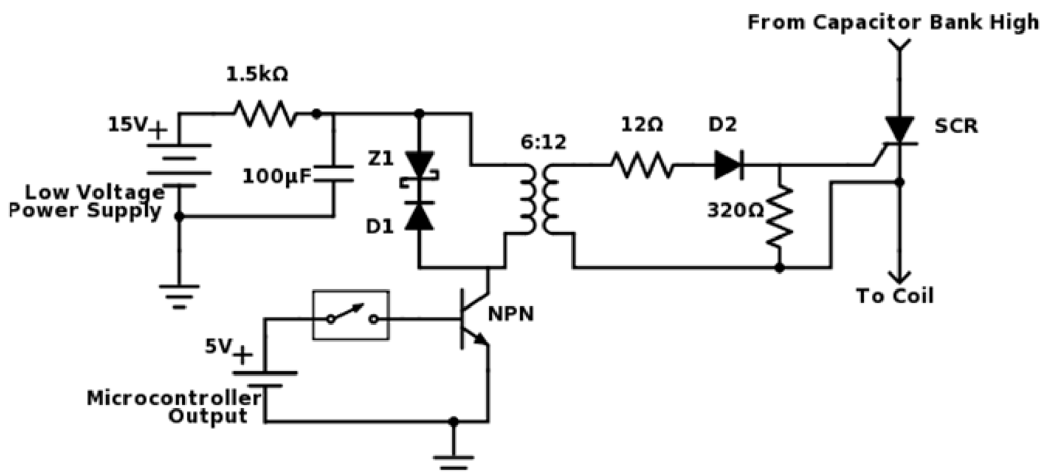


Figure 7: Triggering Circuit Schematic

Figure 7 shows the schematic for the triggering circuit. The main responsibility and need for the triggering circuit is to shape the trigger signal that will go into the gate of the SCR. Triggering the SCR requires a minimum of 150mA flowing into the SCR gate as well as having the SCR gate be biased at least 3V above the SCR cathode.

We achieve this criteria by drawing the current from a 100µF capacitor. The low voltage power supply charges this capacitor through a resistor during the cooldown periods between firings. Once the signal from the microcontroller is high, it turns on the NPN mosfet and a path of conduction is made between ground and the capacitor. The current flows through the left side of the pulse transformer. A voltage and current is induced on the right side of the pulse transformer, flowing through a resistor divider to give us the voltage difference between the SCR gate and cathode.

The pulse transformer consists of a coil winding ratio of 6 to 12, wrapped around a solid ferrite core. The resistor values in the resistor divider on the right side of the schematic allows us to easily increase or decrease the voltage difference between the SCR cathode and gate. Diode D2 ensures that current flows only in the forward direction into the SCR gate, so as not to damage the SCR with a reverse gate current. Diode D1 and zener diode Z1 create a conducting path around the left side of the pulse transformer. When the mosfet turns off, it cuts of the path of current flowing through the pulse transformer. Since current in the pulse transformer cannot go to zero instantaneously, this conducting path through the D1 and Z1 diodes was necessary to allow a path for and to dissipate that excess current.

To ensure the proper functioning of the pulse transformer, saturation must be avoided. According to the next equation, the transformer in our circuit will not saturate within one second at 15V, time enough to turn on the SCRs:

$$\int vdt < NB_{sat}A_{core}$$

$$15V * 1 * 10^{-6}s < N * 0.250 * 13.6 * 10^{-6}$$

$$N > 4.41\ turns;\ N_{low} = 6$$

The aim of the transformation ratio 1:2 is to provide the adequate voltage at the gate.

2.6 SCRs

Current flowing through the coil induces an opposite current in the projectile. These opposing currents create a magnetic field which causes the current carriers to repel each other, allowing the projectile to move since the coil is held in place. To increase the force of the magnetic field, as large of a current as possible is required. We needed a device that was capable of transferring the large amount of energy stored in the capacitor banks to the coils in as little time as possible to get the maximum current. At the same time, the device must be capable of handling the large current without damaging itself. The device that allows us to achieve these criteria is the SCR, silicon controlled rectifier.

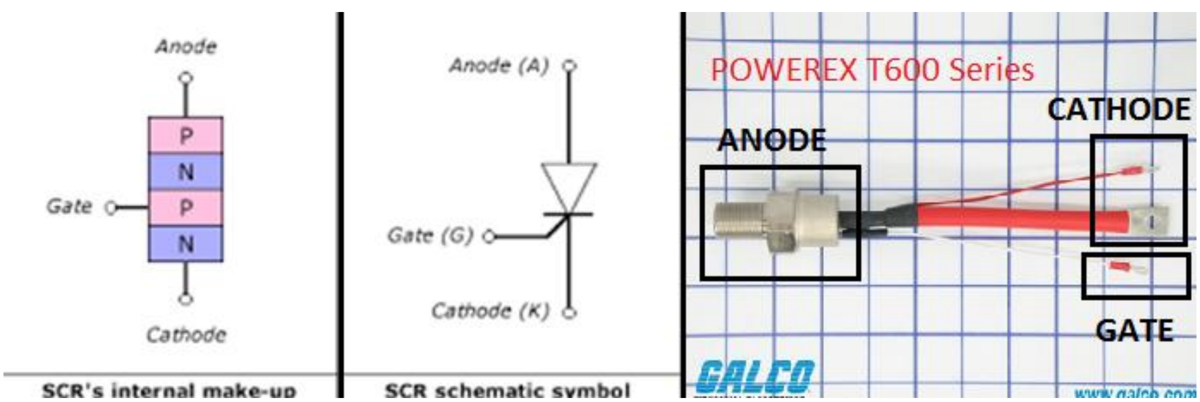


Figure 8: Layout of the SCR

Figure 8 shows the internal, schematic, and physical representations of the SCR. The SCR, or thyristor, is a gate controlled diode. It is made up of alternating layers of P-doped and N-doped semiconductor material. A trigger signal is sent to the SCR through the gate, which then allows current to flow from the anode to the cathode. The gate signal required to trigger the PowerEx T600 series of SCRs which we used for this project is 3V at 150mA [6].

The SCR differs from more common transistors such as the MOSFET or BJT in that the trigger signal is only required to be a pulse. Triggering the SCR sends it into the on state. Similar to a latch, the SCR will remain in the on or forward conducting state until the current flowing through from anode to cathode drops below the minimum holding current. This simplifies the need for a more complex triggering circuit, since we only need to control when the SCR turns on, and not worry about the turn off condition. The SCR will automatically stop conducting once the capacitors have been discharged enough that the current becomes minimal. Furthermore, a SCR in general has a much higher power rating than a MOSFET or BJT.

There are three main modes of operation for the SCR, they are summarized in table 1.

Table 1: SCR Modes of Operation

Mode of Operation	Description	T600 Series Specifications	Use in the Coilgun
Reverse Blocking	The cathode is at a higher voltage than the anode. Since the diode is reverse biased, no current flows.	600V Reverse Blocking Voltage 25mA Leakage Current at 600V	Mode not used in Coilgun
Forward Blocking	The anode is at a higher voltage than the cathode. Since the trigger signal into the gate has not been given, the SCR is in the off, non-conducting state.	600V Forward Blocking Voltage 25mA Leakage Current at 600V	Used to prevent capacitor from discharging into coils until trigger signal arrives.
Forward Conducting	The anode is at a higher voltage than the cathode. The trigger pulse has been given to the gate. The SCR transitions into the on, conducting state and current starts to flow, and will continue to flow until it drops below the minimum holding current.	175A Average On State Current 5500A Peak Surge Current	After the trigger signal arrives, the capacitors discharge through the coils. The SCR will automatically transition into the non-conducting state after discharge.

2.7 Coil Windings

Each stage has two coil windings in parallel. These coils are wrapped around the barrel of the coilgun to provide the magnetic field that accelerates the projectile. The coils are held in place by epoxy.

A major concern was that the resistance of the coils was so low that the system was underdamped. This could potentially cause the thyristors to fail because of current flowing from the coils to the bank of capacitors. Estimating that each coil has around 20 turns and neglecting the effect of the mutual inductance with the projectile and the common magnetic flux between each pair of coils of each stage, we ran a simulation to determine whether this effect could happen and what approximated current peak will take place in this system.

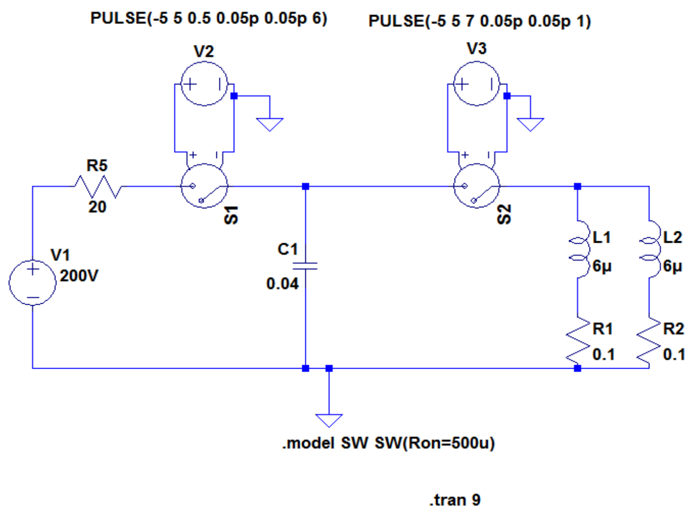


Figure 9: Simulation schematic

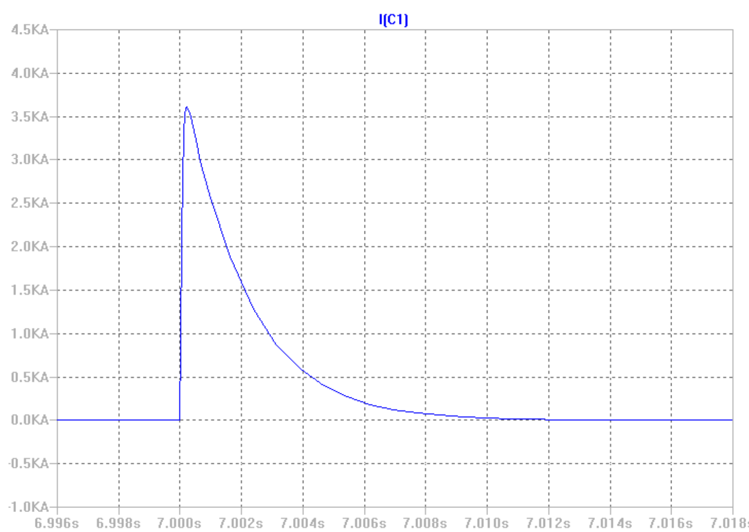


Figure 10: Current transient

Figure 10 shows that with our estimations, the system is not underdamped. Additional testing was necessary to get a more realistic idea of the circuit's characteristics, but we felt that this was a good starting point.

3. Verification

We were able to satisfy the requirements that appear in our R&V table in appendix A. The coilgun has been made into a safer and more reliable device that is suitable for demonstration at Engineering Open House.

The longevity of the SCRs was the main concern for our project. The signal to the gate must fulfill certain requirements to make the operation of the coilgun stable and reliable. Moreover, we carried out a deep analysis of the limits of the switching device to make sure they are not exceeded. The last part of our high level verification involved determining the damping coefficient of the system and its possible implications on the failure of the system.

3.1 SCR stress analysis

One of our first considerations for ensuring the longevity of the SCRs was the maximum current flowing through them. If the current exceeded the 5.5 kA that the SCRs are rated for, then that could explain the high failure rate.

Measuring the current through the SCRs proved difficult. The current probes available to us were not rated for multiple kiloamps, so we could not measure the current directly. We attempted to use a current transformer to step down the amperage to a level that would be measurable, but the pulse was too short to be picked up by the transformer. As such, we were forced to measure the current indirectly. Specifically, we monitored the voltage across the capacitors while firing the coilgun. The current through the capacitors, and therefore through the SCRs, could be determined from the slope of the voltage.

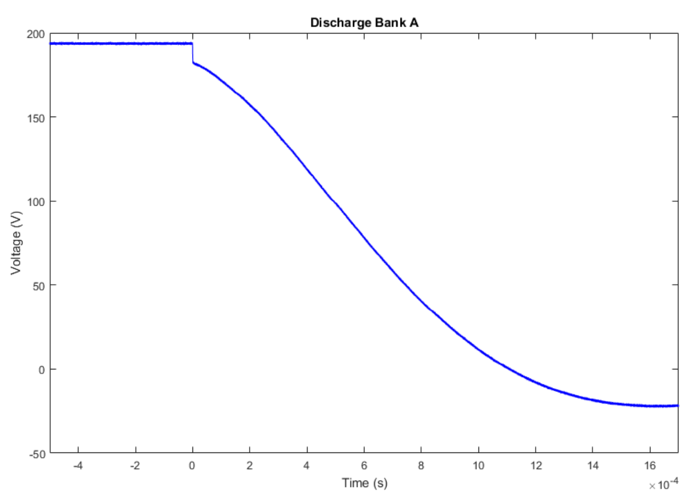


Figure 11: Capacitor Discharge During Coilgun Fire

The first dip in the graph occurs because the coils act as a plain wire instead of an inductor for a very short period of time. This causes a rapid decrease in voltage in the capacitor due to the momentary shorting to ground. To determine the current flowing from the bank of capacitors we used the Ordinary Least Squares fitting and applied the capacitors equation.

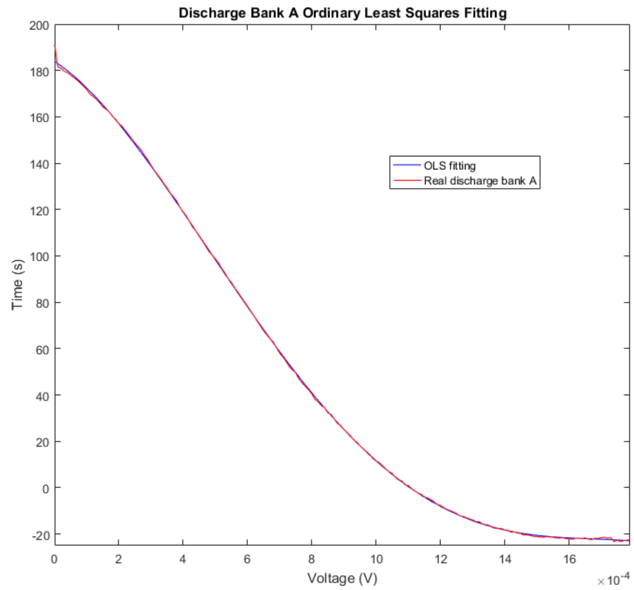


Figure 12: Ordinary Least Squares Fitting of Capacitor Discharge

To determine the point in time in which the current is maximized, we find the point in which the derivative of the function reaches its maximum. The value of this maximum current is smaller than the maximum value that can be handled by the number of SCRs that are installed in parallel for each bank.

$$\frac{dV_c}{dt}_{max} = 2.06 * 10^5 V/s$$

$$Capacitor's\ equation: i_C = C\frac{dV_c}{dt}$$

$$i_{C_{max}} = C\frac{dV_c}{dt}_{max} = 0.03 * 2.06 * 10^5 = 6.18kA$$

From this, we determined that the peak current from the capacitors is 6.18 kA. While this exceeds the tolerance of a single SCR, each bank of capacitors has at least two in parallel. If they are dividing the current evenly, then each will only receive 3.09 kA, well within their rating.

3.2 Trigger signal analysis

Our next consideration was whether or not the triggering circuit could provide the necessary voltage and current to turn on up to three SCRs in parallel. SCRs connected in parallel share the same gate voltage, same cathode voltage, and same anode voltage. Current flowing into the gate for each SCR, however, might not be shared equally if there is inadequate current to trigger all the SCRs. If not all of the SCRs were being turned on at the same time, then it is possible they would not share the same anode to cathode current and thus allow overloading of the peak forward current to occur.

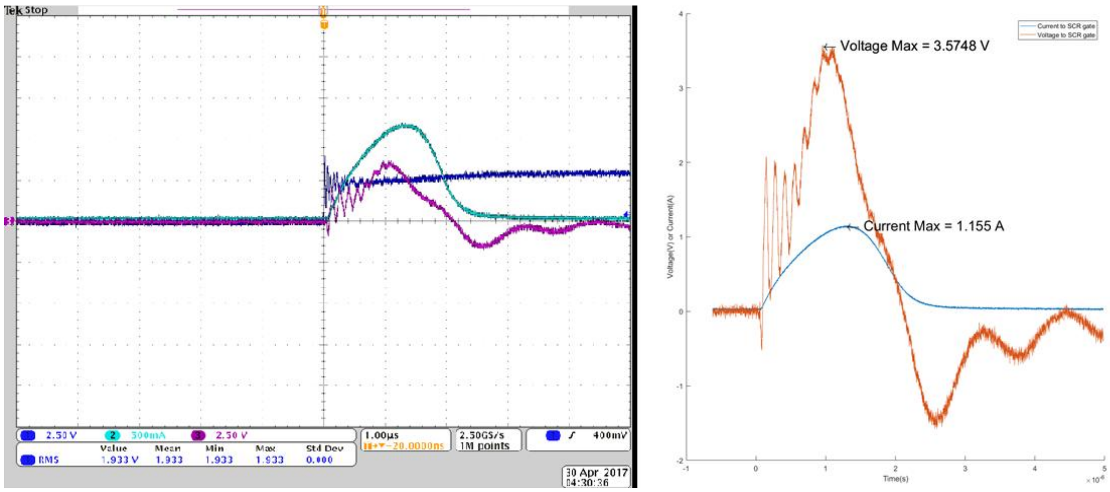


Figure 13: Voltage and Current into SCR Gate

Figure 13 shows the output from our triggering circuit, which is the signal that goes into the gates of the parallel connected SCRs. The dark blue on the left side of figure 13 is the output from the microcontroller. The microcontroller is incapable of instantly giving a zero to 5V pulse, it oscillates on the rising edge. It takes time for the microcontroller firing signal to reach steady state high, and that oscillation is translated into the triggering signal, which is shown in the rising edge of the orange voltage plot on the right of figure 13. The pulse transformers and diodes in the firing circuit prevent sudden changes in the current, which is the reason why the current plots in teal and light blue of figure 13 are much smoother.

The right side of figure 13 shows the output of the triggering circuit with voltage in orange and current in light blue, scaled in the vertical axis in terms of volts or amperes. We notice that our peak gate voltage is around 3.6V, which is higher than the 3V necessary to trigger the SCRs. We also note that the peak current is 1.155A, which is more than adequate to trigger two or three SCRs in parallel. The maximum number of SCRs in parallel we have is 3, meaning we need at least 450mA to trigger. With this, we can be that our updated triggering circuit is providing the necessary voltage and current to turn on all SCRs.

3.3 Coil voltage analysis

As a safety precaution, we needed to make sure that the voltage of the coil returned to ground as soon as possible after firing, because the coils were not enclosed and could be accidentally touched. For this test, we measured the voltage across the capacitor and coil simultaneously during a limited firing. Due to the open capacitor bank testing, we limited ourselves to ⅓ of the voltage of an actual firing. We gave the triggering circuit the firing signal and measured the discharge voltages.

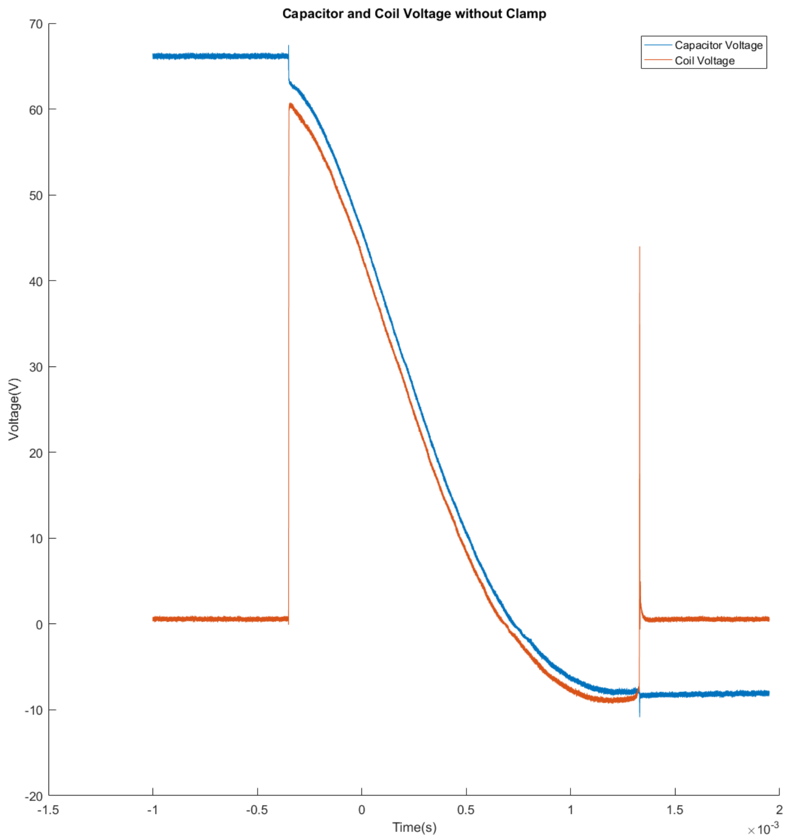


Figure 14: Limited Firing Coil and Capacitor Voltages

Figure 14 shows the resulting voltage plots of the capacitor in blue and coil in orange. There are three main regions and two important points to note. Area 1 occurs before the SCR has been given the triggering signal. The coil is at ground and the capacitor remains at a constant high voltage because the SCR leakage current at around 66V is very small. Area 2 occurs after the SCR has received the triggering circuit. The SCR connects the capacitor bank to the coil and the capacitor starts to discharge through the coil. The voltage of the capacitor and coil mirror each other in area 2, the difference being the resulting voltage drop across the SCR and the natural resistance of the wires and coil windings. Area 3 occurs after the SCR has turned off and no current flows. The coil returns to ground and the capacitor stays at a constant negative voltage.

The first important point occurs when the SCR initially transitions into the conducting state. There is a sharp decrease in voltage of the capacitor, the result of a momentary short as we have already discussed before. The SCR connects the capacitor bank to the coil, resulting in a large voltage spike in the coil. The second important point occurs when the SCR turns off. A zoomed in portion of this important point on figure 14 is shown in figure 15.

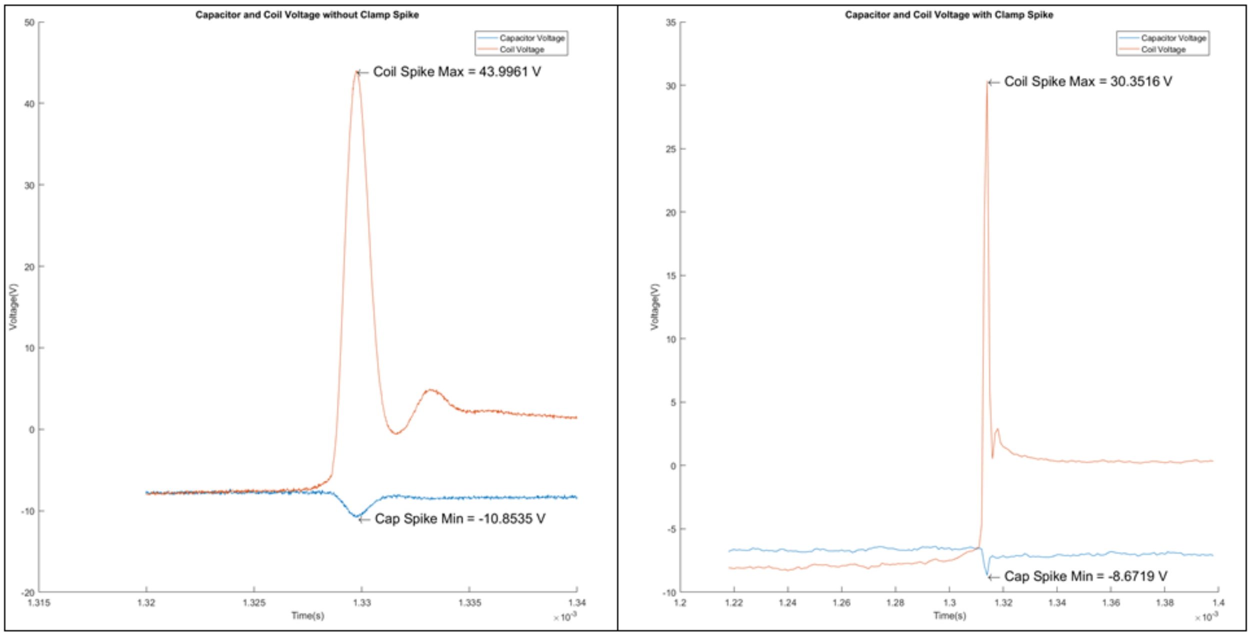


Figure 15: Coil Voltage Spike

The voltage across an inductor is proportional to the change in current through the inductor. When the SCR turns off, there is a sudden decrease in current. This extreme change in current causes the voltage across the inductor to spike, as shown in Figure 15.

We attempted to mitigate the effect of this voltage spike by introducing a clamp across the coil. This clamp consisted of a resistor and diode in series. When the voltage spiked in the coil, the diode would turn on and start to dissipate the excess voltage across the resistor. Our hope was that this would quickly dissipate the residual energy in the coil and return the voltage of the coil to ground. Our testing results in Figure 15 showed that the clamp did in fact reduce the magnitude of the coil voltage spike, but not significantly enough to warrant the extra complexity added to the system. We saw that the voltage spike was very quick, lasting for around 2.5µs. In this short amount of time, the diode would not have had adequate time to turn on to dissipate the excess voltage anyways, as the coil voltage quickly returned to ground with or without the clamp.

4. Costs

4.1 Parts

The team from 2013 purchased the majority of the parts necessary for the operation of the coilgun. We made use of any and all of these parts that were not damaged. Notably, all of the necessary high voltage capacitors and SCRs had already been purchased for us. In total, $1611.07 was spent on parts for the coilgun in 2013 [3].

Table 2: New Parts Cost

Item	Part Number	Retail Cost($)	Quantity	Actual Cost($)
Gate Driver	MIC4420	1.58	8	12.64
Capacitor (100µF)	UVR2A101MPD	0.52	3	1.56
Power MOSFET	MJE3055T	0.73	3	2.19
Zener diode	1N746A	3.36	3	10.08
Diodes (triggering circuit)	MUR115	0.44	6	2.64
Ferrite Core	FT50-43	0.58	3	1.74
Comparator	LT1713	2.55	10	25.50
Header Connector	0039299062	0.90	3	2.70
Rectangular housing connector	3901-20-60	0.47	3	1.41
Resistor (320Ω, 0.25W)	-	0.13	3	0.39
Resistor (12Ω, 0.25W)	-	0.13	3	0.39
Resistor (330Ω, 0.25W)	-	0.13	9	1.17
Resistor (1.1MΩ, 0.25W)	-	0.13	9	1.17
Resistor (20kΩ, 0.25W)	-	0.13	9	1.17
Resistor (16kΩ, 0.25W)	-	0.13	9	1.17
Resistor (1.5kΩ, 0.25W)	-	0.13	9	1.17
LED	-	0.19	9	1.71
Diodes (charge controller)	1N3913	5.00	3	15.00

Contact block	ECX1040-5	3.00	3	9.00
Total	-	-	-	**92.26**

4.2 Labor

Table 3: Labor Cost

Name	**Hourly Rate ($)**	**Total Hours**	**Total Labor Cost** (Hourly Rate * 2.5 * Total Hours)
Theodore Culbertson	40.00	150	15,000
Parker Li	40.00	150	15,000
Alejandro Esteban Otero	40.00	150	15,000
Total	**120.00**	**450**	**45,000**

4.3 Total

Table 4: Total Cost

Original Parts	$1,611.07
New Parts	$92.26
Labor	$45,000
Total	**$46,703.30**

5. Conclusions

5.1 Accomplishments

Our contributions to the project have made it a safer, more effective, and more reliable demonstration tool. Along with the sensor team, we have completed the coilgun to the extent that it can fulfill its intended function as an exhibit for Engineering Open House that is easy to setup, use, and store.

Our modifications to the triggering circuit enable the SCRs to turn on more consistently, reducing the chance of overloading one of them. Our redesign of the charge controller eliminates the risk of damage due to user error. By including of the charge displays as warnings and disconnecting extraneous sockets from the capacitor banks, we have reduced the risk of electric shock. Our testing also enabled us to determine that the firing voltage could be increased to 200 V without damaging any components.

We have achieved speeds of 12.5 meters per second with a two-stage fire. During our test fires, one of the coil windings came loose from the barrel, which stopped further testing until repairs could be made. However, the speed that we achieved met our expectations for a two stage fire, and we are optimistic that a three stage fire would reach speeds of approximately 15 meters per second or more.

5.2 Ethical Considerations

We paid heed to each point of the IEEE Code of Ethics in designing and working on our project. The first point of the code states that we are responsible "to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment" [5]. Our biggest concerns with regard to this point are the use of high voltage electricity and the presence of a fast moving projectile.

The high voltage electricity used by our coilgun presents a serious potential hazard to the user. The capacitors are intended to be charged to 200 V, a level which can cause electrocution. The group from 2013 went to great lengths to isolate the user from these dangerous components, and we have continued with this commitment.

As discussed previously, the capacitor banks are enclosed in boxes which prevent the user from having direct access to the capacitors. An aluminum bar is in place that automatically shorts the capacitors when the cover of the enclosure is removed. This means that the only access point to the capacitors is through the ports on the enclosures, which should have plugs covering them when the coilgun is in use. Our team determined that the sockets on the back of the enclosure rarely saw use, and therefore presented a potential danger. We mitigated this risk by disconnecting these sockets.

The projectile fired by our coilgun is an aluminum projectile 1 inch in diameter and less than 2 inches in length. It is highly unlikely that this projectile will reach speeds exceeding 20 meters per second. Even so, there is some risk of injury from this projectile. As such, we have been careful never to fire the coilgun at a person or at any breakable object. We have always warned anyone nearby before firing the coilgun.

Another significant piece of our commitment to keep others safe involves documentation. The coilgun is meant to be demonstrated at Engineering Open House for years to come, potentially by users who are not familiar with it. We are working with the sensor team to complete a user's manual with instructions for the safe setup, use, and storage of the coilgun. Our instructions clearly outline the procedures necessary to maintain the level of safety that our group has committed ourselves to. Among other things, the documentation instructs future users never to fire at a person or breakable object and to warn bystanders when the coilgun is about to be fired. If this documentation is followed closely, there will be minimal risk of injury from our project.

5.3 Future Work

There are some areas for improvement of the coilgun as a demonstration tool. These are related to improving the ease of setup and enhancing the speed at which the projectile can be fired.

As it stands now, the coilgun has many loose components and wires. These include several PCBs, switches, and resistors, all of which must be connected properly before the coilgun can be fired. This may leave future users of the coilgun confused. As such, our group is continuing to work with the sensor team to enclose these loose components in boxes with permanent connections between them. Our goal is to minimize the number of connections that need to be made when taking the coilgun out of storage. This will make future demonstrations easier and less prone to mistakes.

We designed all of our contributions to the project with the assumption that the capacitors would be charged to 200 V. However, the power supply can be used to provide 300 V, and it is our belief that the capacitors and SCRs could withstand a firing at that voltage. Some redesign of the triggering circuit would be necessary to fire at this voltage, and additional testing would be needed to determine if all components of the circuit could handle the increased power. But if this could be achieved, it would increase the speed at which the projectile fired, making for a more impressive display.

We also experimented with the possibility of including a resistor-diode clamp in parallel with each coil to increase the efficiency of firing and possibly improve the longevity of some components. Our initial test results showed minimal impact, but more experimentation is needed to say for sure if this would be a worthwhile addition to the project.

References

[1] K. E. Reinhard, “A methodology for selecting an electromagnetic gun system”, Texas, 1992.

[2] Paul, James. (2006). *Coilgun Basics* [Online]. Available: http://www.coilgun.eclipse.co.uk/coilgun_basics_1.html

[3] J. Dagdagan, Y. Ko and S. Nanavati, “Multistage Coilgun: Final Report,” Champaign, IL, Mar. 2013.

[4] J. Dagdagan, Y. Ko and S. Nanavati, “Multistage Coilgun: Project Design Review,” Champaign, IL, May 2013.

[5] (2016). *IEEE Code of Ethics* [Online]. Available: https://www.ieee.org

[6] Powerex, “T600 Phase Control SCR”, T600 Series datasheet, APR. 2006

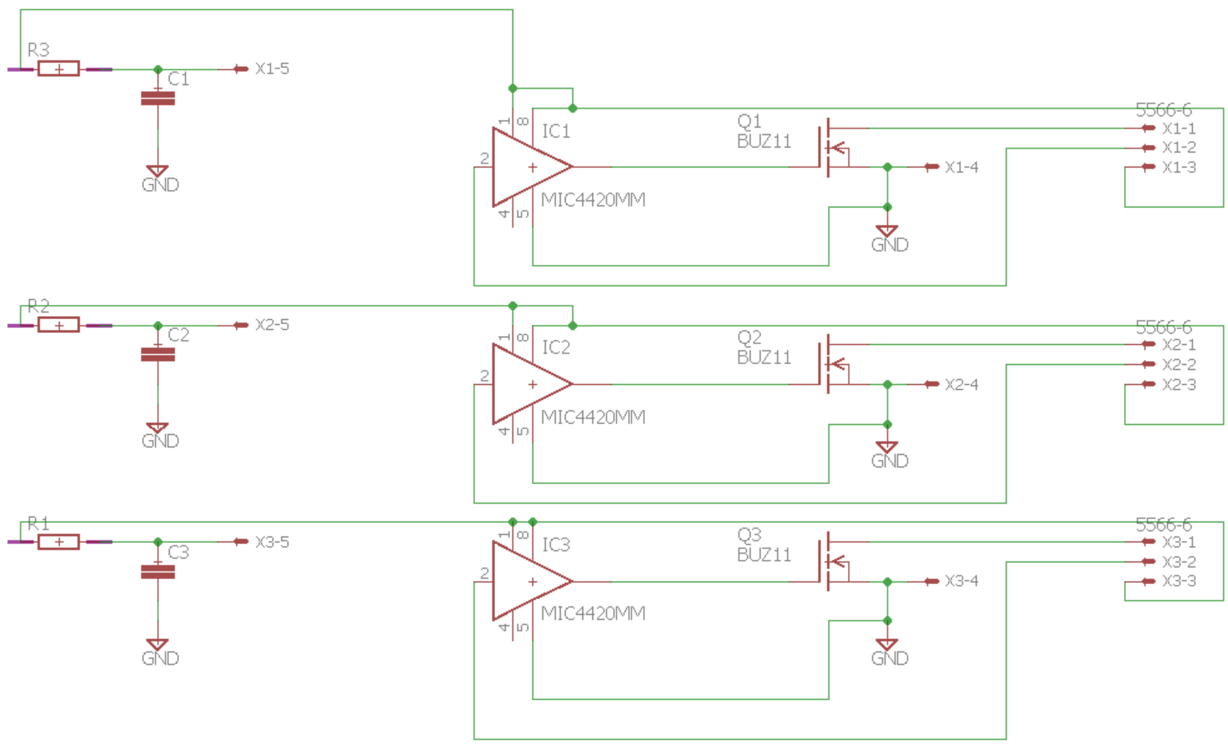
Appendix A: Requirement and Verification Table

Component	Requirement	Verification	Verification Status
High voltage power supply	Power supply must provide 200 V ± 10% voltage and charge a 30 mF capacitor to within 10% of this voltage in 10 seconds or less.	Connect a DMM set to measure voltage across the power supply and record the voltage. Now connect the DMM across a 30 mF capacitor and connect the power supply to the capacitor through an open switch. Simultaneously start a timer and close the switch. When the DMM reads a voltage within 10% of the previously recorded voltage, stop the timer.	Yes
Charging station	1. Capacitors must store at least 95% of the charged voltage for at least thirty seconds. 2. Automatically short the capacitors when enclosure is opened.	1. Charge the capacitors to 200 V ± 10% while monitoring the voltage across the capacitors with a DMM. Record the exact voltage that the DMM displayed, and then disconnect it. After thirty seconds, reconnect the DMM to check if the voltage has dropped by more than 5% of the recorded value. 2. Ensure that the capacitors are discharged. Remove the cover of the enclosure. Check to see that the aluminum bar is making physical contact with both the copper bars attached to the capacitors. Use a DMM to ensure that the resistance between the	1. Yes 2. Yes

		copper bars is less than 0.5 Ω.	
Firing mechanism	1. Provide electrical isolation between high voltage power supply and microcontroller. 2. The pulse transformer must carry the 3 V and 150 mA necessary to turn the SCR on before saturating. 3. The SCRs must withstand at least 100 firings without failing short.	1. Use a DMM to measure the resistance between the output of the microcontroller and the gate of the SCR. The resistance should register as an open. 2. Charge the capacitor of the triggering circuit to 15 V. Measure the voltage across the SCR gate and the current through it with an oscilloscope. Provide 5V to the MOSFET gate to discharge the capacitors through the pulse transformer. 3. Fire the circuit at least 100 times. If there are 100 successful firings with no SCR failing, assume success.	1. Yes 2. Yes 3. Yes
Charge Display	The LED must turn on only when the capacitors are at least 95% of the labelled target voltage.	Begin charging the capacitors while monitoring the voltage across the capacitors with a DMM. The LED must be on when the DMM displays the target voltage and must not turn on before the voltage reaches 95% of the target. Repeat this process for all charge display modules.	Yes
Coil Windings	1. The resistance of the coil windings must be at least 0.04 Ω. 2. Epoxy adhesive must keep the integrity of the coil around the barrel.	1. Use an ohmmeter to measure the resistance of the coil windings. If the resistance is less than 0.04 Ω, a resistor must be added in series with the coils. 2. Check the physical	1. Yes 2. Yes

		condition of the winding structure. Ensure that no parts are loose and that the coil remains in tight contact with the barrel.	
Low voltage power supply	Power supply must provide 15 V ± 10% voltage at 50 mA ± 5%.	Connect the power supply in series with a 300 Ω resistor and a DMM set to measure current. Connect a DMM set to measure voltage across the resistor. Turn on the power supply. Turn off the power supply after taking reading.	Yes

Appendix B: Triggering circuit PCB schematics



Appendix C: Triggering circuit PCB layout