UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Multistage Coilgun Part 2

ECE 445 Design Review

Group 53
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1. Introduction

1.1 Background

The multistage coilgun is a project 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. 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].

Back in 2013, they were successful in firing the gun, but the project still presents some issues that need to be solved. The main issue was the high failure rate of some components, which were easily overloaded due to the high current and voltages present in the system. Other issues include accidental discharging of the capacitor bank due to improper use of the charging control. The system lacked a method to guard against human input error.

1.2 Objective

Two groups are going to be working on this project. Our team will be in charge of designing the triggering circuit and putting it on PCBs. We also want to implement an interface that would facilitate charging of the capacitors. Once this objective is reached we would analyze the current through the SCRs (Silicon Controlled Rectifier) to think of additional improvements that would increase the efficiency of the gun and the speed of the projectile. Our idea is to put a diode and a resistor in parallel with the each coil to prevent the current from flowing backwards, and hence damaging the thyristors.

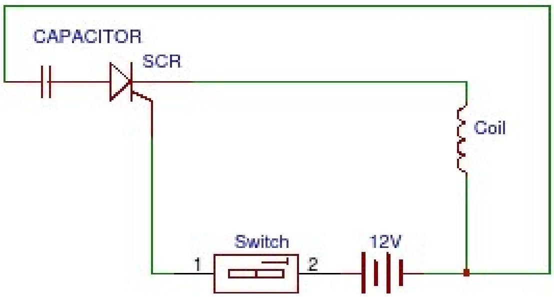

Figure 1: Previous design of the triggering circuit [2]

The issues the actual coil gun present lie in the fact that it has not been fired consistently yet. The SCRs never survived more than 5 firings. Our purpose is to get this gun firing consistently to create a tool for helping other students understand the possible uses of electromagnetic forces. Moreover, the PCBs will be designed to be modular, plug-and-play components, facilitating the operation of the gun and the replacement of damaged parts.

1.3 High Level Requirements

- The gun must perform no less than 100 firings before requiring the replacement of any part of the circuit.
- The projectile will be launched at no less than 14 meters per second.
- The PCBs will be designed to be plug and play. That means we want to have a modular system that is conceived to be exposed to others as an educational tool.

2. Design

The next two figures show the block diagram and the physical design of the coilgun:

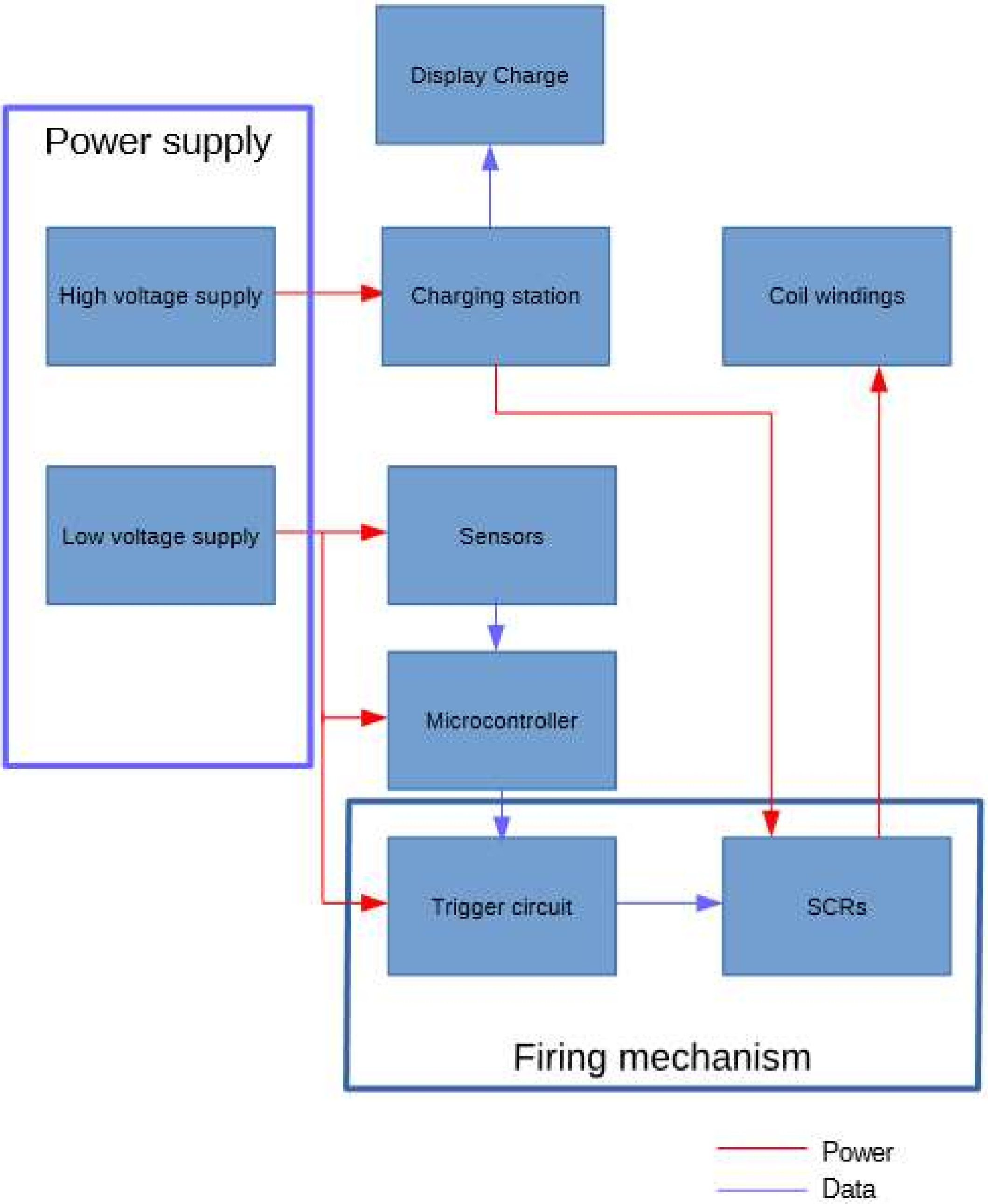

Figure 2: Block diagram

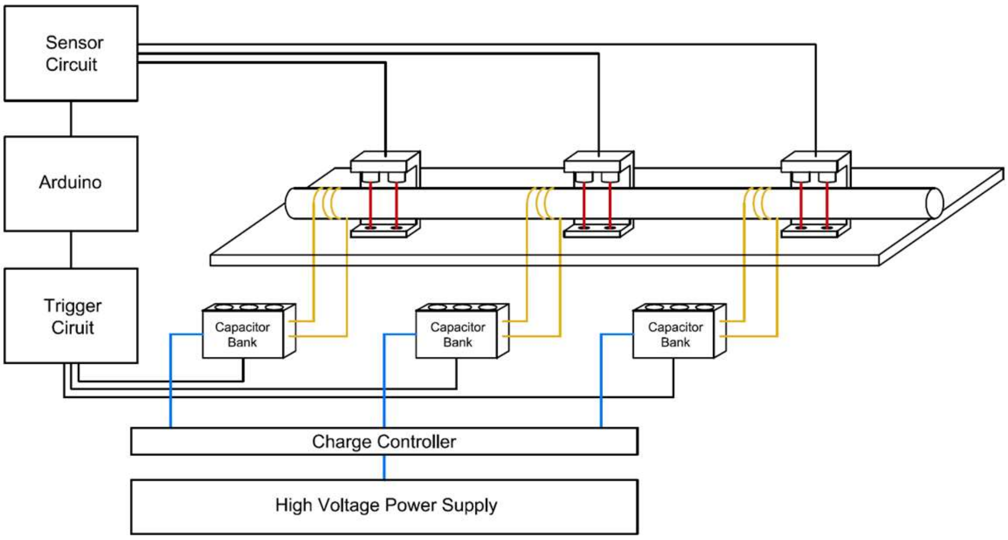

Figure 3: Physical design [2]

2.1 High Voltage Power Supply and Charging Station

The charging station consists of three banks of capacitors that store the energy to launch the projectile. The high voltage DC power supply is connected to these capacitors to provide the needed energy. These two blocks do not need to be redesigned. We will work with the original specifications.

The high voltage DC power supply is provided by four power supplies connected in series mounted on the cart. They will provide the 120 V necessary to meet our requirements.

The charging station includes a bank of capacitors for each of the three stages of the coilgun. The first stage will have four 10,000μF capacitors in parallel. The second and third stages will only have three such capacitors. The capacitors are rated to 450V, but we will only be charging them to 120V.

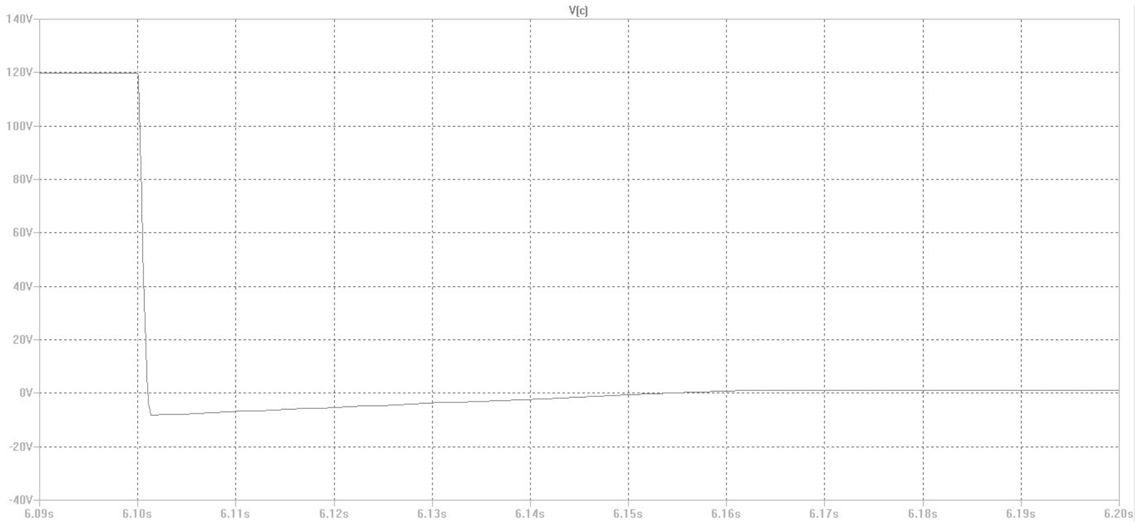

Figure 4: Capacitors discharge

2.2 Firing Mechanism

The thyristor (SCR) acts like a voltage controlled switch. The simplified circuit consists of the charging capacitors, the SCR, and the coils in series. When switched on by the voltage across the two-terminal gate, the thyristor will conduct current from the anode to the cathode. This allows us to prevent the charging capacitors from discharging through the coils before the desired time. The SCRs we have selected have an off-state leakage current of 20 mA. When a high voltage is applied across the two terminals of the gate, current will flow through the thyristor from the charging capacitors to the coils.

The firing mechanism is constituted by the triggering circuit of the SCRs. The objective of this block is to provide the adequate voltage between the gate and the cathode of the SCR to turn it on. At the same time, its design will provide electrical isolation in order to protect the microcontroller and the user from high voltage components of the circuit. The electrical isolation is afforded to us through the transformer.

The 20V power supply is necessary to provide enough voltage to trigger the SCR through the transformer. The transformer provides the electrical isolation between the microcontroller and the firing circuit. The D3 diode is necessary to prevent backflow of current. This ensures that the G node will always be at the same or higher voltage than the K node. The C1 decoupling capacitor will prevent high frequency voltage from passing. DC voltage passes on.R4 and R5 resistors provide the voltage divider to control proportionally the voltage from the transformer that is given to the gate of the SCR. Diode D1 prevents current from flowing through the left side of the left-half circuit instead of through the L1 inductor. Once the L1 inductor begins to oscillate, the D1 diode and the D2 will allow current to flow clockwise while acting as a voltage regulator. The Q1 2N2222 is a NPN transistor that will conduct if the input from the TTL is high. Once the transistor is conducting current, current will be pulled downwards.

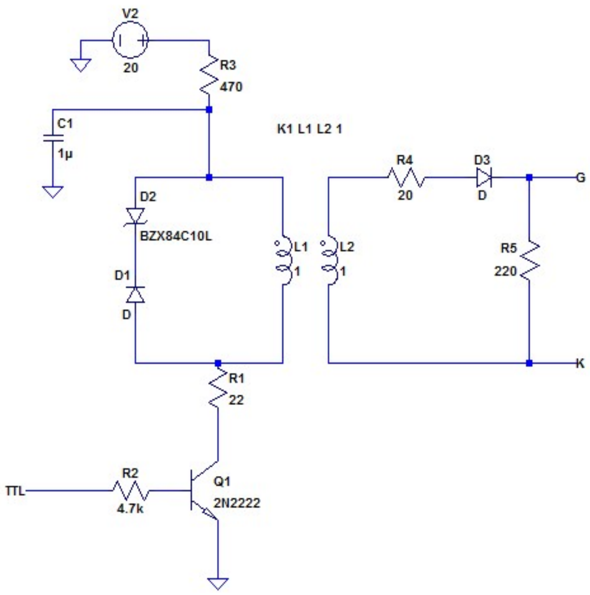

Figure 5: Triggering circuit using a pulse transformer, G and K are the two terminals of the SCR gate [3]

2.3 Display Charge

There is currently no easy way to see if the capacitors have been fully charged. We will implement a system that will light an LED for each capacitor bank that is fully charged. Available comparator circuits cannot handle the 120V that we will be charging the capacitors up to, so we will use a voltage divider to bring it below 5V. This voltage divider must have enough resistance that it will not drain a large amount of power from the capacitors. In particular, we want the capacitor banks to maintain at least 95% of their charge for up to five minutes.

$$\frac{1}{2}CV^2 = \frac{1}{2} * 0.04 * 120 = 288\,J$$

$$\frac{1}{2}CV^2 = \frac{1}{2} * 0.04 * 114^2 = 259.92\,J$$

$$P = \frac{\Delta E}{t} = \frac{288 - 259.92}{5 * 60} = 0.0936W$$

The voltage divider cannot draw more than 0.0936 W of power. This is easily achievable by choosing resistors in the megaohm range.

In addition, we must ensure that the comparator only outputs a high voltage when the capacitors are near 120 V.

$$120V\frac{R_2}{R_2 + R_1} > 5V\frac{R_4}{R_4 + R_3}$$

$$0.95 * (120V)\frac{R_2}{R_2 + R_1} > 5V\frac{R_4}{R_4 + R_3}$$

Choosing common resistor values, we find R_1 = 1.1 MΩ, R_2 = 33.2 kΩ, R_3 = 10 kΩ, and R_4 = 23.2 kΩ. The value of R_5 was chosen simply because it is a common value for protecting LEDs operating at 5V.

$$120V\frac{33.2k\Omega}{1133.2k\Omega} = 3.515V$$

$$0.95 * (120V)\frac{33.2k\Omega}{1133.2k\Omega} = 3.339V$$

$$5V\frac{23.2k\Omega}{33.2k\Omega} = 3.494V$$

This circuit will be replicated for each of the three capacitor banks.

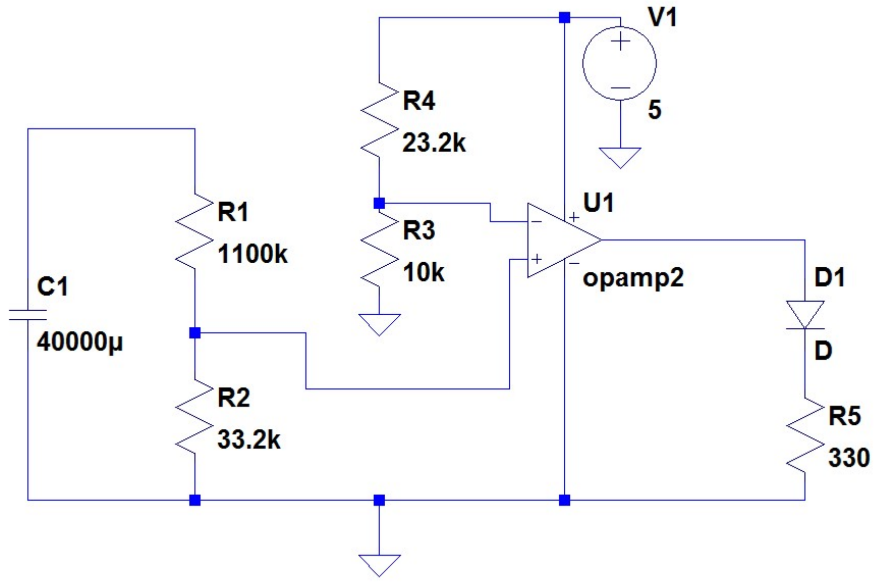

Figure 6: Comparator circuit for displaying capacitor charge

2.4 Coil Windings

The coil windings have already been designed as well. We will work on how to take measurements of several variables to be able to get a deeper knowledge of the device and analyze the feasibility of the improvements we have thought of. A specific ammeter will plot the current through the SCRs, and through the use of the sensors we will know the exact time to fire the coils in order to get the projectile as fast as possible. The research carried with the information obtained will help to figure out the possible improvement of a RD circuit in parallel with the coil that will protect the current from flowing backwards damaging the SCRs.

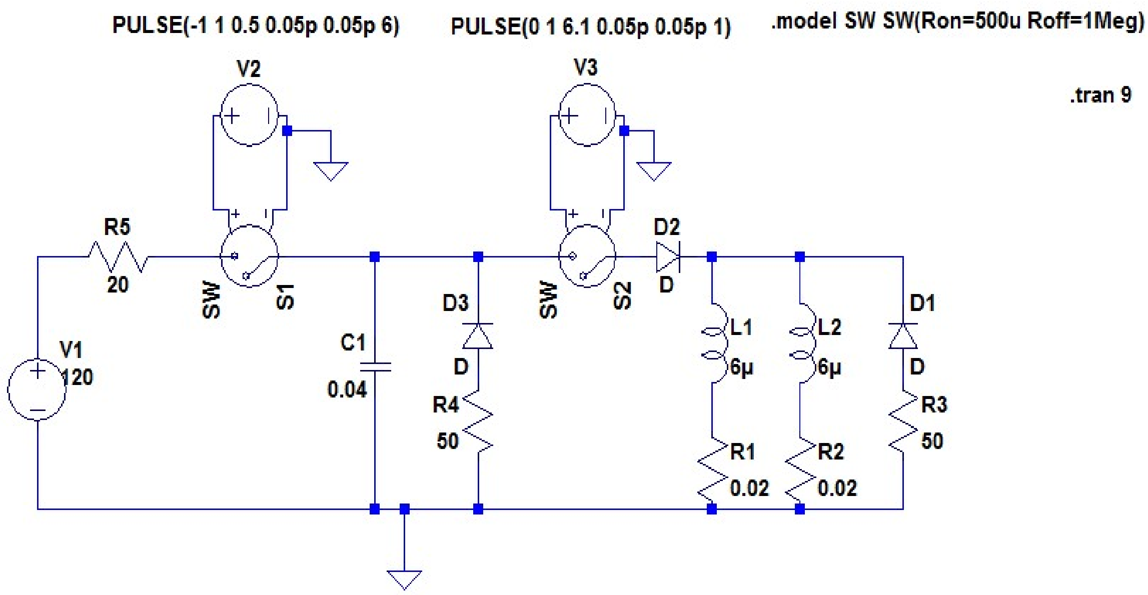

Figure 7: Simulation schematic

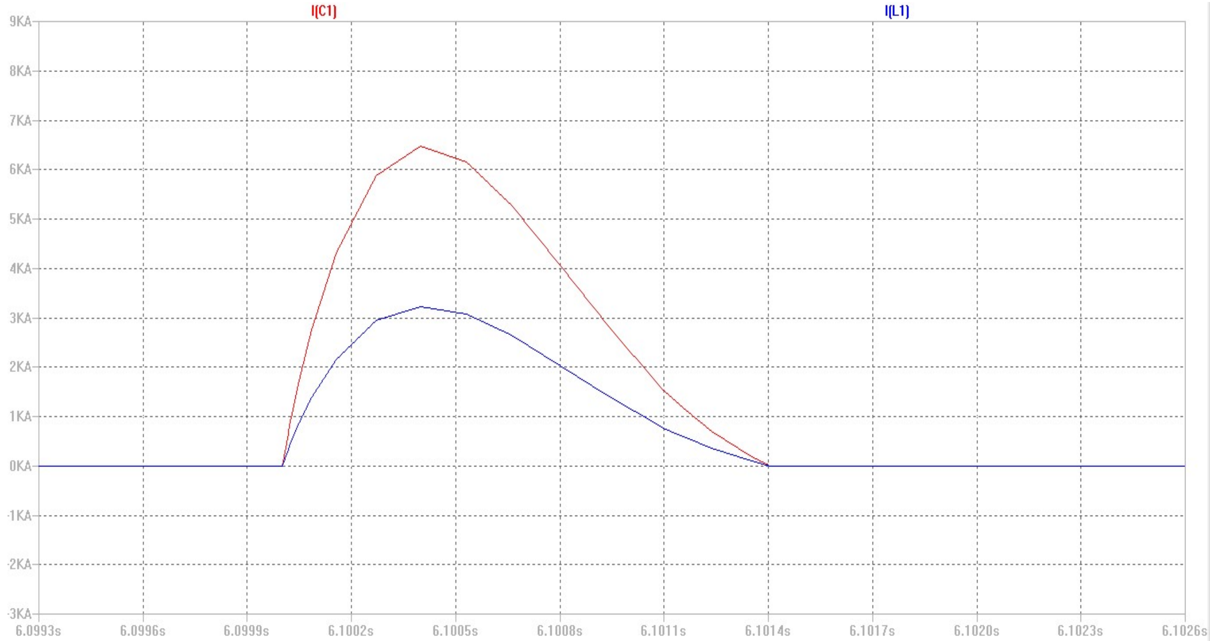

Figure 8: Current through the capacitor (red) and one of the coils (blue) during the triggering

According to our simulation the peak current through each coil will be approximately 3 kA. Taking into account that each stage consists of a pair of coils, the current that the SCRs must carry is two times this value (6 kA). That means that if the SCRs are ideally triggered at the exact same time, each one will have to carry a third of the current through both coils, and that is 2kA. The SCR T610061804BT has a peak one cycle surge (non-repetitive) On-state current of 5.5 kA. As a consequence, it can carry all the current coming from the capacitor in case of a non-simultaneous triggering of the other two SCRs.

Moreover, we are going to add an RD circuit in parallel with the coil to prevent the current from flowing backwards in case some energy is stored in the inductors.

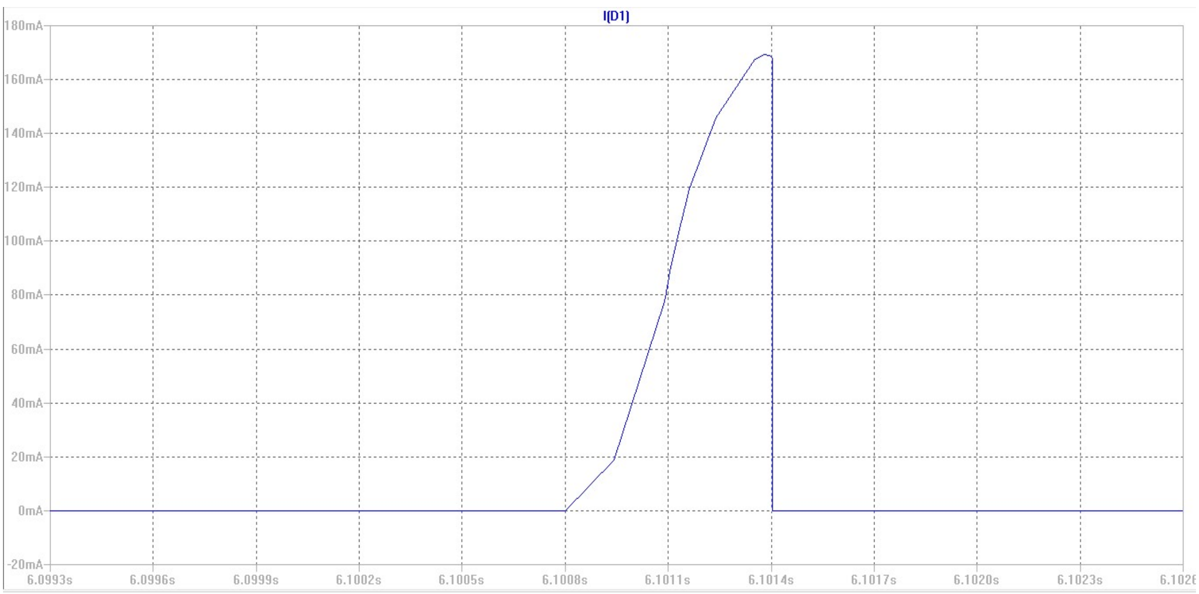

Figure 9: Current flowing into the RD circuit

According to Lorentz' Law, the current induced in the projectile will be opposite, and therefore, this coil gun works with repulsive forces. The armature can be represented a short coil in the stator field and its current is induced by the current flow through the coils . The mutual inductance of the stator and armature can be written as [3]:

$$M = \frac{2\mu}{k}\sqrt{r_a r_s}\left[\left(1 - \frac{k^2}{2}\right)K(k) - E(k)\right]$$

$$where\ k = \sqrt{\frac{4 r_a r_s}{(r_a + r_s)^2 + z^2}}$$

$K(k) = complete\ elliptic\ integral\ of\ first\ kind$

$E(k) = complete\ elliptic\ integral\ of\ first\ kind$

$r_a = armature\ filament\ radius$

$r_s = stator\ filament\ radius$

$z = axial\ position$

There are two possible modes of operation: pull and push mode. In both options the coil should carry a high amount of current when the gradient of the mutual inductance is equal to zero. In that case the force applied to projectiles is maximized:

$$F = I_a I_s \frac{\delta M}{\delta z}$$

Another consideration that must be taken into account is that when the projectile reaches the point of zero mutual inductance gradient, the current through the coils must be set to zero.

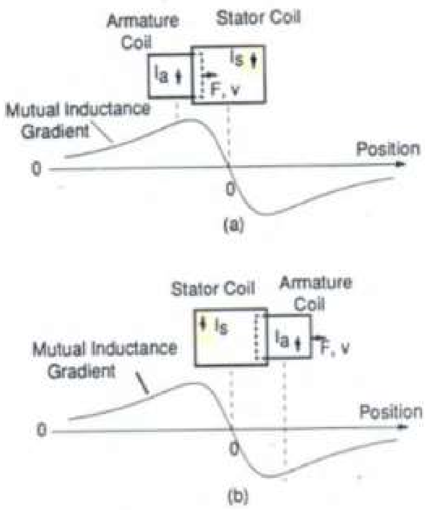

Figure 10: a) Pull mode; b) Push mode [1]

We will measure the resistance of each coil to analyze the damping coefficient of the system. If the value of the resistance of each coil is 0.25Ω the system would be underdamped and this could damage the SCRs. In the next figure, it can be appreciated that in the case mentioned before, the current through the SCRs could reach a value of -120A:

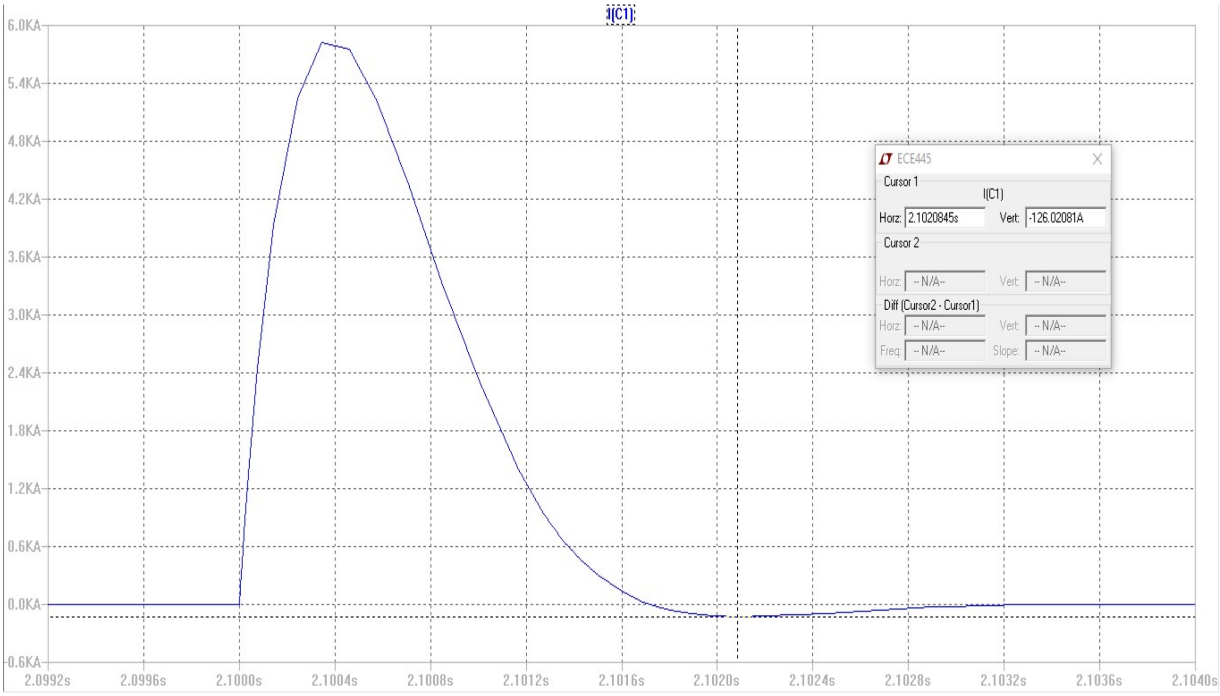

Figure 11: SCRs current with a coil resistance of 0.025Ω

2.5 Low Voltage Power Supply

This power supply will provide the power needed for the microcontroller, sensors and the triggering circuit. This block is primarily being designed by the other team.

2.6 Sensors and Microcontroller

These two blocks will be designed and supervised by the other team. We will try to coordinate our efforts to avoid misunderstandings and the development of incompatible ideas between the two designs.

2.7 Requirements and Verification

Component	Requirement	Verification
High voltage power supply	Power supply must provide 120 V ± 10% voltage with 3 A ± 20% current. [2]	Connect the power supply in series with a 500 Ω resistor. Connect a DMM set to measure voltage across the resistor. Turn on the power supply. Turn off the power supply after taking reading.

Charging station	1. Capacitors must store at least 95% of the charged voltage for at least one minute. 2. Automatically short the capacitors when enclosure is opened and after the coil has been triggered.	1. Charge the capacitors to 120 V ± 10% while monitoring the voltage across the capacitors with a DMM. Disconnect the DMM for one minute, then reconnect it and check if the voltage has dropped more than 5%. Measure with an ammeter the reverse leakage current through the SCRs for each bank of capacitors. 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 copper bars is less than 0.1 Ω.
Firing mechanism	1. Provide electrical isolation between high voltage power supply and microcontroller. 2. The pulse transformer must carry the necessary gate current to turn the SCR on before saturating [3]. 3. The SCRs must withstand at least 100 firings without blowing out.	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. Supply a 5 V pulse to the input of the transformer. The SCR gate, measured with an oscilloscope, should be receiving 3 V ± 20% voltage and 150 mA ± 10%. 3. We will record the number of times we have fired the coilgun before having to replace one of the SCRs. If an SCR survives less than 100 firings, we will need to redesign the circuit.

Display charge	1. The LED must turn on only when the capacitors are at the same voltage as the power supply ± 5%. 2. Measuring the charge of the capacitors must not drain enough power from them to affect their ability to meet their requirements.	1. Charge the capacitors to 120 V ± 10% while monitoring the voltage across the capacitors with a DMM. The LED must be on when the capacitors reach their expected maximum voltage and must not turn on before the voltage reaches 95% of that value. Repeat this process for all three capacitor banks. 2. Verify the requirements on the capacitors with and without the charge display connected.
Coil windings	1. The resistance of the coil windings must be at least 0.04 Ω. 2. Epoxy adhesive must be able to withstand peak temperatures of 200° F and keep integrity of winding structure [2].	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 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 5 V ± 10% voltage at 3 A ± 5% [2].	Connect the power supply in series with a 50 Ω resistor. Connect a DMM set to measure voltage across the resistor. Turn on the power supply. Turn off the power supply after taking reading.

2.8 Tolerance Analysis

Getting the firing mechanism to work properly involves ensuring the correct operations of the thyristors, which is the major challenge of this project. We have to ensure that at any time in the operations, the voltage and current through the thyristor does not exceed its maximum allowable value.

The major flaw with the previous design was that the positive end of the coil inductor was connected to the cathode of the thyristor. There was a large voltage difference between the gate of the thyristor, whose voltage was controlled by a microcontroller (Arduino) and the cathode, which was connected to the coil. The datasheet for the SCR used reported a peak reverse gate to cathode voltage of 5 volts. This was exceeded every time the coilgun fired.

We have considered a new design puts the negative end of the coil inductor on the anode of the thyristor. The cathode is connected to ground, and our firing circuit's use of a transformer allows us to control the gate voltage according to the ratio of windings and resistance values. We can easily maintain a small voltage difference between the gate and the cathode of the SCR. The new design puts the stress caused by the sudden coil inductor voltage on the cathode to anode terminals of the thyristor. The data sheet for the SCR used states an allowable 1600 voltage difference. This gives us a much larger tolerance buffer.

The problem with this option is that with the switches on the low side of the coils, the user would be more exposed to high voltage components. One of our biggest safety concerns is ensuring that users do not have access to the charged capacitors. With the current configuration, all components that are at the same voltage as the capacitors are entirely within the enclosures that the previous group built (see Section 4 for more discussion of our safety concerns and features). If the SCRs were moved to low side, the coils would be at the same voltage as the capacitors. A person could suffer a severe shock if they were to touch any part of the coils while also touching ground. We will examine this risk to see if it can be mitigated. If not, we will have to find a different solution.

Additional testing can be done to determine the magnitude of the voltage difference caused by the sudden surge of current through the coils. We expect that this will be under the 1600V limit. If it is not, we will have to incorporate other means of protecting the SCR.

Another possible cause of the SCRs failing short is backwards current caused by the LC nature of the circuit. This creates a resonance frequency that needs to be accounted for. This frequency affects our triggering times and the rate at which energy can be injected and dissipated. We will measure the resistance of the coils and may add a resistor to ensure that the system is not underdamped. Moreover, we will incorporate and RD circuit in parallel with the coil to prevent the current from flowing backwards.

The input signal of the triggering circuit must fulfill some minimum requirements according to our circuit design. The firing mechanism must generate a pulse long enough to ensure that the SCR triggers. According to the datasheet of the SCRs, the maximum gate current to trigger is 150mA and the maximum voltage to trigger is 3V. The critical rate-of-rise of on-state current is 800A/ s [5]. In our circuit:

$$\frac{di}{dt} = \frac{4.5kA}{300\mu s} = 15\frac{A}{\mu s}$$

We will perform stress tests on the SCRs to establish that they are not damaged, what maximum charge coming from the bank of capacitors they can handle, and if they are being triggered properly. Moreover, we will analyze the leakage current to try to explain the rapid discharge of some of the bank of capacitors.

On the other hand, the SCRs must be triggered at the right time to maximize the energy transmitted to the projectile. Again the study of the best time to fire the SCRs should be coordinated with the time calculations made by the other team to achieve our goal.

3. Cost and Schedule

3.1 Cost Analysis

Labor

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

Original Parts

Item	Cost($)	Quantity	Total Item Cost($)
Photodiodes	1	6	6.00
Lasers	5	6	30.00
OP-Amps (LM324)	0.10	2	0.20
Potentiometers	0.25	3	0.75
Arduino (A000006)	23.95	1	23.95
PVC Pipe	1.50	1	1.50
Capacitors	70.00	9	630.00
Launch Base	3.00	1	3.00
Capacitor Enclosures	6.00	3	18.00
Windings	1.00	6	6.00
Total Parts Cost($)			**719.40**

New Parts

Item	Cost ($)	Quantity	Total Item Cost($)
SCR (Powerex T600061804BT)	79.79	15	1196.85
Resistors	0.15	20	3.00
LED	0.10	20	2.00
PCB	1.50	20	30.00
Comparator LT1713	2.35	3	7.05
Total Parts Cost($)			**1238.90**

Grand Total

Labor	$45,000
Parts	$719.40
New Parts	$1238.90
Grand Total	**$46,958.30**

3.2 Schedule

Week	Objective	Description	Assignment
2/20	Mock Design Review	Finalize Circuit Layout/Design Explore LED charging display schematic	All Members All Members
2/27	Design Review	Build trigger module Build LED display module Ready coilgun for testing	Parker Ted Alex
3/6	Data Collection	Collect Data on current design performance Order SCR and other equipment/parts	All members All members
3/13	Prototype Design Revisions	Finish PCB Layout Additional Data Collection on SCRs Perform simulations for more	Ted Parker Alex

		accurate circuit component values	
3/20	Prototype PCB Deadline	Contact microcontroller group Design link interface between two group's projects	Parker and Alex Ted
3/27	Machine Shop Parts Deadline	Test prototype PCB Fix any remaining issues with prototype PCB Design and submit final PCB layout	Alex Parker Ted
4/3	Revised PCB Deadline	Additional Testing/Data Collection	All members
4/10	Meet Up	Meet with UI group Discuss/fix any compatibility issues Document performance and specifications	Two Groups Two Groups All Members
4/17	Mock Demo	Fix last minute issues Prepare Demonstration	All Members All members
4/24	Demonstrat ion	Demonstrate Coil Gun	All Members
5/1	Final Paper	Write Final Paper	All Members

4. Ethics and Safety

The biggest concerns about our project with regards to ethics and safety involve the use of high voltage electricity and the presence of a fast-moving projectile.

We will make great effort to ensure that the high voltage components of our project do not pose a serious danger to the user. Firstly, we comply with all of the electrical safety guidelines recommended by the University of Illinois. Second, we will ensure that the high voltage components of the system are electrically isolated from any part of the system that cannot handle that level of electricity.

A more complicated, but also more vital, part of the project will be to ensure that anyone using the coilgun will be as well isolated as possible from high current components. The parts that pose the greatest risk of accidental electrocution will be insulated and have warning labels. We are planning to include an LED that will notify users when the capacitors are fully charged. This will serve the dual purpose of improving ease of use and warning users of the risk of electrocution. Documentation of the project will include instructions on how to use and maintain the coilgun with minimal risk of injury.

The group that originally designed this project took several steps to mitigate the risk of electrocution. They designed special enclosures for the capacitor banks that, when closed, prevent contact with any part of the capacitors.

A metal rod was also implemented that would short the capacitors whenever the cover was removed. A spring mechanism would push the metal rod to make contact with two copper rods that are connected in parallel with the capacitor. When the cover is in place, the fiberglass isolation rods will be pressed down, removing the short. With this system in place, the capacitors cannot maintain a charge unless the cover is separating the user from them. There is a risk in shorting a high voltage capacitor, but it is less dangerous than leaving the capacitors charged and exposed.

Our group will continually analyze the enclosures to ensure that they are still functional and that changes we have made to the project do not impede their ability to protect the user. We will replace or redesign any parts of the enclosures that become ineffective or obsolete. [2]

The previous group also wrote a set of procedures in their design document for safely connecting and disconnecting the capacitor banks. These procedures are reproduced here with updates based on our changes to the project [4].

Connect:

1. Ensure the high voltage power supply is OFF and the enclosure lid is secured to the box
2. Connect the high voltage power supply to the input of the charge control circuit. Connect the output of the charge controller to the positive terminal of the capacitor bank
3. Connect the ground of the capacitor bank and charge controller to the negative terminal of the lab bench
4. Connect coil windings using the second pair of large electrical plugs (opposite the power supply connections)
5. Connect thyristor gate and cathode terminals to the trigger circuit using the small banana plugs on the thyristor side of the enclosure
6. Turn ON high voltage power supply
7. Charge capacitors by holding down respective buttons on charge controller until an LED turns on

There are only two cases in which the system needs to be unplugged: storage or malfunction. Again, the coil gun operates at large power ratings so it’s crucial to exercise safety when disconnecting leads.

Disconnect:

1. Make sure all power supplies are OFF
2. Check voltmeter. Check that the voltage is LOW (less than 1 V)
3. If the voltage is HIGH:
    a. DO NOT open the case. The insulation rods will short the high voltage rails and cause damage to the project.
    b. Fire the coil gun again. Notice if this decreases the voltage. If so, repeat process until voltage is less than 1 V
    c. In the event that the voltage is unchanged, the thyristors are malfunctioning.
        i. Carefully disconnect the high voltage power connections
        ii. Carefully connect a high resistance load to the large electrical plugs
        iii. Wait until the capacitors are de-energized and the voltage drops below 1 V
4. If the voltage is LOW:
    a. Disconnect leads from the enclosure
    b. Remove lid from the enclosure
    c. Store enclosure and lid in a safe place

The projectile that our coilgun will be firing is an aluminum cylinder 1 inch in diameter and less than 2 inches in length. A liberal estimate of its maximum speed would be 25 meters per second. Even so, there is some risk of injury. We will never intentionally fire the coilgun at a person, or at another person’s property. We will warn anyone nearby before each firing, and our documentation will instruct future users to do the same. Should the capabilities of the coilgun begin to exceed our expectations, we will reexamine our safety procedures.

According to IEEE Code of Ethics [6], we must commit ourselves to improve the understanding of the technology and its appropriate application. Our goal with this project is to improve what has been already done for the purpose of instructing and inspiring others.

Another consideration is that this project is a continuation of the work done by another group. We will be sure to properly cite their documentation and give credit where credit is due.

5. References

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

[2] J. Dagdagan, Y. Ko and S. Nanavati, "Multistage Coilgun: Project Design Review", Champaign, 2013.

[3] P. T. Krein, “Elements of Power Electronics,” 2014.

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

[5] *Phase Control SCR*, POWEREX, Youngwood, PA

[6] “IEEE Code of Ethics”, 2016.