Electromagnetic Propulsion Device

A.k.a (railgun)

Final Project Report

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Sdmay19-15

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0 Executive Summary

This summary is for brief description on what actually is a electromagnetic propulsion device and why it works.

What is it:

A electromagnetic propulsion device consists of two parallel, conductive rails across which an projectile makes electrical contact. The projectile acts as a wire and connects both rails together which allows current to pass through creating a “basic” RC circuit. It is for this reason that the projectile must also be made from a conductive metal. When current flows into the rails, a magnetic field is created in the space between the rails. This field interacts with the current in the projectile as an active force (according to the Lorentz force). This force accelerates the projectile and produces a mutually repulsive force on the rails. The mutually repulsive force pushes the rails apart, as shown in the image below.

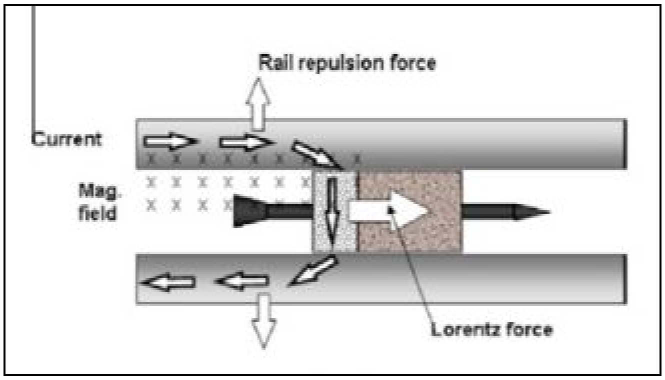


Figure 1: Repulsion Force

Why it works:

Why a electromagnetic propulsion device works is due to the magnetic field that is being produced by the current running through the rails and projectile. The diagram below, shows that if you have a current traveling in a specific direction, a magnetic field will be created, defined by the “Right Hand” rule. When an object is moved through the magnetic field perpendicularly, a force is created to push it out which is known as the Lorentz’s force. As long as we have a controlled current traveling through our rails and a conductive projectile that carries current, the projectile will move along the length of the rails and towards the end. If you reverse how the driving current is entering the rails, the projectile will act the same and be pushed out towards the end, not be pushed the opposite way. This is due to the fact that the current flowing through the rails will generate a magnetic field proportional to the current.

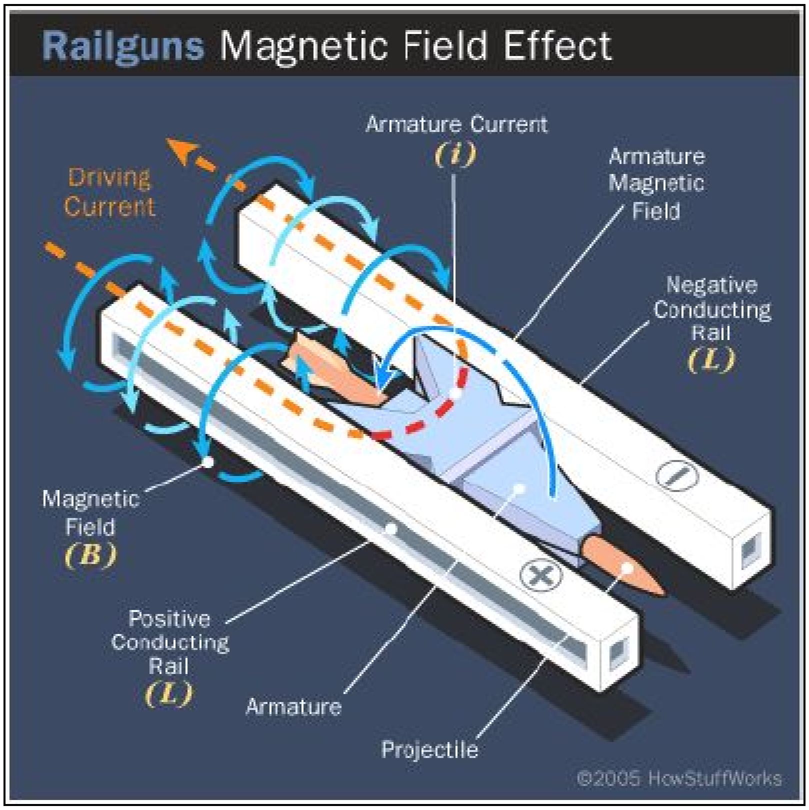


Figure 2: Lorentz's Force

1 Introductory Material

1.1 Acknowledgement

The team would like to thank Iowa State University and the Professors of the College of Engineering for their help and support through this process. Also, thank you to Professor Mani Mina for his mentorship and sharing of expertise in electromagnetics. We also would like to thank, Mr. Mike Ryan who gave us a workspace to craft and material to craft with. Mr. Ryan also used his vast design expertise to assist us with the design process and give us solutions to consider.

1.2 Problem Statement

Currently, the only option for how firearms (projectile launchers) shoot objects is through chemical propulsion. While this method is proven and effective, chemical propulsion has practical limits to how much energy can be output from a fixed barrel size. This energy density limits the speed at which a projectile can leave the barrel from a chemical propellant.

Our proposed solution is to use electromagnetic propulsion. Electromagnetic propulsion can store energy outside of the barrel in a capacitor bank. This greatly increases the energy density for a given barrel size and allows much greater muzzle energies to be achieved.

1.3 Functional/ Non Functional Requirements

Functional Requirements:
- Charge capacitor bank with charging circuit
- Discharge capacitor bank when not in use
- Energize rails with capacitor bank
- Remotely trigger spring mechanism
- Push projectile into rails with spring mechanism
- Launch projectile down range with energized rails
- Repeat shots quickly and safely

Non Functional Requirements:
- Convert 12V to 450V with charging circuit
- Charge capacitor bank in under 2 minutes
- Discharge capacitor bank safely

1.4 Intended Users and Uses

The intended users would be someone who has experience in dealing with EM either with teaching or doing research about it. They also must be trained in how to operate the device the railgun. The users would include:
- Personnel trained to safely operate a railgun
- Professors of electromagnetics
- Researchers in electromagnetic propulsion

The intended uses would include:
- Demonstration of electromagnetic propulsion
- Effective replacement of similar sized chemical propulsion devices

1.5 Assumptions and Limitations

Assumptions:

1. The military needs/wants new technology
2. The difference between magnetic and combustion propulsion is large enough to warrant investment
3. Railguns can be just as accurate as current technology
4. Railguns can be operated in any conditions

Limitations:

1. The cost of this project may be too high for our budget ($1000)
2. Railguns at this stage are single-shot devices
3. The railgun will need a cool-down and recharge period between shots
4. The heat release may be too high for hand-held usage

2 System Design and Development

2.1 Proposed Design

Our proposed design is a fully electronic electromagnetic propulsion device. The design includes a spring mechanism that will give the projectile a quick and powerful push into the magnetic field created by the charged rails. It is necessary to have an initial push because the projectile itself acts as a connection in the circuit. If it is not moving, the current in the rails will weld the projectile to the rails.

Before we are able to fire the spring mechanism, we will need to charge the capacitors using a charging circuit. The charging circuit was designed to multiply an initial voltage by a specific amount and then have a voltage divider to control the voltage output. When testing, we will be charging the capacitor to a specific percentage of the total amount of voltage they are rated for (i.e 10%, 20%, etc.). This is so we have an idea of what to expect according to the calculations we did before. Apart from this charging circuit will be a discharging circuit that will absorb any remaining charge on the rails after firing. This will make the railgun safe to handle, according to our safety procedures.

The capacitors will play an important role in the process of building the design. We have chosen to connect our capacitors in parallel to increase the total capacitance of the design and thus increase the energy stored while staying in a 450V configuration. We chose our capacitors specifically (CAP ALUM 16000UF 20% 450V SCREW) for their low internal resistance and high capacity. This allows the highest energy transfer when “shorted” due to firing the projectile. The capacitor bank will have one input from the charging circuit and two outputs to the rail and discharge circuit for each terminal.

We have chosen aluminum rails in our design because it is a material that is at our disposal. Since we will be dealing with large amounts of current, our main concern with the rails is how quickly it will degrade from friction and concentrated electric discharges. We will monitor the rails overtime during when we are testing.

The projectile will be one piece of conductive metal, aluminum. The projectile is around 2-4 inches in length of contact with the rails to provide proper energy transfer. It is half an inch wide to make a connection with the rails which will be cut and shaped to a specific design to minimize air resistance and velocity loss. Doing this will allow the projectile to operate more efficiently when moving through the air. The single body design will be more expensive to manufacture, but easier to test. It is designed to be contacting the rails as it is fired so that it "closes" the circuit. Otherwise, no magnetic field would be created.

For the base and support structure of the railgun, we will be using polycarbonate. Polycarbonate is a transparent material that falls within the thermoplastics polymer group. What that means is that is has a strong structure that will withstand the force being created and the heat being generated. It will be used as the encasing layer on top and bottom of the rails that hold them in place via screws.

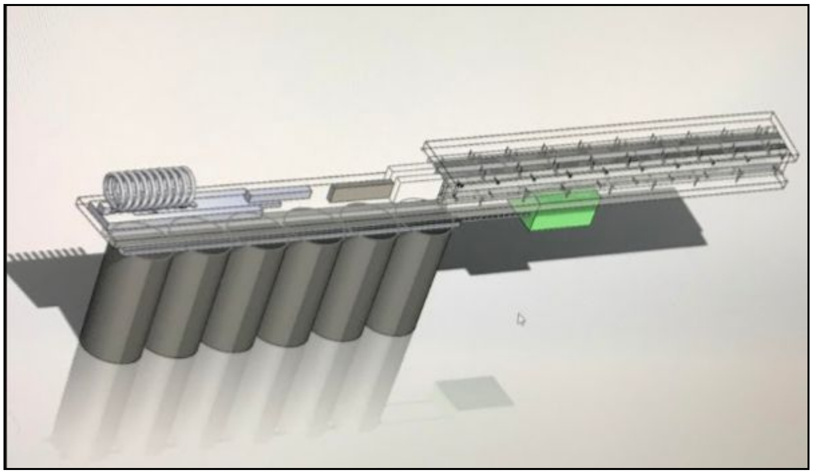


Figure 3: Overall Design for the Project

2.2 Design Plan

Our design plan was to split our group into teams with specific tasks. First, half of the group worked on a Solidworks design of our Electromagnetic Propulsion. Their goal was to create a physical design with dimensions that could be used as a guide to constructing our device. When they finished, the Solidworks information was sent to a metal ship owner who would later help us with a physical draft. The second group worked on the charging circuit design. They followed the design instructions on the LT3751 chip datasheet and altered different areas so it would work for our design. The group did calculations and implemented a design on a PCB board for testing.

For the second semester our group was split three ways for different tasks. The first group was in charge of creating a “Theory of Operation” paper that outlined the theory behind electromagnetic propulsion and explained how and why things worked. The second group worked on a new charging circuit design since the previous one failed to meet standards. The final group began constructing a small scale design as a demonstrational tool and as a base system to run tests on.

2.3 Design Objectives, System Constraints

For the design objectives, the team wanted to make sure that the design was able to accomplish the following:

- Projectile Velocity
    - According to “hypertext.com”, the average speed for a bullet traveling out of the barrel of a rifle (depending on the type of cartridge) is between 370 and 1220 meters per second (m/s). To make our design comparable (or superior to) modern rifles we want to have a final projectile speed inside or exceeding those values.
- Repeatability
    - Modern firearms are capable of firing dozens to even hundreds of projectiles each minute due to their cartridges and reload time. Our goal is to be able to launch one projectile every two minutes. Factors that will influence this are charge time, cooldown time, and reload time.
- Durability
    - We want our Electromagnetic Propulsion Device to have many uses as possible before breaking down. A realistic goal we set is between 10 and 20 uses before the rails need changing.
- Accuracy

    - We will test our design for accuracy at 10, 20, 30, and 50 meters away.
- Cost efficiency
    - According to “Outdoorlife.com”, the average cost of a rifle is between 600 and 1000 dollars so our design cannot be considerably more than that. Since our project budget is $1,000 USD, that will be our limit for materials, technology, and assembly cost.

For the overall system constraints, we wanted to make sure that the materials we have chosen will hold up to the forces that are created. The main materials that need to withstand these forces are the polycarbonate and the screws that are holding everything together. Refer to appendices 7.3 and 7.4 for additional information about the polycarbonate and screws strength’s, and the force calculation.

2.4 Applicable Standards

During the entire process, from the research stage to the designing phase, as a group, we wanted to make sure that we were following standards that were used in the everyday world when creating and designing a new idea. Below are some standards that were applicable to our project.

1. Stable Operation: In an IEEE article about the standards for a High-Voltage Direct-Current system there was a standard that stated the circuit should “be able to maintain stable operation”. Our charging circuit will have to be designed so that it will perform as needed and remain functional during and after it has been used [5].
2. Accuracy: Our charging circuit should charge to values +/- 0.05% of the intended value. In the same document it talked about how values outside of the error range would be unacceptable for the performance [5].
3. Electromagnetic field safety: This document discussed how electromagnetic, magnetic, or electrical fields could be harmful to humans in close proximity. Though our projected magnetic field will be far from harmful levels it will be something we will stay aware of. We will also require the group, during testing, to maintain a safe distance away from the rails to further emphasize safety [4].

2.5 Design Block Diagram

Below is our design block diagram of our process for this project.

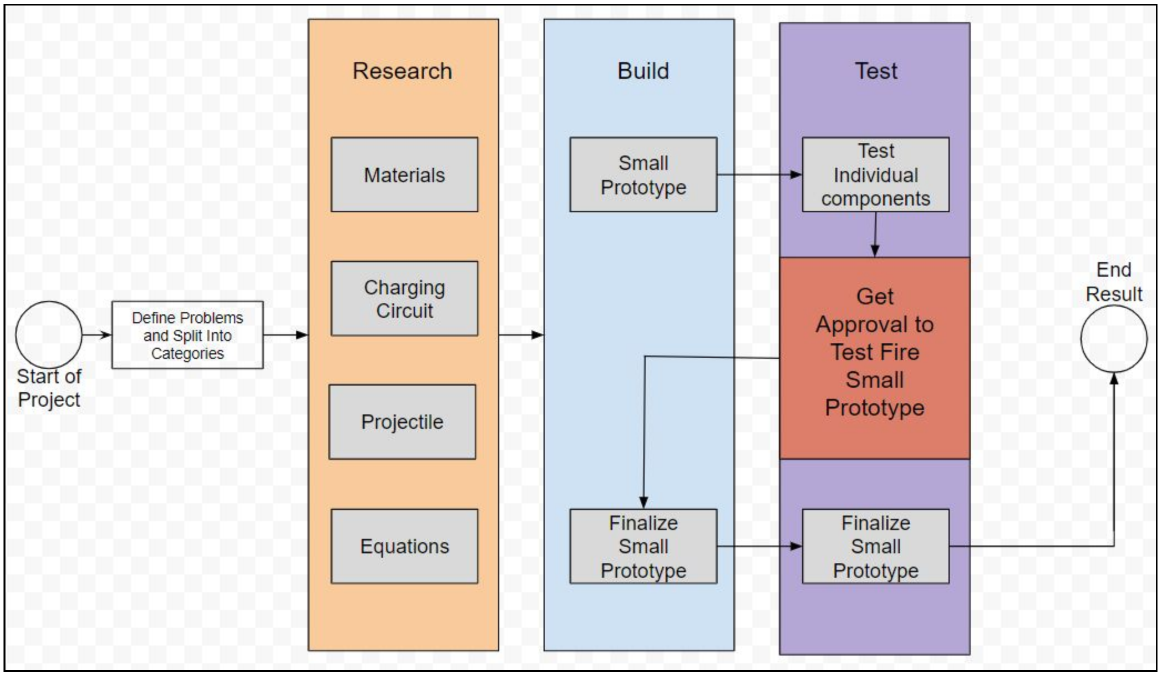


Figure 4: Design Block Diagram

For the start of the project, we broke up the research into four main categories:

- Materials
    - In the materials area, we figured out what materials were on hand at Mr. Ryan’s workshop that would be the best choice for us to use.
- Charging Circuit
    - We needed to figure out how we were are going to charge the capacitors to power our design.
- Projectile
    - What material would be the best choice to use for a projectile and figure out what shapes we should test with.
- Equations
    - Allowed us to show that our calculations and the materials we picked will work for our design we came up with.

Once the research stage was completed, it was then followed by the build and test phases. As you look in the diagram above, you can see that the build and test go in and out of each other. We did this because we first wanted to build a small prototype where we will test the individual components of the design to make sure they work. After we have the necessary results, we then want to get approval by the necessary resources available (i.e. our professors, the risk management program, and the school) to test. Once we get all their approvals, then we would finalize the small prototype and test fire it. If we weren't able to get all of their approvals, we then would need to rethink our design, calculations and materials in order to fix the problem.

3 Implementation

3.1 Software and Equipment

For this project, the team used various software to design the propulsion device. The software used was chosen for the familiarity with all members and we have free and easy access to them by all team members.

Software used:

- Solidworks
    - Used to sketch a 3D design that we could reference when building the device
- Multisim
    - Used when first designing and testing the charging circuit before the circuit was built in order to ensure the design was sound and feasible for our project.

When it came to testing the charging circuit we used lab equipment from a Coover lab. With the experience all team members had we utilized the tools at our disposal to do our testing. All lab safety procedures were followed while testing.

Lab equipment Used:

- Oscilloscope
    - A instrument commonly used to display and analyze the waveform of electronic signals
- Multimeter
    - Is a electronic measuring instrument that combines several measurement functions in one
        - Voltage, current, resistance
- Power Supply
- Soldering Iron

The team has access to a shop and an experienced professional creator/inventor who assisted the team in building the physical components of the device. We used these tools below because they were the ones we needed and were at our disposal and free of charge with a trained professional who ensured it was a safe working environment. Appropriate safety procedures were followed while operating equipment. We also utilized the expertise of those at the metal shops here at Iowa State for the cutting of a number of our projectiles.

Shop Tools Used:

- Drill press
- Bench sander
- Band saw
- Drills
- Various hand tools

4 Testing

4.1 Testing multiple components

Our testing procedure was thought out so that we could test as many components as possible to help us better our results. We felt if we tested multiple components separately we could know how each part worked. This would help when testing the project as a whole so that if it didn't work properly we could change one of the components and test again. We wanted to compare our results to the velocity and energy of a comparable combustible object. Below is a list of the components we wanted to test individually.

1. Charging Circuit
    a. Our plan for the charging circuit was for it to take an input of 12V and have an output of 450V. We constructed the design virtually on Multisim and ran simulation to obtain enough data for equation construction. Once the circuit was physically built we would test it with Coover lab equipment under professional supervision
2. Length and sizing of rails
    a. We wanted to try multiple sizes of rails in our tests to determine if certain sizes of rails would provide better outcomes. Since we are unable to test our project, we didn't get a chance to do this. If we would get a chance, we

were thinking of testing rails that were originally a foot long, an inch and a half in height, and a half inch in width. After that, we wanted to test our rails at 2 ft long to see if the length of the rails would have a big impact on the energy output on the projectile.

3. Length and sizing of projectiles
    a. Similar to that of the rails, we wanted to try different sizes of projectiles to see if those made a difference. First off, we wanted to test a projectile that was an inch in length, a little less than half an inch in width, and an inch and a half in height. This would have given us a maximum amount of surface area with the rails. We believe to provide the maximum energy output we would want the most surface area as possible with the rails for the most conduction. After that test on the projectile, we wanted to decrease the size of it to a little shorter (like an inch in height) and increase the length. We hypothesized this would allow for a longer conduction with the rails and possibly give more energy.
4. Test firing with variable voltage
    a. To provide safe testing, we wanted to use a variac to test with variable voltages ranging from 0-45V. This range is up to 10% of our max voltage the capacitors can charge to. This would provide for a safe testing procedure, but enough voltage to see results from our project.
5. Degradation
    a. We wanted to test and see the amount of degradation that each shot had on the rails and projectiles. We wanted to create a project that would ultimately degrade the projectiles before the rails. This would minimize the amount of maintenance needed to create multiple rails to provide upkeep for the project.
6. Successive shots
    a. We wanted to test how many multiple fires we could accomplish before we had to replace the rails. The goal was to create a project that could make multiple successive shots before we had to replace the rails. If you could only use one shot then had to replace the rails it wouldn’t be very practical.

7. Projectile Velocity

    a. If we could test our design, we would have a high speed camera turned on and pointed at the output of the design barrel. Also out there would be two marked and measured distances. Once the design was fired, we would go to the camera and see how long it took for the projectile to move from the first measured distance to the second. Then we would calculate the velocity from distance over time.

We could not fully test all of these components because we did not have the clearance by Iowa State to do so. To be able to test all of these components we would have had to be cleared by multiple organizations on campus. One of these organizations we would have need approval from was Risk Management. However, Risk Management reviews projects thoroughly and takes a certain amount of time to come up with a result. This amount of time ended up being too long when our project got to a point to where we could submit it to them. Another approval we needed was from our advisor. We wanted to provide a theory of operation document explaining how we think the project will work from beginning to end. This would include a safety portion of which we didn't have 100% complete approval. Our theory of operation includes all of our equations and ideas behind the physics on how and why we think our project would work. For us to turn in our numbers to Risk Management to get our project approved we needed to have our theory approved fully by Professor Mani.

If we had more time, we would get 100% approval from our advisor and then Risk Management so that there would be no question we were testing safely. What we found out in the second semester was that our safety procedures we had in place were not up to standard with what Iowa State wanted to hear. With more time to work on this project we would have had a chance to ask for help and advice from other faculty and advisors.

5 Project and Risk Management

5.1 Task Decomposition and Roles and responsibilities

First Semester

To design our system safe and reliably, we split up into teams to approach each problem with our unique skill sets. The main groups that we split into for the first semester was charging circuit design and structural model design.

Charging Circuit Design

The charging circuit design team consisted of Bret Tomoson, Grant Larson, and Mark Fowler. The main tasks of the charging circuit team was designing an electrical system that could take 12V from a deep cycle battery and converting it to 450V to charge our capacitor bank. Also, the team had to design a discharge circuit that could bring the capacitor bank voltage back to 0V when the system was not in use. The tasks for the charging circuit were shared evenly but each member had a focus for the design. Bret's main role was selecting components that could be used to design the system including the charge controller chip and device specific components. Bret also soldered all of the components once the design had been verified by other members. Mark and Grant's roles were creating a drawing from the given components and verifying all node voltages in the design to ensure components were selected correctly. The majority of their work was to ensure that testing of the circuit could be done safely and efficiently once the circuit was assembled.

Structural Model Design

The structural design team was Max Balzer, Brett Nelson, and Zachee Saleng. The main tasks of the structural design team were to design and create a 3D model of the projectile launcher in SolidWorks that could be used as a guide by our machinist to build and assemble the parts. This design included the rails, supporting structure, device enclosures, a spring mechanism, projectiles, and a mounting base. Max Balzer and Brett Nelson created the design and 3D model together and talked with the machinist to simplify or modify designs as needed. Zachee Saleng helped update documents with the designs.

Project Calculations and Reports

Designing and documenting the progress of the project was another main task of the first semester that required input from all team members. Design work took up a large portion of the semester as team members learned new skills in the design and fabrication of physical and electrical systems. This was done at a pace that allowed all members to safely learn these new skills which added lots of additional time to the project plan that was not expected. Additional work was needed after the first semester’s evaluation to ensure that the project was following the standards that are expected of a Iowa State senior design project.

Second Semester

The second semester required lots of work verifying and documenting all calculations done to build a solid Theory of Operation. Additionally, the charging circuit needed to be reevaluated to create a design that was simpler to create and test. This naturally split the team into two groups for Theory of Operation and charging circuit design.

Theory of Operation

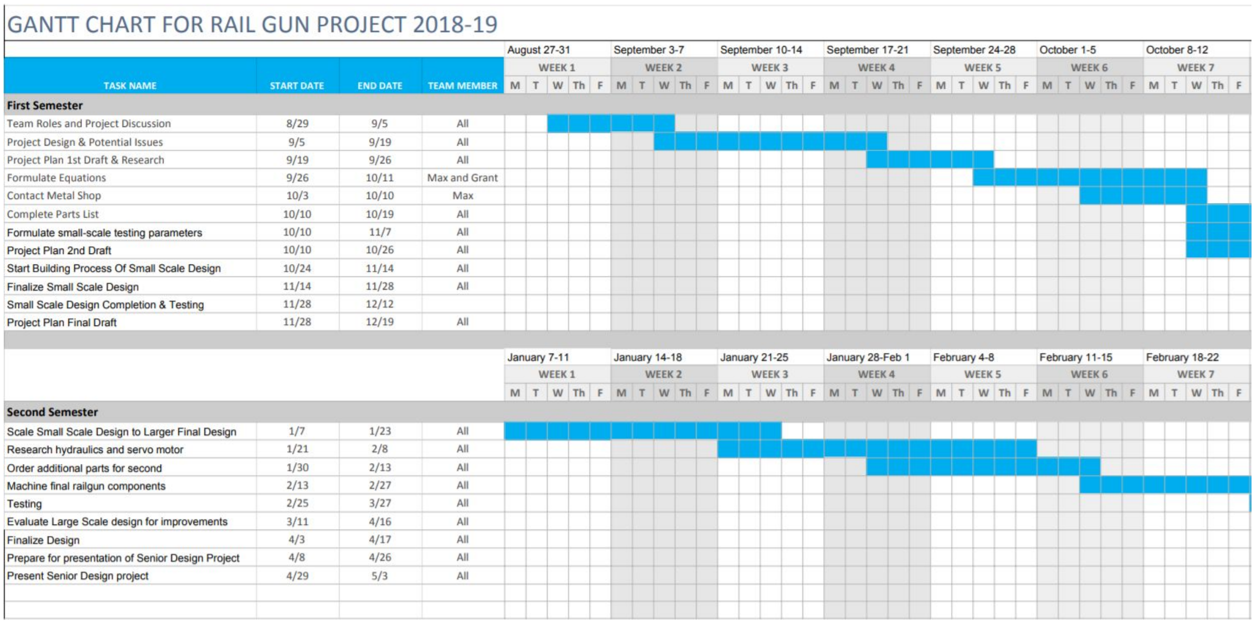
The theory of operation was suggested by our advisor as a way to understand our project on a more technical level and ensure that all claims being made could be backed up by calculations that have been done. This was a large task for the team due to the complex physics involved in the electromagnetics of the system and took the whole semester for the members involved. Bret Tomoson, Brett Nelson, and Zachee Saleng were the group members for the Theory of Operation. Bret’s role was mainly focused on documenting the safety and risks involved in the project from design through to testing. This required research into safety practices of a similar projects and layed out guidelines for the group to follow when working on their individual tasks. Bret also specced and documented the formulas of physical components including structural polycarbonate and fasteners. Brett Nelson and Zachee Saleng worked on understanding and documenting the physics of electromagnetic propulsion which could be used to give expected results.This involved finding formulas for each conversion of energy and defining a clear path from 12V in a battery to projectile velocity. This information was necessary to proceed with physical testing and took the whole semester of work.

Charging Circuit Design

A second semester team was created for the charging circuit to pick up where the previous semester had left off and also finish the design. This team had Max Balzer, Grant Larson, and Mark Fowler working together to design and document the charging system. The previous semester’s design was not able to be tested and finished with the current knowledge of group members so the design was approached with simplicity as the main goal. This would allow the group to design, test and document the circuit safely and to the standards that the class required. Mark Fowler worked on modification of the previous semester circuit to see if the design could be tested or modified for use in the new circuit. Grant Larson worked on designing a new circuit that could be easily tested and built. Max Balzer created the circuit in Multisim for testing and component design and also worked with Mark to test the previous circuit.

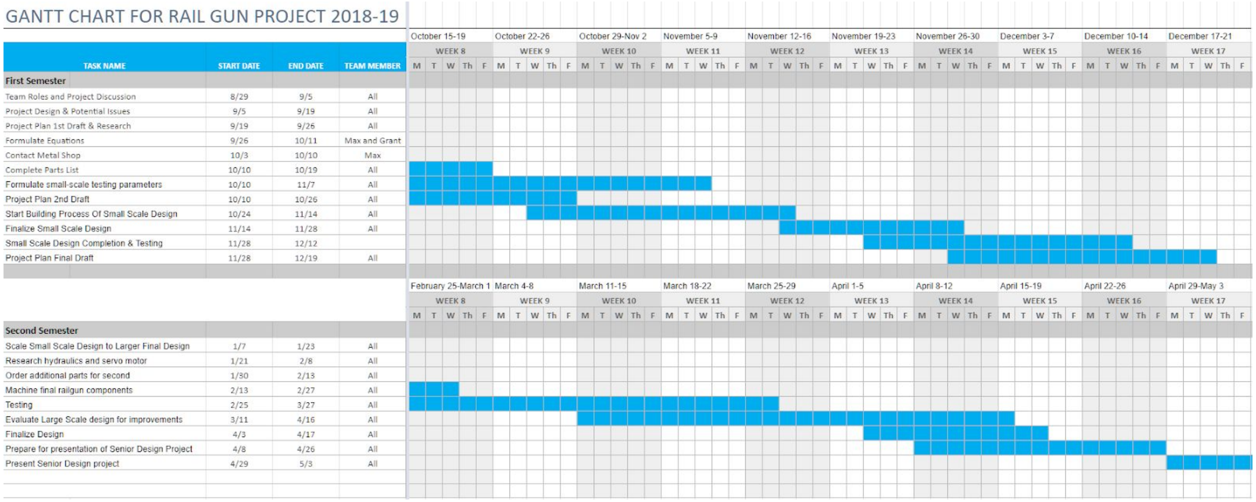
5.2 Project Schedule

Proposed Gantt Chart



GANTT CHART FOR RAIL GUN PROJECT 2018-19

TASK NAME	START DATE	END DATE	TEAM MEMBER
First Semester			
Team Roles and Project Discussion	8/29	9/5	All
Project Design & Potential Issues	9/5	9/19	All
Project Plan 1st Draft & Research	9/19	9/26	All
Formulate Equations	9/26	10/11	Max and Grant
Contact Metal Shop	10/3	10/10	Max
Complete Parts List	10/10	10/19	All
Formulate small-scale testing parameters	10/10	11/7	All
Project Plan 2nd Draft	10/10	10/26	All
Start Building Process Of Small Scale Design	10/24	11/14	All
Finalize Small Scale Design	11/14	11/28	All
Small Scale Design Completion & Testing	11/28	12/12	
Project Plan Final Draft	11/28	12/19	All
Second Semester			
Scale Small Scale Design to Larger Final Design	1/7	1/23	All
Research hydraulics and servo motor	1/21	2/8	All
Order additional parts for second	1/30	2/13	All
Machine final railgun components	2/13	2/27	All
Testing	2/25	3/27	All
Evaluate Large Scale design for improvements	3/11	4/16	All
Finalize Design	4/3	4/17	All
Prepare for presentation of Senior Design Project	4/8	4/26	All
Present Senior Design project	4/29	5/3	All



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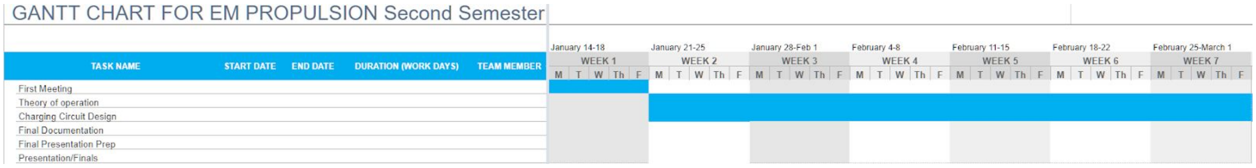
Contact Metal Shop	10/3	10/10	Max
Complete Parts List	10/10	10/19	All
Formulate small-scale testing parameters	10/10	11/7	All
Project Plan 2nd Draft	10/10	10/26	All
Start Building Process Of Small Scale Design	10/24	11/14	All
Finalize Small Scale Design	11/14	11/28	All
Small Scale Design Completion & Testing	11/28	12/12	
Project Plan Final Draft	11/28	12/19	All
Second Semester			
Scale Small Scale Design to Larger Final Design	1/7	1/23	All
Research hydraulics and servo motor	1/21	2/8	All
Order additional parts for second	1/30	2/13	All
Machine final railgun components	2/13	2/27	All
Testing	2/25	3/27	All
Evaluate Large Scale design for improvements	3/11	4/16	All
Finalize Design	4/3	4/17	All
Prepare for presentation of Senior Design Project	4/8	4/26	All
Present Senior Design project	4/29	5/3	All

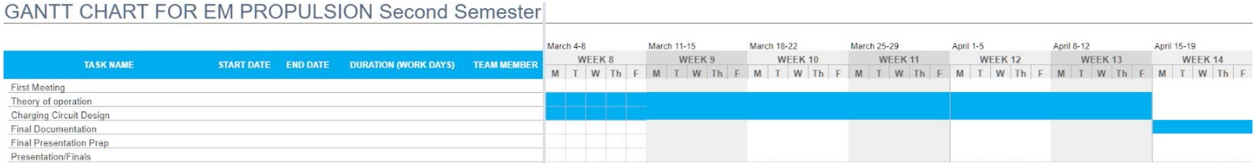
Actual Gantt Chart

The actual schedule of the second semester had a large shift of focus due to a need to understand the project better. Time was spent on the Theory of Operation and charging circuit design to ensure that any work we did would not be done without proper safety evaluation. This proved to be challenging and the whole semester was spent largely focusing on the standards that a projet of this level requires.



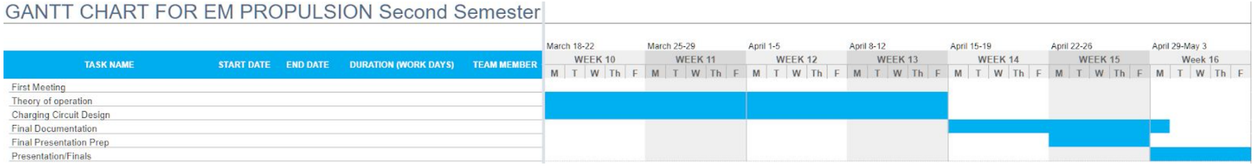
GANTT CHART FOR EM PROPULSION Second Semester

TASK NAME	START DATE	END DATE	DURATION (WORK DAYS)	TEAM MEMBER	January 14-18 WEEK 1 M T W Th F	January 21-25 WEEK 2 M T W Th F	January 28-Feb 1 WEEK 3 M T W Th F	February 4-8 WEEK 4 M T W Th F	February 11-15 WEEK 5 M T W Th F	February 18-22 WEEK 6 M T W Th F	February 25-March 1 WEEK 7 M T W Th F
First Meeting					🟦						
Theory of operation						🟦	🟦	🟦	🟦	🟦	🟦
Charging Circuit Design						🟦	🟦	🟦	🟦	🟦	🟦
Final Documentation											
Final Presentation Prep											
Presentation/Finals											



GANTT CHART FOR EM PROPULSION Second Semester

TASK NAME	START DATE	END DATE	DURATION (WORK DAYS)	TEAM MEMBER	March 4-8 WEEK 8 M T W Th F	March 11-15 WEEK 9 M T W Th F	March 18-22 WEEK 10 M T W Th F	March 25-29 WEEK 11 M T W Th F	April 1-5 WEEK 12 M T W Th F	April 8-12 WEEK 13 M T W Th F	April 15-19 WEEK 14 M T W Th F
First Meeting											
Theory of operation					🟦	🟦	🟦	🟦	🟦	🟦	
Charging Circuit Design					🟦	🟦	🟦	🟦	🟦	🟦	
Final Documentation											🟦
Final Presentation Prep											
Presentation/Finals											



GANTT CHART FOR EM PROPULSION Second Semester

TASK NAME	START DATE	END DATE	DURATION (WORK DAYS)	TEAM MEMBER	March 18-22 WEEK 10 M T W Th F	March 25-29 WEEK 11 M T W Th F	April 1-5 WEEK 12 M T W Th F	April 8-12 WEEK 13 M T W Th F	April 15-19 WEEK 14 M T W Th F	April 22-26 WEEK 15 M T W Th F	April 29-May 3 Week 16 M T W Th F
First Meeting											
Theory of operation					🟦	🟦	🟦	🟦			
Charging Circuit Design					🟦	🟦	🟦	🟦			
Final Documentation									🟦	🟦	🟦 (M)
Final Presentation Prep										🟦	
Presentation/Finals											🟦

5.3 Risks and Mitigation

Risks and Safety

A railgun is a project that when scaled to our final size can have dangerous amounts of power experienced by many of the components. This requires every decision and test to have safety as the top priority. We aim to mitigate any dangers to our team and others through the implementation of strict and thorough safety guidelines. Before testing, each of these safety guidelines will be approved by our advisor, as well as a qualified safety member of the university:

Locations of Operation: The places that we chose to build and test our project must fit the safety requirements of our tasks to ensure that no unnecessary risk is experienced by team members or the public. There are four key areas in our project: machining, assembly, testing, and firing that require safe locations which will be explained below.

- **Machining:** Our project requires machining of materials including: aluminum, copper, UHMW, polycarbonate, and wood. The machining requires proper equipment to safely work with these materials and also a shop space that this machining can be done in. All of our medium-scale machinings was done by Mike Ryan who owns and operates a metal fabrication shop in Mitchellville, IA. One reason Mike Ryan was chosen for our machining was that he supplied the team with the materials to build our medium-scale design including all aluminum, polycarbonate, and copper. Also, these materials are used regularly by his shop and were able to be safely machined by him on his equipment. This eliminated the need for team members to receive safety training on how to operate metal machining equipment and allowed for all of the work to be done by a trained professional.

- **Assembly:** Assembly of the different components in our design has different location needs that depend on the complexity of assembly. The assembly was split into the initial fit of rails and housing, general assembly/disassembly of major components, and assembly of charging circuit components. The initial fit and assembly of the rails and housing were done at Mike Ryan's shop so we could get snug fits of critical load experiencing components using the machines and tools at his shop. This ensured that the load on components would be evenly distributed. The general assembly and disassembly of components is the least dangerous portion of the project, but it is one of the most important parts. During the assembly of our design, all parts must be put together tightly and be in the correct location. After all components have been tested and put together safely, we will use adhesives such as loctite to secure any threaded components. It will require basic hand and power tool use to assemble and later take apart and also the space to do so. For these reasons, the general assembly will be done at a group member Bret Tomoson's house due to the availability of hand and power tools and also a space where the project can be safely stored.
- **Testing:** Testing of our individual components is important to ensure predictable outcomes and will be done before any full assembly is made. This testing requires locations specific to the components to ensure that the proper equipment is available to evaluate our designs and verify them with our calculations. The components that will be tested are the charging/discharging circuit, spring mechanism, and structural support. The testing of the charging/discharging circuit is something that the team is most familiar with due to similar testing in labs but the components involved have higher voltages and currents than usually experienced so extra care must be given to this component. The charging/discharging circuit will be tested in Coover labs that team members have been trained in and are familiar with. This will ensure that all measurements made are accurate and are on calibrated equipment that can handle the loads necessary for our testing. The spring mechanism is a component that will require lots of testing and fine-tuning to reach the desired output for our railgun. This

involves using basic hand tools to fit and tune the positioning of components and also an environment where there is room to work with a large footprint due to the bracing needed for testing. For this reason, our spring mechanism will be tested at Bret Tomoson’s house where the space and tools are available to work on the project without altering the testing conditions. The testing of structural support on the project includes fit checking any component housings, checking the stability of components after assembly, ensuring electrical insulation between dangerous components and users, and overall project rigidity for firing. This will need to be done in the same place as the assembly due to the size of the project and also the testing being done of components after assembly. This will be done at Bret’s house to ensure testing is monitored by a group member at all times to prevent potential tampering.

- **Firing:** Firing is the most important step once all others are completed and will need a safe location to ensure that no one is in danger when testing.

Safe Equipment Use: Safe use of equipment involved in testing is important so that all members who are doing work are trained on and comfortable with the equipment required for the project. The main areas where equipment is used are listed above in the locations of operation.

- **Machining:** All medium-scale machining that was done on the project was done by Mike Ryan with equipment that is used daily in his shop. This eliminated the need for team members to receive safety training on the operation of the equipment and were able to watch the work being done while wearing safety glasses.
- **Assembly:** The initial assembly of the project was similar to the machining and was done by Mike Ryan at his shop. This allowed us to get tight fits of components and have them adjusted or remachined if necessary. General assembly and disassembly of the project after the initial fits were done using basic hand and power tools that are owned by Bret. Cordless drills were the only power tools used and were used to speed up the assembly and disassembly of threaded components. The adjustable clutch on the drill also allowed all components to be torqued to the same amount to get even load distribution.
- **Testing:** Testing of components is something that will have different equipment for each component tested. For the charging/discharging circuit the equipment used for testing was all in the 230 lab or provided by ETG. PPE that was used for anyone handling the high voltage circuits was protective goggles provided by the lab and 12kV electrically insulated gloves to prevent any electrical shocks from being experienced. The power for the circuit was tested using a 120V variac supplied by ETG to test rectification and charging of the capacitors while being

isolated from the wall via a 20A fuse. This allowed us to slowly increase and monitor the voltage to the capacitor. The rectification was first verified using the oscilloscopes and the variac. Next, the capacitor was charged and the voltage was measured with the benchtop multimeter. After the desired voltage was reached, the variac was turned off and the discharge circuit was connected to the capacitor leads while monitoring the multimeter to ensure the voltage was reduced to 0V. The spring mechanism will be tested without using equipment but will be a pass/fail of the projectile being pushed into the rails after the device is triggered. The structural support of the rails and the surrounding base is something that cannot be tested to failure due to the budget restraints of the project but we used math to design the system to withstand repeated shots without losing any structural integrity. The railgun stability was tested by securing all components in their final form and trying to move anything with full bodyweight in any direction. Anything that was not stable from this amount of force was tightened or stabilized with more support as needed. This will prevent the project from falling over and potentially damaging components during testing. This is a very similar process to securing a rifle in a bench to secure it for remote shooting.

- **Firing:** Firing of the project is a very important milestone towards completion but is one of the most challenging to assess from a safety standpoint. This is something that we wanted to allow the risk management department from Iowa State handle to ensure that proper safety standards were met in the final stage of testing. To give an accurate representation of the risk involved in the project, all of the calculations and systems needed to be fully understood by the group members to present for evaluation. This is something that was not able to be done by the end of the semester due to complications with building the charging circuit and completing accurate calculations of the propulsion physics. When this information is found it would also take an additional amount of time for the Risk Management department to evaluate which was not available to us at the end of the semester. This is something that we would have likely completed if given additional time.

6 Conclusions

6.1 Closing remarks for the project

This project overall was challenging and a very good learning experience. It involved many different types of engineering knowledge that we were not accustomed/familiar with such as materials and mechanical engineering. Time management was big as we all had to juggle between this project and other coursework. The biggest issue we faced was not having addressed safety concerns early enough. It was not thought of by any group members or our advisor before it became a necessity to move forward with testing our design. It reiterated how important fully documenting and explaining designs and how they abide by standards will be in the professional engineering workplace.

6.2 Future Additions

Future Additions

- Run a full risk management assessment of the project to ensure proper standards are met before testing.
- Test systems in real conditions with proper safety precautions.
- Compare calculations with measured results to highlight inconsistencies.
- Modify components to increase efficiencies.
- Stress test new design to measure durability.
- Obtain additional funding to improve:
    - Part tolerances
    - Testing equipment
    - Component replacements for wear testing

7 Appendices

7.1 Operation Manual

Below are instructions for safe usage of our Electromagnetic Propulsion device design. Please read before use and have appropriate safety materials.

Step 1: A sweep of the design and the space around it

While the design is non operational check to make sure things are as they should be. The barrel should be clear of any debris or other items and should be held in place by fasteners. If the polycarbonate base or roof can wiggle under stress the fasteners are too loose and need to be tightened.

Step 2: Spring Mechanism Test

Pull back the spring so that tension is applied, then let go and see if it extends forward into the barrel. Next, pull back the spring again and lock it into place. Move backwards until you are into firing position and activate the trigger which should let loose the spring. Repeat one more time with a projectile in firing position and make sure it goes through the barrel without getting stuck.

Step 3: Charging

Attach the capacitors to the charging circuit and watch with a voltmeter to make sure they are charged to the desired amount.

Step 4: Capacitor Bank

Once all the capacitors are charged attach them to the capacitor bank via screws. Make sure they are held there firmly with a simple stress test.

Step 5: Connecting the Wires

Before this step is started, everyone not physically attaching any wires should retreat behind a protective shield. The person left must be wearing voltage resistant gloves and protective eyewear. Then, draw back the spring and place a projectile into firing position. Once the projectile and spring are secure, attach the wires from the capacitor bank to the rails and then join everyone else behind the protective shield.

Step 6: Firing

Trip the spring mechanism and watch as the Electromagnetic Propulsion device moves an ordinary piece of metal with an induced magnetic field.

Step 7: Discharging

After Step 6 has been completed, the individual wearing the protective gear will approach the design and unhook the wires from the rails. Then, they will attach those wires to the discharging circuit and watch with a voltmeter as the capacitors lose any remaining charge they may have. Carefully check all attached capacitors individually to make sure they have no charge.

Step 8: Inspection

Once all capacitors are confirmed to have no charge, the rest of the testing group can come out from the safe zone. Check the design interior for scrapes, cracks, or other deformities.

Caution: the device barrel may be hot after firing so you may have to let it cool down first. If nothing is out of place, feel free to repeat all of the above steps if successive firing is desired.

7.2 Alternative Designs

For our charging circuit, the first design idea had the potential to easily convert 12 volts into 450. The LT3751 chip data sheet gave us information on how is works and how to modify it to fit our needs.

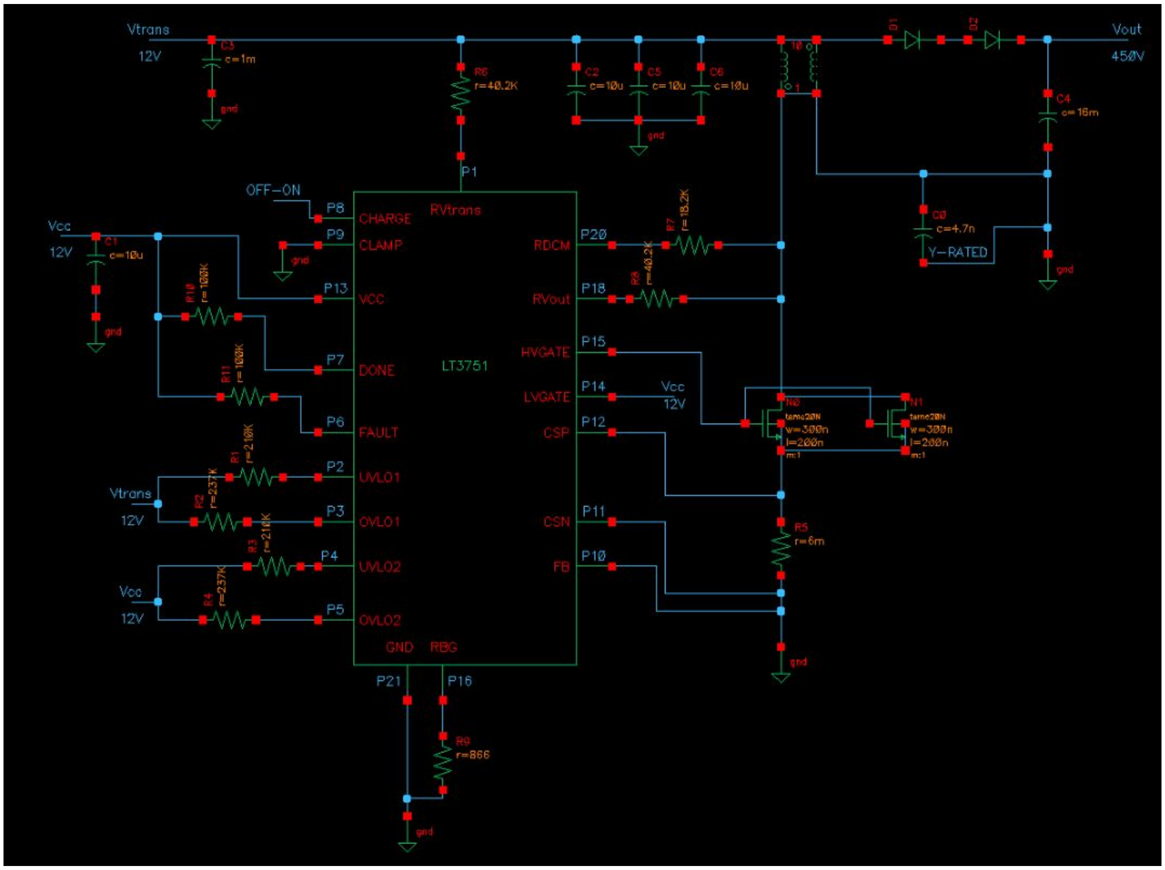


Figure 5: LT3751 Chip

From the schematic above, we modified each output pin to give us desirable outputs. However, once it was implemented in a PCB board it did not work during testing. We may have had broken parts, burned out parts, or did something wrong in earlier stages to cause issues, but we did not know what. That is why this design was set aside in favor of the charging circuit earlier in this paper.

7.3 Information about polycarbonate and fasteners

Below is additional information on the polycarbonate and fasteners.

Shear Limits of Fasteners

Shear limits or shear strength is defined by a material's ability to resist forces that can cause the internal structure of the material to slide against itself [11].

	Minimum Ultimate Tensile Load (psi)	Shear Strength (60% of Tensile Strength with 80% of proof loading) per ¼" bolt. (lbs)	Total Shear Strength(per rail) (lbs) (14 fasteners)
1/4-28 x 1" black oxide ASTM F-835	145000	3410.4	47745.6

Table 1: Shear limits of Fasteners

The force required to break the screws holding the rails in place is shown in the table above with information on the screws from fastenal. The force experienced per screw is found by: Minimum ultimate tensile load (145000) * acceptably shear strength (.6) * proof load (.8) * tensile stress area (2*pi*.125). In order to break each fastener holding the rails in place, we would need to generate a force of 47745.6 lbs on each rail. If the fasteners were broken and the rails were pushed apart, then the projectile will lose its contact points to the rails and the circuit will be broken. This stops the magnetic field from being created and halts the accelerating force on the projectile.

Tensile Limits of Polycarbonate

Tensile load or tensile strength is defined as the maximum tensile load a body can withstand before failure divided by it's cross-sectional areas [1]. What this means is the ability of a material to withstand a pulling force.

	Tensile Strength: Yield (psi)	Tensile Strength: per fastener(lbs)	Total Tensile Strength (14 Fasteners per sheet)(lbs)
Polycarbonate	8500	1062	14868

Table 2: Tensile limits of Polycarbonate

The force required to break the polycarbonate top or bottom piece is shown in the table above with information on polycarbonate from matweb. It is assumed that the force experienced per sheet is: the number of fasteners(14) * diameter of the fastener (.25") * thickness of the polycarbonate(.5")* yield tensile strength per inch (8500 psi). It can be seen that the polycarbonate will always yield before the fasteners due to less strength per joint.

7.4 Calculations

All calculations assume 100% efficiency (no losses)

Below are the equations that we will be using to find critical values that are important figures to know about before any testing is done. All number calculations that are found are not including losses, which means that there will be 100% efficiency in these numbers we find. This will not be the case though when we actually go ahead with testing and gather the data. This is for us to build our design to withstand the possible outcome we calculated, without considering losses. After we complete our testing, we then can compare our finds and figure out the total losses that occur due to friction, heat, etc.. Most of our calculations have to deal with time, so we will be using time constant found from the RC circuit. We will be showing all the way up to five-time constants because after five-time constants, the capacitors will be completely discharged.

Energy Stored in Capacitors

To find the energy stored in the capacitors, we will be using the following formula. Where C is the total capacitance. We have a total of two capacitors, and they are in parallel. Them being in parallel means that we will add their capacitance together. And V is the voltage that the capacitors are charged to [10].

$E = (1/2)CV^2$

C = total capacitance (Farad)
V = voltage stored/charged to (Volts)

Percentage Charged	Volts (V)	Energy Stored in Capacitors (J)
10%	45	32.4
20%	90	129.6
30%	135	291.6
40%	180	518.4
50%	225	810
100%	450	3240

Table 3: Energy stored in Capacitors

Current

To find the current that will be produced, we will be using the discharging capacitor formula [2]. Where V_0 is the initial voltage of the capacitor, this value will be chosen based on a percentage of total voltage for the capacitors as shown in the table above. R is the total resistance of the circuit, which is found by

$(\#rails * resistivity\ of\ al * length\ of\ rails\ (m))/(width\ (m)\ *\ height(m))$. T is the time and Tau is the time constant(τ).

$I\ =\ (V_0/R) * e^{-t/\tau}$

V_0 = initial voltage
R = total resistance
# of rails = 2
$RC = \tau$ time constant
Resistivity of Al (T6-6061) = 39.2e-9 (Ohm meter)
Length of rails (2 feet) = .6096 (meter)
Width of rails (.5 inch) = .0127 (meter)
Height of rails (1.5 inch) = .0381 (meter)
R = 9.877e-5 (Ohms)
C = .032 (Farad)

Number of Time Constants	Time in seconds	Current at 45V	Current at 90V	Current at 135V	Current at 180V	Current at 225V	Current at 450V
0	0.00E+00	455596.3	911192.6	1366788.9	1822385.2	2277981.5	4555963.0
0.5	1.58E-06	276333.1	552666.3	828999.4	1105332.5	1381665.6	2763331.3
1	3.16E-06	167604.5	335209.0	502813.5	670418.1	838022.6	1676045.1
1.5	4.74E-06	101657.3	203314.6	304971.8	406629.1	508286.4	1016572.8
2	6.32E-06	61658.3	123316.5	184974.8	246633.0	308291.3	616582.5
2.5	7.90E-06	37397.6	74795.2	112192.9	149590.5	186988.1	373976.2
3	9.48E-06	22682.8	45365.6	68048.4	90731.2	113414.0	226828.0
3.5	1.11E-05	13757.8	27515.6	41273.4	55031.3	68789.1	137578.2
4	1.26E-05	8344.5	16689.1	25033.6	33378.1	41722.7	83445.4
4.5	1.42E-05	5061.2	10122.4	15183.7	20244.9	25306.1	50612.2
5	1.58E-05	3069.8	6139.6	9209.4	12279.1	15348.9	30697.8

Table 4: Current

Magnetic Field

To find the average magnetic field, we are dealing with a current carrying straight wire. We are finding the average magnetic field because we are not concerned about the magnetic field at various points along the rails. Instead, we only care about the entire rail. We are able to use the Biot-Savart law is to calculate the average magnetic field. The form of this is shown below [8]. Where μ_0 is the permeability constant, r is the radius of the rails, d is the distance separating the rails, and I is the current. The ln term shows us the relationship between the radius of the radius and the distance between the rails.

$B = ((\mu_0 * I)/(2 * \pi * d)) * ln(d/r)$ (Tesla)

Number of Time	Time in seconds	Magnetic Field at	Magnetic Field at	Magnetic Field at	Magnetic Field at	Magnetic Field at	Magnetic Field at

Constants		45V	90V	135V	180V	225V	450V
0	0.00E+00	0.1263	0.2526	0.3790	0.5053	0.6316	1.2632
0.5	1.58E-06	0.0766	0.1532	0.2298	0.3065	0.3831	0.7662
1	3.16E-06	0.0465	0.0929	0.1394	0.1859	0.2323	0.4647
1.5	4.74E-06	0.0282	0.0564	0.0846	0.1127	0.1409	0.2819
2	6.32E-06	0.0171	0.0342	0.0513	0.0684	0.0855	0.1710
2.5	7.90E-06	0.0104	0.0207	0.0311	0.0415	0.0518	0.1037
3	9.48E-06	0.0063	0.0126	0.0189	0.0252	0.0314	0.0629
3.5	1.11E-05	0.0038	0.0076	0.0114	0.0153	0.0191	0.0381
4	1.26E-05	0.0023	0.0046	0.0069	0.0093	0.0116	0.0231
4.5	1.42E-05	0.0014	0.0028	0.0042	0.0056	0.0070	0.0140
5	1.58E-05	0.0009	0.0017	0.0026	0.0034	0.0043	0.0085

Table 5: Magnetic Field

Magnetic Force Experienced by Projectile

In order to find the force that the projectile will experience, we will need the magnetic field, the current and the length of the rails. Since we have two parallel rails with a conductive projectile running between them, the Lorentz force runs directly down the middle of the rails, allowing for the acceleration of the projectile. With that, we are able to use the following formula to find the force that the projectile experiences. This force is referred to as the Lorentz force [7].

$F = I * L * B$

I = current (Ampere)
B = magnetic field (Tesla)
L = length (Meter)

Number of Time Constants	Time in seconds	Force at 45V	Force at 90V	Force at 135V	Force at 180V	Force at 225V	Force at 450V
0	0.00E+00	35082.52	140330.08	315742.69	561320.33	877063.02	3508252.06
0.5	1.58E-06	12906.14	51624.55	116155.24	206498.21	322653.45	1290613.81
1	3.16E-06	4747.90	18991.61	42731.13	75966.45	118697.57	474790.29
1.5	4.74E-06	1746.66	6986.62	15719.90	27946.49	43666.40	174665.59
2	6.32E-06	642.56	2570.24	5783.03	10280.94	16063.97	64255.88
2.5	7.90E-06	236.38	945.54	2127.46	3782.15	5909.60	23638.42
3	9.48E-06	86.96	347.84	782.65	1391.37	2174.02	8696.09
3.5	1.11E-05	31.99	127.96	287.92	511.86	799.78	3199.11
4	1.26E-05	11.77	47.08	105.92	188.30	294.22	1176.89

4.5	1.42E-05	4.33	17.32	38.97	69.27	108.24	432.95
5	1.58E-05	1.59	6.37	14.33	25.48	39.82	159.27

Table 6: Magnetic Force on Projectile

Force Outwards on Rails

Knowing the force that is pushing outwards on the rails is important for when designing our prototype. Having this information, we then can figure out what type of screws and material to hold everything together. Because we are designing our prototype with one pair of rails that are arranged symmetrically, meaning in parallel, we can use the following formula to find the repelling force the rails we will be experiencing, it is given by the following equation [7]. Where μ is the magnetic permeability of free space. I is the total current. L is the length of the rails in meters. And d is the distance between the two opposite rails.

$F = (\mu * I^2 * L)/(2 * \pi * d)$ (lbs)

I = current traveling through rails (Ampere)
L = length of rails (meter)
d = distance between rails (meter)
$\mu = 4\pi * 10^{-7}$ (Henry/meter)

Number of Time Constants	Time in seconds	Outward Force at 45V	Outward Force at 90V	Outward Force at 135V	Outward Force at 180V	Outward Force at 225V	Outward Force at 450V
0	0.00E+00	72.22	288.89	650.01	1155.58	1805.59	7222.36
0.5	1.58E-06	26.57	106.28	239.13	425.11	664.24	2656.96
1	3.16E-06	9.77	39.10	87.97	156.39	244.36	977.44
1.5	4.74E-06	3.60	14.38	32.36	57.53	89.90	359.58
2	6.32E-06	1.32	5.29	11.91	21.17	33.07	132.28
2.5	7.90E-06	0.49	1.95	4.38	7.79	12.17	48.66
3	9.48E-06	0.18	0.72	1.61	2.86	4.48	17.90
3.5	1.11E-05	0.07	0.26	0.59	1.05	1.65	6.59
4	1.26E-05	0.02	0.10	0.22	0.39	0.61	2.42
4.5	1.42E-05	0.01	0.04	0.08	0.14	0.22	0.89
5	1.58E-05	0.00	0.01	0.03	0.05	0.08	0.33

Table 7: Force Outwards on Rails

Initial Velocity of Projectile

To find out the initial velocity of the projectile, we will be using our spring mechanism in order to produce this velocity. This is for the projectile to have initial speed and acceleration when entering the magnetic field to avoid a large amount of current to weld the projectile if it did not have anything speed going into the field. We will be using the spring potential energy formula that will be converted into the velocity for the projectile[9]. The initial velocity will be determined by the displacement, how far we pull the spring back. The spring constant found from Hooke' law. The mass of the projectile.

$v_i = \sqrt{kx^2/m}$

k = spring rate/constant

To find k, we will need to have the mass of the object, the displacement, we will need to define how far the spring moves with respect to the starting position, therefore we will have gravity constant. By having these variables, we are left with this expression.

$k = (mg)/x$

x = distance pulled back (meter)

m = mass of projectile (Kg)

Note: Our mass and distance pulled back are just estimates in order to produce some results. These will be fined tuned to produce the best results (i.e mass and the distance pulled back will be either increased or decreased).

m(lbs) =	0.330693	M converted into kg	m(kg) =	0.15	(This is just an estimate)
x(m) 2 inches =	0.0508	(This is just an estimate)			
k =	28.966535	k=(mg)/x	g =	9.81	
Vi =	0.7059	m/s			

Table 8: Initial Velocity

Final Velocity of Projectile

To find out the final velocity of the projectile, we will be using one of the Kinematic equations. Where the final velocity of the projectile will be determined by the initial velocity, the distance traveled and the acceleration [6], as shown in the picture below. The distance traveled is just the length of the rails. The acceleration is found from manipulating the force equation. We are using this equation because we have the initial velocity from the spring mechanism. We have the distance traveled because that is just the length of the rails. And we have the acceleration due to the force on the projectile from the magnetic force. With these, we are able to find the final velocity of the projectile.

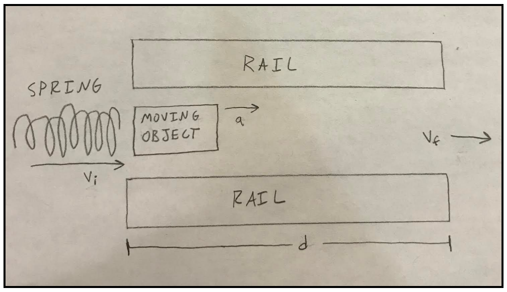


Figure 6: Final Velocity Diagram

$$v_f = \sqrt{v_i{}^2 * 2 * a * d}$$

a = acceleration (m/s^2)

$a = F/m$

d = distance of rails (meter)

v_f = final velocity (meter / second)

v_i = $initial\ velocity$ (meter / second)

Number of Time Constants	Time in seconds	Vf at 45V	Vf at 90V	Vf at 135V	Vf at 180V	Vf at 225V	Vf at 450V
0	0.00E+00	534.00	1067.99	1601.99	2135.98	2669.98	5339.95
0.5	1.58E-06	624.54	1249.08	1873.62	2498.17	3122.71	6245.41
1	3.16E-06	654.71	1309.42	1964.12	2618.83	3273.54	6547.08
1.5	4.74E-06	665.46	1330.92	1996.39	2661.85	3327.31	6654.62
2	6.32E-06	669.37	1338.75	2008.12	2677.50	3346.87	6693.75
2.5	7.90E-06	670.81	1341.62	2012.42	2683.23	3354.04	6708.08
3	9.48E-06	671.34	1342.67	2014.00	2685.34	3356.67	6713.35
3.5	1.11E-05	671.53	1343.06	2014.59	2686.11	3357.64	6715.28
4	1.26E-05	671.60	1343.20	2014.80	2686.40	3358.00	6716.00
4.5	1.42E-05	671.63	1343.25	2014.88	2686.50	3358.13	6716.26
5	1.58E-05	671.64	1343.27	2014.91	2686.54	3358.18	6716.36

Table 9: Final Velocity

7.5 Reference

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