Capacitor Gun

A.k.a (railgun)

Design Document

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Version 2.0

Last Updated: 12/4/2018

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List of definitions

- **EM** - An abbreviation for electromagnetism or electromagnetic(s).
- **Capacitor** - An electronic device used to store an electric charge to be discharged and used later in a certain application.
- **Solenoid** - A coil of wires acting as a magnet while carrying current. Included is an arm called a stroke which extends at a high speed producing a force on an object.
- **Wire Gauge** - A term used to describe the diameter and current carrying capacity of a wire or cable.
- **Lorentz Force** - The force exerted on a moving object by a magnetic force.
- **Muzzle** - Open end of a barrel of a firearm.
- **MJ** - Abbreviation for megaJoule. A joule is a unit of measure for energy. Likewise, KJ is kiloJoule.
- **Breach** - Another term for a door or latch.
- **AC** - an abbreviation for “alternating current” which periodically reverses direction
- **DC** - an abbreviation for “direct current” which describes current that only flows one direction
- **Polycarbonate** - an extremely strong plastic manufactured to withstand heat and pressure

1 Introduction

1.1 ACKNOWLEDGMENT

The Capacitor Gun Project 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 EM. Others who have helped include Professor Neihart who assisted in formulating equations and Mr. Mike Ryan who gave us a workspace to craft our project and equipment 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 AND PROJECT STATEMENT

Currently, the common choice for how firearms (projectile launchers) shoot objects is combustion. While this method is proven and effective, there is a power limit to combustion and also a lack of precision at high speeds due to the lower energy. Railguns have the ability to propel projectiles of greater mass at a much higher velocity due to the concentration of energy that is possible with EM propulsion.

The goal of this project is to create a functional railgun so that one day the design could be used to replace current combustion weaponry. As of now, when you think about railguns, you may think about the large-scale military grade ones. Because of their size and energy outputs, they require complex systems to function properly. These complex systems incur lots of manufacturing and maintenance costs which we aim to eliminate. Our goal is to design a railgun on a much smaller-scale to see if it could be both practical and possible when comparing it to combustion weaponry and current railgun designs.

During this project, we will be using our knowledge from the courses we have taken, and also the knowledge we will gain through researching railgun design. During this course, we hope to accomplish two milestones to ensure a success. Our first milestone is creating a small-scale model that is functional and can be used to improve our design. Our second milestone is taking what we have learned from the small-scale model and applying it to the creation of a large-scale model that can be compared to similarly powered firearms.

1.3 OPERATIONAL ENVIRONMENT

Our final design will be operated outdoors, so it must be able to withstand different weather conditions. The railgun will be encased in a weather-resistant material to shield the components from the elements. It will also be easily portable for quick relocations and adjustments. Our end design will be heat resistant as well because of the high currents and voltages being used. Because the railgun will contain an immense amount of charge it will have a discharging circuit to allow safe disarming of the railgun. While it is operational, there will be no open metal that would allow accidental discharges.

1.4 INTENDED USERS AND USES

Our product is intended for users who have been trained on our design and not the public. This project is a weapon that is dangerous to those who are not experienced with its functionality and design. This is the main reason why it is not intended for public use. Only those with knowledge on the project design and safety measures will use this product.

The project will be a small scale model of what the current United States military uses. Possible uses for our railgun can include replacing turrets and artillery cannons with a large-scale railgun and replacing hand-held rifles with our small-scale railgun. This would improve our weapon systems that are used to protect our nation.

1.5 ASSUMPTIONS AND LIMITATIONS

Assumptions:

1. The military needs/wants new technology
2. The difference between EM (electromagnetic) and combustion propulsion is great enough to warrant investment
3. Railguns can be just as accurate as current technology
4. Railguns can be operated in any conditions alongside current firearms

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 released may be too high for hand-held usage

1.6 EXPECTED END PRODUCT AND DELIVERABLES

By the end of the Fall semester, the final project will be a functional weapon system. It will use EM to fire a projectile with the use of high voltage capacitors and a battery. The deliverables will include:

- A capacitor bank
    - The capacitor bank will consist of four 450V capacitors connected using copper. The use for the capacitor bank is to store charge in the form of electrical energy. This will be used to induce a current in the metal rails which will create an electromagnetic field.
- A battery
    - The battery will be used to charge the capacitor bank. The battery is where the whole project starts. It will charge the capacitors to our specified voltage in order to create the means to fire the projectile.
- Metal Rails
    - The rails are used to carry current in order to create the electromagnetic field. The rails must be made of a conductive metal because the electromagnetic field is created by a current running through it.
- Discharge Circuit
    - Large resistors in series that will be attached to the capacitor bank via a switch. Once activated, the resistors will dissipate any remaining charge in the capacitors and rails making them safe to touch.
- Wires
    - Wires will be used to carry current from the capacitor bank to the rails. These wires must be able to handle the high amounts of current in each segment of the project.
- Projectiles
    - The projectiles are what makes this project a propulsion device. They must be conductive so they can create the electromagnetic force. The projectiles will enter the field and experience what is

known as the Lorentz force. This is created by the current and magnetic field and is what will give the projectiles their acceleration once they enter the rails.

- Charging Circuit
    - The charging circuit will be made up of a specialized chip (LT3751) with supporting components to create a 450V capacitor charger. A 12V input will be fed into the circuit and transformed into a 450V output. This will be done by storing energy in cycles and releasing it into the capacitor bank at increasing power.
- Spring Mechanism
    - The spring mechanism will be two tension springs attached to a drawer slide that will push a wood block. The wood will have a hook on it to allow an area to grab and pull backward. This motion creates a great tension in the springs which hold more energy the farther they are stretched before being released. During this release, the wood block will push the projectile forward and into the opening of the rails. This will allow the projectile to enter the rails at an initial velocity, create the magnetic field and avoid welding in place.

2. Specifications and Analysis

2.1 PROPOSED DESIGN

Our proposed design is a fully electronic railgun. Previously built projects use hardware or compressed air to provide the initial velocity into the magnetic field which adds unnecessary complexity. Our team's final design includes a spring mechanism or solenoid to be used for the initial momentum. The solenoid 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 massive amount of current going through will weld the projectile to the rails.

We do have a few design alternatives that will be determined from available materials, tools, the size of our rails, and projectiles. For the rails, we will test if aluminum or copper is best to use when under maximum load. The material must also be able to prevent degradation of the rails due to the heat and friction of firing. Dielectric and conductive greases will be used as lubricants to decrease friction and increase electrical connection.

Another aspect of our design that will be designed during testing is our projectile. Our initial plan is to make it like a sled/sabot. It will be in the shape of a “U” to maximize contact with the rails while also allowing space to carry a more aerodynamic projectile. The projectile then does not have to be conductive. This gives us more options for projectile materials. The other alternative for the projectile is to use one piece of conductive metal which will be cut and shaped to a specific design to minimize air resistance and velocity losses. The single body design will be more expensive to manufacture but easier to test and potentially higher muzzle energy.

Our capacitor bank will be charged with a special charging circuit. This circuit will have the functionality to allow the user to set the amount of charge (voltage) they want the capacitors to be charged to. This charging process will take some time which unfortunately is unavoidable due to our low budget. There will also be a discharge circuit which will absorb any remaining charge on the rails after firing. This should make the railgun safe to transport.

The proposed design is as shown below. Not all components are present in this sketch but shown is a charging circuit (green box) that is being used to charge the capacitors. The positive side of the capacitors are connected to one rail and the negative side is connected to the other rail. The rails are covered top and bottom with a sheet of polycarbonate which acts as a barrel when put together. A spring mechanism is shown at the end of the rails. This is where the projectile will be loaded. The spring will launch the projectile into the magnetic field to give it the initial push it needs. A discharge circuit (not shown) will be used to make sure the railgun is safe to handle after it has been fired.

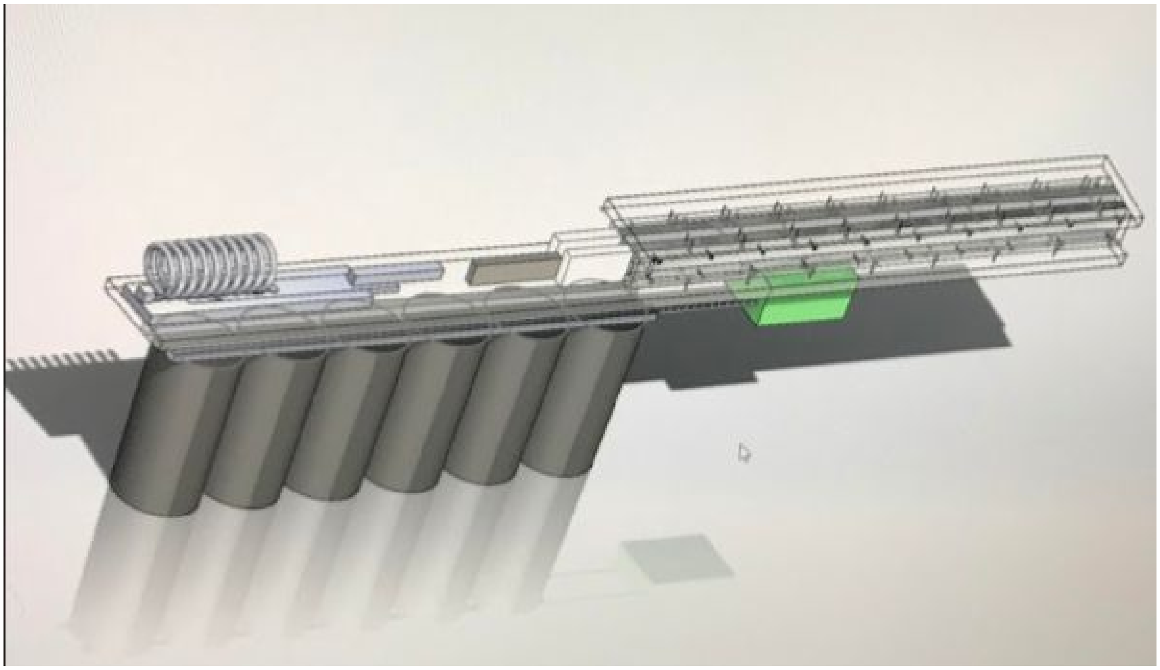


Figure 1. SolidWorks design for the project

2.2 DESIGN ANALYSIS

Currently, our small-scale design has been constructed with aluminum rails, an aluminum projectile, two 450V capacitors connected in parallel, a polycarbonate encasing to hold the rails and capacitors, heavy gauge wire to transfer power, a spring-loaded entry mechanism, and a charging circuit.

We chose aluminum rails in our small-scale design because it was what Mr. Mike Ryan had on hand for us to use. Because of the high amounts of current, we will be using the metal choice may need to be changed if unsuitable. Our main concern with the metal is how quickly it will degrade from friction and concentrated electric discharges.

The projectile will be an all-aluminum piece instead of a sled concept. This eliminates the need to design a special projectile and casing that is conductive and lightweight. The aluminum projectile will have 2-4 inches in length of contact with the rails to provide proper energy transfer. It will be a half inch wide to make a connection with the rails. 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. This design is easier to machine and has more contact area, but is not inherently aerodynamic and will require modifications through testing.

We have chosen to connect our capacitors in parallel to increase the total capacitance of the design and thus energy stored while staying in a 450V configuration. The stored energy is given by the equation: $E(energy) = (½) * C(capacitance) * V^2(voltage)$. 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. At this time we will only charge the capacitors to at most 50% of their capacity.

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

Figure 2: Chart showing amount of energy in our capacitors at each percentage.

The polycarbonate encasing is just a layer on top and bottom of the rails that hold them in place via screws. They were available at Mr. Ryan’s shop for us to use so we did not specifically choose them but they have promising properties. They should be able to resist the heat of the rails and be dense enough so they are not damaged by the projectile being fired. The polycarbonate is a strong material so it will also be able to hold the rails at the correct spacing once the magnetic field is produced.

Heavy gauge wire was chosen to carry the current from each component to the rails. The gauge of each link was determined using common ampacity ratings of insulated wire under their intended loading conditions.

We chose to make a spring-loaded projectile entry device for our project. Our design is basic in the sense that we will pull back a push rod hooked to springs to the desired length. Then, when we want it to push our projectile forward, we pull the string which in turn releases the drawer slide holding the rod. We chose this method over an electrical solenoid mainly for cost reasons, so we can stay under our budget, but also complexity reasons. This is a design we intend to simplify if budget allows.

Our charging circuit was chosen/designed specifically to convert 12V from a portable battery to 450V within the capacitor bank. This was done by utilizing a Lt3751 chip, MOSFETS, a flyback transformer, resistors, and rectifiers. The Lt3751 is commonly used as a high voltage capacitor charger from a 12-24V input by triggering charging cycles of energy storage and then discharge across the transformer to the capacitor bank. The functionality of our circuit is currently being tested and may be modified under further evaluation.

Currently, our calculations for the forces the railgun and projectile will be experiencing are limiting the continuation of our design and testing due to safety concerns. The calculations and numbers, which are in the appendix section, have reached a stop due to our confidence in our physics. Our calculations rely heavily on time varying currents and magnetic fields which will need to be discussed and verified with our project advisor to ensure we can be confident that our numbers will provide a safe testing phase. We have obtained most of the formulas we need to complete our work but will be working in the next semester to make sure the data is calculated correctly. Once the calculations have been verified and approved, we will continue with our build and test phases.

3 Testing and Implementation

3.1 INTERFACE SPECIFICATIONS

We will not be using any hardware or software interfaces for this project. Our design does not include any computer connections.

3.2 HARDWARE AND SOFTWARE

Lab equipment located in Coover Hall will be used for preliminary testing of the charging circuit. We will be using a Function Generator to create a voltage source to help test the charging circuit by creating a 12V DC input. Then we will use a Digital Multimeter to measure the voltages at certain points of our circuit to make sure we are getting the expected outcomes.

3.3 FUNCTIONAL AND NON-FUNCTIONAL TESTING

Our testing will happen in 3 phases: 1) testing our charging circuit. 2) testing our small-scale design. 3) testing our final design

1. Testing our charging circuit

Once the charging circuit is completed, we need to attach a 12V AC power source to it and see what it outputs. Below is a diagram of what the circuit looks like. We would need to attach a Voltmeter to the “C4” capacitor and make sure it is charging. We would also need to monitor the current in the diodes with a Digital Multimeter.

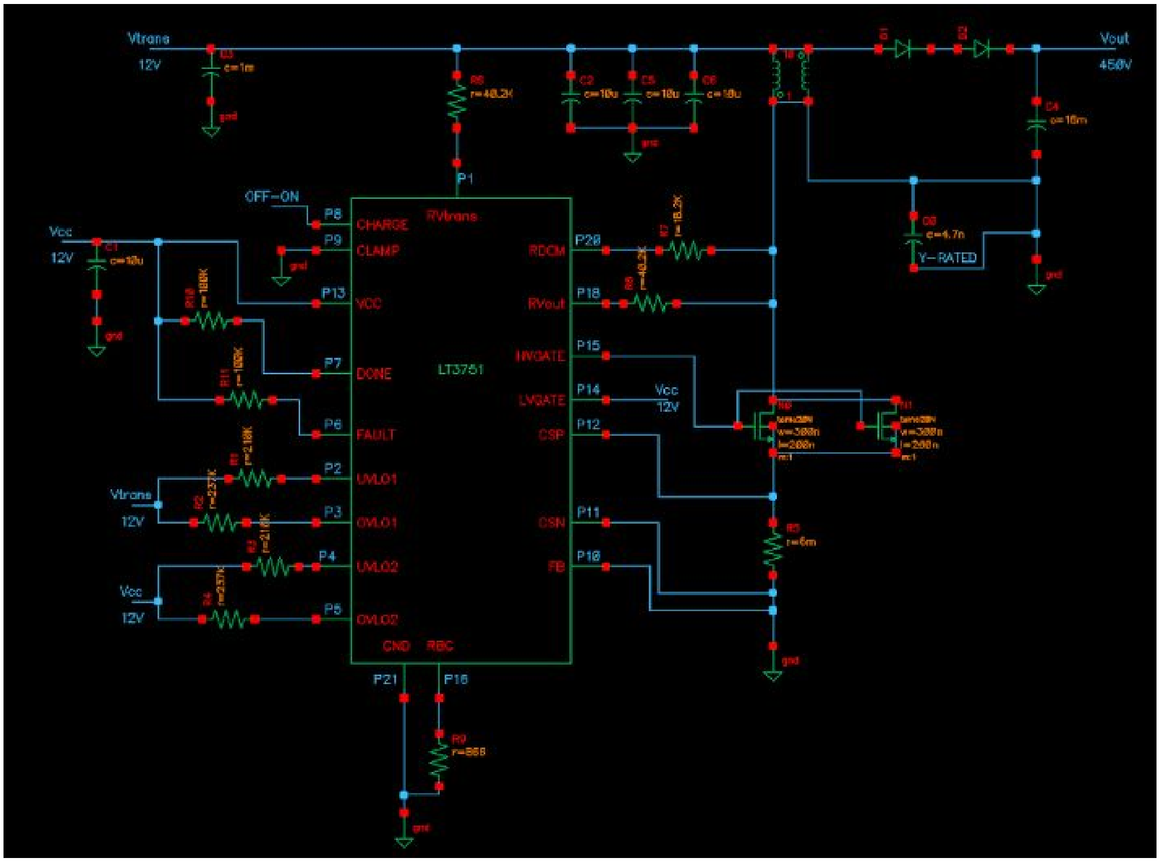


Figure 3. Schematic for the Charging Circuit

If the charging circuit works, we will then test how long it takes to charge a single capacitor to 450V by starting a timer as we input 12V AC.

2. Testing our small-scale design

Testing our small-scale design will first start off as assembling the design of it and then firing the railgun. If it works then we know our design is correct.

First, we have expected numbers based off our design in section 4.3 and the formulas we used to get them.

Given that the design works (produces a magnetic field and moves a projectile) we will test a few different things:

- How each shot degrades the rails and the polycarbonate. We will test this by taking repeated shots and see how the materials hold up.
- How fast the projectile is fired with one capacitor, then two. This will be tricky, but the best way we can do this is to have a powerful camera watching the end of the muzzle as the railgun is fired. We will have distances marked and record the time it took the projectile to reach each spot after it leaves the barrel.
- Projectile testing and designing. We will test how much contact area is ideal for effective usage, what material(s) are best to compose the projectile, and what designs are aerodynamically ideal.
- Our railgun will be tested for accuracy once an ideal projectile is chosen. We will test this by going to a gun range and shooting at a target. If there is a certain amount of precision in our shots, then we can calibrate a target based on that data.

3. Improving our final design

At this point with our project all of the relevant tests to check sustainability, reusability, and operability should have been completed on the small-scale design. To test our final design, we will first assemble the full-size railgun and make sure it fires.

3.4 PROCESS

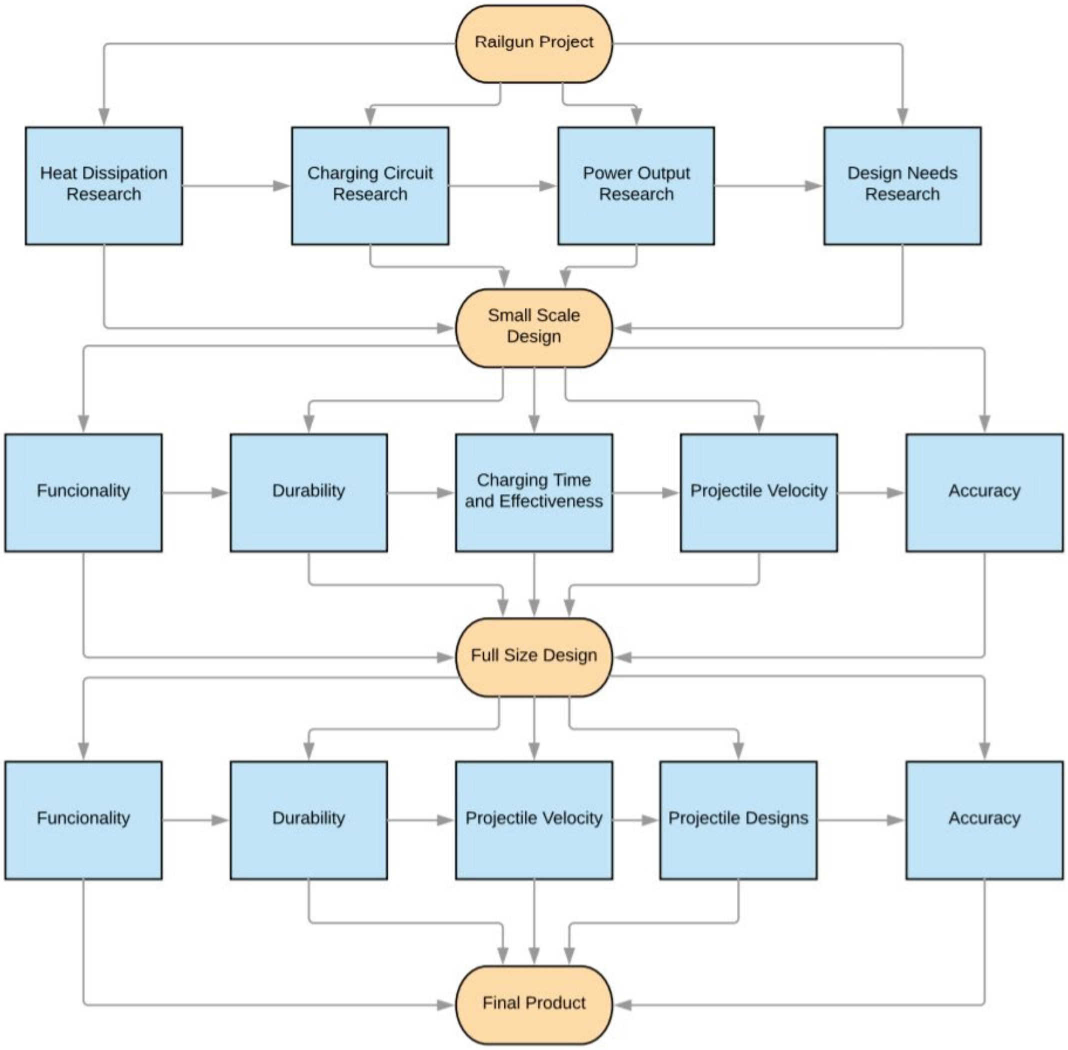


Figure 4. Testing Flowchart

Test Methods:

1. Functionality: Tests to see if the railgun fires by using it in a controlled environment.
2. Durability: Record how many uses we can get out of our railgun before it degrades to an unsafe state. We will look at the rails mainly and record the damage caused by heat and friction.
3. Charging Time and Effectiveness: We will record how long it takes to use our Charging Circuit to bring our capacitors to 450 volts. We will do this with a timer and voltmeter connected to the capacitors.

4. Projectile Velocity: During each successful usage of our railgun we will record the projectiles exit speed. We will do this using a pre-measured area and a high-powered video camera to record each shot. With that data, we can calculate its speed quite easily with the velocity equation.

$$V(velocity) = D(distance)/T(time)$$

5. Accuracy: We will take the railgun to a gun range to test its accuracy against targets at a certain distance away.
6. Projectile Designs: We will use different projectiles periodically to see how velocity and accuracy are affected. We will do this to find the best design for ideal functionality.

3.5 RESULTS

Official testing has not begun due to the charging circuit not being completed and will begin when configured correctly. Before we test, we first will find the calculations for all of the unknowns we are testing for. From our appendix, there are our calculations for some of the unknowns we found. These calculations are calculated for the absolute maximum values they can be with no losses. Here is just an general idea of what we might expected before testing. For some of these values though, they do not make sense to us. Before we think about testing, we will be working on to fixing these values to make more sense to us.

The physical circuit is being tested for accurate assembly and the node voltages are being examined.

Charging Circuit:

We are expecting results for this to be very direct in the sense that it works, or it doesn't. The circuit is designed to charge the capacitors to 450V in a short amount of time, roughly 2 minutes. The discharge time is equal to the charging time. As they charge, we are expecting a waveform as shown below.

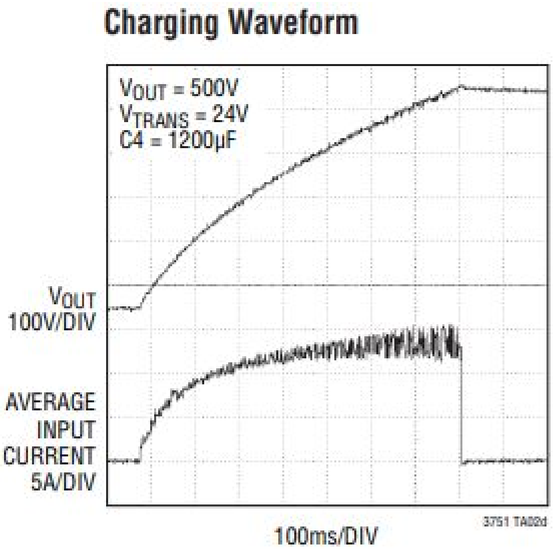


Figure 5. Charging Circuit Waveform

The voltage and current should rise logarithmically until they reach their max values and then stop. We are also testing the voltages at certain ports of the LT3751 chip (see Figure 2) to reassure that it is working properly.

Small-scale design:

We are unsure of the results we should be expecting when testing the small-scale design. Number one we expect it to work, but the exit velocity, accuracy, repeatability, and time to cool off are all unknowns.

Improving small-size design:

Once data has been gathered on the small-scale design, we expect to formulate equations that will relate to increasing its power and performance. That will give us an idea of what to expect once we are at full strength.

The main issues with testing our railguns will be safety and finding a place to do so. We plan on running tests inside of a gun range or out in a secluded field.

4 Closing Material

4.1 Conclusion

To this point, we have completed preliminary calculations, constructed a small scale railgun, and assembled the charging circuit. Our goal this semester was to put the railgun together and run various tests on it. Then, next semester we can assemble the full-sized, optimized railgun and confirm that it works.

Unfortunately, we have not completed the testing to this point so that will need to be done early next semester. Once that is completed, we can work to better our design before its final demonstration. This is the best course of action because each step we take towards completion is dependent on the previous step being finished.

We still plan on having a functional and near perfected design by the end of the spring semester. It will meet our standards for accuracy, time to recharge, time to cool, muzzle energy, and exit velocity (these standards will be compiled later).

4.2 REFERENCES

"LT3751 Datasheet." *Mouser Electronics*, www.mouser.com/datasheet/2/609/LT3751-1504101.pdf.

4.3 APPENDICES

Energy Stored in Capacitors:

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

C = total capacitance

V = voltage stored/charged to

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

Current

Discharging Capacitor Formula (RC):

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

RC = time constant calculated by the overall resistance and capacitance

V_0 = initial voltage

$R = (\#rails * resistivity\ of\ aluminum * length\ of\ rails\ (meters))/(width\ (m) * height(m))$

Magnetic Field

$$\mathbf{B}(s) = \frac{\mu_0 I}{4\pi s}\widehat{\varphi}$$ Biot-Savart Law

$$\mathbf{B}(s) = \frac{\mu_0 I}{4\pi}\left(\frac{1}{s} + \frac{1}{d-s}\right)\hat{z}$$ - Magnetic Field experienced

$$\mathbf{F} = I\int_r^{d-r} \mathrm{d}\boldsymbol{\ell} \times \frac{\mu_0 I}{4\pi}\left(\frac{1}{s} + \frac{1}{d-s}\right)\hat{z} = \frac{\mu_0 I^2}{2\pi}\ln\left(\frac{d-r}{r}\right)\widehat{x}$$

u_0 : *permeability constant of aluminum*

I: current

s = perpendicular distance of rails

d = separation of the rails from center axes

r = cross section of rails

Initial Velocity of Projectile

Spring Constant Formula converted into Potential Energy converted into Velocity:

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

k = spring rate/constant

x = distance pulled back (m)

m = mass of projectile (Kg)

Final Velocity (at end of barrel)

$$v_f = v_i + 2 * a * d$$

a = acceleration (m/s^2)

d = distance of rails (m)

Force Outwards on Rails

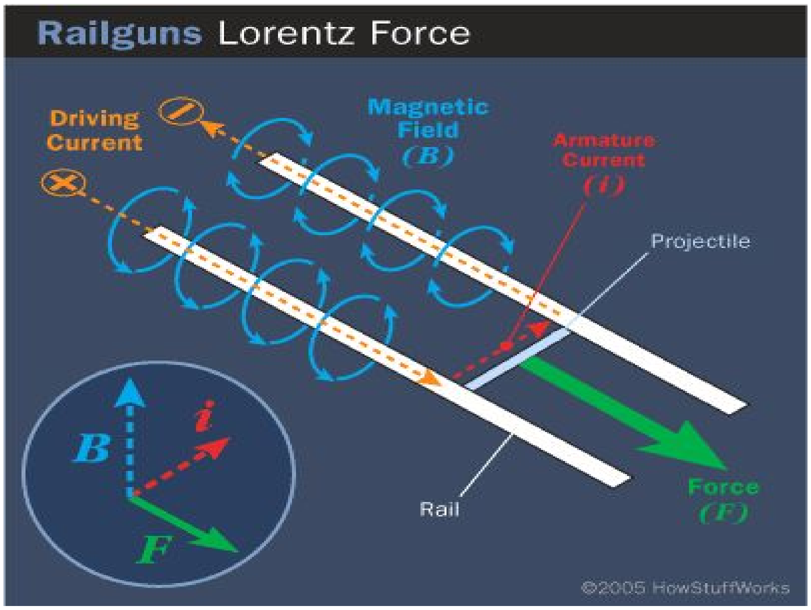
$$F = I * L x B$$

I = current through rails

L = length of rails

B = magnetic field

Force on Projectile (Lorentz's)



B = magnetic field (T)

i = current (A)

F = force on projectile (N)

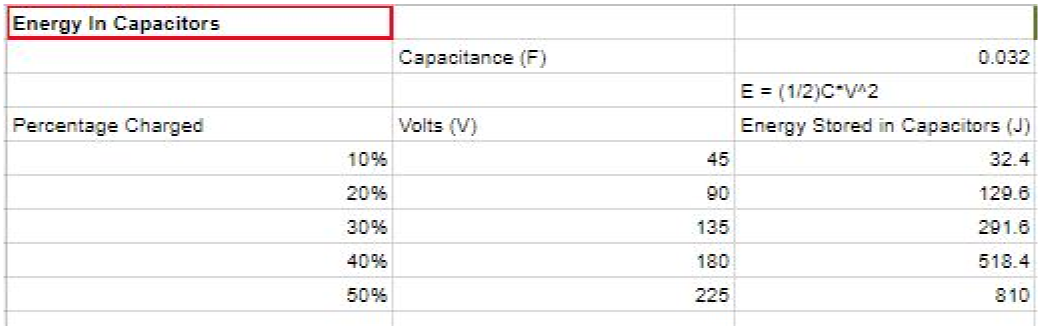
Shear Limits of Fasteners

	Minimum Ultimate Tensile Load (N)	Shear Strength (60% of Tensile Strength with 80% of proof loading). (N)	Total Shear Strength(per rail) (N)
1/4-28 x 1" black oxide ASTM F-835	23464.37	11262.9	157680.56

Safety

We will take certain measures for safety when testing our project:

1) We will contact a gun range and see if they could provide us with a safe environment to test. If not, two of our group members own private land we could use. We would be secluded from public areas and other people on this land.
2) No matter what, when we are in the process of testing our design, all group members will stand behind a protective shield. The shield will be made of a sturdy material and be 25 yards away from the capacitor gun.
3) We will have a mechanism that can “fire” the projectile without us being near it. This could be a simple string attached to a pin that we could pull or a timer that releases the spring after a minute.
4) When testing, our max voltage we will charge the capacitors is 50%. In the table above you can see the energy we will have stored at those levels. Note: all number calculations assume no losses which will not be the case. The numbers shown are absolute maximum values these variables could take.



Energy In Capacitors		
	Capacitance (F)	0.032
		E = (1/2)C*V^2
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
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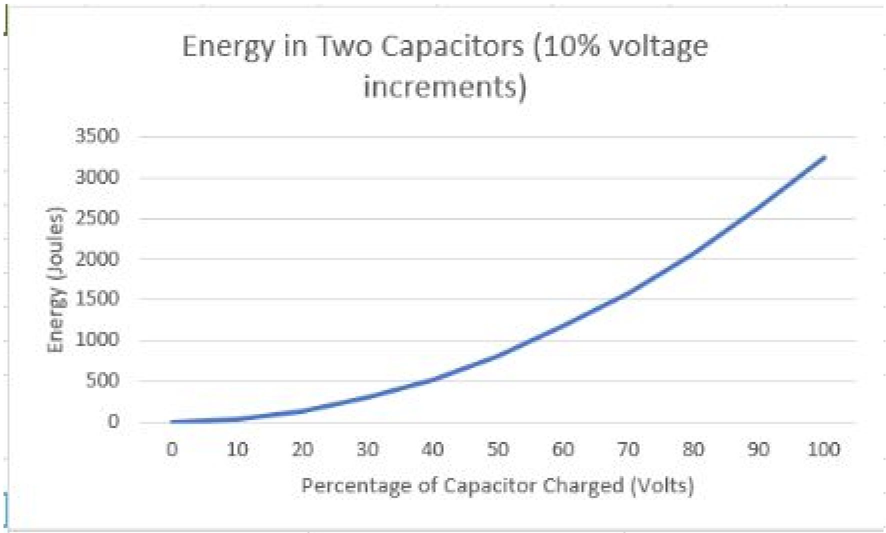
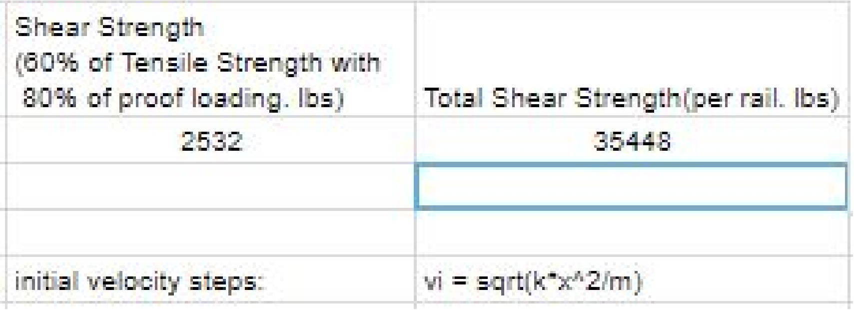
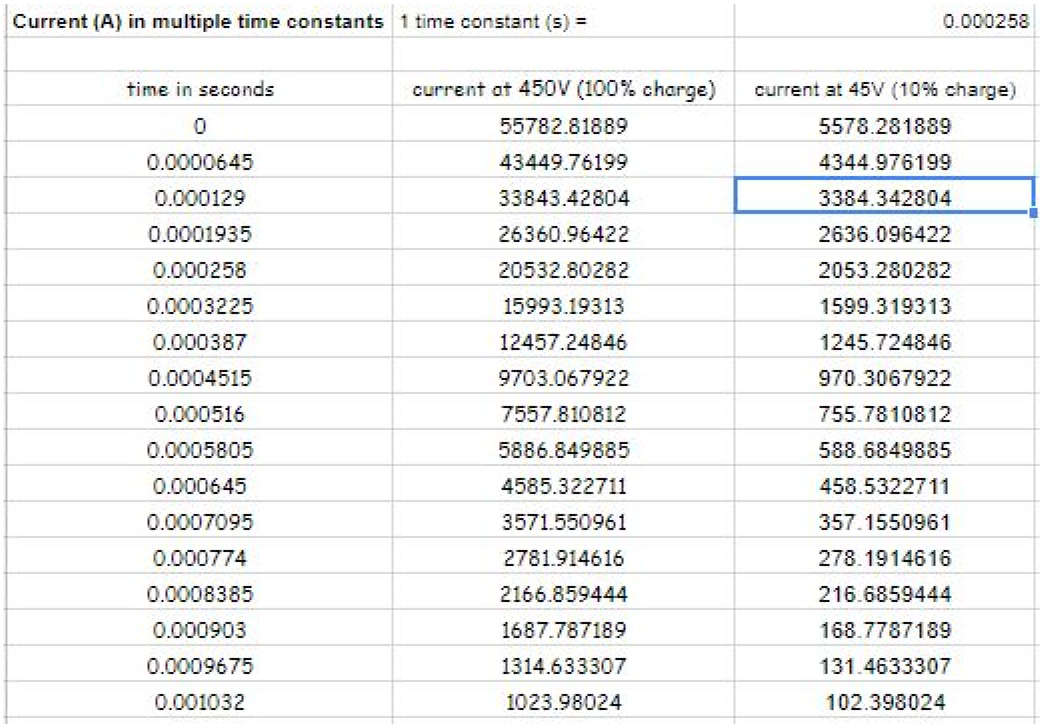


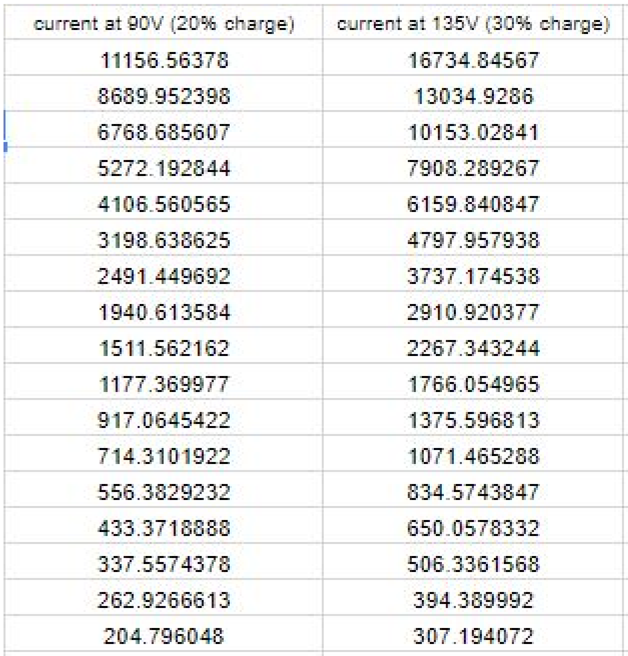
Shear limits of fasteners	
	Minimum Ultimate Tensile Load(lbs)
1/4-28 x 1" black oxide ASTM F-835	5275
magnetic field between rails	
Velocity of Projectiles	final velocity^2 = vi + 2*a*d



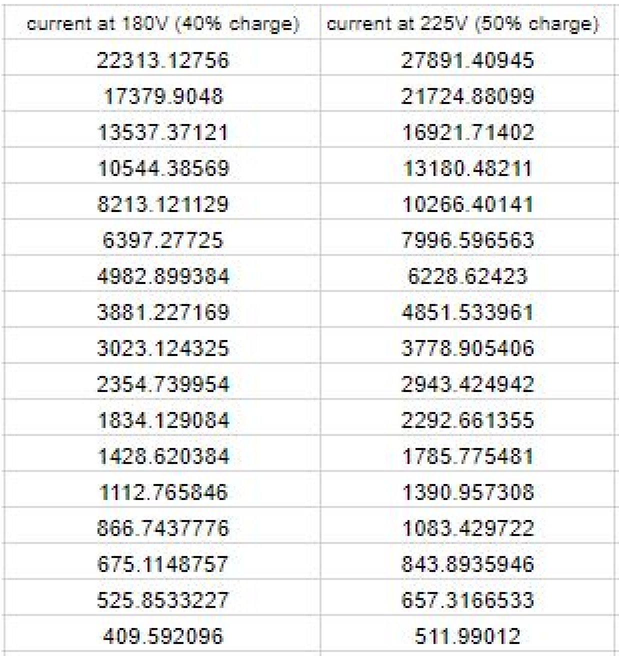
Shear Strength (60% of Tensile Strength with 80% of proof loading. lbs)	Total Shear Strength(per rail. lbs)
2532	35448
initial velocity steps:	vi = sqrt(k*x^2/m)



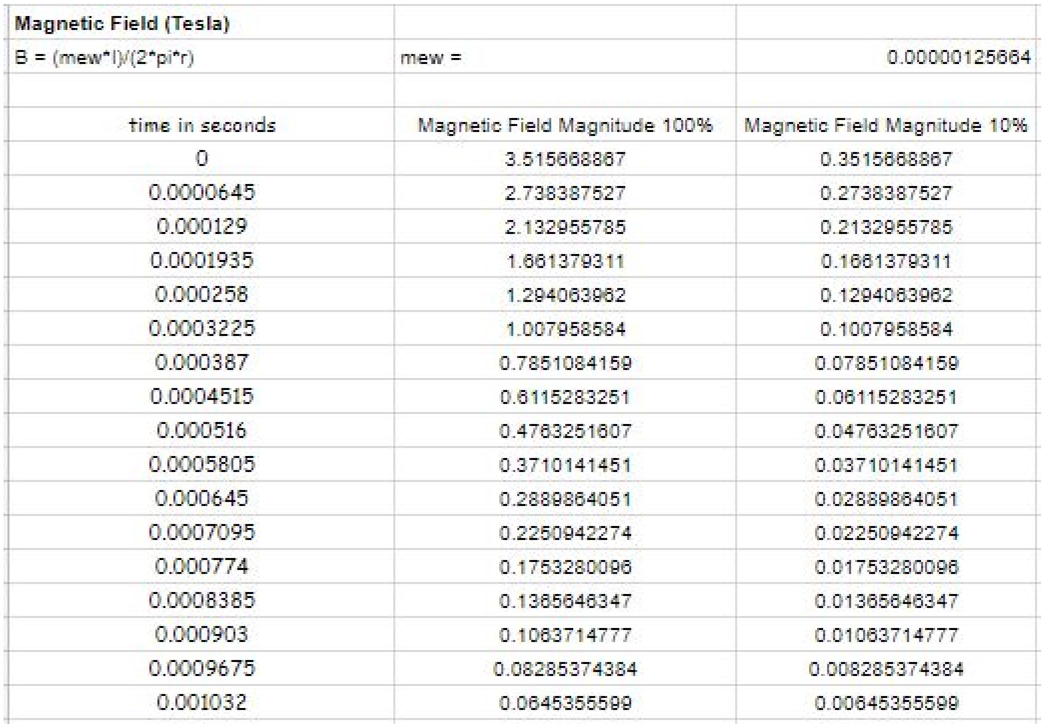
Current (A) in multiple time constants	1 time constant (s) =	0.000258
time in seconds	current at 450V (100% charge)	current at 45V (10% charge)
0	55782.81889	5578.281889
0.0000645	43449.76199	4344.976199
0.000129	33843.42804	3384.342804
0.0001935	26360.96422	2636.096422
0.000258	20532.80282	2053.280282
0.0003225	15993.19313	1599.319313
0.000387	12457.24846	1245.724846
0.0004515	9703.067922	970.3067922
0.000516	7557.810812	755.7810812
0.0005805	5886.849885	588.6849885
0.000645	4585.322711	458.5322711
0.0007095	3571.550961	357.1550961
0.000774	2781.914616	278.1914616
0.0008385	2166.859444	216.6859444
0.000903	1687.787189	168.7787189
0.0009675	1314.633307	131.4633307
0.001032	1023.98024	102.398024



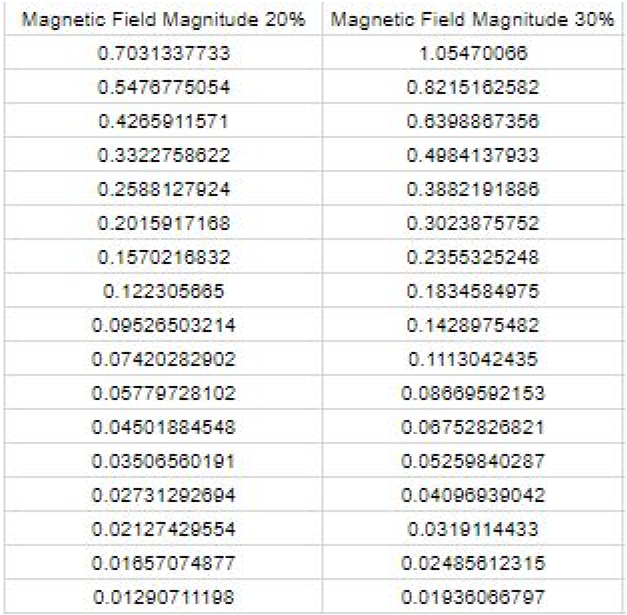
current at 90V (20% charge)	current at 135V (30% charge)
11156.56378	16734.84567
8689.952398	13034.9286
6768.685607	10153.02841
5272.192844	7908.289267
4106.560565	6159.840847
3198.638625	4797.957938
2491.449692	3737.174538
1940.613584	2910.920377
1511.562162	2267.343244
1177.369977	1766.054965
917.0645422	1375.596813
714.3101922	1071.465288
556.3829232	834.5743847
433.3718888	650.0578332
337.5574378	506.3361568
262.9266613	394.389992
204.796048	307.194072



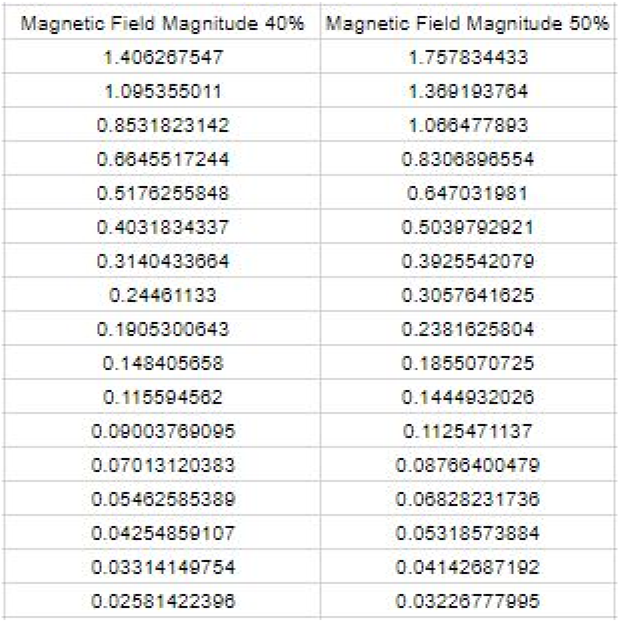
current at 180V (40% charge)	current at 225V (50% charge)
22313.12756	27891.40945
17379.9048	21724.88099
13537.37121	16921.71402
10544.38569	13180.48211
8213.121129	10266.40141
6397.27725	7996.596563
4982.899384	6228.62423
3881.227169	4851.533961
3023.124325	3778.905406
2354.739954	2943.424942
1834.129084	2292.661355
1428.620384	1785.775481
1112.765846	1390.957308
866.7437776	1083.429722
675.1148757	843.8935946
525.8533227	657.3166533
409.592096	511.99012



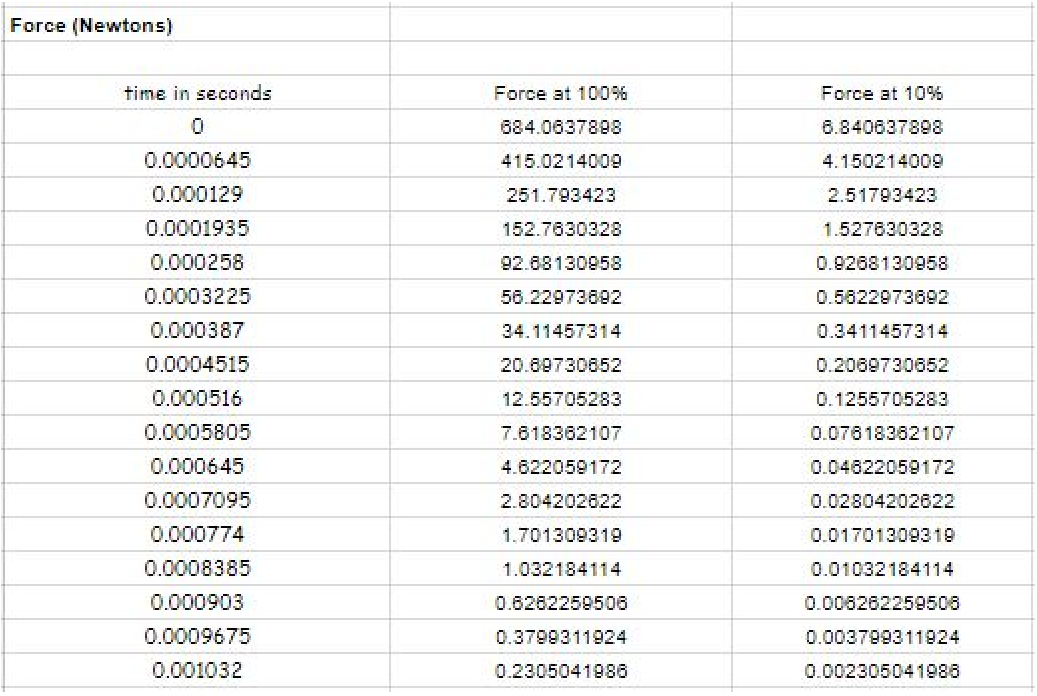
Magnetic Field (Tesla)		
B = (mew*I)/(2*pi*r)	mew =	0.00000125664
time in seconds	Magnetic Field Magnitude 100%	Magnetic Field Magnitude 10%
0	3.515668867	0.3515668867
0.0000645	2.738387527	0.2738387527
0.000129	2.132955785	0.2132955785
0.0001935	1.661379311	0.1661379311
0.000258	1.294063962	0.1294063962
0.0003225	1.007958584	0.1007958584
0.000387	0.7851084159	0.07851084159
0.0004515	0.6115283251	0.06115283251
0.000516	0.4763251607	0.04763251607
0.0005805	0.3710141451	0.03710141451
0.000645	0.2889864051	0.02889864051
0.0007095	0.2250942274	0.02250942274
0.000774	0.1753280096	0.01753280096
0.0008385	0.1365646347	0.01365646347
0.000903	0.1063714777	0.01063714777
0.0009675	0.08285374384	0.008285374384
0.001032	0.0645355599	0.00645355599



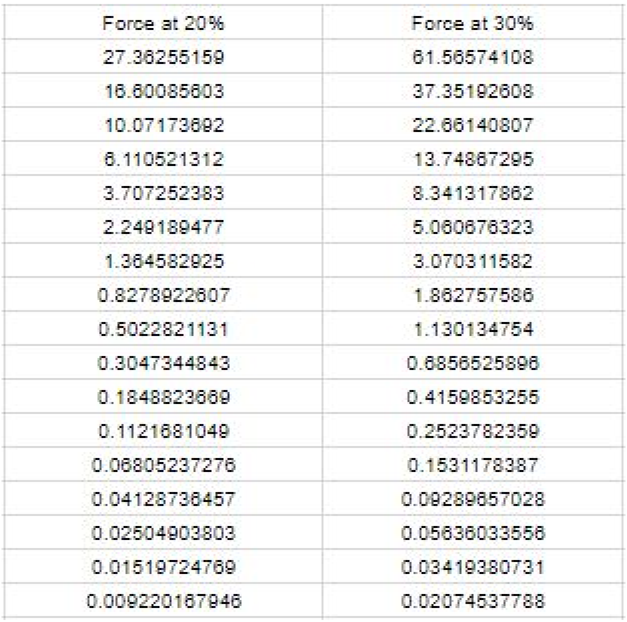
Magnetic Field Magnitude 20%	Magnetic Field Magnitude 30%
0.7031337733	1.05470066
0.5476775054	0.8215162582
0.4265911571	0.6398867356
0.3322758622	0.4984137933
0.2588127924	0.3882191886
0.2015917168	0.3023875752
0.1570216832	0.2355325248
0.122305665	0.1834584975
0.09526503214	0.1428975482
0.07420282902	0.1113042435
0.05779728102	0.08669592153
0.04501884548	0.06752826821
0.03506560191	0.05259840287
0.02731292694	0.04096939042
0.02127429554	0.0319114433
0.01657074877	0.02485612315
0.01290711198	0.01936066797



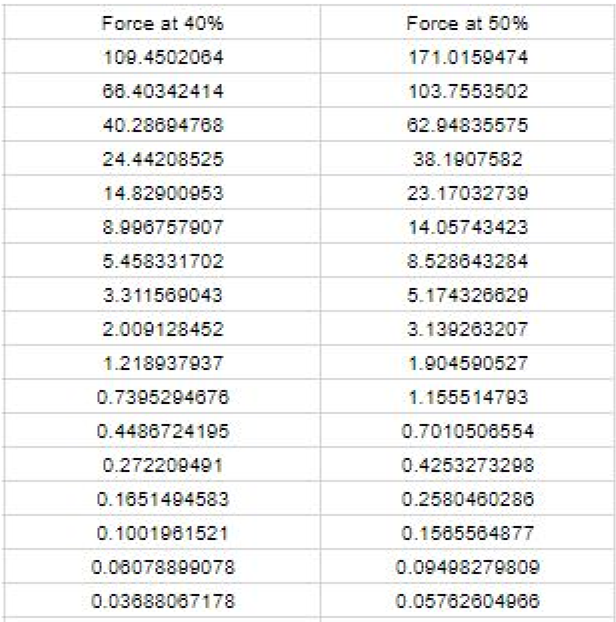
Magnetic Field Magnitude 40%	Magnetic Field Magnitude 50%
1.406267547	1.757834433
1.095355011	1.369193764
0.8531823142	1.066477893
0.6645517244	0.8306896554
0.5176255848	0.647031981
0.4031834337	0.5039792921
0.3140433664	0.3925542079
0.24461133	0.3057641625
0.1905300643	0.2381625804
0.148405658	0.1855070725
0.115594562	0.1444932026
0.09003769095	0.1125471137
0.07013120383	0.08766400479
0.05462585389	0.06828231736
0.04254859107	0.05318573884
0.03314149754	0.04142687192
0.02581422396	0.03226777995



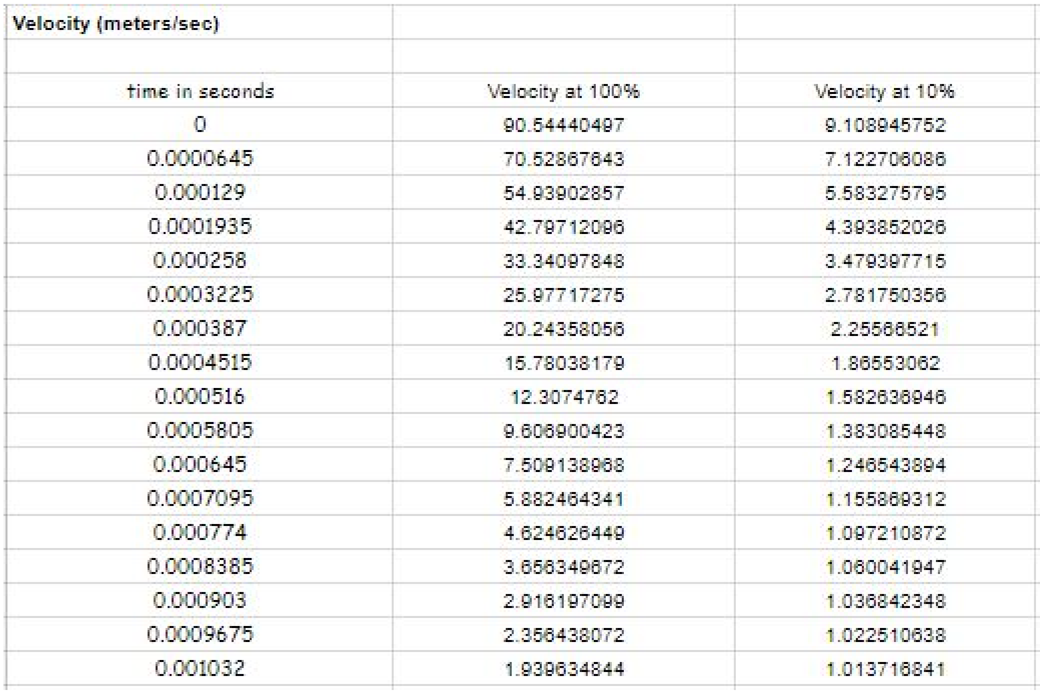
Force (Newtons)		
time in seconds	Force at 100%	Force at 10%
0	684.0637898	6.840637898
0.0000645	415.0214009	4.150214009
0.000129	251.793423	2.51793423
0.0001935	152.7630328	1.527630328
0.000258	92.68130958	0.9268130958
0.0003225	56.22973692	0.5622973692
0.000387	34.11457314	0.3411457314
0.0004515	20.69730652	0.2069730652
0.000516	12.55705283	0.1255705283
0.0005805	7.618362107	0.07618362107
0.000645	4.622059172	0.04622059172
0.0007095	2.804202622	0.02804202622
0.000774	1.701309319	0.01701309319
0.0008385	1.032184114	0.01032184114
0.000903	0.6262259506	0.006262259506
0.0009675	0.3799311924	0.003799311924
0.001032	0.2305041986	0.002305041986



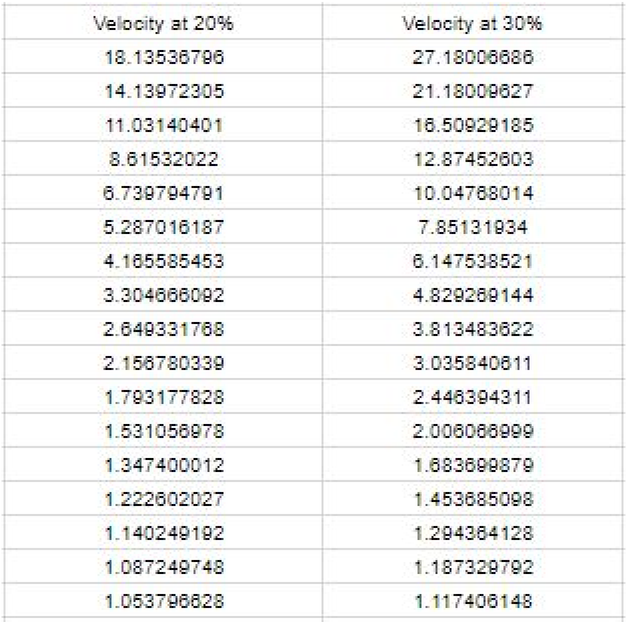
Force at 20%	Force at 30%
27.36255159	61.56574108
16.60085603	37.35192608
10.07173692	22.66140807
6.110521312	13.74867295
3.707252383	8.341317862
2.249189477	5.060676323
1.364582925	3.070311582
0.8278922607	1.862757586
0.5022821131	1.130134754
0.3047344843	0.6856525896
0.1848823669	0.4159853255
0.1121681049	0.2523782359
0.06805237276	0.1531178387
0.04128736457	0.09289657028
0.02504903803	0.05636033556
0.01519724769	0.03419380731
0.009220167946	0.02074537788



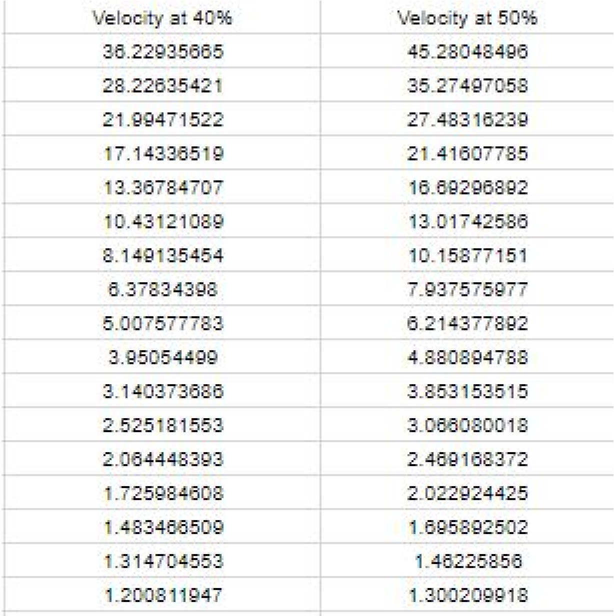
Force at 40%	Force at 50%
109.4502064	171.0159474
66.40342414	103.7553502
40.28694768	62.94835575
24.44208525	38.1907582
14.82900953	23.17032739
8.996757907	14.05743423
5.458331702	8.528643284
3.311569043	5.174326629
2.009128452	3.139263207
1.218937937	1.904590527
0.7395294676	1.155514793
0.4486724195	0.7010506554
0.272209491	0.4253273298
0.1651494583	0.2580460286
0.1001961521	0.1565564877
0.06078899078	0.09498279809
0.03688067178	0.05762604966



Velocity (meters/sec)		
time in seconds	Velocity at 100%	Velocity at 10%
0	90.54440497	9.108945752
0.0000645	70.52867643	7.122706086
0.000129	54.93902857	5.583275795
0.0001935	42.79712096	4.393852026
0.000258	33.34097848	3.479397715
0.0003225	25.97717275	2.781750356
0.000387	20.24358056	2.25566521
0.0004515	15.78038179	1.86553062
0.000516	12.3074762	1.582636946
0.0005805	9.606900423	1.383085448
0.000645	7.509138968	1.246543894
0.0007095	5.882464341	1.155869312
0.000774	4.624626449	1.097210872
0.0008385	3.656349672	1.060041947
0.000903	2.916197099	1.036842348
0.0009675	2.356438072	1.022510638
0.001032	1.939634844	1.013716841



Velocity at 20%	Velocity at 30%
18.13536796	27.18006686
14.13972305	21.18009627
11.03140401	16.50929185
8.61532022	12.87452603
6.739794791	10.04768014
5.287016187	7.85131934
4.165585453	6.147538521
3.304666092	4.829269144
2.649331768	3.813483622
2.156780339	3.035840611
1.793177828	2.446394311
1.531056978	2.006066999
1.347400012	1.683699879
1.222602027	1.453685098
1.140249192	1.294364128
1.087249748	1.187329792
1.053796628	1.117406148



Velocity at 40%	Velocity at 50%
36.22935665	45.28048496
28.22635421	35.27497058
21.99471522	27.48316239
17.14336519	21.41607785
13.36784707	16.69296892
10.43121089	13.01742586
8.149135454	10.15877151
6.37834398	7.937575977
5.007577783	6.214377892
3.95054499	4.880894788
3.140373686	3.853153515
2.525181553	3.066080018
2.064448393	2.469168372
1.725984608	2.022924425
1.483466509	1.695892502
1.314704553	1.46225856
1.200811947	1.300209918