The Trinity Gauss Rifle

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Introduction:

Background:

A coil gun, by definition, is a magnetic projectile accelerator that launches a ferromagnetic object (in our case a low carbon steel rod) through the magnetic field created by a current through a coil of wires. The first coil gun was developed and patented by a Norwegian scientist, Kristian Birkeland, in 1904. In 1933, a Texan inventor, Virgil Rigsby, developed a stationary coil gun that was designed to be used like a machine gun. It was powered by a large electrical motor and generator. It appeared in many contemporary science publications, but never piqued the interest of any armed forces.[1]

Theory:

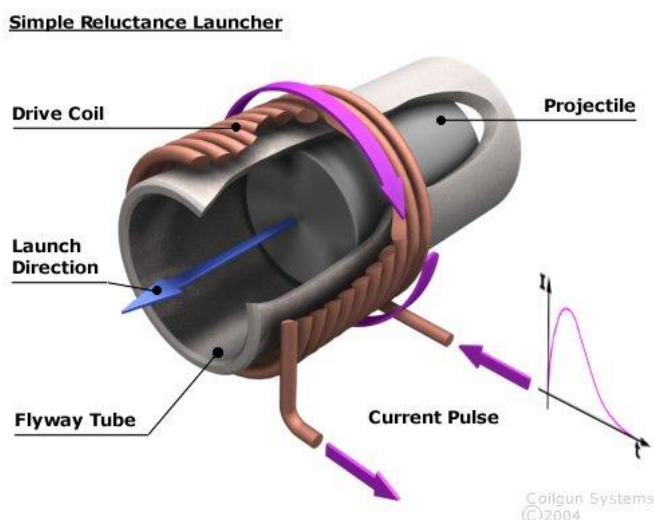


Figure 1: Labeled Stage

The theory behind a gauss rifle is relatively simple. A coil is wound over a non-conducting 'flyway' tube and the projectile is positioned at an end of the tube. If a short current pulse is passed through the coil, the coil induces a magnetic field through the center of the rod. The ferromagnetic projectile will proceed to accelerate into the coil, and, if this pulse is terminated just as the projectile gets to the middle of the coil, it will leave with a significant gain in velocity. Perhaps the most important details of the coil gun design are the correct timing and shaping of the current pulse. If these factors err, then the projectile risks losing most of its speed. The right hand rule dictates that if you wrap your right hand around the coil in the same way that the coil was wound, your thumb will point in the direction of the launch. By reversing the current, you can change the launch direction.

[1] "Silent Machine Guns Are Fired By Electromagnets", June 1933, Popular Mechanics

Rationale:

We undertook this ambitious project with the understanding that it would require a significant amount of understanding in electricity and magnetism. This project is highly relevant to our study of physics, as it requires extensive knowledge of several important concepts of electricity: voltage, current, resistance, power, semiconductor behavior and transistors. Since we have begun our study of electricity and magnetism during the second term, we believe that this experience has helped us achieve a mastery of the course materials.

Plan:

For our coil gun, dubbed the Trinity because of its triple capacitor power bank, we decided to create a design featuring a control board and a PVC barrel. We were able to purchase the parts required ourselves, and then construct and test the performance of the coil gun. The coil gun would contain a laser cut panel, obtained from the Tech Shop, so that it could easily be operated. We would include several switches to operate the rifle. It would be primarily designed to function at high velocities with light weight projectiles. We all have some experience in either robotics, electronics, or hardware and we felt qualified to complete the project.

Challenges: The major challenges of this project were finding a stable and secure power supply that provides the 400V for charging the capacitors, controlling the large current and voltage safely, making sure that the multiple stages of the gun are activated/shut off correctly based on the feedback of the optoschmitts, and calculating the correct number of turns for each stage using a proper simulation program. We also anticipated that there might be technical failures in the circuit, though this turned out to be a much more serious problem than we expected.

Objectives:

For our coil gun to function properly as to our specifications, we needed to accomplish several goals. Our coil gun must be

1. Powerful enough to penetrate a soda can
2. Shoot a ¼ inch cylindrical bullet
3. Charge itself from either wall or battery power
4. Have safety precautions built in such as a lockout switch and safe discharge abilities
5. Have multiple stages, the later ones activated by photogates

Design:

Computer Simulations with FEMM and Lua Script:

Why a Computer Simulation?

When we were designing the Trinity Gauss Rifle, one of the primary pieces of information that we needed was the number of turns of the coil. However, to optimize the number of turns we have to determine the current graph and pulse profile of the gun, which is determined by resistance, voltage, capacitor charge, and inductance. Therefore there is no good function to determine speed of a projectile powered by a capacitor discharging through an inductor. This meant we had to either do a lot of advanced mathematics, or use a simulator such as FEMM!

The velocity is determined by its acceleration, and acceleration is determined by the electromagnetic force on the projectile. To calculate the force, we originally tried to use the formula: $F = \frac{1}{2} NI \, d\Phi/dx$, but ultimately we had to calculate df/dx, or the rate of change of flux linkage with the projectile displacement. Mathematically, flux is defined as following:

$$\Phi = \iint F(x,y,z) \cdot d\vec{A}$$

Here, Φ stands for the flux of a vector field through a surface A. $F(x,y,z)$ represents a vector field defined on Euclidean three-space and using Cartesian Coordinates. $\vec{A}$ stands for the area vector of the surface the flux is passing through. It is generally represented by $dr \cdot |A|$, which is the product of the vector derivative of the normal vector to the surface at any point and the scaler area of the small region that one is integrating on.

Physically, a magnetic flux represents the number of magnetic field lines passing through a given surface, or if one regards magnetic field of the coil as a flow of vector, then the flux represents the "amount" of magnetic "flow" through a surface in a given period of time. Gauss's law relates the flux with the electric field strength of a given field at any point with the flux, which in turn can be easily calculated in some situations. However, our situation was fairly complex and thus we could not calculate this by had due to the moving projectile.

We had to rely on the algorithms built in the FEMM program to calculate the flux at any given moment. FEMM (Finite element method magnetics) uses finite element analysis to determine the flux through each small region (the yellow spider webs in the image below) and therefore can determine flux linkage and force very well.

FEMM

Our simulation is designed to iteratively determine the force acted on the projectile, so we had to learn how to use the FEMM software with Lua scripting. We first made the axial-symmetric diagram of the solenoid and projectile to create a FEMM simulation. We then added each object into its own control group (group 0 for the coil and group 1 for the projectile), and we set the material for each group as well as the environment around it (in this case, air). As shown in the screenshot of the simulation before calculation, there are different layers on the outside that simulates the infinite extension of the flux lines. This is part of the FEMM boundary system that emulates the infinite environment in a finite space. Then, we run the program and FEMM automatically calculates the flux, flux density, force and other relevant quantities for us. The program runs iteratively, meaning that it will run one simulation, determine force, then determine delta x and move the projectile accordingly, then determine the next voltage from the capacitor, then determine the current through the inductor, and finally run the simulation again for the new parameters. We did this 100 times with a time step of 0.05 milliseconds, or 5ms total.

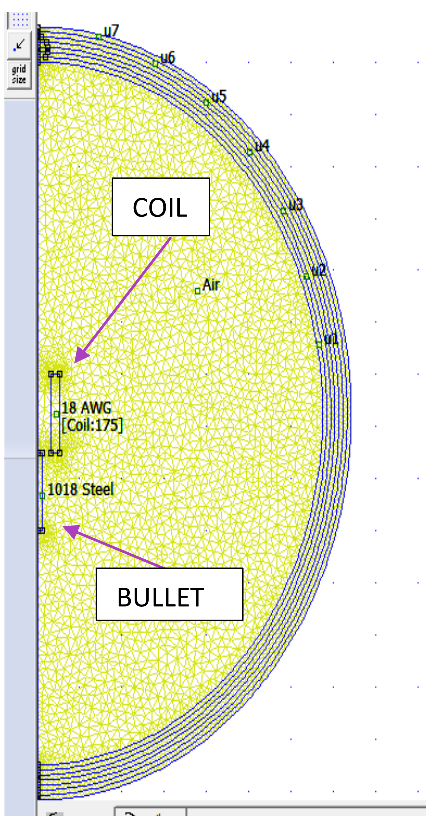


Figure 2: The picture above is a screenshot of our FEMM simulation preprocessor

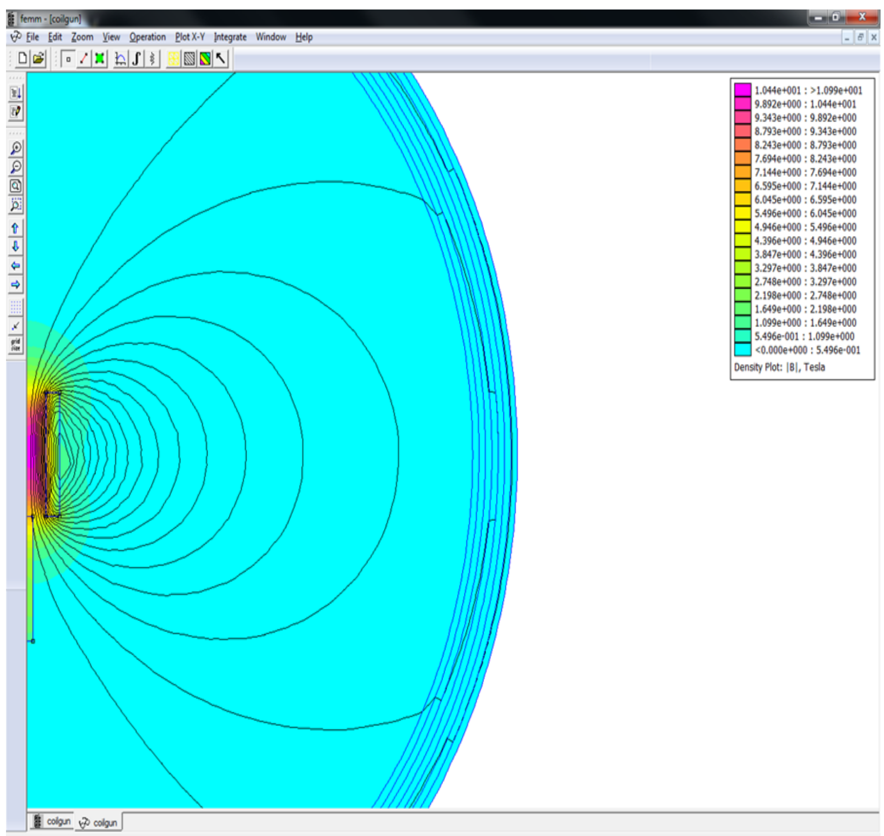


Figure 3: The picture above is a screenshot of our FEMM simulation after we ran it. The colorful pattern on the right shows the difference in flux density.

Lua Scripting

Lua script with core formula implemented - Notepad

File Edit Format View Help

```
showconsole()
mydir="./"
open(mydir .. "coilgun.fem")
mi_setfocus("coilgun.fem")
mi_saveas(mydir .. "coilgun_temp.fem")
mi_seteditmode("group")
Cv = 350
Li = 0
R =
L =
C =
D = true
derivative = {dv = 0; di = 0}
state = {V = Cv; I = Li}


function derivative.getNext (v, i)
      self.dv = (-1 * math.pow (2.718281, -11.5129 * v)) / C
          self.di = (Cv - Li * R) / L
end

function state.nextState (V, C)
        derivative.getnext(V, C)
        temp1dv = dv;
        temp1di = di;
        temp1V = self.V + 1/2 * dt * temp1dv
        temp1I = self.I + 1/2 * dt * temp1di
        derivative.getNext(temp1V, temp1I)
        temp2dv = dv;
        temp2di = di;
        temp2V = temp1V + 1/2 * dt * temp2dv
        temp2I = temp2I + 1/2 * dt * temp2di
        derivative.getNext(temp2V, temp2I)
        temp3dv = dv;
        temp3di = di;
        temp3V = temp2V + dt * temp3dv
        temp3I = temp2I + dt * temp3di
        derivative.getNext(temp3V,temp3I)
        temp4dv = dv;
        temp4di = di;
        finaldv = (temp1dv + 2 * temp2dv + 2 * temp3dv + temp4dv) / 6;
        finaldi = (temp1di + 2 * temp2di + 2 * temp3di + temp4di) / 6;
        self.V = V + finaldv
        self.I = I + finaldi
end
for n=0,30 do
    mi_analyze()
    mi_loadsolution()
    mo_groupselectblock(1)
    fz=mo_blockintegral(19)
    print((15-n)/10,fz)

    if (n<30) then
        mi_selectgroup(1)
        mi_movetranslate+(0,d)
    end
end
mo_close()
mi_close()
        temp3di = di;
        temp3V = temp2V + dt * temp3dv
        temp3I = temp2I + dt * temp3di
        derivative.getNext(temp3V,temp3I)
        temp4dv = dv;
        temp4di = di;
        finaldv = (temp1dv + 2 * temp2dv + 2 * temp3dv + temp4dv) / 6;
        finaldi = (temp1di + 2 * temp2di + 2 * temp3di + temp4di) / 6;
        self.V = V + finaldv
        temp3di = di;
        temp3V = temp2V + dt * temp3dv
```

Figure 4: The image above is a screenshot of the Lua Script Code that we implemented in FEMM. This code section was from an earlier version of our code, which contained the main-method state.nextState() that we used, but lacked some other details.

The FEMM program allows for the customization of the runtime by implementing a Lua script. For each iteration, we found the algorithm to generate the next "state", which was a Lua object that contains information of the current condition of the coil, namely the voltage across and the current through it at a given minimal time interval. The algorithm generates the next state based on independent formulas that approximate the derivative of the voltage and current, and then the algorithm uses the Runge-Kutta method for fourth degree to construct an estimation of the next state of the coil after a time interval of 0.05 milliseconds. The heart of this algorithm, the Runge-Kutta method, integrates ordinary differential equations representing the magnetic system using a step-wise approximation which subdivides the time interval and calculates the derivative at various points between the given state and the next unknown state. The mathematical form of this method for a fourth degree equation looks as following:

$$
\begin{aligned}
k_1 &= h\, f\,(x_n\,,\, y_n) \\
k_2 &= h\, f\left(x_n + \tfrac{1}{2}\, h,\, y_n + \tfrac{1}{2}\, k_1\right) \\
k_3 &= h\, f\left(x_n + \tfrac{1}{2}\, h,\, y_n + \tfrac{1}{2}\, k_2\right) \\
k_4 &= h\, f\,(x_n + h,\, y_n + k_3) \\
y_{n+1} &= y_n + \tfrac{1}{6}\, k_1 + \tfrac{1}{3}\, k_2 + \tfrac{1}{3}\, k_3 + \tfrac{1}{6}\, k_4 + O\left(h^5\right)
\end{aligned}
$$

When actually implementing this method, we discarded the error term O(h^5) in the last line of these equations. We used this method, "state.nextState()", in our main code twice, for both voltage and current. Then we simply put inside the for-loop, change the setting of the system based on the calculated current, and FEMM will automatically calculate the rest for us.

Barry's Coil Gun Inductance Simulation

Barry's Coil Gun website provides us with a useful inductance simulator that generates approximations of the inductance of the coil and the resistance of the coil based on the size of the coil and the gauge of the wire. This was helpful for inputting the parameters for our FEMM simulations. We found that the inductance of our ~200 wind coil was about 0.252 mH, and the resistance 0.246 ohms, as shown in the screenshot below.

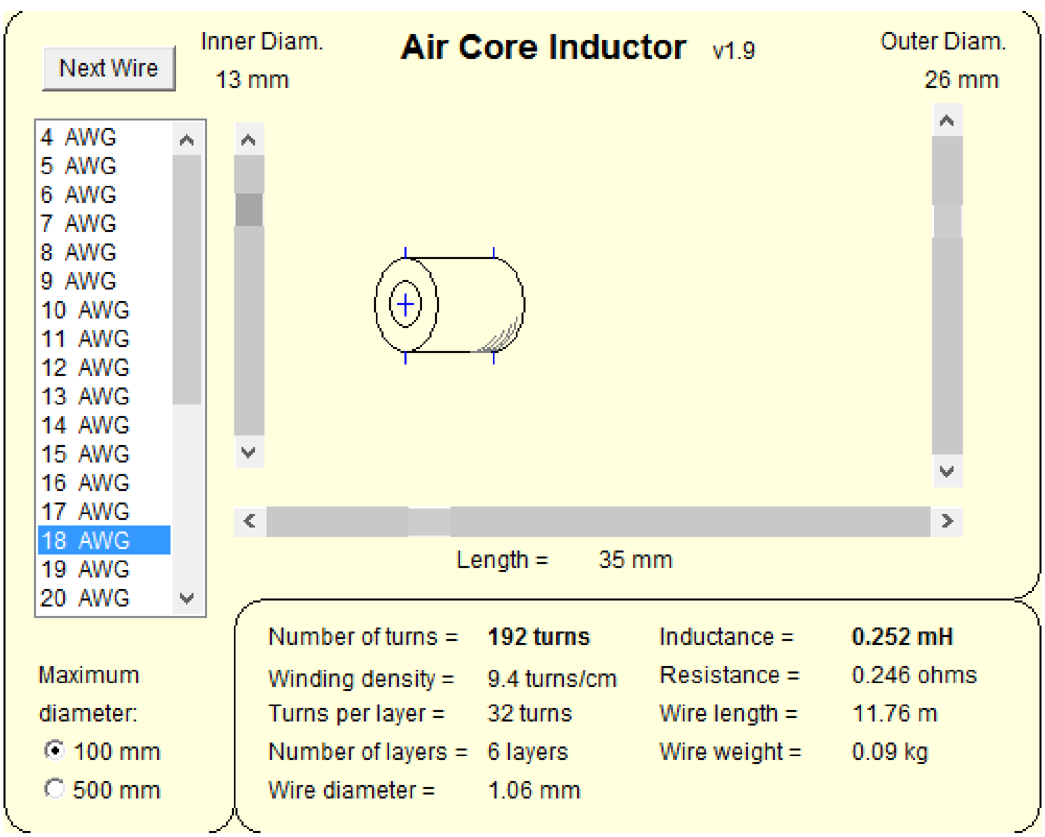


Figure 5: The image above is a screenshot of the inductance simulation found on Barry's Coil Gun website.

Conclusion

The whole process of simulation took a significant amount of time, but the simulation achieved its objective. The FEMM simulation determined that 208 was the correct number of turns to use in our coils for optimal force. This number used the assumption that the approximations of the algorithms and simulations are effective. For simplicity's sake, we rounded 208 down to 200, and made 200 turns of our coils.

Materials:

Part:	Purpose:	Source:	Qty:	Notes:
Mag Wire	Coils	Amazon	At least 20ft	We used 18 AWG wire
Capacitors	Charge storage/Fuel Cells	eBay	3	We used 3900uF 400v capacitors. Careful, they can and might kill you
Light switches	Control panel	Home depot	7	1 for logic power, 1 for arm, 3 for cap disconnects, 2 for charge/discharge
Key switch	Safety	Amazon	1	In series with trigger button
Button	Trigger	Amazon	1	Get one with an LED
Voltmeters	View capacitor charge level	Amazon or eBay	4	Get 0-400v dc meters for the frame
1/8 in plywood sheet	For control panel	Amazon	2x 1ftx2ft	For laser cutting, so get some that is relatively un-warped.
½ in plywood sheet	For mounting electronics	Home Depot	2ftx2ft	Get a relatively un-warped one, so that everything mounts neatly
1x4 lumber	For mounting control panel and other electronics	Home Depot	2x 2ft long pieces plus extra	Cut gaps underneath so the wires can go under.
2x2 lumber	For mounting barrel	Home Depot	3x 1ft pieces	Cut at angles so the barrel is above the caps and gun power parts
SCR Thyristors	For trigger mechanisms	eBay	4	We used 1kv 110A SCR Thyristors salvaged from a broken CO2 Laser.
9v batteries	For charging the caps	Anywhere cheap	35	Put them in series
Light bulbs and light bulb mounts	For resistors to prevent capacitor and battery damage	Home depot	2	Mount them on a standoff so you can get to the base. We used 200w light bulbs. Get extras as they burn out pretty easily.

Tools Required:

Knowledge of operation and safety of the following tools is required to successfully construct this Gauss Rifle:

- Drill press
- Angle grinder
- Laser cutter at TechShop
- Hand drill
- Soldering iron
- Use of lighter and heat shrink tubing
- Hot glue gun
- Screwdrivers
- Multimeter
- Assorted glues including:
  - Superglue, wood glue, hot glue
- Assorted consumables:
  - Heat shrink tubing
  - Duct tape/electrical tape
  - Wood screws

Specifications:

- Thyristor
  - 110 A - Current
  - 500~1200 V - Voltage
- Capacitor
  - 400V - Voltage
  - 3900uF – Capacitance
- Power Supply (old)
  - Transformer
    - 120V to 240V at 500VAc
  - Variac
    - Input: 120-volt AC, Output: 0~130 volt AC, 3 Amp Slow Blow Fuse
    - Max VA: 300VA, 3 Amp. Max (surge)
- Power Supply (New)
  - 9v battery x 35 (~340v at full charge)

Construction of the Frame:

Different from our ROV project last term, there is not as much requirement on the frame. However, the frame does need to have enough space on it to hold each electrical system. These systems range from controlling the charging/discharging of the power bank to firing. Aesthetics was not one of our primary concerns, but we did want the frame to be neat and clean kept so that the wires would not tangle and everything could be modified and repaired easily.

Requirements for the frame and our solutions:

- Command Console
    - The full design called for 7 switches, 1 button, 1 key switch, and 6 voltmeters to control the charging, discharging and firing sequence. Therefore, the organization of the frame should put all the voltmeter and switches together so that the user of the gun can easily have access to all information concerning the conditions of all components of the gun and can react quickly when something goes wrong (which proves vital when in later testing the variac is blown up).
    - In order to create the console, we laser cut several 24x12 inch plywood sheets at Techshop. This was fast and easy; we just had to screw in all the components in their respective slots/holes, and it ended up looking professional.
- Strength of base
    - We used a half-inch plywood board as the mounting base for our gun. That might have been overkill (it is actually fairly heavy), but its structural strength proved to be useful as the mounted components (the capacitors, Variac and the transformer) were all very heavy.
- Position of barrel
    - Ideally, the coil should be placed parallel to the ground. Otherwise, the rifle becomes harder to aim with.
    - The barrel should also be some distance above the board so that it is relatively easy to aim at any object (it would be difficult to look along the barrel if it is attached directly to the board) and aiming manually is the only way that we can actually hit anything.
    - We mounted the barrel on 2x2 lumber stuck out vertically from the board but also tilted inwards like a triangle. This allowed us to isolate the barrel and also have some solid structural integrity.
- Materials

    - Wood is easy to use, an insulator inherently, and relatively cheap. This makes wood a perfect material for our purpose.
    - For the barrel we initially used copper, which canceled our coil's electromagnetic field and resulted in the fact that our initial design did not work. As a result, we had to switch to a clear PVC pipe, which is safe, fairly easy to process, and not too expensive.

Electronics:

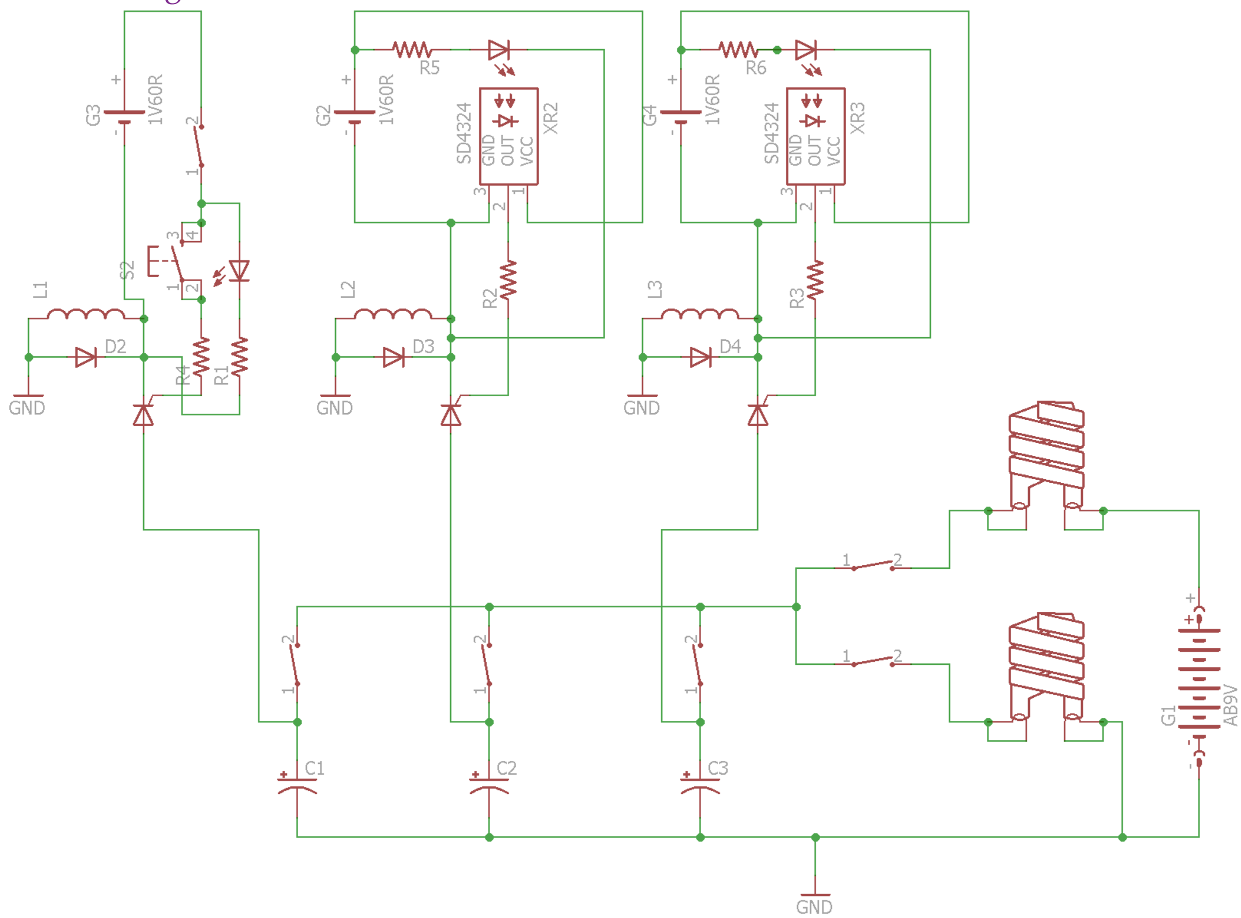
The Trinity Gauss Rifle is an electromagnetic projectile accelerator, so therefore it relies on a considerable amount of high voltage circuitry to function. Safety was our top priority while wiring these electronics, as the capacitors store a massive amount of energy and can easily kill you.

Requirements for the electronics:

- Power Source:
    - Must be either battery or wall powered
    - Must have a 350v DC power source to charge the capacitors
    - Must be capable of supplying reasonable current during the charging process (at least a few amps) so that we can charge the capacitors relatively quickly.
- Capacitors:
    - Must be high voltage (~400v) and high capacity (at least 3000uF)
    - Must be in relatively good condition, ie few dents/holes.
- Switches:
    - Capable of switching at high speed
    - Capable of withstanding a 1kA 400v burst of electrical energy
    - Does not need to be turned off, as we can calculate the timings of the capacitor discharge and allow it to shut itself off.
    - Because of this we decided to use SCR Thyristors which are incredibly cheap compared to IGBT's, large MOSFET's, or JFET's but they provide massive current and voltage capabilities that a common switch or relay cannot.
        - The caveat of thyristors is that they do not shut off until the current flow through them drops to zero, but because we are using capacitors the current will drop to zero when they fully discharge. We do however have to calculate the time this takes as a function of the number of winds/resistance and inductive properties of the coil.

- We ultimately used 1.2kv 110A SCR Thyristors, with part number c158pb.

Circuit Design:



Charging/Discharging the capacitor bank

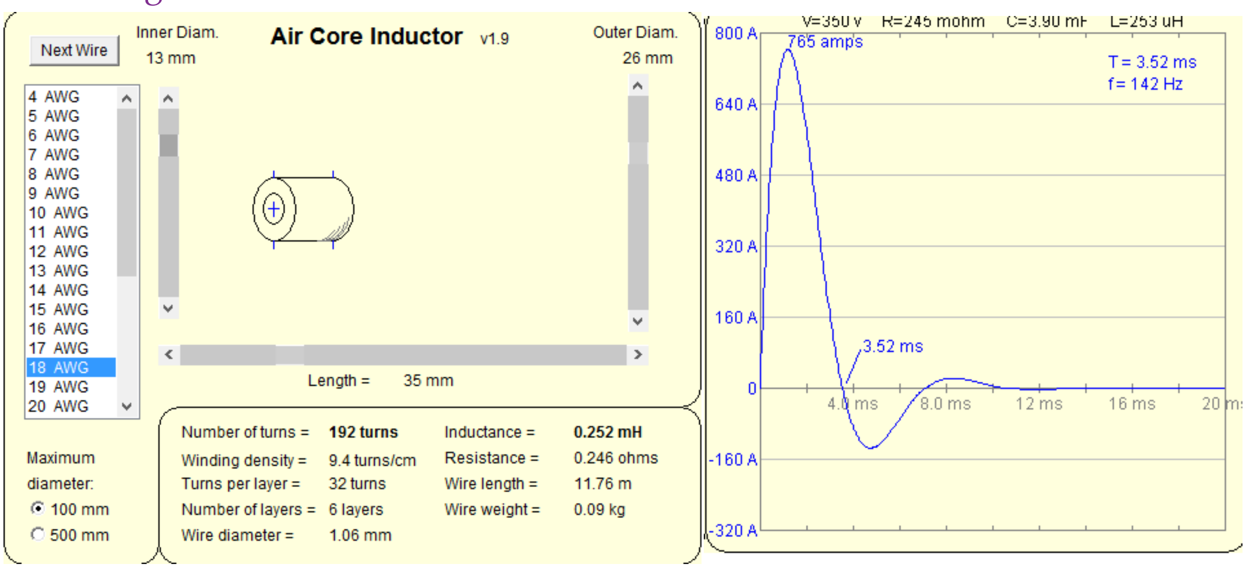
The heart of the Trinity is the three capacitors for which it is named. They are charged as shown through a light bulb to the 9V battery chain. The light bulbs are actually incandescent, but I could not find that symbol in EAGLE electronics CAD, so a CFL bulb will do in the schematic. Anyways, the discharging circuit works the same way, and grounds the capacitors through a light bulb. We actually found that discharging all three together at 350v is enough to burn out the bulbs, so they must be discharged individually.

Switches/Triggering:

The switches were determined earlier to be SCR Thyristors for their low price and ultra-high endurance to large voltage/current. The triggering is done by applying a current of few hundred mA from the gate to the cathode. The first stage is triggered by a simple push button and a key switch. The LED is the pilot light on the switch.

Later stages are supposed to be triggered by an optoschmitt based photo-gate, which would begin the pulse immediately when the bullet enters each coil.

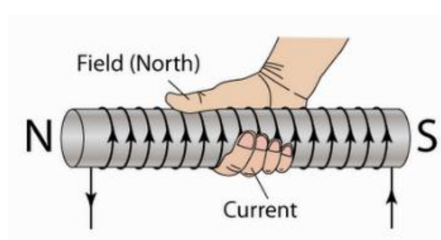
Coil Design:



These are the results from Barry's Coil Gun simulator. As you can see, we have a pulse time of about 3.52mS at 765 A peak. This is similar to our expectations from FEMM, as the Lua script was written with the same calculation techniques as the inductor current graph on Barry's website.

Winding the coils was a pain, but we used a drill attached to a metal insert in the pipe to spin the pipe. We had to use the metal insert because the pipe was wider than the drill's max size. Ultimately we used 200 turns for a round number, but because we could not wind the coils perfectly the actual resistance was slightly higher than the predicted resistance. Had we used lower AWG wire, we could have slapped more turns on it for the same resistance and similar inductance, and had a more powerful gun. It would have been much harder to wind though.

The coils are wound tightly around the tube, with the current flowing clockwise looking forwards according to the right hand rule to push the projectile forwards. We wired a diode antiparallel to the solenoids, so that we could protect the thyristors from the massive inductive kickback from the coils.



Safety and control panel wiring:

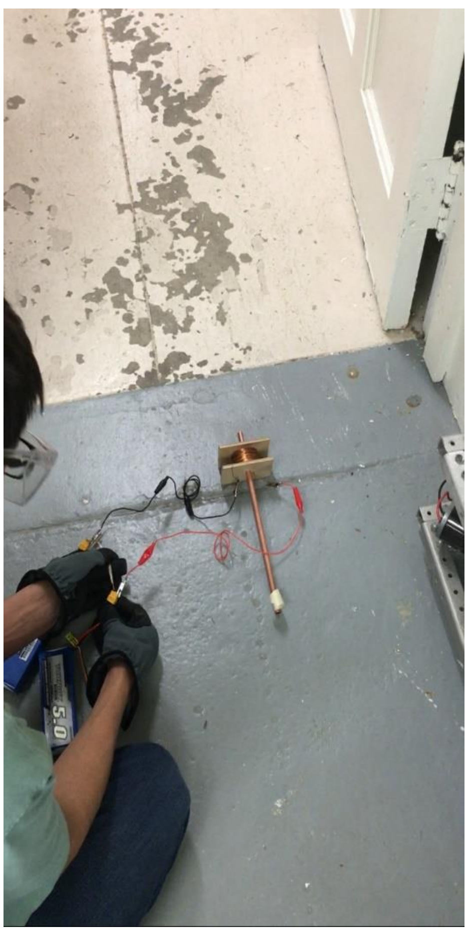
For safety, all controls were kept in a single panel, and voltage feedback is given every step of the way, from the initial voltage from the power supply to the voltage of each capacitor. We also used light switches behind switch panels to protect the user from any arcing and shorts. A key lockout was used to eliminate the possibility of accidental firing.

Testing the Trinity Gauss Rifle:

Testing timeline

- Prototype Test: January 10th
- Single Stage Test: February 17th
- Single Stage Penetration Tests: February 18th
- Multi Stage Tests: week of 2/22

Prototype Test



When we conducted this Prototype Test we had very different ideas for the structure of the gun. We were still using copper tubes as our barrel then, and we planned to use LiPo batteries as our power source, with at most 8 stages of coil assembling into a hand-held gun. We only finished coiling and testing one stage of the initial gun design, and we wanted to verify the practicality of our design and see whether the projectile could be accelerated by the coil or not. To our surprise, though we "fired" the testing stage multiple times, the projectile never moved.

This result surprised us and made us reflect on the potential flaws in our design. Eventually we realized that the copper barrel was what was messing with the magnetic field of the coil. Because it was conductive, the magnetic field ultimately induced eddy currents in the barrel which would create a reverse magnetic field, somewhat cancelling out the first one. We then switched from a copper barrel to a thick transparent PVC pipe as our barrel, which worked well. This test also concluded that the LiPo setup with 15v at 100A was not enough power.

Failed Power Supply Test: (old system)

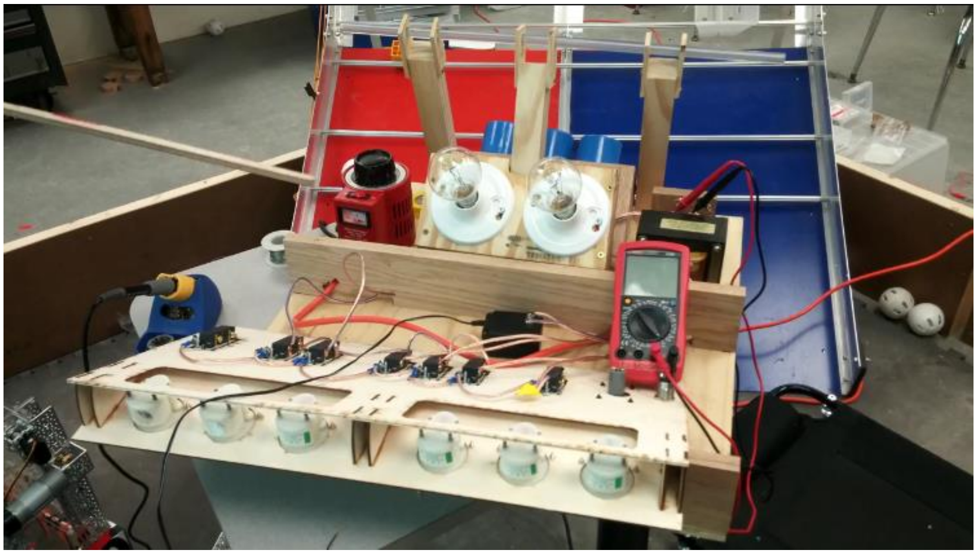


Figure 7: The image above shows the failed power supply test. This was taken moments before the Variac caught on fire.

One of the crucial systems to Trinity Gauss Rifle's functionality is the 350V DC power supply system. The power of the gun comes from the energy stored in the 3900 uF capacitors, which we first elected to charge using wall power. The 120v ac would be transformed through the variac and ebay transformer to about 260v, then rectified to about 360v dc.

When we actually connected the wall power to the Variac, we immediately realized that something was broken because the transformer returned the wrong voltage—in fact much lower voltage than we anticipated. When we repeated our tests, the Variac started to smoke and caught on fire. This failed test permanently damaged the Variac (decimated the apparently useless fuse, and while it did not melt the fuse it burnt through the wire connections on the input), and as a result we had to remove the Variac and transformer from our circuit system, since we did not have enough time to replace/repair the damaged Variac.

We also tried plugging the transformer alone directly to wall power with no load, just like their schematic said to, which caused it to bubble and smoke. It also did not actually provide the promised 240v, instead providing about 80 which is curious. This suggests it had internal shorts, and taught us not to buy 50 year old ACME transformers from ebay. Running the transformer is not actually the same as just shorting the power source through a wire, because it has a massive inductive load (impedance) therefore it should not have burnt just due to being plugged into the wall.

We eventually had to purchase about 35 9V batteries and use them in series as an alternative source of ~340V DC power supply. This actually worked surprisingly well and after about 30 shots they have only dropped by about a volt each.

Single Stage Test (Success!)

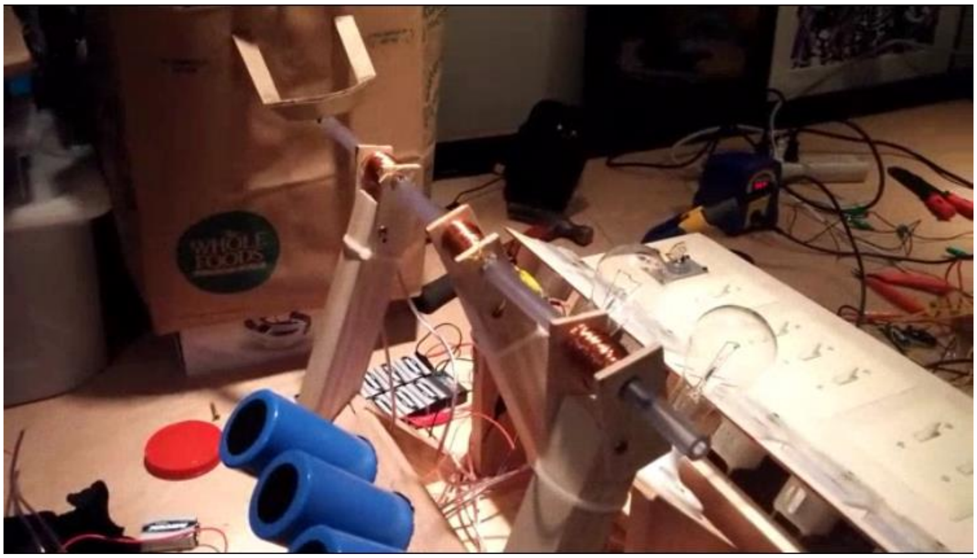


Figure 8: The image above is the first ever firing test of Trinity Gauss Rifle at a bag of paper. Firing was successful.

After we decided that 9V batteries would be the back-up plan for power supply, we were able to finish re-wiring the entire system and eventually test the functionality of the gun on Thursday night. This time the test was a success. The Trinity was able to shoot projectiles at speed above our expectations and penetrate into a bag of newspapers with only 150V and one stage. The 9V batteries turned out to be surprisingly fit for this purpose and the voltage before and after charging the capacitors was very minimal.

However, we could not get the second and third stages to function reliably. The laser gates tended to work only some of the time, reading always high or always low, and not changing when the projectile was inserted. This was unexpected as previous tests of the photogate system in isolation worked very well. This may have been due to hot glue congealing the sensors or improper aim of the optoschmitts and IR emitters. We already ordered a few 10mm gap photo interrupters for 1.95 each on sparkfun. They are basically an LED in one side and a phototransistor, Schmitt trigger and voltage regulator in the other. That is basically the optoschmitt and IR emitter in one package. I will wire it into the system this week.

(Mostly) Finished Trinity Rifle:

Figure 9: The image above shows the discharging of one of the capacitors. The lightbulb becomes extremely bright for a moment, as the electrical energy is rapidly converted to light.

Figure 10: Moment of impact!

Figure 11: The Trinity Gauss Rifle completely penetrated a full can of ginger ale.

These final tests of the gun were to determine what the powerful first stage could do. As you can see, it did a good amount of damage to the soda cans. We tested 2 full Pepsi cans and a ginger ale, all of which it punched completely through on the first shot. We also determined that the optimal placement for the 2-inch bullet is exactly before the first stage, with the front of the bullet at the opening of the first coil. This is the case because the capacitor discharge time is about 3.5 milliseconds, which slightly more than the time it takes to accelerate the 2-inch projectile from rest to the middle of the coil. The current graph from before illustrates this. The goal is to have the projectile in the “sweet spot” of the coil (with the front in the middle) a little after the current peaks, which makes the most use of the current while also preventing “suck back” into the coil.

Efficiency Analysis:

Unfortunately we had no way to measure the real world muzzle velocity of the Trinity. It was too fast for video analysis (none of us had slow-motion phone cameras beyond 100 frames per second) and we had no projectile speedometer. If we can assume 60 ft/s which is a reasonable estimate based on other similar guns, we can determine that:

<u>Projectile:</u>

60ft/s = 18m/s

E = ½ m v^2

18^2 * 10g * ½ = 16.2J of kinetic energy

<u>Capacitor:</u>

E = ½ C V^2

½ * 0.0039 * 350^2 = 240J of electrical energy

<u>Efficiency:</u>

16.2J/240J = **6.5%** efficiency for a similar gun to ours. We hope to measure our velocity when the additional photogates come and get our own value for this.

Ultimately for Gauss rifles to become practical weapons, capacitor size would need to be greatly reduced and efficiency must increase. One surefire way to increase efficiency is to case the coils in an iron core, funneling more of the magnetic flux through the projectile. This is what Barry from Barry's Coilguns did in his Mark IV gun, and determined that it had a massive effect of performace.

Reflection

Looking back on the project now, there are a few things to which we can attribute our problems. We should have done more in depth research in the field of magnetism before we started designing our structure. This would have allowed us to learn that using a copper rod as the barrel would conflict with the magnetic field we were aiming to achieve in our coils. We also did not plan on backups and contingencies. Word of warning: nothing ever goes according to plan. We did not have much time for testing. Scheduling conflicts resulted in there being a span of a two weeks where we could not meet to work on the Coil Gun. This came back to bite us when we tested our rifle and discovered that our Variac/Transformer setup would not work. We were pushed to work quickly, as the deadline fast approached, and come up with an alternative power supply. We swapped out a direct wired power source for forty 9 Volt batteries connected in series. Had we discovered this earlier, we could have bought double the batteries for a *lower* price online, but we were forced to pay 2$ per battery at Walmart.

Overall, though, this project was a success. Even though we had to work hard during the last few days given unforeseen complications, we were still able to successfully fire the Trinity. As of now, we have the first stage working and are well on our way to get the second and third. The only problem with them is with the photogates, which can easily be fixed. Those stages are already wired and hooked up for use. We learned much from both each other and our struggles.

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