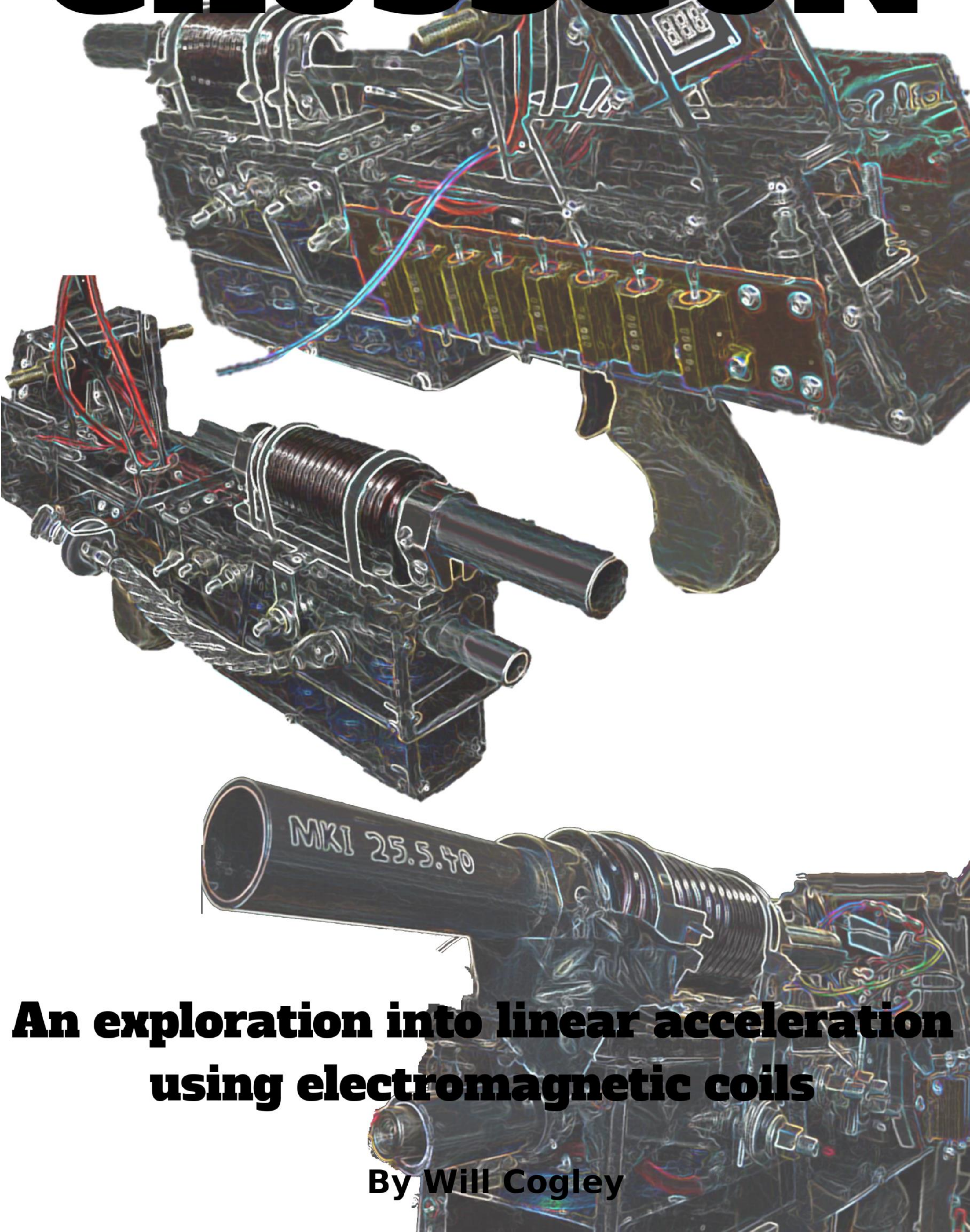
GAUSSGUN



An exploration into linear acceleration using electromagnetic coils

By Will Cogley

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1.1 Aim

The Aim of this project is to build a fully functioning handheld electromagnetic linear accelerator (Coilgun/Gauss gun), and to explore the practical applications of electromagnetic coils. This research will combine the various findings of others as well as my own findings on linear acceleration using electromagnetic coils, and finish with a product that will demonstrate these findings. It can be used by other people as a tool for learning or for practical help with creating a similar product.

1.2 Criteria and Constraints

The final model must fulfil the following criteria:

- Must be capable of accelerating a small projectile with reasonable force
- Must be handheld and ergonomic
- Must be portable and not require to be plugged into the mains constantly
- Must be safe for reasonable use
- Must be reasonably cheap and use easily acquired materials

1.3 Practical Applications

The concept behind a Coilgun is transferable to a number of practical applications, including the following:

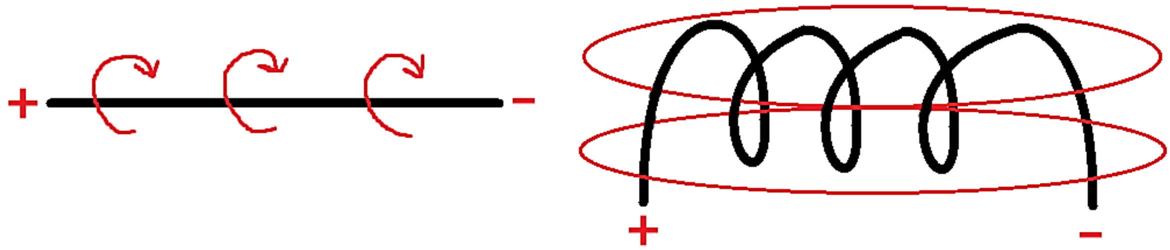
- Solenoids
    - An electromagnetic coil which moves a metal "slug" either linearly or through a small angle of rotation. Used in a variety of applications, ranging from simple locking mechanisms to starter motors in engines.
- Launching projectiles into orbit
    - NASA once proposed a 4000 ton coaxial Coilgun which would send 10 million tons of materials to L5 (A point along the path of the earth's orbit where the sun and earth provide a stable gravitational equilibrium) in order to set up a base for massive space colonisation.
- Military applications
    - Coilguns are under research for military applications by the USA and are predicted, if successful, to yield weaponry which is almost silent, fires projectiles 30% faster, and has twice the fire rate.
- Transportation
    - Maglev trains are already in use which utilise magnetism in order to create an almost frictionless surface for the train to glide over, allowing it to reach speeds of up to 581Kmh^{-1} (The fastest recorded speed for a Maglev train to ever reach in Japan, 2003) This concept is applicable to any other form of transportation, and research could eventually lead to vastly more efficient ways to travel.

2 Exploring Solenoids

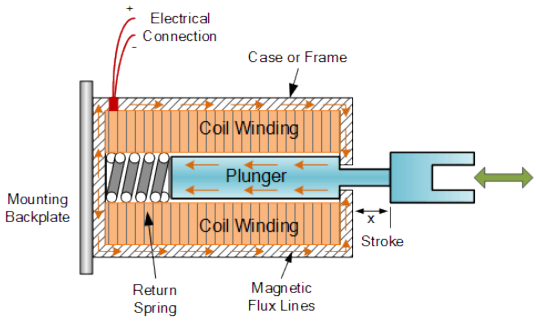
Creating a Coilgun will involve actually creating a solenoid from its base materials if we want to maximise efficiency. Therefore, by looking at existing solenoids and their various uses in industry we will be able to improve our understanding of them and potentially bring new ideas to the world of Coilguns, maximising the potential of our project.

2.1 Solenoid Theory

Solenoids consist of an electromagnetic coil and a high permeability core (can easily be magnetised to facilitate attraction). In a straight wire, a magnetic field would be set up around the wire when powered, but when the wires are coiled with all turns in the same direction, the strength of the electromagnet is increased because the field around the wires add together, and the field will be centred on the coil. The main factors affecting the strength of a solenoid are current, permeability of



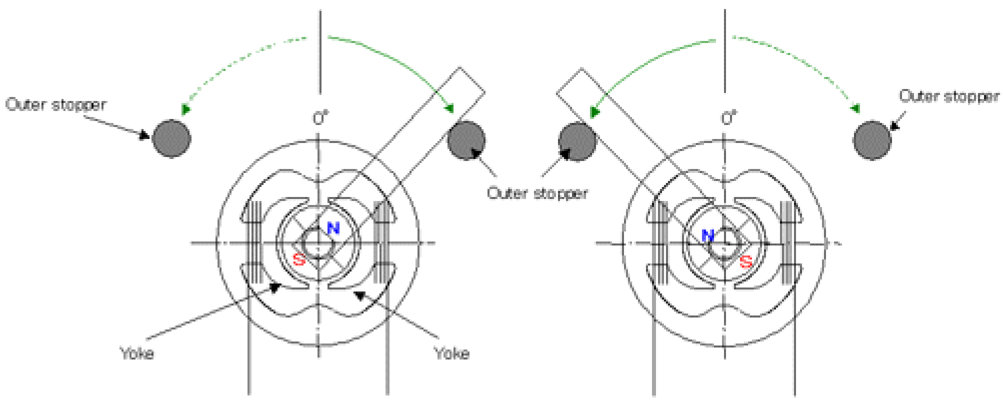
the core, and the total number of turns of wire. It is also worth noting that too many turns will increase the resistance of the circuit and lower the current, meaning that an optimum number of turns must be found in order to maximise strength.



2.2 Types of Solenoid and Applications

Solenoids have a huge range of practical applications. At their most basic, they push or pull a metal "slug". The simple solenoid opposite is used to lock a door electrically. It uses a spring which is compressed upon activation of the solenoid, enabling the plunger to reset to its original position once the current is taken away from the circuit. A system such as this could be useful in our project. For instance, a locking mechanism could be implemented using a small solenoid to hold a loaded projectile in the barrel of the Coilgun before it is fired, enabling the Coilgun to be handled at any angle of rotation without risk of the projectiles falling out. It would be activated by pulling the trigger, making it move out of the way then returning to its original position with the assistance of a small spring.

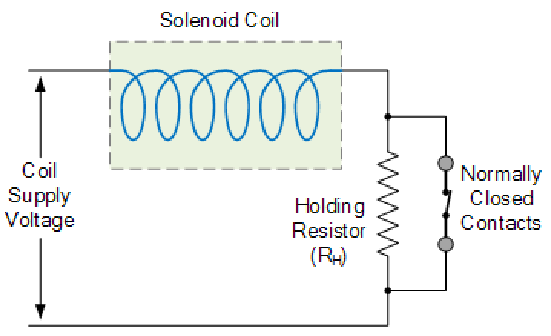
Another type of solenoid is the Rotary Solenoid. They are designed to rotate through a small angle, generally no more than 90°. Their function is to replace motors in certain systems, where a lesser angle of movement is required. They work using a very similar principle to



linear solenoids, except the coil rotates a permanently magnetised disc rather than moving a slug.

2.3 Designing an Efficient Solenoid

Solenoids can be somewhat inefficient, since some of the electrical energy supplied to them is converted into heat. Their efficiency can be increased by using a holding resistor, so that once the solenoid has been moved into position; the voltage can be lowered slightly. This is because the



holding resistor is normally shorted out by the switch (which can be a driver such as a transistor), but when the contacts are opened, the resistor will lower the voltage – see opposite diagram from http://www.electronics-tutorials.ws/io/io_6.html . Another important concept in increasing solenoid efficiency is duty cycles. This is simply the percentage of time that the solenoid is on for, and it should be reduced to be as minimal as possible. This will be an important factor to consider when we make our Coilgun.

As a final note on solenoids, the website http://www.ledex.com/solenoid/solenoid-basics.html provides some useful tips on designing a solenoid. It states that there are 8 essential considerations for designing/implementing a solenoid. These are:

- Stroke
- Force/Torque
- Voltage
- Current
- Duty Cycle
- Temperature
- Operating time/Speed
- Environmental
- AC/DC
- Life

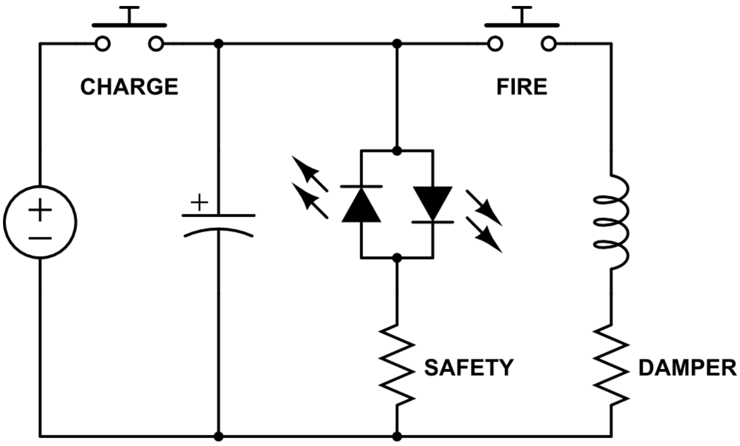
A few of these will need to be taken into greater consideration upon further development of my ideas, but certain ones are immediately clear. *Stroke* generally refers to the distance through which the solenoid's slug will move (which should be kept to a minimum in solenoid design), but since I want the projectile to move as far as possible minimising the stroke is not a relevant issue for me. *Force* will need to be as high as possible with regards to the design of the solenoid, and also capable of handling very high current. *Voltage and current* will be considered in depth when we design our circuit. *Duty Cycle* needs to be kept to a minimum, so timing circuits will be involved in making the coils as efficient as possible. *Temperature* must be considered in depth in the building phase, and heat sinks or other cooling systems may be required. Critically, *operating speed* will be as high as possible. *Environmental* factors should be considered later on, but the more efficient the circuit the better on a number of levels. I already know that we will be using *direct current* in order to utilise capacitors in the design. *Lifespan* will also be maximised.

3 Existing Coilguns

A Coilgun or Gauss gun is a simple device for linear acceleration using one or more electromagnetic coils. The concept is actually very simple: A large current is passed through a metal (usually copper) wire which generates a uniform magnetic field which, provided certain variables such as current and number of turns are fulfilled, will attract a ferrous projectile towards its centre. This is also the concept behind solenoids, which are now widely used in a vast range of applications. However, the critical difference between a Coilgun and a solenoid is that a Coilgun allows the projectile to travel beyond the electromagnet. This concept has a wide range of practical applications ranging from small tools such as nail guns all the way to the much more large scale such as NASA's coaxial electromagnetic launcher for firing projectiles such as shuttles into orbit.

3.1 Simple Circuit

Despite the fact that Coilguns have been around since the early 1900s, a relatively small amount of research has been conducted into them, although many hobbyists have published their attempts at building Coilguns. They range from the very simple to very complex. At its simplest and least efficient, a Coilgun's circuit looks like this one from http://www.ericlippert.com/ :

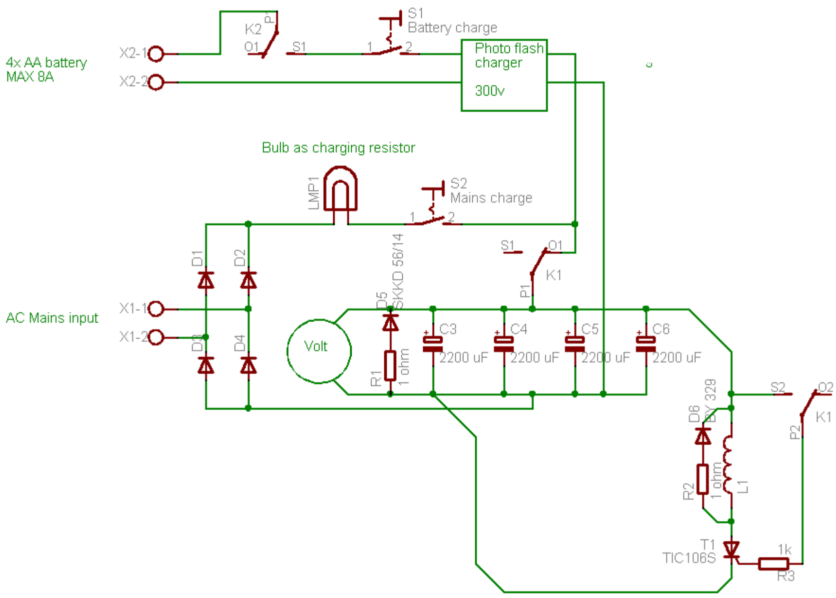


This is simply a charging circuit at the left, to charge the capacitor, and then a trigger which directs the energy stored in the capacitor through the coil. A capacitor is used rather than a battery because a Coilgun needs a short but very high supply of power, which can be provided by a fast-discharging capacitor (a battery would be lower-power and discharge much more slowly). It also features a safety circuit in the middle. One LED is used to bleed the energy out of the capacitors should you charge the gun and forget to fire it, reducing the chance that a fully charged capacitor could discharge through a person touching it. The other LED will light if the battery is put in the wrong way meaning that the capacitor has been charged in the wrong direction (A capacitor charged this way renders it dangerous and unusable).

This circuit is an excellent tool to allow us to understand the basic concept behind Coilguns, but it has a few restrictions which mean that it cannot be easily scaled up to a higher power version. Firstly, the trigger and fire buttons are simply push-to-make switches, which are difficult to find at any current rating above around 20A. Therefore a driver (or several in parallel) would need to be implemented in order to let a user switch the power in a higher amp version without destroying the switching components. Also, if a driver circuit was involved, a fly back diode would also be necessary to eliminate the sudden voltage spike which could destroy a transistor, or even jump across the gap in the push-to-make switch and destroy the capacitor.

3.2 Advanced Circuit

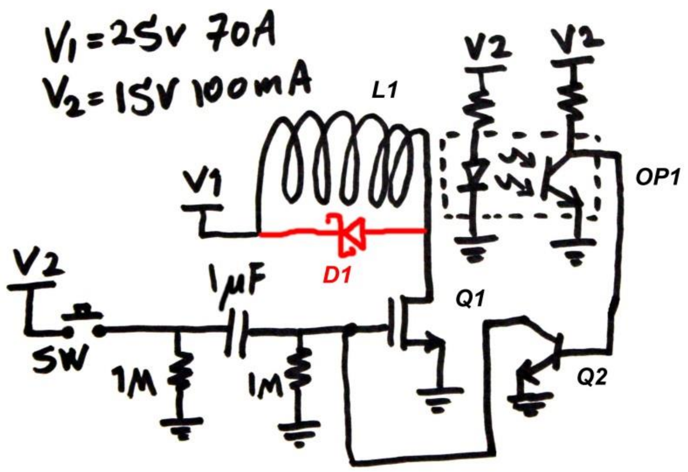
Below is an example of a much more complex circuit – the "MV CoilMaster Mark1 Coil Gun" documented at: http://hackedgadgets.com/2009/05/07/mv-coilmaster-mark1-coil-gun/. As well as



separate circuits used for loading ammunition, laser targeting systems and more, the core Coilgun circuit has been expanded upon. A few ways in which we can see that this system has improved upon the previous circuit is the fly back diode as mentioned earlier, and a bulb which acts as a charging resistor. This has been implemented in order to more safely allow the charging capacitors to dissipate energy (an unavoidable flaw in this circuit). The author notes that the higher wattage the bulb is, the faster the capacitors will charge. A final feature to notice is that instead of using just one capacitor, 4 have been connected in parallel. This means that the total capacitance is equal to all of the capacitances added together (4*2200 = 8800μF/8.8mF). This may be preferable to having a single, larger capacitor depending on the parameters of the individual project.

Upon observation of the housing, it is apparent that a few important points have been taken into consideration. Firstly, notice how the body has been almost exclusively constructed from acrylic and not ferrous metal. This has two benefits, firstly that polymers are generally non-conductive but also because if the electromagnet is powerful enough it could attract parts of its own body into the coil and ultimately destroy itself. Secondly, note how all of the electronics are contained internally, reducing the chance of getting a shock and generally making the design more ergonomic for handheld use.

3.3 Increasing Efficiency

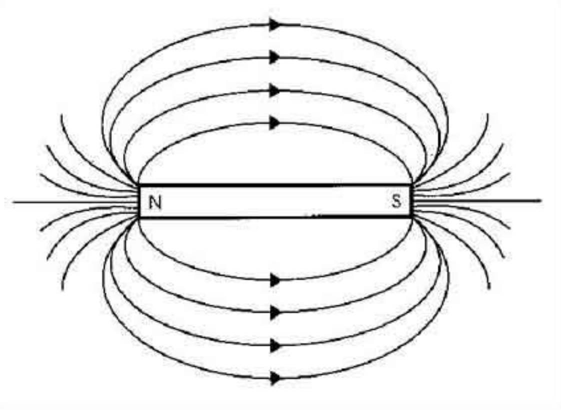


The circuit opposite from the website http://www.electroboom.com/ contains another very important component. This is an infrared emitter/receiver circuit implemented at the end of the coil. Its function is to turn the coil off as the end of the projectile protrudes out of the end of the coil. This circuit vastly increases the efficiency of the Coilgun, by ensuring that no work is done against the direction in which the projectile is being accelerated. Simply put, this minimises the energy expended and maximises the force with which the projectile is launched.

4 Magnetism

4.1 Magnetic Theory

Magnetism is a physical phenomenon produced by the motion of electric charge, which results in either attractive or repulsive forces between objects. When an object is magnetic, it has what can be thought of as a flow of "magnetic energy" flowing from the north pole to the south, which is called magnetic flux (Φ). This quantity is measured in Webbers (Wb), comprised of BA where B is the magnetic flux density in Tesla and A is the cross sectional area of the metallic object interacting with the magnetic field. It is important to that note the amount of magnetic flux flowing through a given area around the magnet changes depending on where it is measured from, this can be visualised by looking at the diagram to the left and noticing that some areas around the magnet have more or less lines drawn in that area (representing magnetic flux).

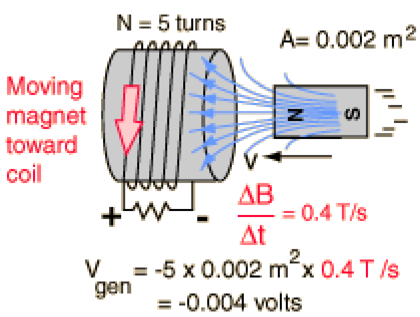


Therefore, certain areas will have more or less magnetic flux flowing through them. The density of the magnetic flux is called the flux density, measured in Tesla where 1 Tesla is equal to $1Wbm^{-2}$. Alternatively, flux density can be measured in Gauss, where 1 Tesla is equal to 10,000 Gauss (Tesla to Gauss: $x10^{-4}$). The Earth's magnetic field is approximately 0.5 Gauss.

Flux linkage is used to describe magnetic flux in respect to a coil. Since most applications of magnetic flux will involve coils in some way, it is important to consider how several aligned wires in series interact with each other magnetically. Flux linkage is simply the fact that a coil in the presence of a magnetic field will have "n" coils therefore "n" times the total cross-sectional area of one wire therefore "n" times the flux. Flux linkage (sometimes denoted as F) is equal to $F = n\phi = nBA$.

4.2 Faraday's Law

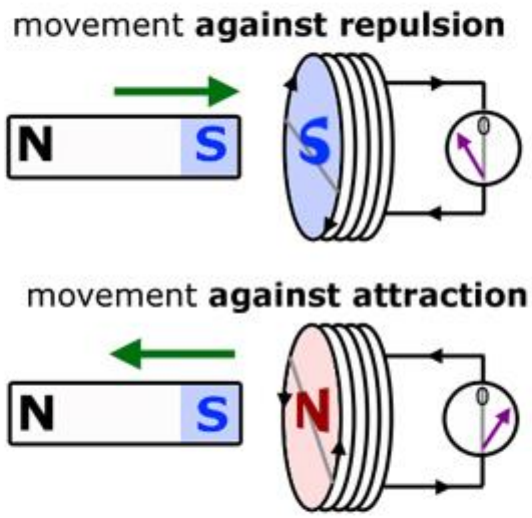
Another very important concept necessary for this project is Faraday's law, which describes how changes in magnetic flux results in a potential difference being set up. It states that: $Emf = -N\frac{\Delta\phi}{\Delta t}$ where Emf is the generated/induced voltage, ϕ is magnetic flux BA in Webbers (B = external magnetic field in Tesla, A = area of coil in m^2), and N is the number of turns. The opposite diagram from http://hyperphysics.phy-astr.gsu.edu/hbase/electric/farlaw.html can be used to better illustrate Faraday's law. It shows a magnet moving towards a coil, with the magnetic field flowing in one direction through the coils. The flux density in Tesla divided by the time of the interaction is a given value since most manufacturers will give the value of flux density. The cross sectional area of the wire is $2mm^2$, therefore the induced voltage can be calculated as - (0.002 x 0.4 x 5), which is -0.004 volts. It's important to understand that only a changing magnetic field induces a voltage – i.e. you couldn't leave a permanent magnet near a coil and expect free energy to be produced.



It's important to note that these laws such as Faraday's law also work in reverse – that is to say that if a current is instead passed through a coil and it interacts with a non-magnetic object, the same concept applies that the number of turns maximises the flux linkage, and as a result, the force on the object. The voltage through the coils can be used to calculate the flux density of the induced magnetic field, effectively using the equation in reverse.

4.3 Lenz's Law

A final law necessary to understand is Lenz's law, which shows how electromagnetic circuits obey Newton's third law that a force generates an equal and opposite reaction force. It simply shows that if a voltage is induced via a magnetic field as discussed, the induced voltage will set up its own magnetic field which opposes the original magnetic field. This can be illustrated by the classic experiment in which a permanent magnet is dropped down a copper tube, and it can be observed to fall much slower than a piece of steel of the same shape. This law is the reason why Faraday's law has a negative sign – because the voltage opposes the magnetic field. Look at the picture opposite from http://www.a-levelphysicstutor.com/images/fields/EMI-LenzL-diag01.jpg. Note how either a negative or positive voltage is induced depending on the direction of the magnet's movement.



Lenz's law has serious implications on the design of my Coilgun. Originally I had thought to use magnetic projectiles to maximise the force, but Lenz's law indicates that this might not be a good idea. This is because when the coil is turned off, the movement of the magnet through the coil would result in deceleration of the projectile. Although, more consideration will be necessary to decide whether or not the increased force of attraction outweighs the negative effect, and therefore whether a magnetic or steel projectile would be better

4.4 Equations for Maximum Efficiency

From this research I am able to much better understand the mechanisms behind magnetism, but also I have a few formulas which will help me optimise my final creation. If flux linkage, $F = n\phi = nBA$ then it is clear that maximising n will maximise the flux linkage and therefore the force on my projectile. Also, if $\phi = BA$ where A represents area, then maximising the area will maximise flux linkage. Of course the flux density B has a large effect too, simply meaning that my electromagnetic coil must be as powerful as possible if I want the force with which the projectile is propelled to be maximised.

When looking specifically at solenoids, there is an equation we can use to find the exact force exerted on the slug, derived from Faraday's law and other equations making up individual components of the law:

$$F = \frac{a(4\pi * 10^{-7})(ni]^2}{(2g)^2}$$

F = Force, **I** = Current, **g** = Length of the gap between the solenoid and a piece of metal, **a** = Area **n** = Number of turns. **4π*10^{-7}** is the magnetic constant in mkgs^{-2} A^{-2}

This equation shows us which values have the greatest effect on the force. Of course, this approximation is very rough and there are a great number of other factors left unaccounted for, however it is useful for seeing which values affect the system. It is very important for **g** to be minimised since:$F \propto \frac{1}{(2g)^2}$. "**g**" is both doubled and then squared, meaning that it should be kept to an absolute minimum. This means that I need to make sure the projectile is as close as it can be to the coils, without generating friction on the walls of the barrel. The number of turns has an important effect as does the current, since the values are multiplied together and squared, so both of these values must be maximised. Of course too many coils will lower the current according to $I = \frac{V}{R}$ because of the increased resistance. "**a**" must be maximised too, and it's important to note that the cross sectional area of the wire is proportional to the current, since a greater area results in a lower resistance.

5 Material Science

In this project, material science will be very important since I will be dealing with very high electric currents and strong magnetic fields.

For the most part, the body of the gun will need to be constructed primarily of materials not attracted to a magnetic field, and non-conductive of electric currents. As discussed previously, steel bolts or similar would be attracted to the coils when they are activated, therefore it will be important to consider what materials I use instead of common steel bolts.

5.1 Permeability

Permeability is a measure of how magnetised a material will become when it interacts with a magnetic field. For the entire body of the gun, it will be important to choose materials with a low permeability. μ_0 refers to the permeability of free space: 4π x 10-7 T m/A. Most materials are very close to this value because most materials are not attracted to a magnet, but some materials such as ferrous metals have permeabilities of up to 1.26 (metglas), with carbon steel at 1.26×10^{-4}. Often permeability is expressed relatively, as μ/μ_0, which would make a vacuum have a permeability of exactly 1, and metglas (which has the highest permeability) would have a relative permeability of 1,000,000.

Diamagnetic materials have a relative permeability of less than 1, and this makes them reduce the magnetic flux density of a magnetic field which they are placed near. Paramagnetic materials have a permeability of just over 1 and will become slightly magnetised in the direction of a magnetic field. Ferromagnetic materials have a changing permeability, and this value rises to a maximum point. Often ferromagnetic materials have a very high relative permeability of 100 or (significantly) more.

5.2 Body

Materials such as PVC, MDF, plywood and acrylic are cheap, strong, and have a relative permeability very close to 1, making them ideal materials for the construction of the body. Some parts however can be not easily replaced with one of these materials, take bolts for example. They need to be very strong. For this reason I will choose bolts made of a very low permeability metal. Aluminium is a paramagnetic material with a very low relative permeability of 1.000022, meaning it will feel virtually no attraction. However, Aluminium is not a common choice for bolts because it is softer than a lot of other metals and the threads of an aluminium bolt will easily strip. Therefore brass may be a better option – having a similarly low μ_r and having an ultimate tensile strength of 550MPa, whereas Aluminium's ultimate tensile strength ranges between 125-300MPa depending on the alloy.

5.3 Projectile

As for the projectile, the permeability must be as high as possible so that it can become easily magnetised in the presence of the magnetic field. Metglas would be the ideal material although sadly it is extremely difficult to obtain. Iron is another metal with a very high permeability. Iron which has been annealed in hydrogen and is 99.95% pure has a permeability of 200,000, but of course this too is extremely hard to obtain. In terms of materials I can easily obtain, low carbon steel is very easy to come across which has a high permeability, and although slightly less available a cobalt-iron alloy would have almost 4x the permeability, with issues arising with availability.

5.4 Barrel

The barrel of the Coilgun must be as thin as possible while still staying reasonably strong. I had initially thought to use PVC tubing since it is so cheap and easy to get, but it is also difficult to find particularly thin so some kind of metal may be best. Also, since diamagnetic materials reduce the magnetic flux they are near, it is important that the tubing has a relatively high permeability. Of course, very thin tubing is hard to come across let alone tubing made of extremely high permeability metals, but this doesn't matter too much since all we really need to do is make sure that the material isn't diamagnetic. For this reason, copper tubing cannot be used. Aluminium tubing is easier to come across so this may be an ideal choice. Steel tubing may not be practical since it is easily magnetised, presenting numerous problems.

6 The Projectile

6.1 Permanent Magnet Dilemma

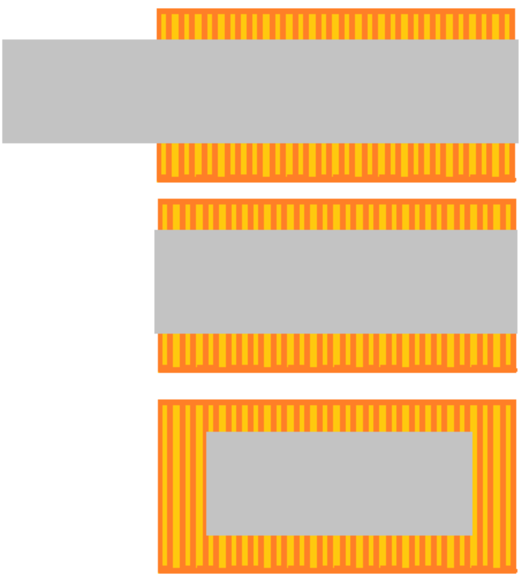
One of the main dilemmas I had with the design of the projectile is whether to use a permanent magnet or simply a high-permeability metal. Using a magnet presents difficulties, firstly because of Lenz's law which would make the magnet decelerate once the coil had been switched off, but also because any fine tuning of the shape of the projectile using tools such as an angle grinder may cause demagnetisation if it gets too hot. Potentially, a magnet could be fired with greater force, since the north pole of the magnet will be attracted to the south pole of the coil, creating a greater force of attraction. This also means that if the coil is not switched off at the correct time there will be a greater force pulling the projectile back towards the centre of the coil, once it has passed through. A simple metal projectile would be much less problematic - it could easily be shaped for maximum efficiency, and if the timing circuit was imperfect this would be much less of an issue.

6.2 Principles of an Efficient Design

While looking at the website http://www.instructables.com/id/Coil-Gun-Projectiles/ I found a number of important considerations for designing a Coilgun projectile. The website followed a hobbyist's experimentation using an existing Coilgun on what would be the most efficient design for a projectile. The principles listed were as follows:

- Length
- Diameter
- Length to diameter ratio
- Material
- Aerodynamics
- Positioning
- Mass
- Flux
- Stabilisation

Length, Diameter, Length to diameter ratio and flux are all related principles. The length should approximately the same length of the coil, this is simply logical thinking. By consideration of the diagram to the left, we can see that the first projectile is large and sticks out of the end of the coil.



This makes it inefficient because the portion of the projectile outside the coil is not being efficiently attracted, and at that point is effectively dead weight. The last projectile is small and doesn't take full advantage of the coil's magnetic flux – there is less volume of metal so less force of attraction (It is, however, preferable to the first projectile because the mass is lower). The middle projectile is best because it will only be attracted to the centre of the coil and so this length takes advantage of the entire length of the coil until it is switched off. Flux is related to diameter, because in order to maximise the amount of magnetic flux acting on the projectile, the diameter of the projectile should be as close as possible to the inner diameter of the coil. This makes sense, because when we look at the equation:

$$F = \frac{a(4\pi * 10^{-7})(ni]^2}{(2g)^2}$$

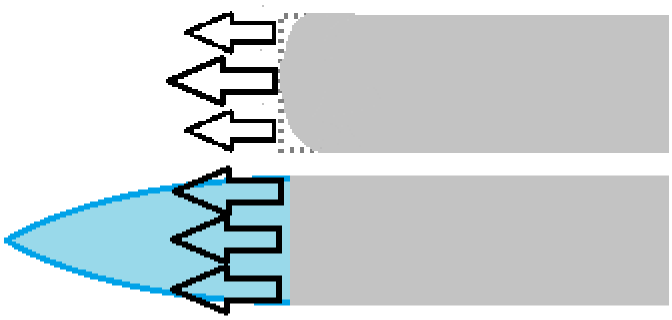
which was discussed previously, we can see that g (distance of gap between core and coil) heavily impacts the total force and should be kept to a minimum. For this reason, the projectile must fit snugly against the walls of the barrel. Length to diameter ratio should be >3:1, because ballistics science indicates that this ratio will keep the projectile flying straight. The website at http://www.instructables.com/id/Coil-Gun-Projectiles/ also indicated that the ratio should not be greater than 5:1 if spin stabilisation is employed, which I will discuss later.

As discussed in the material science section of my research, the material I use for my projectile must be ferromagnetic. Further research has also indicated that most mild steel grades would be a poor choice for a projectile because it has a tendency to retain magnetism after a few shots, causing a multitude of problems which were explored earlier. Soft iron/Low carbon steel remains the best choice, or a cobalt iron alloy provided a supplier can be found. One grade of low carbon steel I found was EN1A steel which has a carbon content of no more than 0.15%. With the other metals in the alloy, the steel is 98-99% pure iron so this is a good choice with low permeability. Coupled with the fact that grade of steel is easily obtained from steel stockists, it may be a very good choice for the projectile

Aerodynamics is a very important point to consider as with any projectile, but the way it works in a Coilgun differs from conventional bullets. If the projectile has an aerodynamic point at the end, there will be air gaps in the design of the bullet which reduce the efficiency and magnetic flux of the projectile. Simply put, there will be less material to attract. The solution is either to have a

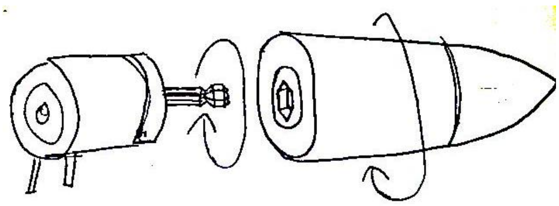
paramagnetic tip on the bullet which does not interfere with the magnetic flux (allowing the metallic section to remain entirely flat and cylindrical), or simply to be cautious of how much you grind away – making the bullet only slightly rounded. It is questionable which would be more efficient, since the tipped projectile would have greater magnetic flux but more dead weight, while the rounded one would have a reduced magnetic flux but lower mass.

Positioning is an important factor; since a capacitor's function is to discharge very quickly the coil will be at its peak efficiency for a very short period of time. If the projectile is too far from the entrance of the coil, it will not be attracted fast enough, and by the time it is at the entrance of the coil the current will be much lower and the projectile won't exit the barrel very quickly.



The mass of the projectile depends on the application of the Coilgun. A projectile of lower mass will have a greater speed, but reduced momentum and force. Therefore this factor is difficult – my Coilgun has no practical application other than to demonstrate magnetic linear acceleration so balancing speed with momentum and force is irrelevant for my purposes. If the Coilgun was being made to launch satellites, I would be able to calculate the exact force needed to send the object of given mass into orbit. For this reason, I will allow this factor to be decided upon by the other factors – i.e. length and diameter.

If the projectile does not fly straight, it will "tumble" increasing drag and reducing accuracy. Taking an arrow for example, fins are used to for stabilisation – but since the projectile needs to fit as snugly as possible in the barrel, this would be very inefficient. One viable method would be to put a spin on the bullet. The website I used for research (http://www.instructables.com/id/Coil-Gun-Projectiles/) suggested that I could use a small claw to grab the bullet and spin it, but also indicated that this would require a very accurate timing system. Another idea it listed was to generate spin in a multi-stage Coilgun by having the coils slightly twisted in order to generate spin, but of course this would present a multitude of other problems. I had the idea of using an Allen bolt and screwing it into the end of the bullet, and then having a small electric motor with an Allen key, which would spin the projectile and wouldn't require a timing mechanism – it would only have a very small amount of friction. Critically, all of these solutions present many other difficulties and the best option would be simply to improve the aerodynamics as discussed.



7 2D CAD and Laser Cutting

Laser cutting has been used since 1965; its very first application was to make holes in diamond manufacturing dies. Since then the technology has advanced greatly, and now laser cutting is a very affordable solution for prototyping and even mass-production in some cases. In simple terms, laser cutting uses a focussed laser beam to cut through a range of materials from cardboard to mild steel. The laser module receives instructions from a computer, which can be programmed to cut any 2D shape using instructions from a client's design. Companies have been set up which allow clients to easily use their high-quality laser cutting services to cut out and engrave a design of the client's own creation. This service is also conducted over the internet, so it's very easy for someone who needs high quality parts to design and receive them over a short period of time.

7.1 Applications

Laser cutting is most suited for early prototypes of a product where cost is less of an issue, since in most circumstances mass production of a product using laser cutting would be inefficient and time consuming. For example, a car manufacturer may need a simple yet strong plate with holes drilled in specific places to enable other parts to be mounted to it. Initially, laser cutting the steel plates may be a good option for tweaking and perfecting a design, but when it came to mass production of the car, the huge amounts of energy needed to drive the laser cutter would likely mean this method was not cost-effective. Once the design had been decided on, a special forming die would likely be mounted on a press, which could churn out thousands of the part very rapidly, using far less energy. Thus, laser cutting is most suited to prototyping.

7.2 CAD

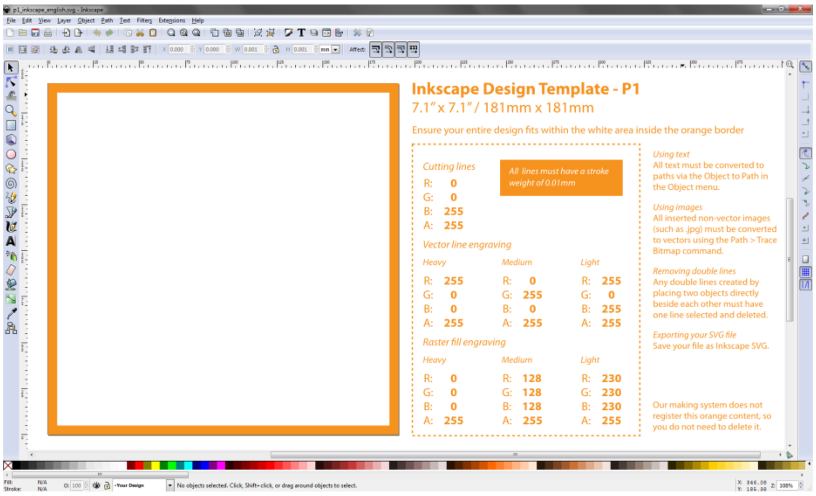
The computer-aided-design aspect of laser cutting has also become very easy and free, whereas in the past it may have required expensive software and/or extensive expertise in CAD. A range of Open-source software such as Inkscape have become available, which provide a very competitive alternative to much more expensive illustration software such as Adobe Illustrator, which would cost hundreds of pounds. With the availability and reasonable pricing of such companies, laser cutting is a very applicable option for the body of our Coilgun.

7.3 Experimental Design

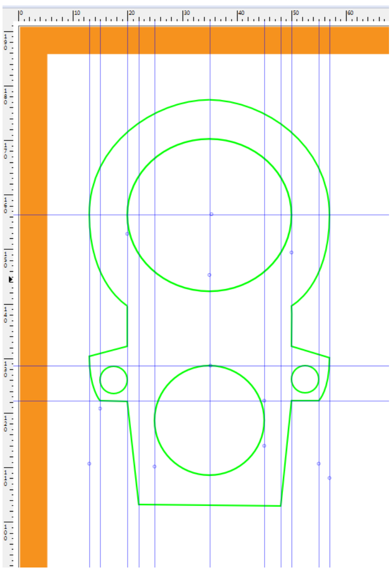
The very first step in creating a laser-cut prototype is to decide on a design on paper. This may involve many reattempts, but will ultimately serve as an excellent reference for the final design. To gain some experience before the final piece, I decided to create a very simple design in Inkscape. I wanted this to apply to the final design, but also to have a few challenging geometric features so I could hone my skills. My design was a simple guide to go over the end of the barrel in order to keep it straight, with another hole which could potentially guide a small laser in order to improve the Coilgun's accuracy. Finally, I added some small holes through which bolts could be secured to the rest of the body in a theoretical final design. For the sake of practise, I wanted the largest hole to be 30mm wide, the laser hole to be 20mm wide and the bolt hole to be 5mm wide.

The next step was to use the sketch to make a .svg template using Inkscape. I followed the guide for making a design in Inkscape on the following website: http://www.razorlab.co.uk/need-help/getting-started/inkscape/. It prompted me to download 3 templates of specific sizes which could be interpreted by their machines. Also, each template corresponded to a set price making it very simple to get a quote. Using their smallest template of 200mm^2, I would only pay £0.65 for

MDF, and even high-quality acrylic was under £2 (Note that this is the cost for materials only, not including shipping or cutting). Below is a screenshot of the starting template.

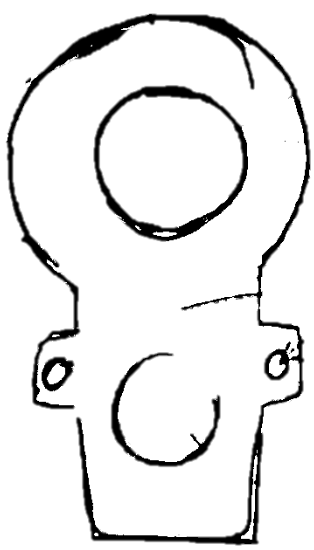


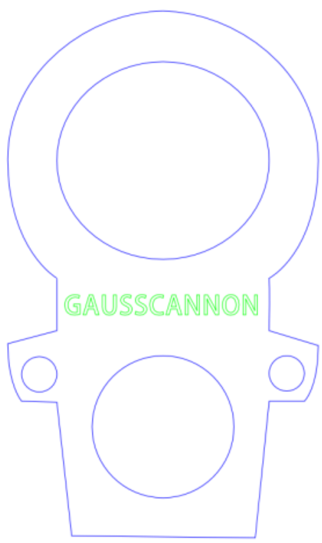
Basic instructions were available on the actual document, and were coloured orange since that specific colour is ignored by their machines. Guides were already set up around the page which allowed me to see the exact measurement of my design in millimetres; this meant that it was very easy to create a precise design. It was also possible to drag out the guides to serve as a point to anchor my lines to (see image to left). Due to the program's intuitive nature, it was very easy and quick to create this simple prototype design using only the pen tool and the circle tool.



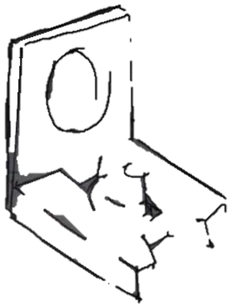
There were also a few considerations I had to take into account. For instance, different materials respond differently to the engraving process, and as such there are certain widths that are too small for the laser cutter to make without it breaking. Therefore, I ensured that no parts of the design were narrower that 2mm, since all materials available at razorlab.co.uk could handle this width.

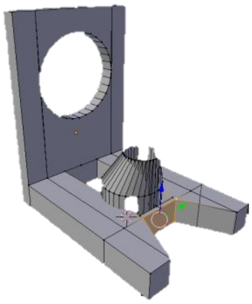
In order to test the engraving service I also added some text to the design. Finally, I set the properties to the appropriate width and colour according to how I wanted the laser cutter to process the information (blue for cutting, green for medium vector engraving). Note that on the screenshots on this document I set the line weight to 0.1 to increase visibility, but the service required that I set them to 0.01.

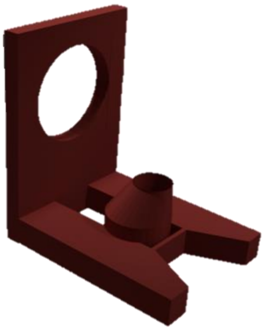


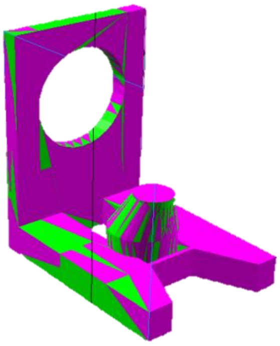


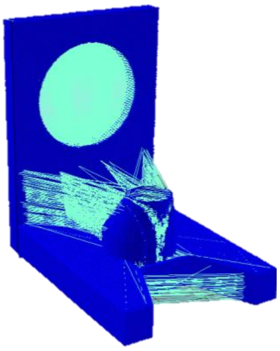
8 Rapid Prototyping and 3D CAD











Rapid prototyping generally refers to the use of 3D printing in order to quickly generate a prototype of a product or part. It has been in use since the 1980s where UV lasers were used to cure polymers, but modern methods generally use PLA or ABS filament which is heated and extruded layer upon layer to create a model. This method has become increasingly accessible in the recent years, as not only have very reasonably priced 3D printers been made available to the general public, but online services have been set up in the same way that laser cutting services have. Although polymers are most often used, recent advances in 3D printing technology have meant that it is now possible to create prototypes made entirely out of metal very quickly and efficiently. This technology uses a thin layer of atomised metal powder, which is heated by a laser, melting tiny areas of the powder together and eventually welding together large sections in order to generate a full model. Empire Cycles have used this technology to create more than just a prototype, and now sell a fully 3D printed titanium bike frame. The extremely precise nature of this method allows structures to be made much stronger using less material, and far more complex shapes can be made allowing other components of the bike to fit securely within the interior of the frame.

For our purposes, 3D printing is an excellent way for me to make parts quickly and perfectly suited to our needs. One major advantage that printing in polymers holds for me is that plastic parts will not be attracted towards the electromagnetic coils. This means that we can replace parts that would normally be made of ferrous metal with 3D printed parts. For instance brackets between sections of the body may be required, and 3D printing would allow me to generate them in the exact size, shape and critically they would not be attracted to a magnet.

8.1 Experimental Design

As with my research on laser cutting, I found 3D printing to be very easy and cheap. 3D CAD can be done with open-source software such as Blender. While not quite as easy to use as Inkscape, I found blender to be very easy after a few online tutorials at https://cgcookie.com/blender. I began with a sketch as before, my idea wasn't really specific to the Coilgun but it could be used as a sort of bracket or to hold tubes like the barrel in place. The important part of the design was that I wanted to test the printer's ability to generate thin sections, round and conical shapes, as well as overhangs so that I could gauge exactly how suited this method would be to different applications within the final piece.

Modelling the design on Blender was very simple. I constructed my shape out of smaller, simple shapes, starting off with a cube and using the extrude tool to raise certain faces, and adding cutaway sections by remodelling the flat surfaces to include circles in their geometry. (Second and third images) I exported the model as an .obj file and imported it into Repetier Host, which can be thought of as a pilot program for the 3D printer (see picture in pink and green). It uses an internal sub-software called “Slicr” to interpret the 3D model into instructions the printer can follow. It then allows the user to see the path the printer will take, and make adjustments based on this (see blue picture). My first attempt didn’t work out, since my model was not “manifold”. This simply means that it wasn’t watertight, meaning that Slicr couldn’t process the information. Using a free model repair service at https://netfabb.azurewebsites.net/, this issue was quickly rectified. I then printed the model.

The printer performed much better than expected, with all shapes very well formed and even the overhang didn’t collapse under its own weight like I expected it to. The only problem was that on the back of the cone some of plastic was too thin and snapped off, but this simply meant that in future prints I would need to be more observant of the minimum thicknesses. The only drawback was that this method took around 2 hours for this fairly small bracket – about 150mm² of filament. Certain printing techniques like having hollow sections would reduce the time taken however, so while printing the final pieces I would have to be aware of this. There was also a slight issue with the very top of the larger circular cutaway, but difficult sections like this can be printed with support material (which can be enabled in the settings of Repetier Host) in order to stop things like this happening.

Overall this experiment proved that 3D printing would be a very viable option for small parts of the final Coilgun, provided a few simple points were observed.

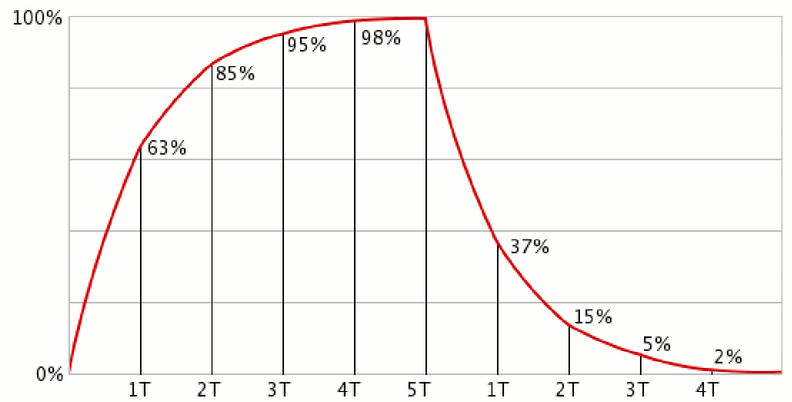
9 Maximising the Force

$$F = \frac{a(4\pi * 10^{-7})(ni]^2}{(2g)^2}$$

The above equation is used to calculate the force a solenoid exerts on its core, although of course it applies to a Coilgun circuit too. As we've already established, area of the wire, number of turns and current must be maximised, while the distance is minimised. All of these factors are easy to control except for the current, which requires a little more thought and calculations. The current in the circuit is equal to the charge stored on the capacitor divided by the time, where the charge is equal to VC (voltage times capacitance). The time which the Coilgun is active for is approximately 0.5-1 second, and this time can also be used to calculate the portion of the charge discharged.

9.1 Current and Capacitance

Take for example a 10µF capacitor charged to 10V, with a resistance of 10Ω on both the charging and discharging circuit. The capacitor would have a charge of VxC=10Vx10F=100C once fully charged, and a time constant of T=RC=10Ωx10F=100s. In 100 seconds, the capacitor would be charged to 63.2% of its maximum charge (100C). After 5 time constants the capacitor is practically fully charged.



When the Coilgun is fired, assuming the coil is active for 1 second, 1% of one time period's worth of charge will be discharged through the coils. The time taken to discharge **to** 36.8% of the total capacitance is also equal to one time constant.

In order to calculate the current at a specific time after the circuit has been closed, use the equation$I = \frac{V}{R}e^{\frac{-t}{RC}}$, (Capacitance is in µF) which gives the value 0.99A. Note that the maximum current immediately after the switch is closed is simply V/R, because t=0 therefore –t/RC=0 therefore e=1 in the equation. In order to have an optimum circuit for firing one shot at a time, I will need to have a high voltage to maximise the maximum current, but also a large enough time constant such that the current stays high for at least 1 second.

9.2 Maximising Stored Charge

I have found that in order to maximise current I need to maximise voltage. One way of doing this would be to use the kind of circuit from a camera flash, which is capable of effectively stepping up voltage in a DC circuit, by using an "oscillator" subsystem to vary the DC current across one side of a transformer so that a magnetic field can be generated according to faraday's law. This in turn induces a current on the other side. The issue with this however is that the energy from the batteries would be drawn very quickly, and circuits used in camera flashes are not rated to deal with high power.

When building the final model, I will need to start by building the coil and its driving mechanism so that I can calculate its resistance and find the ideal capacitance and voltage based on this figure to get to an optimum current. If the resistance can be kept to a very low 1Ω, the time for which the gun can be fired will be massive, however I will need a certain amount of resistance to keep the current at a safe level according to the power rating of the various components. There are a few factors that I will need to balance. I want the time constant to be small to reduce charging time, and also so that a larger portion of the total charge is discharged in the firing time. However, if it's too small on the *discharging* side of the circuit then the current will also be too small according to the equation mentioned earlier. The time constant will have to be sensibly balanced for a minimum charge time and a maximum charge.

A large super capacitor would have the benefit of allowing the Coilgun to be fired multiple times without needing to be recharged (would give a huge time constant where resistance is constant), but super capacitors can only handle small voltages. The capacitors would have to be arranged in series to spread the voltage evenly across them, which sadly lowers the total capacitance of the capacitor bank, although this may still be much larger than a conventional capacitor. A sensible decision will have to be made based on cost, capacitance and simplicity of the circuit.

A sensible middle ground will need to be established between voltage, capacitance and current for safety, portability and projectile force as described in my criteria, and this will be easier to do once I have built the coil.

9.3 Stages

One method of increasing the force with which the projectile is fired is to add multiple stages to the Coilgun, which would entail having several coils in series. This method has the potential to greatly increase the power of the Coilgun, but of course it makes the design more technically difficult. The easiest solution would be to have all the coils switch on when the trigger is pulled, and then have them sequentially turned off. The only issue with this idea is that each coil will need its own switching circuit, and since I plan to work with such high currents the total expenditure of the project will vastly increase because I will need several very high-power components which can handle the current without being destroyed.

The coils would need to be arranged in parallel, each driven by a MOSFET (or several in parallel), and controlled by a timing circuit which uses an infrared detector to switch the coil off just when the projectile begins to protrude. This method would have the same effect as increasing the total number of turns in the coil, so from a practical and economic standpoint, it would likely be easier to increase the number of turns.

10 Overcoming Issues in the Circuit

With so many factors affecting the circuit in different ways, there are a lot of potential problems that may come up in the final model.

10.1 Overheating

Starting with one of the simplest yet most potent potential issues, overheating is a worry when it comes to very high currents. Since the resistance encountered in the coil circuit is to be extremely low, the current will be so high that activating the coils will be akin to short circuiting the capacitors. The massive current generated may be enough to completely melt the copper coil, no doubt destroying the Coilgun and posing a serious threat to the health of the user. This is, however, very easily rectified. Lowering current is simply a matter of adding resistors into the circuit, allowing me to control the current to be the exact value I want according to V=IR. A higher resistance would also maximise RC, the discharging time of the capacitor, potentially allowing more shots to be fired without the need for a recharge. However, I want the current to be high to maximise force. A way to control overheating without worrying about loss of current would be to use a larger diameter of wire, which can handle the high current. I decided on a sensible upper bound for the diameter of my coil's wire – any greater than 5mm and winding will become very difficult and air gaps between the windings will be too large. I looked at a few different charts for tolerances of copper wire at this thickness, and found it to be around the region of 30-70A. A NASA study "Selection of Wires and Circuit Protective Devices for STS Orbiter Vehicle Payload Electrical Circuits" confirmed that copper of 10AWG – 5.26mm would have a temperature rise of 300°F - 149°C at 50A.

A very short burst of current at 50A may be significantly less, however, as all of these assumed the current to be *continuous, i.e*. the current rating is what they can safely handle indefinitely, but no doubt a short burst would be able to handle much more. One way to calculate a more accurate value would be to look at the specific heat capacity of copper, which is $386JKg^{-1}K^{-1}$. Therefore, we can use this value, the mass of the wire and the energy supplied to it (Q=IVt), to calculate a more accurate temperature change. Copper melts at 1000°C, but of course we want to stay well below this value.

If I am to use 5mm wire for my coil, and I use a total of 1 metre, then the total volume of copper is $1x\pi(0.005)^2$=$\mathbf{7.85x10^{-5}m^3}$. Copper's density is 8960kg/m3, so the total mass is $7.85x10^{-5}$x8960= **0.704kg.** If I want to restrict the temperature rise to only 40°C per 0.5 second shot, this will mean that the temperature will reach approximately 60°C assuming it starts at room temperature. Using the equation: Q=mcΔT, I can calculate that this 0.5 second shot with temperature increase of 40°C would use 0.704x386x40=**10,870J** of energy. Since energy is equal to power x time, and one shot in this theoretical calculation is 0.5 seconds, I know that this coil would be able to have a maximum power of **21,740W**. This value is very high and gives me room to alter certain variables, however If I wanted a greater power, I could employ a number of tactics such as:

- Thicker wire
- Greater length of wire (more turns)
- A cooling system such as a fan, heat sink or submersion in water
- Faster shots

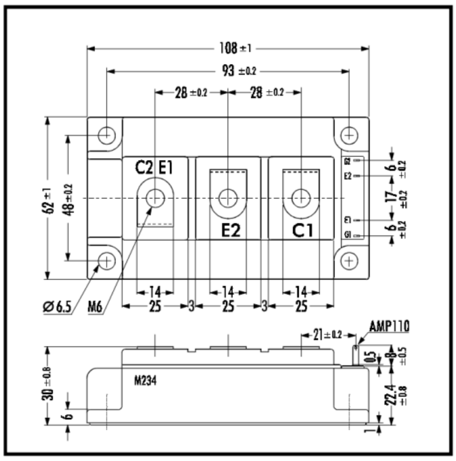
Interestingly, having thicker wire, more turns and faster shots would increase the power of the Coilgun. Once I have built the barrel and mounted the coil, I will be able to calculate a more exact value for the maximum power.

10.2 Choosing Capacitors

Another large issue that has so far been the most problematic factor is finding an appropriately sized capacitor. The initial current which is equal to V/R depends largely on the voltage to which the capacitor has been charged. This is why systems such as a camera flash have their voltage stepped up so high – so that the maximum amount of current will be available in the short period of time immediately after the circuit is closed. The dilemma lies in the fact that conventional capacitors have a very low capacitance in comparison with super capacitors, which can have up to thousands of farads of capacitance, but their drawback is in their inability to handle any voltage over typically around 5V. Using super capacitors I could have much greater firing times, but I would have to be very careful about keeping the resistance low so that I could have a sufficiently high current.

I would also have to arrange the capacitors in series, which lowers their capacitance but increases the voltage tolerance of the capacitor bank. A 500F capacitor with a voltage rating of 2.7V would be relatively cheap and have a massive charge stored on it – 5000C with total stored energy of 25kJ, far greater than most if not all homemade Coilguns, although problems will arise to do with the maximum current. This issue will likely only be solved through testing of various different capacitors at my disposal.

10.3 Switching



In order for my Coilgun to be as effective as possible, I want to integrate an infrared detection feature which switches off the coil as soon as it isn't needed, reducing the duty cycle and increasing the force. This will require a semiconducting switch. The most "heavy duty" of these switches are either IGBTs or relays, which can typically handle 100s of amps but also cost 100s of pounds. Fortunately I have found online marketplaces which sell old and/or refurbished parts for a substantially lower price than new, all tested and safe. I found a FUJI 2MBI200S-120 which, upon inspection of its datasheet at http://www.europowercomponents.com/media/uploads/2MBI200S-120.pdf, I found that it could handle 600A for 1ms at 25°C. Testing will be necessary to see the exact time which my Coilgun will take to fire, but the continuous current is a very high 300A anyway.

An alternative to this would be to wire several MOSFETs in parallel to split up the high current. MOSFETs can often handle at most around 100A, so I could find exactly how much current I expect to pass through them and use that many MOSFETS. Of course this is not an ideal solution and would be out of place on a final production model (as would refurbished IGBTs) but it may be an excellent solution for early prototyping. Also, it is important to consider that often the current does not split as evenly as expected so I would need to overcompensate by around 150% for the amount of current I expect to pass through the coils. If the expected current was 100A and each MOSFET could handle 10A, I would likely use 15 MOSFETs just to be certain that they wouldn't get destroyed.

When using large switching devices, one drawback is that I may need more power than with smaller switches. The gate-emitter threshold for my IGBT is 5.5-8.5V at 200mA, much more than the typical 2V for MOSFETs. This is around 1.5W, so I will need a large capacity battery to power the gate. In the alternative MOSFET circuit, I could have a low voltage, but since the amperage splits at a junction, I would need to think carefully about what protective resistors to use in order to ensure the MOSEFT can switch. The IGBT solution is more robust, but may expend more power. Perhaps a small amount of power from the capacitors could be used to power the switching circuit.

There are also a few other components that will need to have a very high current tolerance, such as a fly back diode and switch, but these are much easier to come across. No doubt many more unforeseen issues will arise in the circuit, so I will work through these as I discover them.

11 Proceeding with Experimentation and Building

A few finer details could not be determined from research alone, and require experimentation to find the most effective way to execute them. However, before any further action is taken, a full health and safety risk assessment is necessary.

		Potential severity of harm		
		Slightly Harmful 1	Harmful 2	Extremely Harmful 3
Likelihood of harm occurring	Highly unlikely 1	Trivial 1	Tolerable 2	Moderate 3
	Unlikely 2	Tolerable 2	Moderate 4	Substantial 6
	Likely 3	Moderate 3	Substantial 6	Intolerable 9

11.1 Risk Assessment

I have used the chart to the left from http://www.hse.gov.uk/risk/images/risk-matrix.gif to determine sensible ratings for the various risks I will encounter.

Activity	Hazard	Risks	Pre-Control Risk Rating	Control Measures	Post-Control Risk Rating
Working with very high wattages of electricity	• Capacitors • Live Wires • Power Source such as power pack or jump starter	• Electrocution • Burns • Fire	6	Keep voltage low so that current is lower than 5mA according to resistance of human skin (around 10,000Ω). Keep electrical circuits away from flammable materials. Do not touch live wires. Wear safety gear where necessary.	2
Firing weapon	• Projectile • Coil Gun	• Being hit by high-velocity projectile • Injury from recoil • Ricochet	4	Only fire in a safe and controlled environment. Limit current if recoil is found to be too high. Never fire at a hard, flat surface. Fire into soft materials.	3
Using tools	• Pliers • Wire strippers • Utility Knife • Hacksaw • Soldering iron	• Incisions • Lacerations • Burns	2	Exercise caution while using tools, and wear appropriate safety gear (gloves etc.) where necessary.	1

11.2 Planning Experimentation

Details which I have yet to determine through experimentation are as follows:

- Shape and construction of an Ideal projectile
- Ideal capacitor type and arrangement
- Ideal heat limit generated in coil by a single shot

Some experiments rely on the barrel of the Coilgun being constructed. These are the ideal heat and projectile, because they require me to actually fire the Coilgun. The ideal capacitor type is difficult to judge by experimentation alone because there are many factors playing into the decision and the best option really depends on the application of the Coilgun. The final factor is the design of a locking device, because one problem I noticed with most Coilgun designs is that they do not consider the practicality of loading projectiles into the barrel, and they are held in place by friction alone. Since my Coilgun is to be ergonomic and practical as defined in my aim, I will design a suitable locking mechanism.

11.3 Ideal Capacitor Type and Arrangement

I had planned to devise an experiment on the ideal type of capacitor to use, but unfortunately I came to the conclusion that there are too many factors to be able to make a final decision based purely on numerical data. The factors are as follows:

- Time constant
    - Time taken to discharge the capacitor – Either large enough so that I can fire several shots with a fully charged capacitor bank, or small such that the time constant is optimised for maximum supplied current with one shot only.
- Peak current
    - Simply the greatest amount of current the capacitors are capable of supplying
- Stored energy
    - Energy on a capacitor is equal to $0.5xCV^2$

Peak current is dependent on the voltage the capacitor is charged to and the capacitance, since the charge stored is =CV. The most likely options in terms of the best components I can get within by budget are 500F 2.7V super capacitors and 10mF 450V electrolytic capacitors. Assuming I charge both at their max ratings, the super capacitor would have a total charge of **1350C** and the electrolytic would have **4.5C,** making the super capacitor the clear winner. In terms of energy stored, the super capacitor would have **1800J,** and the electrolytic would have **1000J**.

Time constant is less simple to compare, since it is not clear whether it would be better to be able to fire many shots in one full charge or to fire single shots that could potentially be more powerful. However, since there is an upper bound for the current I can reach without destroying other components anyway, I have come to the conclusion that It may be better to go with a long time constant, potentially limiting the maximum current (although I could of course lower resistance to alter the time constant). For a longer time period, the super capacitor is certainly the better choice.

A final point to note is that higher voltage capacitors are less safe, even if they store less energy. This is because current is equal to voltage/resistance, and if the resistance of the human body is around 10kΩ, a 400V capacitor could supply 0.04A or 40mA, which can have “possible irreversible effects” -

http://en.wikipedia.org/wiki/Electric_shock# . However, an electrolytic capacitor charged to 2.7V will supply only 0.3mA, which the same website classes as “imperceptible”.

For all of these reasons I have decided to go with the super capacitors. Also, I decided that it may be sensible to wire a few of these in series, to increase the maximum voltage I can have passing through them. This is because I likely wouldn’t be able to use 2.7V because it is very low and most big batteries like car batteries or even jump starters use 12V. 5 super capacitors in series would have a total capacitance of 100F, which is less than one but since voltage is quadrupled, the total energy stored rises to a substantial **7200J**, and charge of **1200C**.

11.5 Projectile and Heat

In order to find the ideal projectile, I will simply test a few different designs of projectiles based on their accuracy, penetrative capabilities, mass and force. Since I will require a working firing system in order to test this, the best option would be to wait until I have finished building the entire Coilgun.

As for finding the upper bounds of the coil’s heat, I will also need to have built some of the Coilgun. However, I will only need the completed coil. By using the exact length of coil in the equation $Q=mc\Delta T$, I will be able to calculate a much more accurate upper bound for the power I can use in my circuit.

12 Finding the Maximum Power

With the coil and barrel built I am now in a position to calculate a sensible upper bound for what power I should use within my circuit. I used a total of 3.55m of enamelled copper wire in my final coil. With these new figures I can calculate a new maximum energy.

Using $Q=mc\Delta T$, I can calculate that the maximum energy I can safely expend in one shot is $(3.55\times\pi(0.005)^2(8960))\times(386)\times(40)=$**38,570J.** This is almost 4x greater than the previously calculated value, due to a greater total mass and increased temperature tolerance. This energy value corresponds to **77,140W** for a half second burst of current. At 12V, this would allow me to use 6428A, which is significantly more than I need. If I were to limit the current to 300A (the current which my IGBT can handle continuously) then my energy at 12V for 0.5s would be 1800J, meaning I could fire my Coilgun 38570/1800=**21** times before causing damage to the coil. In the interest of safety it may be wise to keep my current at 300A.

13 Locking Device

In order for my Coilgun to be as ergonomic as possible, I want to incorporate a system in which projectiles can be held securely in place once they've been loaded, so that they don't fall through the barrel. A huge factor in the efficiency of my Coilgun is the firing time, and every factor will be better if the firing time is reduced. Therefore, it is imperative that the locking system is as fast as possible. Another important factor is how much energy the system will use. Obviously I want to use as little energy as possible, so I will make sure that the final design uses the minimum possible energy. Real-world firearms can easily hold their projectiles in place with friction alone since their projectiles are propelled by an explosion at the back of the bullet, meaning any friction is easily overcome and results in an explosive release of energy. With a Coilgun however, I want as little friction as possible so that no energy is wasted.

I have a few solutions to this issue:

- A solenoid driven arm which rotates to cover the barrel, locking the projectile in place
- A small electromagnet which holds the projectile in the barrel until it is ready to be fired
- Simply making the barrel a tight enough fit such that there is just enough friction to prevent the projectile from falling out

Of course the fastest solution is to use an electromagnet which is capable of switching off the moment the coil is activated, but this would of course draw a fairly large current. The best solution for saving energy would be the tight barrel, but this will reduce the power of the Coilgun slightly, so is not an ideal solution. A solenoid driven arm is something of a compromise between duty cycle and switching time. It would use less energy than the electromagnet since it is only one rapid burst of current, however it would likely take more time to actually move all of the parts, and the complex nature of such a device may present other mechanical difficulties.

It would seem then that the simplest option would be simply to use a small strap (possibly 3D printed) to place over the loading section of the barrel to hold the projectile in place using friction, followed by a small electromagnet. Assuming the bullet weighs 0.5kg, I would need a holding force of over 9.81x0.5=**4.91N** to hold the projectile while it is vertically suspended. In fact, I would likely need up to **10N** to account for jolts or other external forces it would no doubt experience.

Once I have a prototype capable of reliably accelerating projectiles, I will test a basic prototype of each solution and decide which one is the most efficient.

Building Barrel

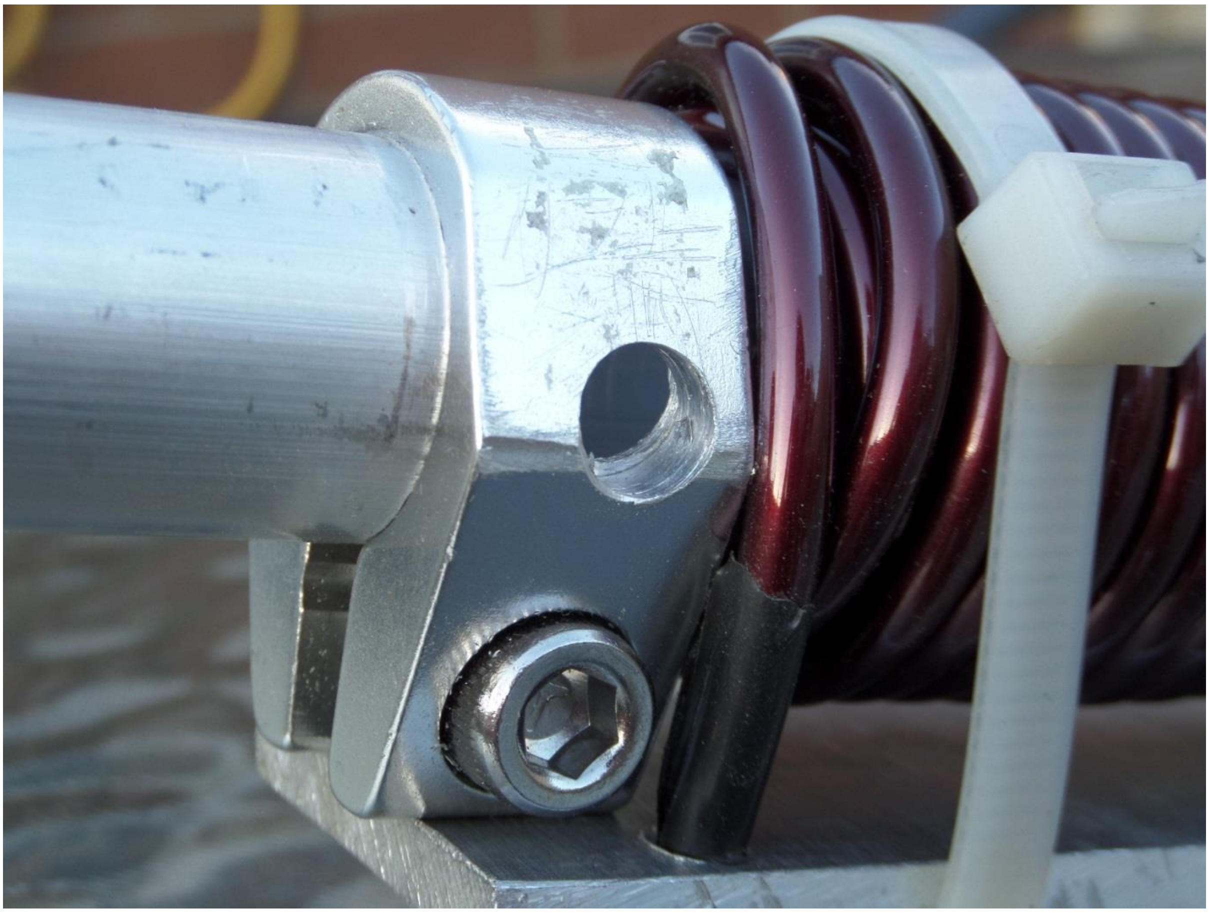
The very first thing I built was the barrel and coil. I started with a 300x25mm (length x diameter) aluminium tube, and marked on it where I would have the coil, infrared detector and projectile

loading area. I calculated that, in accordance with the internal diameter of the tubing, my projectiles would have a diameter of approximately 20mm. I then calculated that according to my research on the projectile, the length of the projectile should be no longer than 5x the diameter (to allow for potential use of spin stabilisation in the future). This means the projectile should be less than 100mm. Using a hacksaw I cut the tube in half to a point 100mm from one end, making an easy way to load the projectile and make sure it is the correct distance from the coil during testing.

I then wrapped the coil, which should be equal to or greater than the length of the projectile (>100mm in this case), so in an effort to use the maximum amount of turns possible I made the length of the coil 110mm. In theory this should give me 44 turns if I were to double over, but in practise I only had 40 because of small imperfections in the coiling process. I secured the coil in place by using two pushbike seat clamps which were made of aluminium, and mounted these on a slab of aluminium with holes drilled with a drill press to feed through the endings of the copper wire.

As a temporary way to keep the slab securely against the clamps, I used some heavy duty cable ties; although in the final build I will find a more reliable and safe way to do this.


I also made a hole through the tube and clamp in order to fit the infrared detection system later on, using a drill press. In order to avoid damage to the enamel layer, I filed all edges that I cut, and wrapped electrical tape around particularly prone areas. This can be removed if it cannot handle the high temperatures, but having it on while I fed the wire through prevented any scratching.



Testing Barrel

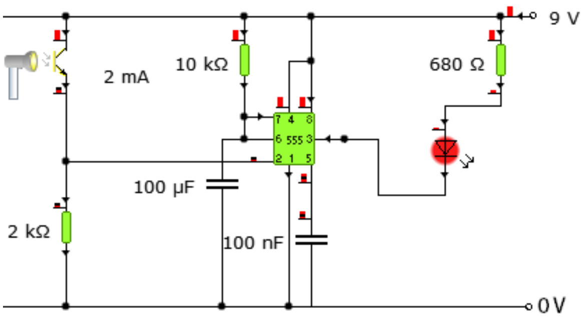
Once I had built the barrel, I used sandpaper to expose the copper of the coil. I then used a jump starter which was capable of supplying 300A of current and attached it to both terminals of the coil. I inserted the EN1A steel blank from which I would cut the projectiles into the barrel and turned the jump starter on, simply to see if the coil would work the way I had anticipated. It attracted the slug with massive force, and suspended it in the centre of the coil, just as I had expected it to, but I had not expected the force to be quite as great. I also tested a tiny steel nail in the barrel and to my slight surprise it was barely attracted at all. This is due to the fact that the nail has a much lower permeability than that of the slug, and also because it is small it does not take full advantage of the entire magnetic flux in the barrel. I knew this, but I certainly did not expect the difference to be as great as it was. Somewhat paradoxically, a larger, heavier projectile is accelerated with much more force than a lighter one. It is important that I remember this when making the projectiles.

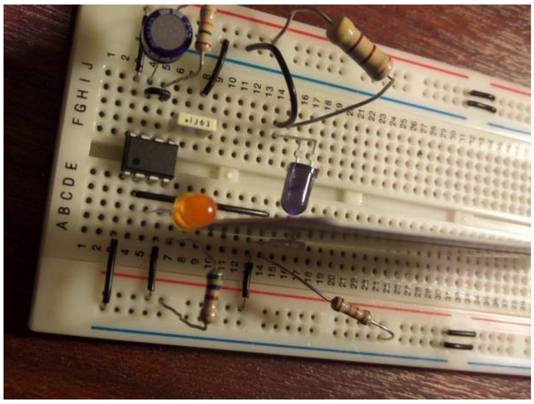
I then took my barrel and coil to the physics lab to find out some more information about it. Using a multimeter I calculated its resistance to be below what the multimeter could measure. I also experimented with different currents by attaching the coil to a power supply using crocodile clips. The current it was capable of supplying was significantly lower than the jumpstarted I had used, but it gave me a good idea of what kind of currents would produce what kind of forces. With the power supply's maximum current of 2.5A, I could feel a very small magnetic force of attraction but this was not nearly enough to move the slug. This is understandable since the current supplied by the jump starter was 120 times greater than the power supply. In order to achieve greater currents I would have to either use a much more powerful power supply or alternatively wire several power supplies all to the coil, effectively stacking up the currents to attain one very large current.

During the testing an issue occurred to me, which was that if the current supplied by the capacitors is too high then all of the other components are at risk of being broken, and I cannot control such high power without extremely heavy duty (and expensive) resistors. My solution was to effectively build a resistor to the specifications I needed. In order to get 300A from a 12V supply, I need a resistance of 40mΩ. Therefore, if I use cable which comes with a resistance rating per metre, I can calculate the exact length I need to make a very low resistance, super high power resistor. If I coil all of the wire up then I am liable to inadvertently create another huge magnetic field, so I will have to be careful about how I wrap up the long length of wire. Perhaps an alternate design could make up this length with additional coils, using the resistance as efficiently as possible, but unfortunately I do not have the funds for all of the heavy duty switches I would need for such a circuit. I could however wind the cable in such a way that the direction of the current alternates, cancelling out its own magnetic field.

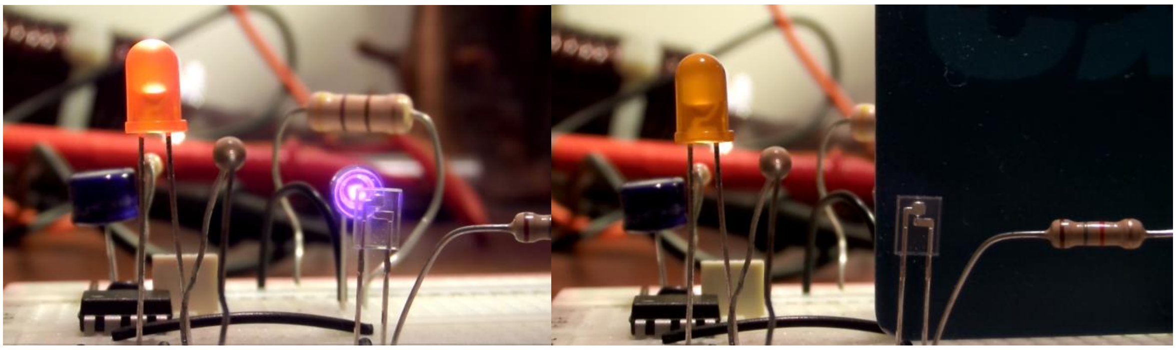
Building Infrared Detection Circuit

Using my circuit diagram which I constructed in Yenka, I constructed the infrared detection part of the system. Its purpose is to detect when the projectile is just at the end of the coil, and turn off the coil at that exact moment, keeping it turned off for around one second.





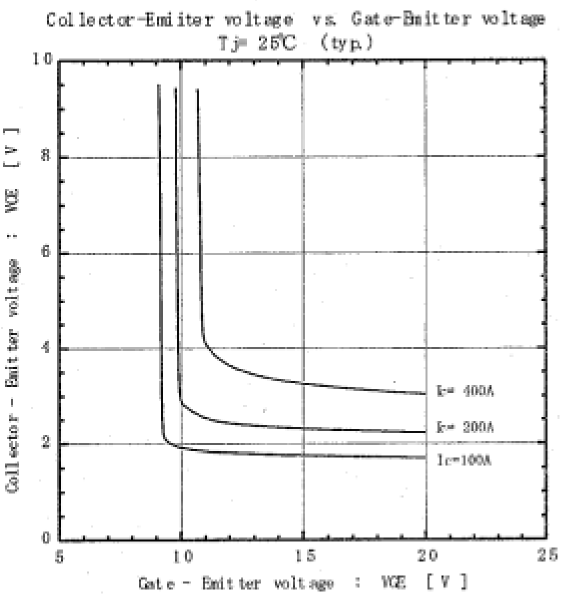
The circuit worked excellently – exactly as planned. The only minor concern is that the LED (which simply represents the signal going into the IGBT) will flicker slightly and infrequently after approximately 1.1 seconds have elapsed if the object blocking the IR is still present. However, this is not a major concern because there will be a trigger between this circuit and the next, meaning the only way that the coil would flicker on and off would be if the person using the Coilgun held the trigger down unnecessarily.

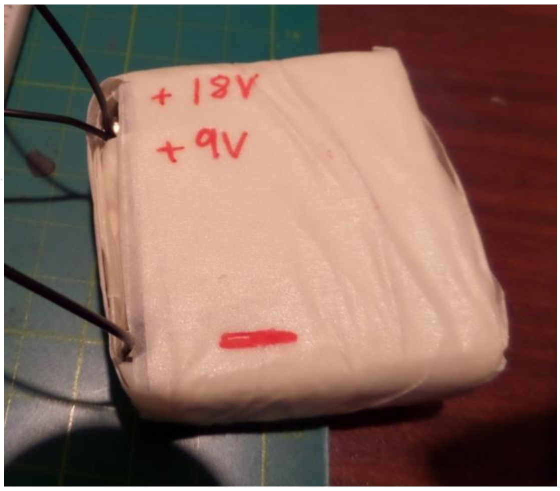


I deliberately did not cut down any of the components in the circuit because I hadn't decided how exactly they would be mounted on the final piece. Therefore the circuit has a messy appearance and troubleshooting is made harder – but this is only a temporary disadvantage.

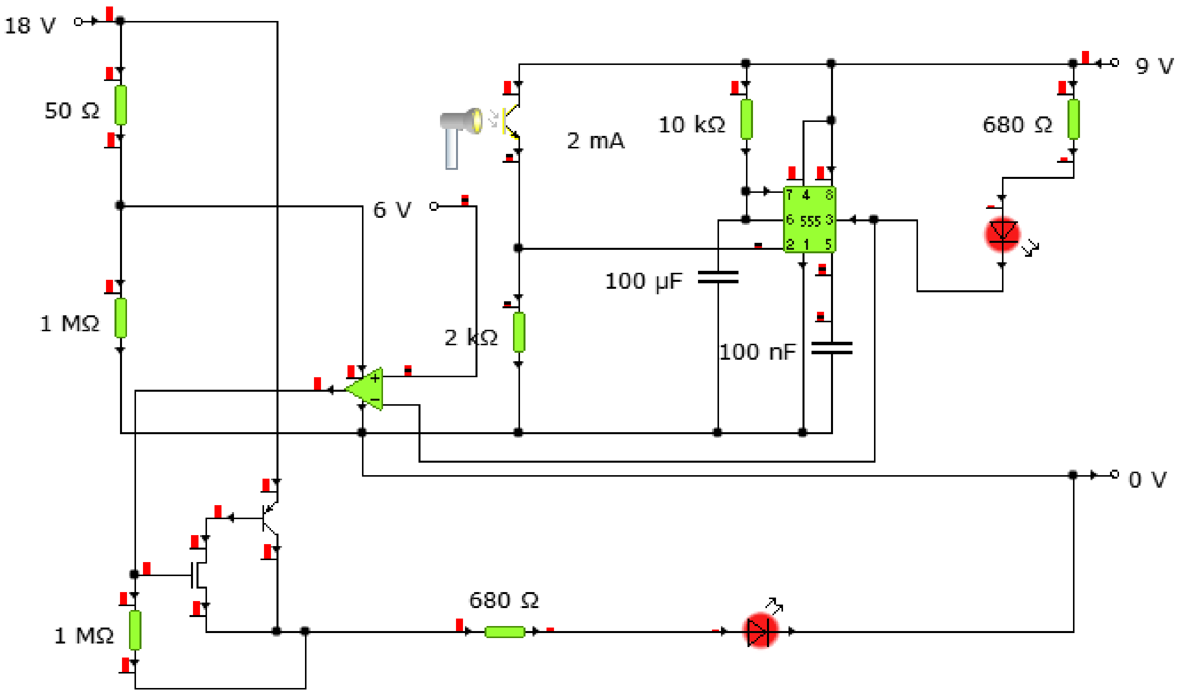
Building the Rest of the Switching Circuit

Once the detection section of the circuit was built, I began to build the switching section which would control when the Coilgun could switch on and off. In order to switch the massive current I needed to use a heavy-duty IGBT, which presented a number of problems. The first of which was that I simply couldn't get it to turn on. Through inspection of the datasheet I noticed that the gate-emitter threshold voltage ranged from 5.5V to 8.5V, and I measured my op-amp to be outputting only around 6V, below the "typical" threshold voltage. This was also backed up by a graph, which showed that for a gate-emitter voltage under about 9V the IGBT was liable to have a large voltage drop from the collector to the emitter. I tried to switch the full 9V of the battery through a MOSFET, but since the battery was not full it could not reach the ideal 9V and the IGBT could not light the LED. My solution was to use two batteries to create a higher voltage of 18V (fully charged) which was enough to switch the IGBT through the op-amp (which was protected by a voltage divider, keeping the voltage as high as possible but limiting the current).

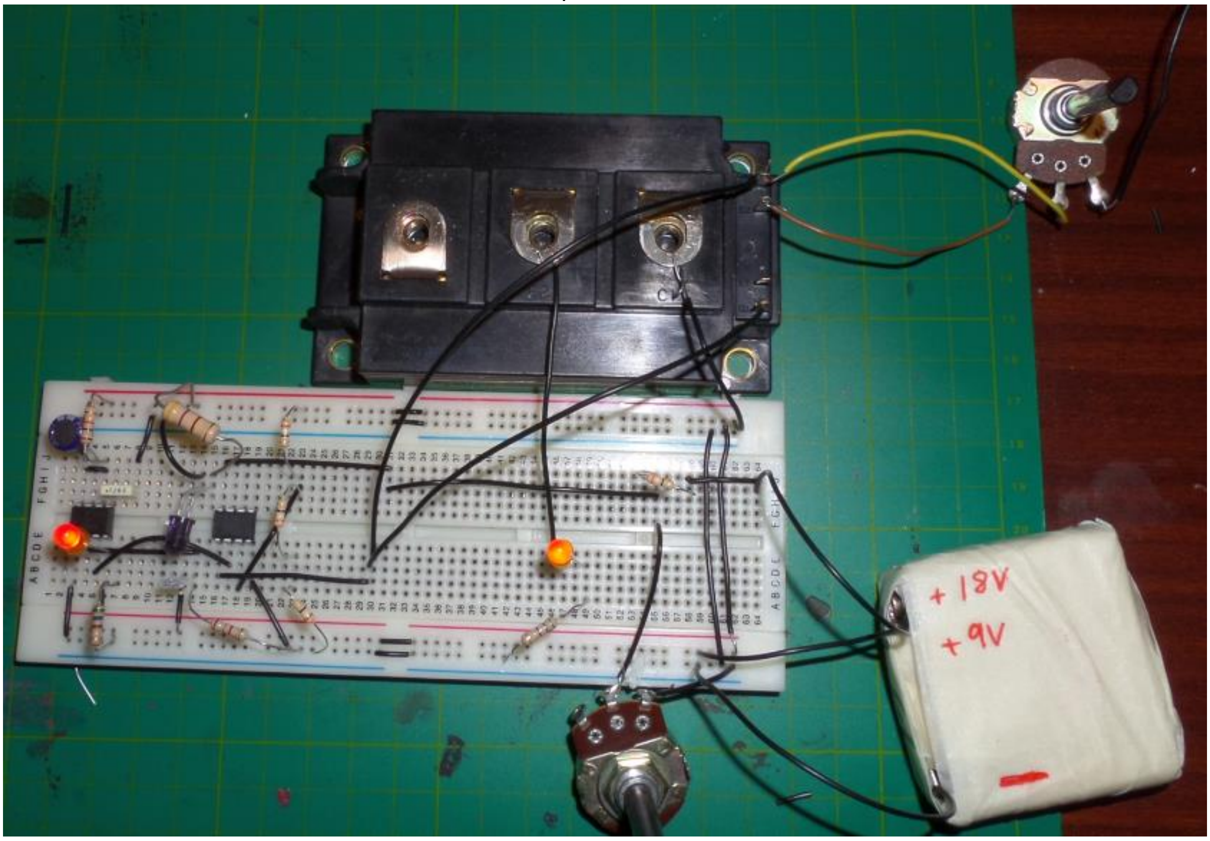


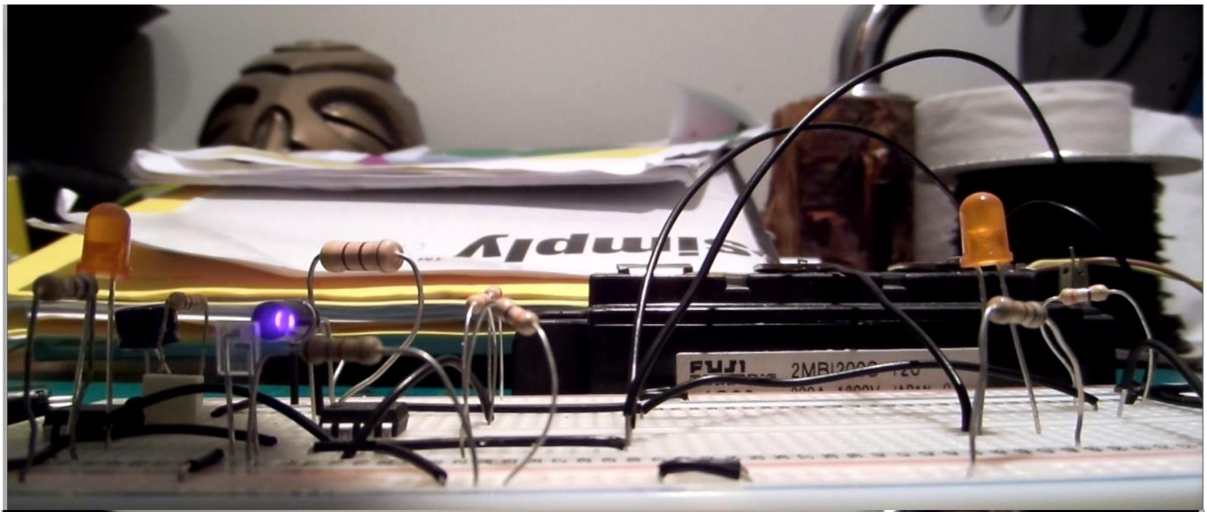


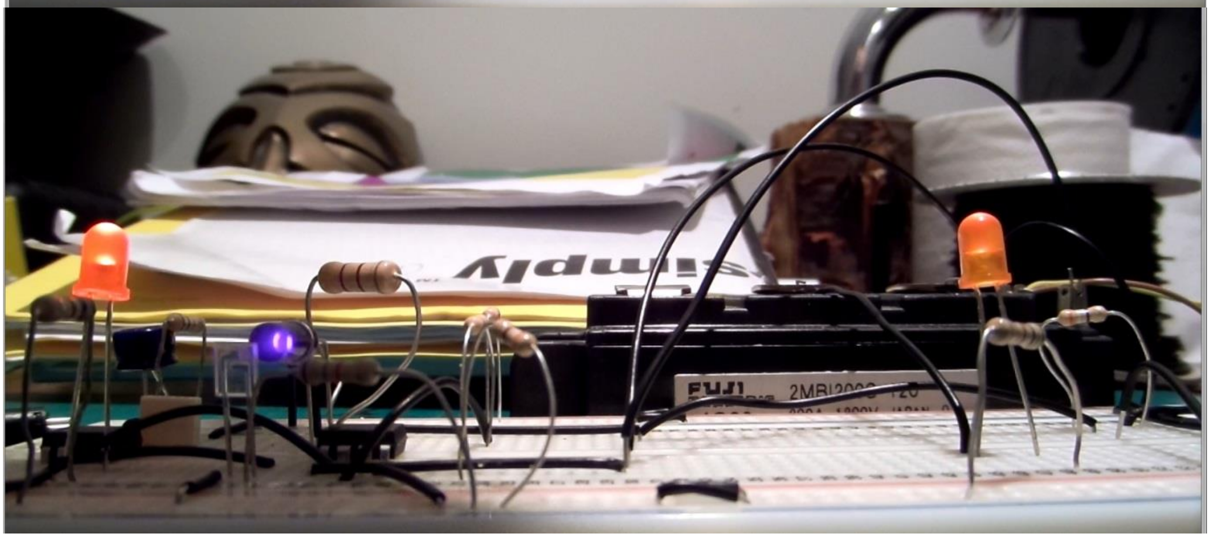
I could now light the LED through the IGBT, but unfortunately it would not turn off once on. In fact, it would get even brighter when it was supposed to be turning back on. Research into IGBTs led me to discover that the gate and collector act as a capacitor and the IGBT will turn on once all of the voltage has leaked off from the capacitor. This explains why it would gradually get dimmer over time. The solution is to add a very high resistance resistor across the gate/emitter to quickly drain the “capacitor”. The final circuit is as follows:



Yet again this circuit was very untidy, simply because I was anxious about cutting down components in case I cut it too short and had to find a replacement



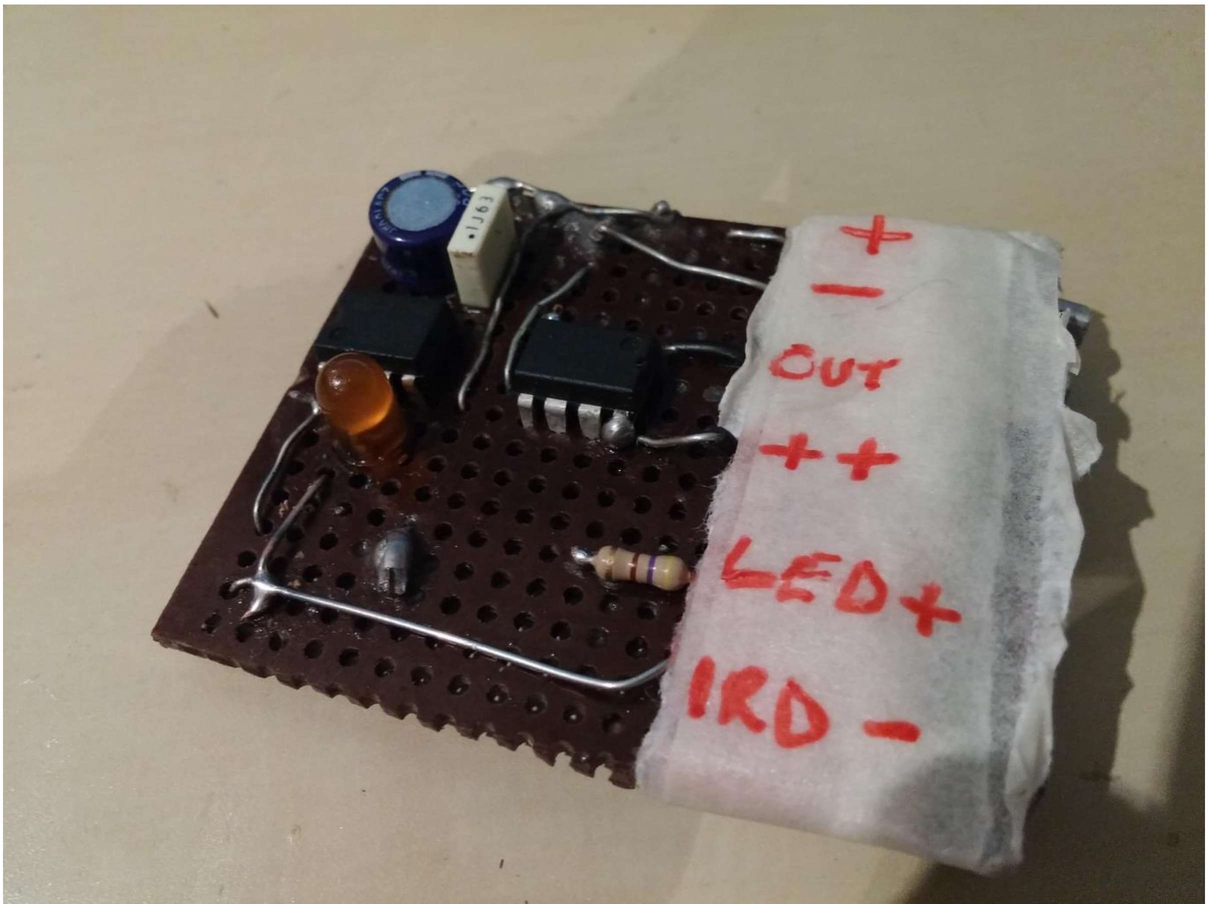




Soldering Driver circuit

Having never soldered before this process took longer than it perhaps should have. I encountered a few problems during soldering. The first was that I couldn't melt the solder, which turned out to be a simple problem involving a layer of rust on the tip of the soldering iron, which I simply removed with a wire brush. The next issue was that I had difficulty in getting the solder to run into the gaps and actually join properly with the metals. I thought this was because I wasn't using enough flux, but as it turned out it was more because I wasn't getting the two objects I wanted to join hot enough. After fixing these issues, the rest of the soldering went slowly but smoothly.

Under the board I used female connectors from a crimping set so that I could easily plug in the various parts later on.

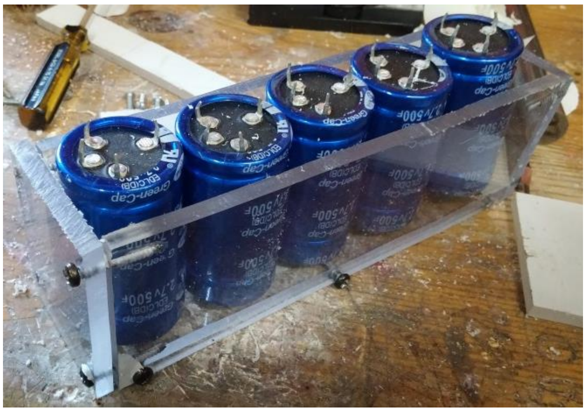


Final Casing

In order to test the functions of the Coilgun, I needed a robust shell to contain all of the components. It would not be adequate to simply test the system laid out on a table, because this would be very dangerous. For this reason I decided to build the final casing of the Coilgun at this relatively early stage of the project so that I could more easily test certain functions.

Capacitor Box

I needed a shell which was extremely robust to cope with what could potentially be large amounts of recoil, large amounts of heat and huge currents. I also needed to keep the cost low, so I used some extremely tough polycarbonate sheeting because I had access to large amounts very cheaply. This material is ideal, because not only is it extremely strong (bulletproof under certain circumstances and used for riot shields) but it is also non-conductive, and cannot be magnetised. A final advantage is that its shape can actually be altered with heat. This is useful but I must be careful that the heat produced by the Coilgun is not enough to alter the shape of the shell.



Since there were so many components to consider, I had a good idea of the shape I wanted but I had to alter my designs as I went in order to compensate for changes in the circuitry or other complications. For this reason I started with simple parts whose function was clear to me.

I started by designing a box to contain the capacitors. This was a simple case of using a jigsaw to cut rectangular sections of polycarbonate and securing them together with screws and epoxy. One issue I had was that the polycarbonate was so strong that my drill would occasionally twist the heads of my screws because they couldn't penetrate into the polycarbonate. However, the solution was just a simple matter of making larger pilot holes. After the basic box shape I added a second wall that wrapped around the box for even greater strength and stability, which also increased the height of

the box and allowed me to mount the actual coil on the top.

I wired the capacitors in series according to my circuit diagram, and drilled holes in the walls allowing me to feed the wiring through.

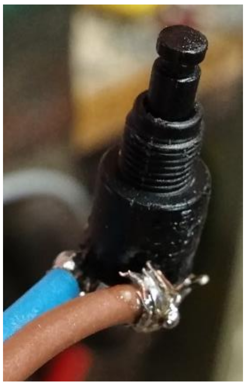
Handle, Trigger and IGBT Compartment

Building on the capacitor box, I decided that the best next step would be to make the rear section which could contain the handle, trigger, and IGBT, but critically it had to be very easy to detach and adjust in the same way that I wanted all of the parts to be. For this reason I used bolts that could be removed using an Allen key, but which were also very large and strong. Again this was simply a case of cutting shapes in polycarbonate sheet, but I also had to very carefully consider how I would fit all of the components into as small of a space as possible.

Making the handle was relatively simple but quite time consuming. I simply cut the rough shape of the handle in hardwood using a jigsaw, and rounded the edges according to what was comfortable to my hands using a variety of tools including a Stanley knife, sanding tools and the jigsaw.

The end result was not extremely well finished or highly “polished” because I lacked the time to be focussing too much on such a minor thing. Critically, it was thick and strong.

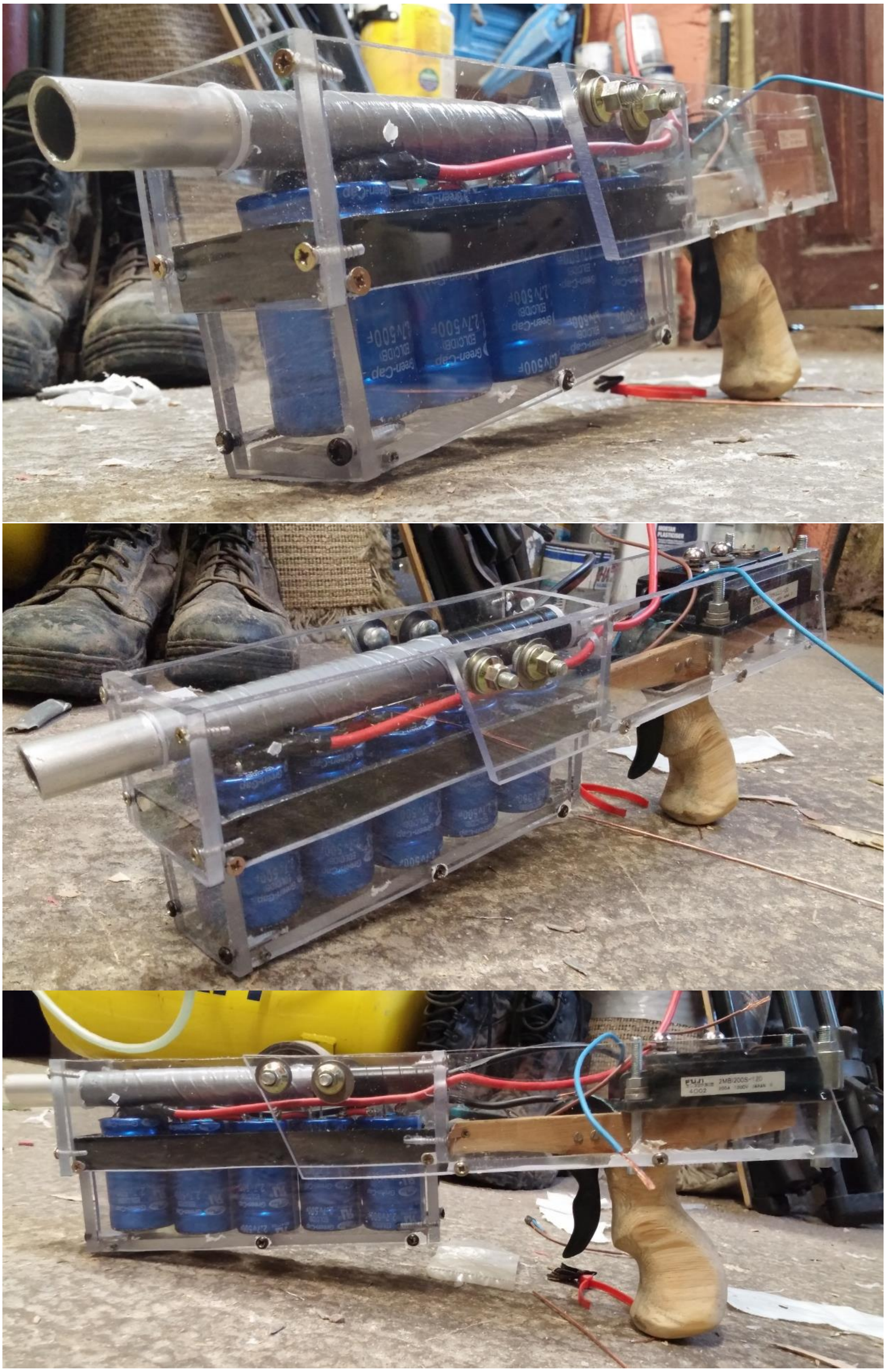
I also cut a hole in which I could mount the trigger mechanism, and gave the trigger a coat of matte black simply for aesthetic purposes, and glued a spring to the top.



Mounting all of these parts together was a very simple affair, I simply screwed the handle to the polycarbonate base and used bolts to mount the IGBT above the back of the handle. I encountered a small problem because the button in the trigger mechanism broke off. In the end this played to my advantage because I was able to very easily solder two wires to each terminal. I used a generous amount of solder in order to ensure the terminals would not touch each other, which would be very problematic, resulting in the coilgun firing at random.

Test Assembley

The two sections of the coilgun ended up joining seamlessly, and it is clear not only by the construction but by the feel of the object that it is very robust.



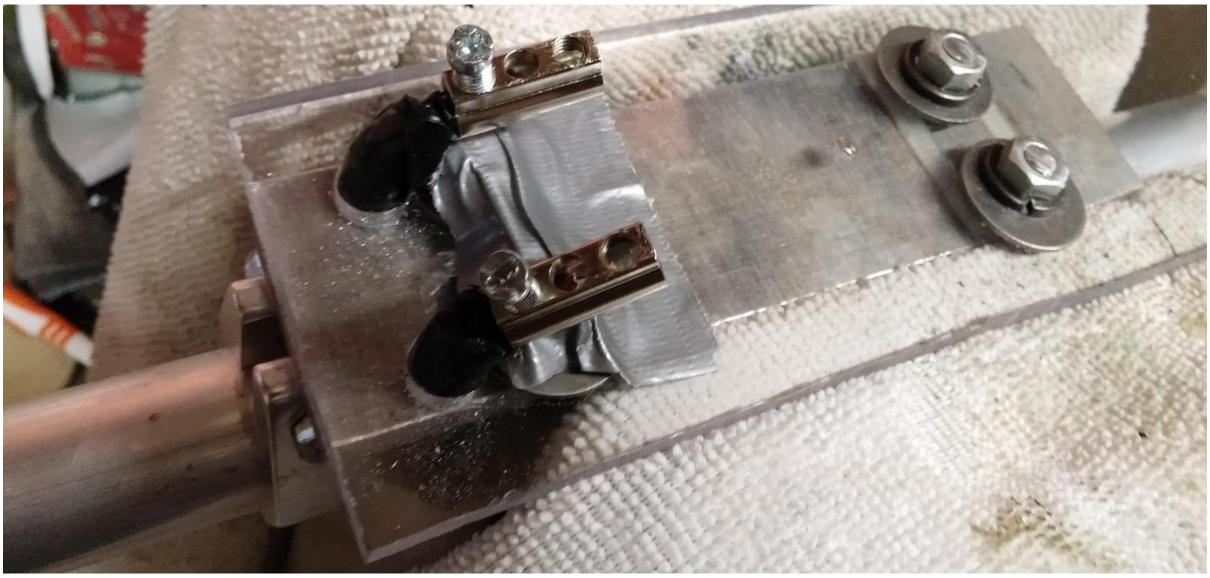
Note in the progress pictures above how I have inserted an aluminium pole through the capacitor box – this will carry the wiring for and contain the accuracy laser.

Mounting Coil

The next challenge was to find a way to mount the coil in a way that I could easily remove it should I need to, while being extremely strong to be able to withstand recoil. My first Idea was to use some very large and sturdy brass bolts to mount the coil and barrel on to a piece of polycarbonate, but this was very problematic because the bolts were so large that they wouldn't allow the barrel to be mounted on top of the capacitor box. Also, the heads of the bolts were causing a continiuty problem because they had made contact with the inner copper on the coil. This would be a huge problem because the circuit would simply short through the bolts and not the coil, likely with much less resistance, therefore huge current, which could pontentially be enough to start melting metal components of the coilgun.

I found some much smaller bolts with a rounded head, and insulated vunerable areas of the coil.

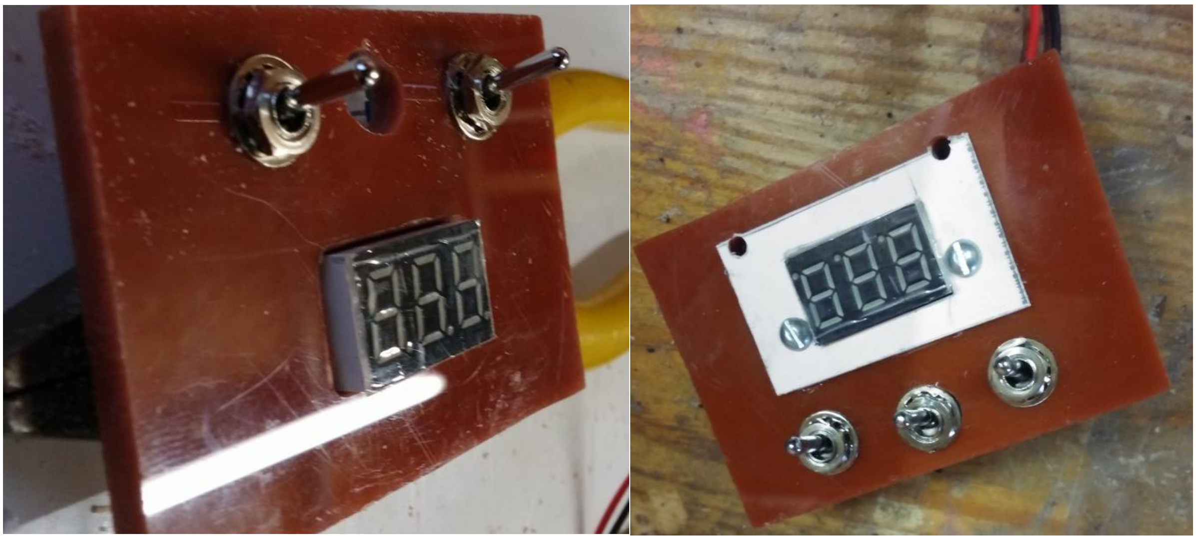
The next issue was one which I hadn't considered, and that was how I would run cable through the capacitor box and into the coil. I first tried to solder the contacts but the mass of copper was much to large to be heated adequately. I also considered using a blowtorch to solder at a higher temperature, but this would not be sensible given that the polycarbonate would probably melt. In the end I went with some heavy duty junction boxes and removed the white casing to reduce the size, and allow them to be mounted in the box taking up minimal space.



Control Panel

I tested the fit of all of the different sections, and then turned my attention to the wiring of the circuit. I wanted all of the wiring to fit discretely inside the back of the coilgun so I built a box to be mounted above the trigger box. Firstly I used some thinner, more workable acrylic to make a "control panel" which I could mount the switches and voltmeter on.

This section had to be the most easily removed and most acessible, so I tried to design it in such a way that I could easily access the wiring.



Safety Consideration

It also came to my attention at this stage that some parts may have to be mounted on the exterior of the gun, due to a lack of space inside the gun. One option would be simply to have built the casing to be much larger and more spacious, but I felt as though a smaller and more compact design was more sturdy than a much larger and cumbersome one. Fortunately since I am working with such low voltages the risk of electric shock is minimal to non existant with a few safety precautions. The highest voltage I am working with is 18V from two 9V batteries which poses no threat since the current supplied by the barreries is significantly limited by their internal resistance. I am also using capacitors charged to 12V, but this should not be enough to induce a large enough current to do any damage, as the resistance of human skin when dry is at least 10kΩ, giving a current of about 1mA, not enough to even be felt. One important safety considerqation I wil have to take however is not to operate the Coilgun with wet hands, since this lowers the skin's resistance to around 1kΩ, enough to potentially do some harm.

First Test Projectile

In order to get the Coilgun into a working state I needed a projectile which I could use, despite the fact that I intended to experiment to find the most effective Coilgun. Therefore, I made the simplest projectile that I'd planned to use, which was simply a piece of low carbon steel bar with a very slightly rounded end. I simply cut the bar using a hacksaw, then used a bench grinder to round the end and used sandpaper to neaten it up.

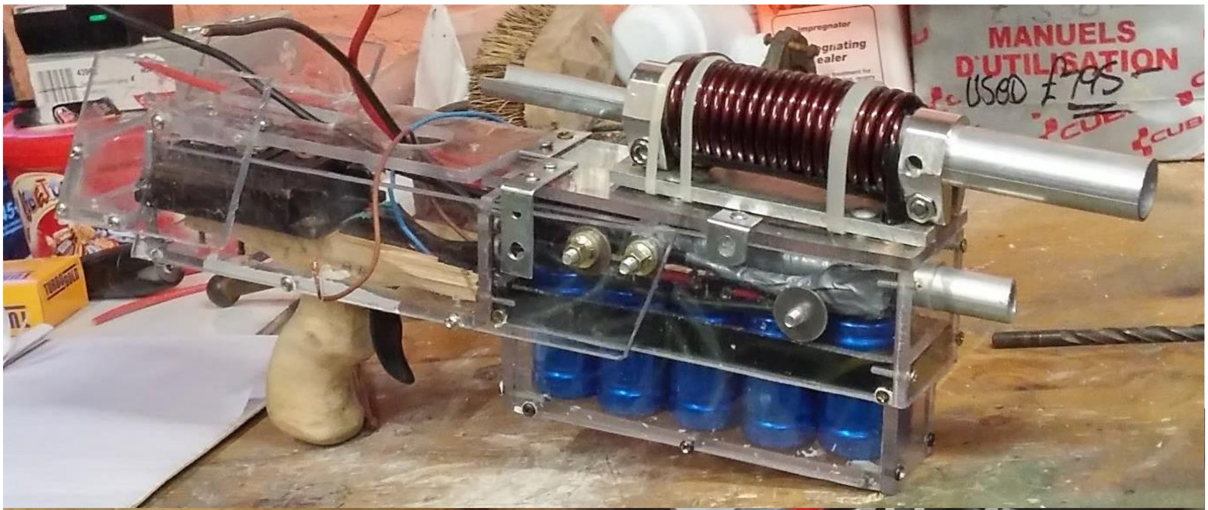

Electronics Compartment

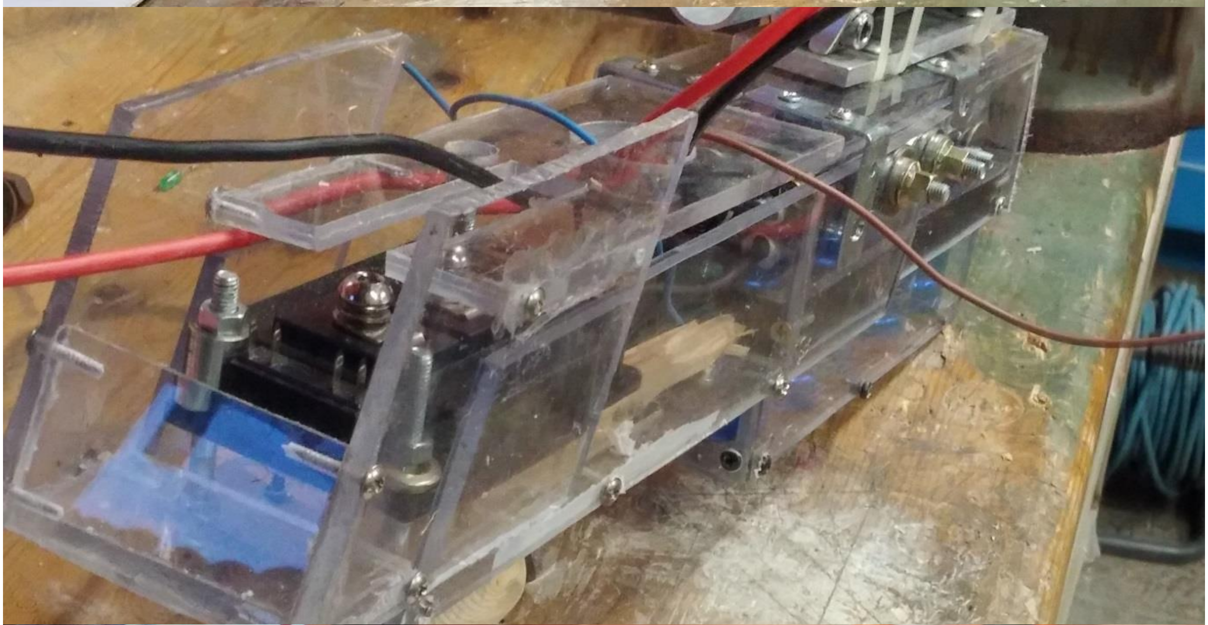
Using the same polycarbonate sheeting again I created a back section which I screwed and epoxied together a box which could easily be mounted on the back and easily removed to make wiring much easier.

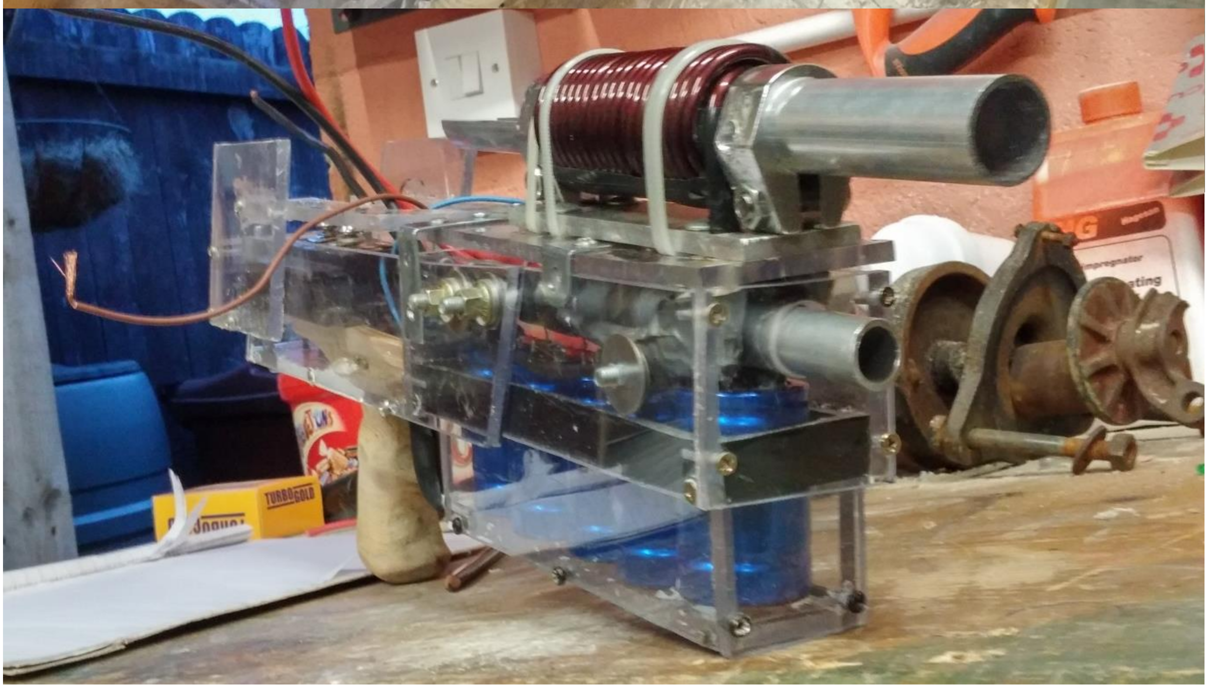
I had less trouble this time with the polycarbonate because I ensured that I drilled long enough pilot holes and held all of the parts in position with epoxy before screwing them together. This did result in a slight loss of aesthetic appeal since the epoxy ruined the clear transparent effect of the polycarbonate, but this was not at all a concern for a prototype.

Test Assembly II

I continuously test fitted all of the sections throughout the build to ensure that I hadn't made any mistakes that would result in the pieces not fitting together well.

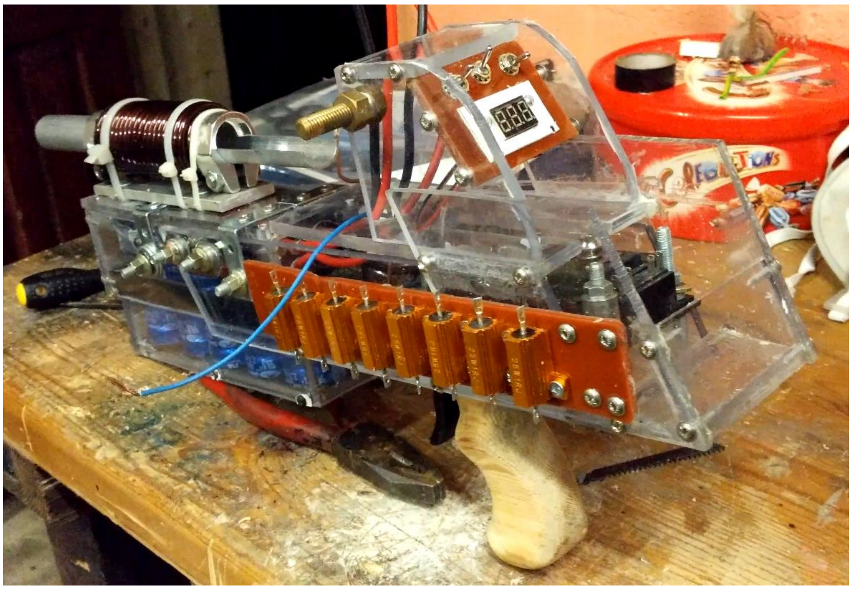






Finishing

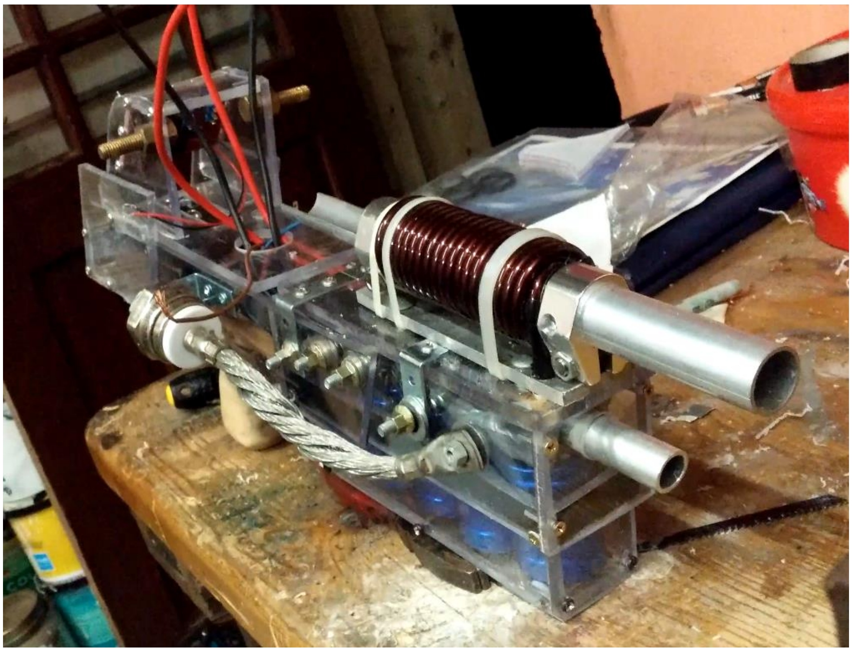
I mounted my resistor array on the rear panel, and modified a right angle bracket to support the diode. I put everything together and wired all of the pre-planned connections. It took a while to get the Coilgun to fire, as I was having problems with the switching mechanism. This turned out to be a missing connection which would link the negative side of the batteries with the negative of the capacitors. Also, I had another problem which was that the trigger could not provide enough resistance to actually make two distinct states of on and off voltage; rather the voltage was high regardless of the on/off state of the switch. Since the switch was so deeply contained under the wiring of the Coilgun, I wired a temporary connection between the capacitor and battery which I could use as a trigger while the Coilgun is in its stand.



13 Redesigning Barrel, Post Build Research

The first test fire was a colossal disappointment. The force provided by the coils was significantly less than expected.

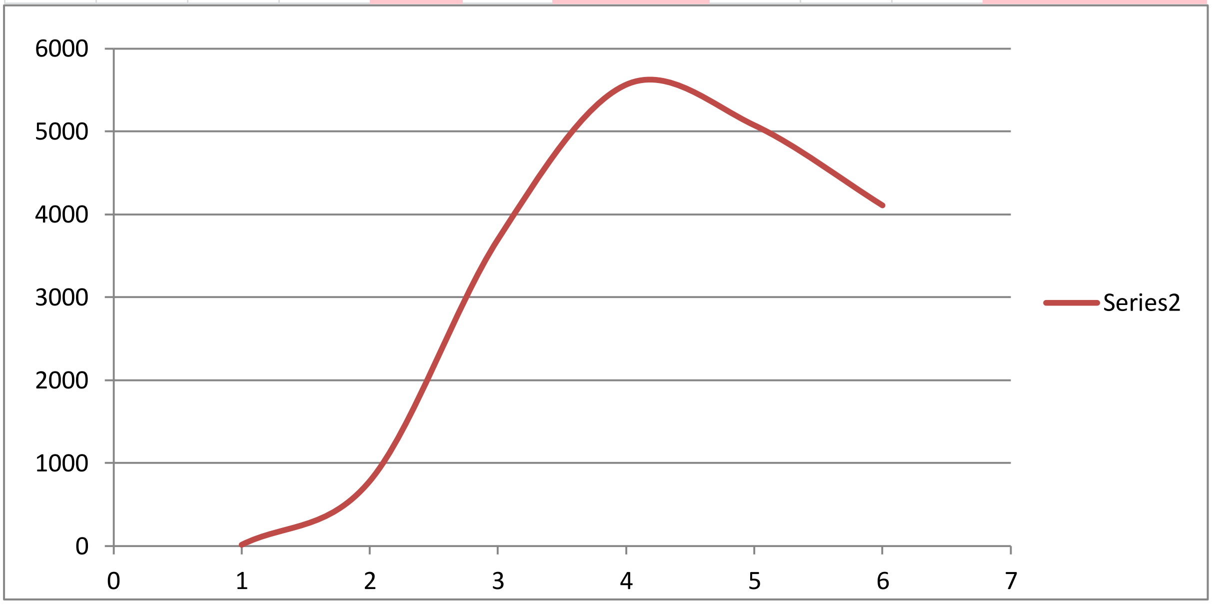
Upon reinspection of my choice of barrel and coil diameter, I realised that there was a large amount of inefficiency that I had not considered. Since the diameter of the tubing was almost an inch, the projectile also was a similar thickness and at this thickness it was around 100mm long. Given that it was steel, its mass was simply too high. The force required give the projectile a reasonable acceleration would have to be massive, and I had not fully considered this because I was more concerned with the fact that a large projectile would take advantage of all of the magnetic flux in that area.



By reducing the diameter of the barrel, I significantly increase the amount of turns I could have for the same length of wire, and the projectile that would fit in the barrel would be significantly lighter. Also, by reducing the diameter of the wire I could have even more turns. Of course I needed to balance the diameter of the wire with the resistance that a smaller diameter would have, affecting the current. In order to find the ideal diameter of current I found out the length of wire in 1kg for each diameter of wire, and found out the resistance, current, number of turns for the barrel I am currently using. I also figured out how these factors would affect the force in the force from a solenoid equation and found 4mm to have the highest coefficient of F. I also calculated all of the same values for a smaller diameter barrel to see if the same trend would appear, and I found that a thicker wire was slightly more effective for a smaller diameter barrel.

The force was largely dependent on the resistance, which was difficult to calculate. I took the resistance of the coil of the specific diameter, and added 0.03 which was the approximate resistance of the rest of the circuit. When I removed 0.03 from the values of resistance, my graph resembled an exponential slope with the thicker wire being always the better option. This is not true however, because thicker wires become extremely hard to wind, especially around the planned smaller barrel, and they would also mean that the resultant barrel is extremely wide. 5mm wire was very difficult to wind by hand around my 28mm barrel, I think that it would be almost impossible to wind it around a 16mm barrel, let alone using 6mm. Also, the further away from the core the coils are, the less effective they will be in adding to the force delivered, which is not accounted for in the equation. In both instances (25mm barrel and 16mm barrel) I found 4mm to be the most effective diameter of wire given my parameters. My current barrel has a calculated force of 1837N (which is of course an overestimate, and assuming g=2mm), and using 4mm and a 16mm barrel my projected force is 5600N. Although both figures may not be accurate, not accounting for voltage drop over the IGBT and various other areas of inefficiency, I will have a marked increase by switching to these parameters.

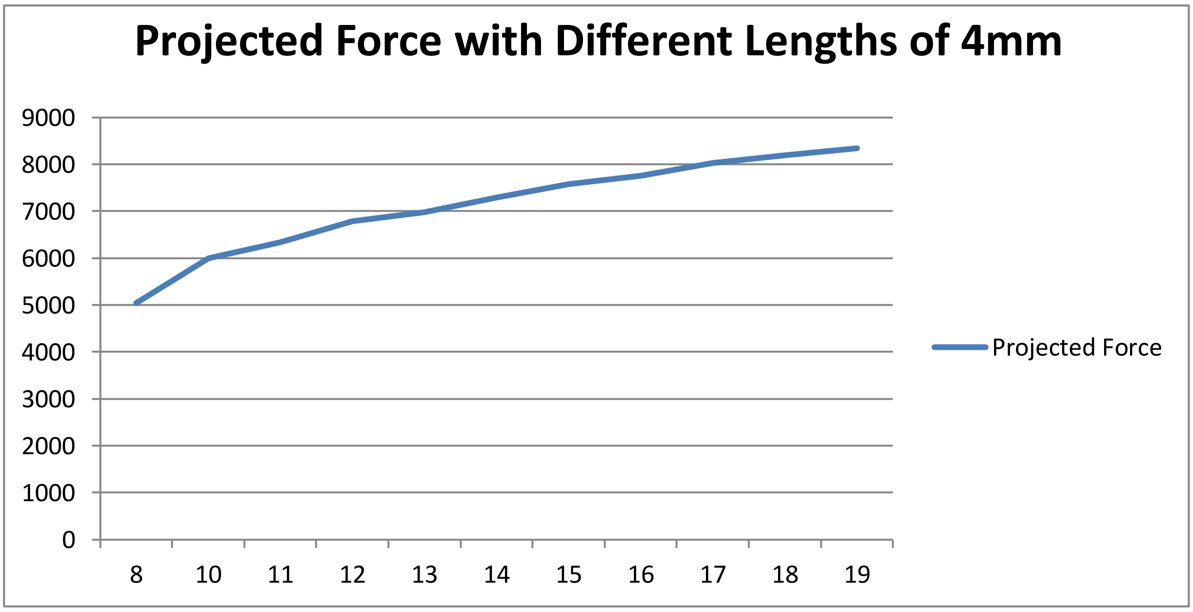
V/V	L/m	R/Ω +0.03	I/A	Diameter	n (25mm)	F (25mm)	weight/kg		n (16mm)	F (16mm)
12	572	49.8	0.240964	0.5	4600	0.15200092	1			
12	143	3.18	3.773585	1	1150	9.319458348	1		1500	15.85541118
12	35	0.22	54.54545	2	280	461.7213144	1		365	784.6023228
12	16	0.0687	174.6725	3	130	2296.49218	1		165	3699.526603
12	14.4	0.0615	195.122	3.15	116	2515.568138	1		150	4206.323061
12	12.7	0.0546	219.7802	3.55	100	3012.455579	1		126	4782.574477
12	10.2	0.0458	262.0087	3.75		0	1		105	5266.952583
12	9	0.0421	285.0356	4	73	3428.078372	1		93	5563.792427
12	7.9	0.0395	303.7975	4.25		0	1		82	5547.031148
12	7.1	0.038	315.7895	4.5		0	1		73	5325.406763
12	5.7	0.03496	343.2494	5	46	3084.338643	1		59	5073.99944
12	4	0.0324	370.3704	6	32	2502.428444	1		41	4107.990444



I also calculated different gauges available to me around 4mm, but found exactly 4mm to be the most efficient. I then began to experiment with what would happen if I used greater than or less than 1kg of wire for 4mm. What I discovered is that more wire is always preferable in my specific situation up to a cut-off point, and I could reach much higher values by having more and more windings up to a point at which the coil is to large and the coils are too far away from the core to have much effect. The cheapest wire available to me is sold by the kg, and 18m of coil would result in a barrel around 9cm wide (which is bordering on being too large to be sensibly mounted) so the best option available with my timescale and budget would be to buy 2kg and leave around 1m for wiring, giving me a projected force output which is 4.5x greater. If I make more reliable connections and lower the resistance as much as possible to increase the current, this figure may be as high as 5x or 6x the force output. Using a projectile which is 2.5x smaller in diameter, scaled down would be around 2.5^3 lighter (16x). This would mean that under exceptional circumstances, the acceleration of my projectile could be (16x6=) 96x greater. Even if the force calculation proves to be very far off the mark, reducing the barrel size will still yield an increase in acceleration of 1600% and it's very

Unlikely that using the different wire parameters will have no effect at all. I also tested other widths than 4mm, but found these to follow the trend of being inefficient compared to 4mm.

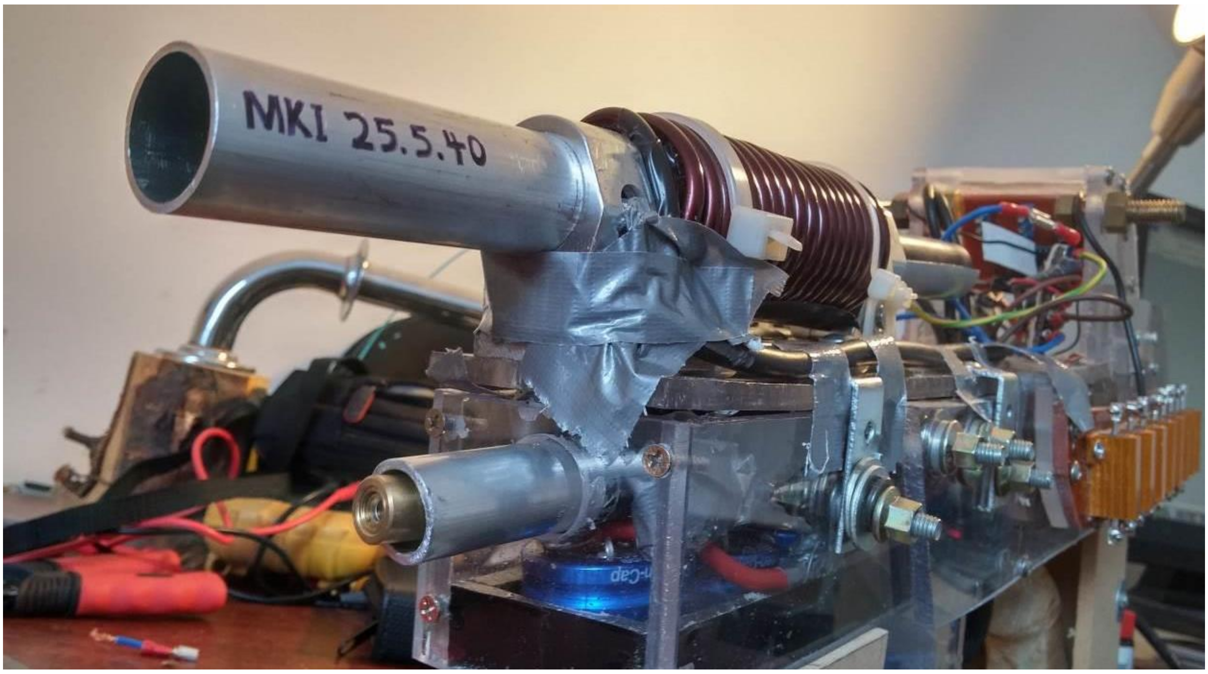
Alternate weights for 16mm						
12	8	0.04088	293.5421	4	86	5045.966255
12	10	0.0436	275.2294	4	100	5997.858766
12	11	0.04496	266.9039	4	106	6337.651278
12	12	0.04632	259.0674	4	113	6785.611624
12	13	0.04768	251.6779	4	118	6983.300565
12	14	0.04904	244.6982	4	124	7289.733657
12	15	0.0504	238.0952	4	130	7585.685714
12	16	0.05176	231.8393	4	135	7756.185999
12	17	0.05312	225.9036	4	141	8033.250434
12	18	0.05448	220.2643	4	146	8188.431633
12	19	0.05584	214.8997	4	151	8337.431695



Another improvement which could vastly increase efficiency would be to take a critical look at the switching mechanism, and where exactly the projectile is in relation to the coil when it switches off. Just looking at my barrel I can see that the projectile blocks the infrared signal just after the end of the coil, at which point the projectile is actually being pulled in the wrong direction. This means that the placement of my Infrared detection circuit is actually reducing the power of my Coilgun by a fair amount. The best option would be to have the switch inside the coil, just at the point where the projectile is in fully within the boundaries of the coil in the centre of the coil the force on the projectile is equal in all directions, so this is the ideal time to switch off the coil. To do this, I will have to leave a small gap in between the coils so that the LED and phototransistor can be inserted.

As a final improvement, I want to work on the variable “g”, length of gap between solenoid and the core. Although the maths behind the equation is clear to see, it became apparent to me exactly how much of an effect this variable has on the power during my brief experimentation with firing the MKI barrel. I originally thought it was broken because I had placed my projectile just slightly too far outside of the coil, and it wouldn’t fire. Moving it closer by about 2mm totally fixed the problem, and this made me very conscious of the gap between the coils and the projectile on the cross sectional axis, which is currently at 3mm. If I recalculate the projected force output using g=3mm the force=900N. If my gap is equal to 0.5mm (a very ambitious figure), my force would be equal to 33,000N. Again, I don’t doubt this figure is very ambitious but if the relationship between the variables is the same then I know to expect a huge increase in power by reducing this gap.

11The new barrel, MKII, is likely to massively improve the efficiency of my Coilgun.



The only other major problem with the design of my Coilgun is that I’ve opted to use low-voltage super capacitors with exceptionally high capacitance, but very low voltage capabilities. Initially I had overlooked the resistance of short lengths of wire and connections within the system, but it has become apparent that the very high current necessary is difficult to attain at such a low voltage of 12V, even though the total “on time” of the capacitors is more than adequate. If the reconstruction of the barrel does not prove to be adequate to sufficiently improve the Coilgun, then it may be necessary to look into alternate capacitors, time and budget permitting. Initially I had to choose between electrolytic or super capacitors, and I opted for super capacitors which have given me a huge advantage in the number of fires, safety, and ease of charging, but unfortunately it may become necessary to sacrifice some of these to attain a higher voltage. Of course time and money is an issue here, so I cannot say for certain at this point in the project if this is a viable option, but if it becomes necessary then higher voltage capacitors are certainly an option to look into. At any rate, I will vastly improve the quality of the connections between components to lower resistance as much as possible, and increase wire diameter where I can, and hopefully this should allow me to go to the limit of my current capabilities. It's worth remembering that my super capacitors, though low voltage, can deliver an almost unlimited amount of current provided I have a low enough resistance.

Rebuilding the Coil

With my newly calculated values, I set about rebuilding the coil for greater efficiency. Using the same method I wrapped the enamelled copper wire around the new, narrower barrel. However, before I was able to complete the barrel and integrate it into the rest of the Coilgun, a few critical components appeared to be damaged that had to do with the construction of the gun, so although I was able to re-build the barrel I was not able to mount this to the body properly. Unfortunately, when I tried to do this I found a few other components to be damaged – the infrared LED and the entire circuit board was not functioning. Conscious of my time and money restraints I decided at this point that I had enough evidence to be able to continue without rebuilding the entire model. My findings indicated that the new coil could indeed propel the projectile with more force (although not quite as much as I had expected) and I was able to record some footage of a makeshift experiment where I fired the projectile out of the barrel in a clamp.

Final Conclusion, Reflection and Analysis

The aim of my project was to produce a fully functioning handheld electromagnetic linear accelerator (Coilgun/Gauss gun), and to explore the practical applications of electromagnetic coils. This involved a large amount of research into magnetism, the principles behind solenoids and electromagnetic coils and a few other specific areas of research which contributed towards the final piece. It also involved practical engineering skills when I came to actually construct the Coilgun, including using a variety of engineering tools and requiring me to think in abstract ways in order to complete the project. The criteria I aimed to meet were:

1 Must be handheld and ergonomic
2 Must be portable and not require to be plugged into the mains constantly
3 Must be safe for reasonable use
4 Must be reasonably cheap and use easily acquired materials
5 Must be capable of accelerating a small projectile with reasonable force

I am confident that I have met most of the criteria. The Coilgun I built is handheld and ergonomic because it was designed to be held by the rear handle with one hand and a grip at the front, and it is both light enough and its weight is adequately well-distributed to be easy to hold and use. I think that the main thing that sets it apart from all of the other Coilguns that I've seen is that it is capable of being charged from any 12V DC power supply, including jump starters, car batteries, car outlets etc. making it much more portable and easy to use than anything else I've come across. This leads on to criteria 3, which is that it is totally safe for reasonable use. Obviously it is designed to fire projectiles so it can never be considered completely "safe" but by using a 12V capacitor bank I was able to completely avoid any hazards arising from risk of electrocution. The only thing that could make it unsafe is the amount of heat it is capable of generating, but within reasonable use it cannot fire enough times on one full charge to get very hot at all, as I deciphered in my calculations earlier on, but this is also evident through the fact that on inspection no parts were hot. Number 4 was more for my own ease of completing the project within my limitations, but I have kept to a reasonably low budget. Finally, my Coilgun is capable of accelerating a projectile, and although the force it is ejected with is less than I would have liked, it is a proof of concept and I know that I could vastly improve its power should I have the time and money to do so.

During this project I learned more than I could have expected, with knowledge from all corners of science and engineering including magnetism, CAD design, prototyping methods, materials science, solenoids, a broad range of new electronics knowledge and ballistics. My practical skills were vastly improved and I learned the importance of precision and knowing about when I need a close tolerance or a loose one, and how my measurements should be adapted to fit this.

As stated earlier, I was not totally satisfied with the power of the Coilgun in the end. Unfortunately I think that the only realistic solution would be to use high voltage electrolytic capacitors and have them charge up from mains electricity. This would take away the main point about how my model can run using a 12V DC supply however, so with unlimited time and money I would have drastically altered the Coilgun's design to use much thicker wire in all sections and have them well soldered in all areas to reduce the resistance to a point where I could get much higher currents. I would also select a more expensive IGBT capable of switching higher currents with a smaller voltage drop and lower resistance. I would also make a more robust, tougher and lighter body, perhaps using welded aluminium sheeting (although this could bring about issues with shorting if any wire were to touch the casing.) measured and constructed to a much higher degree of accuracy.

In the future I'd like to thoroughly test the limits of what can be achieved by Coilguns running on easily usable power sources. One idea I considered was if it would be possible to completely forgo using capacitors at all, and instead step up mains electricity to a huge voltage and experiment by trying to build some kind of super high voltage switching device, perhaps in the form of a heavy duty relay which splits to reduce current. I would also like to test a variety of ways in which solenoids and other magnetic phenomena can be applied to other applications, such as electric motors which interest me greatly. As far as the engineering and development side of the project goes I would like to continue to experiment with different construction methods and perhaps build a Coilgun with a far more robust casing, even using aluminium welded together as mentioned earlier. There are a wide variety of different techniques and materials I'd like to work with.