UNIVERSITY OF
WATERLOO

Development of an Electromagnetic Projectile Device

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Summary

An eight-stage electromagnetic projectile device is developed for the purpose of realizing a video that illuminates the design and production process, as well as the finished product. The resulting video on YouTube was viewed 1.1 million times within a week of posting.

This type of device is commonly referred to as a “coilgun” because of its use of solenoids wound about the barrel and is not to be confused with a railgun. Powered by a 24-cell lithium ion battery pack, the device can propel steel projectiles (12mm diameter, 70 mm long, and with a mass of 61g) at 27.5 m/s and achieves approximately 5% energy efficiency.

The completed device was found to be effective in achieving the spectacular destruction of glass bottles and shattering a 9.5 mm thick sheet of tempered glass. The gun satisfies Canadian criteria for not being a firearm.

A visually interesting mechanical design for the gun is produced that does not compromise operator safety while still allowing operability and maintainability. The design accommodates operation of the device as a shoulder-fired weapon. The final assembled device weighs 15kg, making it ill-suited to freehand operation.

Metal-oxide-semiconductor-field-effect-transistors (MOSFETs) are used for control of the electromagnetic elements. The current levels and timing are optimized to achieve optimal performance. Printed circuit boards (PCBs) are designed for the control systems and power systems. A safety system was implemented to prevent unintended firing. A method for determining optimal timing parameters was developed and utilized to maximize muzzle velocity.

Further development will focus on increasing projectile velocity, improving feedback reliability, stabilizing the projectile, decreasing the gun’s weight, and adding magazine fed repeating action. There exist significant opportunities to modify the design to improve performance.

1 Introduction:

Hacksmith Entertainment is an engineering company that produces one-off prototypes of novel devices, typically inspired by fictional devices, such as those from the Marvel film series. In March of 2019, a contract with Wargaming Group Limited was secured requiring the publishing of a video by Hackmsith Entertainment detailing the design, production, and testing of a coilgun. The primary business purpose of this undertaking is to make a video to be posted on the Hacksmith Entertainment YouTube channel.

A coilgun propels a projectile by means of one or more high strength hollow core solenoids that exert a electromagnetic force on the projectile, moving the projectile towards the center of the solenoid. The solenoid's magnetic field is switched off when the projectile reaches the solenoid center, permitting the projectile to continue forward under its own momentum. Several of these solenoids, referred to as stages, are placed in linear succession such that earlier stages direct the projectile into later stages, resulting in acceleration of the projectile.

1.1 Objective

The intended outcome of this project is to produce a visually interesting coilgun that propels a ferrous projectile capable of destroying targets in a visually and audibly interesting way.

1.2 Constraints and Criteria

1.2.1 Constraints

The device was required to:

- Not be a firearm under Canadian law. This is achieved by either
    - not exceeding a muzzle velocity of 152.4 m/s, or
    - not exceeding a muzzle energy of 5.7J [1]
- Look cool on video (i.e.: visually and audibly interesting).
- Be capable of repeated, consistent firing without significant manual work between shots.
- Not pose a safety risk to the operator
- Achieve electrical isolation between user controls and any high-voltage circuitry.
- Have all electrical inputs fuse protected to prevent battery fires.
- Not exceed the maximum safe burst discharge current rating of the battery system.

- Have a weight low enough that a single person can pick up, hold, and point the assembled device.
- Be operable in a rifle-like manner.
- Be maintainable, and permit replacement of all electrical components after non-destructive disassembly.

Several factors were prescribed arbitrarily during the design process:

- The device will use four Basher 6S 4000mAhr 60C lithium ion battery packs wired in series, providing 100V and permitting a maximum safe discharge current of 360A for a 10s burst [2]
- The device must be able to fire 12mm diameter, 70mm long steel dowel pins.
- Switching devices should be in TO-263 “D^2PAK” semiconductor package.

1.2.2 Criteria

- Cost should be minimized.
- Ease of assembly should prevail over cost or weight reductions, as all assembly work is done manually in a modest shop.
- All other things being equal, a higher muzzle velocity is preferred, provided it does not exceed the 152.4 m/s legal limit.

2 Electrical Development

In its simplest form, a coilgun consists of a hollow solenoid, a timer, a switch, a power supply, and a projectile [3]. The solenoid's magnetic field is switched on when the projectile is behind the solenoid, producing a force on the projectile, and instantaneously turned off when the projectile arrives at the centre point of the solenoid.

The electrical system is required to switch the coil, reduce the coil current without sustaining damage, and time these actions optimally. These electronics must be supplied with power to permit their operation. The coils should be designed to make optimal use of the available power.

2.1 Stage count

The projectile kinetic energy, or muzzle energy, of a coilgun is linearly proportional in the ideal case to the number of stages on the device. Attempts to calculate a predicted muzzle energy from a single stage were not successful. The stage count was therefore determined as the largest number of stages that would fit within the available barrel length.

As part of the agreement with the project's sponsor, the coilgun was to be mounted to a plastic replica of a battleship to upgrade the onboard armaments. The refitted vessel was christened *Boaty McGunface* and is seen in Figure 1. The length of the boat then became the primary factor in determining stage count.

Figure 1 Boaty McGunFace with coilgun attached.

It was considered unreasonable to have the barrel assembly of the coilgun dramatically exceed the size of the battleship. The number of stages was then determined by dividing the length of the boat (along the coilgun barrel axis) by the projectile length plus 12.35mm for non-coil components, including separators and assembly aids. The result was that eight stages would fit, so eight stages would be built. The control electronics were designed to accommodate twelve stages, permitting future expansion.

2.2 Power electronics

2.2.1 High current switch

The prescribed semiconductor packaging precludes use of electromechanical switches, leaving a short list of methods for controlling the current. The available semiconductor devices for switching of high current DC are bipolar junction transistors (BJTs), metal-oxide semiconductor field effect transistors (MOSFETs), and insulated gate bipolar transistors (IGBTs).

At the expected operating voltage of 100V, plus a wide margin of safety, the switching device would require a minimum breakdown voltage of 150V between the source and drain, in the case of the MOSFET, and between the emitter and collector, in the case of the BJT and IGBT.

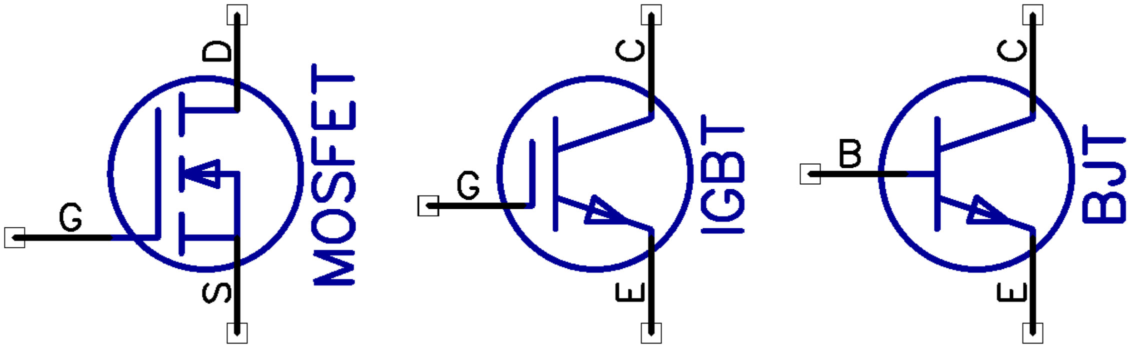

Figure 2 Switching transistor symbols with abbreviated pin labels

MOSFETs provide a resistance between their drain and source nodes that varies with the voltage between their gate and source nodes. BJTs provide an effectively constant voltage drop along the current path, which at high currents can result in less power dissipation than an ohmic voltage drop like in a MOSFET. BJTs require a current to be driven through their base pin to permit multiple times that current to be transmitted through their collector. IGBTs combine the benefits of BJTs and MOSFETs but come with a dramatically raised cost for a given current capacity. They are driven with a capacitive gate as opposed to a drive current and feature an effectively constant voltage drop across the current conduction path.

At the currents expected in this device, MOSFETs were found to be the optimal device in this package and voltage rating. The highest current capacity device available was the Infineon Technologies IRFS4115TRLPBF [4].

2.2.2 Flyback suppression

With the power transistors chosen, an appropriate means of flyback suppression is the next concern. In general, the goal of flyback suppression is to reduce the magnitude of the voltage produced when switching off the power supply to an inductive load, in this case an accelerator coil. This voltage is referred to as inductive kick [5]. At the currents involved in a coilgun, without flyback suppression, the voltage on the high side of the switch will destroy the switch, rendering the coilgun inoperable, and possibly set the device on fire. Adequate flyback suppression is achieved by providing a current path parallel to the inductive load that permits current to continue to travel through the load after the driving transistor has been switched off. Typically, a power diode installed antiparallel to the load is used to accomplish this, as shown in Figure 3, although certain other methods are preferable under different circumstances [6].

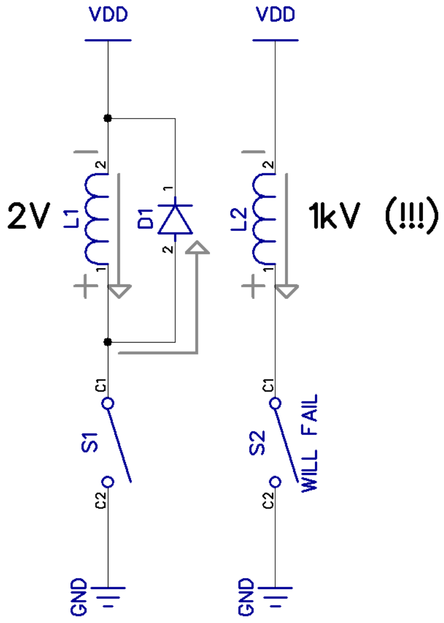

Figure 3 Inductive load flyback suppression. Unsuppressed inductor L2 will produce a voltage high enough to drive current through S2 when the switch is opened. Values are representative.

Quickly reducing the current to zero benefits the overall performance of the coilgun to a small degree. Ideally, the coil magnetic field strength would become zero the instant the coil switch is turned off. However, this is not possible because coils are inductive, prohibiting an instant change in current, and subsequently prohibiting an instant change in their magnetic field strength. Faster flyback suppression will make for better performance, as the coil can be more quickly shut off at the optimal time, reducing the amount of pull-back from the coil as the projectile travels past the coil's midpoint while the field is still active.

The length of this flyback current is reduced by introducing a resistor in series with the diode to produce a voltage proportional to the current. Provisions were made in the electrical design, seen in Figure 4, to accept a power resistor, but it was replaced with a zero-ohm link in production due to complications that arose in practice (the power resistors failed explosively due to the immense power dissipation).

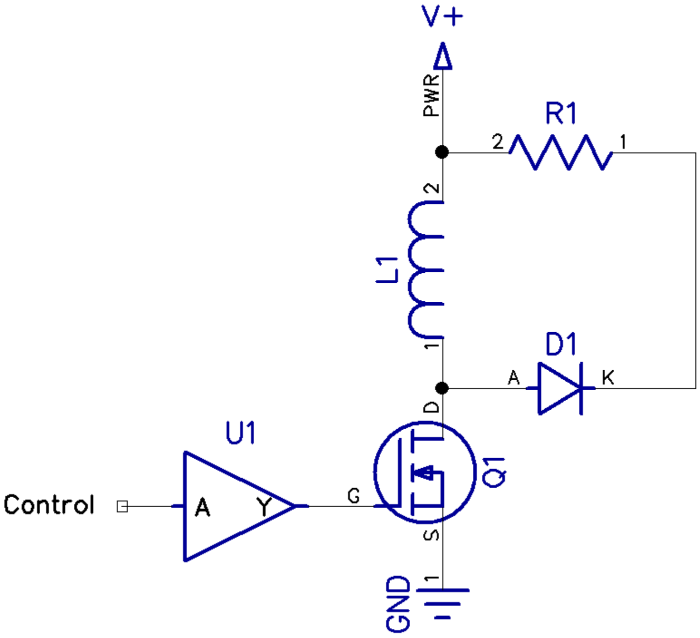

Figure 4 Complete power electronics schematic

At the expected current levels, a diode antiparallel to the coil will sufficiently reduce the flyback voltage to the supply voltage given a reasonable factor of safety on the MOSFET's breakdown voltage. As a single component flyback solution, the Infineon Technologies IDP45E60XKSA1 diode was found to be adequate, and safe to operate at up to 162 amperes in a 10ms half-sinusoidal pulse [7]. The expected current pulse is higher than 162A but shorter. Testing proved this device to be effective at the current levels encountered in practice.

2.2.3 Switch driving

To control a MOSFET at high powers, a gate voltage in excess of typical microcontroller operating voltages is required. 15V is typically the maximum recommended gate voltage. A gate driver circuit is used to permit control of the MOSFET by the microcontroller. This circuit is available as a single component for ease of assembly.

To achieve electrical isolation between operator-facing components and high-voltage components, an isolating gate driver was selected. ON Semiconductor's FOD3182 in a ceramic, eight-pin, dual-inline package (DIP-8) was chosen for its low cost, ready availability, and suitable performance [8]. This device is driven by current control on the input side. The driver side connects the output to the ground supply rail unless a certain current is passed through the input side, in which case it connects the output to the positive voltage supply rail. This permits easy driving of the MOSFET's gate at a higher voltage greater than the operating voltage of the control circuitry.

A 15V TDK-Lambda PAH50S48-15/V power supply was chosen for its availability and ruggedness. A printed circuit board was designed to hold the power supply, jumpers for control inputs, a 2200 µF output smoothing capacitor as per the instructions from TDK-Lambda [9], and terminals for the power input and output. The power supply PCB was connected via ribbon cable to a header on each stage control PCB. The power supply received 50V from a fuse protected line connected to the midpoint of the battery pack.

2.2.4 Power transmission and termination

The circuit boards responsible for handling the current through the coils require a source of current. Several options were considered for connecting the PCBs to the battery pack: soldered wires, screw terminals, and busbars. The inherent possibility (and repeatedly realized risk) of having to replace a damaged PCB immediately reduces the appeal of soldered wires for inter-stage connection of the high current supply. Terminal-based solutions would require intricately terminated wires to branch off and reach all eight stages and might dramatically complicate assembly and maintenance of the device. Busbars permit easy disconnection from the power supply, and solve the issue of mounting the PCBs, as the busbars form an adequately durable connection to the chassis.

Large exposed pads with two M3 screw clearance holes 40mm apart were designed as PCB elements. The PCB would be screwed directly onto the busbars through these holes, forcing surface contact between the PCB pad and the exposed copper surface of the busbar. To connect the battery leads, threaded holes are drilled and tapped in the busbar at one end to permit screwing of wire lugs onto the copper.

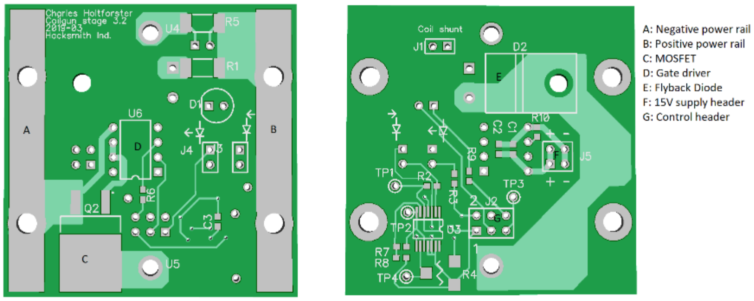

Figure 5 Power switch board annotated rendering

2.3 Coil design

The goal in coil design is to achieve the largest possible impulse on the projectile. This is related to the force on the ferromagnetic projectile, which is in turn related to the coil's magnetic field strength, measured in Teslas. The field strength, B, of a solenoid is given in Equation 1 [10]

Equation 1 Long solenoid approximation for field strength

$$B = \mu \frac{n}{L} I$$

where B is magnetic field strength in Teslas, μ is the magnetic permeability of the system, I is the coil current in amperes, n is the number of turns, and L is the length of the solenoid in metres.

For a fixed current, the largest force is therefore achieved as the number of turns goes to infinity or as the length goes to zero. Unfortunately, the current is not fixed, but the voltage is. This complicates matters dramatically, as increasing the number of turns lengthens the wire in solenoid, increasing its resistance. This reduces the current term faster than it increases the turns term, lowering the magnetic field strength with an increasing number of turns for a given gauge of wire.

This relationship suggests that a single turn of wire would maximize the field strength for a fixed voltage. This would also maximize the solenoid current, raising it above the 360A limit on the batteries. A suitable compromise was required.

Furthermore, the resistivity of wire varies with its cross-sectional area. This also affects the number of turns that can be wound per unit length of the solenoid. A hundred turns of a very thin wire will have a much higher resistance than a hundred turns of a thicker wire, and so the thicker wire will have a higher magnetic field strength.

To ease computation, a piece of software was written to calculate the resistance and field strength per amp of solenoids with a given diameter of wire, resistivity of wire, diameter of inner mandrel, outer diameter, and length. A table of options was produced, considering the availability of materials and the current handling capability of the switches selected previously. The full table of considered options is available in Appendix A.

14 American Wire Gauge (AWG), 65mm outer-diameter coils were selected as the optimal choice for the initial stage. Given some conservative estimates for coil timing, smaller coils were specified for later stages. The anticipated nominal diameters for all eight stages are given in

Table 1.

Table 1 Provisional coil diameters by stage

Stage #	Expected on time [μs]	Maximum current for IRFS4115TRLPBF [A]	Diameter [mm]	Expected current [A]
1	10,500	190	65	137
2	2,100	200	60	167
3	1,500	200	60	167
4	1,200	200	60	167
5	1,000	280	55	185
6	1,000	280	55	185
7	1,000	280	50	233
8	1,000	280	50	233

Due to complications in assembly, the actual coil currents always exceeded the expected current. This was considered in selecting the coil diameter.

2.4 Feedback

It was originally planned to have the device operate with closed loop feedback. An infrared-filtered photodiode was placed radial to the barrel, opposite an infrared light emitting diode (LED), so that the projectile passing between the two devices would produce a measurable signal. A transresistance amplifier and comparator circuit was implemented on each stage controller to permit the use of this feedback system. A potentiometer was added as the reference for the comparator, allowing for user-adjusted sensitivity for each stage. The output of the comparator is returned to the main control board through the bus.

2.5 Control electronics

A Teensy 3.5 microcontroller breakout board, seen in Figure 6, was used as the basis for the controller board. The isolating gate drivers on the high-current switches were driven via open-collector outputs connected to individual digital output pins on the microcontroller. 22nF capacitors were added in parallel with all inputs to the controller board to reduce the risk of electrostatic damage to the board circuitry.

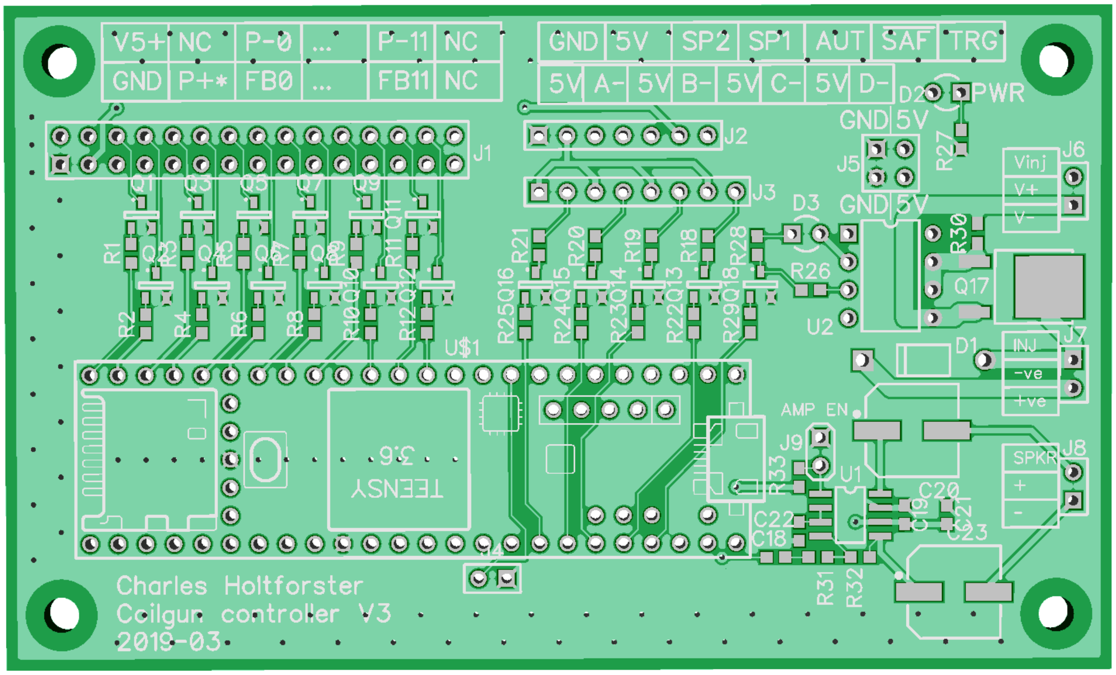

Figure 6 Rendering of unpopulated controller board

The gate drivers' common positive inputs were connected to the board through the shared wiring harness. This signal was connected directly to the "armed" signal from the operator controls, ensuring that the gate drivers were incapable of activation if the "armed" switch was in the off position. The "fire" switch connected a digital input pin directly to the 5V rail.

To accommodate planned future design enhancements, several unused features were added to the control board. To permit autoloading, an optically isolated MOSFET switch is included on the controller PCB, along with connections for a high voltage supply and an arbitrary load. To permit inclusion of sound effects, a power amplifier connected to a digital-to-analog converter pin on the microcontroller was furnished. Support for four extra solenoid stages was included, for a total of twelve stages.

3 Mechanical Design

3.1 Considerations

3.1.1 Safety and operability

As laid out in the design requirements, the coilgun must be comfortably operable. It goes without saying that safely operable follows from that requirement. Potential hazards to the operator are both mechanical and electrical.

The primary mechanical hazard is the same mechanical hazard inherent to all guns: obstructing the muzzle will result in personal injury. The combined weight and length of the constructed system rendered this hazard irrelevant, as it is impractical for the operator to put their hand in front of the muzzle while holding the gun. There are no other moving parts that present a mechanical safety hazard.

The electrical safety hazard is posed by the presence of high voltage within the system when it is connected to power. Efforts are made to keep high voltage supplies isolated from user controls and contact surfaces. To this end, the device’s barrel must maintain straightness, the power delivery busbars must be held rigid and electrically insulated from the operator, and all other PCBs must be mounted securely and insulated from the chassis.

3.1.2 Appearance

After safety, the primary consideration is the requirement that the completed device look cool on video. To this end, standard firearm accessory rails [11] should be provided such that optics can be mounted along the topmost surface of the gun, and a consistent visual feel should be adopted for the entire assembly.

Images from video games, movies, television shows, and firearms literature were referenced to establish a plan for a look and feel to the device. Chief among the referenced materials were developer previews of the fictional “MAGRAIL” from Tripwire Interactive’s *Killing Floor 2* (Figure 7), and marketing material for DesertTech’s MDR rifle (Figure 8).

Figure 7 Killing Floor 2's MAGRAIL/Railgun weapon, rendered in game. Tripwire Interactive. Available http://media.tripwirecdn.com/052616/railgun.jpg

Figure 8 DeserTech MDR. Available https://deserttech.com/images/mdr_landing/mdr-top-image.png

Beyond just looking cool, the coilgun must be operable in a rifle-like manner. This informs many factors of the mechanical design. There must be provisions for holding the coilgun with the operator’s right hand such that a trigger and safety are readily operated with that hand, while the operator’s left hand can provide support and stabilization to the barrel of the gun. The gun needs a stock to provide stabilization.

Several key features were directly inspired by the depictions previously mentioned. The widened flat section atop the stock was used as a cheek rest. Having the stock double as a receiver, as per the MDR and every other "bullpup" style rifle, was managed to a certain degree. The stock is slightly taller than the barrel assembly, as shown in Figure 9, to allude to firearms designs across fiction and reality, increase the height of the stock for operator comfort, and because the electronics would otherwise not have fit inside.

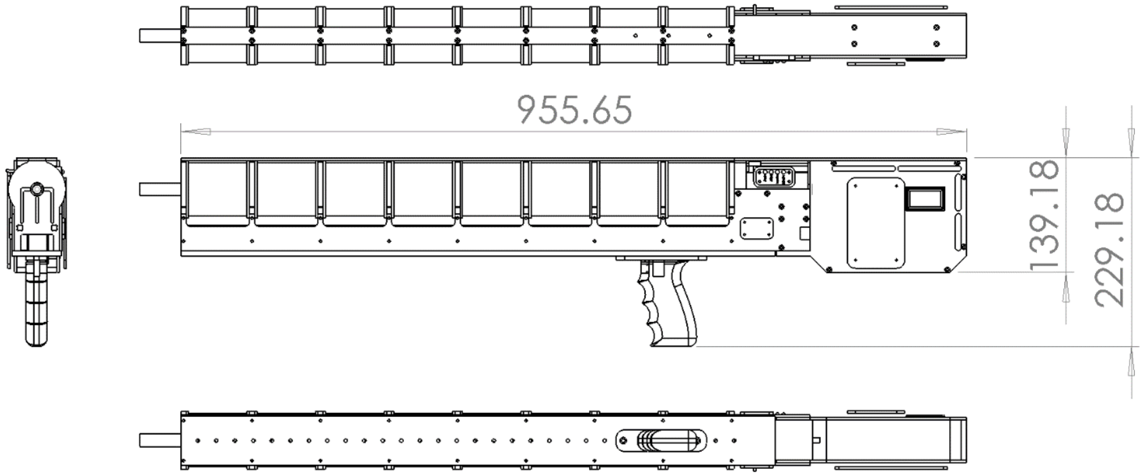

Figure 9 Drawing of complete assembly of coilgun without optics or upper rail. Dimensions in millimetres.

3.1.3 Tools and materials

The accessibility, convenience, and consistency of computer-numerical-control (CNC) plasma cut sheet steel in the Hacksmith Entertainment workshop made for an attractive method of construction. It was chosen as the production method for the outer frame of the gun. To avoid having to rely on the dimensional accuracy of plasma cut parts, and to preserve utmost maintainability, the steel components were assembled with machine screws rather than fusion welding or adhesives.

Several components would have been exceedingly difficult to manufacture with traditional machining processes and were therefore 3D printed. Laser cut acrylic was used to form clear removeable covers over hazardous components, while maintaining serviceability.

To attain a consistent and visually distinct surface finish on steel parts, a rotary drum surface restoration tool was used to produce a sanded finish. This sanded finish was sprayed with high gloss clear coat to enhance the finish and provide protection during assembly and handling.

3.2 Design

For ease of assembly and design, the coilgun is split into three major subassemblies: barrel, loading mechanism, and stock. The barrel assembly contains the barrel, the coil stages, the busbars, and the feedback optics. The loading mechanism is a self-contained module that advances the next projectile to be fired to a consistent position in the barrel. The stock contains all ancillary electronics. The grip, and sight rail were considered separately from these subassemblies.

3.2.1 Barrel assembly

The barrel assembly contains the busbars, inner barrel, and coils parallel and stationary. This is achieved using milled polycarbonate plates (referred to as “separators”), to both keep the barrel and busbars from moving relative to the frame, and to keep the coils from shifting. These separators were themselves held in position by the outer frame of the assembly, seen in Figure 10, composed of plasma cut steel plates on the top and sides for rigidity, and an acrylic cover on the bottom to prevent accidental operator contact with the busbars.

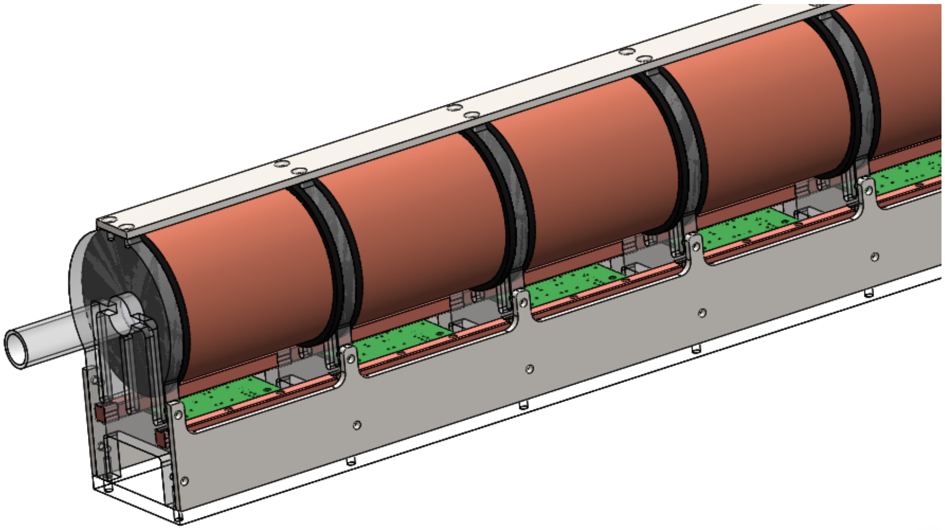

Figure 10 Representative portion of barrel subassembly showing barrel, separators, top plate, side plates, and coils.

The separators are secured to the top and side plates with M3x0.5 socket head flat screws, while the bottom cover is secured with M3x0.5 socket head cap screws to the separators. The busbars are retained by a friction fit with the busbars. The use of adhesives or fasteners was deemed unnecessary as insertion of the busbars required a hammer. The busbar holes were rounded at the corners to permit machining with a CNC mill.

Blind cuts are made in the front face of each separator to permit placement of the feedback optoelectronics, and to permit one lead of the solenoid to reach the controller PCB. These features are visible in Figure 11.

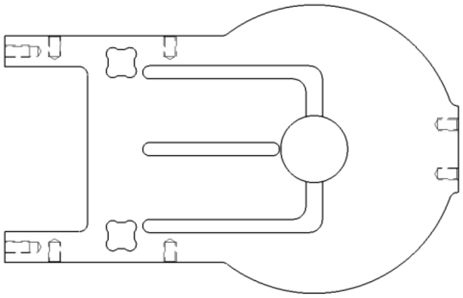

Figure 11 Stage seperator model showing all features. Component is milled from 6mm polycarbonate.

The side rails feature holes every 82.35mm for screwing into the stage separators. The upper holes in this pattern are mounted on small tabs that extend above the rest of the profile. This was solely a cosmetic decision. To permit assembly of the entire gun, a large tab with screw holes was added to the back ends of the rails, see Figure 12. A hole was added to this tab to permit access to the screw terminals on the busbars without disassembling the gun. This necessitated the addition of a removable acrylic cover for these holes.

The rectangular cut out on the back edge of the barrel side plate was introduced during early design revisions to accommodate a magazine release lever. This feature was inadvertently retained despite the design having abandoned magazine-fed operation.

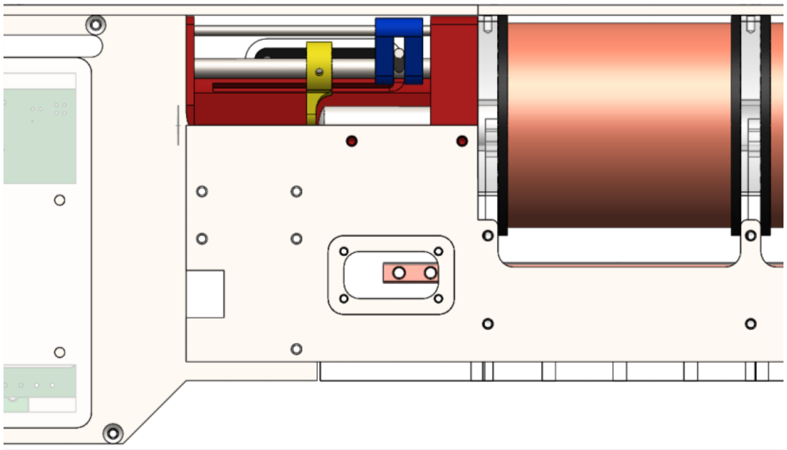

Figure 12 Connection of stock, loading mechanism, and barrel assembly. Fasteners and countersinks not visible. Colours added for clarity.

3.2.2 Loading mechanism

To fire a gun more than once, a method must exist for loading a projectile into the barrel. Provisions for an autoloading mechanism was designed into the control electronics but went unused. The coilgun was then to be a single-shot style of gun, where each shot would be loaded by hand into the barrel of the gun before being fired.

The loading mechanism must reliably push the inserted projectile into the barrel of the gun to a consistent depth. The mechanism should then keep the projectile situated until it is manually moved.

Borrowing from firearm design, a system resembling in form and function a bolt-action rifle was devised. The bolt refers to the assembly moved along the barrel axis to move the projectile forward, then rotated to lock the bolt and prevent backward motion of the projectile. A magnet was used to prevent forward motion.

This component was 3D printed from Polyethylene Terephthalate Glycol (PETG) plastic, and hand adjusted to permit smooth motion with all of the sliding components. The full bolt assembly is shown in Figure 13. The body has two primary axes: the bore axis, about which the barrel and projectile are centered, and the bolt axis, about which the carriage rod is mounted.

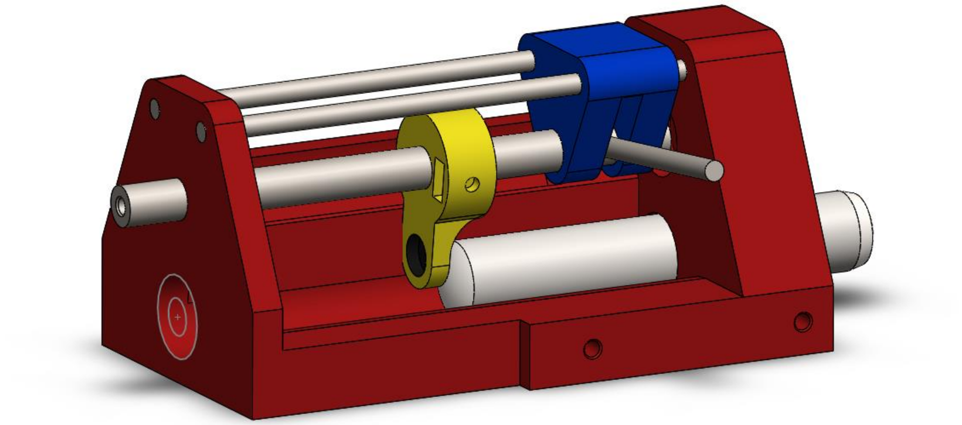

Figure 13 Breech block assembly, with carriage shown in blue, bolt face shown in yellow, and body shown in red. The projectile extends out the right side. The two pins flush with the left face are the sliders

A setscrew holds the bolt face onto the rod attached to the bolt carriage, permitting adjustment of the depth to which the projectile is moved. The crosspin in the carriage rod protrudes through the rod and into the track cut in the curved face in the body behind the rod. The same crosspin functions as a bolt lever for the gun, permitting the user to unlock the bolt from the body and move it backwards to permit loading. The front face of the loading body has a round indent that mates to the end of the barrel, ensuring concentricity.

3.2.3 Stock assembly

The stock, visible in Figure 14, must contain the 15V power supply, the 5V power supply, the main control PCB, and a voltmeter. It also must function as a stock for the rifle's operation to permit bracing of the device. The use of plasma cut sheet steel ensured a consistent visual styling between the barrel and the stock.

Milled plastic spacers were used to provide a dimensionally accurate spacing between the two sides of the stock to permit their attachment onto the back of the barrel assembly, as well as to prevent the operator from touching any internal electrical contacts.

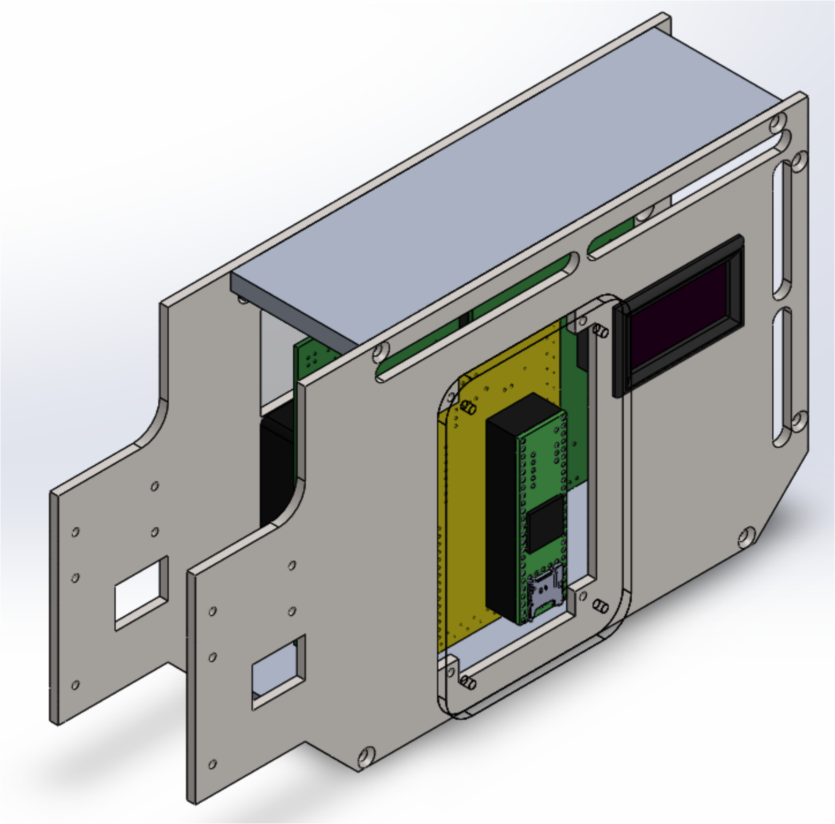

Figure 14 The stock assembly with ancillary electronics installed

The controller PCB was mounted on the left plate behind an opening to permit connecting wiring and programming of the microcontroller. The space to the aft of this panel was used to mount a digital panel-mount voltmeter. The right plate retained both the 15V and 5V power supplies and doubled as a heatsink. Openings were introduced to the plate to permit access to the electrical connections on the power supplies.

An area between the barrel's lower plate and the lower plate of the stock was left uncovered to permit the ingress of power supply wiring from the external battery pack.

3.2.4 Other components

The top plate was another component formed from plasma cut steel. It provided a consistent upper surface for attachment of the sight rail, and structural rigidity to prevent the gun bending around the connection between the stock and barrel subassemblies. The grip was modelled with inserts for a safety switch on the left side and a trigger under the index finger on the front side. Counterbored holes were added for M4 socket head cap screws, shown in Figure 15. (These were replaced with M5 screws when the wrong tool was picked up when tapping the corresponding holes in the barrel bottom plate.)

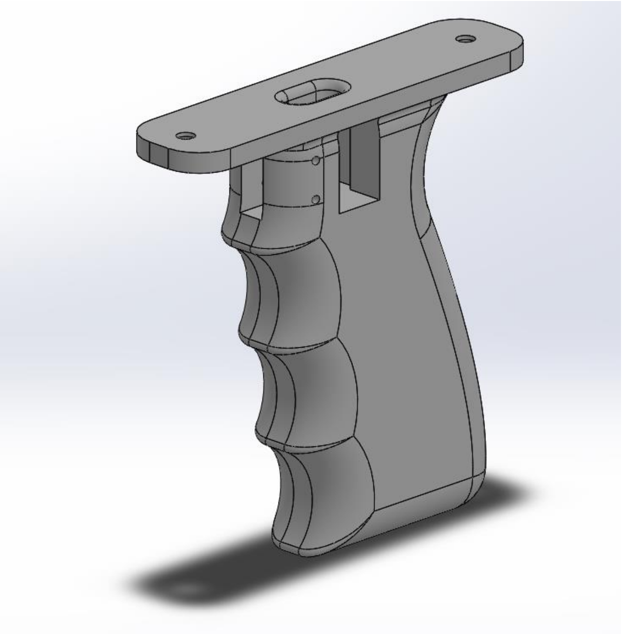

Figure 15 Coilgun pistol grip, showing cutouts for trigger, safety, wiring, and fasteners.

4 Control and Software Design

Optimal performance from a coilgun is achieved by optimizing the timing for the activation of the coil switches. Ideally, the feedback system could permit for automatic determination of the timing. The feedback system was however entirely non-functional as built. Without feedback, the software complexity decreased dramatically.

To simplify development, the microcontroller was programmed in C++ in the Arduino programming environment. The primary functionality of the program consisted of a single loop that checked for inbound serial communication and changes to the user control status and updated the associated indicator lights. The program would enter a firing sequence if the trigger and safety signals were in the correct states. In the firing sequence, the program would turn on the coils in a progressing sequence for a programmable and known period of time, then briefly prevent entering the firing state to prevent dry-firing due to trigger contact bouncing.

4.1 Expectations

Calculating the optimal performance of a coilgun is difficult. Determining whether optimal performance has been achieved should be possible via these rules:

1. With optimal timing, the kinetic energy imparted to the projectile by each stage will be equal, since the force applied to the projectile is a function not of time but of distance, leaving the same work being done by each stage.
2. Because of 1., the velocity of the projectile should increase with the square root of the active coil count.
3. If the velocity of the projectile compared to the stage count matches the prescribed curve, then the optimal performance has likely been achieved.

Due to practical issues, these rules do not hold exactly. Higher-current stages should impart more kinetic energy than lower current stages. Stages where the magnetic field cannot fully develop before the projectile arrives will not impart as much kinetic energy as other stages. This suggests that later stages would provide far more kinetic energy, but on higher current stages, it is possible that the coil cannot be left powered-on for longer than a certain period of time without destroying the switch, limiting the energy that can be imparted to the projectile by that stage.

Over the course of tuning and testing, four stage PCBs required complete replacement due to switch failures caused by overly aggressive tuning. These were from stages 6, 7, and 8, all in separate events. Another PCB was scrapped following an incident with the hastily installed replacement for stage 7 in that first incident. At one point, a 0.1-ohm power resistor installed in the flyback circuit on stage 7 exploded, launching itself off of the board and landing on a table adjacent to the device. This event ended further experimentation with diode-resistor flyback suppression, so the tuning of that parameter is not discussed.

4.2 Single Stage Tuning

The single-stage technique permits a single stage's coil to be active at any moment during the firing sequence. This produces a sawtooth-like current profile, as seen in Figure 16. Each ramp is a single stage drawing current and forming a magnetic field. The profile shown is that of the highest performance tuning that was achieved, firing a 24m/s (18J) projectile

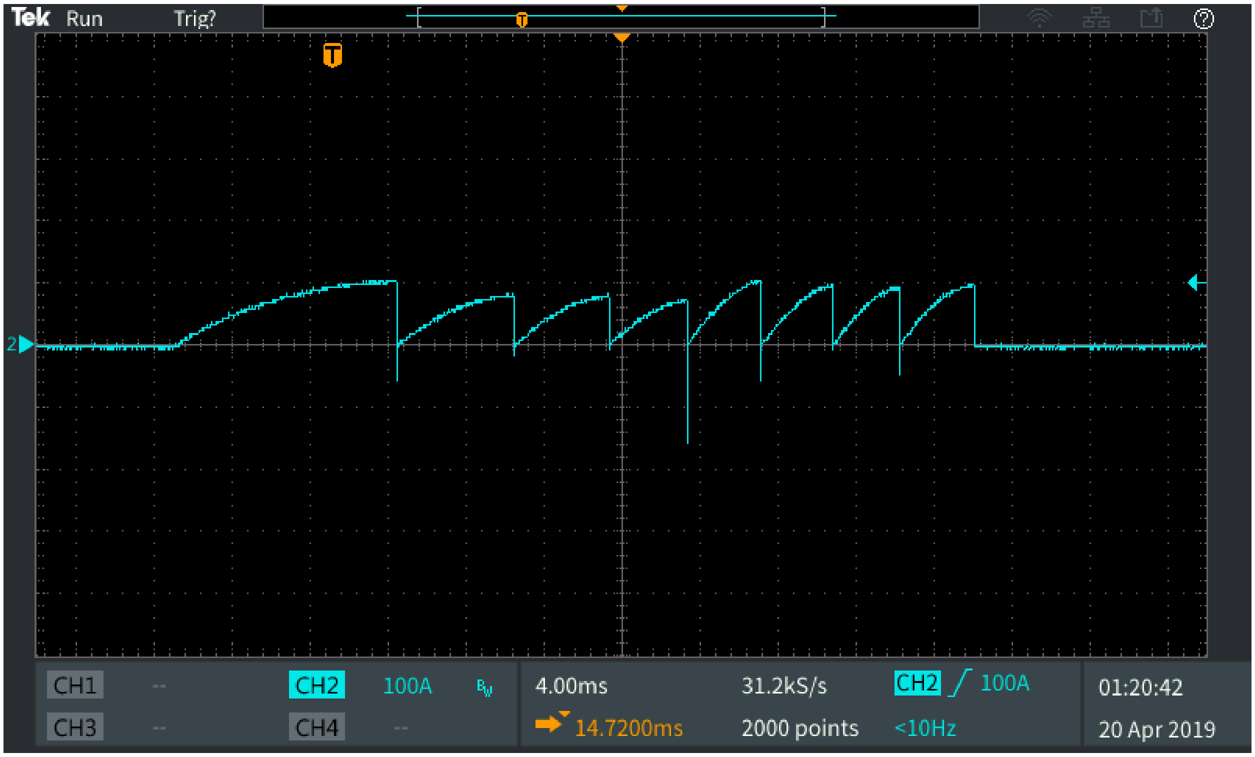

Figure 16 Single-stage tuning current trace. 24 m/s projectile

4.3 Dual Stage Tuning

Higher muzzle energies were achieved by having the controller turn on the stages in pairs. In this strategy, coil *i* and *i+1* are both powered simultaneously for each stage. This permits the next stage to reach a higher magnetic field strength before being switched off. The significantly higher coil current can be seen clearly in Figure 17. A muzzle velocity of 27.5 m/s and muzzle energy of 23.0J was achieved with this strategy, presenting a 13% speed increase compared to single stage tuning, and a 27.6% increase in muzzle energy.

Figure 17 Dual stage tuning. Current, voltage, and power measured through and across battery connections.

Manually integrating the power curve gave an approximate total input power of 420J. This suggests a 5.7% energy efficiency for the device. The combination of power lost outside of these measurements and integration errors would suggest that a 5% efficiency is a more realistic upper limit.

4.4 Performance

The performance achieved came very close to the ideal performance increase per stage, shown in Figure 18. Incremental performance diminished on stages 6, 7, & 8. This reflects a decision to intentionally reduce performance to increase device reliability after several stage boards failed catastrophically during tuning. Except for the last three stages, the device's performance closely matched what would be expected of ideal timing.

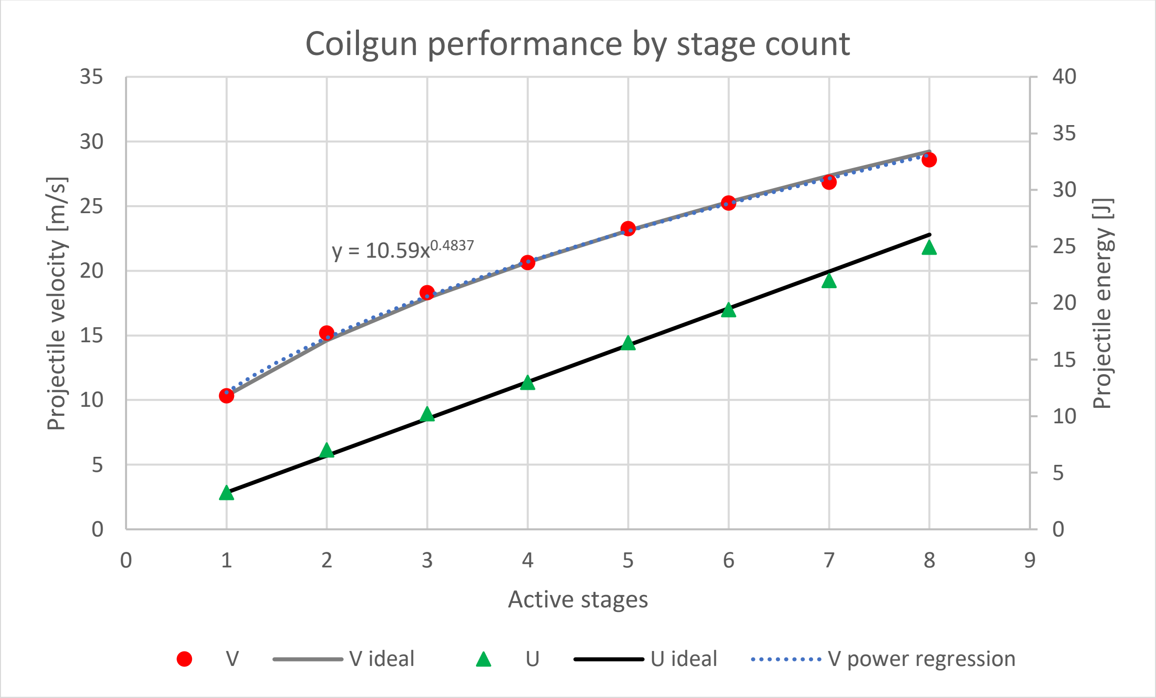

Figure 18 Ideally extrapolated and realized performance numbers against active stage count for dual-stage tuning

This adherence to the projected values indicates that diminishing returns are unlikely to be encountered without dramatically increasing stage count, and that linear energy performance gains can be achieved by increasing stage count. Without changing the electrical design, the primary constraint on performance remains the maximum weight of the device.

Visible in Figure 17 is a significant drop in supply voltage during the firing pulse. This is due to either voltage sag in the batteries or resistance in the wiring leading to the busbars. Reducing this effect would permit higher coil currents and higher performance.

5 Conclusion

5.1 Results

An eight-stage electromagnetic projectile device was successfully designed, prototyped, and tested. The project was delivered within schedule and budget. The completed prototype was visually impressive and capable of enacting impressive visible damage to multiple targets. The device was capable of destroying a glass soda bottle, a pane of 3/8” tempered glass, and a beer can.

Most importantly, from the perspective of the project sponsor, the resulting video, posted to YouTube, had been viewed 1.4 million times as of May 12, 2019.

Figure 19 Pane of 3/8” tempered glass shattering and dispersing upon being shot with the coilgun. Copyright Hacksmith Entertainment Ltd. Used with permission.

5.2 Recommendations

There exist several opportunities for improvement to the design. The projectile velocity is lower than the legal maximum, the device is uncomfortably heavy, the projectile is unnecessarily large, a hundred amperes of power capability is left unused, and the rate of fire is significantly limited by the single shot design. Several of these issues are complimentary. Increasing the safe switching current would permit for fewer windings of wire in the coils, making for a lighter gun. Switching to a smaller projectile would necessitate shorter coils, requiring the use of thinner wire to stay below the maximum current while increasing the projectile velocity. With increasing magnetic field strength, magnetic saturation of the projectile will eventually be achieved, dramatically reducing efficiency and setting a practical upper limit on the performance that can be achieved for a given number of stages. With improved current switches, the adverse affects of increased inductance can be mitigated by turning on stages far earlier than is currently possible.

As per the recommendation of several viewers of the video on YouTube, some form of projectile stabilization is required to prevent pitching and yawing of the projectile. This can be achieved by modifying either the projectiles or the launcher.

Better implementation of the feedback system could permit better performance with arbitrary or inconsistently loaded projectiles, loosening the tolerance on an autoloading mechanism, and enabling dramatically increased rates of fire from a magazine instead of single shots. Automatic fire is substantially more impressive on video than single shot operation!

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Appendix A: Table of coil dimensions

14AWG magnet wire, 1.7mm diameter, 0.829 omh/100m. Calculated with 100V, 0.05ohm supply.

Coil OD (mm)	Wire used (m)	Windings	Resistance (ohm)	B/V	B/I	I (A)	B (T)
80	127.17	787.5	1.05	1.50E-05	1.43E-05	90.6	1.291E-03
75	117.33	726	0.97	1.43E-05	1.47E-05	97.8	1.439E-03
70	98.77	665	0.82	1.29E-05	1.57E-05	115.1	1.811E-03
65	81.72	603	0.68	1.15E-05	1.69E-05	137.5	2.324E-03
60	66.2	542	0.55	1.00E-05	1.83E-05	167.0	3.050E-03
55	59.01	480.5	0.49	9.31E-06	1.90E-05	185.5	3.528E-03
50	45.76	419.5	0.38	7.87E-06	2.08E-05	232.9	4.835E-03
45	34.02	357.5	0.28	6.44E-06	2.28E-05	301.2	6.878E-03
40	28.73	296	0.24	5.73E-06	2.40E-05	347.1	8.346E-03