Coil Gun Design Guide

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POWER SOURCE (Where the current for the coils comes from)

Battery: A battery powered coil gun will offer less acceleration per stage due to batteries' inability to provide as much current as capacitors. This can either be compensated for by having a large high current battery bank, or having several stages that each give a smaller acceleration to the projectile. The advantage, however, is that a battery powered coil gun will be able to fire much more rapidly, as it does not need to charge between shots. You also avoid the complexity of creating a charging/discharging circuit that keeps all stages electrically isolated from one another.

Capacitors: Capacitors seem to be the best choice for raw power in a coil gun, as many can be charged to an obscenely high voltage and then discharged very rapidly, though a capacitor powered gun will require a charging circuit. The best setup is for each stage to have its own capacitor(s) so that it will benefit from maximum voltage when firing. Multiple parallel capacitors per stage are preferable, as they will have lower parasitic inductance and equivalent series resistance. An ideal coil gun will have progressive stages with decreasing capacitance and increasing voltage as shorter and more powerful discharges will be needed in later stages. Keep in mind that your capacitors do not need to fully discharge. A 100V capacitor has expended %75 of its stored energy when it is discharged down to 50V.

SWITCHING (How the current through the coils will be switched on/off)

Relays/Mechanical switches: This is not advisable, a good coil gun requires rapid switching and mechanical devices take several milliseconds to actuate. It can certainly be done, it just won't be efficient.

SCR/Thyristor: This seems to be the popular choice, as these devices can handle absurd amounts of current and are easy to use. However, once switched on they cannot be switched off until the current stops flowing. This means that you can only use them with capacitor powered guns, and that the capacitance/resistance of each stage has to be carefully controlled to get the ideal pulse length. The other option would be to fire your stages early so that the capacitor is discharged by the time the projectile gets to the center of the coil, however this could be inefficient if you're wasting capacitor charge too early.

MOSFET/IGBT: This is the option for precision control over your pulse length. However, you will need to ensure that you use several complimentary devices for reliable operation. You will need a gate resistor to reduce ringing, a fly-back diode across the coil to prevent semiconductor failure from back-EMF, a gate driver for fast and complete switching, and possibly a snubber capacitor to eliminate any additional back-EMF caused by the capacitors. As for MOSFET vs IGBT, it comes down to preference. IGBT's can be found with astronomical voltage/current ratings, but MOSFETs are able to be wired in parallel to increase current capacity whereas IGBT's cannot.

Recoil: When using MOSFET's or IGBT's, the abrupt turn off that they go through creates huge voltage spikes caused by current induced from the collapsing magnetic field of the coil. The easiest way to handle this is to use a fly-back diode. However, this causes the coil to freewheel and ramp-down slower. You can use a flyback diode in series with a resistor or a reverse-bias zener diode to suppress freewheeling of the coil. You could also redirect that voltage spike to the capacitor of the next stage to improve the ramp-up of the next coil while also preventing freewheeling of the current one. Though that last solution is a bit difficult to implement as you can end up getting extreme LC oscillations in your circuit if you're not careful.

TIMING (How we control when the current is switched on/off)

Sensors: Controlling your stages with sensors is an easy way to avoid having to do calculations or tuning for timing. It is strongly suggested however that you build your sensors in a way that they can be adjusted forward/backward to home in on ideal timing. Because coils have a 'ramp down' time where it takes a moment for their field to dissipate, placing a sensor so that a projectile will hit it when it is exactly in the center of the coil will result in the coil slowing the projectile down as its field ramps down. You can also just intentionally place the sensors too early, and add an adjustable delay to them. As for sensor type, optical seems to be the only viable option, as they have a latency of several nanoseconds compared to several milliseconds on something like an induction sensor. To avoid noise from the coils, ensure that sensor wires are twisted with a ground wire and that they run parallel to the barrel.

Software: Relying on software timing seems to be the best way to get precise & adjustable timing of your stages, however you will need to redo your timing any time you make an adjustment to your capacitors, coils, or projectile. Ideal timing can be found through simulation or trial and error. It is advisable to create multiple timing profiles that you can switch between if you intend on changing voltages or projectiles. A 16MHz microcontroller like the Arduino Nano seems perfectly capable of fast and accurate timing provided that your code is well written and you do not try to do too many things at once. In a simple test where a Nano was programmed to (upon receiving a trigger signal) 1: Save the current time, 2: Switch coil A OFF, and 3: Switch coil B ON, the Nano completed the whole operation in 10.2 microseconds. This time could be improved by either using a faster microcontroller, or rewriting the code to use direct registry manipulation. Keep in mind you will still need at least one sensor to measure final projectile speed.

COILS

Number: Adding additional coils/stages will yield diminishing returns on speed. You will reduce the complexity/size/cost of your gun if you focus on having a small number of highly optimized & powerful stages.

Wire thickness: Wire thickness affects what I call the ‘Field Constant’, or how much the field strength will increase by per amp flowing through the coil. Assuming the supply voltage and dimensions of two coils are the same, a coil with thicker wire will ultimately make a stronger magnetic field, but a coil with thinner wire will produce a field more *efficiently.* That is to say, the second coil will have a stronger field per amp of current flowing through it. Wire thickness must also be considered in reference to the intended voltage of the coil gun. If we’re building a low voltage gun, we want thick wire so that our coils experience the highest possible current and thus produce the strongest field. However, on a high voltage gun, such thick wire may cause us to exceed the current limits for our switching devices.

Volume: The volume of a coil directly corresponds to its RL time constant, which is how long a coil takes to ramp up to maximum current (aka maximum field) and down to zero current. Regardless of any other factor, a larger coil will take a longer time to reach its maximum current & field than a smaller coil. More importantly, it will take a longer time for its field to collapse when you switch it off. This can result in a coil slowing down a projectile after it has passed through the center when the field should be gone. This can be compensated for by turning off your coils earlier, but this is not ideal because we miss out on the window of time where the projectile is *close* to the middle, when it’s experiencing maximum acceleration. While it might sound tempting to always opt for small coils, they draw exponentially more current due to lower resistance, and sometimes a coil can be *too fast* for the speed the projectile is moving. An ideal coil gun will use progressively smaller coils with faster time constants, this allows for the most efficient acceleration up to a high speed.

Width: Wider coils (Width being the coil's diameter) are flatout undesirable. If we look at two coils with the same wire thickness, length, and supply voltage, the wider coil will have a slower RL time constant, produce a weaker field, and possess a lower field constant than the narrower coil. So why don't we use coils that are only one layer of wire thick? The answer is current draw. A one-layer coil might have 50 milli-ohm of resistance, which means on a 100 volt coil gun it would draw **2 kilo-amps** of current, which would fry the majority of switching devices you can afford. So we need to carefully balance our wire thickness and our coil width to get our target current draw.

Length: A longer coil will produce a field that extends out further but that is overall weaker. This would result in a steadier acceleration on a projectile. One benefit of a longer coil lies at the center where the force on the projectile flips and begins to slow it down. In a longer coil this flip is much more gradual, so a gun utilizing longer coils will be more forgiving about imprecise timing of the stages.

Coil additions: A ferrous metal sheath or metal end plates can be placed around a coil to increase its inductance. This will make the field that it produces much stronger, but will also increase the ramp up/down time for the coil. On another note, placing permanent magnets around a coil to create a 'halbach' coil has zero observable effect on coil's field strength.

Temperature: Copper's resistance changes by approximately %4 per 10° C. Since a coil's field scales with its current draw, if your coils heat up to 35° C they will only produce %96 of their normal magnetic field, and if you cool them to 0° C, they will produce %110 of their normal magnetic field.

Current draw: All of the factors mentioned above can be tweaked to get to a target current draw for a given coil. One helpful note to mention is that if the time a coil spends turned on is shorter than 4-5 times its RL time constant, it will not hit peak current. We can fix this by over-rating our coil. For example if we've optimized a coil to draw 100 Amps in order to match our switching device's current rating, but it is only reaching 50 Amps in the 2 millisecond window we pulse it for, we could increase the thickness of wire so that its non-pulsed current draw is now 200 Amps. Alternatively, we could reduce the coil's time constant by making it slightly smaller, thus shortening the time to ramp up to 100 Amps.

PROJECTILE

Projectile material: You can either go for a ferrous projectile that will be attracted by the coils, in which case any metal with high magnetic permeability will be ideal, or you can go for a non-ferrous metal armature that will be repulsed by the coils, using something like copper or aluminum. This is due to the metal's diamagnetic properties, where a magnetic pulse will induce currents within the armature that will create their own opposing field. Either setup will require different timing profiles, however I believe that a repulsive coil gun has the potential to propel a projectile faster since we won't have to worry about the ramp down of the coils slowing down the projectile. Lastly, it is also possible to use a low-coercive permanent magnet projectile. Doing so would allow you to attract and then repel the projectile, thus achieving the highest possible velocity. Keep in mind this would require a more complicated firing circuit that would allow us to change the direction of current, thus flipping the magnetic field when the projectile is at the center. There is also the downside of your ammunition now being expensive and fragile.

Projectile mass: Because additional coils give diminishing returns on speed, and because it gets harder to turn a coil on/off faster and faster, it is worth noting that you can frequently get higher muzzle energy by shooting a more massive projectile at a slower speed. In tests, I had found that I could propel an iron rod at the same speed regardless of its mass, but struggled to propel even a lighter rod any faster. So I opted for the heavier rod for its higher muzzle energy.

Projectile length: Similar to coil length, a longer projectile will result in a smoother acceleration, and a more gradual flip from speeding up to slowing down when reaching the middle of a coil. So a longer projectile can compensate somewhat for imprecise timing, up to a point. If you're planning on making a very powerful coil gun, I would avoid using too long of projectiles though. On my gun using 7.5 x 100mm iron rods, I managed to bend the rods when shooting hard objects at full power. Combined with the tight tolerances of my barrel, this rendered the rods unusable afterwards.

Projectile width: A wider projectile will always experience more force from a coil. A larger cross-sectional area means that when the projectile is near the center of the coil, there are more metal atoms for the magnetic field to exert force on. Because of the square-cube law however, there is a sweet spot. If we double the width of our projectile, it has four times the mass and will require four times the force to accelerate it at the same rate. You will have to experiment with this on your own to find the sweet spot for your setup. Another thing that changes when you vary the projectile width is the saturation flux of the projectile. When a projectile is saturated with flux, increasing the strength of an external magnetic field will yield diminishing returns on the force that the projectile experiences. Therefore it is advantageous to use a projectile with a high saturation flux when building a high power coil gun. Since iron or steel gets saturated at a flux density of about 1.5 Tesla, if your coil gun creates fields stronger than that, it may be in your best interest to increase the width of the projectile and coils, as a larger projectile can accommodate the same amount of flux at a lower density, thus remaining below its saturation flux density.

BARREL

Thickness: It's obvious that you want a barrel that is rigid and low friction, however the thickness of the barrel is also important considering that the coils are wrapped around it. Any gap between the inside of the coil and the projectile will reduce the number of magnetic field lines interacting with the projectile. For example, in a baseline using a 7.5mm projectile inside of a 8mm ID x 10mm OD barrel with a coil wrapped around it, it was found that the projectile experienced a %10 stronger field when switching to an 8mm ID x 9mm OD barrel with a coil possessing the same number of turns. Keep in mind that part of this increase comes from the lower resistance a coil wrapped around a smaller barrel will have.

Length: On coil guns opting to use software to control timing, a longer barrel with more spaced out stages can ease the difficulty in writing/optimizing your program since the time spans the stages will be firing for won't overlap. Additionally, this setup/program will be easier to run for a slower microcontroller. If you'd prefer to have compact coil spacing and you are running into microcontroller speed issues, a good approach would be to have each stage controlled by a small/cheap microcontroller like the ATTiny85.

Material: While it might be tempting to opt for a metal barrel, this will reduce the efficiency of your gun since the coils will induce eddy currents in the metal. Metal also presents a danger of causing your coils to short circuit, since there will be a high voltage potential between the innermost layer of wire and the metal barrel. The best materials seem to be carbon fiber or glass since they are rigid, heat resistant, and non-conductive. Glass also has the added advantage of being transparent, which will allow you to place optical sensors without drilling holes in your barrel.

Barrel additions: I suggest attaching non-metal braces to your barrel that will sit forward & aft of each coil. While firing, the coils will obviously experience an initial impulse pushing them backwards, and then a less obvious impulse pulling them forward caused by the hysteresis in the projectile and the ramping down magnetic field of the coil attempting to stay coupled. Braces on either side of your coils will prevent them from moving out of place and from putting extra drag on the projectile.