Development of a superconducting coil gun system

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Decades of research on superconductivity and cryogenics yielded results that have been essential for a number of fascinating developments, primarily in medical and industrial applications. Most of the developments stem from the ongoing research into the strange behavior and unique properties of superconductivity, which has yet to be fully explained. Superconductivity was first observed by Heike Kammerlin Onnes, a Dutch physicist in 1911, who found that mercury immersed in liquid helium lost all resistive properties. The Meissner effect, observed in 1933 by Walther Meissner, and Robert Oschenfeld caused a repulsion of natural fields from within a superconducting material, basically the fundamentals behind the Maglev train. The 1962 development of NbTi (Neobium-Titanium) wire by Westinghouse made it possible for practical applications of superconductivity to begin, initially demonstrated through the construction of superconducting particle accelerators in research laboratories. Naturally, several decades of advancements in the field of cryogenics occurred during the same time-frame and have made storing and producing cryogenic liquids, increasing the variety and efficiency of superconducting devices. Sandia Laboratories developed a coil-gun primarily for use in the transportation networks, capable of launching high-speed trains, and potentially spacecraft, both equally suitable applications in the civilian fields. The military applications have recently been discovered through the successful use of a superconducting Electromagnetic pulse (EMP) bomb against the Iraqi satellite TV station in 2003, as well as several successful tests of superconducting rail-guns, the latest by the U. S. Navy using a 35 MJ rail-gun in 2008. It its simplest form, a coil gun consists of a barrel, one or more coils, a power supply, switch, and control electronics. Each coil, and its corresponding power section and electronics is called a ‘ stage’. As each ‘ stage’ is added, the velocity of the projectile is increased through magnetic acceleration. Standard coils are typically wound from specially coated copper wire, called “ magnetic wire” around a non-conductive coil form. Its comparably poor efficiency (vs. NbTi wire) is offset by low costs and a decent price-performance ratio. Since no coil guns have thus far utilized superconducting coils, no superconducting wire has been necessary in any design, removing the need to spend a large sum of money on wire with benefits that cannot be utilized. All traditional coil guns have also used large, high voltage electrolytic capacitors to supply power to the coils. Utilizing the formula P= EI, the power (P) delivered is proportional to the voltage level (E) multiplied by the current (I), which can easily exceed several kilovolts. The power increase corresponds to an increase in the strength of the magnetic field produced, as well as the amount of heat produced by resistance encountered in the coil. Using (E/R)2(R)= E2/R, I= E /R to calculate the heat produced by a coil, the degree of resistance is responsible for the increase in heat generation, as well as the reduction in power due to the resistance encountered by the electrical current. Because the voltage rating and energy storage of an electrolytic capacitor are inversely proportional, several large, heavy capacitors are needed to provide enough energy storage to discharge across each stage, in a multi-stage gun; this amounts to one or more banks of capacitors, which takes up a considerable amount of space, and requires bus bars, voltage regulators, step-up transformers, and additional circuitry to insure safe and reliable operation. Electrolytic capacitor banks also require a rather extensive time to charge, so the down-time between each shot can be fairly lengthy. The recharge time can be reduced by using a diode circuit to transfer excess current at the end of each shot back into the capacitor bank, which yields a faster recharge time, and, therefore, a faster Rate-of-Fire (RoF). The timing array for standard coil guns typically consists of an optical sensor embedded in the coil form, which must be made of a clear material, usually restricting potential options to plastic or glass. Plastic coil forms can melt during operation due to the amount of heat dissipated during use. Glass is mostly unaffected by heat but is reported to shatter, possibly due to contracting coils, or the ‘ shockwave’ created by the projectile travelling down the barrel.[1] These two options strictly limit the size and power of conventional coil guns, as dumping huge amounts of current through standard coil forms immediately renders them useless. Metal coil forms can also be used but are structurally inefficient, due to the need to modify them to prevent damaging eddy currents, which reduces their structural stability. In the event of massive heat build-up, the insulation surrounding the wires can melt, shorting to the metal coil form, resulting in a loud noise, light flash, an explosion, and a large electrical arc. Switching mechanisms typically include MOSFETs, IGBTs, SCR switches, Flash tube switches, and a spark gap. All of these devices are capable of discharging the high voltages required for the operation of conventional coil guns. The above options are listed by efficiency from greatest to lowest. Metal oxide-semiconductor field-effect transistors (MOSFETs) are densely compacted transistor arrays that come in a huge variety of types, but the switching types, pMOSFET and nMOSFET, are the ones most applicable to this topic.[2] Insulated Gate Bipolarized Transistors (IGBTs) are MOSFET-controlled P-N-P-N junctions. [2] Initially, they were subject to failure and inefficiency but have recently become far cheaper and more durable; increasing the effectiveness of IGBT based designs. They typically have extremely high pulse-power ratings, making them very suitable for standard coil-guns and other energy weapons. Silicon Controlled Rectifier switches (SCR switches) are simply a P-N junction with a gate, when the voltage passing through the rectifier exceeds the rated voltage, the gate opens, allowing it to conduct; once the voltage decreases, the gate closes again.[2] SCR switches are an effective means of switching high voltage current several thousand times per second, making them ideal for pulse-power applications. Flash tube switches are simply the use of a camera flash tube to activate the coils, which is very rudimentary and inefficient, usually a staple of the low-level hobbyist projects. Using a spark gap is dangerous and is only suitable for the lower voltage demonstration models. Ideally, the barrel of a coil-gun would be made out of a non-conductive, high-strength metal, impervious to friction damage. Since there is no such material, choices are rather limited when it comes to choosing a barrel. All barrels must be metallic, so the problems created by eddy currents are always significant. They must also be durable and are preferably poor conductors. Barrels must not be easily magnetizable, which means that iron, steel, and other iron containing alloys are not an option. These parameters limit conventional metals to the choices of aluminum or titanium, titanium being preferable due to its vastly reduced conductivity and impressive structural strength. Hard anodized aluminum and titanium are the preferable variants, as they will not conduct and posses an anodic layer that yields impressive material strength and hardness. Chemically treating the barrel with special compounds designed to reduce friction and increase durability and protection, i. e. ‘ bluing’ compounds and varnishes, can further enhance the efficiency of the coil-gun system. Having discussed the inefficiencies, history, and components of a standard coil-gun, the paper will now discuss the design, components, effectiveness, and feasibility of a superconducting coil gun system. This section of the paper will also present easy-to-read charts, and tables, so that a clear understanding of the system can be achieved. First, in order to understand how a superconducting coil gun can work, it is important to visualize the coil-gun and its systems, so several pictures detailing individual components and the system itself are provided to aid in the effort to understand the proposed system. The system of delivering cryogenic fluids to the jacketed coils is the primary need for designs and visual aid, as a superconducting coil gun design is otherwise similar to a standard coil-gun.

Fig. 1 contains four main components: The distribution manifold, the twin jacketed cryogenic cooling system, the Liquid helium tank, and the Liquid Nitrogen tank. The distribution manifold contains a series of automated release valves, similar to those found on common pressure cookers, which operate when the operating pressure exceeds a certain point, releasing gas and excess pressure. These valves also avoid the risk of asphyxiation, as gas pressure is released in small amounts, rather than in a large jet of pressurized gas, which will quickly cause loss of consciousness and/or death. Ideally, the distribution manifold is manufactured from aluminum and completely encased in thermal insulation to prevent freeze-burns upon contact with the manifold and to increase the useable lifespan of the expensive liquid helium. Capping the end of the manifold is a pair of pressure gauges that display Psi readings from both the Liquid Nitrogen and Helium segments; the gauges serve to alert users of potential pressurization hazards, and aids in the calculation of the coolant vaporization rate. Each cryogenic cooling system consists of a porcelain-zirconium coated aluminum or titanium tube (coil-form) welded inside two cylinders. Each cooling system is self-contained, and during assembly, the cooling systems are slid onto the barrel. Contraction of the metals during operation brings the cooling system and the barrel to a perfectly tight fit. The two cylinders form an inner (Liquid helium) and an outer (Liquid nitrogen) jacket. The first of these cylinders contains liquid helium, and completely surrounds the coil-form. The intake pipe for this cylinder passes through the nitrogen cylinder to extend beyond the unit, so it may be attached to the distributing manifold. The two wires lead from the coil-form exit this cylinder through two small holes and passes through two similar holes on the outer jacket. The outer jacket is coated in thermal insulation and contains the exit hole for the inner jacket intake pipe and the intake pipe for the liquid nitrogen jacket itself. This is shown in Figure 7. The coil-form ideally consists of an extremely thin aluminum or titanium tube coated in a porcelain zirconium composite, which will satisfy the requirements for being both non-conductive and suitable for cryogenic temperatures, in addition to its characteristic durability. The coil form can also consist of a hard-anodized aluminum or titanium cylinder, which will also satisfy the requirements. Anodized metals should not be used to assemble the barrel, as the anodized layer has a high friction coefficient, resulting in degrading performance losses. Once the cooling system is completely assembled, it can be slid onto the barrel, or vice versa, to create the main segment of the weapon system. Having now discussed the cryogenic aspect of the superconducting system, this paper will now turn to the electronic systems necessary to operate a superconducting coil-gun. Concerning the power supply of a superconducting coil-gun, it should incorporate a microprocessor controlled voltage regulator to insure a steady current supply and provide adjustments in minor increments to avoid precipitating a quench effect. Superconductivity provides an interesting problem. Once in the superconductive state, current can persist in the coils indefinitely. Using a conventional switch would not be effective, as the current would never leave the coils. Thus, a permanent magnetic field would be created, suspending the projectile at the center of the field within the barrel. If an abnormal termination results in the quench effect, how can the entire concept work if a pulse operation is required? The answer lies in the use of Josephson junctions to actuate switching in the superconducting coils. Josephson junctions can be cycled ten times faster than any of the previously mentioned switching methods and would yield an extremely high theoretical RoF. Josephson junctions utilize the Josephson Effect, which occurs when current is passed through a wire placed next to a pair of superconducting objects. The wire creates a magnetic field that lowers the critical current in the insulating layer (i. e. wire insulation) between the two objects, causing resistance to build in the objects. The resistance halts any superconducting operation. [3] Since this cycle can occur several thousand times per second, Josephson junctions are the perfect device for quickly charging and discharging the coils and is practically the only known device that would do so. The use of Josephson junctions removes the need to wait a several minutes to return the coils to a normal state, and due to the ability of Josephson junctions to operate several thousand times per second, a theoretical rate of fire that could easily exceed the fastest multi-barrel weapons (i. e. Gatling guns at 4600 to 10, 000 RPM) [3]. Control circuitry for both standard and super-conducting coil-guns are similar in that they both incorporate many of the same components, such as trigger logic circuits, VARIAC units, step-up transformers, twin diode-discharge circuits, charging circuits, power rectifiers, and miscellaneous circuits to indicate the status of voltages, charge capacity, etc. Extra circuits that are needed for the superconducting variant include; a circuit to monitor the temperature, pressure level, and quantity of the cryogenic coolants, a voltage regulator circuit to insure an extremely steady voltage output to the coils, the circuitry for a simple laser timing gate, and the circuitry required to operate the Josephson junctions. The technologically complex and currently developing technologies of lithium-hybrid ultra capacitors would yield the most suitable energy storage device for a coil-gun.[4][5] A device that combines the characteristics of both the high-energy storage of a lithium-ion/polymer battery and the excellent power density of the ultra capacitors offers numerous benefits that make up for the shortcomings of both. Additional components (in lieu of a micro-computer) include the Trigger Logic board, laser sensors, power supply circuit, voltage regulator, voltage regulator controller circuit, discharge recovery circuit, and the Timing board. Trigger logic boards can be found on most coil guns, and more commonly, on electronic paintball markers. These boards control switching when a condition (Trigger pull) is activated; once the condition is activated, the logic board closes the switch, allowing a current pulse to travel from the power supply to the coils. The pulse creates the magnetic field that is activated for a fraction of a second. The timing board is responsible for the activation and deactivation of the coils in a perfectly tuned sequence. As each laser sensor is tripped by the projectile, the timing board deactivates the coil that the round is entering, and activates the one directly ahead of it, causing optimum acceleration. The laser sensors themselves are extremely inexpensive and can be found in children’s toys, also crucial in laser-timing gates for velocity calculations. The response time of the timing board and laser sensors is extremely crucial to the operation of the device, as efficiency and power will be greatly reduced if the timing sequence is not perfect. Once the sequence is complete, any excess current leaves the coils through a pair of Diodes acting as a recovery circuit, and is returned to the capacitors. The lack of resistance from the coils and the super cooled operation prevents most of the energy from being lost as heat. Most of the excess energy used for each shot can be returned to the capacitors, which have an approximate 90%+ efficiency rating, which couples with the efficiency of the coils leading to an extremely efficient design.[4][5] One of the main benefits of a superconducting device is the benefit of not requiring high voltages, and therefore, the heavy, expensive, and dangerous high voltage components (1 to 20+kV) that accompany such a design. The low voltage requirements (1. 7V+) of the coils means that the entire device can be made of components that are less expensive, lighter, more efficient, and far safer. The basic idea of the electronic section is to create a stable, low voltage power supply, a Josephson junction switching capability, a precise timing board, and an effective Trigger logic board. Those are the necessary groups required for operation, comprised of components mentioned, and discussed immediately prior.

Factor

Increases:

Decreases:

Efficiency

Power

Coil length Increase

Field Strength, length of magnetic field

Efficiency, reduces available barrel length

Varies

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Voltage increase

Field Strength

Safety requires circuitry modification.

Varies

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Temperature Decrease

Conductivity

Creates temperature related issues

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Increase in barrel, or coil-form thickness

Durability, structural strength

Field strength

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Pressure increase in cryogenic tanks

Usability of manifold system

Presents potential explosive hazard

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Increase in burst disk/pressure relief ratings

Usability of manifold system, (not dependant on gravity feed)

Presents potential explosive hazard, and asphyxiation

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Abnormal Termination of Operation (Quench)[5]

Causes catastrophic failure, potential weapon value.

Field strength, entropy, electric current, spike in localized magnetic fields (EMP potential), extreme vaporization of cryogenic fluids

Safety, presents multiple lethal hazards, explosive, arc, voltage dump, EMP potential, Magnetic shattering, shrapnel, asphyxiation, concussive blast.

Unknown

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Projectile Mass

Varies with field strength and projectile’s metallic properties

Varies with field strength and projectile’s metallic properties

Varies

Varies

Projectile Density

Varies with field strength and projectile’s metallic properties

Varies with field strength and projectile’s metallic properties

Varies

Varies

Projectile Magnetic Permeability

This increases the speed at which the projectile can be accelerated

Increases saturation rate, decreasing re-usability.

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Saturation Rate

No positive effects

Magnetically Saturated projectiles are less efficient than non-saturated projectiles

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Number of coil layers

Increases power and efficiency, but only the first two layers have significant effects

Increases size, weight, cost.

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Wire Gauge

Higher Gauge= less resistance, less current handling and heat dissipation

Dissipation.

Lower Gauge= more resistance, more current handling, more heat, larger coil size

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Distance of Projectile from Center of coil

Closer – Field strength increases, EXCEPT in superconducting fields, where strength is uniform throughout

Varies with projectile length, size, coil length and size, field intensity, timing method, and projectile properties.

Varies,

When

Optimized, ^

Varies,

When Optimized,

^
Pulse duration

Needs to be extremely precise, optimized pulse duration yields massive increases in efficiency and power

If pulse duration is not timed correctly, the projectile will lose velocity, perhaps coming to a stop in the barrel.

Varies, when Optimized, ^

Varies, when Optimized, ^

Barrel Thickness

Increases stability, structural strength

Reduces power and efficiency, as it increases the distance from field to projectile, and is also subject to material permeability ratings

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Barrel material composition

Conductive – requires slotting to prevent eddy currents, can be thinner, increasing power and efficiency,

Non-conductive, may be weak, lacks durability, possible friction-ignition.

Varies

Varies

Wire material composition

Different metallic properties affect conductivity, ductility, resistance, durability, etc…

NbTi wire properties:

Very high conductivity

Low temp-superconductor

Low resistance

Brittle

If low resistance ^

If low resistance ^

Barrel Friction coefficient

If coefficient is low, then friction losses will be minimal, prolonging barrel life.

If coefficient is high, then friction will reduce projectile velocity, efficiency, and create heat damage and barrel wear.

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Barrel Magnetic permeability

If high, then projectile will be more easily magnetized, increasing efficiency and power

If low, then projectile will take longer to become magnetized

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Given the vast array of variable factors listed above, computing any sort of field intensity, efficiency, velocity, or nearly any other aspect of coil-gun operation is practically impossible to do without actually building a device to test and acquiring hard data. The most efficient way to compute these crucial factors is to run several tests to achieve a set of data, average the results, use a spreadsheet to list these effects, and graph the data on a calculator or specialized computer program. While it would be delightful to demonstrate the efficiency, velocity, and field strength of the superconducting coil gun proposed in this paper, the design parameters and test data simply do not exist for computations to be possible. At best, assuming theoretical parameters were used for all components, approximately fifteen separate formulas would have to be utilized to acquire ‘ ball-park’ results. The sheer number of variables and miscellaneous ‘ x factors’ would horribly skew those results anyways, making it pointless, if not impossible, to accurately calculate theoretical efficiency and velocity without a test model. However, put simply: Efficiency for a superconducting coil gun starts at a theoretical 99%. For every factor or variable considered, efficiency can only become reduced, or remain the same. Assuming a successful design, perfect timing sequences, and minimal friction losses, efficiency could ballpark 70-90%. The velocity can be computed by using the parameters required for the theoretical 99% efficiency rating and the estimation provided based on the myriad of factors concerning power output. However, velocity can be calculated using existing formulas already derived from the testing of traditional coil-guns, as the basic mechanisms remain the same and, therefore, minimal deviation from the standard form is to be expected due to the device utilizing superconducting coils. Efficiency is calculated by dividing the input value over the output value, which is determined by measuring the input energy, and the output energy (in joules). Energy input is the current applied to the coils in each pulse, while Energy output can be either velocity, or the energy produced upon impact. This is a vastly simplified form of the equation sets presented after the glossary. What remains easily quantifiable is that a superconducting coil gun will undoubtedly yield greater efficiency and power. The only remaining difficulty is calculating how much of an increase it yields. Unfortunately, the only reliable way to determine the efficiency and projectile velocity would be on a case-by-case basis, and design parameters would play the largest role in determining each device’s theoretical efficiency and power output.

While this paper has thoroughly discussed the feasibility and possibility of a working and effective superconducting coil gun and found the design and implementation entirely feasible, actual tests are needed to acquire any concrete results, due to the numerous factors affecting theoretical computations. At approximately $200 per meter, NbTi wire is far from inexpensive, making hobbyist tests nearly impossible to fund. Military research facilities have the funding and tools at their disposal but are currently focused on the pursuit of laser based weapons, and rail-gun development despite the numerous advantages a superconducting coil-gun has over a rail-gun:

Far less expensive

Minimal barrel wear

No need for several Megajoule (MJ) pulse power supplies

Far more compact

Far more efficient

No spray of explosive metal particles and ‘ plasma plume’ following each shot

The next logical step in the pursuit of a superconducting coil-gun would simply be to acquire funding, and to commence research and development. Perhaps in the future, the military or private interests will pursue this goal, leading to further research and advancements in the fields of cryogenics, superconductivity, and energy storage, with the potential result of the active fielding of a superconducting coil-gun weapon system.

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