

Operating Principles and Future Potential of Next-Generation Gunpowder-Free Launchers: Coil Guns

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Introduction

Coil guns, also known as electromagnetic launchers, represent a significant advancement in projectile propulsion technology, utilizing electromagnetic fields to accelerate projectiles without the need for traditional chemical propellants. The historical development of coil guns can be traced back to the early explorations of electromagnetic propulsion, with initial designs focusing on single-stage systems. However, as research progressed, the introduction of multi-stage coil guns allowed for increased projectile velocities and improved efficiency, making them attractive for various applications, including military, aerospace, and even recreational uses (Dayi & Vijayan, 2017; Abdo, 2023; Çoramık et al., 2020). The operational principle of coil guns involves the sequential activation of electromagnetic coils that generate magnetic fields, propelling a ferromagnetic projectile along a barrel. This method offers several advantages over conventional firearms, such as reduced wear on components due to the absence of physical contact between the projectile and the coils, as well as the potential for higher muzzle velocities (Coşkun et al., 2010; Giès et al., 2020). Recent studies have demonstrated that optimizing coil configurations and utilizing advanced materials can significantly enhance the performance of coil guns. For instance, splitting a single coil into multiple smaller coils activated in sequence has been shown to improve energy transfer and efficiency (Giès & Soriano, 2019; Giès et al., 2020). Looking towards the future, the potential applications of coil guns are expanding rapidly. Innovations in design and materials are paving the way for their use in launching microsatellites from aircraft, which could revolutionize the aerospace industry by providing a cost-effective and efficient means of deploying payloads into orbit (Abdo, 2023). Additionally, hybrid systems that combine features of both coil guns and railguns are being explored, potentially leading to even greater versatility and performance (Domin, 2021). The integration of advanced computational modeling techniques, such as finite element analysis, is also expected to play a crucial role in the design and optimization of coil guns, allowing for more precise control over performance parameters (Liu et al., 2009; Abdo et al., 2016). Furthermore, the military applications of coil guns are being actively researched, with the potential for hypervelocity projectiles that could exceed conventional weapon capabilities.

(Darnse & Singh, 2003; Dayi & Vijayan, 2017). The development of systems capable of achieving muzzle velocities exceeding 2000 m/s has been reported, although widespread deployment in military contexts may still be some time away (Darnse & Singh, 2003). The ongoing advancements in power electronics and energy storage technologies are likely to enhance the feasibility of these systems, making them more practical for real-world applications (Coşkun et al., 2010; Lee et al., 2013). In conclusion, the evolution of coil gun technology reflects a dynamic interplay between historical advancements and future possibilities. As research continues to refine designs, optimize performance, and explore new applications, coil guns are poised to become a significant component of modern propulsion systems across various fields.

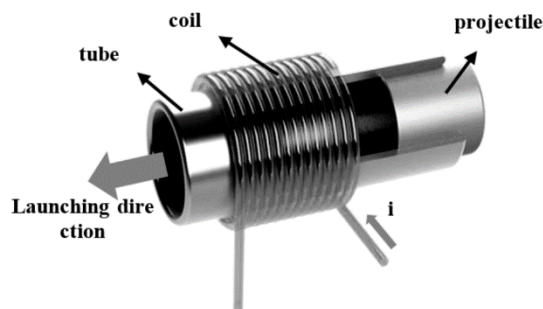
The Working Principle of a Coil Gun

A coil gun, also referred to as a Gauss gun, is an electromagnetic launcher that utilizes a series of coils to accelerate a ferromagnetic or conductive projectile to high velocities. The device operates on the principles of electromagnetic induction, where the magnetic fields generated by electric currents flowing through the coils exert a force on the projectile. The primary mechanism involves the sequential activation of these coils, with each coil energized in a precisely timed manner to ensure continuous acceleration along the length of the launcher. Coil guns are predominantly designed as multistage systems, in which multiple coils are arranged in series along the barrel to maximize performance. At each stage, the coil closest to the projectile is activated momentarily, creating a strong magnetic field that pulls the projectile forward. Once the projectile reaches the center of the active coil, the current is switched off to prevent magnetic drag, and the next coil in sequence is energized. This process is repeated at carefully calibrated intervals, with each subsequent stage further accelerating the projectile. The multistage design offers several advantages, particularly by maintaining high acceleration over a longer distance, thereby increasing the projectile's terminal velocity. Furthermore, the efficient use of multiple stages reduces energy losses that typically occur in single-stage systems, leading to improved overall energy efficiency.

Figure 1 illustrates the structure of the coil used in each stage of the coil gun.

Figure 1

General Structure of Coil Gun Stages (Abdo et al. ,2023)



In Figure 1, the tube represents the barrel through which the projectile moves, while the coil refers to the wire, typically made of copper, that generates the electromagnetic force responsible for propelling the projectile forward. The coil creates a magnetic field that accelerates the projectile, enabling its movement through the barrel.

Components and Structure

A typical coil gun consists of several interdependent components that work together to achieve electromagnetic acceleration. At the core of the system are the coils, also known as solenoids, which are composed of tightly wound conductive wires. When an electric

current flows through these coils, they generate magnetic fields capable of exerting force on a nearby ferromagnetic object. The projectile is usually made of materials such as iron or steel, which are strongly attracted to magnetic fields, allowing the coils to pull the projectile toward their center. To supply the necessary energy for rapid acceleration, the system relies on a power source, typically a set of capacitors or high-capacity batteries, which can discharge high-current pulses in short bursts.

The precise control of these pulses is critical for efficient operation, and this is managed by a switching system. The system typically includes sensors, such as photoelectric or Hall effect sensors, and control circuits that detect the position of the projectile and trigger the sequential activation and deactivation of the coils. This ensures that each coil is turned off before the projectile reaches its center to prevent deceleration, and that the next coil in sequence is energized at the right moment to continue accelerating the projectile. All of these components are housed within a barrel, which serves as a guiding structure, keeping the projectile aligned with the intended trajectory as it moves through the gun. The coordinated operation of these elements allows the coil gun to convert electrical energy into kinetic energy, propelling the projectile at high speeds.

Figure 2

Multi-Layer Coil Gun Base Components and Working Diagram (Lee et al. ,2013)

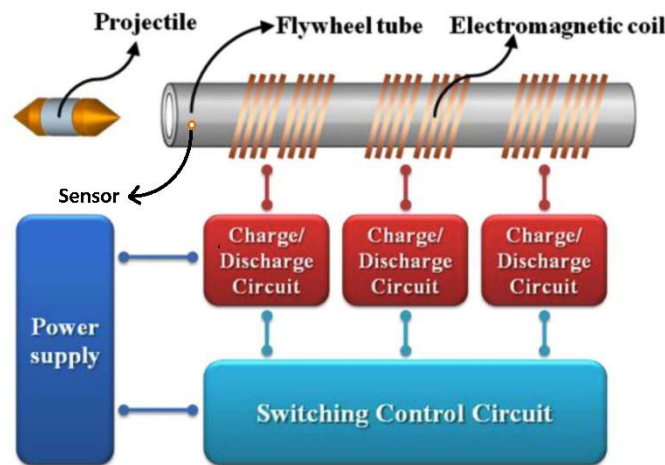
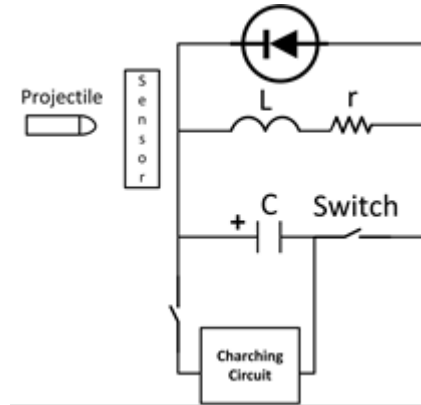


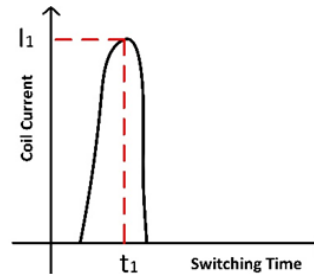
Figure 2 illustrates the structure of a multi-layered coil gun. In this figure, a single projectile is shown along with several key components: coils to generate a magnetic field, capacitor charging circuits, switching control circuits to produce an instantaneous magnetic field across the coils, and a power supply. Additionally, to detect the projectile's approach and activate the triggering mechanism, a sensor is positioned before each layer of the coil gun. This sensor setup enables precise timing and control, enhancing the efficiency of the magnetic propulsion as the projectile progresses through each stage.

Working principle of the coil gun

A classic coil gun comprises several key electrical components, including a coil, diode, charging circuit, switching element, and power supply. These elements work together to generate the magnetic force needed to propel a projectile through the coil gun's barrel. When the capacitor in the charging circuit discharges, the switching element rapidly directs current through the coil, creating a magnetic field that accelerates the projectile forward. The basic electrical circuit diagram of a coil gun is shown in Figure 3, illustrating how these components are integrated to achieve projectile motion.

Figure 3*The Electrical Circuit Used for Each Stage in a Coil Gun System*

When examining the working principle of a coil gun, it becomes clear that as soon as the sensor detects the projectile, it generates a triggering signal for the switching circuit. This signal activates the solid-state switch within the switching circuit, transferring the energy stored in the capacitor to the coil. The instantaneous current generated through the coil creates a strong magnetic field, drawing the ferromagnetic projectile into the coil. Once the projectile moves past the sensor, the switching circuit cuts off the current passing through the coil, ending the magnetization process. This switching action results in an instantaneous current through the coil, as illustrated in Figure 4. This cycle is then repeated for each stage of the coil gun, with the next sensor triggering the corresponding switching circuit as the projectile progresses. By precisely timing each stage's activation, the coil gun enhances both acceleration and energy efficiency, achieving a powerful and controlled launch.

Figure 4*Coil Gun Coil Switching Timing*

At time t_1 , the maximum current will flow through the coil, causing the highest level of magnetization to occur at this moment. If the projectile has passed through the center of the coil and the switch has not yet opened, the magnetic field within the coil will reverse, leading to a reversal of the magnetization. This causes the coil to exert a force on the projectile in the opposite direction, effectively attempting to decelerate or stop the projectile. The operation of the coil gun can be explained step by step, and this process can be broken down into four main stages for clarity. Each stage plays a crucial role in efficiently accelerating and directing the projectile, ensuring optimal performance of the system.

Magnetic Attraction and Acceleration

The operation of a coil gun relies heavily on the magnetic attraction generated by the coils. When an electric current passes through a coil, a magnetic field is created around it. If the coil is energized while the projectile is at a specific distance, the magnetic field attracts the projectile toward the coil. As the projectile approaches the center of the coil, the magnetic attraction increases and reaches its maximum at the coil's midpoint. This

phase is critical because the magnetic force provides the primary acceleration that propels the projectile forward. However, if the projectile remains in the coil's magnetic field for too long, it may begin to slow down due to the symmetrical nature of the magnetic force. Therefore, to maintain efficient acceleration, careful control over the duration and timing of the coil's energization is required.

Deactivation of Coils to Prevent Deceleration

To prevent deceleration, the coil must be turned off just before the projectile reaches the coil's center. If the coil continues to be energized after the projectile crosses the midpoint, the magnetic force will act in the opposite direction, slowing the projectile instead of accelerating it. The precise deactivation of the coils at the right moment is essential to avoid this opposing force. This is achieved through sensors and control circuits that monitor the projectile's position in real-time. Sensors, such as Hall effect sensors, optical sensors, or infrared detectors, are positioned along the barrel to detect the projectile's approach to the coil. Once the sensors identify the optimal point, they trigger the control system to deactivate the coil. This step ensures that the projectile exits the coil with maximum speed, preparing it for the next stage of acceleration.

Sequential Activation for Continuous Acceleration

In multi-stage coil guns, several coils are arranged along the barrel in sequence to provide continuous acceleration throughout the launcher. As the projectile moves through the first coil and reaches maximum speed, the subsequent coil is energized to further accelerate the projectile. This process repeats across multiple coils, with each stage adding to the kinetic energy of the projectile. The synchronized activation of coils is vital to maintain a smooth transfer of energy between stages. If the coils are not activated in the correct sequence, the projectile may lose momentum or experience irregular motion. The control system ensures that each coil is activated precisely when the projectile reaches the ideal point, providing uninterrupted acceleration throughout the length of the barrel.

Energy Storage and Discharge

Coil guns typically rely on capacitors to store the required electrical energy, as they are capable of releasing high currents in short bursts. These capacitors accumulate energy over time and discharge it rapidly when needed, producing intense magnetic fields. This quick release of energy is essential for generating the powerful magnetic forces required to accelerate the projectile efficiently. In some advanced systems, multiple capacitors are used in combination to form capacitor banks, ensuring that sufficient energy is available for each stage of the coil gun. Additionally, the discharge process must be precisely timed to coincide with the projectile's position within the coil. Any delay or misfire could result in a loss of energy, reducing the overall efficiency of the system. Some coil guns also incorporate energy recovery mechanisms to improve efficiency. For instance, the back electromotive force (back EMF) generated when coils are turned off can be redirected back into the capacitors, allowing for partial energy reuse. Proper management of this back EMF is crucial to prevent it from interfering with the operation of the control circuits. The efficient operation of a coil gun relies on the careful coordination of magnetic attraction, precise deactivation of coils, and synchronized multi-stage activation, allowing for the effective conversion of electrical energy into kinetic energy. Each stage of acceleration requires meticulous timing to ensure that the magnetic field reaches its peak when the projectile is optimally positioned within the coil. To avoid deceleration, the coil must be deactivated just before the projectile reaches the midpoint, as any delay would result in opposing forces. In multi-stage systems, multiple coils are arranged sequentially along the barrel, with each coil activating at the precise moment the projectile reaches it, ensuring smooth energy transfer and continuous acceleration. Capacitors play a crucial role by storing and rapidly releasing electrical energy in high-current bursts, aligning with the projectile's movement to generate intense magnetic fields. Advanced systems may use capacitor banks to ensure sufficient energy availability,

while energy recovery mechanisms, such as the reuse of back electromotive force (back EMF), further improve efficiency. Performance optimization also requires addressing practical challenges related to heat dissipation, power stability, and material selection. The rapid discharge of high currents generates significant heat, which, if unmanaged, can impair performance or damage components. To prevent this, advanced designs incorporate cooling systems or heat sinks. Additionally, the continuous charge-discharge cycles of the capacitors demand a stable and reliable power supply to ensure consistent operation. The material properties of the projectile are equally important, as high magnetic permeability is needed for maximum attraction, while a lightweight structure helps achieve higher velocities. In some designs, non-magnetic or conductive projectiles are used with customized coil configurations to meet specific performance requirements. By effectively managing magnetic forces, optimizing energy storage, and incorporating advanced control mechanisms, modern coil guns push the boundaries of electromagnetic acceleration, offering a robust platform for both research and practical applications.

Coil Guns Current and Future Perspectives

Coil guns, classified as gunpowder-free weaponry, continue to be developed and refined in various research and experimental contexts. They offer distinct advantages, including low projectile costs, extended barrel life, and the ability to increase muzzle velocity by adding multiple stages along the barrel. Currently, coil guns are predominantly used in experimental and demonstration settings, such as scientific research, non-lethal defense applications, and educational laboratories, where they serve as practical examples of electromagnetic propulsion principles. For instance, their deployment in scientific environments showcases their capacity for precision and controlled acceleration, while educational demonstrations highlight their potential as a non-traditional propulsion system. Given these attributes, coil guns are seen as promising candidates for future applications in defense, industrial material processing, and even space exploration. Their potential to revolutionize various fields continues to grow as new research in materials, energy efficiency, and switching technologies advances.

Current Status of Coil Guns

Coil guns, also known as electromagnetic guns or Gauss rifles, have shown significant potential in various fields, including military applications and scientific research. Currently, their use is primarily limited to experimental setups and educational environments, where they effectively demonstrate the core principles of electromagnetism. These devices function by using electromagnetic coils to accelerate ferromagnetic projectiles, eliminating the need for traditional propellants like gunpowder. Recent progress in coil gun technology has focused on improving the design of electromagnetic coils, capacitor banks, and switching circuits. Innovations in high-energy capacitors, more efficient switching mechanisms, and better cooling techniques have led to improved system performance. Despite these advances, coil guns are still largely restricted to controlled settings for non-lethal defense, scientific demonstrations, and hobbyist applications, with limited adoption in commercial or military settings. There are still a few challenges that need to be addressed to unlock the full potential of coil guns, particularly in terms of energy efficiency, scalability, and practical implementation. A key issue is the high energy consumption required for larger projectiles and higher velocities. Furthermore, achieving precise control over projectile acceleration and targeting remains a significant engineering challenge.

Future Prospects of Coil Guns

The future of coil guns offers intriguing possibilities, with the potential to revolutionize numerous sectors, particularly in defense, space exploration, and medical technologies. As advancements in coil gun design continue to address current limitations—such as energy efficiency, precision control, and scalability their application scope is expected

to broaden significantly. These future applications of coil guns can be categorized into four main domains, each representing a promising area of impact where electromagnetic acceleration technology could provide substantial advantages.

Military and Defense

The potential for coil guns to impact military and defense applications is significant, particularly in naval and space defense systems. The advantage of launching projectiles without the use of explosive propellants offers safety benefits, such as reduced risks related to weapon storage and transportation. Additionally, coil guns may be adapted for kinetic energy weapons, potentially replacing conventional firearms for non-lethal crowd control or enabling more precise targeting in combat situations.

Space Exploration

One of the most promising applications of coil gun technology lies in space exploration. Unlike traditional rocket propulsion systems, which rely heavily on fuel, coil guns could provide a more energy-efficient means of launching payloads into orbit. This innovation could drastically reduce the cost of space missions and facilitate the transport of materials for space stations, satellites, or even lunar or Martian colonies.

Energy and Efficiency Enhancements

Future advancements in energy storage technologies will likely lead to significant improvements in the efficiency of coil guns. Innovations in high-density energy storage systems, such as superconducting magnetic energy storage (SMES) and advanced capacitors, could enable the development of coil guns capable of launching heavier payloads at greater speeds and with enhanced accuracy. Furthermore, advancements in power electronics may minimize energy losses during operation, further improving system efficiency.

Medical Applications

The principles underlying coil gun technology are also being explored for medical purposes, particularly in drug delivery and tissue repair. Electromagnetic propulsion could enable precise, non-invasive delivery of medical capsules or micro-robots to specific locations within the human body. This application holds potential for minimally invasive procedures, targeted therapies, and improved patient outcomes, while also reducing recovery times.

Conclusion

In summary, although coil gun technology remains in the early stages of development, its potential applications are extensive and span multiple fields. With continued advancements in materials science, energy storage, and electronic control systems, coil guns are expected to play an increasingly significant role in various industries. As innovations in high-capacity capacitors, efficient switching circuits, and durable magnetic materials progress, the practical capabilities of coil guns will likely expand, making them viable for an even broader array of uses. Ultimately, coil guns stand on the cusp of pushing the limits of electromagnetic propulsion, offering transformative and sustainable possibilities across defense, space exploration, and scientific research, among other applications.

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