Max Megee

Honors University Physics II

Dr. John Stewart

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Elements of a Successful Coil Gun

A coil gun is a simple application of the magnetic force on two dipole moments in a magnetic field. All coil guns need three components to operate smoothly. The first is a solenoid, or coil, that is wound around the launching barrel. The second is a source of high voltage that causes a high current to quickly flow through the solenoid (Fullem and Benedict 2009, 181). The final component needed is a projectile with ferromagnetic qualities.

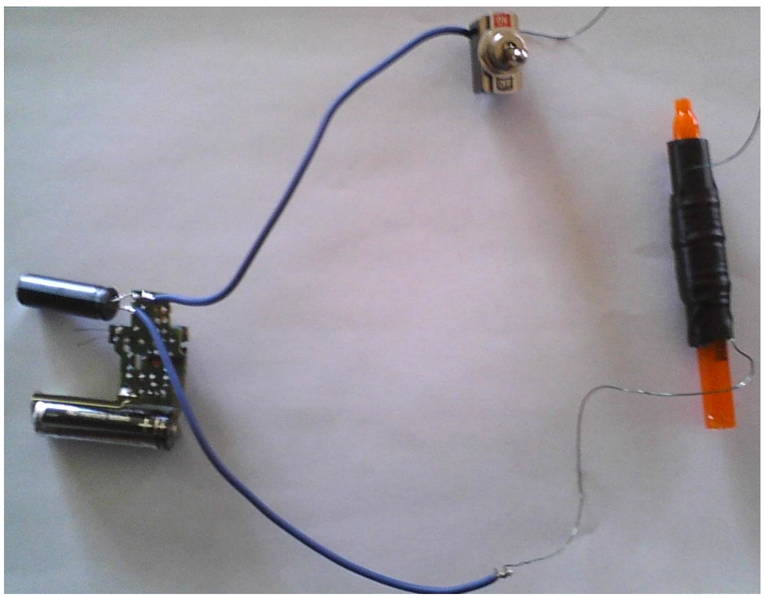
When current flows through a finite solenoid, a dipole magnetic field is created. This field possesses a dipole moment parallel to the cylindrical axis of the solenoid. Therefore, the solenoid acts like a permanent magnet with a non-uniform magnetic field with its moment aligned in the direction of fire. This is a key element in launching the ferromagnetic projectile, and will be discussed later. The coil gun built for this project implements three separate, replaceable solenoids, each wound with 200 turns of 24 gauge wire, and each with differing layers of wire and differing lengths. According to the infinite solenoid approximation, $B = \mu_0*(N/L)*I$, these manipulations produce differing strengths of magnetic fields for each solenoid, since the number of turns (N) and the amount of current (I) were equal for each solenoid.

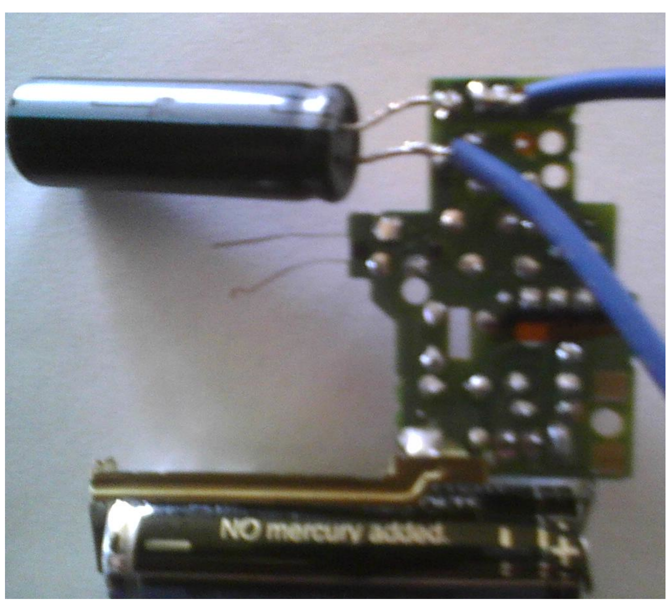
The high voltage source used to create the dipole field in the coil was a 100μF capacitor from a disposable camera flash circuit. This capacitor charges via a 1.5V AA battery to around 250V per launch. Using the equation for potential energy stored in a capacitor, $U = (1/2)*C*\Delta V^2$, where C is the capacitance in farads and ΔV is the potential difference in volts, this creates a potential energy of 3.1J if all of the voltage is discharged when the gun is fired. A capacitor is an excellent source of voltage for a coil gun because it provides a high current to the solenoid. It is also very important, as will be discussed later, that the capacitor provides an exponentially decreasing current to the solenoid in the form of $I = I_0*e^{-t/\tau}$, where I_0 is the initial current, t is the time, and τ is the time constant determined by the capacitance of the capacitor and the resistance in the circuit. This time changing current keeps the projectile from being pulled back into the center of the solenoid after it has been set in motion.

The final component needed for an operational coil gun is a ferromagnetic projectile. This component is extremely important to the physics of the coil gun because an external magnetic field induces the second dipole moment needed for the magnetic force upon the ferromagnetic material. The magnetic field that is present within a material is $B = \mu_0*(H + M)$, where H is the applied field and M is the magnetization of the material (Coren 1989, 76). The magnetization is proportional to the applied field by a term χ_m. This term is called the magnetic susceptibility, and is "the ratio of induced moment to applied field," or in variable form, $\chi_m = M/B$ (Purcell 1985, 421-422). This χ_m term is determined from the subatomic chemistry of each element, and ferromagnetic materials are unique from other materials by this single term. Other materials' magnetic susceptibility is less than 1, but ferromagnetic elements like iron, nickel, and cobalt possess magnetic susceptibilities greater than 1 (Coren 1989, 77). This quality produces a much greater magnetic field and dipole moment within the projectile; thus the projectile experiences a greater force from the solenoid. One last quality about ferromagnetic materials that should be mentioned is that the dipole moment induced within the material is in the same direction as the moment of the applied magnetic field. The projectile used for this project was a ferromagnetic screwdriver bit.

Finally, putting all of the components together, the coil gun launches the projectile via the physics of the magnetic force on two magnetic dipole moments. As stated before, the high current from the capacitor produces a strong magnetic dipole moment on the solenoid directed down the axis of the launch tube. The magnetic field from the coil also induces a dipole moment on the ferromagnetic projectile in the same direction. These two dipole fields may be visualized as two permanent magnets with aligned dipole moments. If a magnetic moment experiences a uniform applied magnetic field, then it experiences zero magnetic force. However, a dipole moment that is aligned with a non-uniform applied field experiences a force toward stronger field. This demonstrates the importance of a finite solenoid, as well as an exponentially decreasing current. The finite solenoid produces a non-uniform magnetic field at its two ends. Therefore, the ferromagnetic projectile that is loaded outside of the coil experiences a force toward stronger field, or in other words, a force towards the center of the coil. However, if the current flowing through the coil were allowed to remain constant, then once the projectile reached the center of the coil it would experience a backward force opposing its motion. Because capacitive circuits have exponentially decreasing current, by the time the projectile reaches the center of the tube the current, and thus the field, is small enough to produce a negligible effect on the motion of the bullet, and momentum carries the projectile out the end of the launch tube.

The following diagrams are pictures of the coil gun constructed for this project. The original flash circuit used a AA battery to charge the capacitor, and a small switch to discharge it through the flash. For the construction of the coil gun, the flash was removed, and the switch fixed to an open position. Two wires were soldered to the two leads of the capacitor, and one of these wires was connected to a new switch. At this point, each solenoid can be inserted into the circuit by connecting one lead to the switch, and the other to the unused wire leading to the capacitor. Current flows from the negative lead of the capacitor, so the right hand rule must be implemented to ensure that magnetic field is produced in the desired direction. With this configuration, the capacitor can be charged when the coil switch is open, and discharged through the solenoid when the switch is closed. To operate the coil gun, simply connect the desired solenoid to the circuit, charge the capacitor with the switch open by inserting the battery, load the screwdriver bit, and flip the switch. With all three elements – solenoid, high current, and ferromagnetic projectile – this basic coil gun launches successfully.





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