

# Laboratory Project 2: Electromagnetic Projectile Launcher

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**Abstract**-You will build a electromagnetic paperclip launcher consisting of a hand-wound coil, capacitor, resistor, and switch. With the switch in its resting position, the capacitor will charge up. When the switch is activated, the capacitor will be connected to the hand-wound coil, which surrounds a small plastic tube into which a small fragment of a paper clip has been inserted. The capacitor and coil constitute a nearly critically damped circuit that causes a rapidly rising and then falling current pulse to create a magnetic field that draws the paperclip fragment into the center of the coil and then disappears. With the velocity attained as it moves to the center of the coil, the paperclip exits the tube and travels distances as large as 20 feet.

## I. PREPARATION

For Lab 2, which will last about three weeks, you will need the parts listed in Table I. You may purchase these parts from the stockroom next to the lab or purchase them elsewhere.

TABLE I  
PARTS LIST FOR LAB 2

Item	Qty	Description
1	1	Coil Kit (small plastic tube, cardboard end-pieces, and wire)
2	1	1 $\mu\text{F}$ Capacitor
3	1	Resistor (value determined by calculations)

## II. LEARNING OBJECTIVES

- 1) Learn how to solve  $RC$  and  $RLC$  circuits using differential equations.
- 2) Learn how to calculate maximum current flow in  $RC$  and  $RLC$  circuits.

## III. INTRODUCTION

For many years, scientists and engineers have explored electromagnetic (EM) launchers for possible applications such as launching projectiles or space vehicles. In 2012, the 16th International Symposium on Electromagnetic Launch (EML) Technology was held in Beijing, China. Sponsored by IEEE, the symposium attracted 250 participants.

The operation of the EM launcher is based on energizing electromagnets that pull a projectile forward and then turn off. The two main kinds of EM launchers are called rail guns and coil guns. In rail guns, a conducting projectile is placed between two parallel rails and a short high-current pulse is applied between the rails. The resulting magnetic field forces move the projectile along the rails, launching it with a very high velocity. A coil gun consists of a series of coils (solenoids) with the projectile placed inside. Applying a short high-current pulse to the coils produces magnetic field forces that move the projectile through the coils and launch it with a very high velocity. In both rail guns and coil guns the short high-current pulses are produced by charging banks of capacitors and then discharging them into the rails or the coils. In rail

guns, current flows through the projectile and an arc occurs between the rails and the projectile, while in coil guns, there is no electrical contact between the coils and the projectile.

Conventional propulsion systems can produce launch velocities up to about 1.6 km/s. Rail guns have accelerated gram-size projectiles to almost 6 km/s. Researchers at the Sandia National Laboratories in Albuquerque, New Mexico (R. J. Kaye, et al., "Design and performance of Sandia's contactless coilgun for 50 mm projectiles," IEEE Transactions on Magnetics, vol. 29, January 1993, pp. 680-685) designed a coil gun expected to produce velocities of 3 km/s in 50 mm diameter, 200 - 400 gram projectiles. These much higher velocities are called hypervelocities. The Sandia launcher consisted of 40 stages. Each stage consisted of a 30  $\mu$ H coil, a 176  $\mu$ F capacitor, a switch, and a cable. A laser-ranger tracked the location of the projectile in the launcher and was designed to switch each capacitor to discharge at the proper time to accelerate the projectile. The capacitors were charged by a 15 kV voltage source to store 20 kJ of energy. The Sandia researchers hoped eventually to achieve velocities in the range of 4-6 km/s, which is sufficient to launch payloads into low earth orbit at reasonable cost. A 960-m long coil-gun launcher consisting of 9,000 coils could accelerate a 1200-kg launch package to deliver a 100-kg payload into low orbit.

The challenges of switching huge current pulses quickly have perhaps been larger than expected in 1993, but the 2012 EML Symposium overview stated "... electromagnetic launchers have even reached sufficiently high speeds to put objects in orbit around the earth." Progress continues.

In this project, you will construct and test an EM launcher circuit, shown in Fig. 1, that is similar in many respects to the coil guns described above, but to avoid the time, expense, and danger involved in constructing a device to launch larger projectiles, yours will be a miniature coil gun consisting of one small coil, shown in Fig. 2, and the projectile will be a short (3-4 mm) segment of wire from a standard paper clip. Because the magnetic forces on the projectile would force it to the center of the coil if a steady current were applied, you will need to design a circuit to produce a short current pulse, and to get sufficient force for launching, the current must be high. Therefore you will also design a circuit to discharge a capacitor into a coil to produce a short, high-current pulse. This project is but one example of many ways in which voltage and current pulses are employed in a variety of devices.

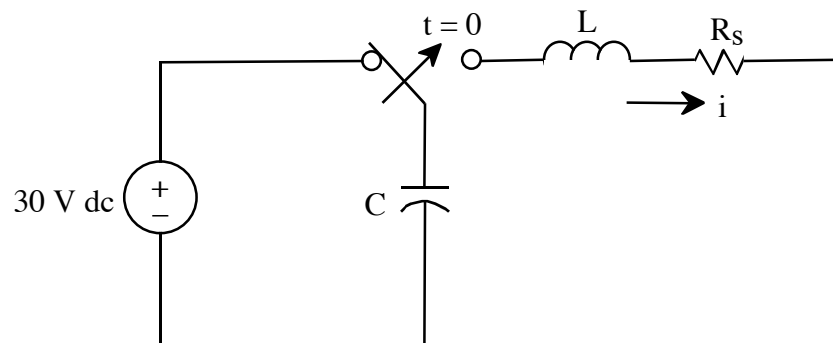


Figure 1. Circuit diagram for the EM launcher.

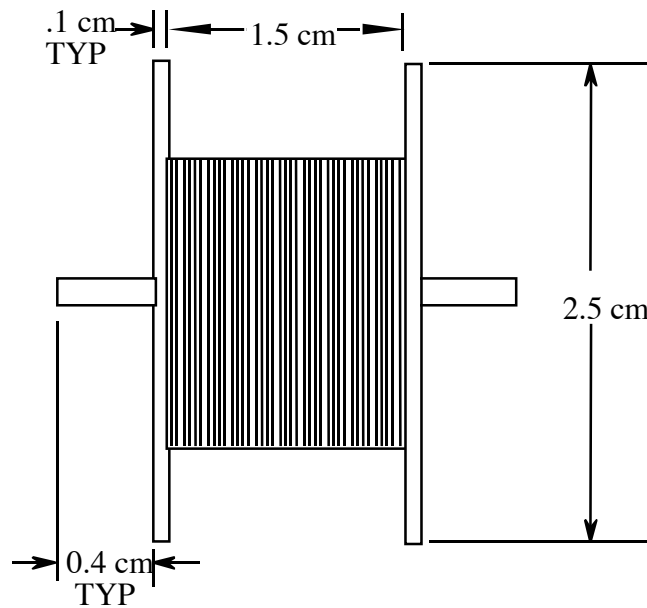


Figure 2. Configuration of the coil.

#### IV. CAPACITOR CHARGING CIRCUIT

The left side of the circuit shown in Fig. 1 is the charging circuit for the capacitor. As shown, however, the circuit is lacking a resistor to limit the current that flows into the capacitor when it is charging. In theory, the current flowing in the capacitor would be infinite when charging starts because the voltage on the capacitor is zero volts. Placing a resistor,  $R$ , between the power supply and the capacitor limits the current, and the limit may be any value we desire, allowing even a small battery to be used for the launcher.

Analyze the capacitor charging part of the launcher circuit by writing a differential equation for the capacitor voltage,  $v_C$ . The equation will involve the power supply voltage,  $V_S$ , the added resistor  $R$ , and capacitor  $C$ .

After solving the equation for  $v_C$  using the general form of  $RC$  solution, find an expression for the charging current,  $i_C$ . Determine the value of  $R$  that would limit the maximum current to 10 mA, (a value that a small battery could easily supply), for a 1.5 V battery used in place of the 30 V power supply, (a standard battery value). Use a convenient value of  $C = 100 \mu\text{F}$ , (not the value for the final launcher).

Using  $C = 100 \mu\text{F}$ , the nearest standard value to  $R$ , and a function generator outputting a 1.5 V square wave at 10 Hz, (to simulate battery and switch), build the charging circuit. Using an oscilloscope, measure the voltage across  $C$  versus time and carefully draw a picture of it in your laboratory notebook, including scales and any other important information. Using cursors on the oscilloscope, measure two points on the charging waveform and determine the time constant of the charging waveform. Compare it with the calculated value of  $\tau = RC$ .

If you decide to use your launcher circuit at home, you can use a battery and your  $R$  to charge the  $C$  in your launcher. You may need to use a higher voltage, however. For example, you can use several 9 V batteries in series. The voltage must be less than the voltage rating of the  $C$ , though, and the value of  $R$  for a given current limit will scale with the battery voltage. Note that the  $R$  value for a given current limit, though, is independent of the  $C$  value. As for the optimal  $C$  value, the following sections delve into that issue.

## V. ANALYSIS OF LAUNCHER CIRCUIT

Analyze the launcher circuit shown in Fig. 2 by finding the classical time-domain solution. That is, write the second-order differential equation for the current  $i$ , determine the appropriate initial conditions, solve the equation, and use MATLAB® to plot  $i$  versus time. To observe the types of solutions that are possible for the launcher circuit, find solutions for two cases:  $C = 2,000 \mu\text{F}$  and for  $C = 2,000 \text{ nF}$ , (i.e.,  $2 \mu\text{F}$ ). Use nominal coil values of  $L = 80 \mu\text{H}$  and coil resistance  $R_s = 0.7 \Omega$ . Write separate MATLAB® programs to plot  $i$  versus time for  $C = 2,000 \mu\text{F}$  and for  $C = 2,000 \text{ nF}$ . Explain why the waveform of  $i$  for  $C = 2,000 \mu\text{F}$  is so different from the waveform for  $C = 2,000 \text{ nF}$ .

## VI. CONSTRUCTION OF COIL FOR LAUNCHER CIRCUIT

Procure a 3.0 cm nonmetallic tube with an inside diameter just slightly larger than the wire diameter of a standard paper clip, two nonmetallic disks about 2.5 cm in diameter, and five meters of 26 gauge insulated wire. (This is the coil kit available in the EE Stockroom.)

Precise design of the coil is too complicated for you to undertake in this short project, but here are some factors to consider. The force on the projectile increases as the gradient of the square of the magnetic field produced by the current in the coil. The strength of the magnetic field, and therefore the gradient, increases with the number of ampere-turns. The gradient also changes with the ratio of the length to the diameter of the coil. For maximum acceleration, the current in the coil must be zero by the time the projectile passes the center of the coil. Although the equation for the magnetic field along the axis of the coil is fairly straightforward, the equations of motion of the projectile are too complicated for you to solve in the time available for this project. If you wish, you may try some different coil configurations (long and slender, short and fat). Otherwise, you may use the approximate configuration and dimensions shown in Fig. 2, which have been found to give good results with about five meters of wire.

After you wind your coil, sand the insulation off the ends of the wires so good contact with the launcher circuit can be made. The current that flows in the coil is quite high during launch, (as you can verify by calculations), so it is vital to minimize the contact resistance.

Using an  $RLC$  meter in the lab, measure the value of  $L$  for your coil. Measure the resistance,  $R_s$ , of the coil using both the  $RLC$  meter and a multi-meter. Compare the values obtained by each method. Do they agree?

You are now ready to compete with other students to see who can launch a fragment of paper clip the farthest. For the projectile, use a 3 to 4-mm length of wire cut from a standard paper clip. Your TA will supply the rest of the launcher circuit that is pre-equipped with a switch and capacitors, saving the expense of procuring large capacitors. Launch the projectile by discharging the capacitor across the coil. Record the distances for three launchings.

## VII. CALCULATION OF KEY LAUNCHER VALUES

Record the value of capacitance used in the launcher circuit. In theory, an optimal launcher might use critical damping to produce the fastest possible pulse. Determine the value of capacitance that would yield critical damping for your coil and compare it with the value of capacitance in the launcher circuit. Comment on the difference and explain what you think are the tradeoffs involved.

For the actual  $R$ ,  $L$ , and  $C$  values used in the launcher circuit, use calculus to find the time  $t_{i \max}$  at which the maximum current flows in the coil. Recall that a maximum occurs when a derivative is equal to zero. By substituting  $t_{i \max}$  into the equation for the coil current, find the

maximum coil current in amps. Finally, using the component equation for the inductor and Ohm's law for  $R_s$ , find the voltage across the coil when the current is at its maximum:

$$v_L = L \frac{di_L}{dt} \quad (1)$$

### VIII. NOTEBOOK AND REPORT

Turn in a copy of your laboratory notebook pages and a separate formal report. Refer to the grading information on the course website for the section numbering to use while writing the formal report. Use the IEEE format for typesetting. Information about the IEEE format, including a template file, is available on the course website. Additional information about writing the report and keeping a notebook is listed in the *Course Procedure* on the course website. Note that Matlab<sup>®</sup> plots, if they are listed in the contents of the report, must appear both in the laboratory notebook *and* the formal report.