# DESIGN OF A SINGLE STAGE SUPERSONIC RELUCTANCE COILGUN (RCG)

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*Abstract*

This paper presents a simple technique to design a single stage supersonic electromagnetic reluctance coilgun (RCG) for use in defense applications. Using a hybrid technique for coil optimization based on analytical, finite element analysis (FEA) and circuit simulation, the design parameters are determined and analyzed. Further, the characteristics of the selected key components such as power supply and switching devices are presented. The RCG circuit is also presented and results obtained from Pspice model are interpreted to optimize the pulse shape through the appropriate selection of the circuit components. The RCG is tested at several power supply voltages and performance characteristics of the RCG are also presented.

## I. INTRODUCTION

In the late 1980's, an electromagnetic accelerator was built and pioneered by the Norwegian scientist Krristian Olaf Birkeland [1]. Since then, extensive research activities have been carried out in order to explore the possibility of utilization of such technology in many applications [2,3,4]. From a military point of view, coilguns are attracting more attention to be used as an alternative to the explosive/chemical propulsion weapons due to their higher muzzle velocities with silence firing and less manufacturing cost for the kinetic energy projectiles.

In general, there are two distinct types of coilgun [4, 5]. The first is the reluctance coilgun which is basically a solenoid that can launch iron or steel projectiles by precise timing of the coil current. This type of coilgun uses the attractive ferromagnetic properties of the projectile to generate acceleration. The second type is the induction coilgun in which the accelerating force is repulsive and generated from the eddy current induced in the non-ferromagnetic projectile due to the current build up in the coil. In this research the design of the reluctance coil gun is discussed.

## II. OBJECTIVE

The objective from the design exercise is to develop a theoretical model and to obtain a performance data that can be used for model verification and assessment. Accordingly at this stage, a scaled down demonstrator is considered rather than the design of a large-scale models. The design technique is implemented on a small caliber (5.56 mm) projectile and compared to the available M16 rifle. The design data for the coilgun can then be experimentally validated and compared to those obtained from the M16 test results.

## III. DESIGN REQUIREMENTS

The proposed coilgun is designed to handle small caliber ammunitions such as those used for M16 (5.56 mm) rifle. Such a gun would be an ideal model due to the following main reasons; Simple construction, testing and handling, energy sources, triggering devices and other accessories can be easily procured, ballistic effect assessment & result comparison.

The design of the gun can be customized for one or more of the following requirements; Hand held remote gun, ring mounted gun & self contained package.

## IV. DESIGN CALCULATIONS

The specifications of the M16 bullet given in **Table 1** are used in the preliminary calculations for the electromagnetic design of the coil. A cylindrical projectile is considered for simplicity of manufacturing, optimum flux linkage and electromagnetic force build up. Hence a steel bullet of 2.60 g mass would have 5.56 mm in diameter and 14.00 mm length assuming mass density of 7700 kg/m3 for the steel. A set of design variables are defined, these are:

Coil length, $C_l$ , Coil inner diameter, $C_{id}$, Coil outer diameter, $C_{od}$, Winding diameter, $W_d$

**Table 1**: Main Specifications for 5.56 bullet under consideration (M16 rifle)

| Calibre, (mm) | Mass, (g) | Muzzle velocity (m/s) | Types |
|---|---|---|---|
| 5.56 | 2.6 | 960 | Steel core |

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The aim of this research is to design a single stage supersonic coilgun throughout the best combination of the above mentioned design variables. This can be achieved by maximizing the electromagnetic field intensity, generated by the current passing through the coil windings, hence maximizing electromagnetic force exerted on the projectile to achieve higher muzzle velocities per single stage. Therefore as a prerequisite, the velocity of the projectile at the exit of the single coil stage is set to 350 m/s and the coil axial length is set to the calculated projectile length which is 14.00 mm. For mechanical support of the coil and rigid coil construction, enough tube thickness (coil former) should be considered, hence the coil inner diameter is set to 8.00 mm.

An exploded view of the coilgun is shown in **Figure 1**. When the coil is energized, the projectile is experienced a minimum force at the coil edges. However, the force is increased while the projectile is advancing through the coil until a maximum force is reached when the projectile front face is at the coil centre (**Figure 2)**.

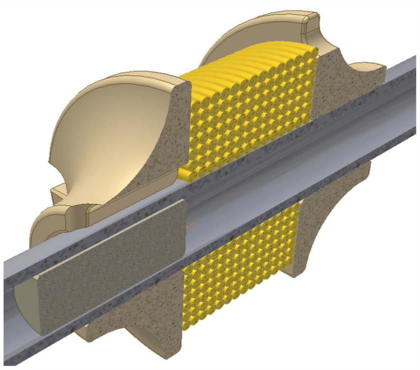

**Figure 1**: Exploded view of the coilgun.

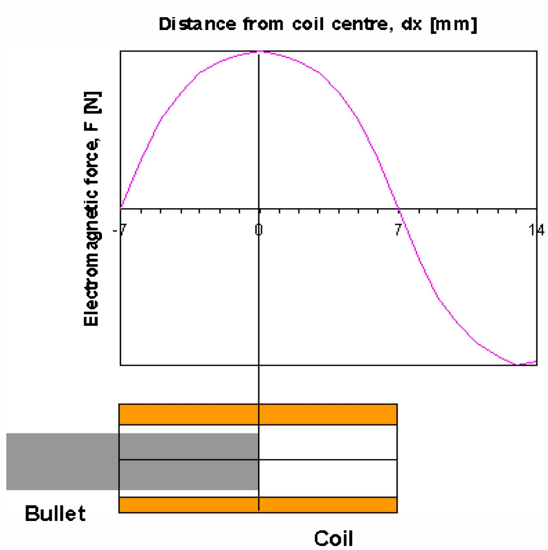


**Figure 2**: Typical diagram for electromagnetic force vs. distance from coil centre

To determine the winding diameter and coil outer diameter, a set of ranges are defined for both variables and an optimum design point is located where the maximum magnetic field intensity is achieved using the following analytical solution [3].

$$H = \frac{N_t I (C_{od}/C_l)\left[\sinh^{-1}(C_{od}/C_l) - \sinh^{-1}(C_{id}/C_l)\right]}{\left[C_{od} - C_{id}\right]} \qquad (1)$$

where $N_t$ is the total number of turns and I is the coil current. If a unit voltage is applied from a power source, then the current drown can be calculated as follows:

$$I = \frac{V_S}{R_C + R_S} \qquad (2)$$

where $R_S$ is the source internal resistance and for the preliminary calculations 0.1 $\Omega$ is considered and $R_C$ is the coil resistance at room temperature and can be calculated as follows:

$$R_C = \frac{4\rho(C_{od}^2 - C_{id}^2)C_l}{W_d^4} \qquad (3)$$

where $\rho = 1.7 \times 10^{-8}\,\Omega.m$ is the coil resistivity for copper at room temperature. The results obtained from the analytical solution for the range of 10 – 58 mm of coil diameter at different winding diameter (0.50, 1.00, 1.50 & 2.00 mm) are shown in **Figure 3**.

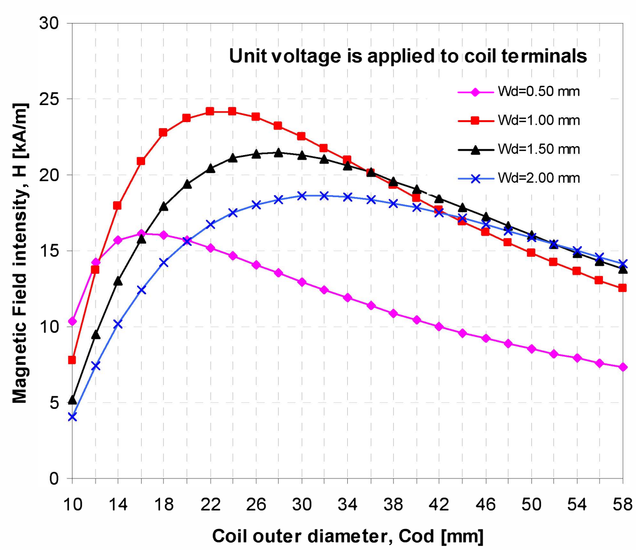


**Figure 3**: Analytical Optimization of coilgun parameters.

After determining the main design variables for the projectile and the coil, it is now possible to proceed with the design calculations of the RCG.

The electromagnetic acceleration required to accelerate the bullet from static to the speed of 350 m/s for a distance $x$ = 7.00 mm which is halfway of the coil length can be found as follows:

$$a = \frac{v^2}{2x} \tag{4}$$

and the force $F$ exerted on the bullet can be determined as follows:

$$F = ma \tag{5}$$

Once the force is calculated, it is required to determine the current that is capable of producing such a force. To do so, FEM model was developed using ANSYS package to accurately predict the force at the stage when the bullet is at halfway of the coil i.e. when it forms a combined core (air and steel). The problem is solved iteratively where current density applied at coil element is varied until the required electromagnetic force is satisfied. For optimum performance of the coilgun, the bullet material is selected from a high magnetic permeability and high magnetic saturation material such as silicon iron boron. Hence, a non-linear solution is performed where the *BH* curve for the material is defined in the FE model. The 3D FE model for the coil and the bullet is shown in **Figure 4** whereas the flux intensity distribution and magneto force FE results are depicted in **Figure 5** and **Figure 6** respectively.

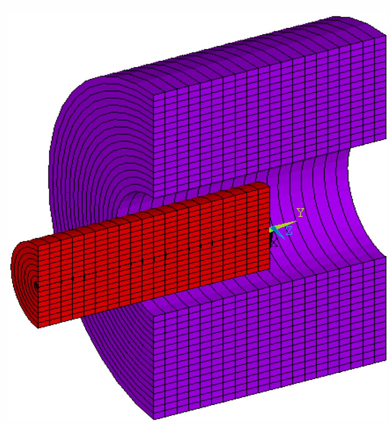

**Figure 4**: FEA Model for the coilgun

It is found from the FEA that a current density of $2500\ A/mm^2$ is required to produce the required force which is 22750 N. The acceleration is calculated from **Eq.** (5) and is found to be 8750000 m/s$^2$. Assuming a constant acceleration per coil and neglecting the bullet friction and air drag, the muzzle velocity at the exit of a multistage coilgun can be calculated as follows:

$$v = \sqrt{v_0^2 + aC_l} \tag{6}$$

It is found that from the above equation that eight stages are required to achieve a muzzle velocity of 989 m/s which is close to that obtained from the M16 rifle as depicted in **Figure 7**.

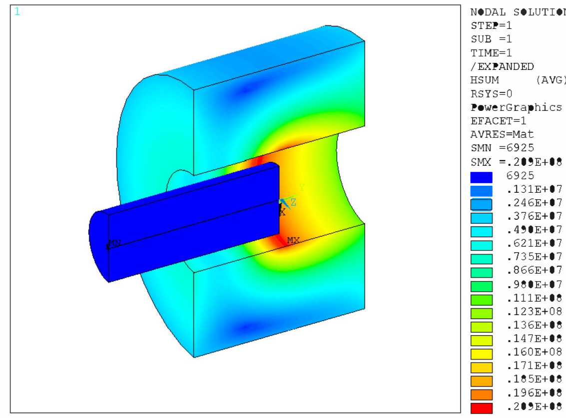


**Figure 5**: FE magnetic flux intensity distribution

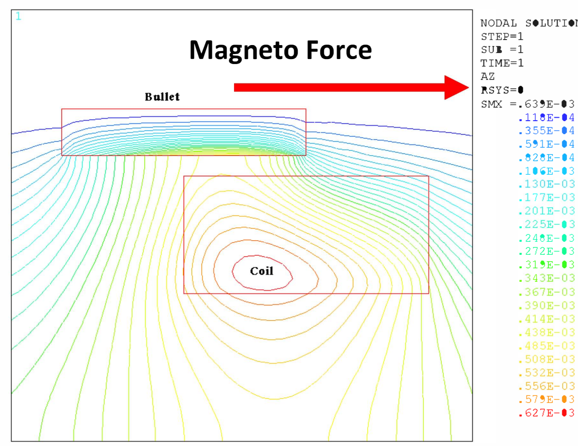


**Figure 6**: FE flux and magneto force

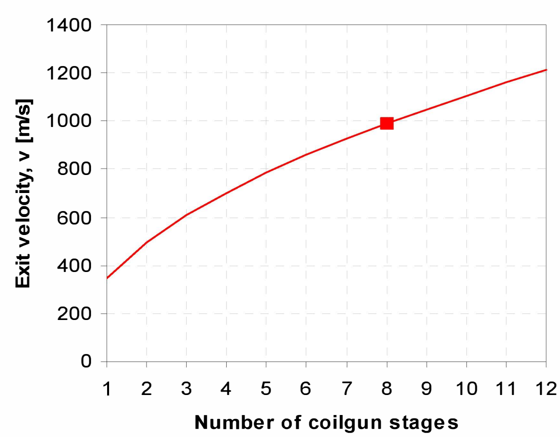


**Figure 7**: prediction of total number of coil stages to achieve the target muzzle velocity of the 5.56 ammo

# V. RCG EQUIVALENT MODEL AND SIMULATIONS

The RCG was simulated using Pspice to predict the performance characteristics of the coil under certain conditions as shown in **Figure 8**. The model has assisted in determining the best circuit parameters combination in order to achieve suitable current wave form and acceptable terminal voltages across the switching devices in order to avoid any damages to the circuit components during firing trails. For triggering purposes, an open loop scheme was used for circuit simplicity. The pulse duration was set for 14 $\mu$ s to to minimize the suck back effect and to allow for the current in the coil to be dissipated exactly at the time when the bullet front face reaches the coil centre.

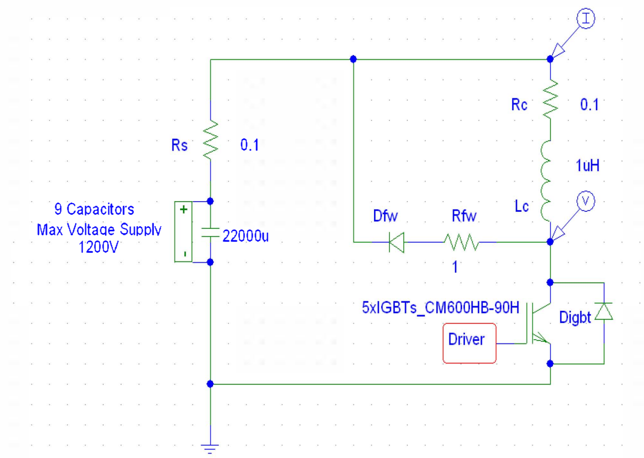


**Figure 8**: Pspice Model for the RCG

The results obtained from the Pspice model for both coil current and voltage across the switching devices are depicted in **Figure 9**.

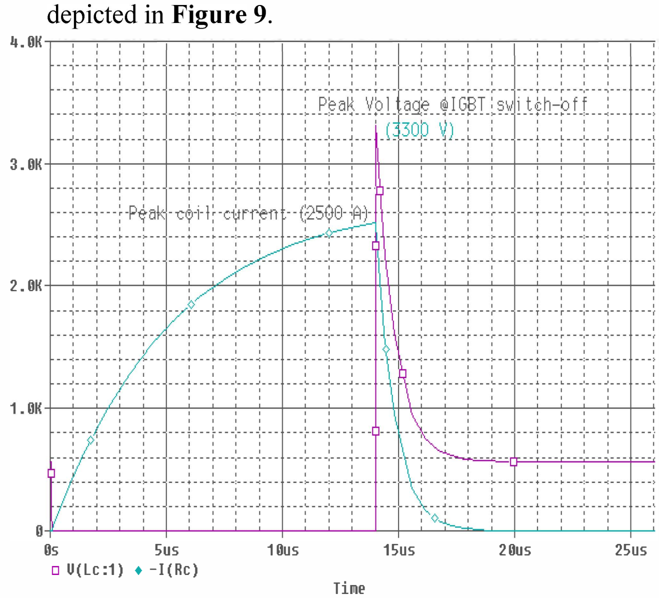


**Figure 9**: Coil current & voltage (simulated)

# VI. RESULTS ANALYSIS

Using the Pspice model, it was possible to perform the fine tuning for the circuit component values in order to achieve suitable waveforms. It is found from **Figure 9** that the current shape plays a vital role in the muzzle velocity of the projectile. The coil current was designed to drop as fast as possible as the IGBT is switched off by using a freewheel diode with resistor [6]. It is noticed that increasing the value of the resistor that is connected to the freewheel diode helps the current to fall in a short duration. However, the voltage across the IGBT increases considerably hence increasing the chances of damaging the IGBTs as the voltage is exceeding the rated voltage of the IGBT which is 4500V (VCE) for the selected module (Type CM600HB-90H). Therefore compromised values of the circuit components were carefully selected in order to achieve the required design specifications while maintaining the components integrity.

# VII. KEY COMPONENTS SELECTION

## *A. Power Supply*

The power supply for the RCG is mainly consisted of nine aluminium electrolytic capacitors connected both in series and parallel in order to achieve the required voltage level. The main characteristics of the capacitors are presented in **Table 2**.

**Table 2**: Main characteristics of the capacitors utilized to operate the RCG

| | |
|---|---|
| Type | Aluminium Electrolytic |
| Manufacturer and Code | KPS223M2G31TM |
| Rated Voltage (each) | 400 VDC |
| Surge Voltage (each) | 500 VDC |
| Capacitance (each) | 22000 uF |
| Quantity | 9 |

For charging purposes, a special charger was developed to charge the capacitor bank to the required level. To achieve the required velocity, a voltage of 565 VDC has to be maintained directly through the charger. However, in most cases, the voltage was controlled and increased gradually for safety purposes.

## *B. Switching Devices*

The IGBT was selected for switching the RCG due to the implications of high voltages, high currents and very fast response/switching time [7] and [8]. The main characteristics of the IGBT under consideration are presented in **Table 3**.

**Table 3**: IGBT main characteristics

| | |
|---|---|
| Manufacturer | Mitsubishi Electric |
| Type | Insulated Type, Model CM600HB-90H |
| Rated Voltage (VCE) | 4500 VDC |
| Rated Current | 600 A |
| Quantity required | 5 |

## VIII. EXPERIMENTAL RESULTS

Using the high voltage high current IGBT it was possible to operate the coilgun at high currents drawn from the capacitor banks of 22,000 $\mu$F. However, several conducted test have shown that a projectile velocity of 212 m/s could be achieved instead of 350 m/s. This discrepancy between simulation and experimental results can be referred to the bullet instantaneous position in the barrel. For this preliminary setup it was not possible to maintain the bullet fixed until the current reaches its peak value of 2500 A. The movement of the bullet inside the barrel during the current rise has instantaneously increased the inductance of coil hence limited the peak current value to 1500 A instead of 2500 A during the pre-set pulse duration (14 $\mu$s). Also when IGBT is switched off the voltage across the IGBT was limited to 2160 V instead of 3300 V as shown in the current and voltage waveforms captured in **Figure 10** and **Figure 11** respectively. To simulate the change in coil gun performance, the coil inductance was gradually modified and tuned to 3.25 $\mu$H in Pspice model to match the experimental results. The modified Pspice simulation result is depicted in **Figure 12**.

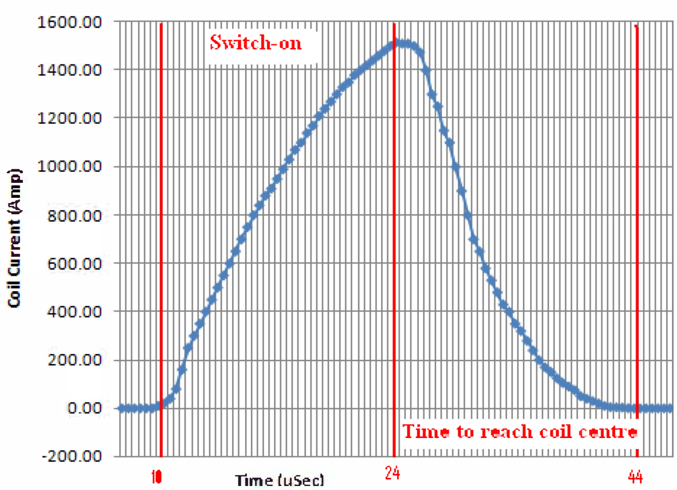


**Figure 10**: Coilgun current waveform (tested)

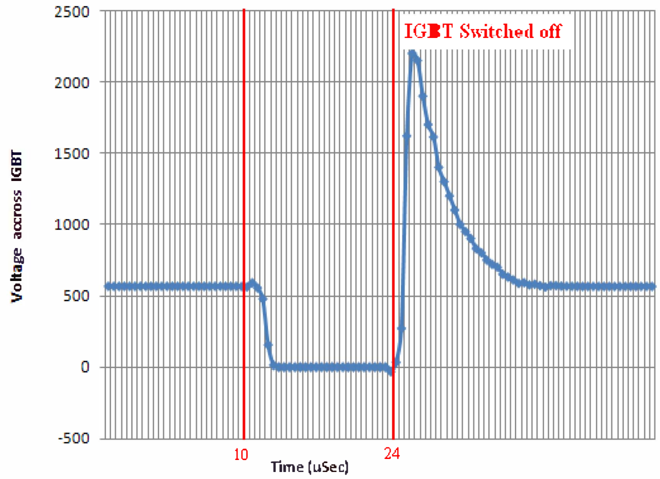


**Figure 11**: Coilgun voltage waveform (tested)

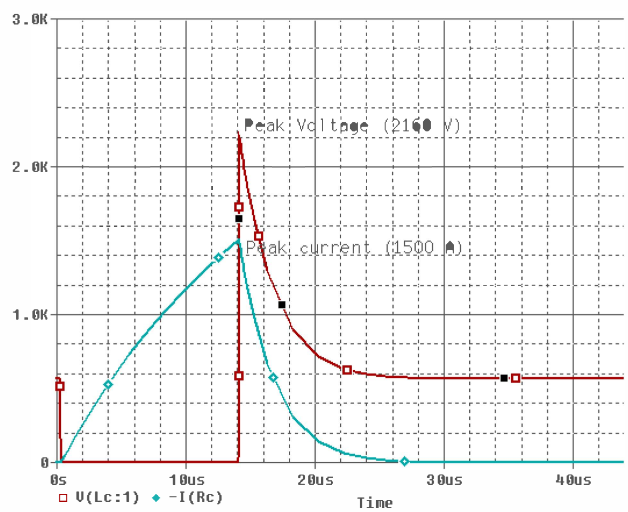


**Figure 12**: Modified Pspice model

The setup for the coilgun demonstrator test rig is shown in **Figure 13** and the design data of the RCG are summarized in **Table 4**.

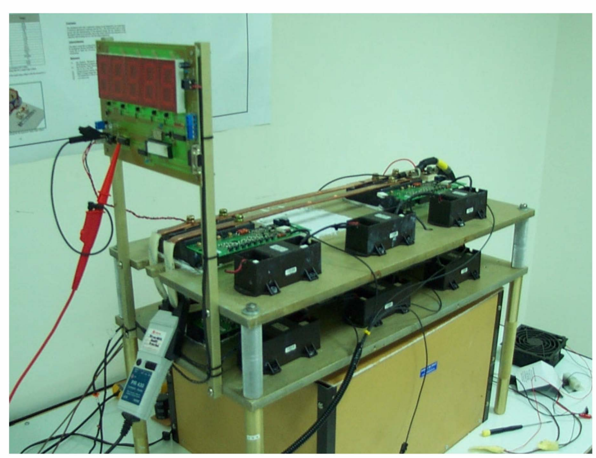

**Figure 13**: Experimental setup test rig for the coilgun demonstrator.

**Table 4**: Characteristics of EM Coilgun

| Data | Values | |
|---|---|---|
| | Expected | Experimental |
| Coil Inductance; (air cored) ($\mu$ H) | 1 | 3.25 |
| Coil resistance ($\Omega$) | 0.1 | 0.1 |
| Source Voltage (V dc) | 565 | 565 |
| Source Capacitance ($\mu$ F) | 22000 | 22000 |
| Coil peak current (Amp) | 2500 | 1500 |
| Electromagnetic force (N) | 22750 | 8425 (calculated) |
| Acceleration (m/s$^2$) | 8,750,000 | 3,240,384 (calculated) |
| Muzzle velocity (m/s) | 350 | 212 |
| Bullet travel time in barrel ($\mu$ s) | 20 | 34 |
| Bullet muzzle energy (J) | 160 | 58 |
| Coil input energy (J) | 3512 | 3512 |
| Coil gun efficiency (%) | 4.55 | 1.65 |

## IX. CONCLUSIONS

The research emphasized on the design of a single stage coilgun and the appropriate selection of the coilgun items in particular the capacitors and the IGBT. A good match between the simulation and experimental results was observed. Hence a multistage coilgun can be built with more confident using sequential pulsed technique and more advanced control and triggering circuit [9]. The promising results show that higher muzzle velocities can be achieved if certain precautions are considered. Measures such as fixing the bullet at the barrel edge for a specific duration where the peak current is obtained can be exploited. Advanced prototype can be developed to achieve higher coilgun efficiencies (in the excess of 2 - 3 %). Therefore the scope for further research is still valid. However, one has to consider some of the major issues for such an application where heavy weight, large size and complexity are the main consequences of the development.

## X. ACKNOWLEDGEMENTS

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