Arizona State University

Senior Design Project

Linear Electromagnetic Accelerator

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Abstract

The goal of this paper is to improve linear solenoidal accelerator technology in order to help the health and safety of many people by creating a silent accelerator with no propellant hazards like its industrial counterparts. The biggest issue is that current technology is extremely inefficient. We plan to increase the efficiency by using multiple coil stages, photogates to precisely time when each coil state turns on and off, a battery-charged capacitor power source for the fastest energy release, and ferromagnetic materials. To implement the groups design we will follow a specific weekly schedule that designates time to research design methodologies, perform simulations, and perform hardware tests.

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1 Introduction

A linear magnetic accelerator is a projectile accelerator that uses a single coil, or multiple coils, to accelerate and launch a ferromagnetic projectile. Not only does this technology apply to long-range artillery, anti-missile defense systems, and transportation, it also "has the potential to reduce the cost of access to space by several orders of magnitude" [1]. This paper will focus solely on the application towards long-range artillery. One of the advantages to its chemical gun counterpart is that it is completely silent since there is no chemical explosion. They will eliminate propellant hazards and have the potential to be a revolutionary step towards electromagnetic weaponry. Unlike conventional guns, linear magnetic accelerators have no moving parts and therefore are less likely to break mechanically. With their biggest downfall being low efficiency, we plan to increase this efficiency through research and experimentation [2] [3].

2 Prior Work

Some widely explored topics of previous research are transportation and space. Linear electromagnetic accelerators can be used to create Magnetic Levitation Transports (MagLevs) that are able to replace railway systems. Rather than a vehicle running along a track and creating friction, MagLevs hover above the track which allows "much higher speeds to be attained than are safely achievable on any other form of ground based public transport" [4]. This proves that this technology will benefit the health and safety of the population while providing more efficient public transportation.

As previously stated, linear electromagnetic accelerators are also very economic and can significantly reduce the cost of space access [1]. Technology very similar to ours, but much larger in scale, was used by the Discovery Channel and Professor Roger Angel for a planned demonstration where they launched trillions of 2-foot lenses in space [5]. The goal of the project was to use lenses to diffract the power of the sun and the corresponding linear accelerator utilized is shown in Figure 1.

Figure 1: Linear Accelerator Used to Launch Lenses into Space

Research directly related to electromagnetic (EM) weaponry has proven to be difficult to find. Most of the EM weaponry knowledge has been gained through military research that we do not have access to. We have collected knowledge mainly from hobbyists, a couple engineers that have linear magnetic accelerator websites, and our previous studies. Hobbyist efficiencies currently range from 2-6% and designs vary dramatically [2] [3].

3 Project Definition

The main scope of this project is to develop a linear electromagnetic accelerator and to optimize its efficiency by testing different design parameters. Some of the main parameters tested to improve efficiency were: number of coil stages, capacitor vs battery for a high voltage power supply, projectile triggering circuitry, and power control circuitry. In order to determine the efficiency of the design we will compare the potential energy stored on the capacitor to the kinetic energy of the projectile using Equations (1a) and (1b).

$$PE = \frac{1}{2}CV^2 \tag{1a}$$

$$KE = \frac{1}{2}mv^2 \tag{1b}$$

The first parameter that we decided upon was using a capacitor for the high voltage energy storage. This was due to the fact that we could vary the voltage on the capacitor while the battery would be limited to a specific voltage. With a larger budget and more time we could purchase various lithium polymer batteries for comparison tests. The next design decision was for the power control circuitry and projectile triggering circuit. We decided upon an Insulated Gate Bipolar Transistor (IGBT) for the control circuit as they were voltage controlled, had quick rise and fall times, and could dissipate larger amounts of DC power. Infrared photogates were used for the projectile triggering circuit; when the projectile blocked the IR sensor in the barrel it would cause the voltage on the gate of the IGBT to go high and trigger the capacitor to discharge through the coil and IGBT.

Once the basic circuit setup was complete, various coil designs were tested. We began with coils of approximately twelve layers of 24 AWG magnet wire and a length of 20mm. We then constructed projectiles ranging from 12 to 24mm to test which length ratio was optimal. After this was completed we began looking at how the number of coil stages on the linear electromagnetic accelerator affected the exit velocity and efficiency of the design.

This project will affect the health and safety of many people. If the group is successful in creating the linear electromagnetic accelerator, the research could be used to create weaponry. All of the safety and health considerations that need to be taken into account when using a chemical combustion weapon would need to be considered when using the linear electromagnetic accelerator in addition to the dangers of working with high voltage electronics.

4 Results

In order to charge the capacitor we needed a voltage source much higher than what a regular battery or power supply could provide. In order to compensate for this we used a DC to DC boost converter to boost the input voltage from 15V to 50-135V. The schematic for this can be seen in Figure 2 [6].

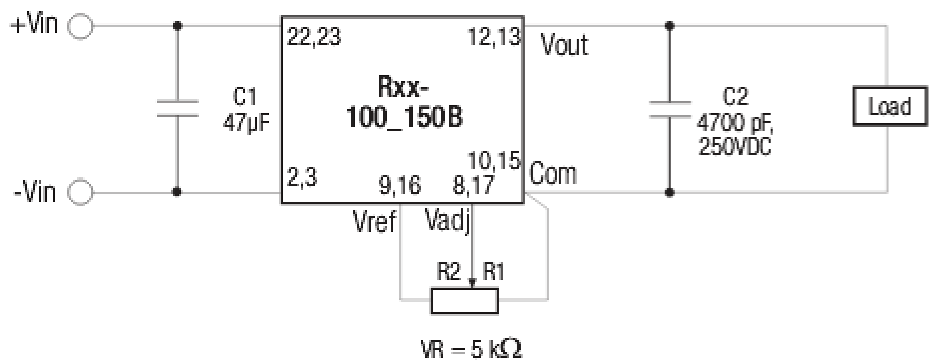

Figure 2: DC/DC Boost Converter

In order to regulate the output voltage the boost converter used a variable resistor that would vary the reference voltage from 0-4V with 0V corresponding to a 50V output and 4V corresponding to 135V.

In order to safely dissipate all of the heat generated by the current pulse through the IGBTs a heat sink and thermal paste were used to reduce the thermal resistance. The maximum junction temperature of the IGBT junction is 175°C [7]. With Equation (2), we were able to determine that the junction temperature will be approximately 37°C; well within the safe operating region of the IGBT [8].

$$T_J = Z_{thJC} \times P_{AV} + T_A \tag{2}$$

Figure 3 depicts the circuitry that was initially used to implement one stage of the linear magnetic accelerator [9].

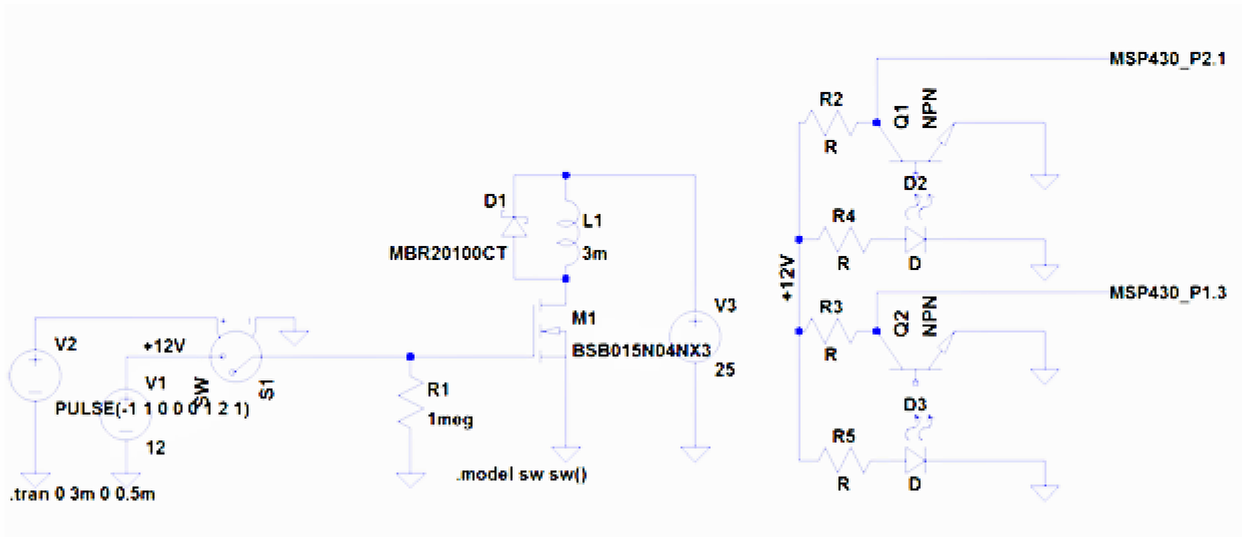

Figure 3: Initial Charging and Trigger Circuit

Simple switching devices such as voltage relays and IGBT transistors will be used to charge the capacitor that will supply the inductor with power. These switch inputs will be controlled by the port pins of an MSP430G2553 microcontroller. Diode, transistor pairs D1,Q1 and D3,Q2 represent photogates. These devices act essentially as switches that signal to the microcontroller when the projectile has passed through certain parts of the barrel. These signals determine how long the solenoid needs to stay on. In addition, the photogates allow the user to know how fast the projectile is traveling. The time between when the first and second photogates are triggered is recorded and then used to calculate the velocity of the projectile.

The microcontroller is configured to operates at its maximum clock frequency, 8MHz, ensuring that the MSP430 will not miss the triggering of any photodiodes [10]. A logical diagram of the firmware used in this application has been provided in Figure 4.

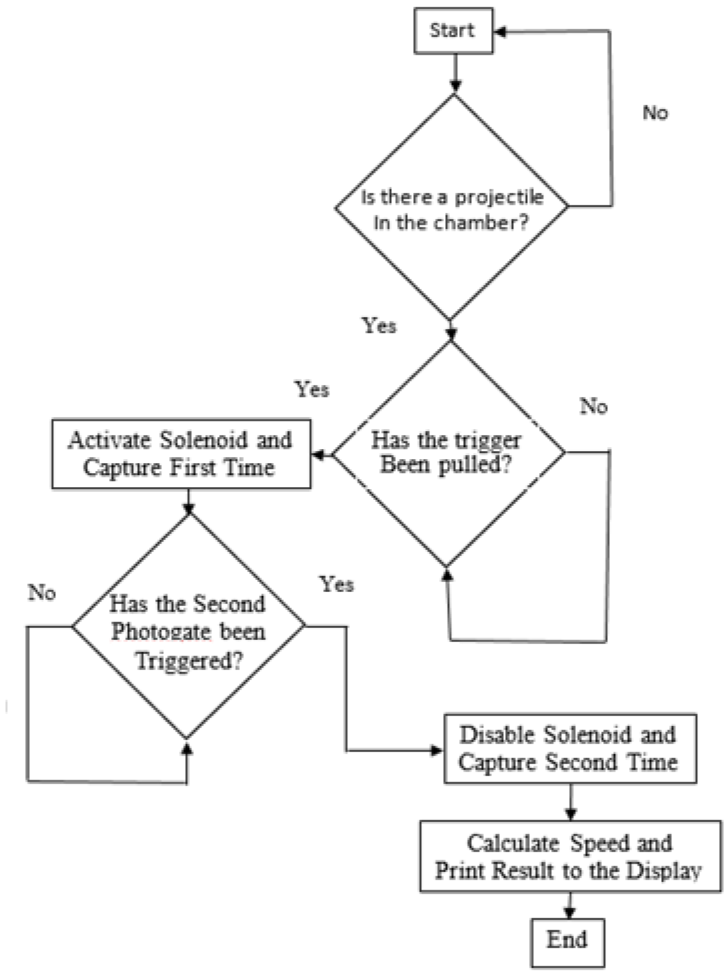

Figure 4: Firmware Logic Flowchart

The efficiency was calculated to be 43.8% as shown in Equation (3).

$$\eta = \frac{\frac{1}{2}mv^2}{\frac{1}{2}CV^2} = \frac{\frac{1}{2}(3.5 \times 10^{-3}kg)(9m/s)^2}{\frac{1}{2}(.018F)(6V)^2} = 43.8\% \quad (3)$$

This efficiency is suspect to error based on comparisons to other linear electromagnetic accelerators [2] [3]. Potential errors could be the measurement of the velocity, the code for the MSP430, or mathematic errors. The voltage drop was measured using a Digital Multimeter so we suspect this value was correct. To measure the projectile mass we used a scale that had a finite precision; we believe it is within ±1g. The group hopes to clarify this issue by the final demonstration.

4.1 Simulations

In order to find how much current is safe to use through the inductor, the following circuit is used to simulate both the current through the IGBT and the voltage at node Z1. Figure 5 represents a single stage of the linear accelerator. Instead of using a switch and an IR sensor, a simple input pulse voltage of 11V is connected directly to the IGBT. In order to simulate the coil in PSpice, we modeled the coil as a series resistance and inductance. For accurate values we measured the resistance and inductance using an RLC meter. The IGBT is connected to the coil with a diode in parallel. The voltage source is a 18000μF capacitor.

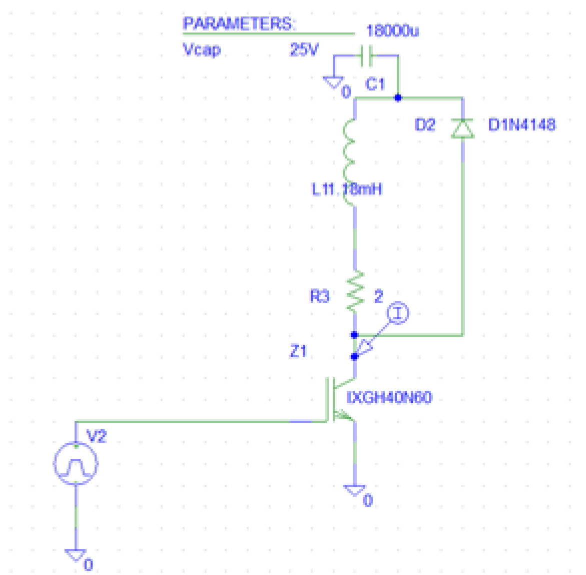

Figure 5: Single Coil and IGBT Schematic

From Figure 5, the resistance and inductance values can be seen to be 2Ω and 11.18mH respectively. The rise and fall times of the input pulse signal are 87ns and 95ns respectively [7]. Figure 6 shows the current through the IGBT when the voltage across the capacitor is swept from 0V to 80V.

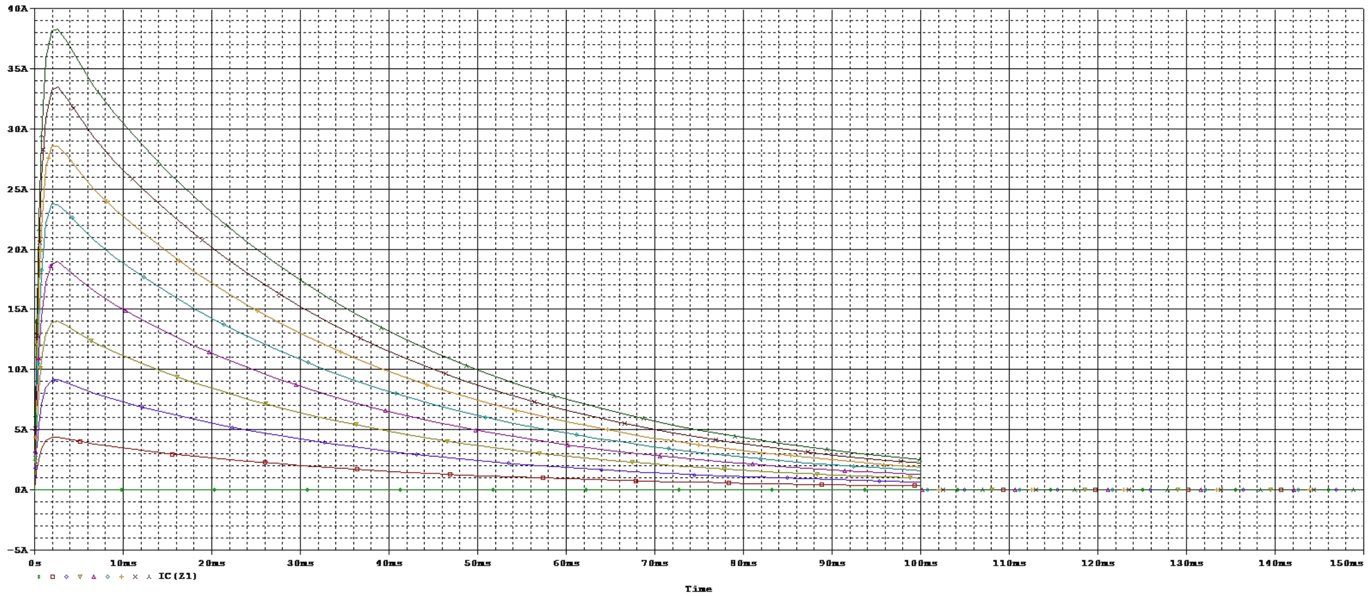

Figure 6: Current through the IGBT vs. Time

As the voltage increases, the peak current increases. This is ideal for the design because current is directly proportional to the magnetic flux density as shown in Equation (4) [11].

$$\oint B = \mu_o n I_{enc} \tag{4}$$

Where μ_o is the permeability of free space, n is the number of turns per unit length, and I_{enc} is the current flowing through the coil.

The voltage caused by the reverse Electromotive Force (EMF) is plotted below in Figure 7. It is necessary to monitor the reverse EMF to ensure that none of the components exceed their rated values and break.

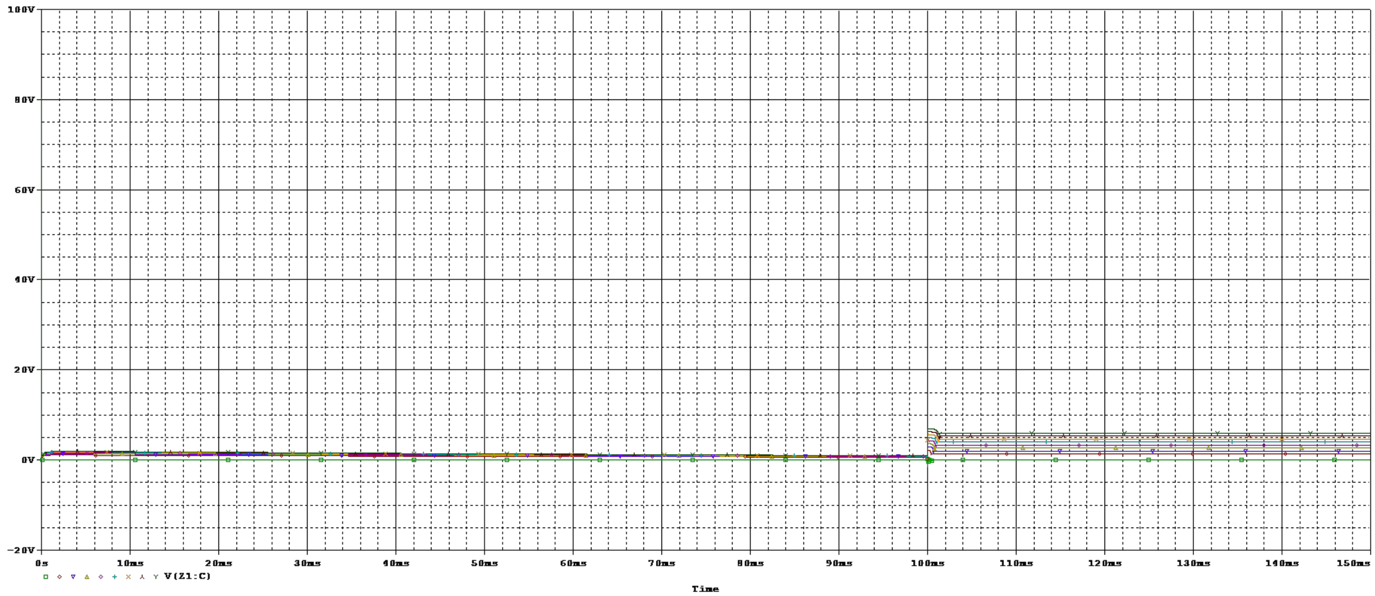

Figure 7: Reverse Voltage vs. Time

Using Figure 6 and Figure 7, we were able to find the maximum voltage across the capacitor that the IGBT can support [7]. The IGBT is capable of 2300W so the maximum voltage that can be applied is 60V. This is demonstrated in Equation (5).

$$P = IV = 60V \times 29A = 1740W < 2300W \quad (5)$$

In order to dissipate more current through the solenoid we tested the idea of parallel IGBTs. Each IGBT can dissipate 2300W of power, however, when two are paralleled the power dissipation increases linearly to 4600W. This concept can be seen in our PSpice simulation below. The schematic is shown in Figure 8.

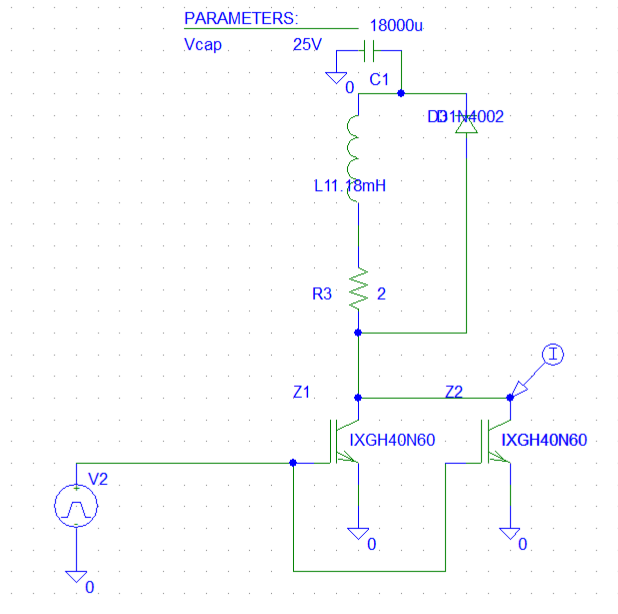

Figure 8: Single Coil and Paralleled IGBTs Schematic

The current flowing through each IGBT is shown in Figure 9. The voltage across the capacitor is swept from 0-80V.

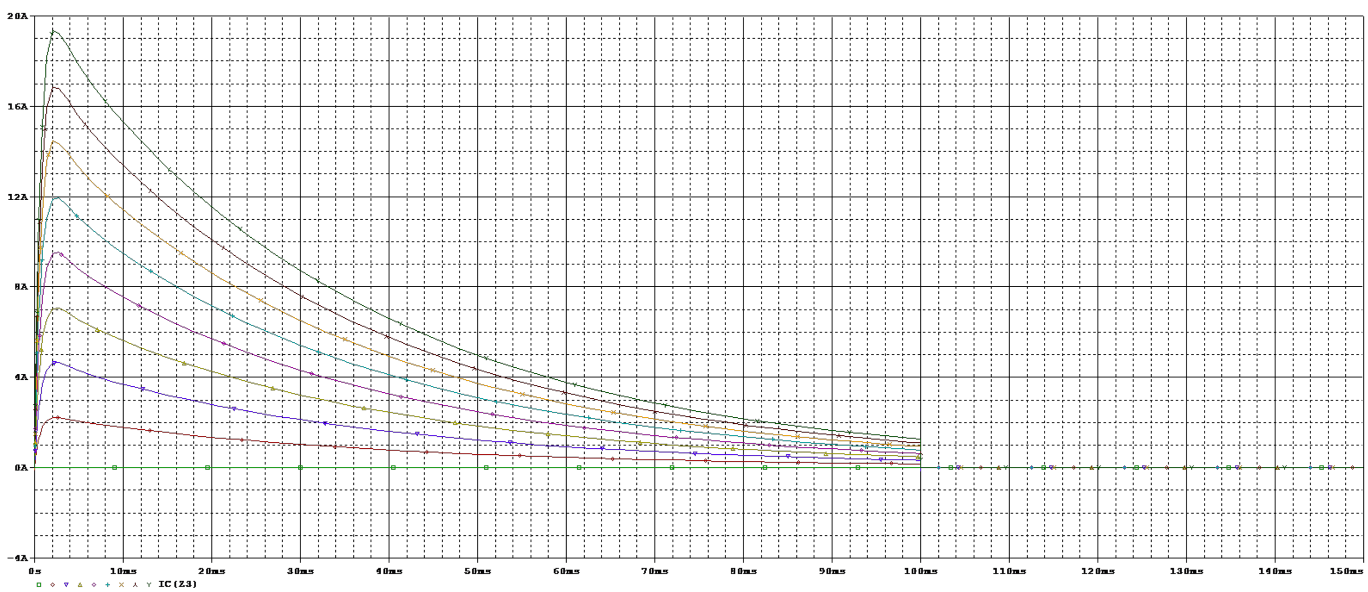

Figure 9: Current through an IGBT vs. Time for Paralleled IGBTs

The simulation verified that paralleling two IGBTs reduces the current by one half. However, when we went to test this with hardware we were unsuccessful. Further work needs to be done to determine the cause of the problem and whether or not this is a viable option for future trials.

4.2 Schedule

Throughout the 2013-2014 school year the linear electromagnetic accelerator group has managed to follow a very strict schedule with very minor adjustments having to be made. During the first semester the group researched into the theory of electromagnetic forces in solenoids to gain a better understanding of how we would propel a projectile through the barrel with enough speed to reach our goal. Next the group began to perform simulations on our solenoid designs with varying currents and windings to compare their different effects so that we could move on to building our test bench. By the end of the first semester the group built our initial test bench to begin field testing of our design.

During the second semester the group started to run into problems with our circuit which caused many scheduled dates to get pushed back. This demanded more hours to be put in per week to get the predecessors of most weekly objectives accomplished. The main issue the group was having was that we weren't using a solenoid with a high enough resistance, so that when we used high voltage we were getting too high of current through our IGBTs and we were destroying them and not understanding why. After performing simulations on our circuit we realized that the current was too high for the components, so we switched to a simpler circuit to avoid unnecessary complexity.

The group has been able to accomplish the main objectives that needed to be finished for this project during the second semester. The group this semester tested IGBTs in parallel in order to increase the voltage put through the coil so that we could dissipate the large amount of heat going through them which was our main concern in the beginning. Finally the group tested varying projectile lengths compared to the length of the solenoid used on the multiple stages. This test was needed to optimize the timing of the IR sensor so that we could get the maximum pull force from the magnetic field through the coil on the projectiles.

4.3 Budget

This semester one of the biggest restrictions on our project was the cost of the materials that were needed to build our linear magnetic accelerator. The group found that we needed high voltage and high currents to get a strong magnetic field through the solenoids to pull the projectile through the barrel. To deal with these high currents and voltages, we needed to purchase components that had high voltage and current ratings which increased the price of each component tremendously. For example, a low voltage IGBT could be purchased for around $4-$5 each on Mouser, while the 600V 300A rated IGBTs our group purchased were $25 each. Higher rated IGBTs would be better for our project, but the costs of them were too high for our budget. For the more expensive items in our project the group compared prices on Mouser and Digikey and found that Mouser consistently had the cheaper price between the two for the same components.

To completely assemble a working magnetic accelerator the group's main components were: the photo-gate sensor, the butyrate barrel, the magnetic wire for the solenoid, the 18mF capacitor, the Schottky diodes, DC/DC converters and the IGBTs. The clear butyrate tubing was specifically chosen for its strong durability and so that the IR photo-gate sensors could detect when the projectile was in place for the current to flow through the solenoids. Another important component was the Schottky Diodes that were used to protect the solenoids and other electrical components from the large reverse EMF the coils produced when the current was shut off. Next we had the DC/DC converters to boost our voltages on the capacitor. We were able to use one DC/DC boost converter to get to 50V, or we could put two in series to get up to 400V on the larger capacitors. Finally we used the IGBTs to control the flow of current to the solenoid in combination with the IR sensors. The IR sensors were used to detect the position of the projectile and turn on the flow of current to the coil. The rest of our components were used to build the initial and final test benches for the project.

5 Future Work

To continue this research one should first find the ideal projectile placement. The group has observed that if the projectile is placed too far back from the coil, it drains significantly more voltage from the capacitor in order for the coil to suck the projectile through the whole coil. In order to increase efficiency, the ideal placement of the projectile is crucial because it will effect both the voltage drop across the capacitor and the exit velocity of the projectile. The length of the projectile also affects the amount of voltage used for the coil to fire. The length will play into the projectile placement/coil length/projectile length ratio, which is crucial to optimize. The group has noticed that the use of photogates to time when the coil turns on and when it turns off works well, but the projectile must be long enough to reach the center of the coil before the IR sensor turns off the coil. Ideally, instead of finding the optimal projectile placement, we think it would be best to have a component that accelerates the projectile before is passes through the first coil.

Different coil gauges should be compared to see which resistance, inductance, and number of turns provides the best results. It is important to take into consideration the resistance of each wire gauge. As the wire gets thinner, the resistance increases. This was beneficial to us because the current was so large that we needed more resistance or certain parts would break because they could not handle large amounts of current. Thinner wire is also beneficial because the more turns the coil has the better the performance will be, as shown in Equation (4). The limiting factor will be how much resistance the design requires. The group found that too much resistance, or too thin of wire, will be detrimental and the projectile will not exit the barrel with as high of a velocity as possible.

Finally, the ideal number of stages should be tested. We suspect that the more stages the accelerator consists of, the more efficient it will be. The limiting factor is that the design needs to be portable and easy to carry. If excessive amount of stages are used then this would make the accelerator too large and heavy to be practical. After a certain number of stages, the increased benefit may not be worth the extra cost as well.

6 Conclusion

During this semester the Linear Solenoid Electromagnetic Accelerator team strived to accomplish goals in the solenoid design, control systems, and power electronics. Before any hardware designs began, the group started with simulating multiple methods of building a circuit that would allow high voltage and current through the solenoid without destroying any of the components. The group finally found a simplistic circuit that mainly utilized 3 major components to control the electromagnetic accelerator. For the power sources the group utilized DC/DC converters to boost low voltages to higher voltages to power the capacitor for the appropriate voltages to be used in the circuits. At the same time the group researched into thermal dissipation by using high power rated IGBTs to ensure we could dissipate the transient heat. With research into controls systems the group was able to use the IGBT and the diode together to direct the flow of current when the IR sensors were turned off. The diode prevented large back EMF from damaging the projects main circuit parts. With the research performed in these different subjects the group was able to maintain a consistent schedule throughout the year. During the second semester the group began to run into problems with components and circuitry design which forced the group to move around the schedule. Even with these adjustments the group was able to put more hours in and accomplish most of the goals of the project.

Throughout the project the group learned many key lessons that are essential for future field work in industry. The most important of these lessons is teamwork. With the complexity of our project if our team had not worked together and problem solved all the issues together we would not have been able to accomplish our goals for this project. The biggest setback for our group was determining a circuit that would function properly without any of the components being destroyed by high currents. After working through the various methods, we were able to come up with a viable solution and move forward with our testing. The next big lesson gained from this experience was on the business side. The group had a set budget we had to work within and the group had to sacrifice expensive parts for lesser quality components so that we could perform experiments and collect data. Finally this project taught us about perseverance. The senior design group created our own project and sought out Dr. Aberle to be our mentor for the project. The group knew nothing about the subject we were about to research on, but we all had a drive to learn more about the theories behind linear solenoid electromagnetic accelerators.

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7 Appendix

The firmware code for the photogates was written in C and is shown below:

```
#include <msp430.h>

/*
* main.c
*/

int counter = 0; //counter that keeps track of time that has passed in microseconds
int time = 0; //time value used for mathematical calculations
//int flag = 0;
//int sec = 0; //time that has passed in seconds (for debugging purposes)
//int min = 0; //time that has passed in minutes (for debugging purposes)
//int hour = 0; //time that has passed in hours (for debugging purposes)
const int distance = 180; //distance between photogates in mm
float speed = 0; //calculated speed
float speed_prime = 0; //calculated scaled up value for speed
//int timer_flag = 0; //flag that enables the timer

int main(void) {
    WDTCTL = WDTPW |WDTHOLD; // Stop watchdog timer
    //setup the clocks
    BCSCTL1 =CALBC1_8MHZ; //set range
    DCOCTL = CALDCO_8MHZ; //set DCO step+ modulation
    BCSCTL3 |= LFXT1S_2; //LFXT1 = VLO
    IFG1 &= ~OFIFG; //clear OSCFault flag
    BCSCTL2 |= SELM_0 +DIVM_3 +DIVS_3; //MCLK = DCO/8, SMCLK = DCO/8
    //setup timer interrupt
    CCTL0=CCIE; //enable CCIE interrupt
    TACCR0=125; //count up to this value (interrupt every 1uS)
    TACTL=TASSEL_2 + ID_3 +MC_1; // set timer 0 as SMCLK, ID-8, MC-2,taie-1
    //setup Port Pins
    //setup I/O pins
    P1DIR |= BIT0 + BIT6; //set P1.0 & P1.6 as an output
    P1DIR &= ~BIT3; //Set P1.3 as an input (firing switch)
    P1DIR &= ~BIT5; //set P1.5 as an input (photogate sensor 2)
    P2DIR &= ~BIT1; //set P2.1 as an input (Photogate Sensor 1)
    //initialize port pins
    P1OUT &= ~BIT0; //set P1.0 and P1.6 low
    P1OUT &= ~BIT6; //P1.0 and P1.6 act as indicatior LEDs
    _BIS_SR(GIE); //enable interrupts
    while(1){
    P1OUT |= BIT0; //Turn on Red LED indicating that no projectile has been loaded
```

```
    while(!(P2IN & BIT1)); //check to see if a projectile has been loaded
    P1OUT |= BIT6; //Turn on the Green LED and Turn off the Red LED indicating that the system is ready to fire
    P1OUT &= ~BIT0;
    while(!(P1IN & BIT3)){ //check if the firing switch has been pressed
    counter = 0;
    }
    while(!(P1IN & BIT5)){
    P1OUT &= ~BIT6; //"fire" the solenoid
    speed = 0; //reset the speed flag (for debugging purposes
    time = counter; //get the time from the interrupt
    speed_prime = (180000)/time; //scaled speed in mm per second
    speed = speed_prime/1000; //speed in m per second
    }
    }
}

#pragma vector=TIMER0_A0_VECTOR
__interrupt void Timer_A (void)
{
    counter++;
    /* if(counter >= 1000){ <- real time clock used for debugging purposes
    sec++;
    counter = 0;
    }
    else if(sec >= 60){
    min++;
    sec = 0;
    }
    else if(min >= 60){
    hour++;
    min = 0;
    }*/
}
```