

IGNITRON TRIGGER CIRCUIT

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Abstract

For my senior project, I will be constructing an Ignitron Triggering Circuit (ITC) for the rail gun that was developed on campus by an AERO Master student. I will be designing a system that can be used with either a capacitor or mechanical discharge system. In order to future- proof the system, it will be designed for the ITC to be compatible with the rail gun Mark 2, which will use a 12 kV capacitor bank.

The purpose of this project is to provide an alternative to the nitrogen injection system used on the current rail gun. The proposed ITC will be more efficient and will eliminate the plasma plume, which in turn will help with data collection.

Acknowledgements

I would like to thank Nolan Uchizono for all of his help in the design and implementation of the ITC. I would also like to express my appreciation to Dr. Ali Shaban for his assistance as my Senior Project advisor, and Jeff Maniglia for his work on the rail gun. Finally, I would like to thank my parents for their support throughout my time here at Cal Poly.

CHAPTER 1 – INTRODUCTION

1.1 Electromagnetic Rail Gun Triggering Circuit

An electromagnetic rail gun (EMRG) operates by applying a very high voltage across a pair of conductive rails in the barrel of the gun. A projectile made out of conductive material is placed between the rails, which completes the circuit. This completed circuit induces a large magnetic field from the current traveling through the rails and the projectile, which will help to accelerate the projectile. Since the projectile is in the rails for a very short period of time, a pulsed power system is used to power the EMRG.

A pulsed power system is one that accumulates energy in the kJ range and then releases it in a very short period of time. Pulsed power is used in many different fields beyond rail guns. Some of the larger fields are radar, pulsed lasers, particle accelerators, and fusion research. Two of the most common forms of energy storage for pulsed power systems are capacitive and mechanical, both of which the Cal Poly Pulsed Power team is working on. The triggering circuit will allow us to choose which energy storage method we would like to test fire, with minimum work for set up. The switching circuit will also allow us to remove the current, less efficient, injection system.

1.2 Background

Currently, the pulsed power circuit is completed through the injection of the projectile into the rails with a 3,000 psi nitrogen injection system. Under this current firing system, the projectile rattles down the barrel, which causes losses due to approximately half of the projectile melting and being left on the rails as it travels downward. We also have an arcing problem since the projectile is no longer in constant contact with each side of the rail gun.

The Ignitron triggering circuit will provide an alternative to the current nitrogen injection system, and permit a projectile to be press-fit into the rails, which will provide greater conductivity. This will also help to reduce the rattle of the projectile. Under the current system, there is a large plasma plume that exits the end of the barrel, which prohibits us from using break screens to get velocity measurements. The plasma sticks to the sheets, and continues to conduct after the projectile has passed through, which renders the timing data useless. We will also be reducing the cost of each firing due to the fact that we will no longer need to have nitrogen refilled each time we would like to fire the rail gun. See Appendix A for the cost breakdown of this project. This will allow for more testing to be done with the rail gun.

CHAPTER 2 – SYSTEM COMPONENT DESIGN

2.1 Ignitron

The Ignitrons are the main system component that the rest of the triggering circuit will be designed around. Four National Electronics NL7218H-100 Ignitrons have been loaned to the project from an Orange County power company. These ignitrons allow for switching up to 15 kilovolts and have peak currents of up to 100 kilo amperes, which is more than enough for the capacitive and mechanical discharge systems. In order to have the ignitrons trigger, and allow the discharge from the mechanical or capacitive discharge, we must supply at least a 5 μ S pulse with a minimum voltage rating of 1500V. These constraints are what the entire ignitron triggering circuit has been designed to meet.

2.2 Arduino

An Arduino was chosen to act as the trigger for the circuit, and send the initial pulse. This eliminates the problem of ringing that occurred when a push button was used. By using an Arduino we can have multiple safety checks built into the triggering circuit, which will prevent the accidental triggering of the circuit and the firing of the rail gun. Once the compulsator is completed, we will have the entire firing mechanism automated so that by a one- button press, the compulsator will spin up, data collection will begin, and the ignitrons will fire. This saves time, and allows us to record more useful data without getting multiple seconds of noise in the data acquisition controller. The Arduino code is listed in Appendix B. As seen from the code, it waits in a static state until the start button is pressed, and once that has happened, it switches over to the state that fires the ignitrons. Once this is complete, the compulsator goes into a

waiting state for 30 seconds, to make sure there is no longer any ringing from the button press, before returning to the state of waiting for the push button to trigger it.

2.3 TTL Inverter

In order for the one-shot chip to fire correctly, it needs an inverted TTL input. In the design of the TTL Inverter we used two MPSA06 npn general purpose amplifiers, along with $4.7\text{k}\Omega$ and $1\text{k}\Omega$ resistors. Figure 1 shows the circuit diagram for the TTL Inverter. A +5V rail was used on the top, with ground on the bottom. The wire on the left shows the input from the Arduino, while the wire on the right connects to the Monostable multivibrator. In order to design the inverter without the external power supply needed for a 5V rail, we decided to have one voltage coming in, and to use three different voltage regulators to dial in the specific voltages we needed.

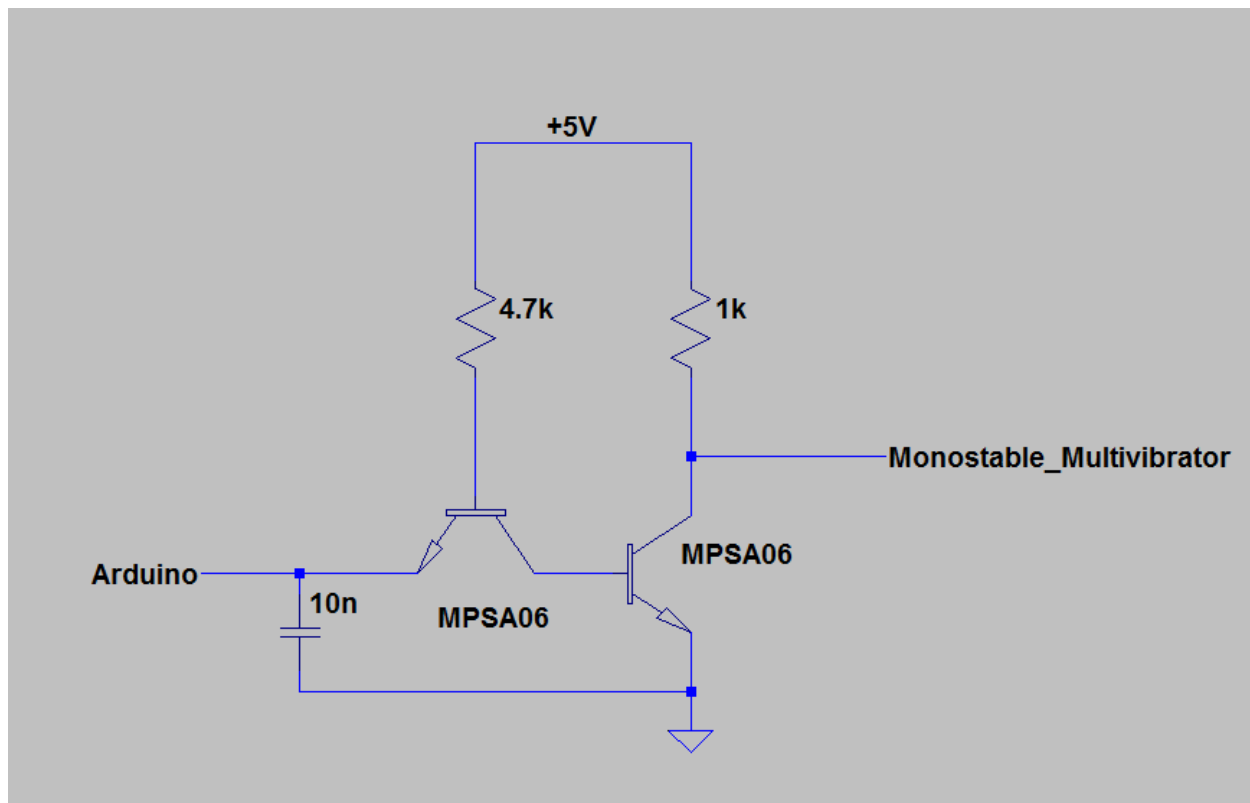


Figure 1: TTL Inverter Circuit

2.4 Monostable Multivibrator

The output from the TTL inverter is used as the input for the Monostable multivibrator, which is used to create the 4.5 mS pulse needed for the triggering of the ignitron. For this circuit, we decided to use Texas Instruments CD 74HCT123E High-Speed CMOS Logic Dual Retriggerable Monostable Multivibrators with Resets. This chip has two different multivibrators, with an inverting and non-inverting output. For the design, only the multivibrator with the non-inverting output was needed. On pin 2 we have the output from the collector of the second MPSA06 NPN transistor. Pin 3, which is the reset pin, is kept at a constant 5V to prevent the resetting of the pulse. The resistor R_x that was placed between V_{cc} at pin 16 and pin 15 was set to 100 k Ω . This resistor R_x is used in the creation of the timing pulse. A capacitor C_x that was

set to 100 nF was connected across pins 15 and 14. This capacitor allowed us to have the timing pulse of 4.5 mS. The formula that gives the pulse length is:

$$t_w = 0.45R_xC_x$$

$$t_w = 0.45(100 \times 10^3)(100 \times 10^{-9})$$

$$t_w = 4.5 \times 10^{-3}$$

$$t_w = 4.5 \text{ mS}$$

The output from the one-shot circuit is on pin 13. We use this output to feed the MOSFET driver, which will be discussed later. Figure 2 below illustrates the one-shot section of the ignitron triggering circuit. Figure 3 shows the completed circuit up to this point, including both the TTL inverter and the Monostable multivibrator.

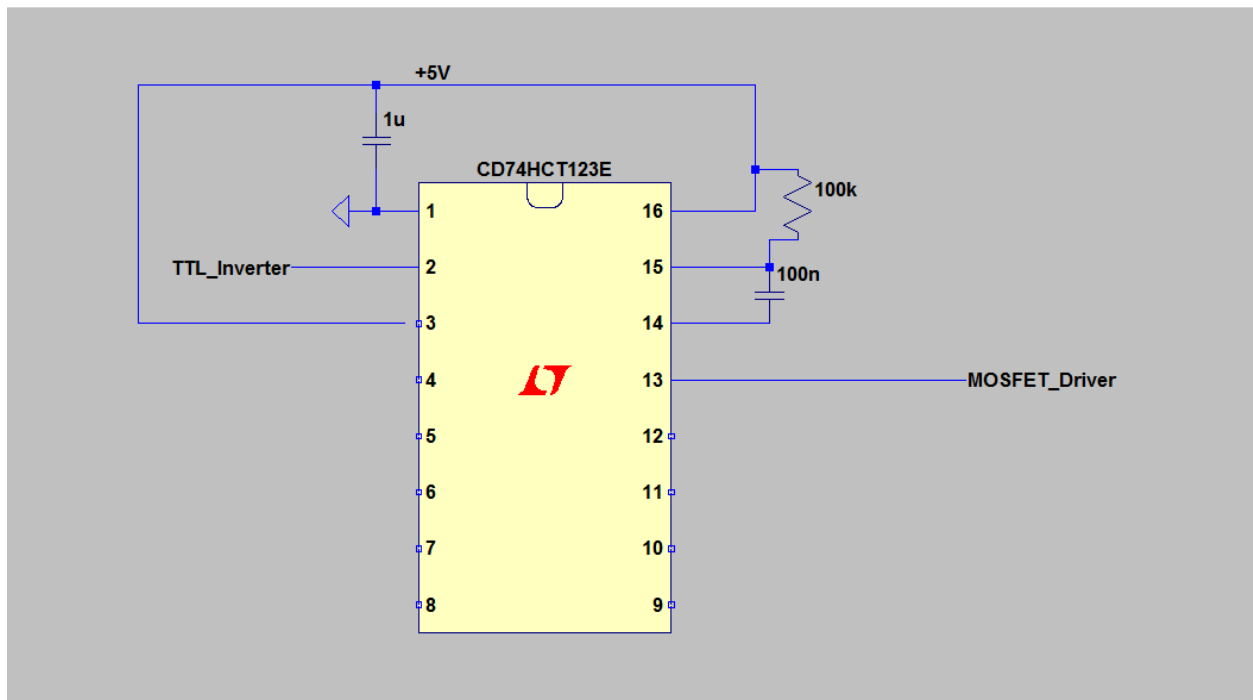


Figure 2: Monostable Multivibrator Circuit

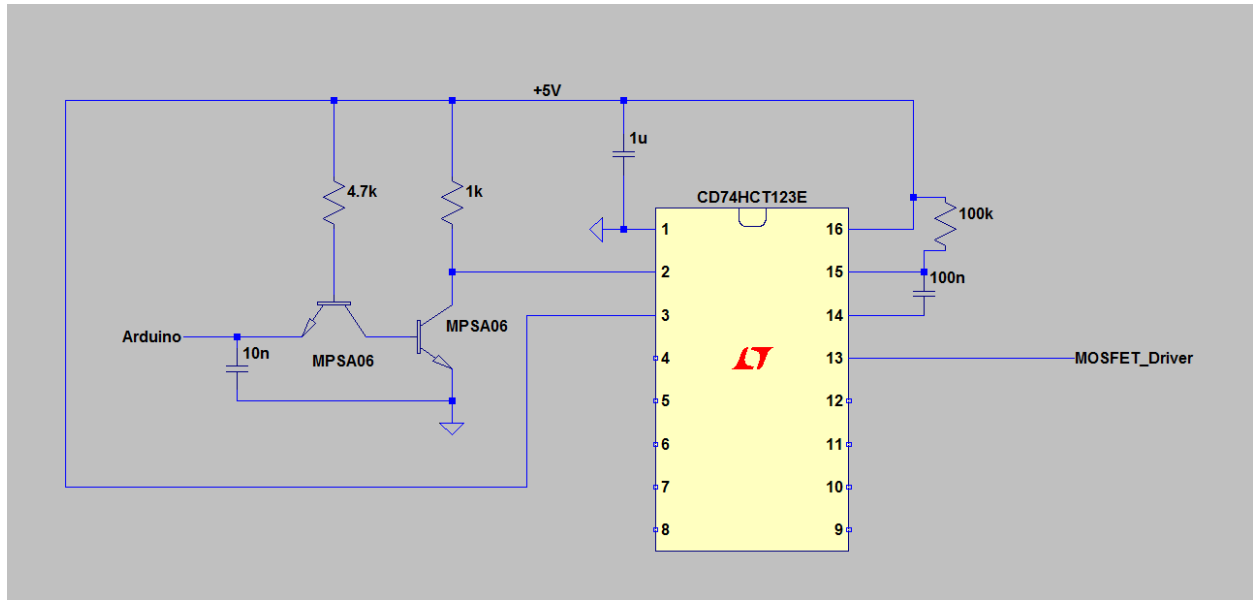


Figure 3: Current System with TTL Inverter and Monostable Multivibrator

When the circuit was originally designed, we were looking for a 10 μ S pulse. This was accomplished by using an R_x value of 22 $k\Omega$ and a C_x value of 1 nF.

$$t_w = 0.45R_xC_x$$

$$t_w = 0.45(22 \times 10^3)(1 \times 10^{-9})$$

$$t_w = 9.9 \times 10^{-6}$$

$$t_w = 9.9 \mu S$$

This configuration with the 10 μ S pulse caused a negative spike to occur when the pulse was completed. In order to avoid this problem, the pulse length was changed to 4.5 mS. which allowed normal operation of the circuit.

2.5 MOSFET Driver

The MOSFET Driver that was chosen for the circuit was the Micrel MIC5021 High-Speed High-Side MOSFET Driver. This chip was selected due to the need for a high-speed driver for the Insulated-Gate Bipolar Transistors or IGBTs. We will be using this to drive 3 IGBTs in parallel, which are used as one of the final steps in the ignitron triggering circuit. For the configuration of this chip, pin 2, which is the input was connected to pin 13 from the Monostable multivibrator. Pins 4 and 5 were connected to ground, while pins 1 and 8 were connected to the 15V rail coming from the second voltage regulator. Pin 3 was left unconnected. In order to reduce some of the noise, a 4.7 μ F capacitor was placed from the 15V rail to ground. Pins 6 and 7 were the output, which were connected to the IGBTs. Figure 4 shows the MOSFET Driver and the connections to it, while Figure 5 illustrates the completed circuit up to this point.

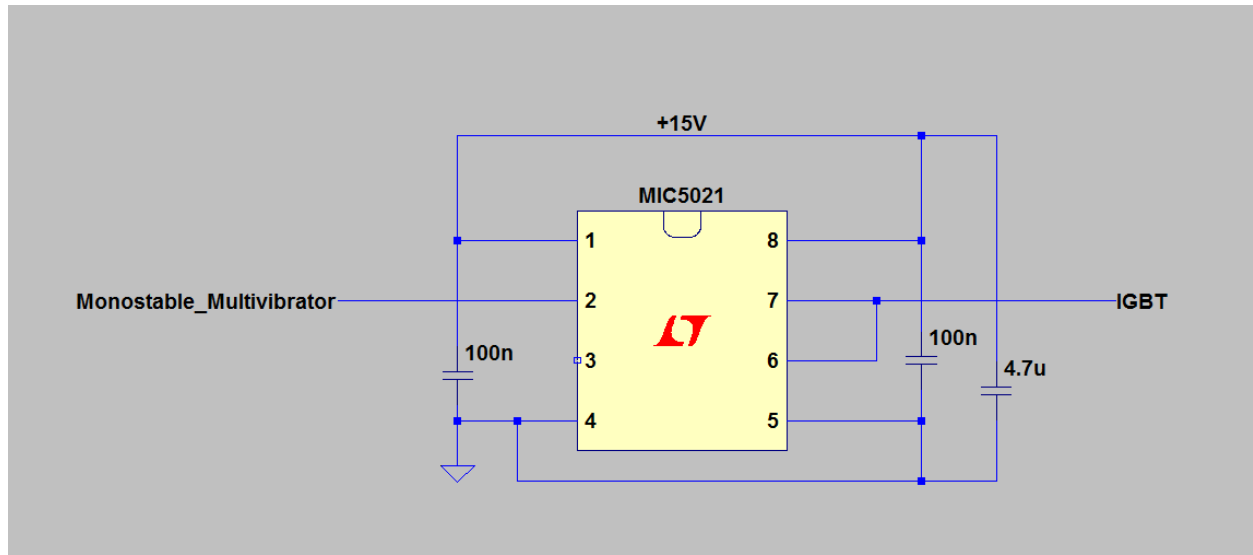


Figure 4: MOSFET Driver Circuit

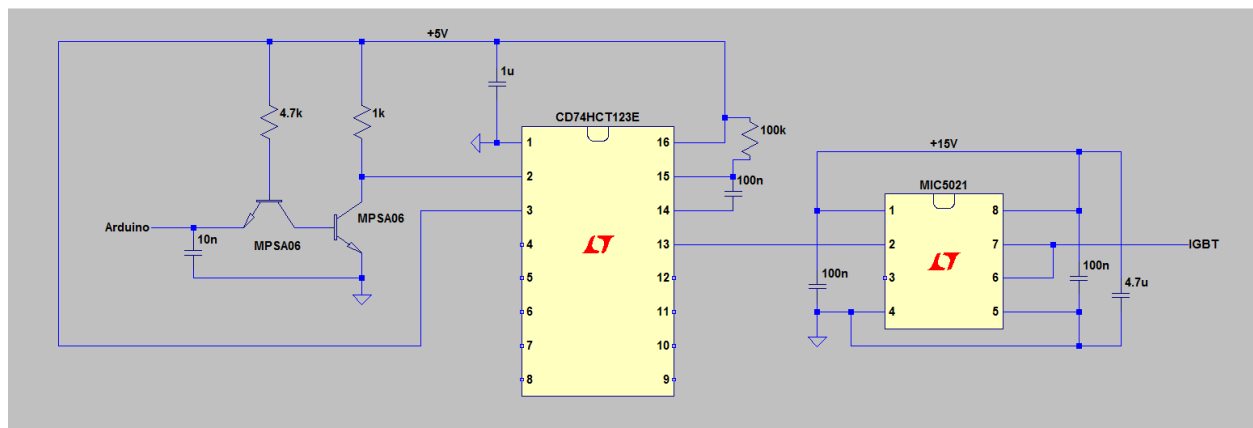


Figure 5: Current System with TTL Inverter, Monostable Multivibrator, and MOSFET Driver

2.6 Insulated Gate Bipolar Transistor

For the final step of the circuit before the transformer, three IGBTs in parallel were used. International Rectifier IRGPS60B120KD IGBTs were chosen, as they have been found to work

well with ignitrons, and these were donated. The max collector to emitter voltage that can be used on the circuit is 1200V, which meets the specifications. Since three were used in parallel, the safety factor was increased to avoid the risk of burning out a single IGBT. The IGBTs were connected so that the output from the MOSFET Driver was connected to the gate, and the capacitor was connected to the collector. On the emitter side of the IGBTs, two diodes were placed to prevent reverse current flow that could cause damage. A circuit diagram of the IGBT is shown below in Figure 6. Figure 7 illustrates the completed ignitron triggering circuit up until the point where it enters the transformer.

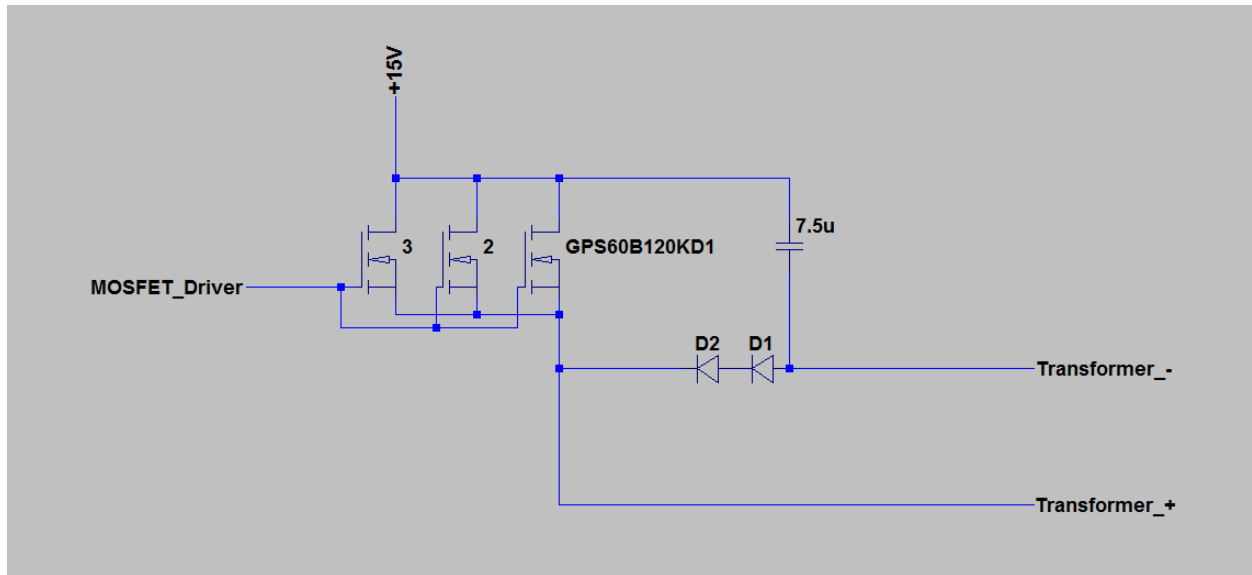


Figure 6: IGBT Circuit

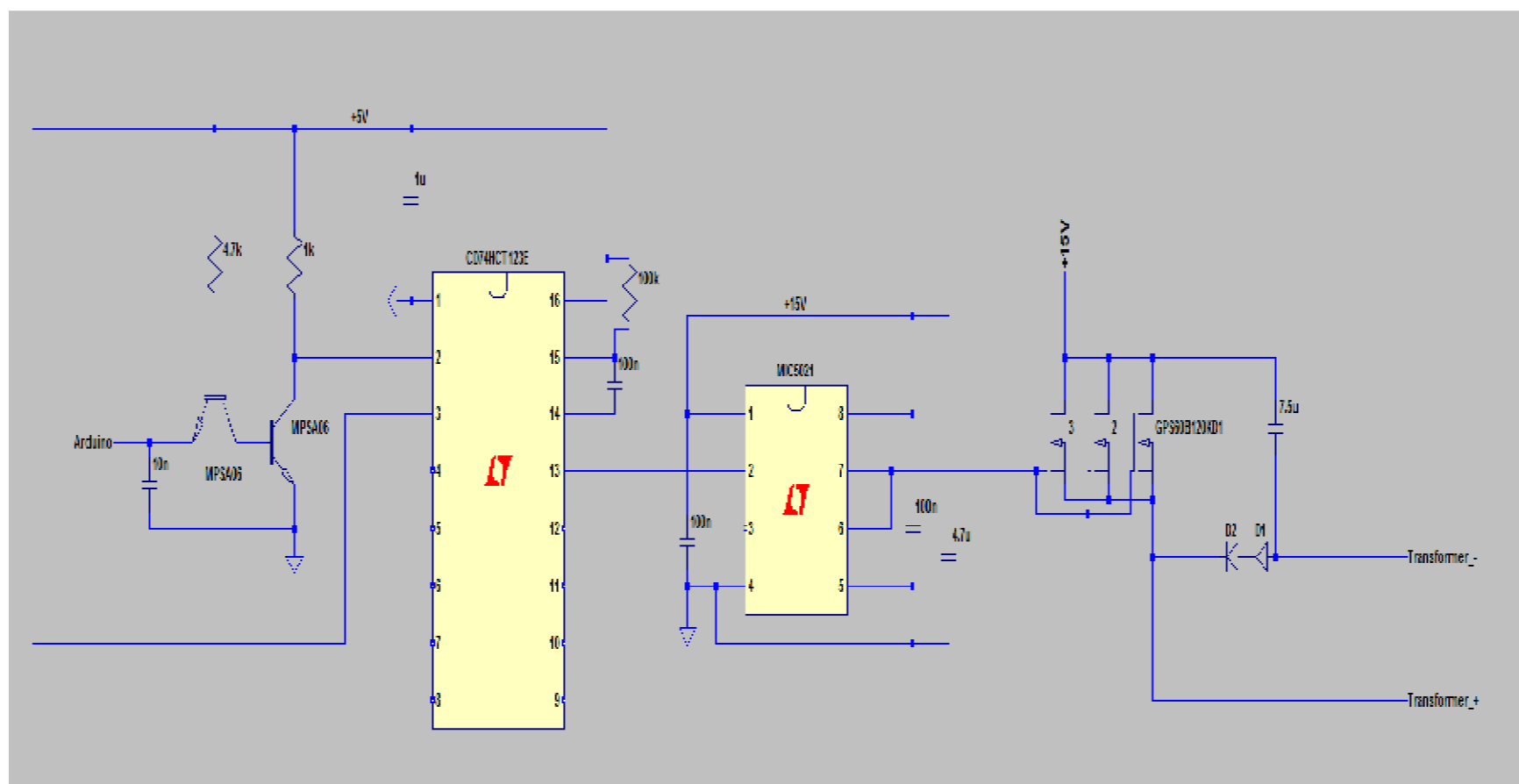


Figure 7: Current System with TTL Inverter, Monostable Multivibrator, MOSFET Driver, and IGBT

2.7 Transformer

While the triggering circuit up to this point gave a 1200V pulse, a pulse of at least 1500V was needed to trigger each ignitron. In order to accomplish this, a transformer was used to step up the voltage. This also allowed all four ignitrons to be driven from the one circuit by having four secondary windings. The use of a transformer also allowed the ignitrons to be separated from the rest of the circuit, so that a possible large current spike would not destroy all of the components. The transformer is very useful, as the ignitron is dealing with thousands of amps, and the triggering circuit is on the milliamp scale. Transformers need a varying current in order to create a magnetic field, which is then converted back to a varying current on the secondary winding. Since the ignitron triggering circuit deals with a pulse, the transformer is a perfect fit for the application. Since we could not locate any wire that met our space and cost constraints, we decided to make the windings ourselves. Wire was needed that could have thousands of volts flowing through it with no sparking, and a combination of copper tape and kapton tape would allow this. Kapton tape is used in space applications and has a breakdown voltage of over 4000V, which is more than what will be seen in any of the windings. Making the wire was also an inexpensive way for us to get the length of wire needed. A 1:4 winding ratio was used for the transformer, which would allow all four ignitrons to fire safely. The number of turns used was 10 for the primary winding, and 40 for each of the 4 secondary windings. Figure 8 shows an LTSpice representation of the transformer, while Figure 9 is a photograph of the completed transformer. Finally, Figure 10 presents the completed Ignitron Trigger Circuit.

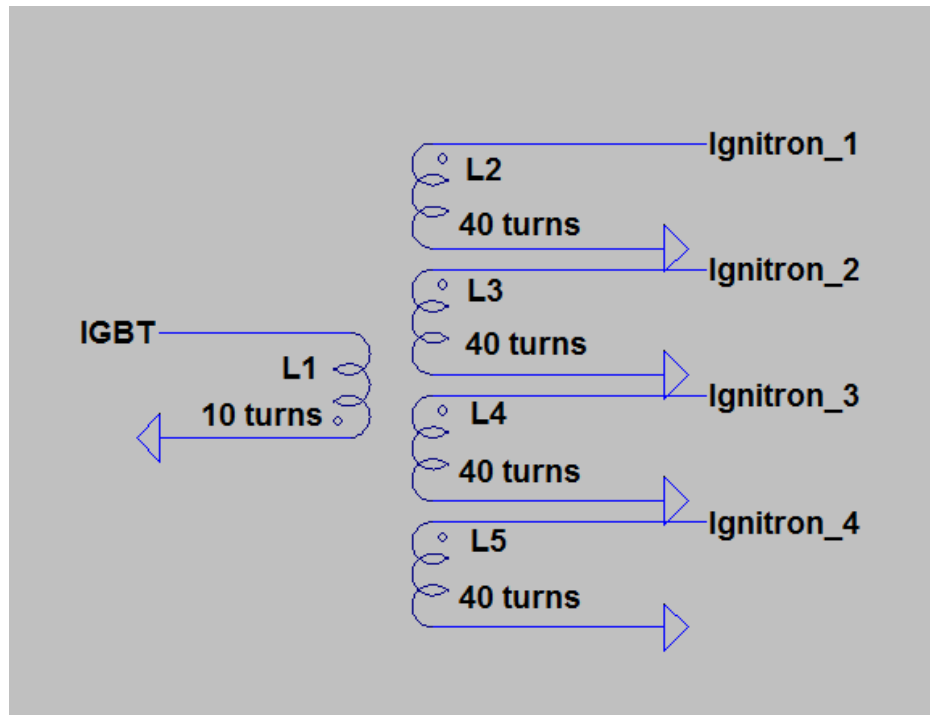


Figure 8: Transformer Circuit

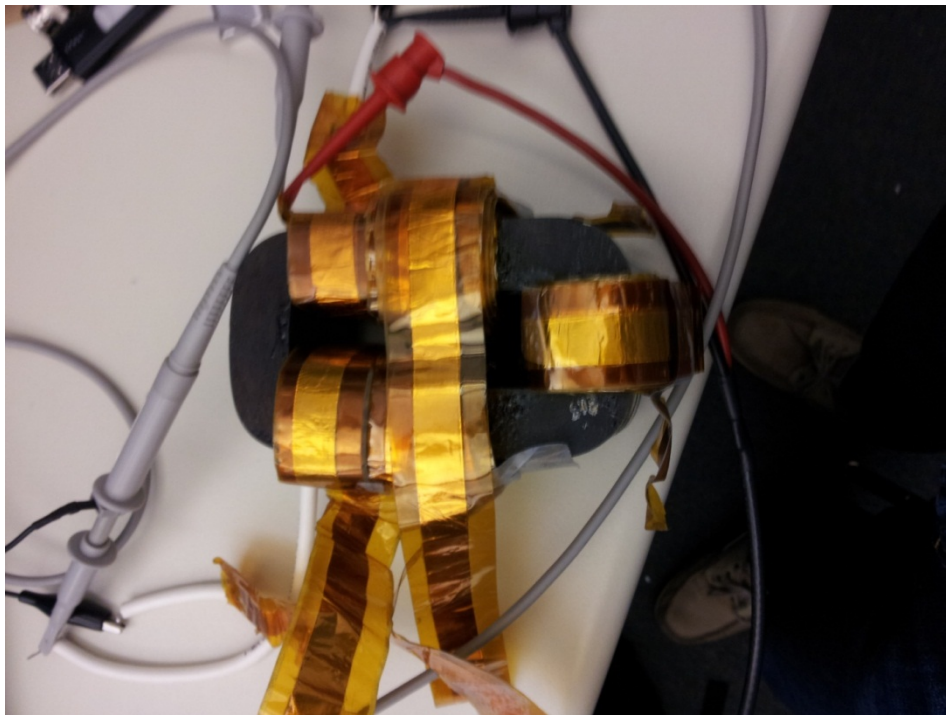


Figure 9: Picture of Completed Transformer

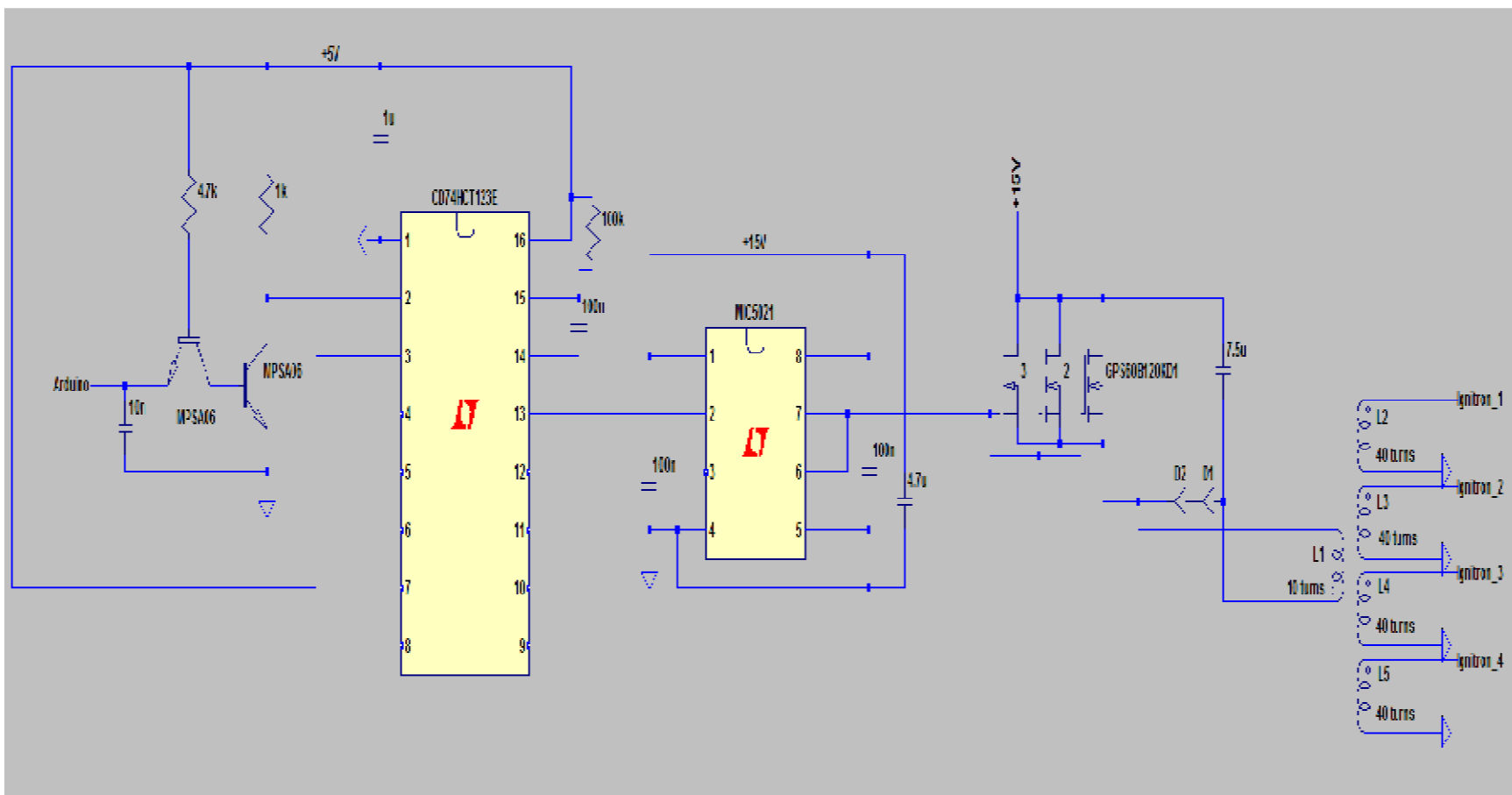


Figure 10: Completed Ignitron Trigger Circuit

2.8 Voltage Regulators

Three different voltage regulators were needed for the ignitron trigger circuit. In order to accomplish this, three LM317s were used to regulate the voltage for each part of the circuit. The formula that was used to calculate what values are needed for both R1 and R2 is:

$$V_{out} = 1.25 \left(1 + \frac{R_2}{R_1} \right)$$

$$V_{out} = 1.25 \left(1 + \frac{1 \times 10^3}{330} \right)$$

$$V_{out} = 1.25(1 + 3.03)$$

$$V_{out} = 1.25(4.03)$$

$$V_{out} = 5.04V$$

The first voltage regulator is a 5V regulator that uses resistors with an R1 value of 330 Ω and an R2 value of 1 k Ω . A 10 nF capacitor was also used going from the input to ground, to help with the noise that was seen in the circuit. Since the input voltage is 24V, a heat sink was used to help dissipate some of the heat that this configuration generated. The 5V regulator was used for the TTL inverter circuit, along with the one-shot Monostable multivibrator. A circuit diagram of this 5V voltage regulator is shown in Figure 11 below.

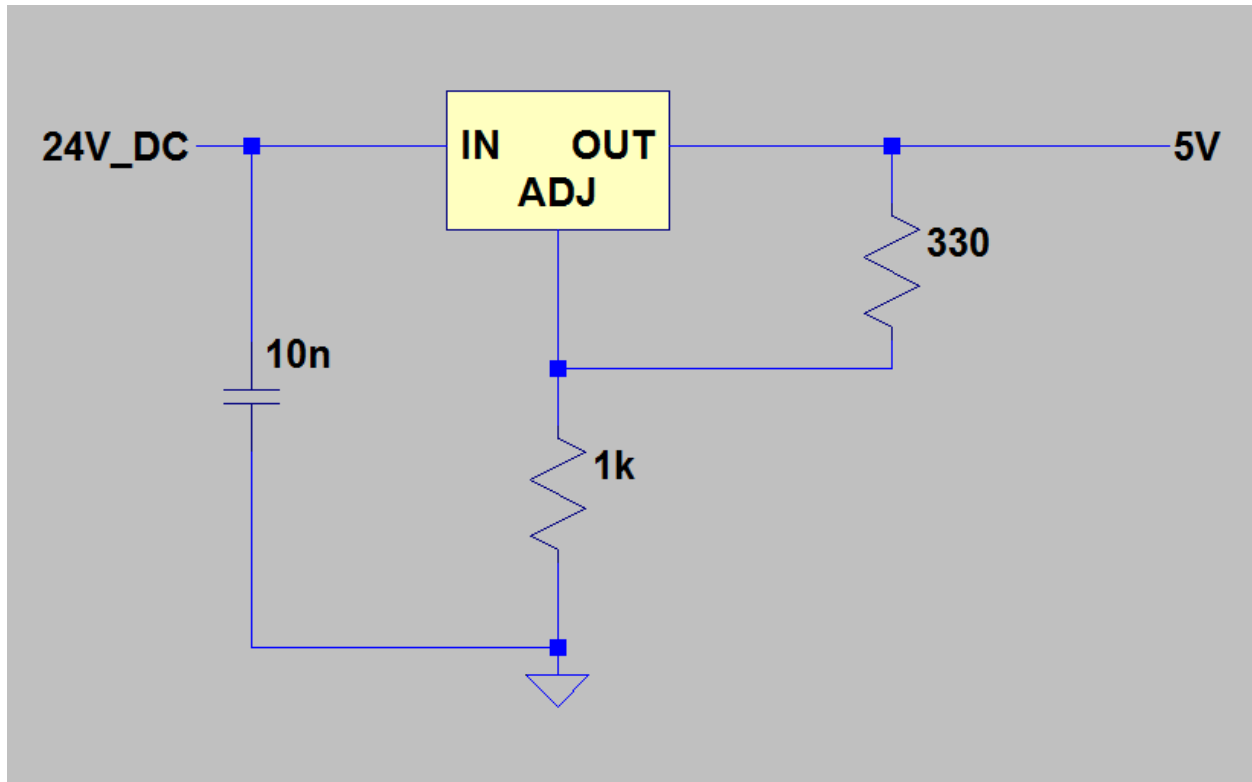


Figure 11: 5V Voltage Regulator

The second voltage regulator that was used was a 15V regulator. For these voltage regulators, resistors R1 with a value of 330 Ω was used, and R2 used a combination of a resistor with value 2.2 k Ω and a potentiometer with a value of 1.45 k Ω . This gave us a combination of 3.65 k Ω , which provided the 15V output that was desired. Another 10 nF capacitor was used on this circuit to help reduce the noise. The 15V output was used for the MOSFET Driver and IGBT. This circuit is show in Figure 12.

$$V_{out} = 1.25 \left(1 + \frac{R_2}{R_1} \right)$$

$$V_{out} = 1.25 \left(1 + \frac{3.65 \times 10^3}{330} \right)$$

$$V_{out} = 1.25(1 + 11.06)$$

$$V_{out} = 1.25(12.06)$$

$$V_{out} = 15.08V$$

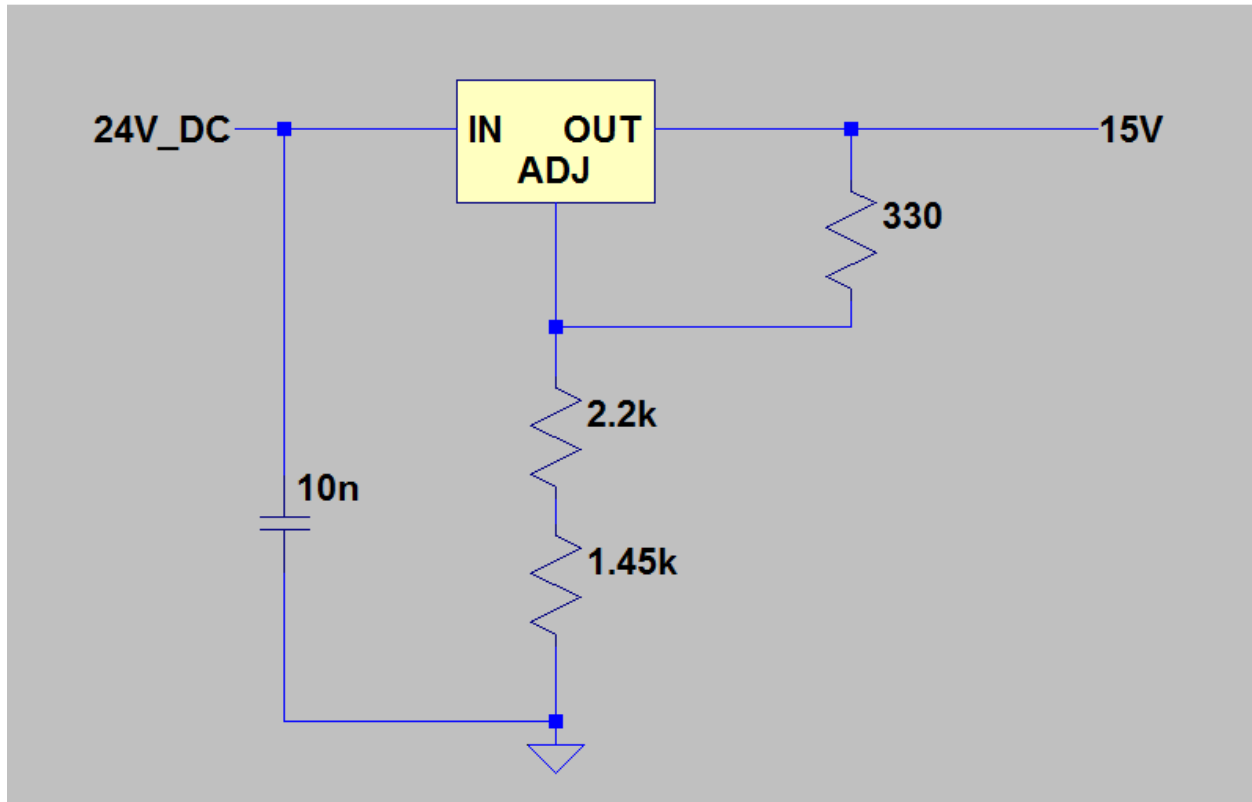


Figure 12: 15V Voltage Regulator

The final voltage regulator that we needed to implement was built to charge the 7.5 μ F 1200V capacitor, which is triggered through the IGBT to switch the ignitrons on. We needed to drive an EMCO GP 15 DC to a DC converter. This would allow the voltage step-up, so that we could charge the capacitor. Since the EMCO GP 15 is proportional between the input voltage and output voltage, we decided to use two potentiometers to set the voltage regulator correctly, so that we would not exceed the capacitor 1200V rating. As configured, R1 is equal to 240 Ω and R2 is equal to 1.3 k Ω . This gives us an output to the DC to DC converter of 8.02 V. Two 10 nF

capacitors were used on this circuit, one on the input as implemented on both of the previous voltage regulators, and one on the output to help with the noise in the DC to DC converter.

Figure 13 below is the circuit diagram for the 8V voltage regulator.

$$V_{out} = 1.25 \left(1 + \frac{R_2}{R_1} \right)$$

$$V_{out} = 1.25 \left(1 + \frac{1.3 \times 10^3}{240} \right)$$

$$V_{out} = 1.25(1 + 5.42)$$

$$V_{out} = 1.25(6.42)$$

$$V_{out} = 8.02V$$

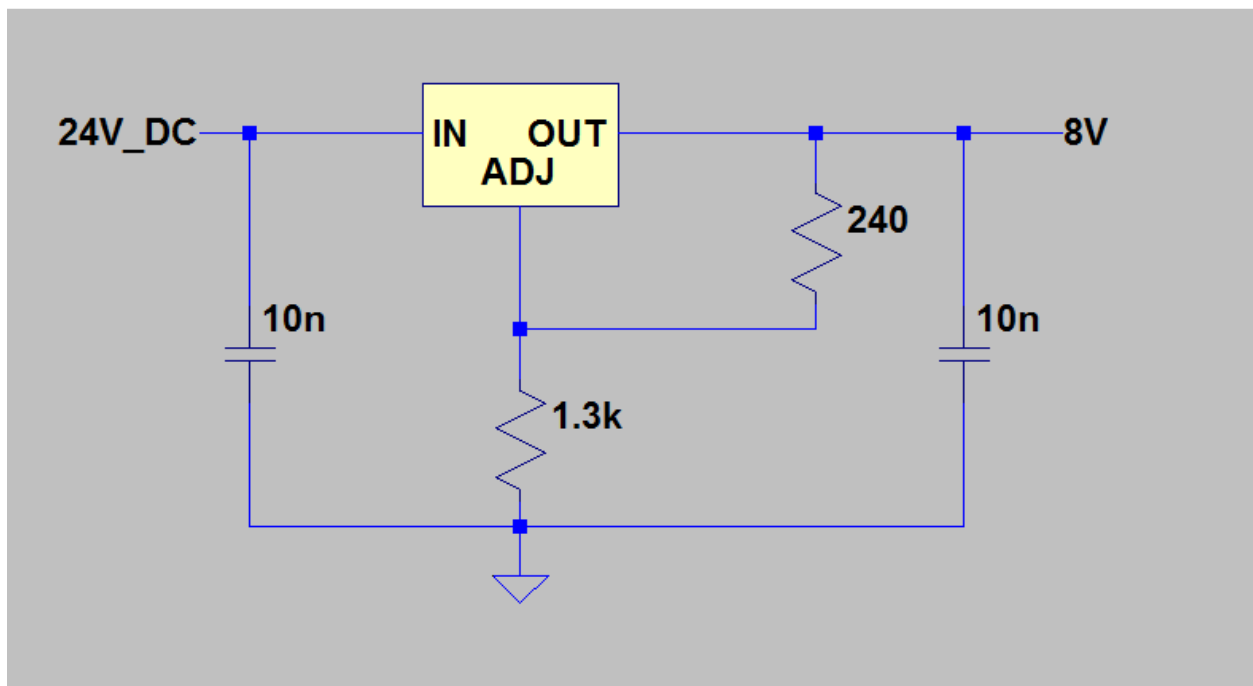


Figure 13: 8V Voltage Regulator

CHAPTER 3 – IMPLEMENTATION AND TESTING

3.1 Implementation

A modular approach was used in the construction of the circuit. When we built the TTL Inverter we used a DC power supply to provide the power, and a function generator to accurately measure the TTL output. The Monostable multivibrator was constructed similarly, using the power supply and function generator to help build the circuit. All of these circuit blocks were first assembled on a breadboard before implementation on a through-hole board. This allowed us to very easily change resistance and capacitance values in the design of the circuits. In Figure 14, you can see how the circuit was laid out on the breadboard. Once we had completed the testing of the ignitron triggering circuit, we moved the circuit from a breadboard onto a through-hole board which is shown in Figure 15.

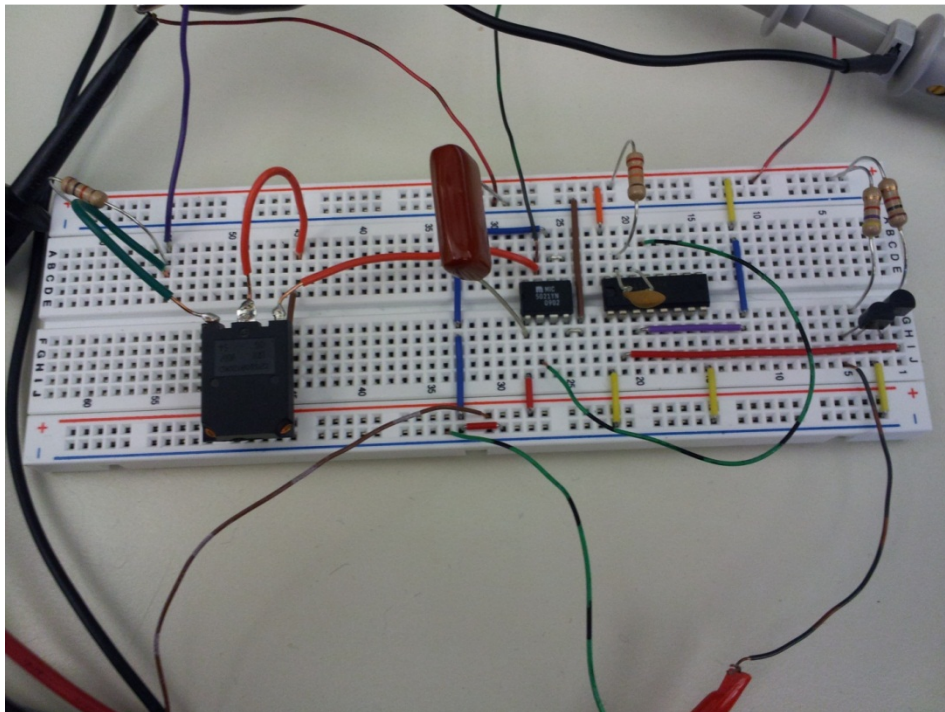


Figure 14: Ignitron Trigger Circuit on Breadboard

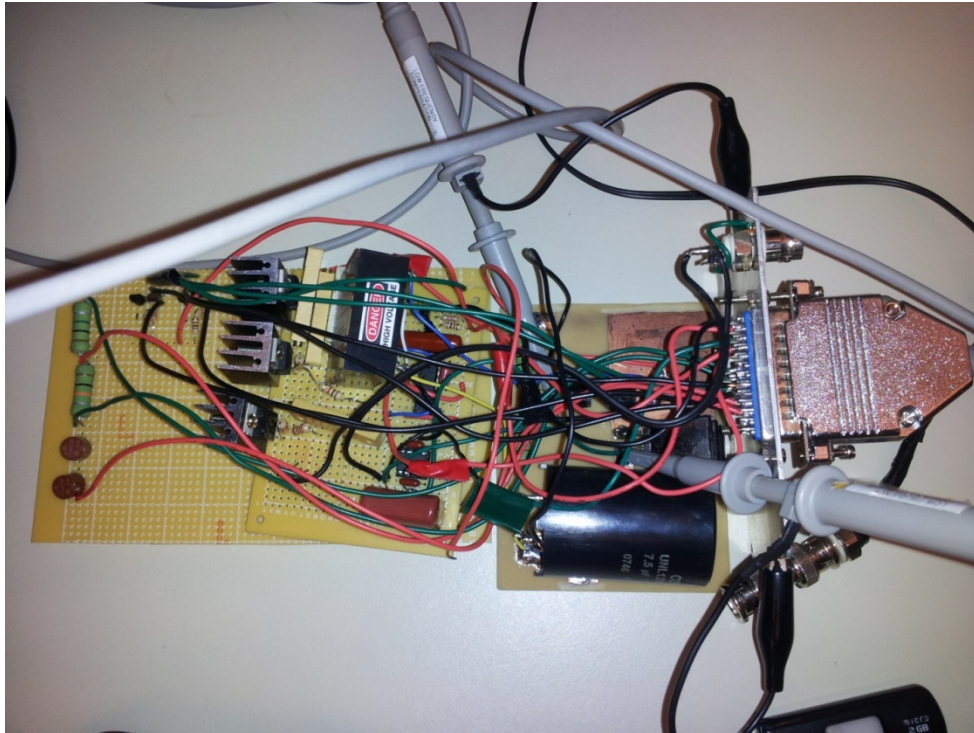


Figure 15: Ignitron Trigger Circuit on Final Board

For the Ignitron implementation we needed to make sure that we had parallel return lines. This is needed due to the fact that the large magnetic fields that are created during firing will cause the mercury to be drawn to one side of the ignitrons, which will damage them. We accomplished this by using four return lines for each ignitron, one on each corner of the ignitron mounting plate. This also allowed us to have a sturdy set-up, which ensured that the ignitrons were always in a vertical position, thus reducing the risk of damage to them. Figures 16 and 17 illustrate the completed ignitron mounting set-up.

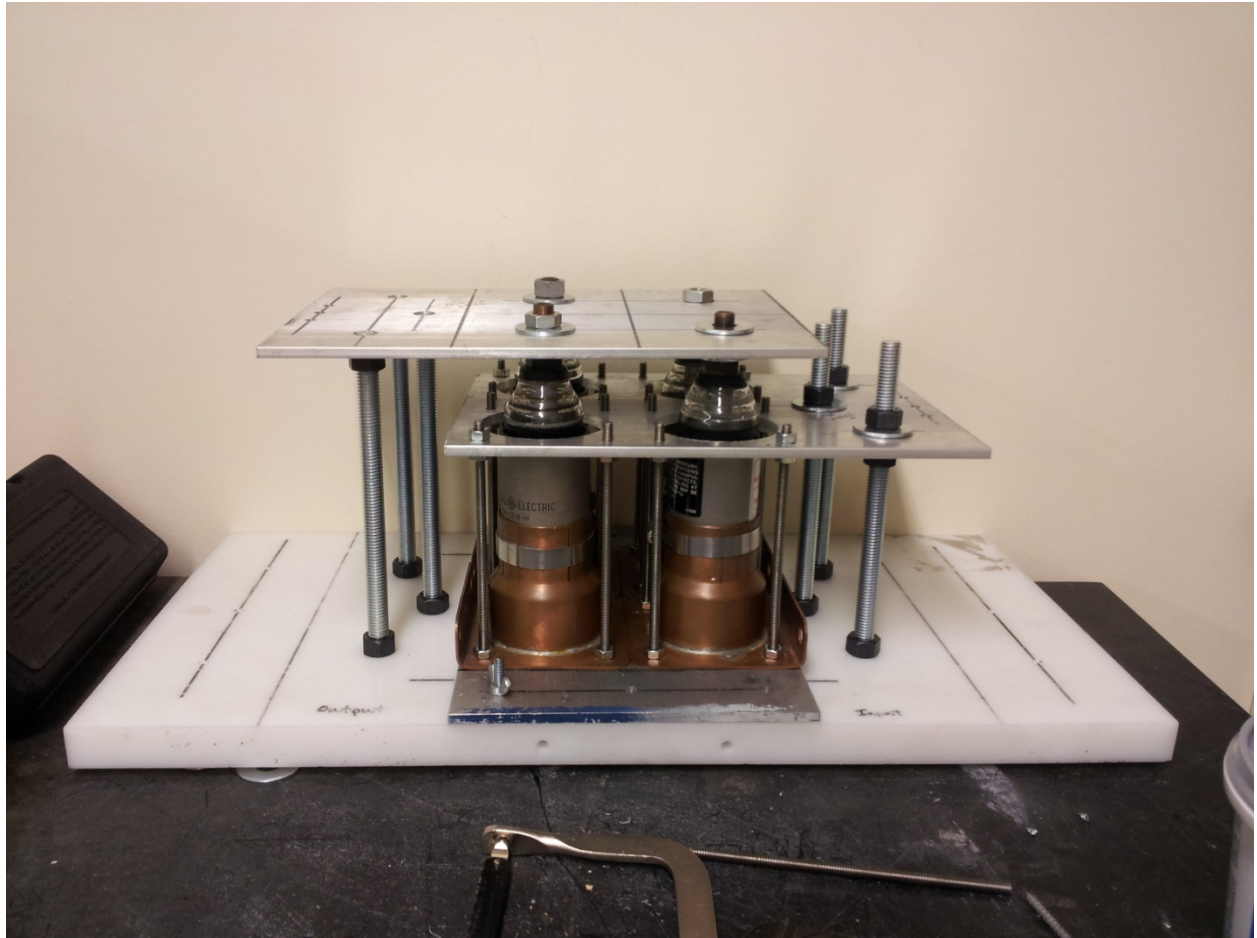


Figure 16: Ignitron Mounting Hardware

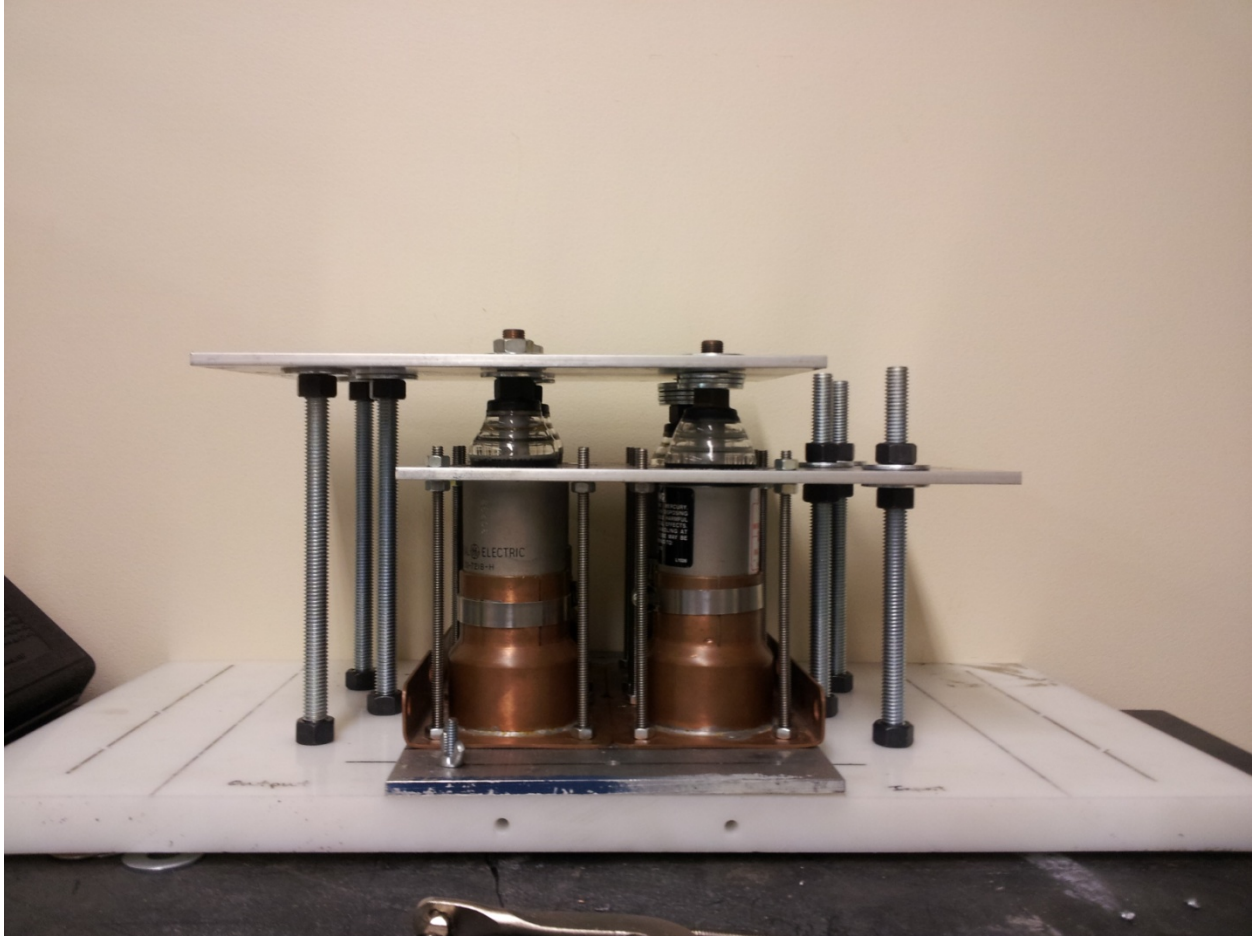


Figure 17: Ignitron Mounting Side View

3.2 Testing

We were able to assemble each part and verify its proper operation. Once each subsystem circuit was combined, some problems arose with noise. Originally, the circuit would send a firing pulse when it was first turned on. This would lead to misfiring of the rail gun, which is not an acceptable outcome of the triggering circuit. In order to find where the noise was coming from, and how it could be reduced, cable lengths were varied to see if they had any effect on the noise. When cable runs of less than one foot were used, the noise was no longer a problem.

During the actual firings of the rail gun, cable lengths of over 50 feet were used due to the fact that the rail gun must be in a bunker, while the switch is in the control room. In order to account for this, a 50 foot long cable was brought into the lab so that testing could be completed with an accurate representation of the firing setup. In order to eliminate the noise, larger capacitors were added in specific locations.

To verify that the Arduino was operating properly, it was tested by itself. This was accomplished by connecting the output of the Arduino to an Oscilloscope, and having it trigger on the pulse to the TTL Inverter. This allowed for the pulse to be displayed, and also verified that no secondary pulses were being sent that might interfere with proper operation. Figure 18 below shows the output from the Arduino.

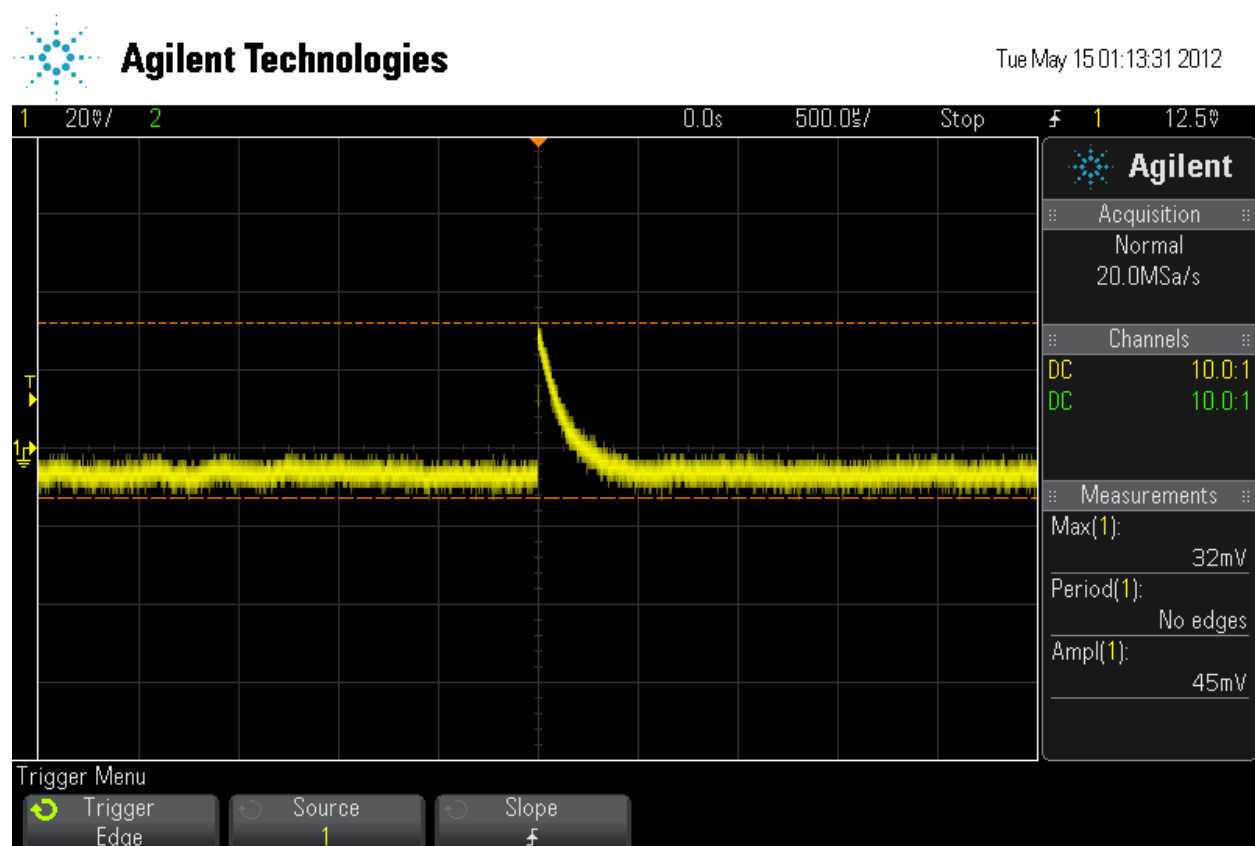


Figure 18: Arduino Output

The next component that was tested was the TTL Inverter in which two MPSA06 NPN transistors were used. This was tested as a stand-alone circuit, and also while using the Arduino as the input. Figure 19 below shows the output that we received when we had the Arduino connected. Channel 1 was the input from the Arduino and channel 2 was the output from the TTL Inverter. As shown in the image, the TTL Inverter worked exactly as planned, and put out the inverted pulse needed.

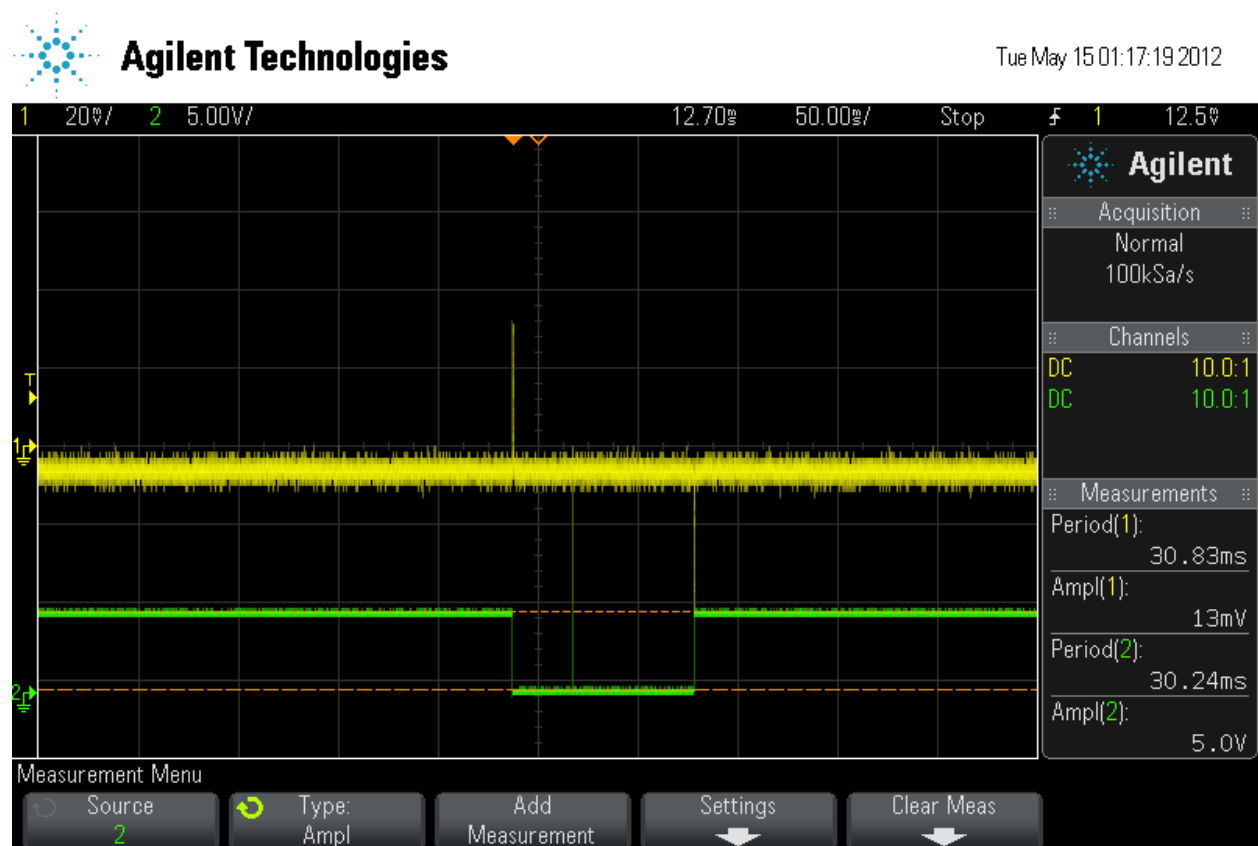


Figure 19: TTL Inverter Output

Next, testing was done on the Monostable multivibrator in the same manner as the TTL Inverter. Figure 20 reveals the scope after the integration of the Monostable multivibrator into the completed circuit with the Arduino and TTL Inverter. Channel 1 shows the output from the

TTL Inverter, which is the input to the Monostable multivibrator, and channel 2 shows the output from the Monostable multivibrator.

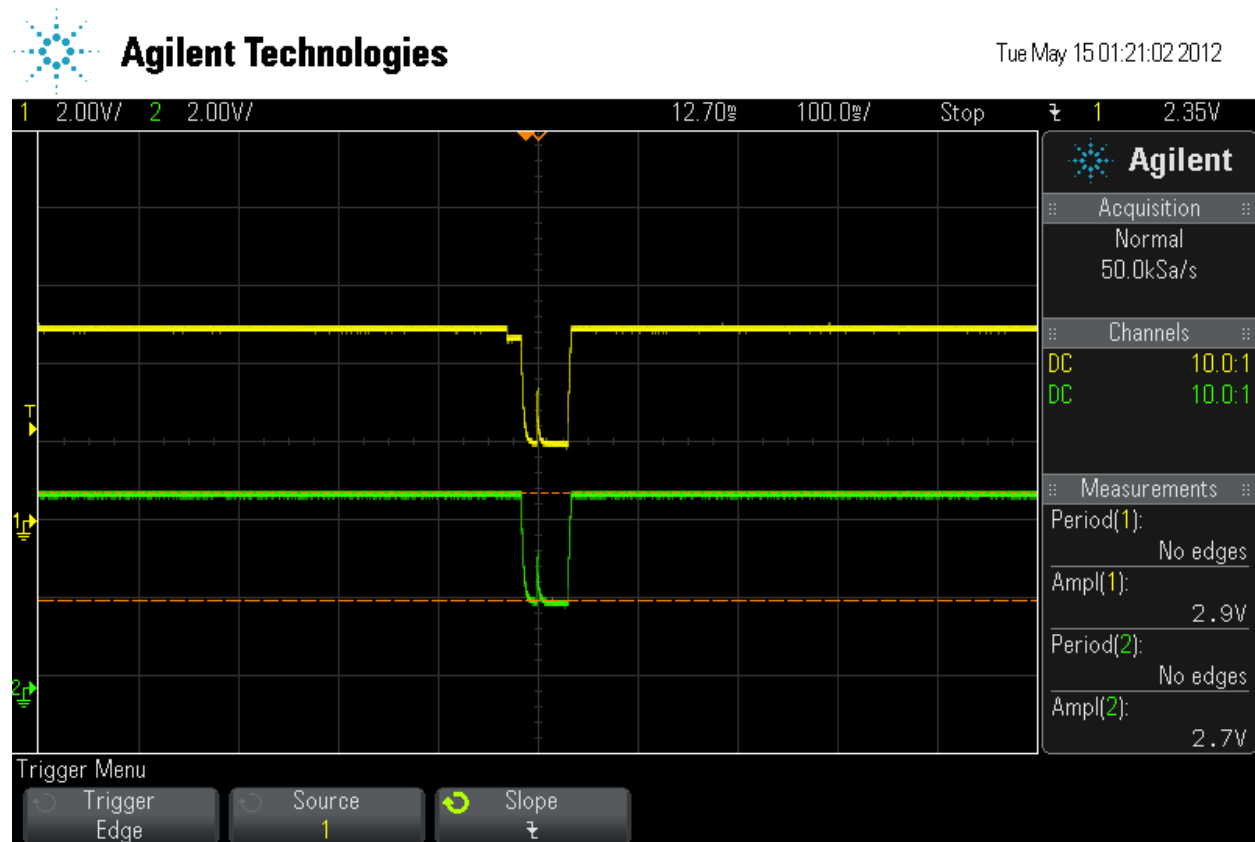


Figure 20: Monostable Multivibrator Output

Since the circuit up to this point was working correctly, we decided to move on and test the MIC5021 MOSFET Driver with the rest of the circuit. While the MOSFET Driver was originally tested as a stand-alone chip, it was decided to test it along with the rest of the circuit so that its proper operation could be verified. Figure 21 shows the image displayed on the oscilloscope during testing. Channel 1 was the output from the Monostable multivibrator that was used as the input for the MOSFET Driver, and channel 2 was the output from the MOSFET Driver. As seen in the image below, the output was a 4 mS pulse with an amplitude of 14.9 V.

While the pulse length is a little bit shorter than was originally planned for, it is still much longer than the 5 μ S required to trigger the ignitrons.

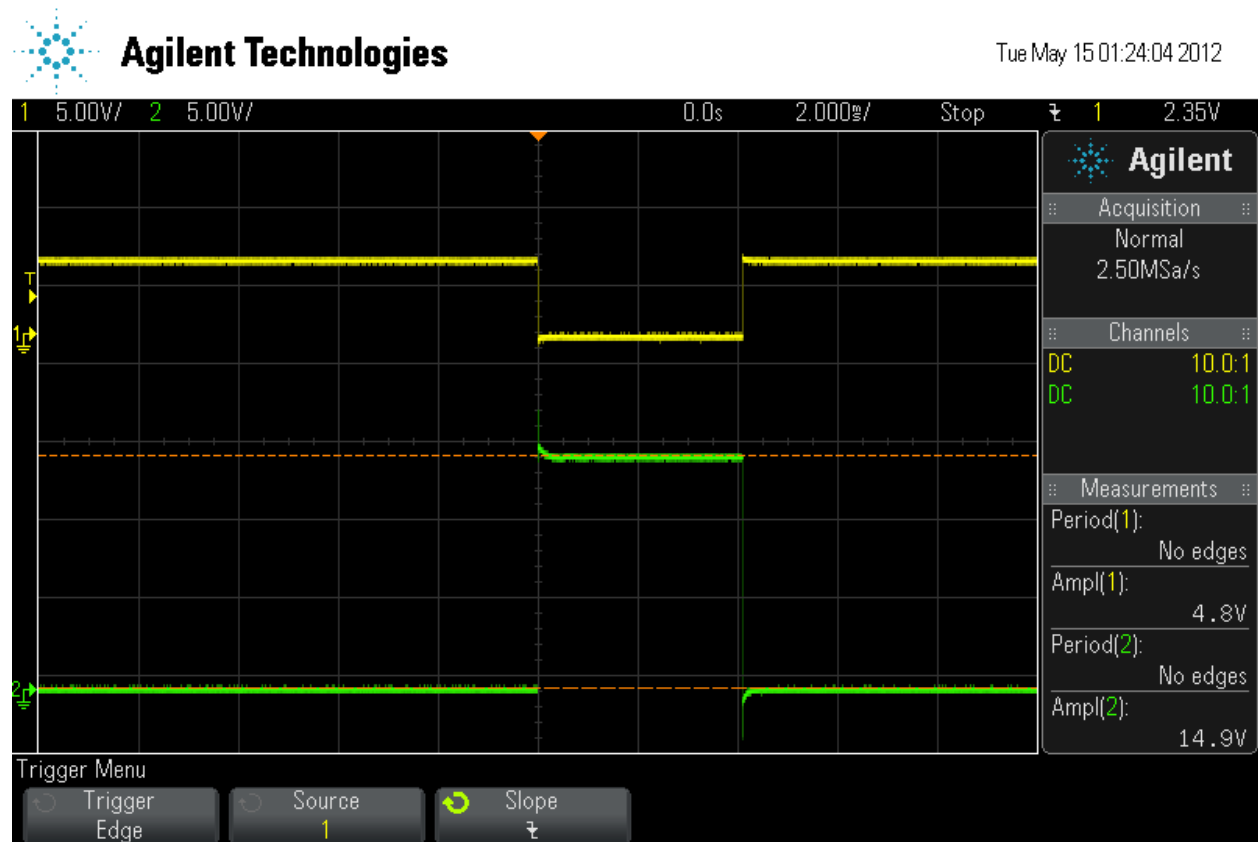


Figure 21: MOSFET Driver Output

The next component tested was the IGBT. At this point, the ignitron triggering circuit needed to be working correctly, as it is not possible to have a function generator supply the pulse that is needed to correctly test the IGBTs. The first few tests that were completed were with the capacitor uncharged, which allowed verification of the proper operation without having the capacitor at 1000V. Figure 22 illustrates the result when the capacitor was uncharged. Channel 1 was the output from the MOSFET Driver that was used as the input for the IGBT and channel 2 was the output from the IGBT.

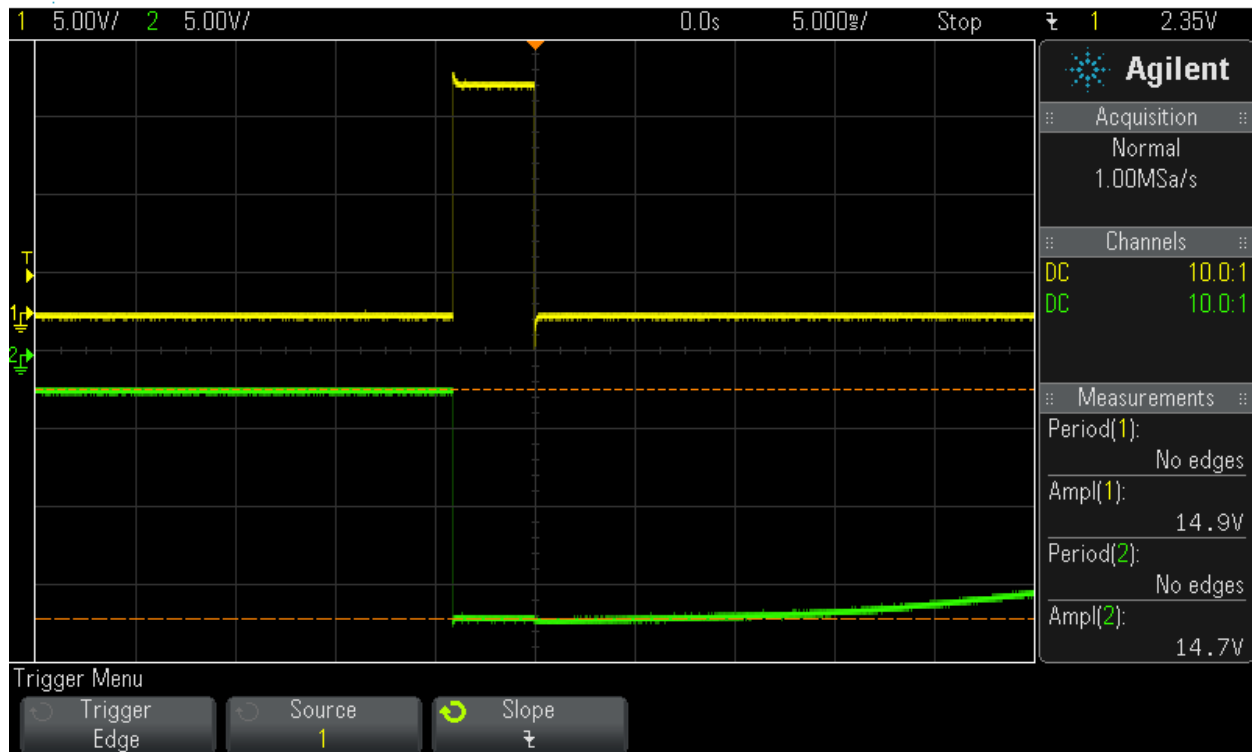


Figure 22: IGBT Output

Now that all of the main components of the Ignitron triggering circuit were working correctly, we moved on to building the three different voltage regulators which would allow the circuit to be completely independent of any lab equipment. The 5V voltage regulator was tested first to see if the design performed as simulated. As seen in Figure 23, the input voltage received was 25.2V and the output was 5V. This is exactly what was intended, and the 5V voltage regulator met all of the specifications set for it.

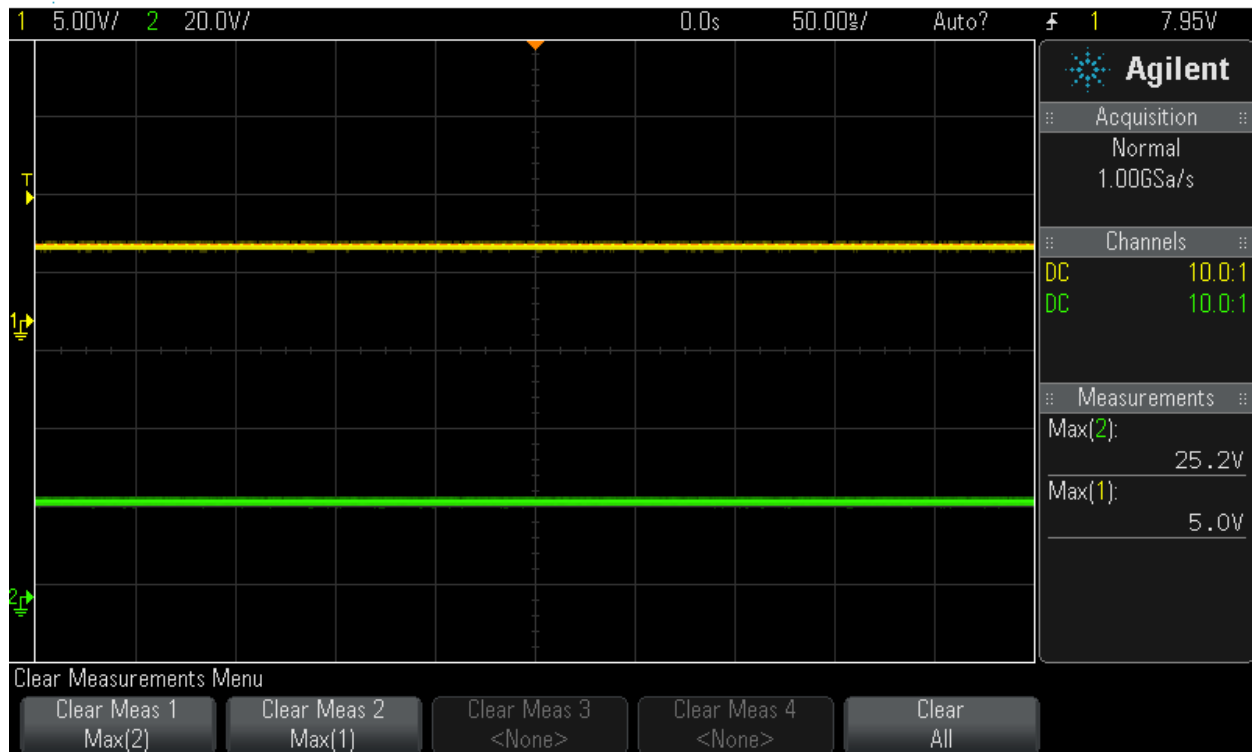


Figure 23: 5V Voltage Regulator Output

The 15V voltage regulator, which was needed for both the MOSFET Driver and the IGBTs, was tested next. As seen in Figure 24, the voltage regulator gave an output voltage of 14.8 V. While this is a little below what was originally planned, it still worked as needed.

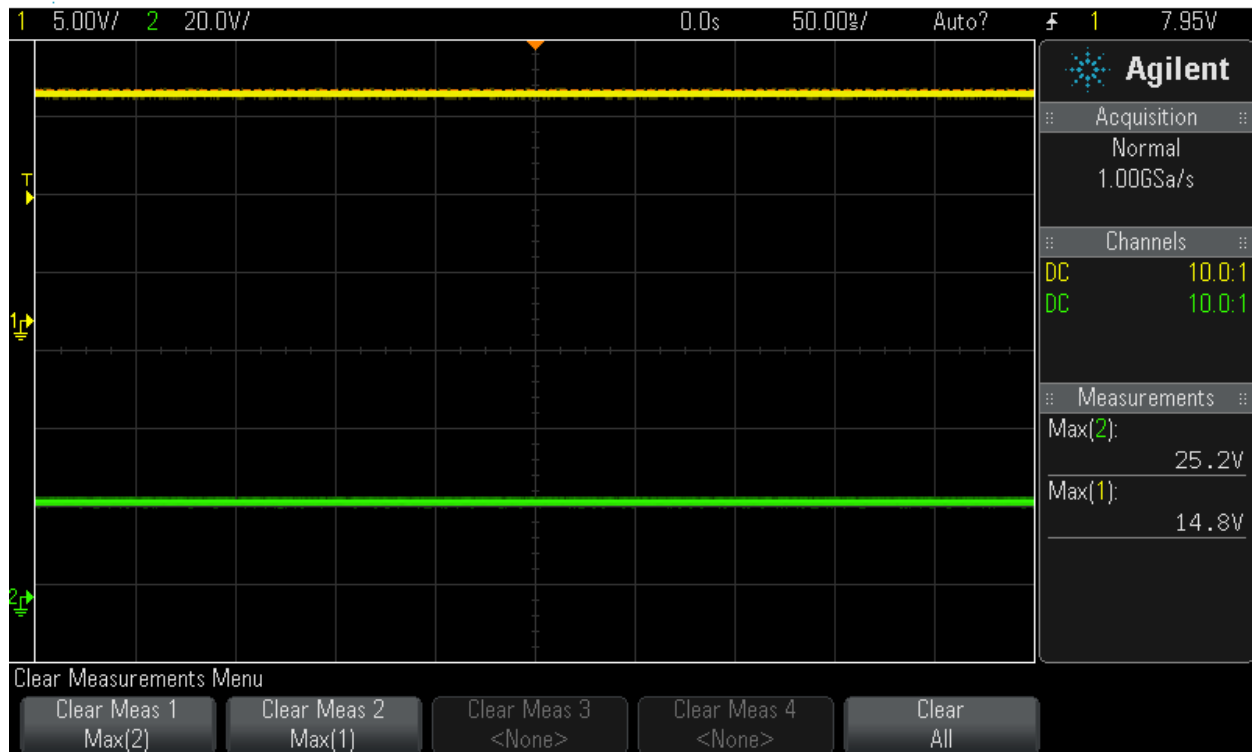


Figure 24: 15V Voltage Regulator Output

The last voltage regulator that needed to be tested was the 8V voltage regulator that is used as the input to the 1000V DC to DC converter. As seen in Figure 25, the voltage regulator worked as planned and gave an output voltage of **8V**.

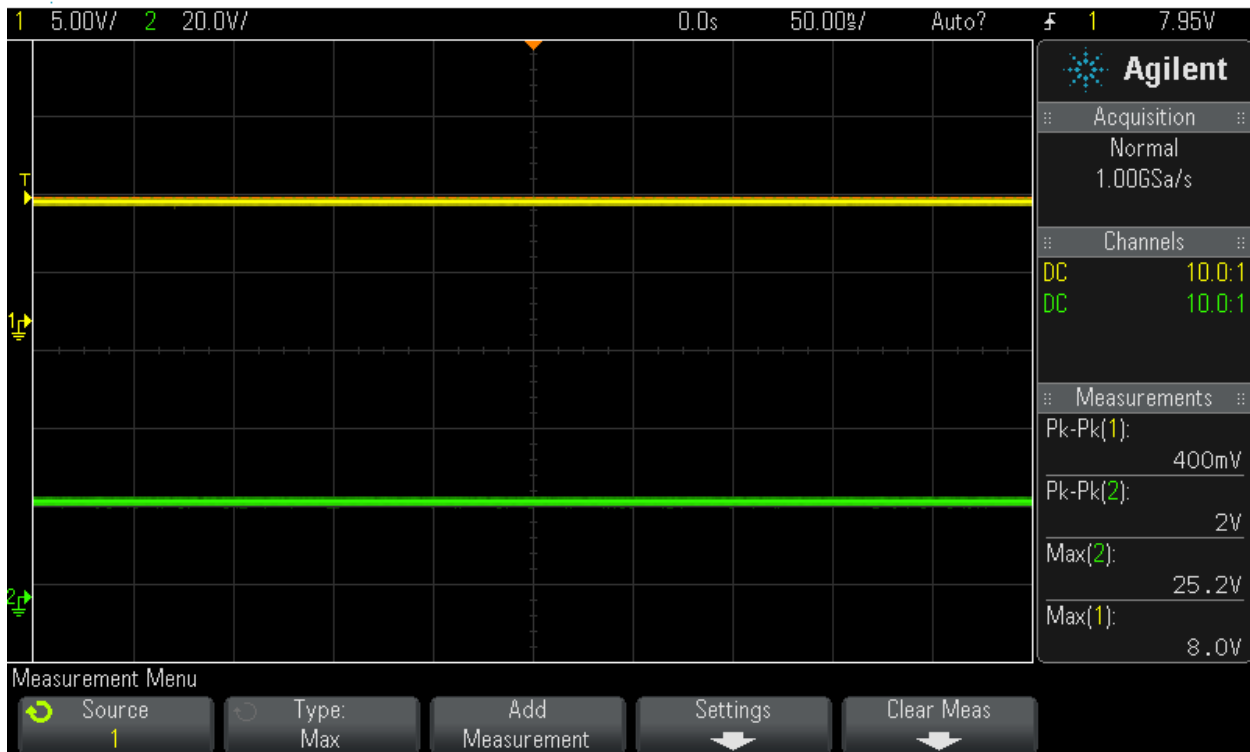


Figure 25: 8V Voltage Regulator Output

In order to test the transformer, we first checked the soldering job to ensure that it was adequate, and then tested the continuity of each of the windings, to make sure the transformer would work. Once this had been verified, we used a function generator to supply a sine wave at 60 Hz that would allow for verification that we had the correct turns ratio. Figure 26 shows how the transformer worked when tested with a single winding. Channel 1 shows the input to the primary winding and channel 2 shows the output from one of the secondary windings.

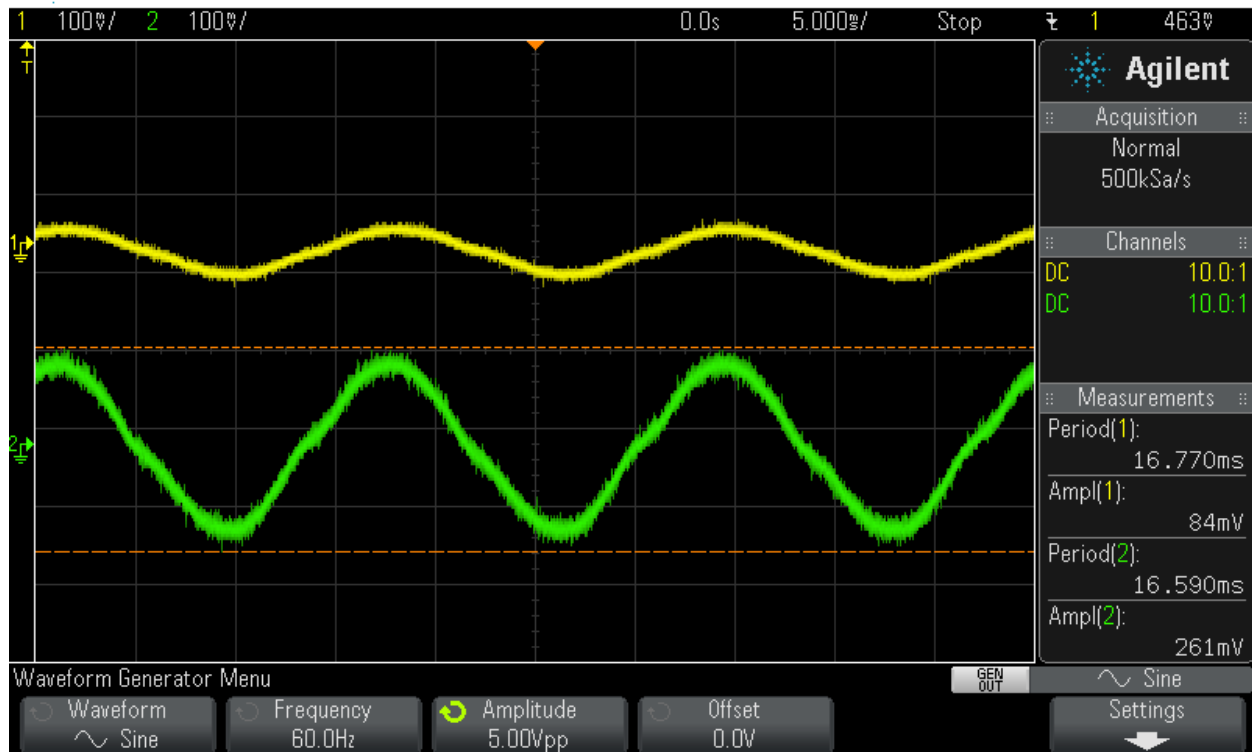


Figure 26: Transformer Testing

When comparing the voltages, it was calculated that the output is 3.11 times greater than the input. While there was concern that it was less than the 4 that was originally planned, it can be explained because it is a homemade transformer. When it was wound, all of the turns did not line up directly on top of each other, which led to some loss in output. The decision was made to test fire the ignitrons with this output, to see if the 3.11 turns ratio would allow a proper firing of the ignitrons. The transformer successfully fired the ignitrons, which allowed us to stay with the 3.11 output.

Once this was verified, the ignitron triggering circuit was test fired with one ignitron using the single secondary winding. Multiple fires of the first ignitron were run to verify proper operation before making the three other secondary windings. The first test conducted was with a

10V charge on the ignitron. The output from this test can be seen in Figure 27. Figure 28 reveals what the output looked like when we ramped the charge voltage up to 50V, and Figure 29 shows what it looked like with a 100V charge. On all three oscilloscope images, channel 1 shows the pulse to trigger the ignitrons, and channel 2 is the output from the ignitrons.

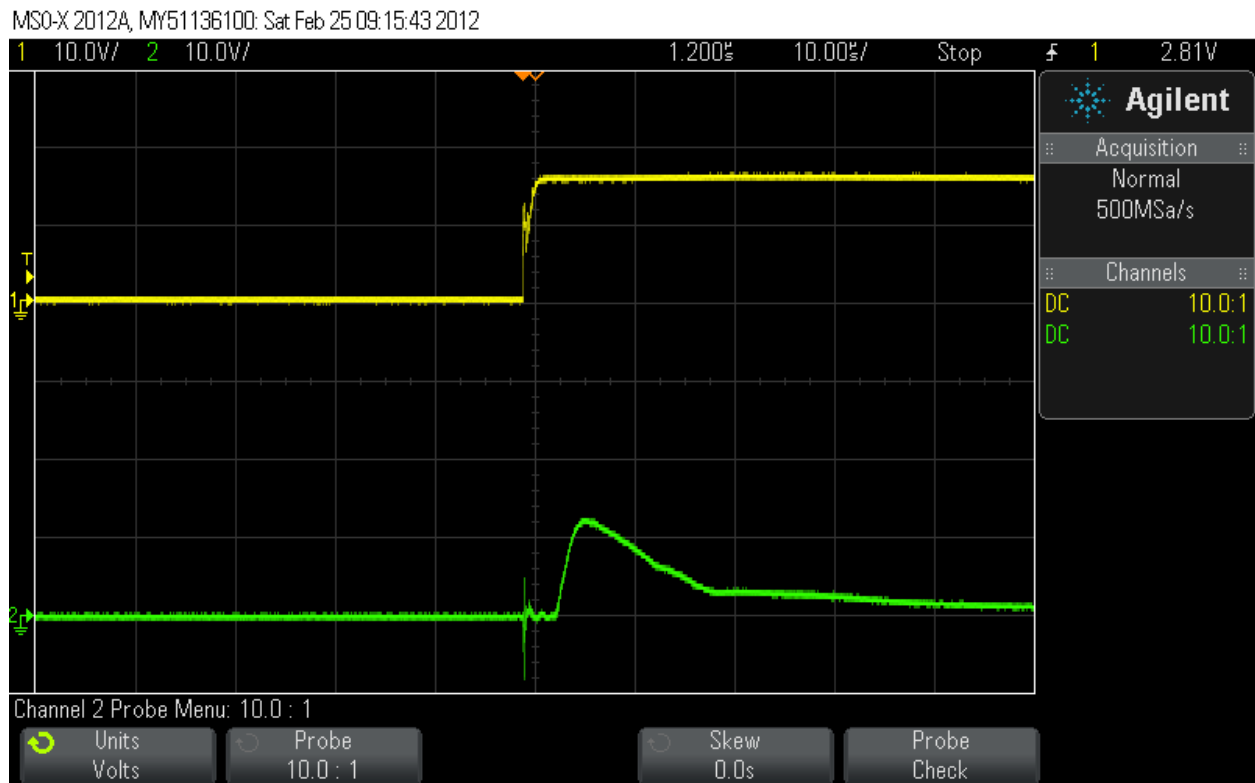


Figure 27: Ignitron 10V Charge

MSO-X 2012A, MY51136100: Sat Feb 25 09:19:42 2012

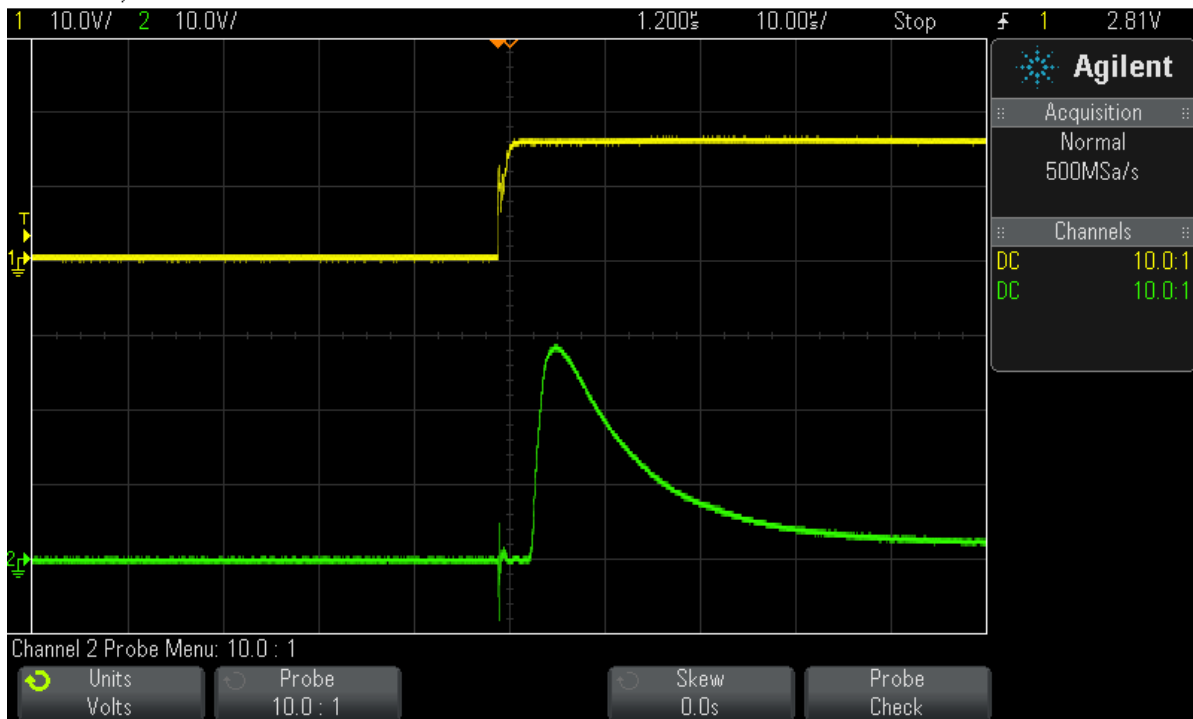


Figure 28: Ignitron 50V Charge

MSO-X 2012A, MY51136100: Sat Feb 25 09:29:21 2012

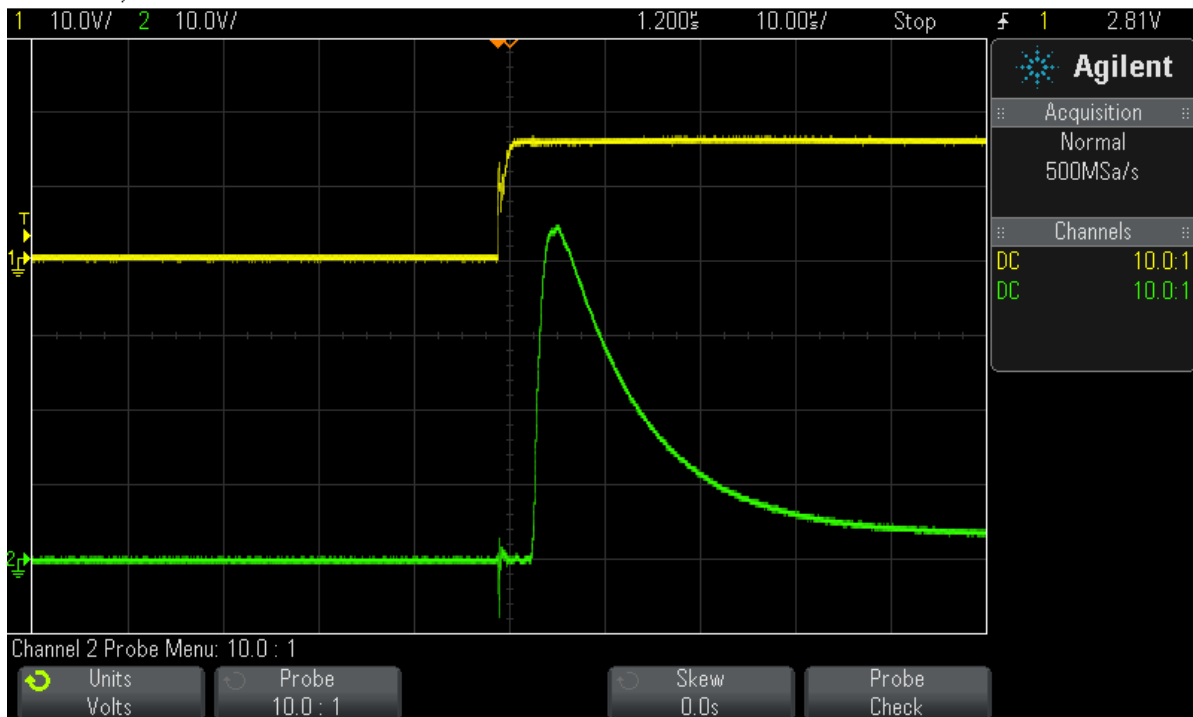


Figure 29: Ignitron 100V Charge

CHAPTER 4 – CONCLUSION

After the testing was completed, it was determined that the Ignitron Trigger Circuit met all of the requirements that were initially set for the project. The circuit succeeded in having a 4.5 mS pulse at around 3000V, which triggered all four of the Ignitrons. An additional test would be to actually use the Ignitron Triggering Circuit on a full-voltage rail gun.

Now that the circuit has been built and tested, we can begin to modify the rail gun so that we can ramp up the tests we are conducting. This will allow us to progress towards the goal of firing at speeds representative of geosynchronous orbit.

The Ignitron Trigger Circuit can now be easily integrated with the compulsator being developed by a group of Mechanical Engineering students, along with Electrical Engineering student Bryan Bennett. Their developments will help to determine the direction we need to go, in order to further improve the electromagnetic rail gun.

Bibliography

Data Sheets:

1. Fairchild Semiconductor MPSA06 NPN
2. Texas Instruments CH74HCT123E
3. International Rectifier IRGPS60B120KD
4. Micrel MIC5021
5. National Electronics NL7218H-100
6. Texas Instruments LM317

APPENDIX A:
PARTS LIST AND COST

Component	Unit Cost	Quantity	Total Cost	Notes
MPSA06	\$0.41	2	\$0.82	
CD74HCT123E	\$0.63	1	\$0.63	
MIC5021	\$2.50	1	\$2.50	Donated
IRGPS60B120KD	\$19.93	3	\$59.79	Donated
LM317	\$0.71	3	\$2.13	
Kapton Tape	\$25.80	2	\$51.60	
Copper Tape	\$28.37	1	\$28.37	
NL7218H-100	\$1887.10	4	\$7548.40	Donated
Arduino	\$30.95	1	\$30.95	
UNL12W7P5K-F	\$24.19	1	\$24.19	
EMCO GP15	\$183.02	1	\$183.02	Donated
Assorted Resistors and Capacitors	\$10.00	1	\$10.00	
Total Cost:			\$148.69	

APPENDIX B:

ARDUINO CODE

```
//All Code Written by Nolan Uchinizo
int ITC_trig = 12;
int button = 7;
int state = 0;
volatile int enable = LOW;
unsigned int count = 0;
unsigned long tmp = 0;
unsigned int oldSREG = 0;

void setup()
{
  Serial.begin(9600);
  pinMode(ITC_trig, OUTPUT);
  pinMode(button, INPUT);
}

void loop()
{
  switch (state)
  {
    case(0):
      Serial.println("EMRG Mk.1 Firing Program.");
      state = 1;
      break;

    case(1):          //Initializes count, then jumps into the waiting state.
      count = 0;
      PORTB = B00000000;
      enable = LOW;
      state=2;
      break;

    case(2):          //Waits for button press.  If pressed, jumps to next
waiting state.
      if(digitalRead(button) == HIGH)
      {
        PORTB |= B00011110;
        state=3;
      }
      else
      {
        state = state;
      }
      break;

    case(3):
      delay(50);
      state = 1;
      break;
  }
}
```