ESD Protection for Preamplifier Circuit in Tracker of Mu2e Experiment

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Abstract:
The mu2e experiment is integral in the search for new physics, in the form of Charged Lepton Flavor Violation via neutrinoless muon-to-electron conversion. The experiment's straw drift chamber tracker contains delicate circuitry that needs protection from the high voltages present during operation. In the interest of saving space and money, the proper amount of electrostatic discharge protection necessary needs to be determined. Preliminary tests indicate only one stage of protection may be sufficient, rather than the two currently present. A test circuit was constructed to simulate a high voltage spark sent to the preamplifiers. This can be used to further test the durability of the ESD protection on the preamps, and can help determine the necessary amount of protection.

Background:

The mu2e experiment seeks to observe Charged Lepton Flavor Violation (CLFV) in the form of neutrinoless muon-to-electron conversion. According to the current understanding of the Standard Model, a muon will decay into an electron and two neutrinos. The observation of a neutrinoless muon-to-electron conversion could lead to new physics, as well as help improve the Standard Model [1].

This experiment will measure the ratio of the rate of muon-to-electron conversions in the Coulomb field of a nucleus to the rate of muon capture on the nucleus, shown in the equation below.

$$R_{\mu e} = \frac{\mu- + A(Z,N) \rightarrow e- + A(Z,N)}{\mu- + A(Z,N) \rightarrow \nu\,\mu + A(Z-1,N)}$$

The current best experimental limit is $R_{\mu e} < 7 \times 10^{-13}$, reached by the SINDRUM II experiment [1]. Mu2e will go four orders of magnitude beyond this value, with an $R_{\mu e}$ of about 6×10^{-17} (90% C.L.), and a calculated single event sensitivity of about 2.87×10^{-17} [1]. In order to accomplish this, an estimated 3.6×10^{20} protons on target are required.

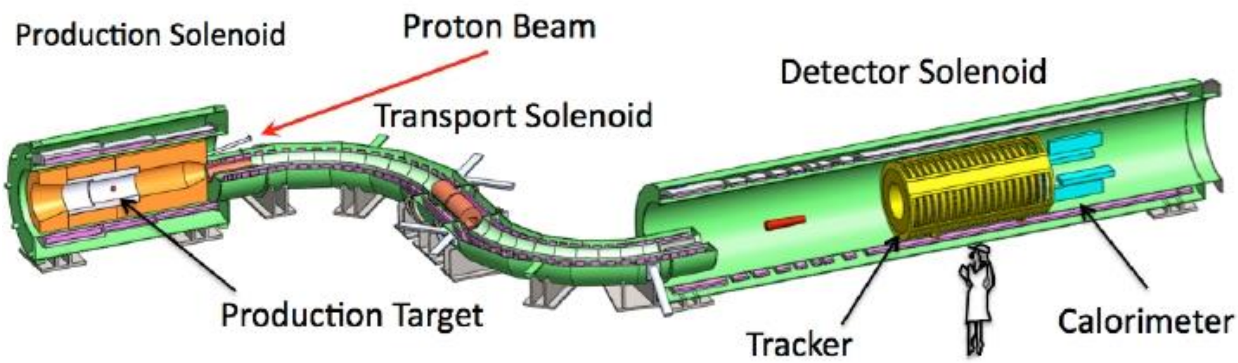


Figure 1: Mu2e Apparatus [1]

Figure 1 shows the apparatus to be used for the experiment. A low momentum beam of muons is produced from an 8GeV proton beam hitting the Production Target. This initially produces mostly pions, which then decay into muons. The Production Solenoid then sends muons with the correct spin into the Transport Solenoid, which in turn selects negative muons with the desired momentum. These muons make it through to the Detector Solenoid, and roughly half of them are captured on the Aluminum target, where they eventually decay. If a neutrinoless muon-to-electron occurs, the trajectory of the resulting electron will be recorded by the Tracker, and the Calorimeter will help confirm the findings.

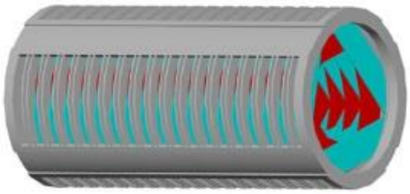


Figure 2: Mu2e tracker [1]

The Tracker, shown in Figure 2, consists of multiple layers of straws. It is designed so that electrons that result from simple muon decay in orbit pass through the center undetected, but those that result from a neutrinoless muon-to-electron conversion follow a helical path through the straws. This concept is illustrated in the cross section of the tracker shown in Figure 3. The straws are composed of 15 µm of Mylar, coated on both sides with 500Å Aluminum to act as electrostatic shielding as well as leak rate reduction, with an additional 200Å layer of gold on the inner surface [1]. The straws contain a 25 μm sense wire in the center at a potential of 1500 Volts, and are filled with 80:20 Ar:CO_2, which becomes ionized when an electron passes through [1]. The charge travels towards the wire via the electric field created by the high voltage, and the resulting signal is transmitted to either end of the straw and read out by a preamplifier (preamp), which helps amplify the signal. This method allows the trajectory of the particle to be tracked, and from that the momentum of the particle can be calculated. In particular, the tracker is looking for paths caused by electrons with momenta roughly equal to those of the original muons – 105 MeV/c. This would indicate a neutrinoless muon-to-electron conversion.

Since the preamps are attached to a high voltage wire, extra precautions are necessary to protect the circuitry. Figure 4 shows the circuit diagram for the preamp. When the straw is functioning normally, the high voltage is blocked from the circuit by the capacitor. However, in the case of a spark between the wire and the straw, or between the leads connecting the preamp to the circuit board, a transient high voltage signal with high frequency is transmitted through the capacitor to the rest of the delicate circuitry.

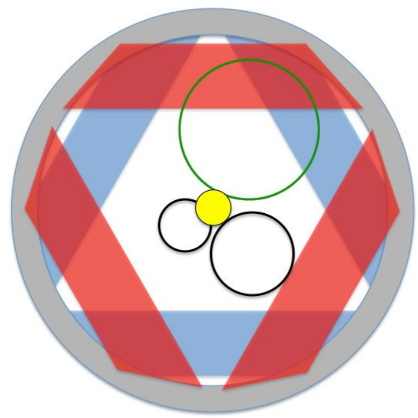


Figure 3: Cross section of tracker. A 105 MeV electron path is shown in green, and electrons with smaller energies are shown in black. [1]

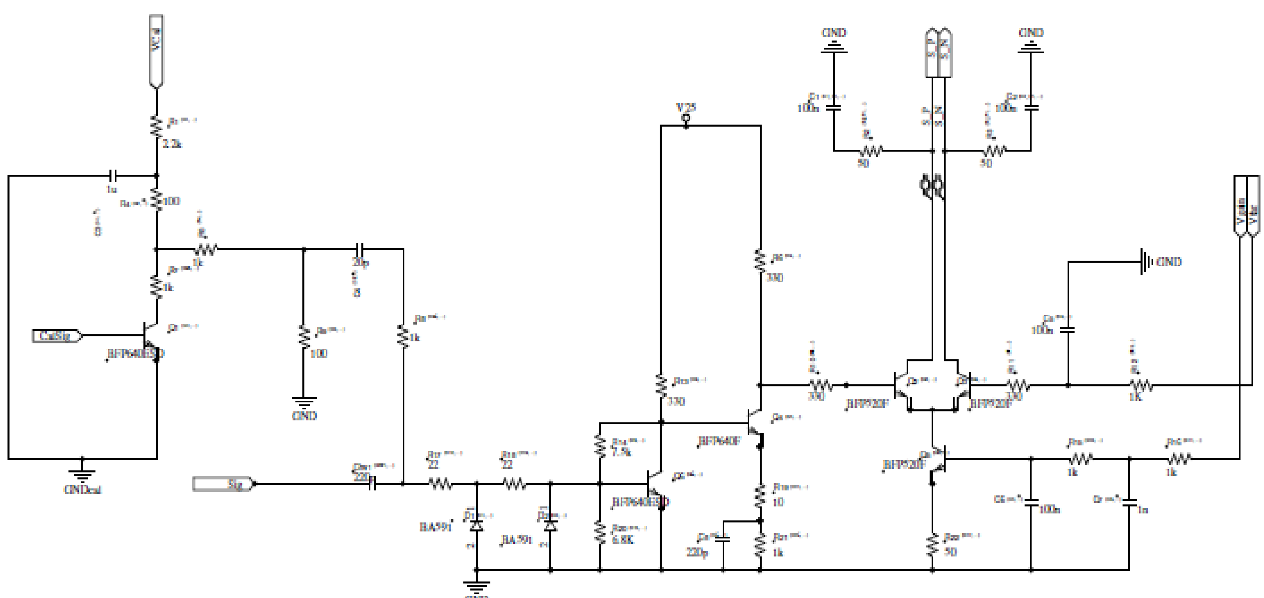


Figure 4: Schematic of preamp circuitry

Figure 5 shows the electrostatic discharge (ESD) protection circuit already in place – two diodes to ground and small valued resistors to draw current away from the input stage transistor on the preamp. In order to save space and money, tests were done to determine whether or not two diodes and resistors were necessary, or if one diode-resistor pair would suffice.

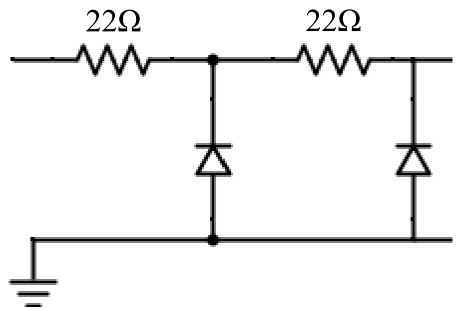
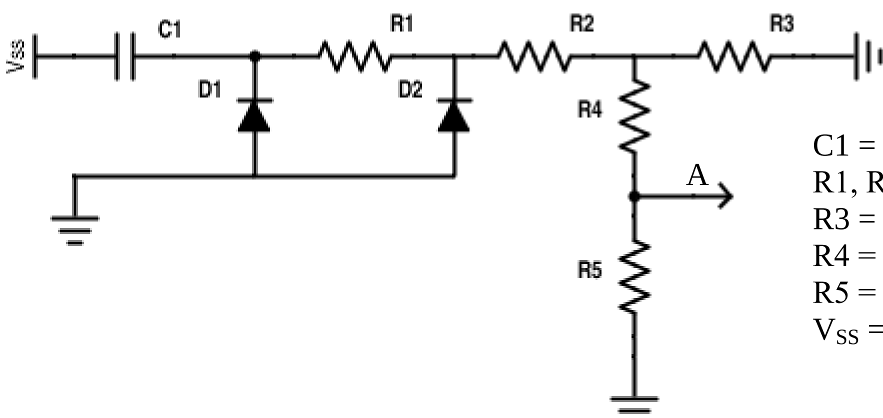


Figure 5: Current ESD protection in preamp circuit

Methods and Results:
Test circuits
Before any experiments were performed on the preamps themselves, test circuits comprised of two diode-resistor pairs, one diode-resistor pair, and no ESD protection were constructed (shown in Figures 6, 7, and 8, respectively). In order to safely measure the spark signals with an oscilloscope, a voltage divider that reduced the signal amplitude by a factor of 50 was added to all three test circuits, as well as a capacitor between the other components and high voltage.



C1 = 200 pF
R1, R2 = 22Ω
R3 = 50Ω
R4 = 2.5kΩ
R5 = 50Ω
V_{SS} = 1500V

Figure 6: Test circuit with two stages of protection

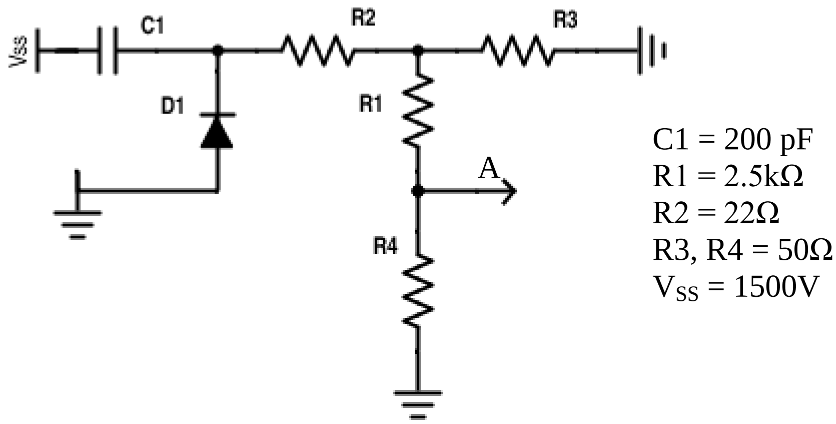


Figure 7: Test circuit with one stage of protection

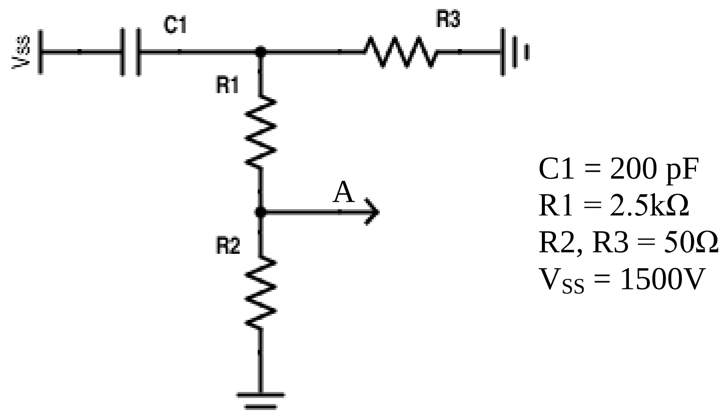


Figure 8: Test circuit with just voltage divider

First, two leads were attached to each circuit – one attached to ground, and one attached to high voltage before the capacitor. 1500 Volts were sent to the circuit, and the leads were touched together to create a spark. This signal was read by an oscilloscope, attached to the circuit at point A. In addition to the voltage divider, two attenuators valued at 20 dB and 12 dB were placed between the oscilloscope and the circuit. This ensured the protection of the oscilloscope from the high voltages used in all tests. A total of ten signals per circuit were collected, and the average amplitude of the sparks formed was calculated.

After all signals were collected, each circuit was attached to a test straw. This test straw used the same 25 µm wire to be used in the actual straws, but the outside was composed of brass instead of Mylar. A spark was created by pressing a metal screw close to the central wire through a hole approximately halfway down the length of the straw. Ten signals per circuit were collected, and the averages of the amplitudes were found.

Finally, the test circuits were attached to an actual Mylar straw. Sparks were formed by gently pressing the outside of the straw to the central wire. Once again, ten sparks per test circuit were recorded, and the signals were averaged. Figures 9, 10, and 11 show sample signals from the Mylar straw spark testing for zero, one, and two stages of protection, respectively.

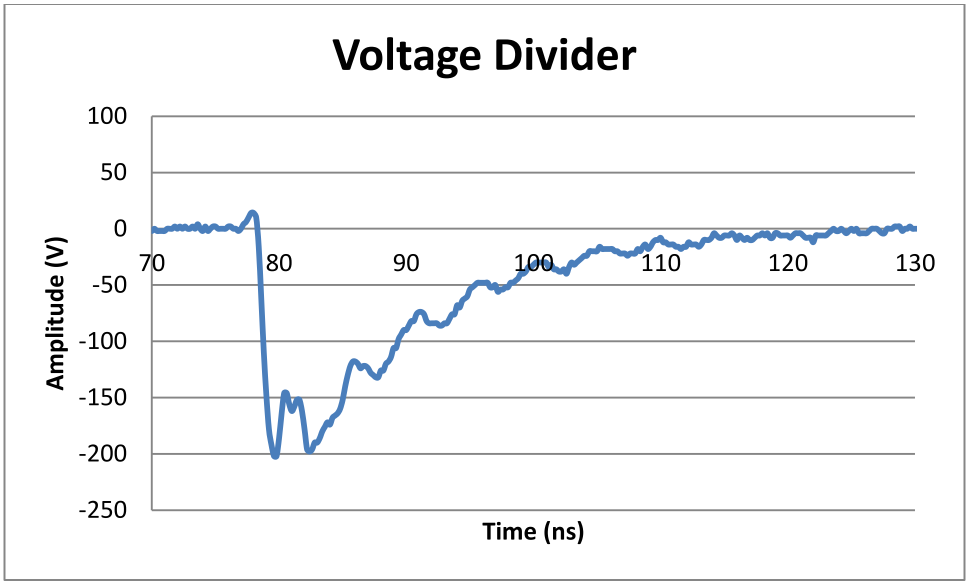


Figure 9: Signal from spark with no ESD protection

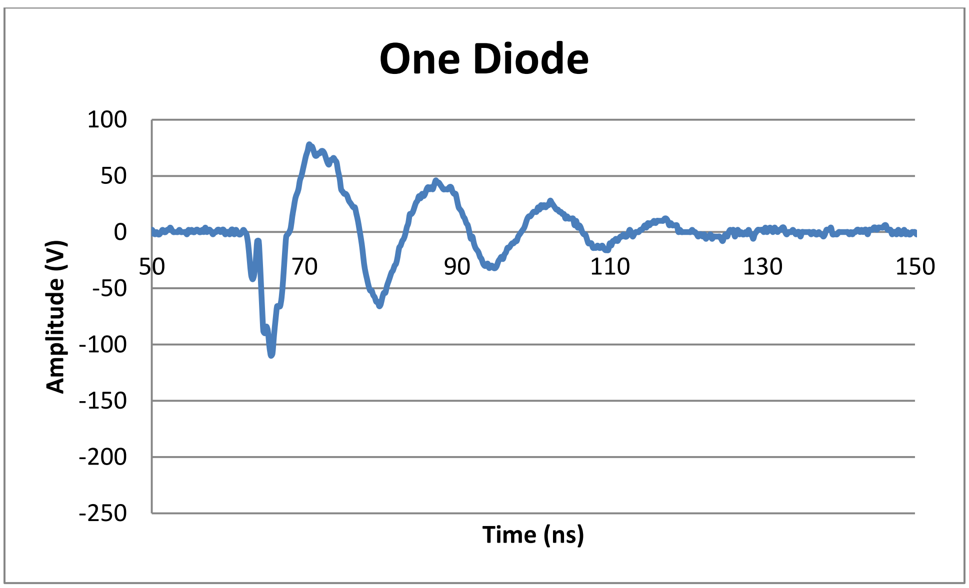


Figure 10: Signal from spark with one stage of ESD protection

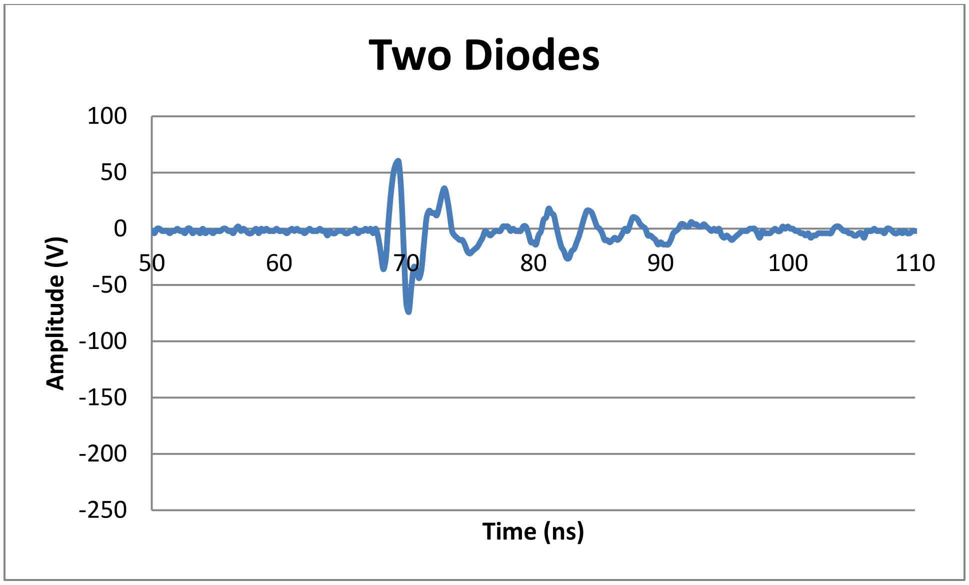


Figure 11: Signal from spark with two stages of ESD protection

The signals in Figures 10 and 11 contain a significant amount of ringing, which is unexpected for a spark. It was determined that the ringing could be due to either having an unstable ground, resulting in the ground bouncing, or parasitic capacitance or inductance of components. The latter is more likely, as the signal remained the same after the connection to ground was improved.

Table I: Average amplitude of spark signals with different sparking media and stages of ESD protection.

Material	Stages of ESD Protection	Average Amplitude of spark (V)
Leads	zero	408.18
	one	132.18
	two	97.87
Brass Straw	zero	353.33
	one	170.60
	two	122.40
Mylar Straw	zero	305.00
	one	95.33
	two	79.67

Table I shows the average amplitudes of all trials. After examining the relative amplitudes of each signal, it was determined that one diode-resistor pair may be sufficient, as the average amplitudes of the sparks differed by at most only 48 Volts. To get further evidence supporting this, preamps were modified and tested.

Preamplifier testing

First, a preamp with both stages of protection intact was used. Before applying any voltage to the circuit, the base-emitter voltage of the transistor in the preamp was measured via a digital multimeter in diode mode. The initial value was 0.835 Volts. 1500 Volts were applied to the preamp, and it was sparked multiple times. The base-emitter voltage was measured again after one spark, five sparks, ten sparks, and subsequent multiples of ten up until 150. The value held for each measurement.

Next, one stage of protection was removed, leaving the ESD protection in the configuration shown in Figure 12. The initial base-emitter voltage was measured as 0.795 Volts, and then the preamp was connected to high voltage and sparked. After only one spark, the base-emitter value was significantly lower than initially, at a value of 0.195 Volts, indicating that the transistor had become damaged. To try to remedy this, the position of the resistor relative to the diode was changed so that the resistor was between the rest of the preamp circuitry and the diode (shown in Figure 13), rather than before the diode. Another preamp was tested with this configuration, and survived up to 150 sparks as before.

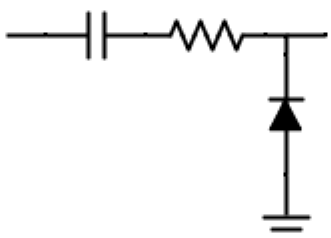


Figure 12: Initial diode-resistor configuration

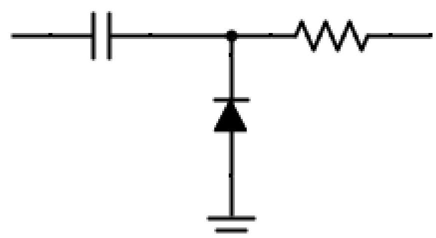


Figure 13: Revised diode-resistor configuration

Advanced test circuit

Since both of the previous experiments indicated that one stage of protection may be sufficient, the next step was to construct an automated test circuit to continue sending sparks to the preamps. The schematic for this test system is shown below in Figure 14.

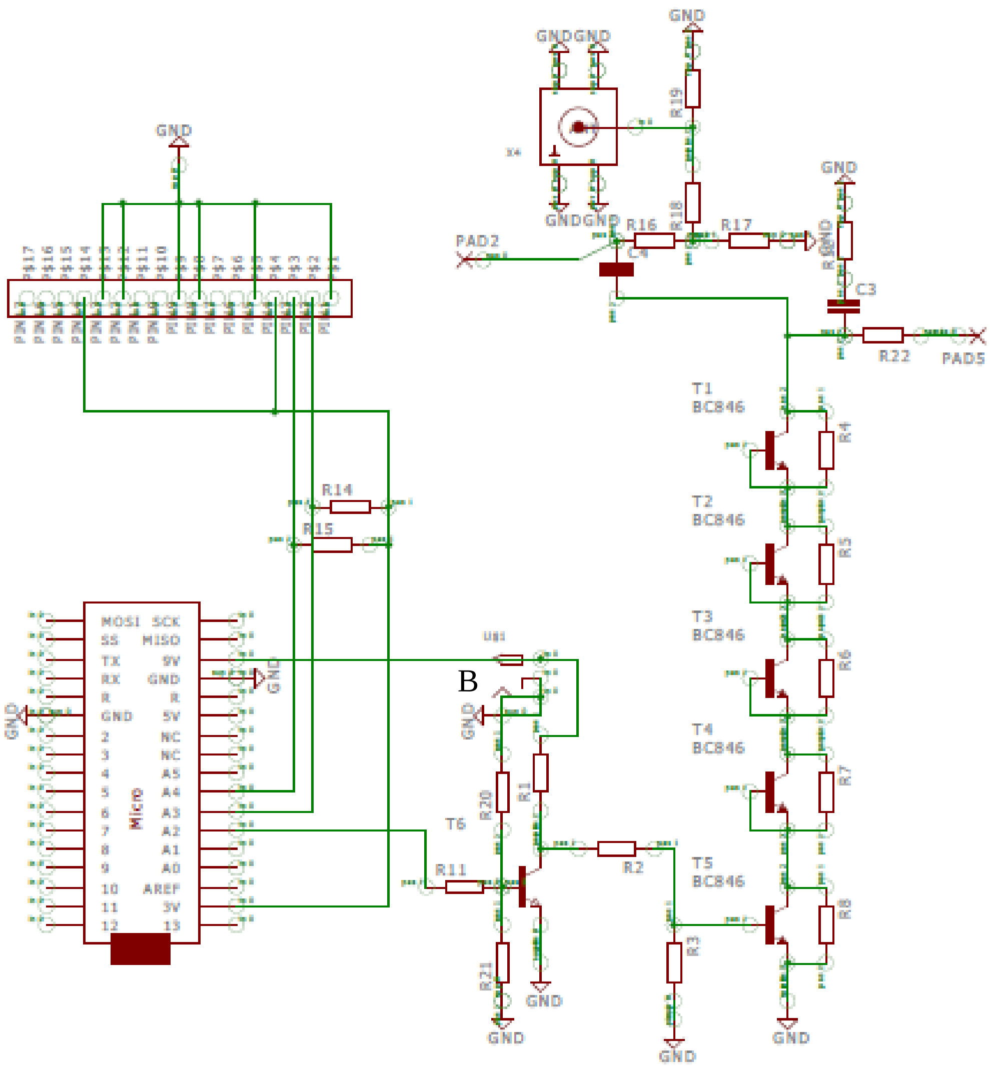


Figure 14: Schematic for preamp durability test circuit. Conceptual design by Vadim Rusu, schematic design by Madeline Lambert.

Transistors T1 through T5 are avalanche transistors, utilized for their fast reaction time (less than one nanosecond). When used in succession, they can create a large amplitude signal with a sub-nanosecond rise time, mimicking the signal given off by a spark. The specific avalanche transistors used in this circuit (Digi-Key part number FMMT417TD) do not avalanche until the collector-emitter voltage is greater than or equal to 350 Volts, and the bottom transistor in the chain (T5) is turned on. This is accomplished by attaching a separate variable power source to a power jack, denoted as B in Figure 14, and sending it through a voltage divider (R2 and R3). The optimal input voltage was found to be between 9.8 and 10 Volts. The last transistor, T6, is a normal transistor that acts as a switch to turn the chain of avalanche transistors on and off. In the design, when T6 is on, T1 through T5 are off, and vice versa. T6 is controlled via a digital pin on an Arduino Micro, and the variable power source from connection B. When the high voltage applied to Pad 5 is above 1750 Volts, and T6 is pulsed off for five microseconds, the transistor chain avalanches, creating a signal shown in Figure 15. Figure 16 is zoomed in to show the rapid fall time of the signal – 1.437 nanoseconds, roughly equal to that of a spark. This signal is sent to the preamp via Pad 2. The preamp is attached to the board by inserting it into the row of 17 pins. This allows for quick removal and insertion of the boards, expediting the testing process. The Arduino code, found in the Appendix, allows the user to input how many times they want to send a spark to the preamp. This greatly reduces the amount of time and manual effort needed to test the durability of the ESD protection.

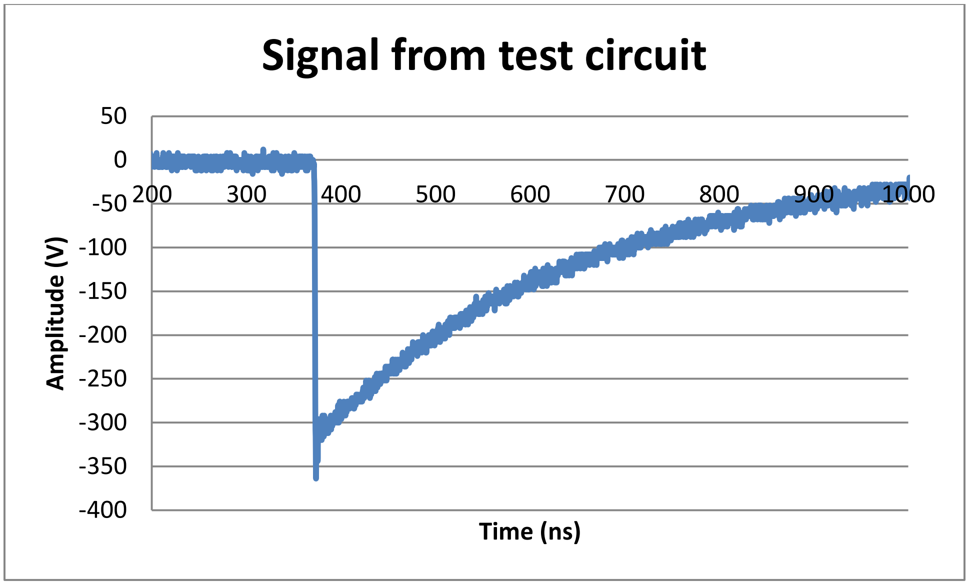


Figure 15: Signal from avalanche transistors

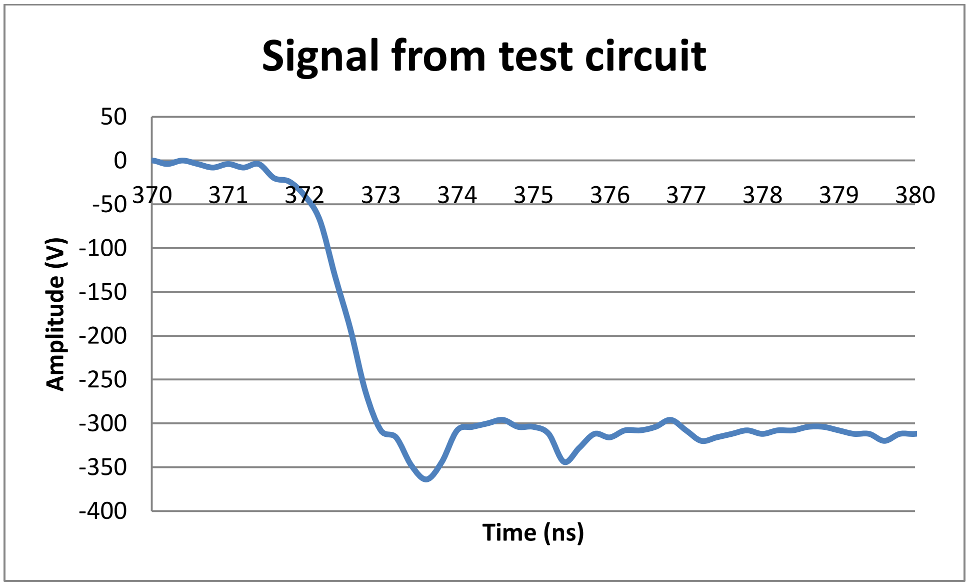


Figure 16: Signal zoomed in to show fall time (1.437 ns)

Conclusions:

After experimentation on model circuits, as well as the preamps themselves, there is some evidence that one stage of ESD protection may be sufficient. The test circuit design can be improved, but overall, it has been shown that it could be used to test the durability of the ESD protection on the preamps.

The avalanche transistors used are delicate and as such, certain precautions need to be taken. Before high voltage is applied to the test circuit, the user needs to ensure that the Arduino pin controlling T6 (Figure 14) is on and outputting five Volts, then ensure the variable power supply is at or above 9.8 Volts. An improvement to the test circuit design would be to add an LED so that it is on when the Arduino pin is off, to decrease the chances of breaking the avalanche transistors.

A further improvement that could be made to the test circuit would be to ensure that high voltage pads were far enough away from other lower voltage pads to decrease the chances of unwanted sparking in the circuit.

Further testing of the effectiveness of one stage of ESD protection is necessary before any more conclusions are drawn.

References:

[1] Fermi National Accelerator Laboratory. “Mu2e Technical Design Report”. October 2014.

Appendix:

Arduino code:

```
int switchPower = A2;
int num = 1;
String inputString = "";
boolean stringComplete = false;

void serialEventRun(void)
{
  if (Serial.available()) serialEvent();
}

void setup()
{
  Serial.begin(19200);
  Serial.println(" Please input a command");
  pinMode(switchPower, OUTPUT);
  digitalWrite(switchPower, HIGH);
}

void loop()
{
  if (stringComplete)
  {
    Serial.println(inputString);
    if (inputString.startsWith("p"))
    {
      // Input should look like: p
      Serial.println("Pin 2 pulsed off");
      digitalWrite(switchPower, LOW);
      delayMicroseconds(5);
      digitalWrite(switchPower, HIGH);
    }
    else if (inputString.startsWith("ton"))
    {
      // Allows user turn on the pin in case something in setup goes wrong.
      Serial.println("Pin 2 turned on");
      digitalWrite(switchPower, HIGH);
    }
    else if (inputString.startsWith("toff"))
    {
      // Turn off pin 2 (DO NOT TURN OFF WHEN HIGH VOLTAGE IS PRESENT)
      Serial.println("Pin 2 turned off");
      digitalWrite(switchPower, LOW);
```

```
    }
    else if (inputString.startsWith("cycle"))
    {
      // Allows user to specify number of sparks to send to preamp
      num = inputString.substring(5).toInt();

      while (num > 0)
      {
        digitalWrite(switchPower, LOW);
        delayMicroseconds(5);
        digitalWrite(switchPower, HIGH);
        // Waits half a second before sending the next spark
        delay(500);
        num -= 1;
      }
      Serial.print("Pin 2 pulsed off ");
      Serial.print(num);
      Serial.print(" times");
    }
    else
    {
      Serial.write("I don't quite know what you're trying to tell me.");
    }
  // Reset all interactions
  Serial.println("Please input a command.");
  inputString = "";
  stringComplete = false;
  }
}
void serialEvent()
{
  while (Serial.available())
  {
    // get the new byte:
    char inChar = (char)Serial.read();
    if (inChar == '\n')
    {
      stringComplete = true;
    }
    else
    {
      // add it to the inputString:
      inputString += inChar;
    }
  }
}
```