Report on the 5x5 Pixel Hadron Monitors for the NuMI Beamline

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Abstract

The hadron monitors are ionization chambers used to monitor mesons in the NuMI secondary beam. The third generation of hadron monitors (5x5 pixel) were fabricated, assembled, and tested between 2021 and 2022 at the University of Texas at Austin. The first 5x5 monitor was produced in the summer of 2021 and the other two in the summer of 2022. The hadron monitor process at UT includes installation of all detector components such as feedthroughs, ceramic plates, and rad-hard coaxial cables as well as assembly & performance testing. The monitors and their components were leak tested multiple times throughout the assembly and were proven to be completely gas-tight. Capacitance and high voltage tests indicate all three monitors were properly commissioned. The first monitor is currently operating as expected in the NuMI beam. AmBe source tests with the 2nd and 3rd monitors show that they are also functioning well and will be ready for beamline use when needed.

1 Introduction

The hadron monitors (HMs) are helium-based ionization chambers utilized to monitor the spatial distribution of the NuMI secondary (meson) beam. The hadron monitors are designed, fabricated, assembled, and tested by Dr. Karol Lang's neutrino group at the University of Texas at Austin. In the summer of 2021, our group commissioned the first 5x5 pixel hadron monitor, now currently operating in the NuMI beamline. In the summer of 2022, we commissioned two additional 5x5 HMs that will serve as eventual replacements to the first.

2 Procedure at UT-Austin

The first 5x5 HM was assembled and tested from May to July, 2021, while the 2nd and 3rd 5x5 HMs were assembled and tested simultaneously from May to July, 2022. The following outlines the complete procedure by which all three HMs were commissioned and tested at the University of Texas.

1. Fabrication and cleaning
    - The main aluminum bodies are fabricated at the UT Department of Physics machine shop.
    - After fabrication, the monitors are cleaned with detergent and methanol.
2. Feedthrough Installation
    - Each feedthrough is fitted with a custom gasket and then installed onto a respective monitor. Gold-coated ground posts are also installed onto the HMs.
    - The monitors are sealed with a temporary silicon gasket and leak tested. Each feedthrough is ensured to be gas-tight before proceeding with the next steps.

Figure 1: A close up of the feedthroughs as used for the hadron monitors.

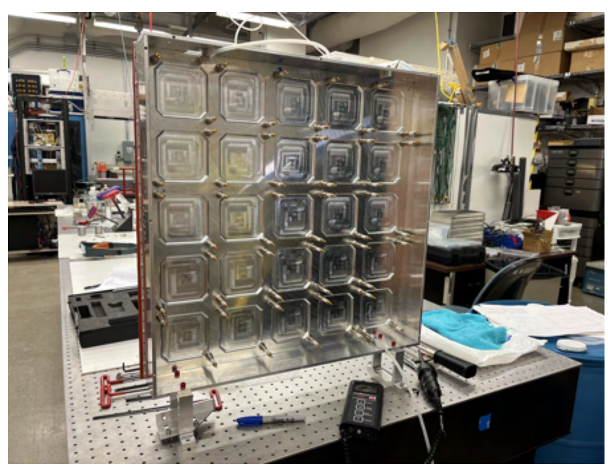

Figure 2: The 2nd 5x5 HM sealed with the silicon gasket for feedthrough leak tests.

3. Ceramic Plate Installation
    - Three ceramic plates, two high voltage (HV) and one signal, are soldered at each HM pixel.

- After installation, we measured the capacitance of each 3 plate capacitor to check that the plates at each pixel were properly connected. The theoretical capacitance of these 3 plate capacitors is approximately 137 pF.
- Following the capacitance tests, high voltage tests are conducted in air (e.g., the HMs are not filled with He). The HV tests allow us to check for electrical shorts. The resultant current was measured with a Fluke multimeter.
- No more than 300 V should be applied to any single pixel at a time.

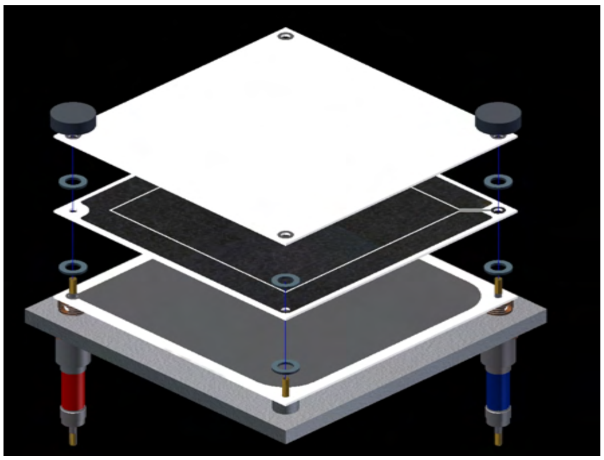

Figure 3: The ceramic plates for a single pixel. The theoretical capacitance is 137 pF.

Figure 4: An image of the 3rd 5x5 pixel HM being HV tested in air.

4. Final Sealing
   - The monitors are sealed with a metal gasket lined along the rim of the base plate and leak tested once again.
   - After the monitors are confirmed to be gas-tight, HV tests are done in helium.
5. Cable Installation
   - The cables are 50 Ω coaxial with silver plated copper wire, Kapton insulation, and 26 AWG size. They are rad-hard to endure high radiation from the beam.
   - Each cable is cut to around 12 meters slightly varying based on their respective pixel's position.
   - The cables are stripped and then soldered to their appropriate feedthroughs and corresponding HV & signal boxes.
   - After installation, we perform continuity tests between the box connections and their respective pixels in order to confirm the cables are correctly connected. Another iteration of capacitance tests allow us to ensure plates did not become unsoldered during assembly.

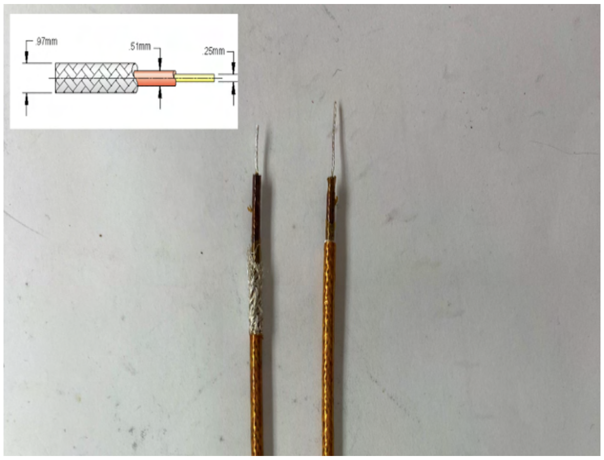

Figure 5: An example of the stripped cable ends with a schematic of the cable layering.

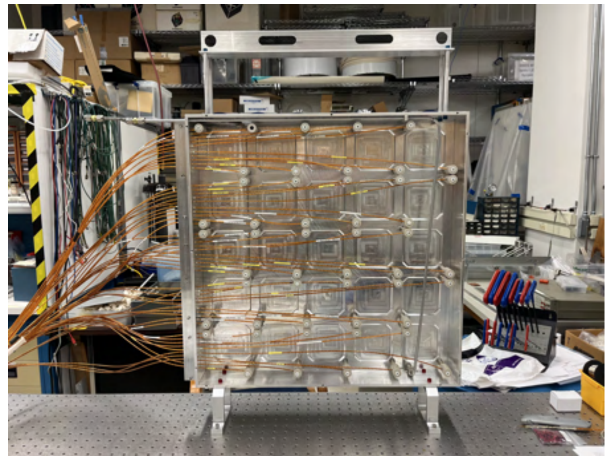

Figure 6: The 2nd 5x5 HM with its cables fully connected.

Figure 7: The inside of the 2nd HM's signal box.

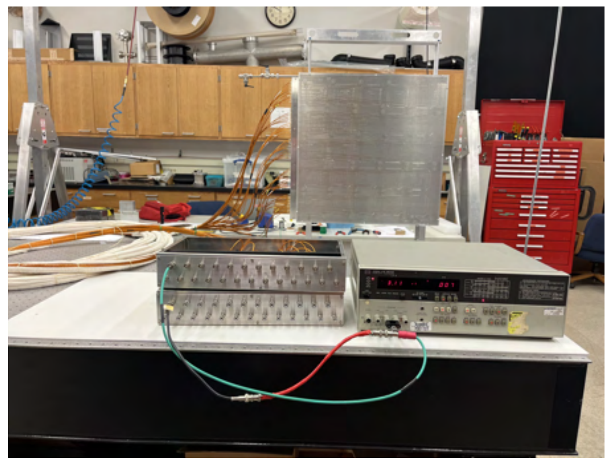

Figure 8: Capacitance testing of HM #3 after cable installation.

6. Source Testing

   - Finally, the functionality of the monitors was tested with an AmBe source.
   - Each pixel was supplied with 161.9 V during testing.
   - The current measurements were done with a Keithley picoammeter.
   - Capacitance and HV tests are meant as simple quality checks throughout the HM manufacturing process and are thus not particularly meaningful post-production. Only source testing provides true information about HM performance capabilities.

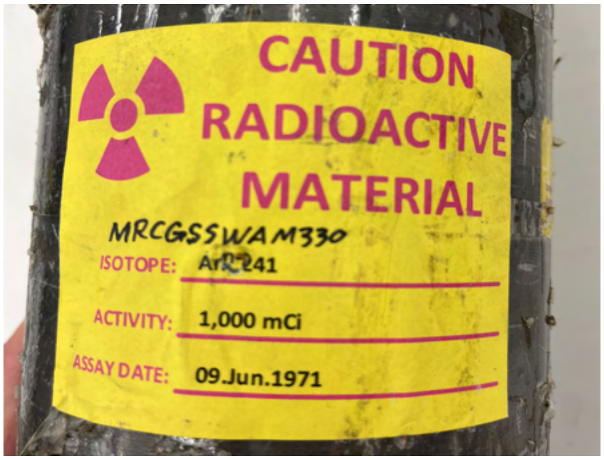

Figure 9: The AmBe source. The calculated activity during measurements was 921 mCi.

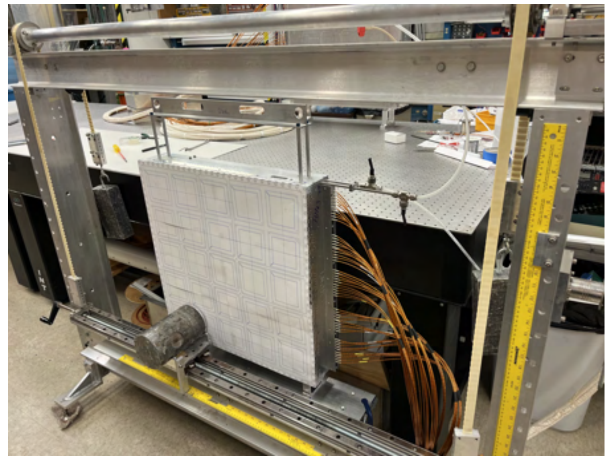

Figure 10: The 3rd 5x5 HM on the test stand as it was being source tested with AmBe.

Figure 11: The Keithley picoammeter used for source testing.

3 HM Testing before Cable Installation

3.1 Leak Tests and Gas Connections

During commissioning, helium was supplied to the monitors through 20 meters of Poly-Flo tubing. The inlet gas was set to a flow rate of approximately 100 cc/min with a pressure of 5 psi. Outgoing gas was released through another 20 meters of Poly-Flo placed into 2 inches of water. These parameters should not be exceeded and were carefully chosen to ensure safe pressure levels inside the HMs. We conducted two major leak tests on each HM, a feedthrough leak test before plate installation and a perimeter leak test after the final sealing. All three monitors were shown to be completely gas-tight.

Figure 12: The device used to leak test the HMs.

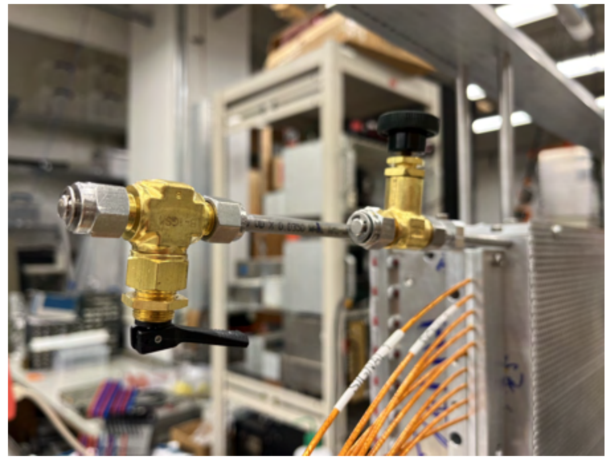

Figure 13: The gas pipes on HM #2 with their attached valves.

3.2 Capacitance Tests

Figure 14 displays results of the capacitance tests for HMs #1, #2, and #3 prior to cable installation. These plots are orientated as if looking at a HM from its downstream side (e.g., pixel 1 is on the top left corner and pixel 25 is on the bottom right). The results show uniformity across all the pixels for the three monitors with every value being within about 2σ of the theoretical capacitance, 137 pF.

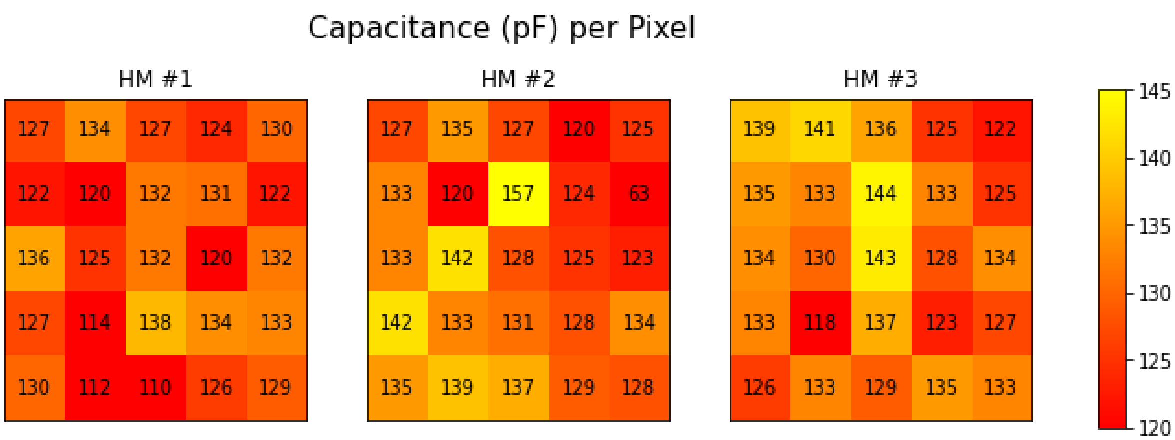

Figure 14: Capacitance tests for the 2nd and 3rd 5x5 hadron monitors.

3.3 HV Tests in Air

Figures 15, 16, and 17 display HV tests in air at 100 V, 200 V and 300 V for HM #1, HM #2 and HM #3, respectively. The currents are volatile and inconsistent as expected in air but demonstrate that none of monitors have an electrical short.

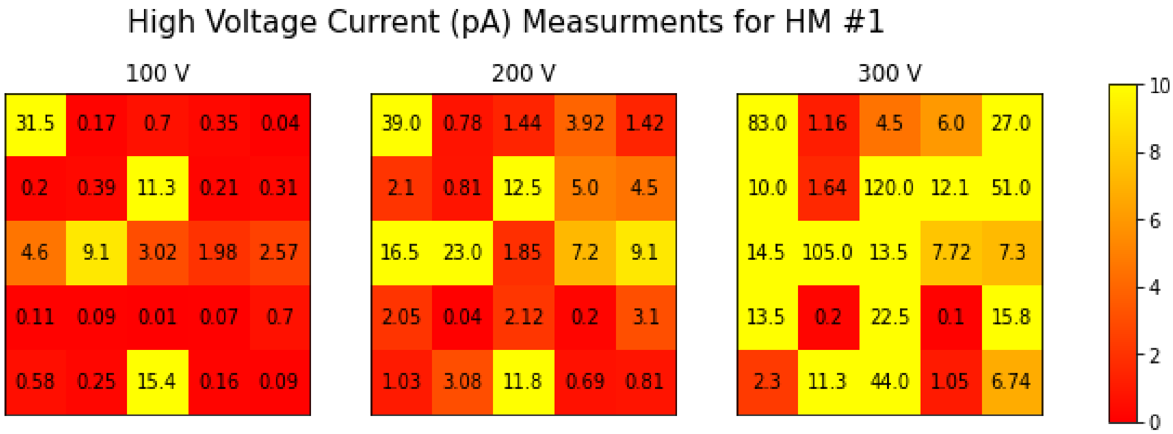

Figure 15: Current per pixel for HV tests in air for the 1st HM.

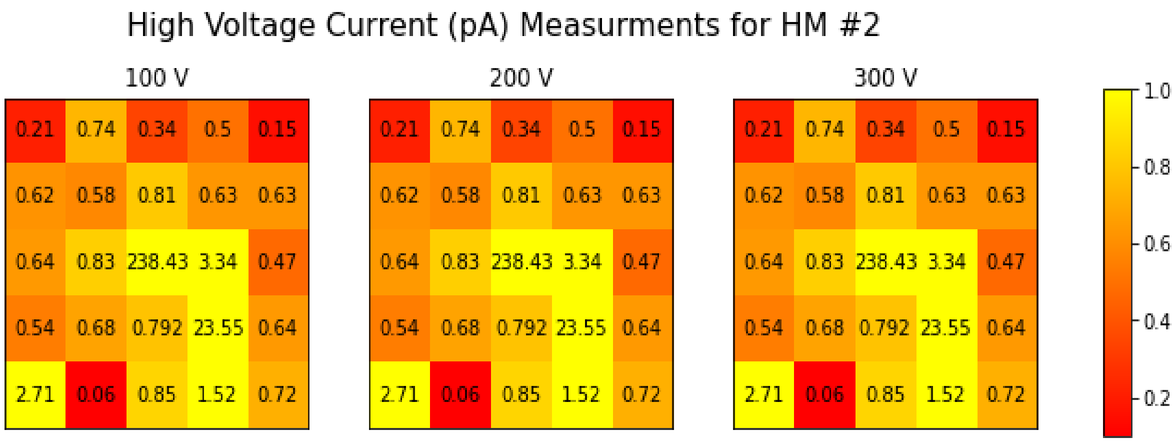

Figure 16: Current per pixel for HV tests in air for the 2nd HM.

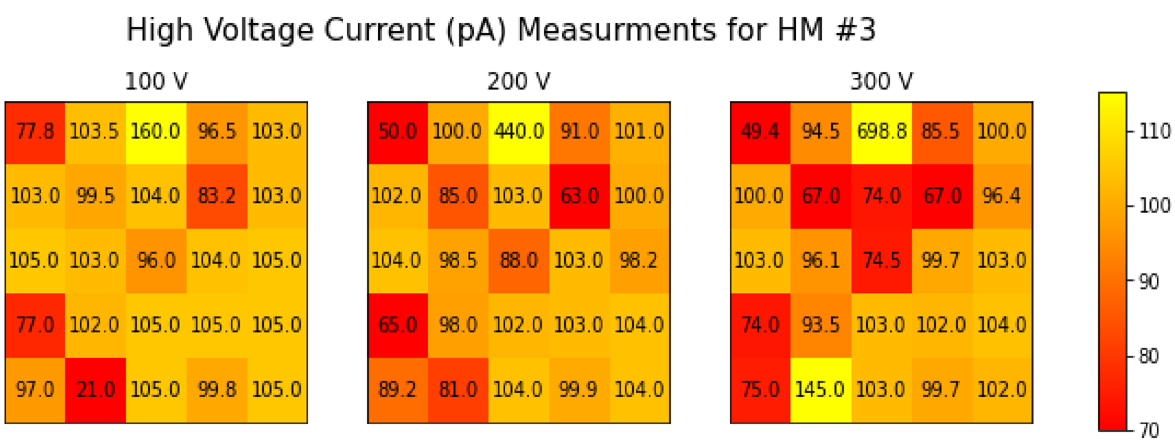

Figure 17: Current per pixel for HV tests in air for the 3rd HM.

3.4 HV Tests in Helium

Figure 18 displays two HV tests in helium for HM #1 conducted in the summer of 2021. Figures 19 and 20 display HV tests in helium at 100 V, 200 V and 300 V for HM #2 and HM #3, respectively. The HV tests for HM #3 were conducted with a less precise ammeter than that used for HMs #1 and #2. The HV in He tests show uniform currents, close to 100 pA, across all the pixels of the three detectors. Pixel readout is quite sensitive to atmospheric conditions and He purity resulting in slight variations between the average current readings from each monitor.

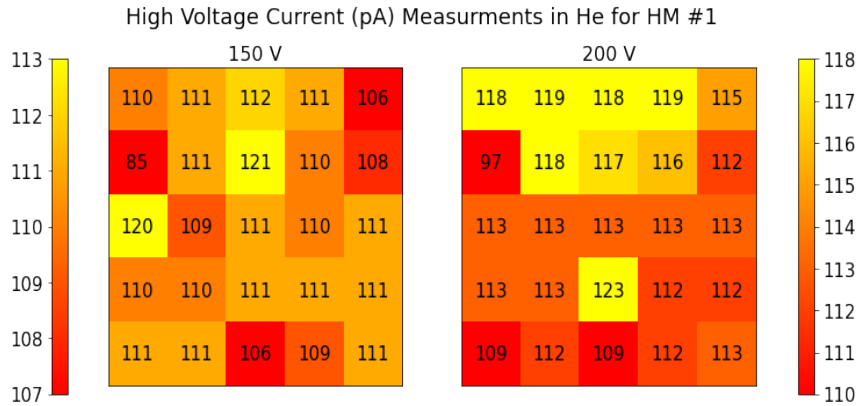

Figure 18: High voltage tests for HM #1 in helium. The heatmaps have separate colobars for clarity.

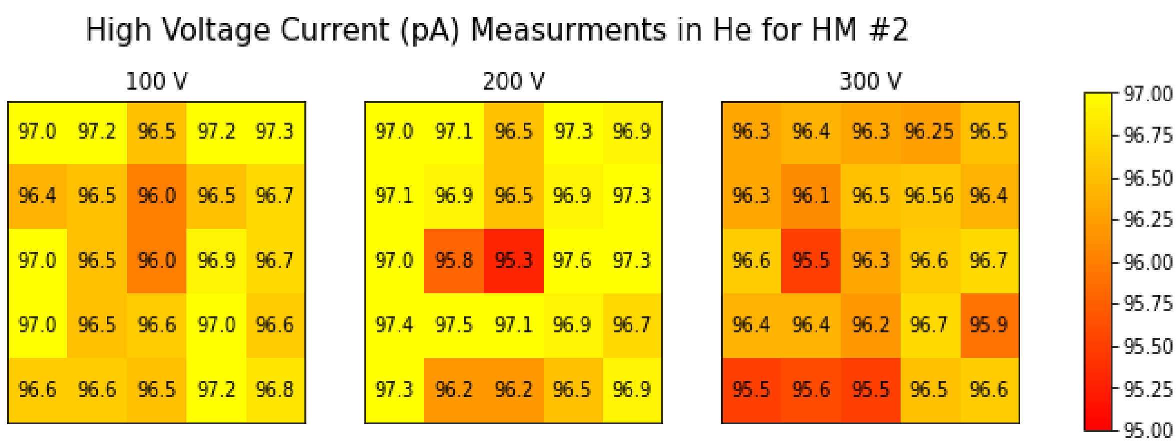

Figure 19: High voltage tests for HM #2 in helium.

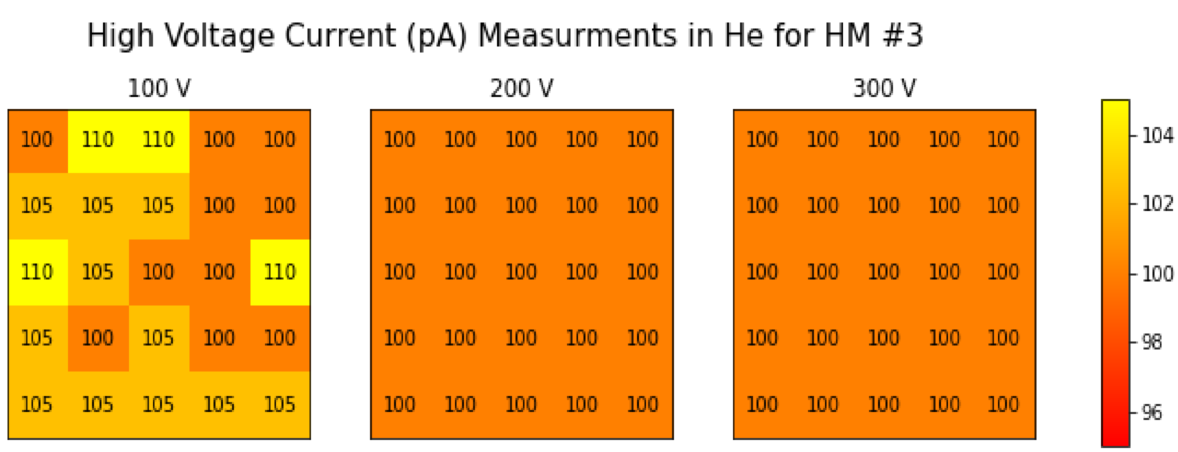

Figure 20: High voltage tests for HM #3 in helium.

4 HM Testing After Cable Installation

4.1 Capacitance Tests

The capacitance of each pixel was measured again after all cables were installed. The cables have a capacitance of 95 pF/m yielding a total capacitance per cable of about 1140 pF. Figure 21 shows the capacitance measurements for the 2nd and 3rd HMs with their cables installed. Overall, we see rather consistent capacitances across both monitors indicating all plates are well connected. Furthermore, we generally see a gradient from the left to right, an expected result following the cable lengths.

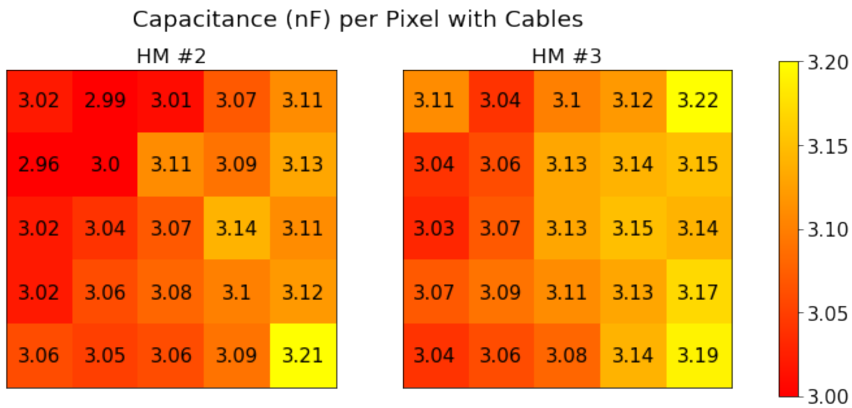

Figure 21: Capacitance tests for the 2nd and 3rd 5x5 hadron monitors with their cables installed.

4.2 Source Tests

Due to some constraints in the summer of 2021, the first 5x5 HM was not source tested in Austin. Figure 22 plots the measured current with the source placed at the center of each pixel for the 2nd and 3rd monitors. The results show that the pixels on both HMs are operating similarly and the HMs are functioning as they were intended.

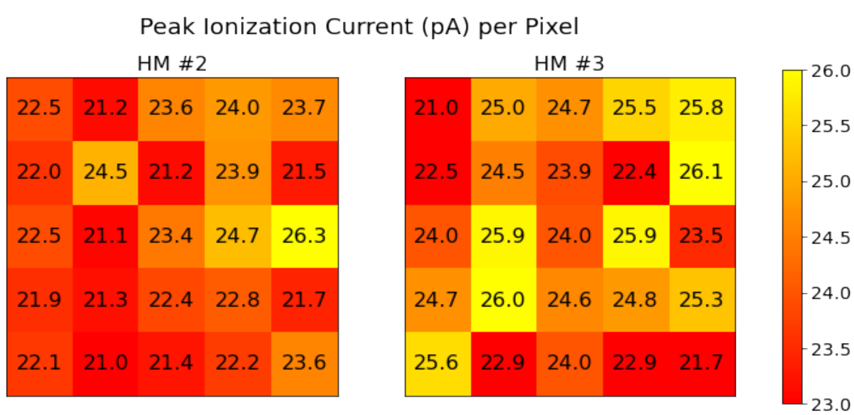

Figure 22: Measured ionization current from HM #2 and #3.

We also measured the current as a function of source position across an entire row (pixels 1-5). Figure 23 displays these measurements and shows that we see the expected trend, the current reaches its minima between pixels and its maxima in the center of pixels. Direct irradiance of the cables with the source did not result in any measured current above background illustrating their radiation hardness.

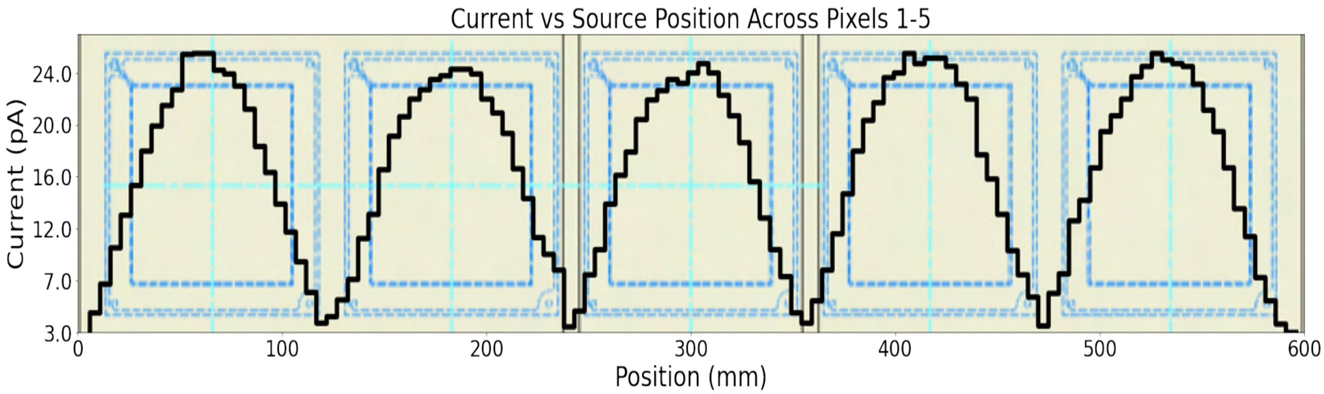

Figure 23: Ionization current vs source position across pixels 1 through 5 for HM #3. Pixel 1 is on the far left.

5 Summary

The 5x5 hadron monitors were commissioned at the University of Texas at Austin over the summers of 2021 and 2022. The tests conducted on the HMs demonstrated that they are all properly assembled and functioning as expected. The first 5x5 HM was delivered to Fermilab on August 4th 2021 and is already in operation in the beamline. The estimated delivery date for the 2nd and 3rd monitors is August 10, 2022. Once at Fermilab, the monitors will be leak and source tested a final time.