A Full-scale High Voltage Test for the protoDUNE Detector's Time Projection Chamber

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science degree in Physics from the College of William and Mary

by

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Contents

Table of Figures

Table of Graphs

Table of Tables

Abstract

Neutrinos are almost massless particles that very recently have been found to change flavors (oscillate). Their only interaction is via the weak force, so they are difficult to detect and require large numbers of target nuclei to detect in significant quantity. The planned DUNE detector is a 40kton Liquid Argon Time Projection Chamber (LArTPC) that is being prototyped to detect neutrino interactions. The purpose of the protoDUNE prototype is to test the engineering designs and performance of the LArTPC using charged particles to ensure and validate that they will work. The protoDUNE-SP detector will be the world's largest single-phase LArTPC, holding 770 metric tons of liquid argon, but it is only a stepping stone to eventually building the full DUNE detector. This full-scale test is to examine the TPC design that will be used for protoDUNE and ensure that it can hold the high voltages necessary for operation in pure liquid argon.

1. Introduction

Neutrinos are electrically neutral leptons (half-integer spin fermions) that are only known to interact by the weak force. Because the weak force is only present on a sub-nuclear scale and neutrinos do not interact by the electromagnetic or strong force, neutrinos do not interact with matter very often and thus are difficult to detect and measure. Neutrinos have 3 flavors, electron, tau, and muon, which correspond to charged particles of the same name, and they also have corresponding antineutrinos. Originally, the Standard Model assumed that neutrinos were massless, however they have been found to require a non-zero mass due to the observation of neutrino oscillations.

Neutrino oscillation is a phenomenon where a neutrino with one flavor is measured to have a different flavor at a later point in time. The effects of neutrino oscillations were observed as early as the 60's when a deficit was noted in the amount of neutrinos the Sun should theoretically produce and the amount of neutrinos actually detected. It was not until recently that neutrino oscillation was experimentally discovered. This discovery not only showed that the Standard Model needed to be adjusted to account for the mass of the neutrino, but it also explained deficiencies seen in neutrino measurements. Neutrino oscillations are important to study because they can give insights into neutrinos and the nature of the Universe, one of the most important being an updating of the Standard Model to account for the non-zero mass of the neutrino.

In scientific experiments neutrino beams are usually made by smashing high energy protons into a target, usually graphite. When the protons collide into the target they often produce positive and negative pions. The positive pions are focused into a narrow beam by a pair of magnetic "horns", and they then decay into positive muons and neutrinos. The muons and neutrinos then run into blocks of concrete and steel. The muons are stopped by these blocks but the neutrinos phase right through

since they rarely interact with matter. What is left then is a neutrino beam that can be used to detect interactions between neutrinos and matter.

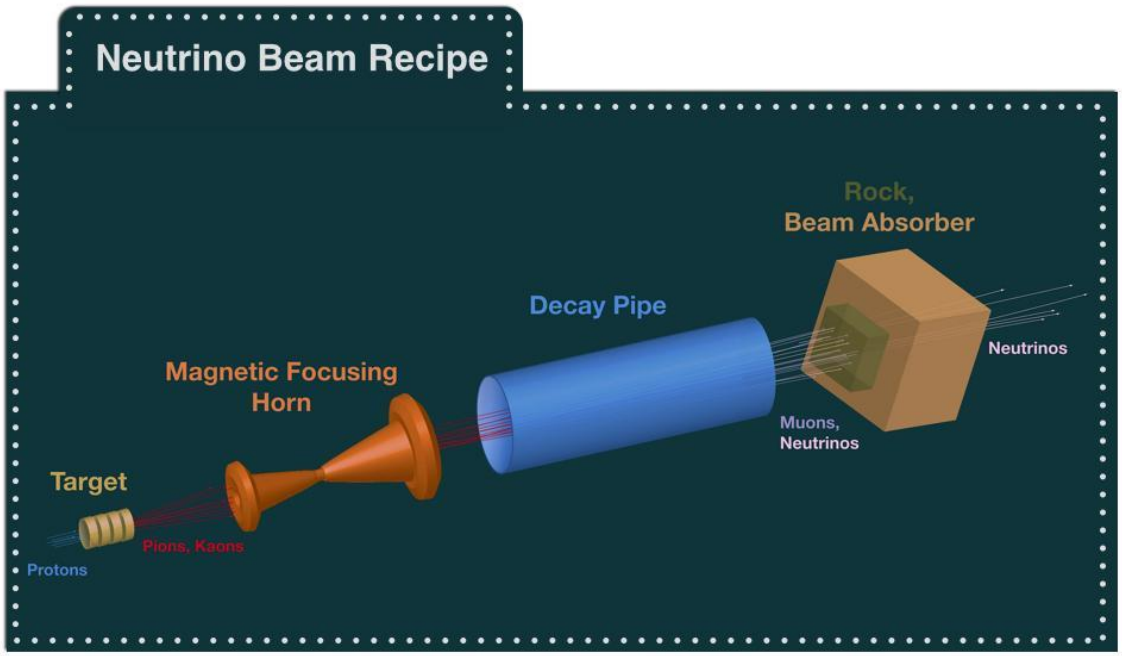


Figure 1. A model of a standard neutrino beam. (Source: Fermilab)

Time Projection Chambers are a type of detector that measures and reconstructs particle trajectories produced, for example, from neutrino interactions. TPC's allow physicists to see more particle interactions and are able to analyze particles in three dimensions. It does this by having a fluid filled volume in an electric field. This is commonly done by a series of high-voltage plates at different voltages to create a uniform field. When charged particles go through the fluid, ionization electrons are drifted in a constant electric field until they hit a wire plane. This charge on the wires creates an electrical signal that can then be measured.

Liquid Argon Time Projection Chambers (LArTPC) use liquid argon as the medium. For the protoDUNE experiment it is particularly useful because liquid argon is much denser than the gases that were used in the first TPC's. Liquid argon is also relatively inexpensive, which is useful when the

size of the detectors are increased to be able to hold several kilotons of the sensitive element. The increased density means that more particles will interact in the detector, considering the already low chance of neutrinos interacting, this increase is significant.

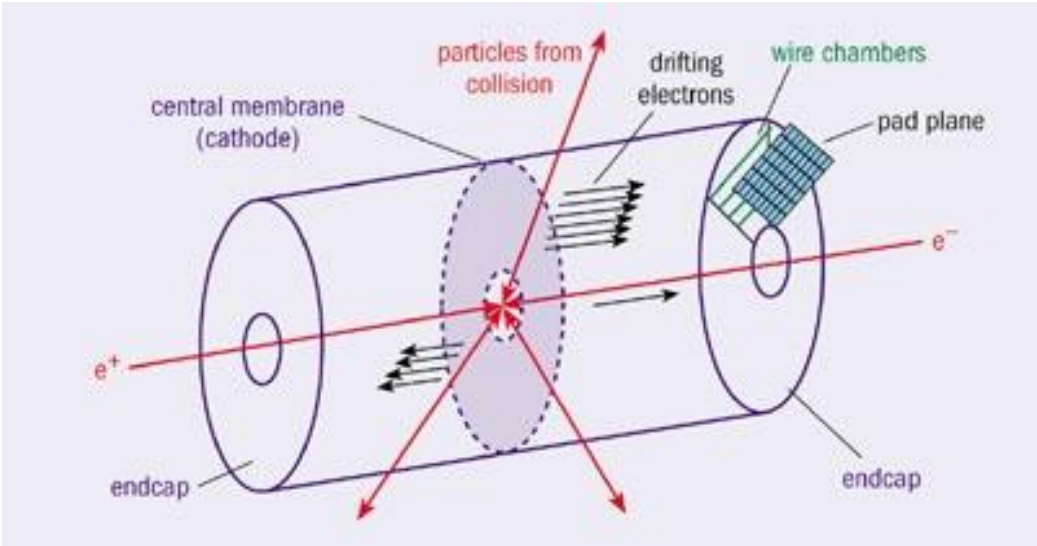


Figure 2. A diagram of a LArTPC showing e^-e^+ collision. Cern Courier[6]

A 35-ton prototype detector was constructed at Fermilab that had effectively the same components as protoDUNE albeit with an older field shaping technology. A preliminary test was done without detector elements in order to check that the desired argon purity and hence electron lifetimes (2.5-3 ms) was able to be achieved in the cryostat. A second test was done that focused on testing the active detector elements. The cathode voltage was set at 60 kV with a drift field of 250 V/cm with intentions to increase the drift field up to 500 V/cm however the test was ended after a pump failure led to the liquid argon being contaminated in a way that was irreversible.[2]

2. Apparatus

The final protoDUNE detector will be the largest single-phase detector LArTPC created to date. The active area will be 7x7x6 m^3 and will hold 770 metric tons of liquid argon. The TPC consists of the field cage, the cathode plane assemblies (CPA), and the anode plane assemblies (APA). The CPA's will

be held at a voltage of 180 kV, a significant increase over the prior full-scale test at Fermilab, in order to provide the 500 V/cm drift field. The APA's are made of stainless steel and the CPA's are made of kapton coated G/O fiber glass. The APA has three parallel planes of wires, the first two being induction wires, and the last being collection wires. The APA's are also wrapped in grid wires that protect the other wires from responding to distant moving charges. The wires are wrapped around the APA at an angle so that readout electronics are only placed at one end of the APA and to minimize dead space. The wires have a diameter of 150 um and are made of copper beryllium alloy, allowing for high tensile strength and good electrical conductivity.

The test I am working on is single part of the detector, and it will be smaller and tested in the cryostat where the 35 ton detector was tested at fermilab. We will be using this smaller scale device to test whether the design can hold voltages up to the desired level.

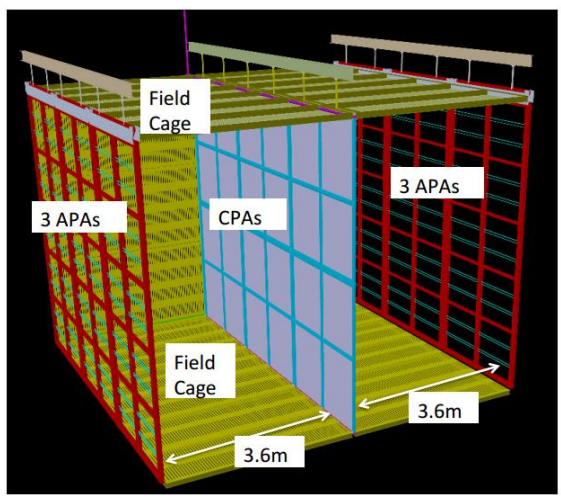


Figure 3. A Schematic of the TPC for protoDUNE[4].

The purpose of the field cage is to surround the electron-drift region both to provide the necessary boundary conditions and to protect the region from any influence that the corrugated, grounded, stainless steel cryostat walls might have. Prior LArTPC's used sheets clad with copper strips that are biased at specific voltages in order to ensure a uniform electron drift field in the liquid argon. For this experiment, a new design for the field cage will be tested using custom designed metal profiles instead

of copper strips. The large edge radii causes there to be a low surface electric field. The change in field cage design is because the final DUNE detector needs to fit down a mineshaft, and thus it will be built in modules that are ~1m wide.

This test is only testing the field cageTPC, protoDUNE has other components including the "cold" electronics (CE) and the Photon Detection System (PDS). All the components, including the TPC, will be placed in a cryostat that will be filled with the liquid argon. This liquid argon will be kept at ~90 K and will be filtered constantly to keep the argon pure and at uniform temperature. Cameras and photomultiplier tubes are also being placed into the cryostat to look for arcs.

3. Assembly

The most important part of assembling the TPC is to make sure everything is cleaned and stays clean. The liquid argon that is being used needs to stay almost completely pure, meaning any contaminants that absorb electrons (like oxygen) must be avoided while putting the detector together. The reason the argon needs to be pure is because a lifetime of 3ms is desired for the electrons so that they can get to the readout. Any contaminants will absorb electrons and reduce the average electron lifetime. To this end, rubber gloves will be used at all times during the process of cleaning and assembly. We will also be wiping down with alcohol all the parts that alcohol safely evaporates on. This includes the profiles, the endcaps for the profiles, and fiberglass structural parts.

Small metal parts such as screws, nuts, etc. were cleaned using an ultrasound cleaner, rinsed off with deionized water, then cleaned again. After the second cleaning, they were rinsed off one last time and allowed to drip dry. Large parts that cannot be cleaned with the ultrasound cleaner were cleaned with a Simple Green detergent solution and then rinsed with deionized water. Components were double bagged while in a clean area before they were moved to the Cryostat at fermilab. After they were moved, the outer bag can be removed before taking the components into another clean area.

The pieces of the detector will be a combination of stainless steel, fiberglass, and nylon plastic. There was some discussion on whether or not to make the profiles that are part of the field cage stainless steel or aluminum. It was decided that these profiles would be aluminum so as to reduce the weight. The endcaps of the profiles are polyethylene in order to counteract the high electric field at the end of the profiles. These endcaps are designed to fit tightly onto the profiles and be kept in place with friction, however they will also be pinned to the profiles to ensure they stay on. If one of the profiles got loose and fell while the field was in place it would cause arcing and be disastrous. The pins are drilled from the endcap to the profile, so endcaps should be kept with their respective profiles to ensure everything matches up.

The flange screws were determined to not have as big a head as would have been preferred. To deal with this, a sleeve will be placed into each screw hole on the walls, which the screws will then be placed into. Then a washer and flange nut will be added on to ensure the screw stays in. The nuts that are being used are self-threading, meaning once a crew is used with a particular nut, it should stay with the nut. When adding the screw sleeves, it was found that some of the sleeves were too big so their size was slightly reduced. Many holes still were not big enough so they were reamed to make them slightly bigger in order to fit the sleeves.

The parts were shipped to fermilab on the 20th of December from William and Mary. During the first week of January construction of the detector began.

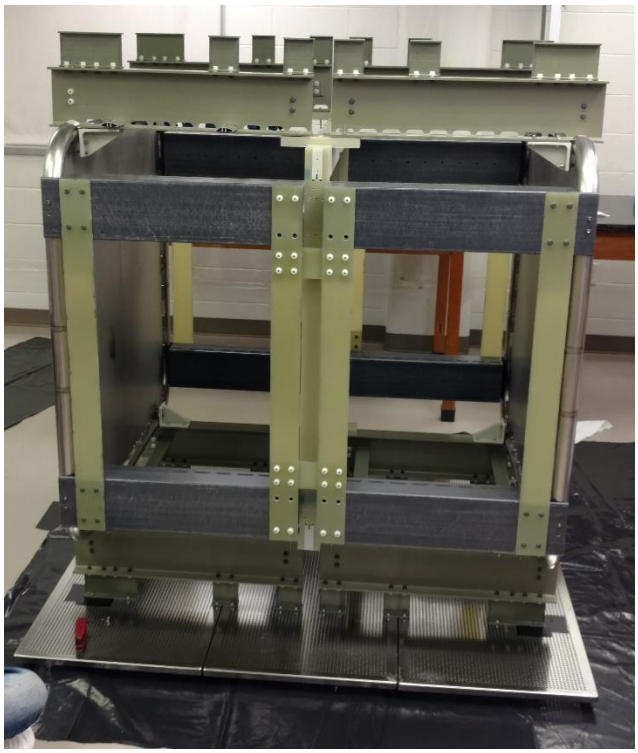


Figure 4. A picture of the completed detector.

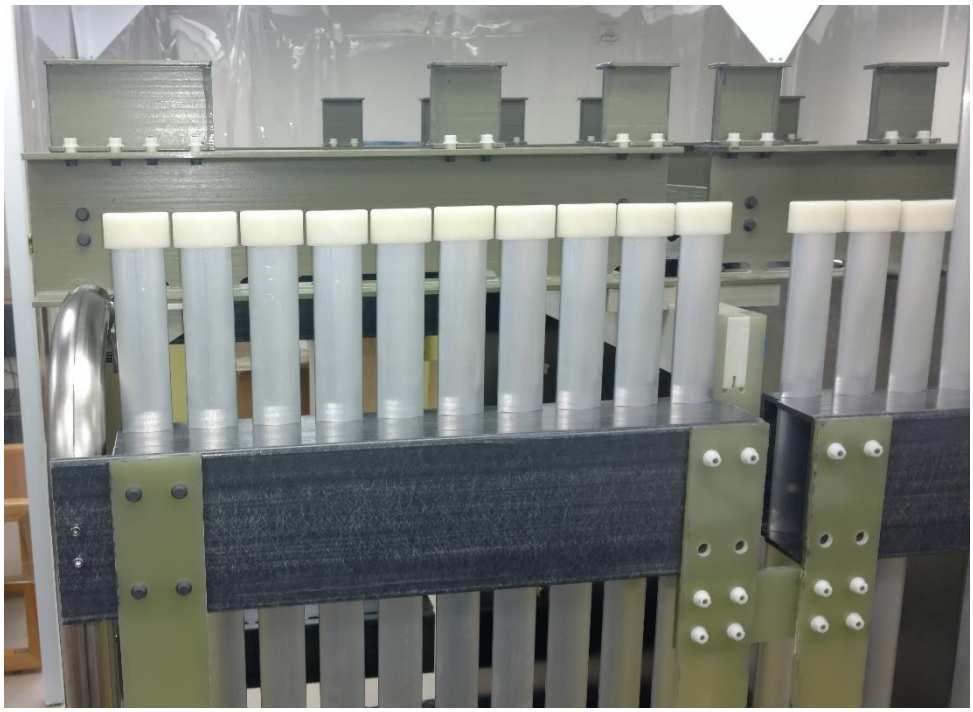


Figure 5. A close-up of the metal profiles.

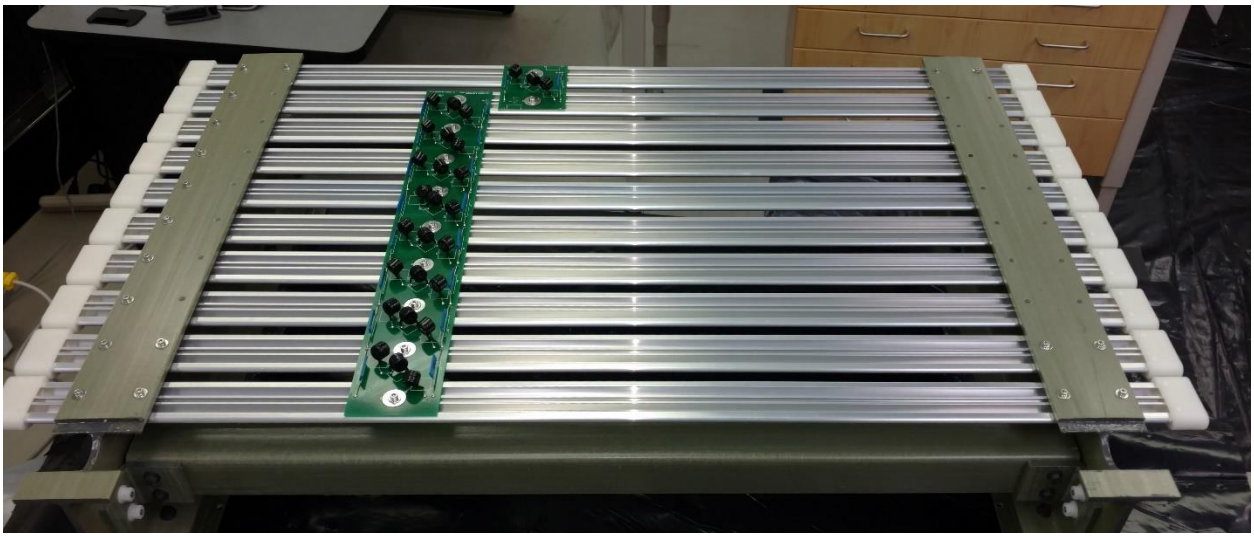
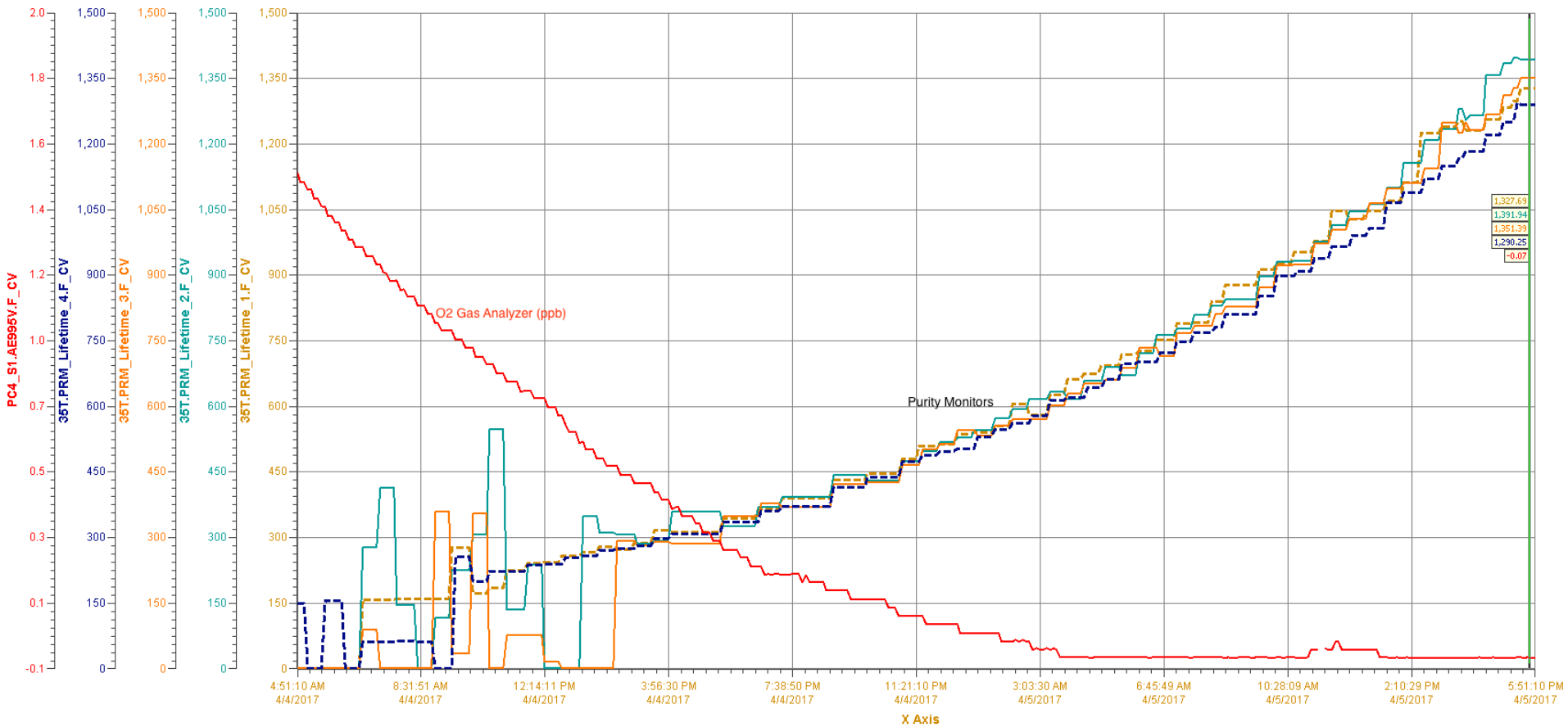


Figure 6. The divider chain on the profiles

4. Phase 1 Testing and Analysis

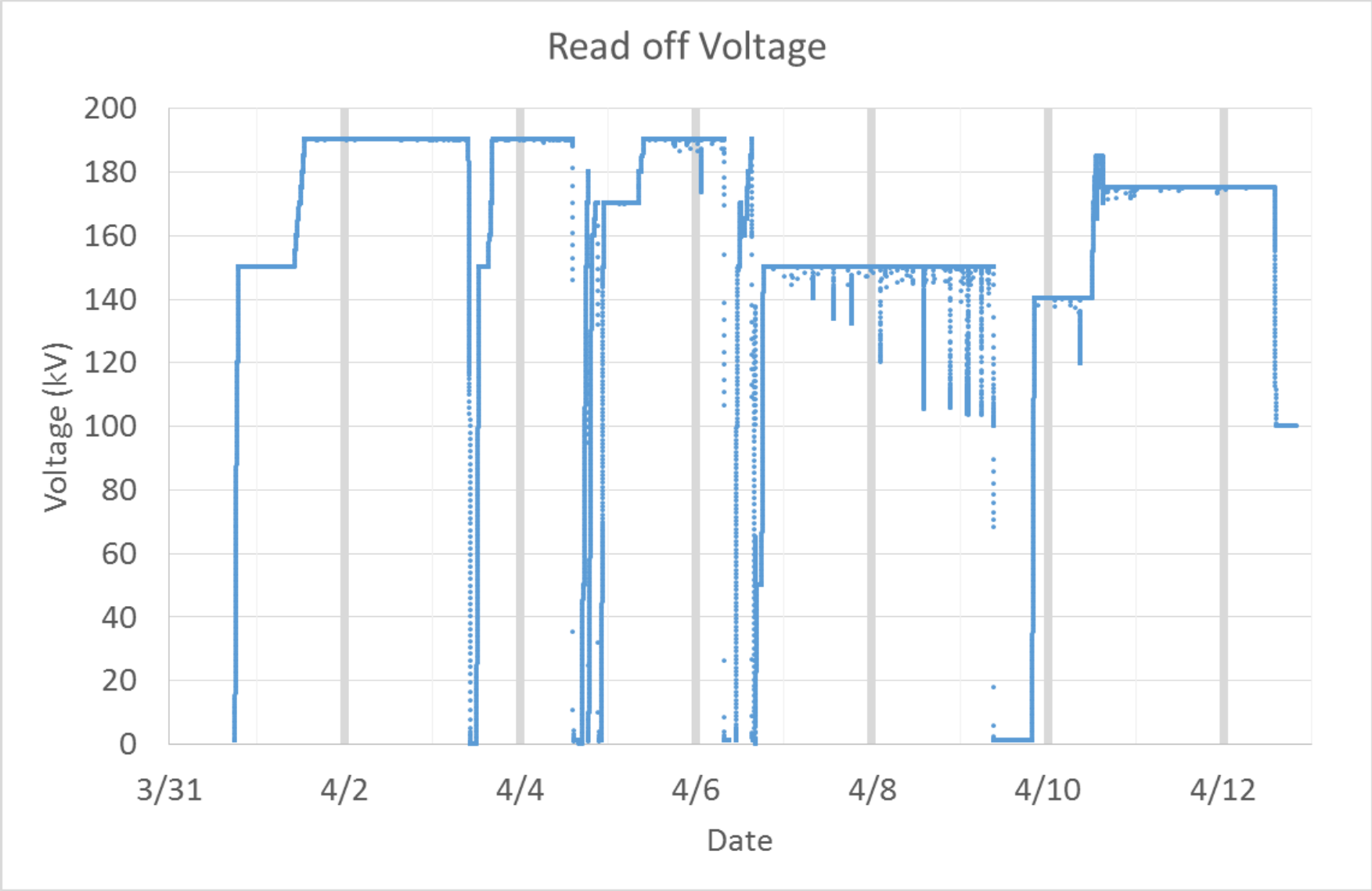
When beginning the full-scale voltage test the voltage was ramped up to 50kV and then to 160kV with argon at a purity of 7ppb. Over the next few days (from March 31st to April 3rd), the voltage was ramped up to 190kV and kept there until the pumps to purify the argon were turned on. The holding point where they left the voltage at overnight was 150kV and after the pumps were turned on the voltage was ramped back up to 190kV. For the next few days the voltage was ramped up to 190kV from various holding voltages however the voltage kept tripping around 180kV. As the purity of the argon increased (starting when electrons had an expected lifetime of ~300us and continuing through an expected lifetime of 5-6ms) the signal got increasingly nosier and the current spiked several times. The filters were then bypassed to contaminate the argon and as the argon got dirtier the signal became better. Below is an image showing the purity levels in terms of electron half-life increasing as oxygen content decreases.



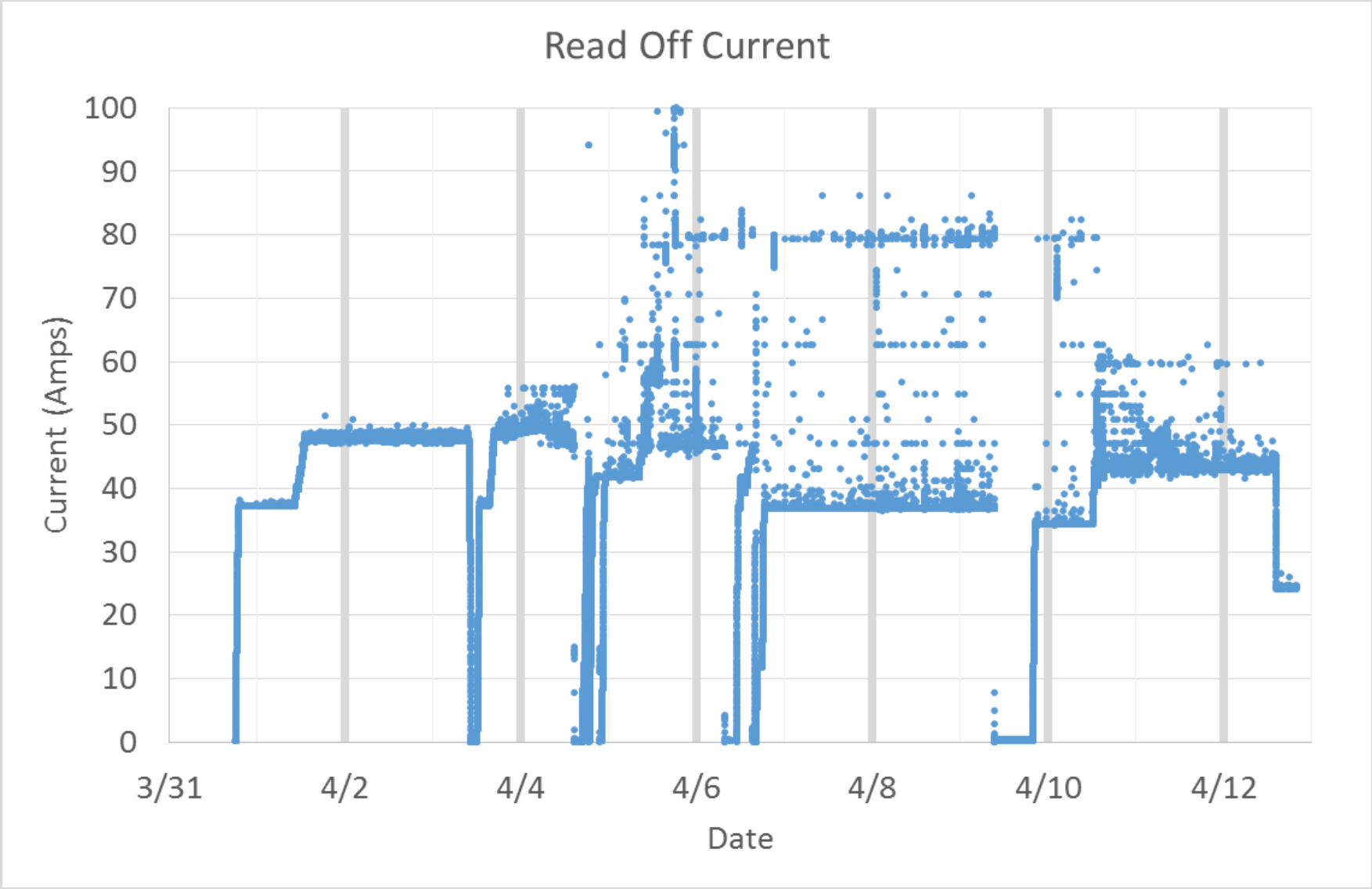
Pen Name	Description	Value	Eng Units	High Over Range	Low Over Range
35T.PRM_Lifetime_1.F_CV	Lifetime calculated from AnodeTrue CathodeTrue and dri...	1,327.7	us	1,327.7	0.0
35T.PRM_Lifetime_2.F_CV	Lifetime calculated from AnodeTrue CathodeTrue and dri...	1,391.9	us	1,396.9	0.0
35T.PRM_Lifetime_3.F_CV	Lifetime calculated from AnodeTrue CathodeTrue and dri...	1,351.4	us	1,351.4	0.0
35T.PRM_Lifetime_4.F_CV	Lifetime calculated from AnodeTrue CathodeTrue and dri...	1,290.2	us	1,294.5	0.0
PC4_S1.AE995V.F_CV	Analyzer Delta F NanoTrace O2 (F_CV)	-0.067	PPB	1.486	-0.069

4:51:10 AM 4/4/2017 5:51:10 PM 4/5/2017

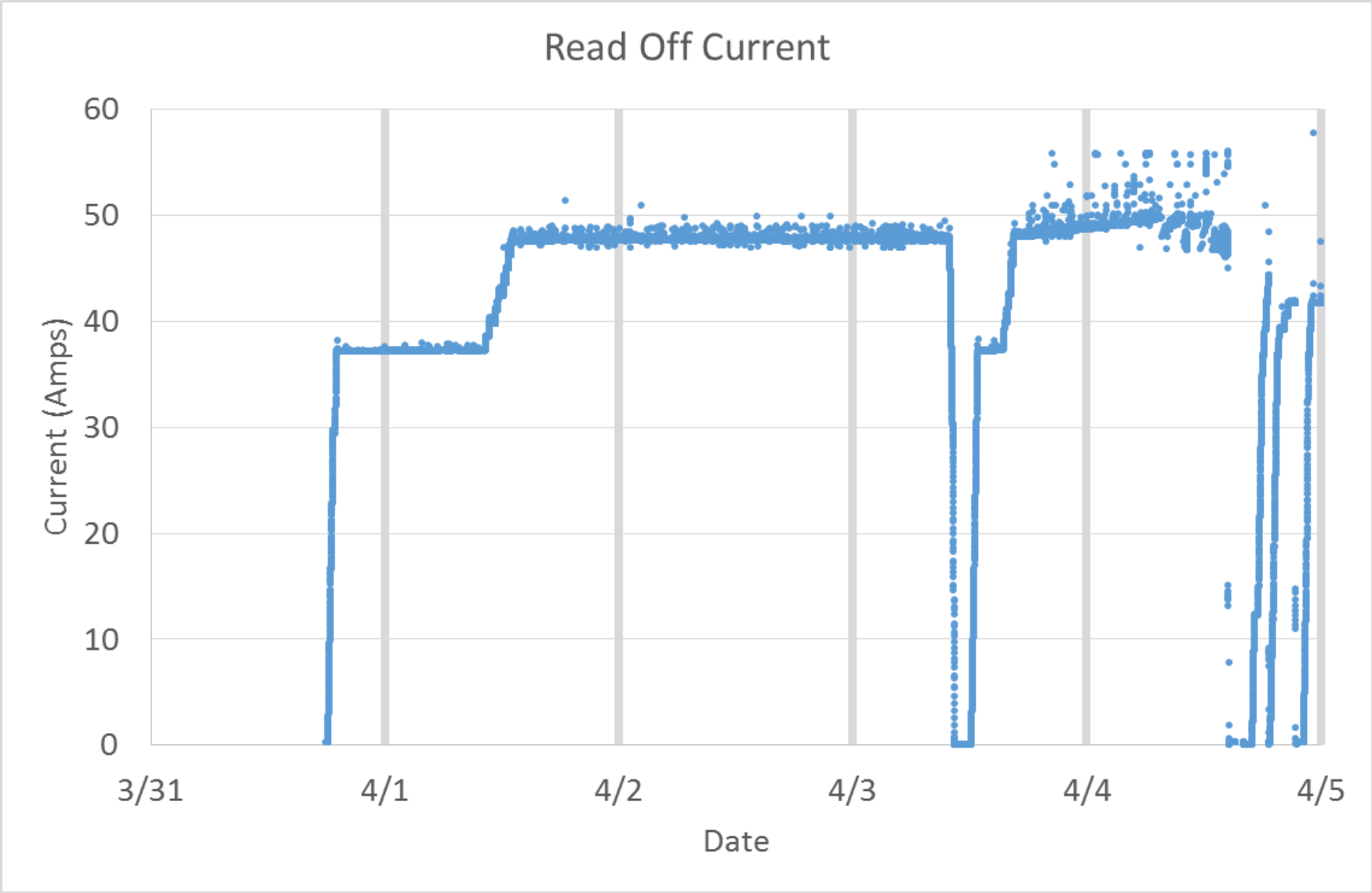
Figure 7. A graph of the purity of the Lar.



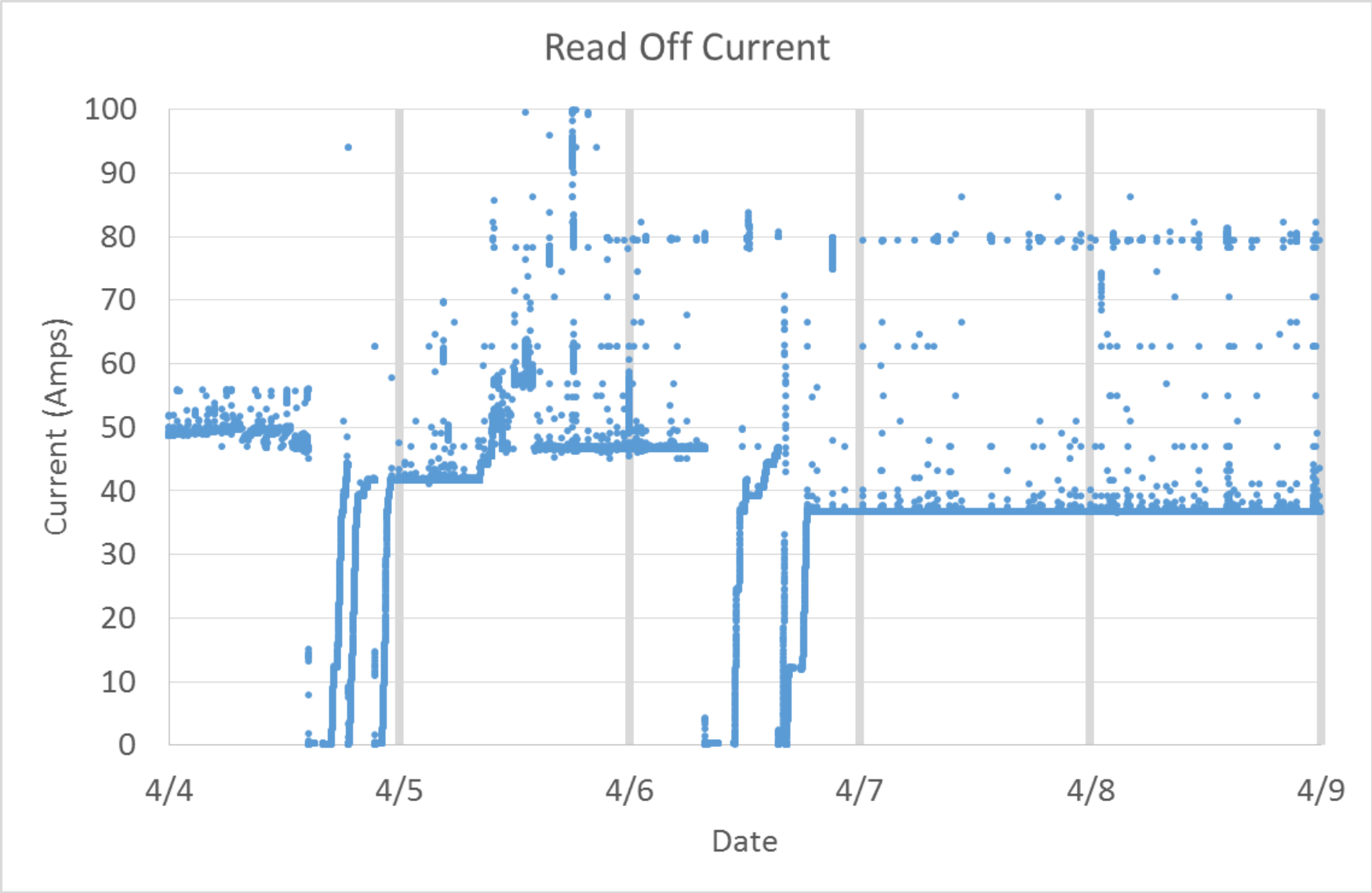
Graph 1. The read off voltage from the power supply.



Graph 2. The read off current from the power supply.



Graph 3. A close-up of the previous graph showing noise even in dirty argon.



Graph 4. A second close-up showing the current jumps.

Graphs 1 and 2 above show the read off current and the read off voltage from the power supply. As can be seen, the voltage was steady when the argon was contaminated, experiencing only a few trips during the ramp up. As the argon was purified, the voltage began to glitch more often. Eventually the device began to hit the current limit setting when siting at 170kV and tripped when trying to ramp to 190kV. After this the voltage was set to hold at 150kV but there was still a high amount of current draw. The argon was purposefully contaminated on the 10th and the current jumps began to grow smaller and became steadier as time went on.

Graphs 3 and 4 are close-ups of the current when it was relatively stable and when there were a lot of spikes. While many of the spikes were to various amounts of current, many of them were to the same level of 80 amps, this is due to the current limit setting of the power supply and shows that without the current limit, the spikes would have been even greater. What is interesting to note is that the current was fuzzy even when the argon was contaminated showing that there was at least something affecting the current even when the argon was not pure.

The cameras did not see anything when the current spiked and neither did the photomultiplier tubes. The PMT's do work as they saw light from cosmic rays, so whatever is causing the spikes is also not creating any light. This leads to the idea that there might be streamers being created in the detector that are causing the large amounts of current draw. Streamers do not cause any light and are transient streams of electrical discharge that can occur when a medium is exposed to a large electrical field and does not readily absorb the charge. This behavior was unexpected.

Below is an image of the circuit diagram to show how the circuit works. The gaps between the resistors on the upper part of the diagram is where the profiles would be located and "leg" in the upper part has an equivalent value of 5R where R is a 1 GΩ resistor. The resistors on the east and west branch have an equivalent value of 6.12R and end in a resistor of negligible value in order to see what the pick off voltage is.

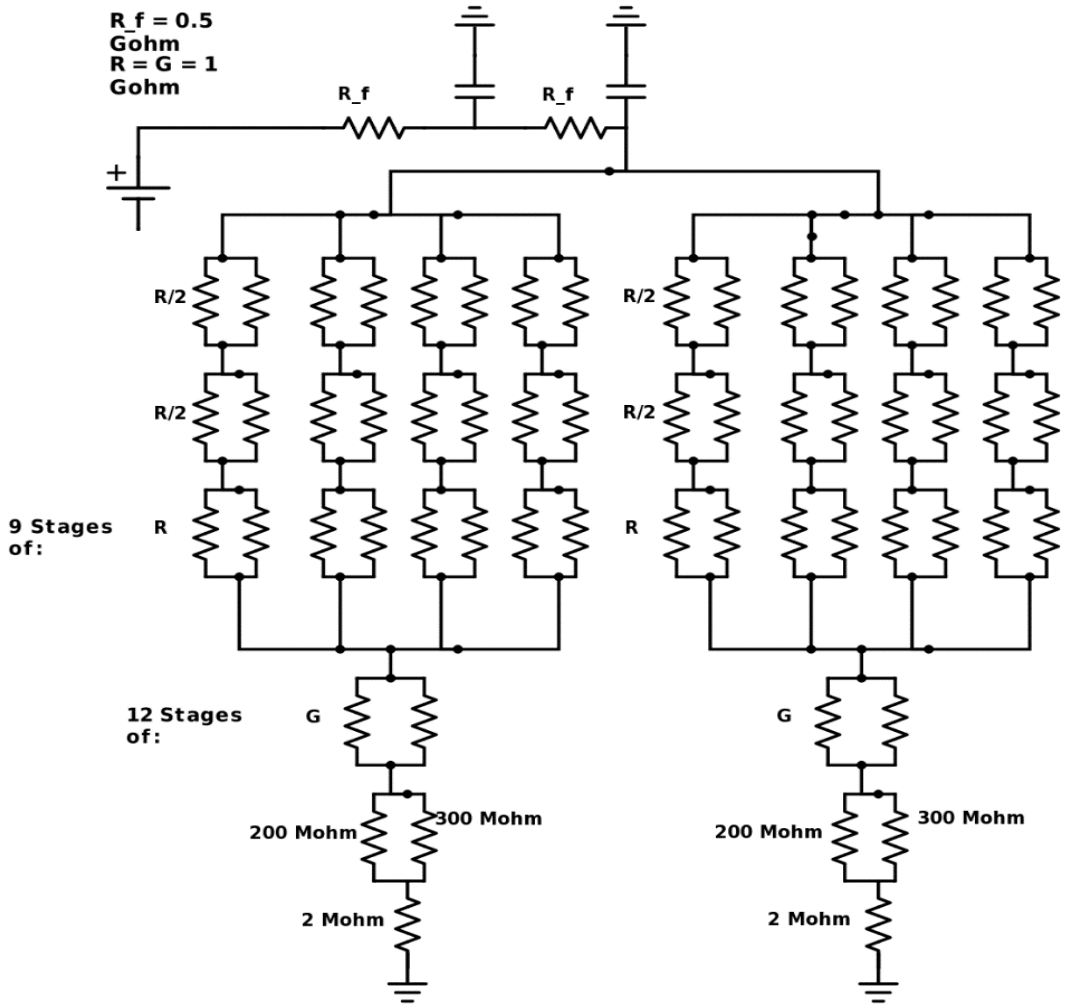
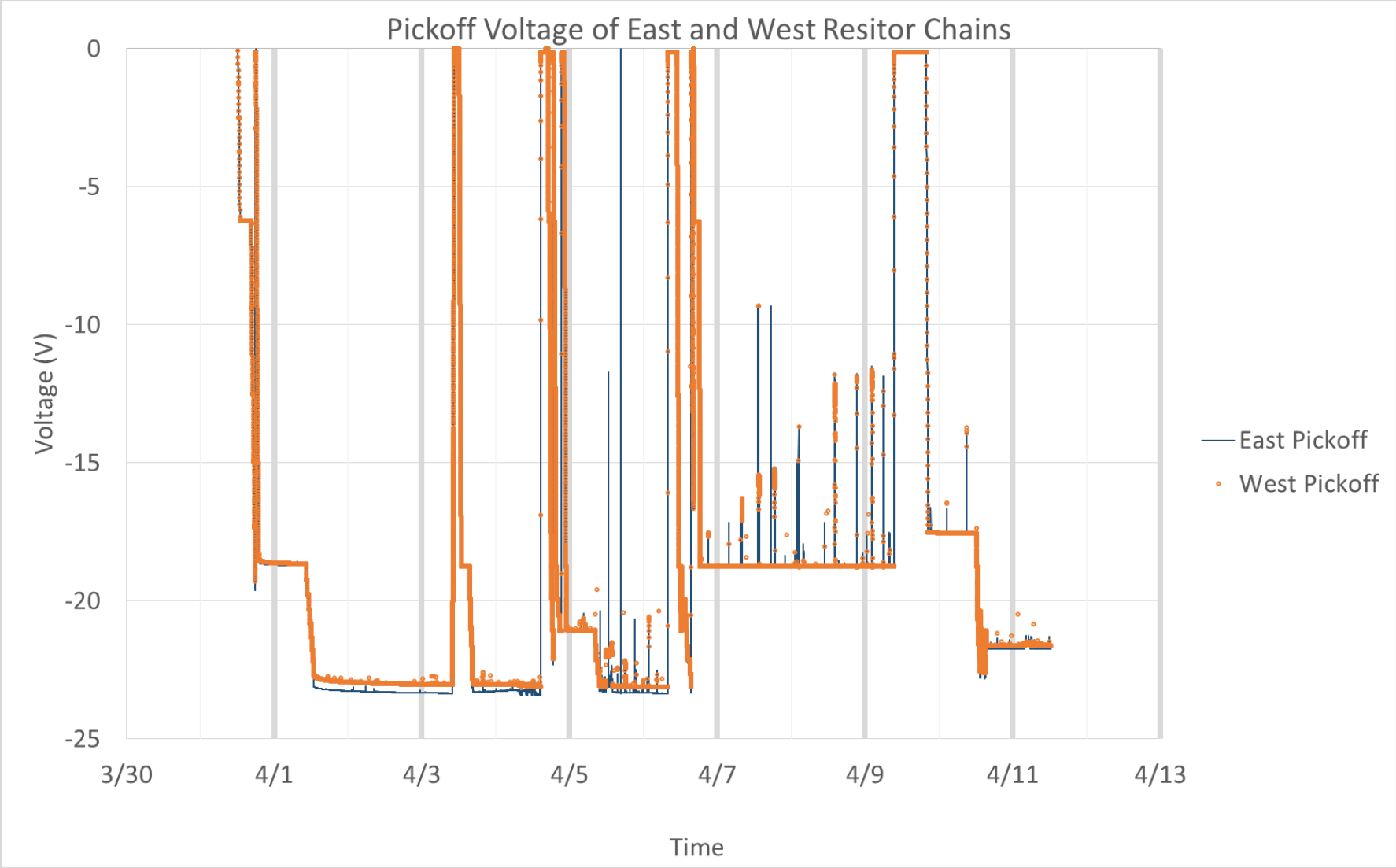


Figure 8. The circuit diagram.

As can be seen in the graph of the pick off voltages below, there is a voltage difference between the east and west pick off voltages. This is possibly due to a sustained flow of charge near an insulating surface due to charge buildup By comparing the fractional change in resistance with various resistors missing to the known fractional difference in the voltages it is possible to see the location of the leakage. The east pickoff chain has been arbitrarily chosen as the reference point for what the voltage should be at so that an analysis of the fractional resistance can be done.


Pickoff Voltage of East and West Resitor Chains
0
-5
-10
-15
-20
-25
Voltage (V)
3/30
4/1
4/3
4/5
4/7
4/9
4/11
4/13
Time
East Pickoff
West Pickoff

We will be looking at the average fractional voltage for the two times where the voltage was relatively stable and differed. These times are during the 2nd and the 4th. Below is a table for the average fractional voltages.

Date	Fractional Voltage
2-Apr	0.987
4-Apr	0.989
Average	0.988

Table 1. Average fractional pickoff voltage

For the resistor values each leg has a total R of 5R and the resistor series after that has a total R of 6.12R. When all resistors are intact those will be their R values and as such that will be what is compared to for the fractional resistance. Note that because the resistors are in parallel, if one resistor in a parallel pair is removed that causes the total resistance to increase. Because the fractional voltage is so close to 1, the removal of one leg or the removal of any resistors from the last series is outside the possible bounds.

Total R	Leg 1 R	Legs 2,3,4 R	Last stage R_tot	Fractional Resistance	Resistors removed	% diference
7.370	5	5	6.12	N/A	N/A	N/A
7.870	5	5	6.62	1.068	G	7.77%
6.870	5	5	5.62	0.932	G x2	5.82%
6.370	5	5	5.12	0.864	G x3	13.35%
7.385	**5.25**	**5**	**6.12**	**1.002**	**R/2**	**1.41%**
7.885	5.25	5	6.62	1.070	G, R/2	7.96%
6.885	5.25	5	5.62	0.934	G x2, R/2	5.60%
6.385	5.25	5	5.12	0.866	G x3, R/2	13.12%
7.354	**4.75**	**5**	**6.12**	**0.998**	**R/2 x2**	**0.99%**
7.854	4.75	5	6.62	1.066	G, R/2 x2	7.56%
6.854	4.75	5	5.62	0.930	G x2, R/2 x2	6.05%
6.354	4.75	5	5.12	0.862	G x3, R/2 x2	13.61%
7.336	**4.5**	**5**	**6.12**	**0.995**	**R/2 x4**	**0.75%**
7.836	4.5	5	6.62	1.063	G, R/2 x4	7.34%
6.836	4.5	5	5.62	0.928	G x2, R/2 x4	6.31%
6.336	4.5	5	5.12	0.860	G x3, R/2 x4	13.88%
7.399	5.5	5	6.12	0.940	R	4.96%
7.899	5.5	5	6.62	1.150	G, R	15.14%
6.899	5.5	5	5.62	1.083	G x2, R	9.18%
6.399	5.5	5	5.12	0.866	G x3, R	13.10%
7.296	4	5	6.12	0.925	R x4	6.55%
7.796	4	5	6.62	1.132	G, R x4	13.62%
6.796	4	5	5.62	1.064	G x2, R x4	7.45%
6.296	4	5	5.12	0.856	G x3, R x4	14.29%

Table 2. Calculated fractional resistance

In the table above it can be seen that the closest fractional resistance to the fractional pickoff voltage is 0.995, which corresponds to four R/2 resistors shorting out for one leg. More than likely it is due to the circuit boards charging and the conditions in the Lar due to the charge build up and emitted charge from components, in which case the circuit needs to be checked to find out where the faulty components are.

5. Conclusion

The first detector test had an issue with the current draw constantly spiking in pure argon, which causes the voltage to trip and means that the voltage necessary for the detector cannot be maintained. Once both of these issues are solved, testing will have to continue to see if there are arcs

in the argon and whether the detector can handle the necessary voltages. Thankfully the location of the charge is relatively known and it corresponds to a part of the detector that had the design updated already so it can be fixed.

Going forward the tests that need to be done is to find out what is causing the streamer effect and how to prevent it. In the short term a test will be done to see if the detector can hold at the desired voltage of 190kV in contaminated argon and to see what voltage can be held in pure argon. Once these are done, some more tests looking for arcs and sparks could be done while diagnostics are being run to find out where the problems are.

Considering the purpose of the test was to find any possible issues with the detector, the test can be considered successful. While the streamer behavior was unexpected they did not see many arcs and those they did see can be avoided by ramping up the voltage slower. It is also possible the issue will be avoided due to an update in the design meaning it might not be much of an issue at all.

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