

Design Testing of the Small Monitored Drift Tubes for the Phase II Upgrade of the ATLAS Muon Spectrometer

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Abstract

The new high luminosity environment at the Large Hadron Collider necessitates an upgrade of detector technology. For the Muon Spectrometer at the ATLAS experiment, this upgrade will take place in 2 phases. Phase II of the upgrade will begin during Long Shut Down 3, so development of new technology is currently underway. During this, existing Monitored Drift Tube (MDT) chambers in the BIS region will be replaced with small MDT (sMDT) chambers to create additional space for other upgrades. This thesis focuses on the design testing of new sMDTs that will be used in the prototype Phase II sMDT chamber: Module Zero. General specifications such as end plug diameters and tube bending were measured, in addition to the wire tension and dark current. Overall, the newly produced sMDTs were majoritively within specification and led to the successful construction and operation of the Module Zero prototype sMDT chamber.



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1 The Large Hadron Collider

1.1 The LHC and ATLAS

The Large Hadron Collider (LHC) is well known as the world's largest and most powerful particle accelerator to date. The LHC ring spans a circumference of 27km and is lined with superconducting magnets to guide the hadronic particle beams into one another [2]. Most often, the LHC collides 2 proton beams together. The LHC currently achieves a center of momentum collision energy of $\sqrt{s} = 13\text{TeV}$, with a peak luminosity of $L = 1.37 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$ for such collisions, making it the most powerful collider [1]. The LHC is designed for a collision energy of $\sqrt{s} = 14\text{TeV}$, while the peak luminosity has already superseded design expectations [1]. The ATLAS experiment is 1 of 4 main experiments located at one of the collision points on the LHC. ATLAS is 1 of 2 general purpose detectors, the other being CMS, that famously worked to discover the Higgs boson. The other 2 large experiments, ALICE and LHCb, work on more specific experiments.

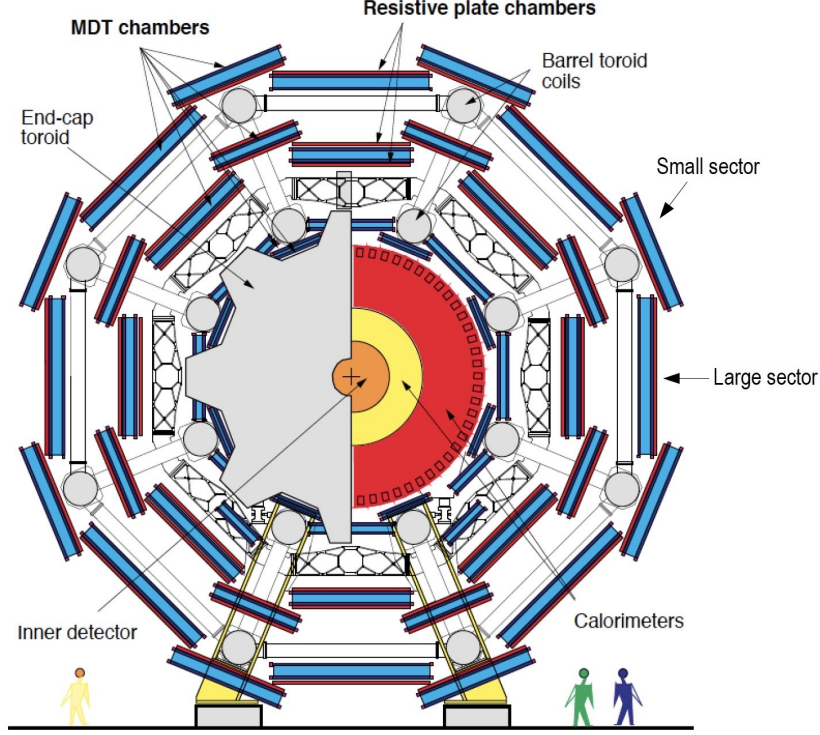
The timeline of LHC upgrades spans decades from now. The current upgrade of the LHC as a whole will turn the accelerator into the High Luminosity LHC (HL-LHC). This upgrade will allow for more precise studying of electroweak symmetry breaking, in addition to other Beyond the Standard Model (BSM) physics [1]. In order to keep up with the increasing luminosity of the LHC and fully exploit the potential of the collisions, the technology of each experiment must be upgraded. The ATLAS upgrades will be taking place in 2 phases. Phase I upgrades are being completed as Long Shut (LS) Down 2 concludes. Phase II upgrades will begin in LS3. Hence, the research and development of Phase II technology is currently underway.

1.2 The Muon Spectrometer

Accurately measuring properties of muons created at the LHC is a crucial data channel. As mentioned, one of the main goals with the upgrade of the ATLAS experiment is to further investigate electroweak symmetry breaking. This is dependent on measuring the Higgs boson couplings that are involved in its different decays. Hence, precisely measuring the Higgs branching ratios is critical. Channels such as $H \rightarrow ZZ^{(*)} \rightarrow 4\mu$ and $H \rightarrow \mu\mu$ are of particular interest for coupling measurements [1]. On the other hand, muons are also valuable for testing new BSM theories. This depends significantly on having a high muon transverse momentum resolution and accurate event reconstruction [1].

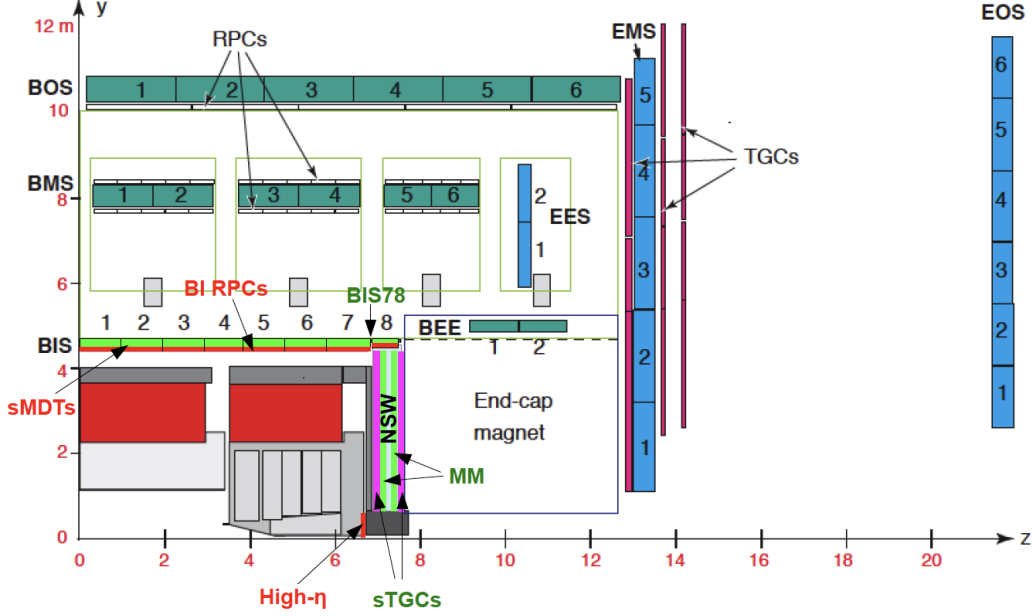
The cross section of the Muon Spectrometer is shown in Figure 1 [1]. One can consider the overall

Figure 1: Cross section diagram of the Muon Spectrometer as of Run 1 and 2. Muon detection takes place on the outer 2 blue rings of the diagram.



detector to be a large, layered cylinder. The 2 end caps of the detector are commonly referred to as 'wheels', while the cylindrical part is referred to as the 'barrel'. Particles collide at the center of the diagram and the resultant particles are sent into the detectors surrounding the interaction point. Muons pass through the inner most detectors, the Calorimeters, and are detected using precision and trigger chambers. The precision chambers consist of Monitored Drift Tube (MDT) chambers and Cathode Strip Chambers (CSC), while the trigger chambers consist of Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC). The Muon Spectrometer has 3 large, air-core superconducting toroidal magnets that create a magnetic field of approximately 0.5T in strength [1]. Since the muon is a charged particle, its trajectory upon creation is curved due to the magnetic field. This change in direction takes place in the bending plane of the detector, which serves as the 'precision coordinate' for muon track measurements. For a muon with transverse momentum of $p_T = 1\text{TeV}$, the sagitta of its path is on average $500\mu\text{m}$ [1]. The sagitta of a path is the maximum deviation away from the 2 end points of the path connected via a straight line. The path of the muon is measured using hits across the series of precision chambers that the muon passes through. The global ATLAS coordinate system employs the following choices: the interaction point is the coordinate origin, the positive z axis is along the beam line and the positive x axis points towards

Figure 2: Small sector of the Muon Spectrometer displaying Phase I and II upgrades. Phase I upgrades are shown in green text and Phase II upgrades are shown in red text. Note the sMDTs in the BIS region, which this thesis focuses on.



the center of the LHC ring [1]. The coordinate system is right handed. If one defines a polar angle θ relative to the z axis, or beam line, then the pseudorapidity at the LHC is defined to be $\eta = -\ln(\tan(\theta/2))$. MDT chambers cover a pseudorapidity of $|\eta| < 2.7$, but in the inner most end cap wheels, CSCs are used for the $2.0 < |\eta| < 2.7$ region [1]. In order to ensure that the chambers re-create the most accurate muon path, their positions relative to one another and other reference objects are monitored in real time using an optical alignment system. The system is calibrated with the toroidal magnetic field off, so the path of the muon is once again straight. The RPCs in the barrel region, $|\eta| < 1.05$, and the TGCs in the end caps, $1.05 < |\eta| < 2.4$, serve as triggers for muonic events and also serve to measure the muon path in the non-bending coordinate of the toroids ('second precision coordinate') [1]. From there, the High Level Trigger preforms full track reconstruction, drawing on hits from the precision and trigger chambers. This yields the final refined muon path and transverse momentum measurement.

The Phase I upgrade of the Muon Spectrometer replaced the original small wheels with the New Small Wheels (NSW). These NSWs employed small strip TGCs, or sTGCs, for precision tracking and triggering. The Phase II upgrade looks to replace some existing precision chambers with newer models, in addition to a large replacement of front-end, trigger and readout electronics. The chamber replacements comprise of installing new RPC and small MDT (sMDT) chambers in certain regions.

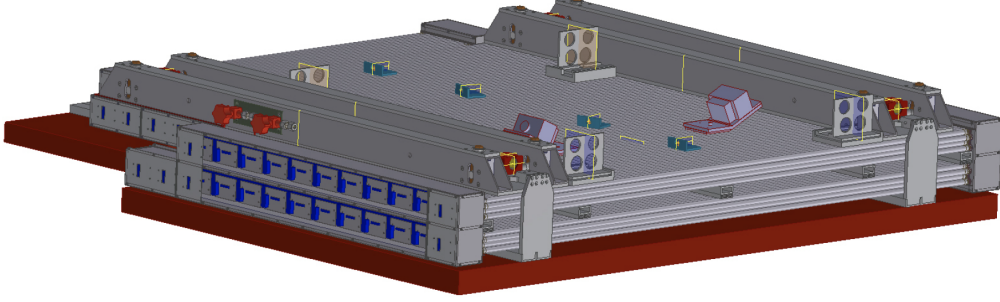
Figure 2 shows where these upgrades will be taking place on the Muon Spectrometer [1]. Phase II upgrades are shown in red text, while upgrades from LS2 are shown in green text. These upgrades must be qualified for 'ultimate' high luminosity conditions, such as an instantaneous luminosity of $L = 7.5 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$ and an integrated luminosity of $\int L dt = 4000 \text{fb}^{-1}$ [1]. The current efficiency and momentum resolution of the MDT system is not of significant concern to ATLAS, but the electronics will need significant upgrades for the high luminosity environment [1]. For the chamber upgrades, new RPCs will be installed onto inner-barrel (BI) MDT chambers. The old RPCs would not be able to perform at the same and desired efficiency in the high luminosity environment. Installing new RPCs introduces a challenge with the available space in the inner barrel small sector (BIS) region. In order for this installation to be possible, the existing BIS MDT chambers will have to be replaced with the thinner sMDT chambers. The new RPC and sMDT chambers will then be able to fit in the existing BIS MDT locations. The large sector of the detector does not experience this spacing issue. Therefore, research and development for the new BIS sMDT chambers is ongoing.

1.3 sMDT Chambers and Tubes

Small and regular MDT chambers operate based on the same guiding principles. The chambers are comprised of hundreds of Monitored Drift Tubes, each filled with a gas mixture of Ar:CO₂ (93:7) [1]. The gas mixture is chosen such that it is easily ionized by charged particles that pass through the tubes. As a muon passes through a MDT, it causes an electron avalanche that drifts towards the wire due to its potential and produces the signal that is read out by the electronic systems on the chamber.

The main physical difference between a small MDT and a regular MDT is simply the diameter of the tube. sMDT tubes have a diameter of 15 mm, exactly half of the regular MDTs. sMDTs operate with the same gas mixture, pressure and gain as regular MDTs. The high voltage is also somewhat lower at 2730V, instead of 3080V [1]. Due to the smaller radius of the sMDTs, the maximum drift time is 175ns instead of 720ns, as well as a lower cross section that is exposed to radiation [1]. Overall, the use of sMDTs over regular MDTs results in 8 times lower occupancy. sMDT chamber performance has been studied inside and outside of the LHC. During the Phase I upgrade, 16 new sMDT chambers with RPCs were installed in the BIS sectors. Figure 3 shows a diagram of the BIS78 chamber in combination with the new RPC [1]. This Phase I upgrade improved triggering in the barrel to end cap transition region, $1.0 < |\eta| < 1.3$, as well as served as guidance for the Phase II sMDT upgrade. In Phase II, 96 new sMDT chambers will be installed in the BIS1-6

Figure 3: BIS78 sMDT chamber diagram with optical alignment sensors shown on top and RPC shown on the bottom.



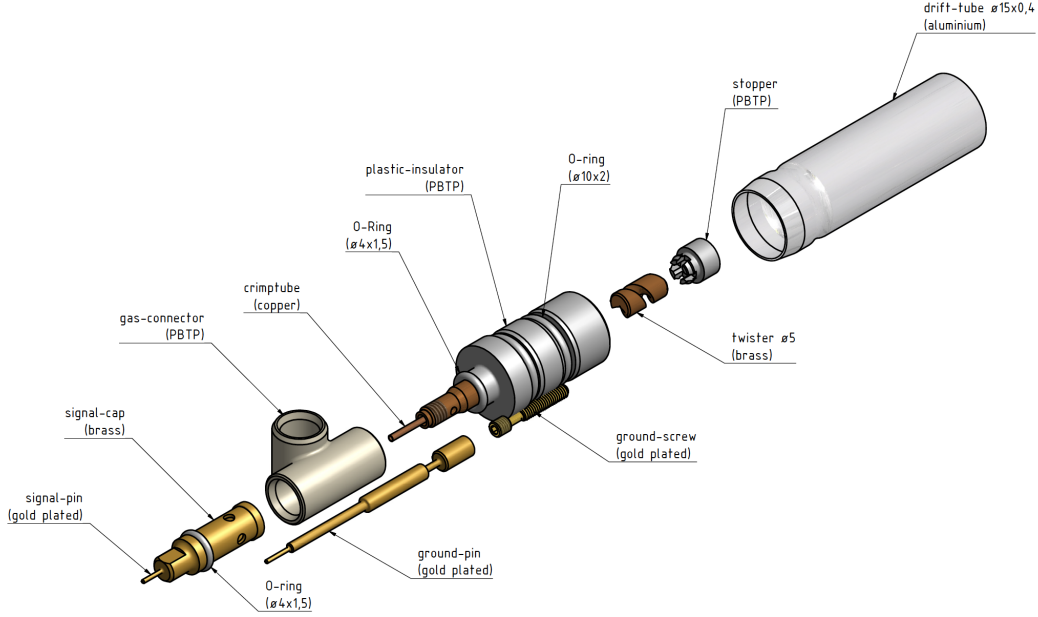
region. Therefore, these chambers will need to be mass produced in order to meet the needs of the Phase II upgrade. The University of Michigan is currently one of the institutions preparing to complete this mass production of sMDT chambers. Over the past few years, significant time has been dedicated to the first prototype sMDT chamber, known as Module Zero. This chamber will serve as an example of the university's capability to mass produce the new sMDT chambers according to ATLAS's specifications.

2 Research Objectives

Although the overall sMDT chamber construction takes place at the University of Michigan, the construction of the sMDTs that make up the chamber takes place elsewhere. These sMDTs are then shipped to the University of Michigan for further testing before being used in the Module Zero chamber. Even minor defects in sMDT construction can lead to significant challenges during the sMDT chamber construction and operations. Therefore, it is imperative that the most important aspects of the sMDTs are to specification before implementation in Module Zero.

Figure 4 shows an expanded view of the end plugs of a sMDT [1]. Both end plugs of a sMDT are designed to be identical and the tube length separating the end plugs is approximately 1.6m. The sMDT in Figure 4 actually ends at the crimp tube part, while the gas manifold that the sMDT is inserted into begins at the gas-connector. The larger cylindrical structure of the crimp tube (in between the tip of the crimp tube and O-ring) needs to make solid connection with the signal pin for proper alignment and signal reading. Ensuring that this part is the proper diameter is therefore important. Furthermore, sMDTs were immediately rejected if the thin portion of the crimp tube was significantly bent, since this would also cause the issues just stated. The 1.6m tube is only

Figure 4: Expanded view of the parts that make up the end plug of a sMDT.



15mm in diameter and made up of aluminum. Therefore, the tube is fairly susceptible to bending during construction and transit. Bent sMDTs cause significant misalignment issues when attempting to connect both ends of the sMDT to the gas manifolds in chamber construction. Quantitatively measuring the amount of bending in the sMDTs is therefore critical to a successful sMDT chamber.

In addition to making electrical connection with the end cap electronics, the 2 end plugs hold the wire that runs through the sMDT. Most often, sMDTs will be positioned lengthwise in the LHC. Therefore, it is crucial that the wire tension is great enough to minimize the effects of gravitational sag. Incorrect wire tension can lead to a non-uniform cylindrical geometry for a sMDT, which directly influences the track reconstruction of the muon. Since these sMDTs have arrived fully constructed, indirect measurements of the wire tension must be employed. Since these wires are so crucial to the muon track reconstruction, even small inaccuracies in the wire current / voltage can have an effect on measurements. Therefore, one must consider the dark current present through the wire, even though this is on the scale of nano amps. sMDTs with too high of a dark current cannot be trusted to produce accurate measurements in the chamber and therefore will not be used. sMDTs that pass all of these tests will be the best possible tubes for the Module Zero prototype. In order to track this information for each sMDT, a database was created. This was very helpful once testing was completed and chamber construction began.

3 Methods of Analysis

Since the same set of tests will be completed for each sMDT, the most natural way to organize results will be in histograms. Rather than explain the analysis methods in each results section, a general description of data analysis methods will be given here to guide future sections. One of the most important aspects that characterizes a histogram is the number of bins used to group the data. Altering the number of bins can lead to different results so it is important to standardize this. All histograms appearing in this thesis will have the number of bins determined by the statistical rule:

$$N_{bins} = \sqrt{N}, \quad (1)$$

where N is the number of data points being considered. Furthermore, outliers in a randomly determined data set can drastically alter binning and results. Outliers can be identified as data points not falling into the interval:

$$[Q_1 - 1.5 \cdot I, Q_3 + 1.5 \cdot I], \quad (2)$$

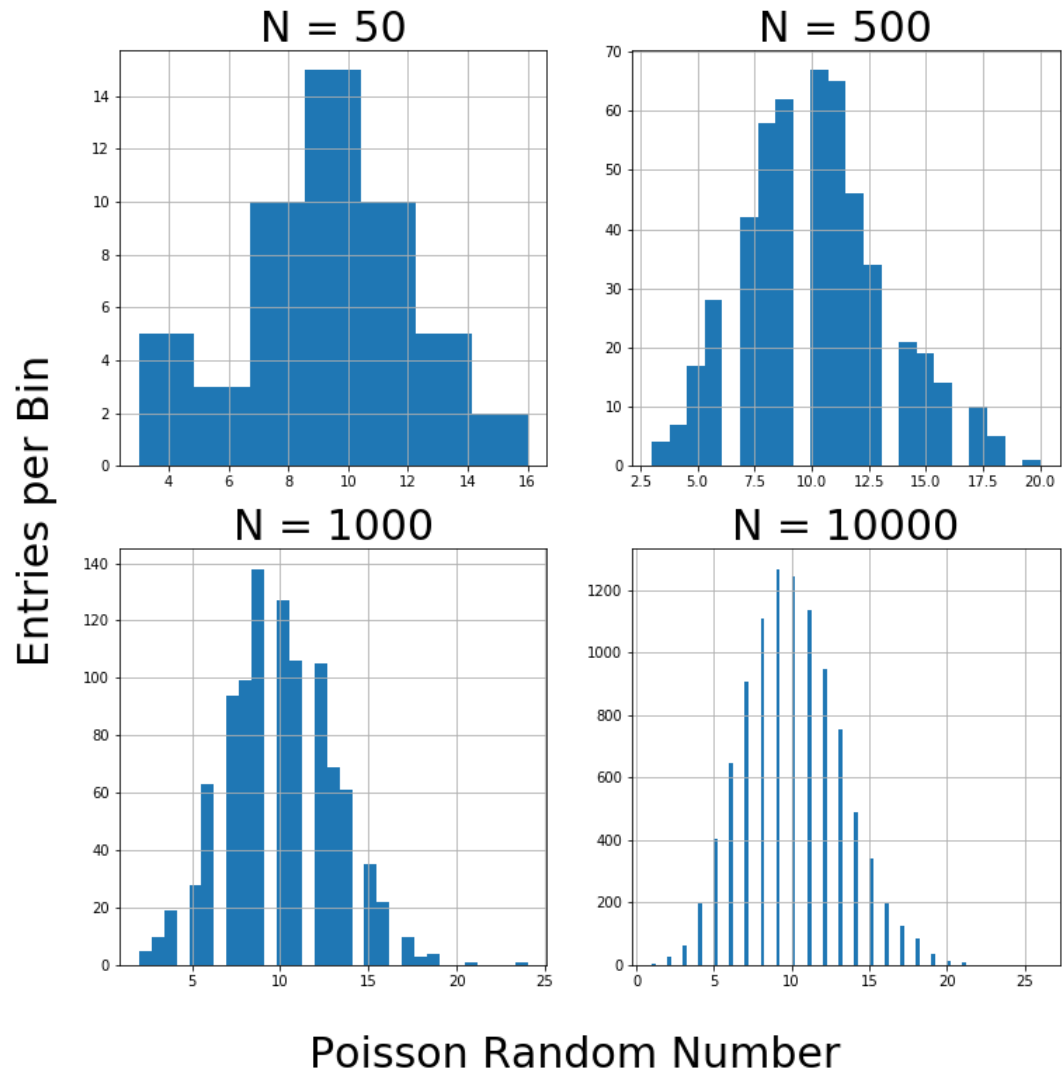
where Q_1, Q_3 are the first and third quartiles and I is the interquartile range. Therefore, histograms included in this thesis will only include data points that fall in this interval, unless otherwise stated. Note that the number of bins was determined once this outlier cut was applied to the data. Once the number of bins and data set is determined, one can utilize the results of the histogram further. According to the Central Limit Theorem, as the number of data points increases, the histogram associated with those data points approaches a Gaussian distribution. Figure 5 displays the Central Limit Theorem in action for sets of random variables generated according to a Poisson distribution with mean $\lambda = 10$. Notice how as the number of data points, N , increases, the histogram of the data set becomes more Gaussian in nature.

Since hundreds to thousands of data points were collected for each test, fitting the resulting histogram to a Gaussian function is justified. The family of nonlinear curves that the histograms were fit to are of the form:

$$f(x) = ae^{-b(x-c)^2}, \quad (3)$$

where a, b and c are real, free fitting parameters to be determined by the fitting algorithm. In order to determine the fitting parameters for each histogram, the curve fit SciPy package was used. This package uses the Levenberg-Marquardt algorithm, a method of solving nonlinear least square

Figure 5: Example of the Central Limit Theorem for a random number generated according to a Poisson distribution with mean $\lambda = 10$.



problems, such as nonlinear curve fitting [3] [4].

In order to determine the success of a curve fit to a histogram, the fitting parameters can be compared to the coefficients of a normal distribution. Consider a normal probability distribution given by:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}, \quad (4)$$

where σ and μ are the standard deviation and mean of the distribution, respectively [5]. In comparison to the Gaussian curve in equation 3, one can determine the mean and standard deviation of the data based on the fitting parameters. First note that the factor of $1/\sigma\sqrt{2\pi}$ in equation 4 ensures that this distribution is normalized to 1. For a histogram, this is not necessarily the case. One option would be to divide the entries per bin by the total number of data points to create a probability distribution. However, this would lead to less helpful figures visually. Therefore, it would be incorrect to make a comparison between the parameter a and $1/\sigma\sqrt{2\pi}$. Instead, one has the freedom to compare the parameters b and c to the normal distribution function. This leads to the following equations:

$$b \pm \sigma_b = \frac{1}{2\sigma^2} \implies \sigma = \frac{1}{\sqrt{2b}} \quad (5)$$

$$c \pm \sigma_c = \mu. \quad (6)$$

Here, σ_b and σ_c are the uncertainties present in each parameters value. In order to determine uncertainty present in the standard deviation, denoted σ_σ , based on σ_b , the uncertainty must be propagated according to [6]:

$$\sigma_\sigma^2 = \left(\frac{\partial f}{\partial b}\right)^2 \sigma_b^2, \quad (7)$$

where according to equation 5:

$$f(b) = \frac{1}{\sqrt{2b}} \implies \left(\frac{\partial f}{\partial b}\right)^2 = \frac{1}{8b^3}. \quad (8)$$

Hence,

$$\sigma_\sigma^2 = \frac{1}{8b^3} \sigma_b^2. \quad (9)$$

Now assuming that uncertainty is positive, one has:

$$\sigma_\sigma = \frac{1}{2\sqrt{2b^3/2}} \sigma_b. \quad (10)$$

Summarizing this result with equations 5 and 6, one has:

$$\sigma = \frac{1}{\sqrt{2b}} \pm \frac{1}{2\sqrt{2}b^{3/2}}\sigma_b \quad (11)$$

$$\mu = c \pm \sigma_c. \quad (12)$$

The parameter uncertainties σ_b and σ_c are determined by the set of parameters' covariance matrix. This matrix is simultaneously calculated while the parameters are being determined in the SciPy algorithm, making this programming package very efficient. The i, j th entry of the covariance matrix, K , is defined by [7]:

$$K_{ij} = \text{Cov}[X_i, X_j], \quad (13)$$

where X_i and X_j are some random variables. This matrix is clearly symmetric ($\text{Cov}[X_i, X_j] = \text{Cov}[X_j, X_i]$) and since $\text{Cov}[X_i, X_i] = \text{Var}[X_i]$, the diagonal entries provide the variance of each parameter. Hence, to find each parameter's uncertainty from the covariance matrix, one just needs to calculate the square root of the diagonal entries in the matrix.

The mean and standard deviation determined by the fitting parameters can be compared to the mean and standard deviation calculated from the data sets using the usual statistical definitions:

$$\mu_{stat} = \frac{1}{N} \sum_{i=1}^N x_i \quad (14)$$

$$\sigma_{stat} = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \mu_{stat})^2}, \quad (15)$$

where x_i denotes the i th data point's value. Note these values should be calculated based on the same data set that populated a histogram, so outliers should once again be removed. So long as the *statistical* mean and standard deviations are within the *fitting* mean and standard deviations' uncertainty ranges, or:

$$\mu_{stat} \in [\mu - \sigma_c, \mu + \sigma_c] \quad (16)$$

$$\sigma_{stat} \in \left[\sigma - \frac{\sigma_b}{2\sqrt{2}b^{3/2}}, \sigma + \frac{\sigma_b}{2\sqrt{2}b^{3/2}} \right], \quad (17)$$

then it can be concluded that the model applied to the histogram accurately represents the data at hand. This is simply because up to the uncertainty present from modeling the data, the model replicates the statistical results.

Figure 6: Example usage of the micrometer measuring the end plug diameter of a sMDT.



4 Construction Tests

4.1 End Plug Measurements

Testing the overall construction of a given MDT is rather straightforward but nonetheless critical. Assuring that the MDT components are produced within the correct specifications leads to the best possible chamber assembly. Bent MDTs can lead to misalignment with end cap electronics and therefore output incorrect data. Oversized end plugs can cause a MDT to not fit into the end cap electronics and potentially damage them, whereas undersized end plugs can lead to improper electrical connection with the electronics. Measuring the end cap diameter and the amount of bending present in a MDT were the 2 main physical construction tests performed before approving new sMDTs for the Module Zero prototype.

For each sMDT, a precision electronic micrometer was used to measure the diameter of both end plugs. While this seems trivial, it is rather easy to misuse this tool when making such precise measurements on the order of 10^{-6}m . This issue lies in over tightening the micrometer around the end cap. It is rather difficult to *feel* when the micrometer is tight enough to make the measurement, so once solid contact with the end cap was made, the extra fine-tuning knob was used to very delicately and accurately tighten the micrometer to its final location. Improper use of the tightening knobs can make a difference in as many as a few micrometers and thus lead to incorrectly approving

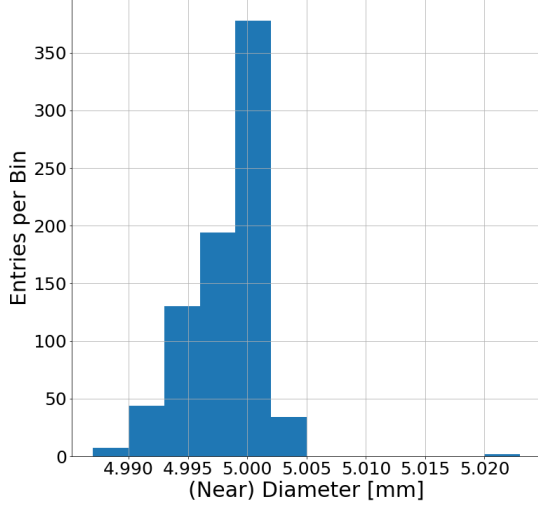


Figure 7: Near end plug diameter histogram without any cuts made to the initial data set.

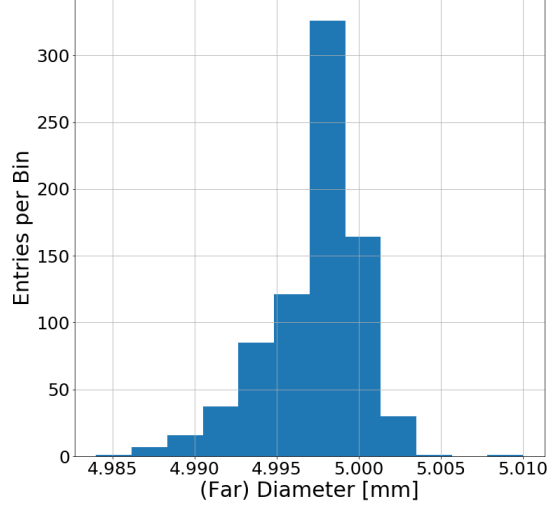


Figure 8: Far end plug diameter histogram without any cuts made to the initial data set.

or rejecting MDTs. In order to further improve the accuracy of the micrometer, the tool was recalibrated to zero before each testing session. The threshold value for the diameter of the sMDT end plug is set at a maximum of 5.0mm [1]. The micrometer and an example measurement are shown in Figure 6.

4.2 End Plug Results

Since each sMDT has 2 end plugs, the location of the bar code on the MDT was used to denote which end plug was being measured. Therefore the 2 groups of measurements fall under the categories of "near" end plugs, for those closest to the bar code and likewise for "far" end plugs. In order to highlight the presence of outliers, the uncut data sets are displayed in the histograms in Figures 7 and 8. Measurements appearing around the 5.02mm mark in the Figure 7 and around 5.01mm in Figure 8 are well removed from the majority of the other data. Applying equation 2 from the Methods of Analysis section, these outliers will likely be removed in the cut data set.

The histograms displaying the data sets with cuts being enforced are displayed in Figures 9 and 10. As expected, the suspected outliers have been successfully removed. From now on, outliers will be removed from all following histograms for the sake of brevity. These figures also display the results of the Gaussian curve fitting to the binned data. Figure 11 displays a comparison of the

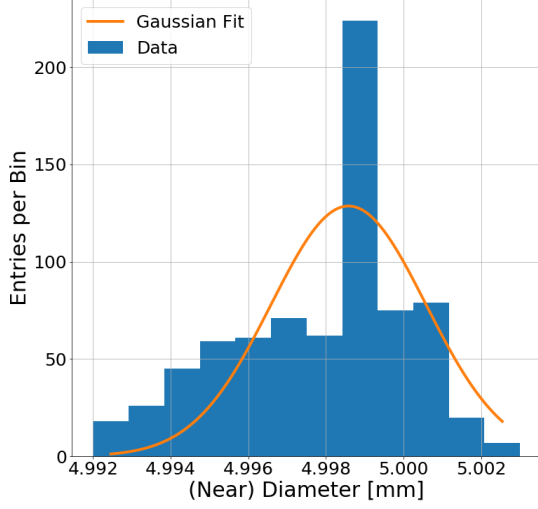


Figure 9: Near end plug diameter histogram with cuts from equation 2 enforced and Gaussian regression based on the binned data.

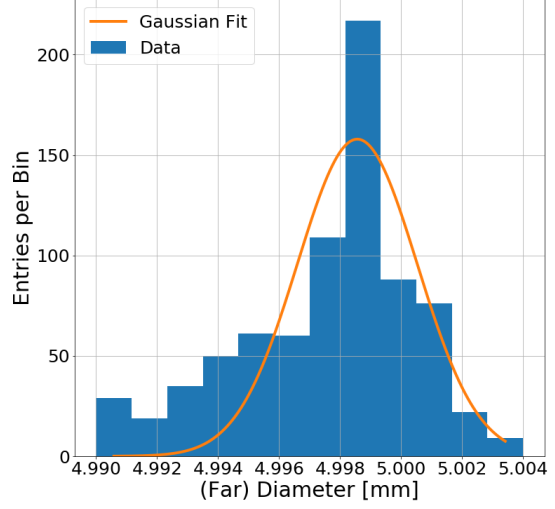


Figure 10: Far end plug diameter histogram with cuts from equation 2 enforced and Gaussian regression based on the binned data.

Gaussian curves from Figures 9 and 10. Visually, these curves very nearly represent data sets with similar means and spreads. This can be further examined quantitatively as well.

The fitting algorithm determined the following relevant values for each Gaussian fit:

$$\text{Near diameters: } b = (1.25 \pm 0.64) \cdot 10^5 \text{ mm} , c = (4.99858 \pm 0.0005) \text{ mm} \quad (18)$$

$$\text{Far diameters: } b = (1.29 \pm 0.46) \cdot 10^5 \text{ mm} , c = (4.99856 \pm 0.0004) \text{ mm}. \quad (19)$$

Thus, using equations 11 and 12, the mean and standard deviation for each data set based on the fitting algorithm are:

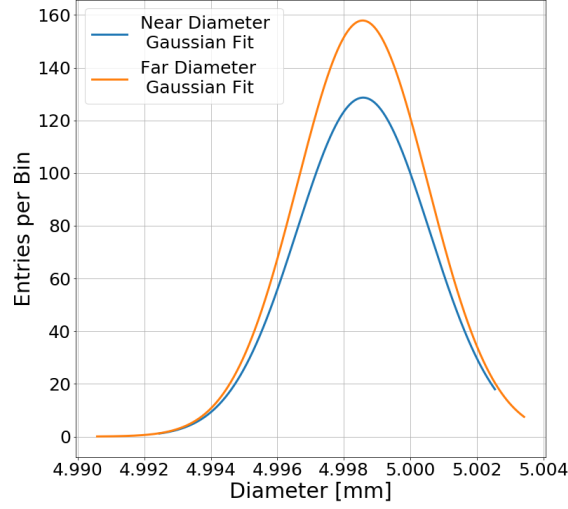
$$\text{Near diameters fitting results: } \mu = (4.99858 \pm 0.0008) \text{ mm} , \sigma = (2.0 \pm 0.5) \cdot 10^{-3} \text{ mm} \quad (20)$$

$$\text{Far diameters fitting results: } \mu = (4.99856 \pm 0.0004) \text{ mm} , \sigma = (2.3 \pm 0.4) \cdot 10^{-3} \text{ mm}. \quad (21)$$

Now to examine the validity of the model, the statistical mean and standard deviation of the data sets were computed according to equations 14 and 15:

$$\text{Near diameters statistical results: } \mu_{stat} = 4.9979 \text{ mm} , \sigma_{stat} = 2.4 \cdot 10^{-3} \text{ mm} \quad (22)$$

Figure 11: Comparison of histograms from Figures 9 and 10.



$$\text{Far diameters data results: } \mu_{stat} = 4.99875\text{mm} , \sigma_{stat} = 2.7 \cdot 10^{-3}\text{mm}. \quad (23)$$

Examining the uncertainties present in the mean and standard deviation results determined by the fitting parameters, it can be concluded that the statistical results are consistent with the fitting results. This consistency reflects the accuracy of the Gaussian model chosen and the cuts performed on the initial data sets. Furthermore, the similarity of each data set's mean and standard deviation reflects that there were no systematic errors in installing the end plugs into a given sMDT. In comparison to the threshold diameter size issued in the MDT TDR, on average, the sMDTs' end plugs were within the target value. Hence, the average sMDT should be acceptable to be used in Module Zero based on its end plug sizes. Of course, tubes that were considered outliers or simply above the threshold value should be (and were) rejected as Module Zero tubes.

4.3 Tube Bending Measurements

The tube bending test was designed to measure the maximal distance between the tube of a sMDT and a level surface. As one would imagine, the majority of bending present is a rather small amount. Therefore, an optical microscope was positioned where the sMDT makes contact with the level surface. In order to determine the maximum amount of bending present, the sMDT was slowly rotated using one of its rubber end cap protectors. Once the orientation was set, it was critical that

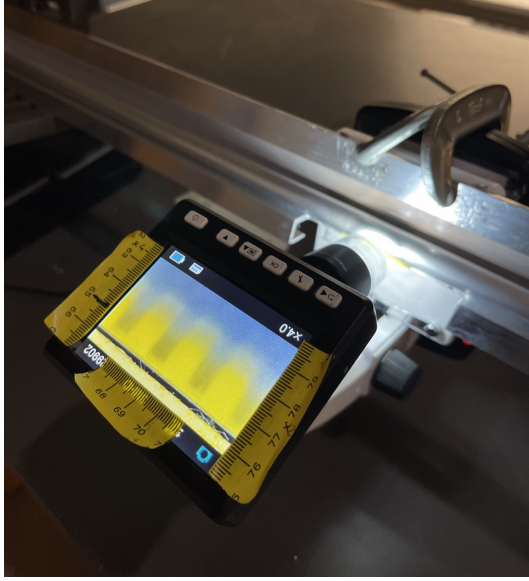


Figure 12: Example sMDT bending test for a tube with a **small** amount of bending present. The gap between the sMDT and the surface is the thin black line on the screen.

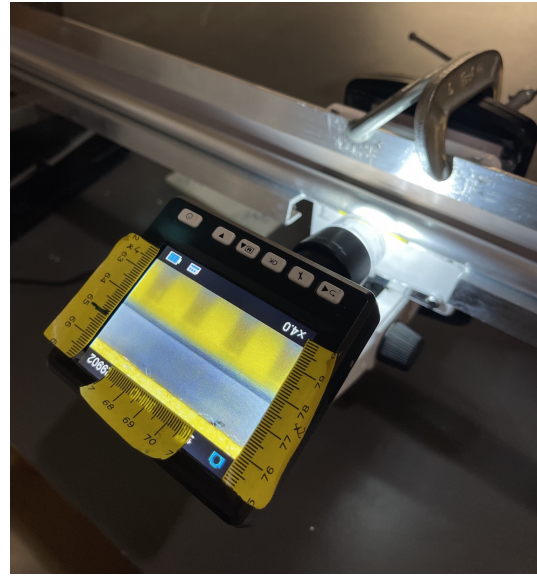


Figure 13: Example sMDT bending test for a tube with a **large** amount of bending present. The gap between the sMDT and the surface is the large grey line.

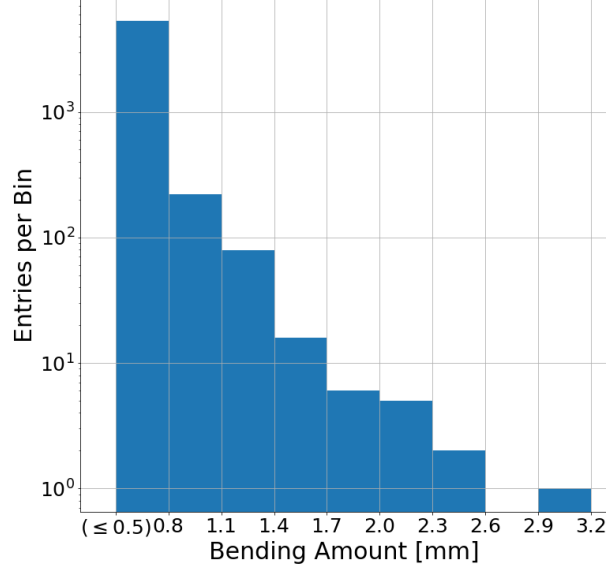
both ends of the sMDT were in contact with the level surface. If one was not making natural contact with the surface, this would lead to inaccurate bending measurements.

The optical microscope has different zoom settings. The most common one used for tubes without severe bending is a 4x zoom. A cut-up ruler was physically placed on the side of the display screen of the microscope to record the distance between the surface and the bottom of the sMDT. One had to account for the amount of zoom present in the microscope before recording the amount of bending. Figures 12 and 13 display examples of the bending test for sMDTs with a small and large amount of bending present, respectively. In order to expedite the testing process, sMDTs that had an amount of bending less than 0.5mm present did not have their exact amount recorded. Bending amounts larger than 0.5mm were exactly recorded. This did not present an issue for determining whether or not a sMDT passed the bending test since the maximum amount of bending that is allowed is 0.8mm [1]. Hence, those $\leq 0.5\text{mm}$ were very safe to use in the Module Zero prototype.

4.4 Tube Bending Results

Since the ATLAS group decided not to record the exact value of bending for sMDTs with bending less than 0.5mm, the histogram of recorded bending values will not appear as a normal distribution. Instead, the first bin containing measurements of 0.5mm will be significantly greater than the rest

Figure 14: sMDT tube bending histogram. The first bin contains events where tube bending was less than 0.5mm to 0.8mm, inclusively.



of the bins. This is simply because events that would have been below 0.5mm are now being added into this single bin. This is depicted in Figure 14 which summarizes the sMDT bending for sMDTs tested at the University of Michigan. Since the first bin was so saturated with events, a log scale was used on the y axis for better visualization.

Since the usual analysis of fitting a Gaussian curve to the binned data cannot be applied in this case, the statistical results can still be quoted (with some bias):

$$\text{sMDT Bending: } \mu_{stat} = 0.54\text{mm} , \sigma_{stat} = 0.16\text{mm}. \quad (24)$$

Since the exact values of bending less than 0.5mm were not recorded and were instead valued at 0.5mm, this significantly affects the mean bending amount, which therefore influences the standard deviation as well. If the exact values of bending were known, the mean would be less than its value in equation 24. This would have caused a greater spread in the measurements, which would have increased the standard deviation. Either way, the values in equation 24 should be considered with this explanation in mind. Overall, the majority of newly produced sMDTs were not bent past the threshold value of 0.8mm.

Figure 15: sMDT wire tension test setup. The surface of the sMDT is grounded, while the end pins make contact with the voltage source wiring. The middle image is the bar magnet at the midpoint of the sMDT. Images are broken apart due to the length of the tube.



5 Tension Test

5.1 Experimental Overview

The tension test was designed to precisely measure the tension of the wire inside a sMDT. Since the sMDTs arrived at the University of Michigan laboratory fully constructed, indirect methods for perturbing the wire were needed. The overall setup relied on sending a voltage pulse through the wire while the sMDT was placed in an external, static, homogeneous magnetic field, which caused the wire to oscillate. The wire then experienced an induced Faraday current from the magnetic field that was used to track the amplitude of oscillations over time. A Fast Fourier Transform (FFT) was applied to the output signal to determine the frequency of oscillation and thus the wire tension.

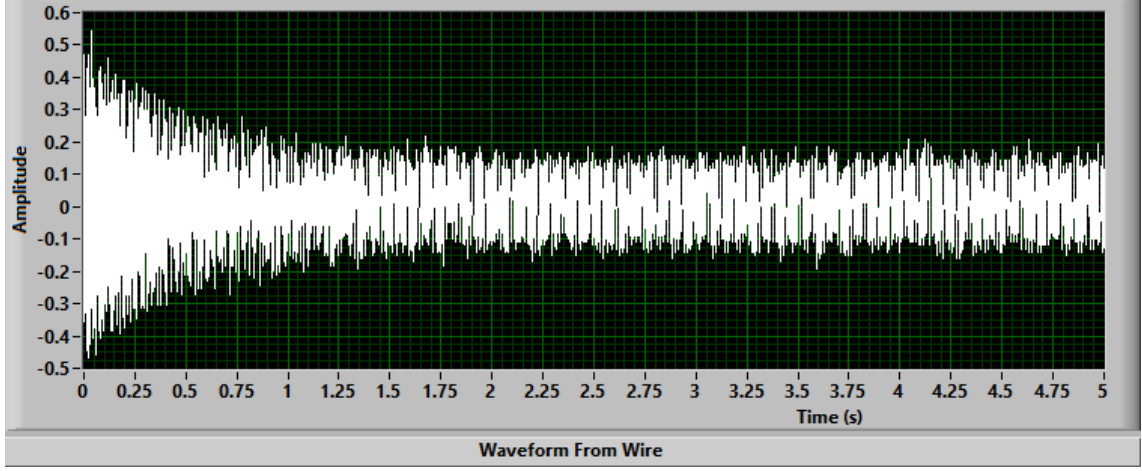
First, the sMDT was snapped into tube holders that grounded the surface of the sMDT, while allowing the end pins to make electrical contact with wiring connected to a voltage source controlled by the nearby computer. The length of the tube was then measured and uploaded into the Lab View interface that automated the tension test. The linear mass density of the wire was set at $38.5\mu\text{g}/\text{mm}$, which was assumed to be constant in all tests as in accordance with the MDT TDR [1]. An external, static, homogeneous magnetic field was created using 2 large bar magnets at the midpoint of the sMDT. See Figure 15 for a depiction of this setup.

A voltage pulse was then sent through the wire when the test began. Due to the magnetic field at the center, the wire was subject to the Lorentz force, given by:

$$\vec{F} = I \int d\vec{\ell} \times \vec{B}. \quad (25)$$

Since the current and the magnetic field are not parallel in this setup, the resultant force displaced the wire from its equilibrium position. Once the pulse ends, the dynamics of the wire's position

Figure 16: Amplitude over time for the SMDT wire tension test. Note the overall damped oscillatory shape of the waveform.



obeys the wave equation with 2 fixed ends. This results in damped oscillations over time back to its equilibrium position. Now, although the magnetic field is static in the lab reference frame, in the reference frame of the oscillating wire, the magnetic field is oscillating over time. Consider Faraday's law:

$$\mathcal{E} = -\frac{d\Phi_B}{dt}, \quad (26)$$

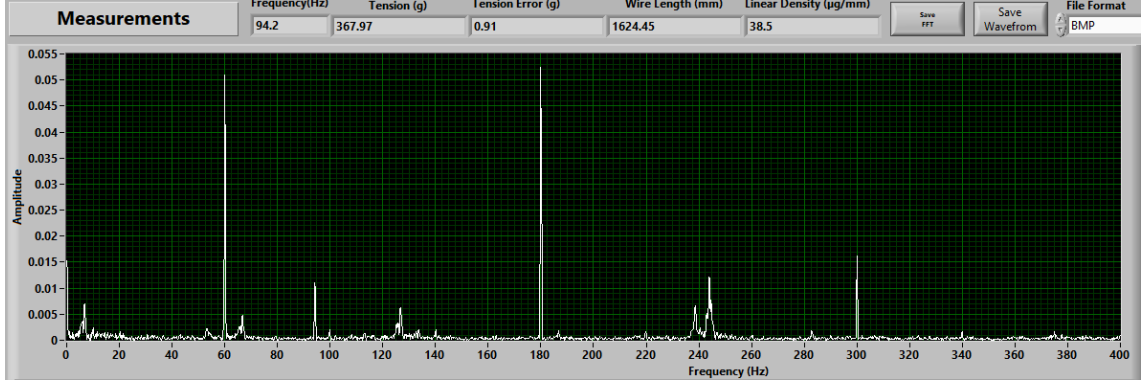
where

$$\Phi_B = \int_S \vec{B}(t) \cdot d\vec{A}. \quad (27)$$

Since there is a time dependent magnetic flux, $\Phi_B = \Phi_B(t)$, there is an induced EMF on the wire and therefore an induced current through the wire. This signal was read out, amplified and further processed. Since the output signal was recorded in the time domain, a FFT was applied to the data to finally determine the frequency of the oscillations. Figures 16 and 17 display the Lab View generated data plots. These highlight key aspects of this methodology. In Figure 16, the overall shape of the wire's amplitude over time displays damped oscillatory behavior, as expected from the explanation above. The FFT of the waveform in Figure 17 displays a multitude of peak frequencies; however, this experiment only considers a subset of the possible frequencies in which the maximum is located. In this example, it was approximately 94Hz.

Once the frequency of the wire undergoing an oscillation is known, the tension in the wire can be calculated. When the wire is displaced from its equilibrium, its equation of motion is *nearly*

Figure 17: FFT of the waveform in Figure 16. The algorithm views a subset of the frequency spectrum and determines the maximum within that range.



determined by the wave equation (in 1 dimension):

$$\frac{\partial^2 \phi}{\partial t^2} = v^2 \frac{\partial^2 \phi}{\partial x^2}, \quad (28)$$

where $\phi = \phi(t, x)$ is the displacement from equilibrium and v is the velocity of the wave and depends on the physical problem at hand. However, this neglects that the wire's displacement is actually damped by gravity and (a very small amount) of air resistance. In order to account for this, equation 28 must include a damping term. The most common model to account for damping is to add a term that opposes the object's velocity [8], similar to when one accounts for air resistance in projectile motion equations. The wave equation that the wire actually obeys is given by:

$$\frac{\partial^2 \phi}{\partial t^2} + k \frac{\partial \phi}{\partial t} = v^2 \frac{\partial^2 \phi}{\partial x^2}, \quad (29)$$

where k is the damping constant for the system with units $[k] = \text{s}^{-1}$. One can go through solving this PDE with separation of variables and obtain the solution (for a 2 fixed end system), up to a choice of initial conditions for the wire [8]:

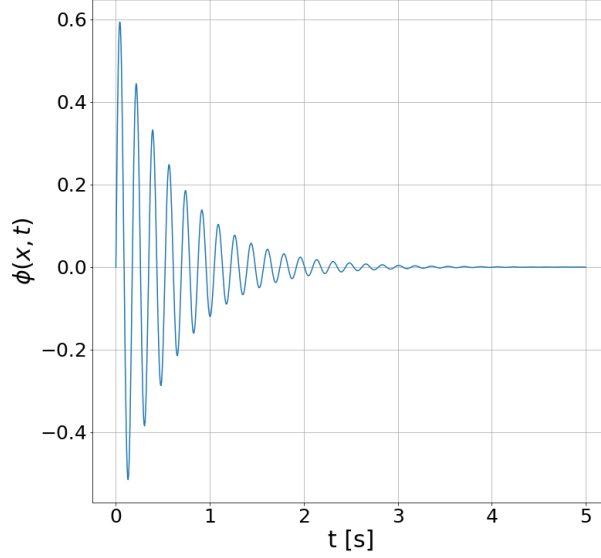
$$\phi(t, x) = \sum_{n=1}^{\infty} \left[c_n \cos(\omega_n t) + d_n \sin(\omega_n t) \right] \sin\left(\frac{n\pi x}{L}\right) e^{-\frac{1}{2}kt}, \quad (30)$$

where

$$\omega_n = \left(\frac{vn\pi}{L} \right)^2 - \frac{k}{2}, \quad (31)$$

and c_n and d_n are constants that can be determined if one knows the initial displacement and velocity of the wire as a function of x . Figure 18 displays an example of such oscillations. Now, 2

Figure 18: Example of damped oscillations according to equation 30.



important conclusions can be made from this analysis for the purposes of the sMDT tension test. First, as seen in equation 29, the velocity of the oscillations has not been changed and is still given by v . Second, based on sinusoidal and exponential decay factors in equation 30, the displacement of the wire indeed obeys damped oscillatory motion as suspected. Recall this suspected behavior was observed in Figure 16 and now it has been proven. Compare Figures 16 and 18 to see the similarities. Note in Figure 16, the tail of the amplitude over time is much larger than the theoretical prediction due to noise being picked up at small amplitudes. Overall, the general wave forms are the same.

Since the velocity of the oscillation has not changed between equations 28 and 29, one can use known results concerning the velocity of an undamped wave. For a wire with 2 fixed ends, the velocity is given by:

$$v = \sqrt{\frac{T}{\rho}}, \quad (32)$$

where T is the tension in the wire and ρ is the linear mass density of the wire. Recall that ρ is known for this test and the frequency of the oscillation was just determined. Exchanging v for $v = \lambda\nu$, where λ and ν are the wavelength and frequency of oscillation, respectively, we have:

$$\lambda\nu = \sqrt{\frac{T}{\rho}}, \quad (33)$$

or

$$T = \rho\lambda^2\nu^2. \quad (34)$$

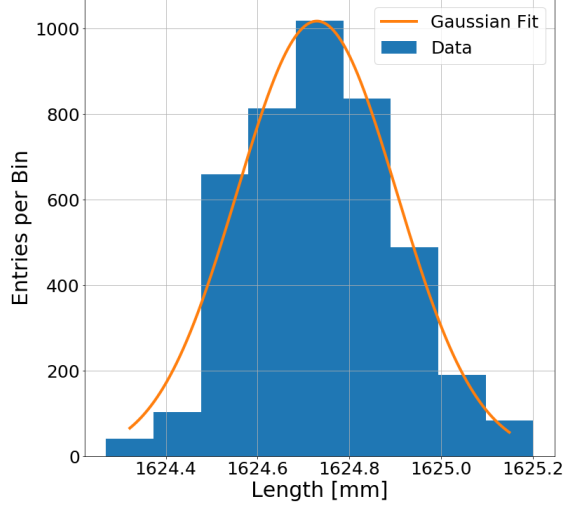


Figure 19: Histogram with Gaussian fit of the length measurements for each sMDT.

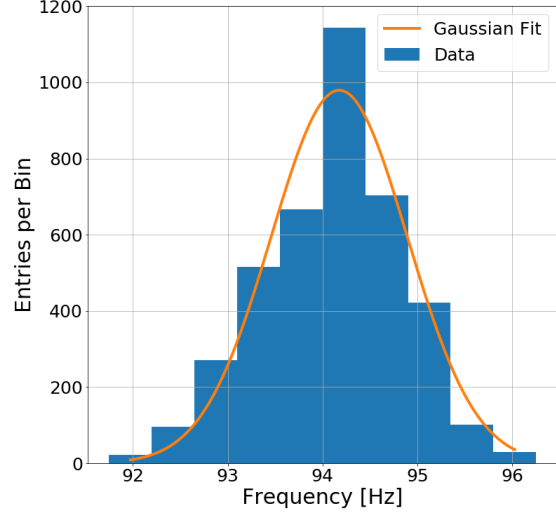


Figure 20: Histogram with Gaussian fit of the frequency measurements for each sMDT.

Fortunately, based on this experimental setup, one does not need to know λ . Since the magnetic field created the initial Lorentz force at the center of the wire, the resulting oscillations can be considered to be (approximately) first order standing waves. In this case, the wavelength is just given by $\lambda = 2L$, where L is the length of the wire that was measured at the start of the test. Putting this all together, one has the following result:

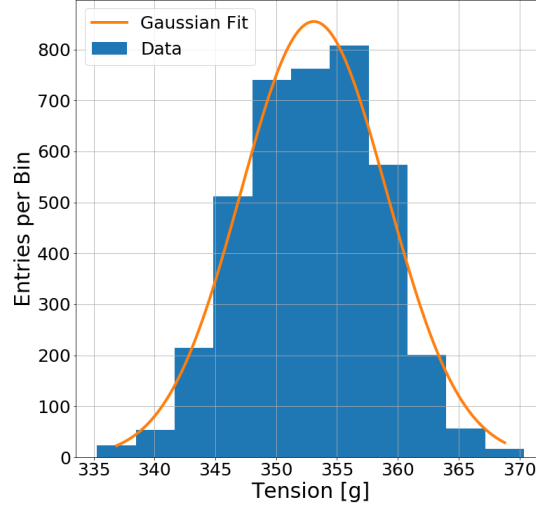
$$T = 4\rho\nu^2 L^2. \quad (35)$$

For the tension test, the Lab View program returns the tension in units of mass instead of units of Newtons, as equation 35 expresses. To account for this, one just needs to divide equation 35 by the acceleration due to gravity, g :

$$T_{[mass]} = \frac{T}{g} = \frac{4\rho\nu^2 L^2}{g}. \quad (36)$$

Now all variables have been measured from this experiment and one can find the tension in the wire. This equation and process is automated in the Lab View program so that one can immediately see the tension after running the test for the frequency and sort sMDTs accordingly.

Figure 21: Histogram with Gaussian fit of the tension measurements for each sMDT.



5.2 Tension Test Results

Figures 19-21 display the histograms with Gaussian fits for the length, frequency and tension that were recorded for the sMDTs. The relevant parameters that were determined for each fit are:

$$\text{Length: } b = (16.5 \pm 2.11)(\text{mm})^{-2}, c = (1624.739 \pm 0.011)\text{mm} \quad (37)$$

$$\text{Frequency: } b = (0.97 \pm 0.17)(\text{Hz})^{-2}, c = (94.18 \pm 0.06)\text{Hz} \quad (38)$$

$$\text{Tension: } b = (0.013 \pm 0.001)\text{g}^{-2}, c = (353.09 \pm 0.30)\text{g}. \quad (39)$$

Using equations 11 and 12, the standard deviation and mean determined by the fitting parameters are:

$$\text{Length: } \mu = (1624.73 \pm 0.01)\text{mm}, \sigma = (0.17 \pm 0.01)\text{mm} \quad (40)$$

$$\text{Frequency: } \mu = (94.2 \pm 0.06)\text{Hz}, \sigma = (0.71 \pm 0.06)\text{Hz} \quad (41)$$

$$\text{Tension: } \mu = (353.09 \pm 0.30)\text{g}, \sigma = (6.02 \pm 0.30)\text{g}. \quad (42)$$

Now, comparing these values to the mean and standard deviation calculated according to the statistical definitions in equations 14 and 15 results in the following:

$$\text{Length: } \mu_{stat} = 1624.74\text{mm}, \sigma_{stat} = 0.167\text{mm} \quad (43)$$

$$\text{Frequency: } \mu_{stat} = 94.08\text{Hz} , \sigma_{stat} = 0.73\text{Hz} \quad (44)$$

$$\text{Tension: } \mu_{stat} = 353.28\text{g} , \sigma_{stat} = 5.72\text{g}. \quad (45)$$

Hence, by comparing the statistical values to the values determined by the fitting parameters, one can see that each statistical value is within the parameter's uncertainty range. Therefore, the Gaussian models found for these histograms are accurate representations of the data. The specification value of the wire tension is set at $(350 \pm 15)\text{g}$ [1]. The lower end of this range presents more issues than being over 365g. Looking at Figure 21, the vast majority of the sMDT wire tensions were within the specification range and therefore could be used in Model Zero.

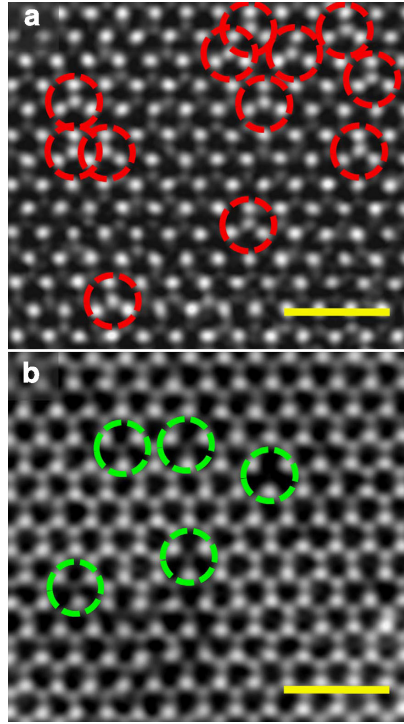
6 Dark Current Test

6.1 Experimental Overview

The MDTs and sMDTs that are used outside of the LHC rely on cosmic ray data to simulate operations. Inside the LHC, they operate based on resultant decay particles from the initial hadronic interaction. In any circuit that relies on an external signal source like MDTs, the dark current of the circuit is a small current that is present even when no particles are interacting with the system. In other words, charge is generated even when no external radiation is entering the detector. Dark current is often generated due to crystallographic defects present in the materials used to construct the circuit. Crystallographic defects are irregularities in expected patterns in crystalline solids. Figure 22 displays an example of what Crystallographic defects look like at the microscopic level [9]. These irregularities lead to additional electrons and holes being formed for current to flow at random [10]. As one can imagine, in nearly pure solids, this dark current is extremely small. This is exactly the case for MDTs. The order of magnitude that the threshold dark current is placed at for an MDT is on the order of nano amps. Thus, accurately measuring such small currents is nontrivial.

2 main methods of measuring the dark current in sMDTs were developed in the University of Michigan ATLAS Electronics Laboratory. In the summer of 2019, a group of researchers, including myself, designed a large printable circuit board (PCB) that would be capable of measuring the dark current in sMDTs, while being compatible with the existing sMDT test stand. The dark current measuring PCBs relied on an amplifier in addition to many resistors and capacitors. The test stand supplied the sMDTs with high voltage and the gas mixture that was needed to simulate operations

Figure 22: Example of Crystallographic Defects. Image a displays unexpected atoms disrupting the regular pattern. Image b displays vacant atoms creating holes in the pattern. The yellow bar represents 1nm of distance.



with cosmic rays. The fully assembled PCB is shown in Figure 23. High voltage wiring was also created that connected the PCBs to end cap electronics and DAQ wiring to collect data using a National Instruments DAQ system and Lab View interface. These PCBs could measure the dark current in up to 3 sMDTs per board. Since up to 48 sMDTs could be placed in the test stand at once, housing for these PCBs was created to organize wiring and ensure there was no improper electrical contact between boards or wires. Figure 24 displays the boards inside the housing, along with the wiring just described above.

There was one clear downside to the existing test stand - it took the average experimenter 30-40 minutes to insert sMDTs into the test stand properly, and a similar amount of time to remove them. With the construction of the Module Zero prototype approaching and the necessity to test thousands of new sMDTs, this was going to cost a lot of time just to get each dark current test running. This issue led to the innovation of the new sMDT test stand that allows users to interchange sMDTs significantly faster and easier. For this, the tubes were inserted into one end of the high voltage connection and then a clamp was used to seal the other end of the tube into the high voltage connection. This made running the dark current tests much faster. Additionally, this dark current test set up allowed for individual sMDTs to be tested over time. The PCB dark current set up

Figure 23: University of Michigan dark current measuring circuit board fully assembled.

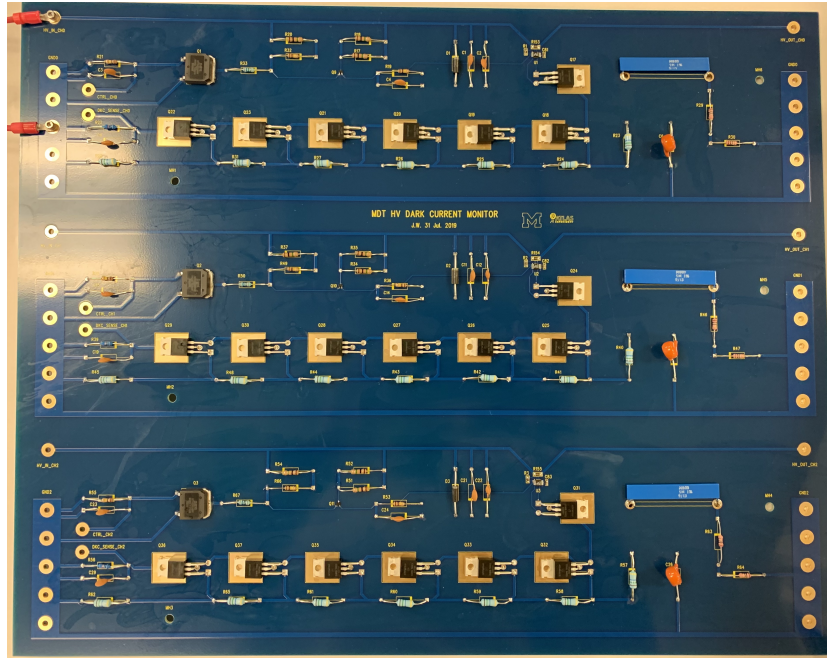


Figure 24: Dark current circuit boards in housing container. On top, the red wires supplied high voltage to the boards to power them. On the bottom, the white wiring led to the DAQ system.

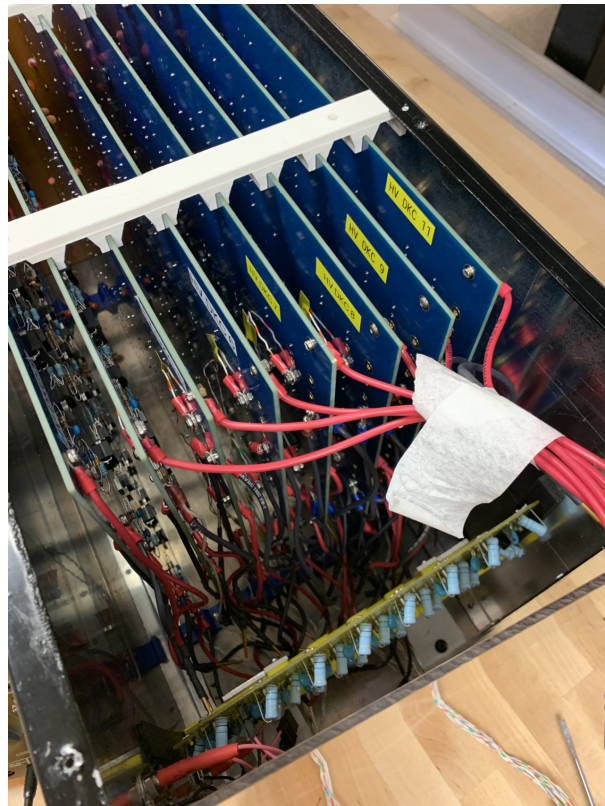
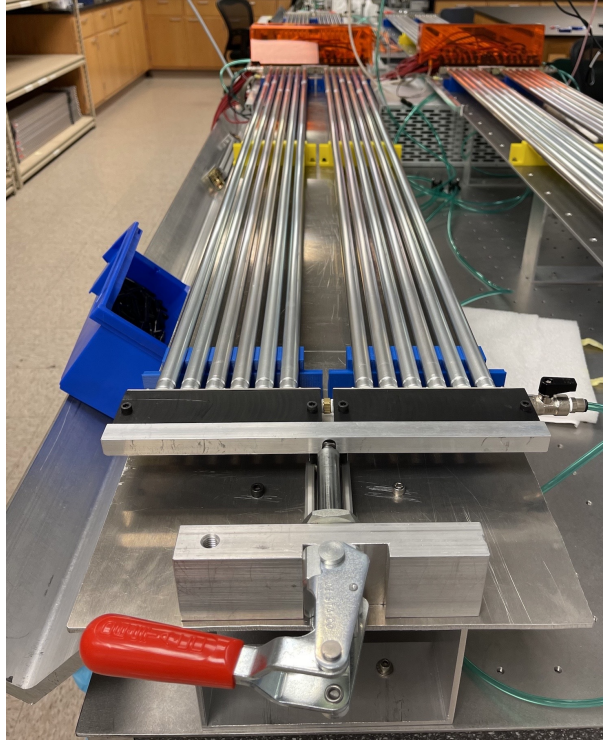


Figure 25: CANE dark current test setup. The red handle controlled the clamping system that would quickly secure sMDTs into the gas distribution system and high voltage connection.



required a full layer's worth of sMDTs to be inserted and tested, due to the way in which the gas was distributed in that system. The initial difficulties with this set up revolved around gas leakage from the sMDTs due to improper sealing from the clamp but this was soon resolved. To measure the dark current from sMDTs in this test station, a CANE power source was used to provide the high voltage while simultaneously recording the dark current present in the sMDTs. Figure 25 displays the clamping system for the CANE dark current test setup.

The current CANE dark current test station has been configured for sMDTs, instead of regular MDTs, tests and was used to examine the new sMDTs that were produced for Module Zero. The PCB dark current test station has now been configured for regular MDTs. Testing of a batch of 48 sMDTs would take hours since the dark current at the beginning of a run was significantly higher than were the dark current value that the sMDT equilibrated to over time. Determining whether or not a new sMDT would pass the dark current test was therefore based on the last dark current value recorded in the test session. Based on that value, tubes were sorted according into OK, WARNING, and BAD groups. OK sMDTs were those with a dark current less than 2nA, WARNING sMDTs were those with a dark current larger than 2nA and BAD sMDTs were those with a significantly larger dark current. Individual sMDT profiles will be shown in the following section.

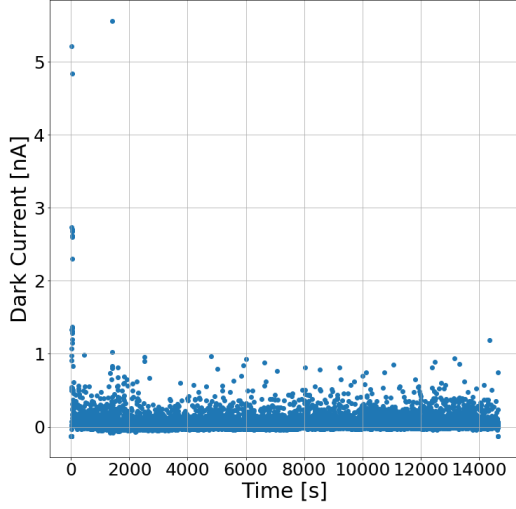


Figure 26: sMDT that displayed a consistently low dark current over time.

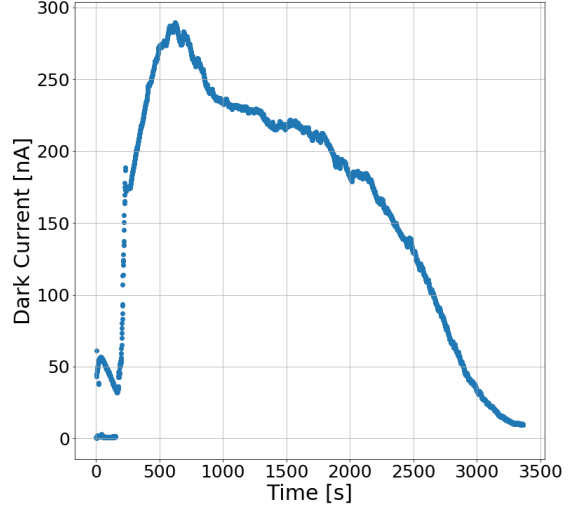


Figure 27: sMDT that displayed a large dark current in the beginning of the test, but then settled into the desired range.

6.2 Dark Current Test Results

There were 3 main types of behavior for the dark current over time for a given sMDT. Figure 26 shows a sMDT that started with a low dark current and maintained this behavior over time. Figure 27 shows a sMDT that began with a high dark current, but over time became well-behaved. Finally, Figure 28 shows a sMDT that displayed erratic behavior throughout the duration of the test. Clearly, sMDTs such as these failed the dark current test, while profiles such as those in Figures 26 and 27 passed the dark current test and were denoted as OK sMDTs. The OK sMDTs were within the specified dark current amount and were therefore able to be used in Module Zero.

Figure 29 displays a summary of the final dark current measurement made on the OK group of sMDTs. This histogram contains data that was cut based on equation 2 and was then fit to a Gaussian curve. Notice that some final dark current measurements on sMDTs were recorded as negative. This is nonphysical since current cannot actually be negative and can be attributed to a current very near zero that was systematically, incorrectly measured by the CANE system.

The relevant parameters that the fitting algorithm determined for the Gaussian curve were:

$$\text{OK sMDTs: } b = (3.80 \pm 0.89)(\text{nA})^{-2}, c = (0.44 \pm 0.04)\text{nA}. \quad (46)$$

Using equation 11 and 12, the mean and standard deviation for OK sMDTs final dark currents based

Figure 28: sMDT that displayed chaotic dark current behaviour throughout the test. sMDTs such as these did not pass the dark current test.

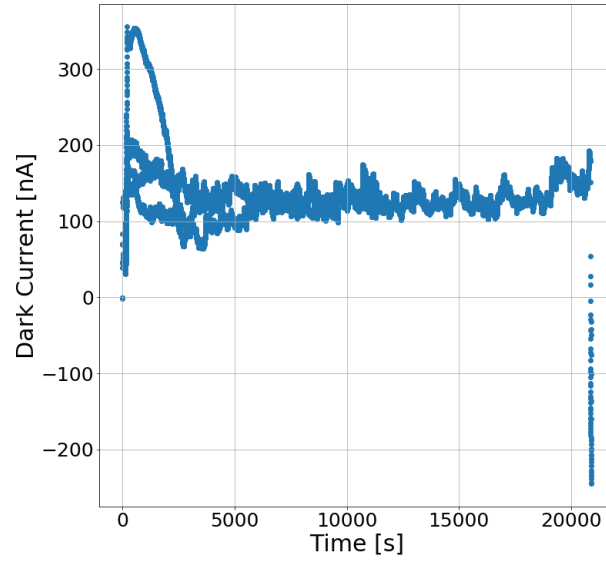
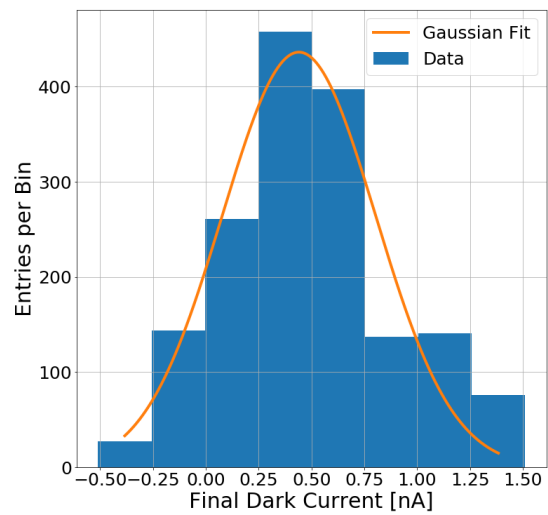


Figure 29: OK sMDT group final measurement dark current histogram fit to a Gaussian curve.



on the fitting parameters are:

$$\text{OK sMDTs: } \mu = (0.46 \pm 0.04)\text{nA} , \sigma = (0.39 \pm 0.04)\text{nA}. \quad (47)$$

In comparison, the statistical mean and standard deviation are:

$$\text{OK sMDTs: } \mu_{stat} = 0.49\text{nA} , \sigma_{stat} = 0.42\text{nA}. \quad (48)$$

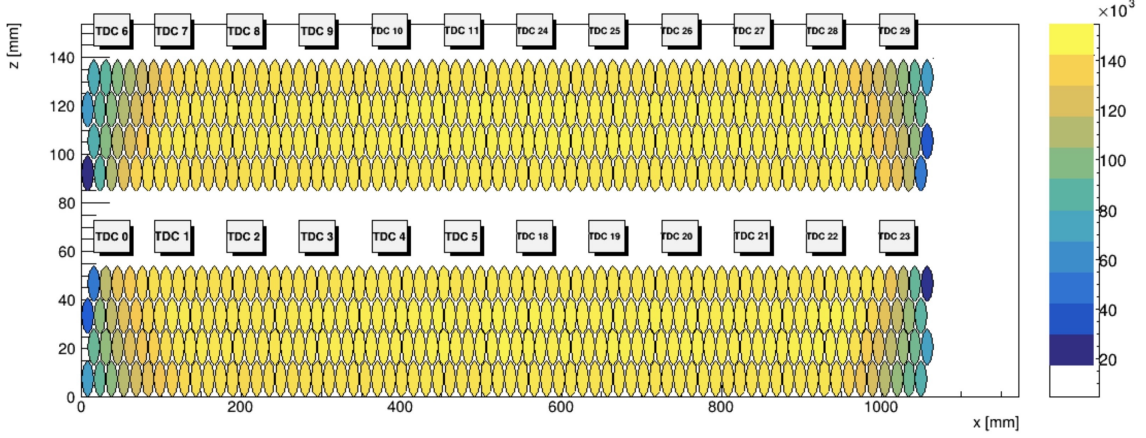
Therefore, each statistical result lies within the uncertainty range of the fitting result. Hence, the Gaussian fit is an accurate representation of the OK sMDTs final dark current measurement. As for the WARNING and BAD sMDTs, there are not enough data points to create an accurate histogram of the results. There were only 3 WARNING sMDTs, with final dark currents of 2.26nA, 2.15nA and 3.24nA. The BAD sMDTs (only 14 tubes) ranged from tens to hundreds of nano amp final dark currents, significantly off of the specification final dark current value. Overall, the majority of newly produced sMDTs were within specification and able to be used in Module Zero.

7 Module Zero Performance

The culmination of all the sMDT design tests is the construction and operation of the Module Zero chamber. Recall that the Module Zero chamber is a prototype of the BIS chamber type. This chamber design consists of 2 multi-layers of sMDTs, each containing 70 tubes across and 4 tubes high, for a total of 560 sMDTs. These tubes were drawn from the sMDTs that performed best throughout all tests summarized in this paper. A database was created to track tubes on an ID basis so that these 560 'best' sMDTs could be selected. Significant time and effort were dedicated to using precision equipment to install and align the sMDTs on the chamber. Before the tubes were installed in the 'comb' that dictated the overall alignment, the comb hole diameter and pitch was measured. Overall, these measurements were in very good agreement with the specification [11]. The combs were then aligned on a granite table and clamped to the table once the optimal alignment was achieved. From there, the first multi-layer of sMDTs was installed, followed by a spacer frame, and then the second multi-layer. To secure all the sMDTs in their desired location, an automated gluing machine was used.

A precision height gauge was used to track the relative heights of the sMDTs upon installation.

Figure 30: Heat map of hits in Module Zero sMDTs that passed clustering.

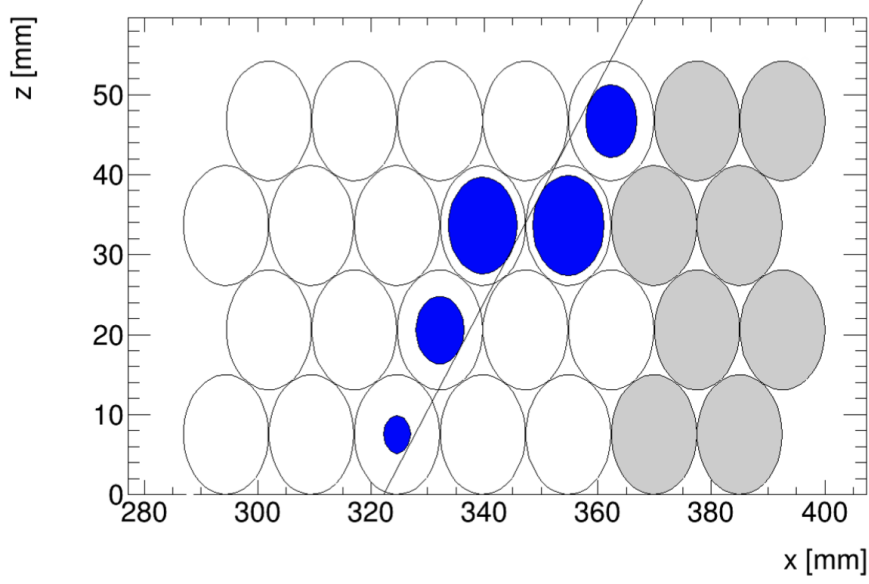


Overall, the relative heights of the sMDTs are in excellent agreement with the specifications. For example, layer 8 on the high voltage side of the chamber experienced a slope in relative height of only $-0.12 \mu\text{m}$ when fit with a linear regression [11]. This reflects a very level layer, which was the case for the entire chamber. Each side of the multi-layers only experienced a standard deviation in the relative height of sMDTs in the range $15\text{-}36 \mu\text{m}$ [11]. Again, these are well within the desired values.

Once the chamber was properly assembled, it is important to ensure the sMDTs are functioning correctly. Figure 30 shows a heat map of hits that ‘passed clustering’ for the Module Zero chamber [12]. Hits that passed clustering triggered the expected number of sMDTs to be used in track reconstruction. Hits that did not pass clustering had too many sMDTs triggered during an event. From Figure 30, it is clear that the majority of sMDTs are homogeneously detecting hits, as expected. One may notice that the sMDTs on the edges of the chamber received less hits than the inner sMDTs of the chamber. This is because sMDTs on the edges are less likely to pass clustering, so those sMDTs are cooler (less filled bins), which is to be expected.

In order to reconstruct the path of a muonic event, the time to radius, rt , function is used. This is a function that correlates the time of a signal to the radius at which it occurred in a sMDT. Therefore, determining the radius at which the event happened in each sMDT allows one to retrace the event. The rt function is parameterized using degree 10 Chebyshev polynomials and optimizing their fitting parameters [12]. Once the rt function is determined, the track reconstruction can take place. Figure 31 shows an example of how this is done based on different radii for each sMDT. In this case, in the absence of a magnetic field, the path is expected to be straight, as demonstrated by Figure 31 [12]. Overall, after further corrections to path reconstruction (time slewing corrections)

Figure 31: Muon track reconstruction from the Module Zero prototype. The muon path is straight here due to the absence of external magnetic fields.



the resolution of the Module Zero chamber is $89.3 \pm 8.3 \mu\text{m}$ [12]. The specification resolution is set at $106 \mu\text{m}$, so the resolution of Module Zero is well within this specification [1]. Recall that for a muon with transverse momentum of $p_T = 1\text{TeV}$ in the presence of the LHC magnetic field, the sagitta of its path is on average $500\mu\text{m}$. Therefore, the Module Zero chamber would be able to accurately resolve muonic events at the LHC. The success of this prototype shows the capability of the University of Michigan ATLAS group to construct the future BIS and similar style chambers for the Phase II upgrade.

Many factors are attributed to the success of this chamber overall. Of those factors, ensuring that the best possible SMDTs were used cannot be neglected. The bending and end plug testing of SMDTs aided the successful construction of the chamber. Measuring the tension and dark current of the wires allowed for highly functioning SMDTs to fill the chamber.

8 Acknowledgements

Foremost, I would like to thank my adviser Professor Bing Zhou for my first opportunity to work in the ATLAS electronics laboratory 2 years ago and for guiding this thesis. I have learned many lessons over the past 2 years, many of which I know I will retain moving forward. I would also like to thank Dr. Edward Diehl for introducing me to the ATLAS group and teaching a significant amount

about how the Muon Spectrometer and the LHC work. Last but certainly not least, I would like to thank Professor Thomas Schwarz for his continued guidance during my undergraduate career.

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