Construction and testing of sMDT tubes at the University of Michigan for the ATLAS Muon Spectrometer upgrade

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ABSTRACT:

This paper reports on the design and construction of infrastructure and test stations for small-diameter monitored drift tube (sMDT) assembly and testing at the University of Michigan (UM) to prepare for the ATLAS Muon Spectrometer upgrade for the high-luminosity program of the Large Hadron Collider. Procedures of the tube assembly and quality assurance and control (QA/QC) tests are described in detail. More than 99% of the tubes meet the tube QA/QC specifications based on 2100 tubes built at UM. The UM test stations are also used for QA/QC testing on the tubes constructed at Michigan State University. These tubes are being used to construct the sMDT chambers which will replace the current MDT chambers of the barrel inner station of the Muon Spectrometer.
1 Introduction

The ATLAS Muon Spectrometer will receive a major upgrade in the next long shutdown (LS3) of the Large Hadron Collider (LHC) to cope with the much higher interaction rate of the High-Luminosity LHC (HL-LHC) [1]. The central (barrel) region inner station of the Monitored Drift Tube (MDT) chambers will be replaced by new chambers using small-diameter MDT (sMDT) tubes of 15 mm diameter, half that of the previous MDT. The smaller tube radius reduces both the maximum drift time (from 750 ns down to 180 ns) and the tube cross-section which lowers the tube occupancy by a factor 8 for improved performance in the HL-LHC. Furthermore the smaller volume of the sMDT detector makes space for the installation of a new trigger tRPC (thin resistive plate chamber) detectors to improve the Level-1 muon trigger efficiency in the HL-LHC environment.
A total of 96 new sMDT chambers will be built to replace the Muon Spectrometer BIS1 to BIS6 MDT chambers, where BIS stands for Barrel-Inner-Small (sectors). Half of these will be constructed at the Max Planck Institute for Physics in Munich (MPI), Germany, and the other half in the US at the University of Michigan (UM) and at Michigan State University (MSU). The sMDT drift tube design and parameters are described in detail in [2]. Table 1 lists the major tube parameters.

| Parameter         | sMDT                          |
|-------------------|-------------------------------|
| Tube material     | Aluminium AW6060-T6/AlMgSi    |
| Tube surface      | Surtec 650 chromatization     |
| Tube outer diameter | 15.000 mm                     |
| Tube wall thickness | 0.4 mm                        |
| Tube length       | 1615 mm                       |
| Tube straightness | 0.5 mm / tube                 |
| Wire material     | W-Re (97:3)                   |
| Wire diameter     | 50 $\mu$m                     |
| Wire resistance   | 44 $\Omega$/m                 |
| Wire tension      | 350 ± 15 g                    |
| Gas mixture       | Ar:CO2 (93:7)                 |
| Gas pressure      | 3 bar (abs.)                  |
| Gas leak rate limit | $< 1 \times 10^{-8}$ mbar $\times$ cm$^3$ per tube |
| Gas gain          | $2 \times 10^4$               |
| Wire potential   | 2730 V                        |

**Table 1**: sMDT tube materials and operating parameters

The endplugs (Figure 1) consist of a precision brass wire locator, called a twister, inside a central brass insert (both manufactured by Pöschl) which is molded into a PBTP plastic body manufactured by the Institute for High-Energy Physics (IHEP) at the Kurchatov Institute in Protvino, Russia. IHEP also makes the crimp tubes and stoppers (which lock the locators in the endplugs). Two grooves on the plastic outer surface hold o-rings which make a gas tight seal between the endplug and the tube inner wall.

26000 precision tubes are needed for the Michigan chamber production. MSU is responsible for tube assembly and initial Quality Assurance (QA) tests after which tubes are delivered to UM. Tubes are tested again at UM to verify all specifications are met before chamber assembly.

Early in the R&D period for sMDT construction tooling and the production cycle UM also built and tested 2600 tubes, 500 for R&D in 2018 and 2105 for chamber mass production during the summer of 2021. With three students working 8 hours per day, a production rate of 50 tubes/day was reached consistently in summer 2021, including all the QA tests on the constructed tubes.

This document describes the infrastructure and tooling used in building tubes at UM, and the methods used to assess the quality of all tubes used in sMDT chamber production at Michigan.

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1Pöschl Präzisionsteile GmbH, [https://www.poeschl-gmbh.eu/home.html](https://www.poeschl-gmbh.eu/home.html), Industriestr. 10, 82110 Germering Germany, Tel. 089/894454-0, Fax 089/89445444
Figure 1: (a) Tube design, with an exploded view of the end-plug components [2]. (b) The components and assembly of an endplug. All dimensions are in mm.

2 Infrastructure

The ATLAS “tube room“ is a 12 × 8 m² lab space dedicated to drift tube assembly and QA testing. It is organized into multiple work stations for the construction and testing of sMDT tubes. Figure 2(a) and (b) show the tube construction station and the dark current test station in the tube
room, respectively. Each station is set up on a $3.66 \times 1.22 \, m^2$ flat optical table. Once a tube is assembled, its straightness, gas tightness, length, wire tension, and dark current are measured. In addition, a large storage structure accommodating up to 3,000 tubes was built to handle the logistics for chamber mass production. Table 2 lists the UM tube room work stations. These stations are arranged so that all of them can be operated at the same time, optimizing the tube construction and test efficiencies.

| Station name in the tube room                  | Purpose   | Tubes per station |
|-----------------------------------------------|-----------|-------------------|
| Wire stringing and tensioning                 | construction | single           |
| Swaging endplug onto tube                    | construction | single           |
| Length and tension measurement               | QA        | single            |
| Straightness measurement                     | QA        | single            |
| Gas leak at 3 barA measurement               | QA        | single            |
| Dark current measurement                     | QA        | 48                |
| Reverse HV treatment                         | QA        | 48                |

Table 2: UM tube room stations.

Lab cleaning is performed twice a day to maintain a pristine environment. Personal protection equipment (lab-coat, shoe covers, hair nets, gloves and disposable masks) are easily accessible immediately upon entry and are required at all times, with the exception of the gloves which are used only when handling tubes.

3 Tube Construction

The tube construction infrastructure and test stations were designed and built at UM during the R&D phase (2018-2020) of the ATLAS muon detector upgrade project. Using raw tubes from the manufacturer Mifa Alumninum\(^2\) 500 drift tubes were constructed and tested to commission and verify the infrastructure and tooling. These tubes were used to build an sMDT prototype chamber at UM to demonstrate the tube construction and test procedures. Michigan sMDT chamber mass production started in May 2021. Knowledge and technologies for tube production and testing were shared with MSU for tube mass production. One batch of 2105 sMDT tubes was built at the UM site in the summer of 2021 to supplement the tube construction effort at MSU to assure that the early sMDT chamber production schedule at UM could be met.

The tube construction process involves three main steps: preparation of raw aluminum tubes; tube assembly; and quality assurance tests of each constructed tube. This section will focus on the construction process carried out at the UM site.

3.1 Tube straightness measurement

Mifa supplied all raw sMDT tubes for both MPI and Michigan, delivered in crates of 702 tubes each. Michigan’s tubes were sent by truck to CERN and then by air freight to Michigan. All incoming tubes were inspected at CERN and at UM before tube construction.

\(^2\)Mifa Alumninum, Rijnaakkade 6, 5928 PT Venlo, E, The Netherlands: https://mifa.eu/en, info@mifa.nl, T: +31 77 389 88 88, F: +31 77 389 89 89
One requirement is the tube straightness: the specification calls for no more than 0.5 mm deviation when a tube is resting on a flat surface. However, nearly 20% of early tube shipments exceeded this specification. To measure tube straightness a system with an optical technique using a microscope was developed. The system consists of a straight V-shape bar that has a flat surface (flatness < 0.05 mm) with straight backstop to keep the center-line of the tube at the focal point of the microscope. The microscope looks at the the center bottom of the tube where it should touch the flat surface. The tube is rotated in the V bar to allow measurement of the maximum distance between the tube and the surface. The microscope has a built-in screen which is set to 20X magnification (see picture on Figure 3 (a)). This technique assumes that the greatest out-of-straightness deviation (referred to as sagitta) will be at the center along the tube length. Plots in Figure 3 (b) and (c) show the fraction of tubes accepted in two lots as a function of the cut used to reject bent tubes. About 87% of the tubes met the specification of the tube straightness requirement. Based on these measurements it was decided to relax the original cutoff specification and to only reject tubes with more than 0.8 mm sagitta, about 6% of those delivered in 2020 and 2021. The rejected tubes (slightly over 1,000) were sent back to the manufacturer for straightening treatment and returned to Michigan at the end of 2021. Three identical optical measurement devices were built at UM and sent to the tube production company (MIFA in Netherlands), CERN, and MSU. This test is now a routine check of the tube mass production. After using the UM measurement technique the company adopted a stricter QA/QC protocol which reduced the fraction of bent tubes delivered to about 2%.

3.2 Aluminum tube and endplug preparation

Although tubes are cleaned at the factory, it was found that additional cleaning reduced the dark current drawn by tubes. In the initial stage of R&D tube production ~12% of tubes exceeded the dark current limit. To reduce this high dark current failure rate the 2105 aluminum tubes used for summer 2021 tube production at UM were each re-cleaned by swabbing the interior with isopropyl alcohol (IPA) soaked wipes prior to the tube construction. The interior of each tube was swept three times with fresh lint-free wipes wrapped around a small cylindrical piece of foam and soaked in IPA for each sweep. This cleaning plug fit snugly inside the tube and was pushed through the tube with a clean acrylic rod to ensure the entire length of the interior was wiped clean. The exterior
was also cleaned with IPA-soaked lint-free wipes. The cleaned tubes were stacked on foam saddles from the original packaging and the ends were lightly covered with lint-free wipes to allow the IPA to evaporate completely. After all tubes were cleaned, the two ends of each tube were temporarily closed with clean rubber caps to keep the interior free of dust. The thoroughly cleaned tubes had a failure rate of only ~3% in the dark current test, significantly lower than that observed in early tube tests. In addition, it was found that negative HV treatment, described in Section 4.4.3, could recover any tubes failing the initial dark current test.

The endplug is assembled with two o-rings, a twister, and a stopper (see Figure 1 (b)). Individual parts were given a 15 minute ultrasonic bath in IPA before assembly and a further 5 minute ultrasonic bath after assembly. After air drying the endplug assemblies were stored in clean plastic packaging until used.

3.3 Tube assembly

This section describes the tube construction stations for tube wiring and swaging, and the tube assembly procedures.

3.3.1 Wiring station

The tooling for wire stringing consists of two vacuum chucks that hold the tube rigidly in a straight line and aligned with the wire feed. Each chuck is fitted with a pneumatically controlled end-plate on which is mounted a pair of cam-operated crimp jaws (Figure 4a) which squeeze the 1.0 mm O.D. crimp pin down to 0.7 mm. The spool of wire is mounted on a magnetically damped spindle to allow smooth pulling. At the other end is a three wheel tension meter and a linear actuator for stretching the wire to the desired tension (Figure 4b).

![Figure 4](a) Wire crimp jaw. (b) The wire pulling actuator and tension meter used to stretch the wire before crimping.

3.3.2 Swaging station

The second station used in tube construction is the swaging station (Figure 5), where the thin walls of the tube are deformed (swaged) to compress and seal against the o-rings on the endplugs. The swaging head is a custom built rotary device that gradually forces 3 roller heads radially inward.

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3Luma Metall Fine Wire, Kalmar, Sweden
4Warner Electric Precision Tork MC2, 1-20 oz-in torque
5Electromatic Equipment Co., Tension Sensor model TE-500-22
6Parker Linear Motion Drive Model No. ETS32-802QA21-GK200-A
as they are rotated around the tube (Figure 5a). The head, designed at MPI and built at MSU, is driven by an Isel rotary motor \(^7\). Figure 5b shows the side view of tube swaging set up, including a structure to hold the tube when inserting it into a rotational head.

![Swaging rotational head](image1.png) ![Side view of swaging set up](image2.png)

**Figure 5**: The rotary swaging head for creating indents around the tube at the o-ring locations

### 3.3.3 Assembly procedure

The tube construction process starts by placing an aluminum tube on the vacuum chuck to hold the tube securely. The tube interior is vacuumed to remove any residual dust. The 50 µm tungsten-rhenium wire is secured to a shuttle which is carefully pulled through the tube using a gentle vacuum. The wire is drawn over pulleys which prevent the wire from contacting the tube wall. A magnetic brake controls the un-spooling wire to prevent tangles while wiring the tube. The wire is then cut, leaving 0.5 m excess wire at each end. The wire ends are threaded through endplugs at each end of the tube and then the endplugs are inserted into the tube ends until seated. Next, crimp pins are threaded onto each wire end and inserted into the endplugs. One end of the wire is then secured to a stationary clamp. The other end is fed through the tension monitor, stretched by hand to around 200 g and then secured to another clamp attached to the actuator (Figure 4b). The fixed-end crimp pin (soft copper, 1 mm OD) is crimped (pinched by jaws to 0.7 mm, see Figure 4a).

An online control program based on LabView [3] moves the actuator and monitors the wire tension while the wire is gradually pulled until the tension reaches 400 g. This tension is held for 30 seconds, and then the tension is slowly reduced to 325 g. Note that later in the process the tube swaging will increase the wire tension to 350 g. The second crimp pin is pushed with tweezers into the endplug until it touches the brass core to insure the tension is not altered by the movement of the crimp pin. The crimped thickness of each crimp pin is measured to ensure that it is no more than 0.71 mm which is the value needed to hold the wire securely. Excess wire protruding from the crimp-pins is cut off leaving a stub of about 2 mm.

After the tube is wired, the wire tension is measured in the tension test station (details in Section 4.3) to verify the tension value as set. At this point, a tube with an insufficient wire tension can easily be disassembled and all components, except the wire and crimp-pins, can be salvaged for another construction attempt.

\(^7\)Isel Model Drehachse ZD 30, Belt drive with stepper motor, Model No. ETS32-802QA21-GK200-A
Each end of the wired tube is then mechanically deformed in the swaging station to lock the endplugs in place and produce a tight o-ring seal between the plastic endplug and the interior wall of the tube. This is done with the rotating set of three rounded rollers that create smooth indents around the circumference of the tube at each of the two o-ring locations (Figure 5a). The innermost indent is made such that the width of the tube in the groove measures 13.7 mm or less. This swaging process introduces an additional 25 g of tension in the wire due to the slight stretching of the tube. After swaging a final tension test is done to confirm that the wire inside the constructed tube has a tension of $350 \pm 20$ g. Once the two endplugs are swaged the tube construction is done and a bar code sticker is put on the tube with a unique serial number for identification.

4 Quality Control

Both individual parts and assembled tubes must pass a number of quality checks. Random checks of the endcap brass precision brass surface are done on each batch received to ensure the diameter is within the specification of $5.000^{+0.00}_{-0.01}$ mm. Tube roundness and diameter are verified with the precision endplugs to be well within tolerances. The straightness was discussed in section 3.1.

The QA tests on all constructed tubes, whether built at MSU or UM, include components visual inspection, tube straightness, leak tightness, assembled tube length, wire tension, and dark current. The detailed procedures and test results are described in the following sections.

4.1 Tube visual inspection

Constructed tubes are first given an visual inspection to check for defects such as dents or cracks in the tube wall, badly swaged endplugs, or severely bent crimp pins. Bent crimp pins are carefully straightened. Tubes with unrecoverable problems are rejected and flagged in the database.

4.2 Tube leak tightness test

The constructed tube is required to be leak tight with an upper limit of $1 \times 10^{-8}$ cm$^3$ × mbar/s with the tube at 3 bar (absolute) pressure. As shown in Figure 6(a), the leak rate test is performed with a helium leak detector connected to a vacuum vessel 25 mm ID × 1.8 m long. One end of the tube being tested is sealed with a brass cap and an o-ring (as shown in Figure 6(b), the other is screwed into the cap of the vacuum vessel, which allows the tube to be pressurized with 3 bar Helium (see Figure 6(c)). O-ring seals are lubricated with IPA to prevent twisted o-rings. IPA is used as a lubricant since it completely evaporates and leaves no residue that might contaminate the drift gas. The tube is inserted into the vessel, the end flange is sealed, and the leak detector set to pump out the vessel. When the background He level reads about $1 \times 10^{-6}$ cm$^3$ × mbar/s the tube is filled with Helium gas to a pressure of 3 bar A. Leaks can be found within 30 seconds of pump-out. When this test is completed the Helium is vented through a snorkel to the outdoors.

The goal of this test step is to establish the tightness of the seal. No data was stored for this test, only pass/fail. All the tubes built at UM passed the ATLAS gas tightness requirement.

4.3 Tube length and wire tension measurements

The tube length and the wire tension are measured using the station shown in Figure 7. A tube is placed in the V-shaped aluminum bar with its midpoint inside a U-shape magnet, and a linear
Figure 6: (a) Set up of the tube leak test station. (b) Interior end of the tube is sealed with this brass piece. (c) Feed-through end of the vacuum vessel with a tube connected. Most of the tube is inside the vacuum vessel. The tube is pressurized with Helium to 3 barA.

digital scale \(^8\) is used for the length measurement. Before any session of measurements, the digital linear gauge (precise to \(\pm 10 \, \mu m\)) is calibrated with an aluminum rod of length 1624.5 \(\pm 0.1\) mm. Then a tube is placed into a V-shaped bar with the two ends resting in 3D printed saddles (in blue in Figure 7) so that one end can be pressed against a stopper. The operator makes sure that a good electrical contact is made at both extremities (tube grounded and wire connected the electrical circuit). The digital scale head is brought into contact with the endplug of the tube and the length of the (fully assembled) tube is recorded. The measured length distribution of the tubes built at UM is shown in Figure 8. A maximum difference in tube length slightly larger than 1 mm is observed. None of the tubes built at UM were rejected due the length being out of specification.

Wire tension is then measured using the same set up with the following procedure. The aluminum tube is tied to the ground on the V-shaped bar and the wire is connected to the custom multiplexing circuit shown in Figure 9. The circuit consists of an analog multiplexer, signal generator, instrumentation amplifier, and the sMDT itself. The role of the multiplexing circuit is to trigger wire vibrations in the sMDT by directing pulses from the signal generator to the sMDT and then to send the signal from the discharging sMDT to the instrumentation amplifier. The

\(^{8}\text{Mitutoyo ABSOLUTE Digimatic Scale Units Series 572, https://www.mitutoyo.com/webfoo/wp-content/uploads/E316-572R_ABS_Digi_ScaleUnits.pdf}\)
Figure 8: Distribution of the measured length of the tubes built at UM.

An instrumentation amplifier is connected to a data acquisition (DAQ) system which consists of an multipurpose I/O device (NI USB-6008) interfaced to a computer. A software program with a graphic user interface was developed to allow setting of wire tension measurement parameters, such as the measured tube length, and to perform real time analysis and measurements.

Figure 9: Circuit for wire tension test.

After the external pulse is stopped the wire oscillates at its natural frequencies (see eq. 4.1 from [4]):

\[ f_n = \frac{n}{2L} \sqrt{\frac{T}{\rho}}, \]  

that converted to the tension expressed in grams is \( T = \pi L^2 d^2 f_n^2 \rho / g \). With the nominal sMDT wire parameters \( L = 1597 \text{ mm} \), \( d = 50 \mu\text{m} \), \( \rho = 19.7 \text{ g/cm}^3 \) and \( g = 9.81 \text{ m/s}^2 \), the first resonant frequency of 93.3 Hz corresponds to a tension of 350 g. The frequency is measured with a custom

\*National Instruments USB-6008 Multifunction I/O Device, https://www.ni.com/en-us/support/model.usb-6008.html
LabView program which uses a fast Fourier transform (FFT) to find the first resonant frequency and thus the wire tension.

In order to have a standard definition of tension and compare the results measured at UM with those measured by MSU during the tube construction, the value quoted uses the nominal (fixed) length of 1597 mm, so that only the frequency \( f_1 \) is a measured parameter.

A second tension measurement is made at least two weeks after the first measurement to check for any significant drop in tension. If a drop larger than 18 g in 2 weeks is found, the tube is rejected.

The results of the wire tension measurements for tubes made at UM are shown in Figure 10. A total of 2 tubes out of the 2105 built (0.09%) did not pass the tension tests.

![Figure 10](image)

**Figure 10:** (a) Tube wire tension, and (b) tension drop after at least 2 weeks.

### 4.4 Dark current measurement

The tube, at 3 atmospheres absolute pressure of the working gas mixture, Ar:CO\(_2\) (93:7), operated at 2800 volts and must draw less than 2 nA of dark current. The high voltage (HV) test set up (shown in Fig. 11) and procedure are described in this section.

#### 4.4.1 HV test station

The HV test station at UM holds 4 groups of 12 tubes. Tubes are inserted into 4 sets of gas-manifold blocks to pressurize them. The gas-manifold blocks, machined from acetal plastic (polyoxymethylene POM), allow 12 tubes to be plugged in with a simple push of a handle to make the tube mounting process simple and quick. The 5 mm cylindrical precision brass part of the endplugs of the 12 tubes are inserted into thick o-rings which are built inside the gas-manifold to make a gas-tight seal. The design drawing of the set up is shown in Figure 12.

The input gas pressure is regulated to 3 barA and fanned out to the 4 gas distribution blocks, each with its own input and output shut off valves. The output of the 4 blocks is fanned into a single flow meter and a bubbler. Initially the flow is set high (3 SCFH) for an hour to flush at least 3 volumes through the tubes. It is then turned down to a few bubbles per second (flowing around one gas volume per day) for testing.
4.4.2 Power supply system

The power supply system consists of a CAEN SY5527 mainframe which hosts two 24-channel AG7326 HV modules, able to deliver up to 3.5 kV per channel with 500 pA resolution for current measurements, with GECO (GEneral COntrol) monitoring and data acquisition software. Two places along the tubes are held rigidly to make good contact with a grounding strip. One of the two end manifolds is fitted with spring-loaded contacts for applying high voltage to the wire. The spring contacts are hard-wired to HV cables plugged into 48 individual channels of two modules of the CAEN HV power supply. For a correct dark current measurement, the pedestal current level for each channel must be subtracted from the current measurement. The pedestals are found by turning on the high voltage with no tubes connected and measuring the average current on each channel for a period of one hour. The pedestals are stable except if the humidity becomes too high and must be re-calibrated if the relative humidity exceeds 50%.

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Figure 11: Test Stand with 48 tubes with the CAEN SY5527 mainframe, with the CAEN GECO monitoring program running in the connected computer.

Figure 12: Tube mounting diagram for dark current test station

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[10] Universal Multi-channel Power Supply System with 4 Channel 3.5 kV, 1.5/0.15 mA (4W) Common Ground Dual Range Boards, https://www.caen.it/products/sy5527/
4.4.3 Dark current measurement

To measure the dark current the tubes are placed in the gas manifolds and the voltage is ramped up to +2,900 V and dark current readings are recorded for at least 4 hours. If the average current over the last hour of the test is below 2 nA, the tube passes the test. Some tubes show dark current above the limit in the first hours after the HV was turned on, very often with a decreasing trend as shown in Figure 13 (a), but sometimes the dark current increases in time leading to a tube failing the test (see Figure 13 (b)). Dark current are retested for all tubes received from MSU to insure they are fully burned-in before being used in chamber construction.

![Figure 13](a) Example of a tube recovered from initial high dark current, and (b) one that instead developed higher and higher dark current in time. Note the different scales.

4.4.4 Tube burn-in with negative HV

Tubes that failed the dark current test are treated with negative HV (-3 kV for 30–60 minutes) on a separate test station, and then reassessed via the standard HV test. If the tube fails again, then treatment with negative HV is repeated. All tubes with high dark current have responded to this treatment so that not a single tube had to be rejected in the dark current test and treatment procedure.

In the 2105 tubes built at UM in the summer of 2021, a total of 67 tubes (3.2%) were initially measured to have dark current above 2 nA. All of them were recovered with either longer HV burn-in time or via the negative HV treatment. Figure 14 (a) and (b) show the measured dark current distributions of the UM built tubes, and the tube burn-in time distributions, respectively.
Figure 14: (a) Distribution of the measured final tube dark current, and (b) the burn-in time (right), where the three spikes corresponds to the most common test lengths: day time (just a few hours), overnight (typically about 15-16 hours) and over the weekend (normally around 64 hours).

5 Tube Production Database

All the information gathered in tube production and testing is recorded into a local database (DB) for production QA/QC monitoring, and a subset of the data is uploaded to a master chamber production DB encompassing both US and German chambers. UM receives the QA measurements for the tubes delivered by MSU, used in part as a first data-point in the history of the tubes tests at UM, and the UM results are shared back with MSU for cross-checks and validation. All the test results from the UM test stations are saved in text files, with a format that can be read by different databases (MS Access, MySQL, Oracle, Jason, etc). The most natural choice is a relational database, since all information to be saved is relative to many single tubes, each one with a history of production and test results. In the tube DBs the barcode serial number is used as the primary key for retrieving information. The barcode is also the link between the entries of the tubes layout in a sMDT chamber and the associated test results.

ROOT [5], an analysis framework used commonly in high energy physics, is chosen locally to store, retrieve, and quickly plot the distributions of the test results. A few C++ classes have been developed to read the station measurement results and convert them into a set of text files for each tube. At the end of the process all the test conditions and data relative to a tube are saved into a "TTree" of the ROOT file with an entry for each tube. To ease access to tube test data, separate "TTrees" have been created for each station. In addition, there is a "master" tree with all the tube test information.

While filling the "TTree", a set of standard plots for each test is automatically saved and a local web page is automatically created to show the results history of all tests.

Eventually, all the production and test information are uploaded to the CERN sMDT production database which records information for all of the detectors to be installed in the ATLAS experiment.
6 Conclusions

Fully functional stations for sMDT tube production and testing were designed, built, and successfully used at the University of Michigan for the ATLAS HL-LHC muon detector upgrade project. A total of 2105 tubes were built at UM and tested for sMDT chamber production. The rejection rate of the UM constructed tubes is below 0.1% from the QA tests. In addition, over 14,000 tubes built at MSU have been fully tested at UM.

Tubes passing all tests have been used to construct 30 sMDT chambers so far out of the 50 of the whole production task. All the chambers meet the stringent precision and performance requirements, which will be reported in a separate paper.

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