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the degree of Doctorate of Philosophy in Particle Physics

The Design, Construction and Testing of the Straw Tracking Detectors
for the E989 Muon g-2 Experiment at Fermilab.

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Abstract

The requirement of science, to stretch the boundaries and our understanding of the standard model, is the driving force for the continuous development of our knowledge of the building blocks of the Universe. Experiments are designed, built and tested to support the theories of the mathematicians of the physics community and the theorists help interpret the experimental results, looking for avenues of new physics. However, as is known in both science and human nature, nothing is ever perfect - there is always room for improvement.

The E989 Muon $g$-2 Collaboration experiment at Fermi National Accelerator Laboratory (otherwise known as Fermilab), aims to quantify the muon anomalous magnetic moment to unprecedented precision and looks to increase the accuracy of the measurement by fourfold of the predecessor experiment - E821 at Brookhaven. The discrepancy between the theoretical prediction of the anomalous magnetic moment of the muon and the experimental results, has given tantalising indication of new physics, prompting an “upgrade” for systematic accuracy on the E821.

The particular focus of this thesis details the design, construction and quality testing of the straw tracking modules for the E989 experiment. The author was one of the dedicated technicians who built and tested the tracker modules at the University of Liverpool High Energy Physics (HEP) department, she built and quality tested the modules, wrote the procedural document for the build and subsequently was involved in the Run I startup, shut down and data taking shifts (for Run I and Run II) which contributed to the recent release of the first unblinded data.
Declaration

I declare that this report was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

Figure 1: Kayleigh Thomson at 9 years old, polishing a mirror for a 20" Dobsonian Telescope - the beginning of a physics career.
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Figure 2: David Thomson with the TROK 30” Dobsonian Telescope, built at the Thomson Residence.
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Figure 3: Left to right - Jake Jackson, Dr. Barry King, Kayleigh Thomson, Dr. Saskia Charity
and Dr. Will Turner whilst on tour at Fermilab with Dr. Brendan Casey - Barry and some of his
students.
“The more we learn about the world, and the deeper our learning, the more conscious, specific, and articulate will be our knowledge of what we do not know; our knowledge of our ignorance. For this indeed, is the main source of our ignorance - the fact that our knowledge can be only finite, while our ignorance must necessarily be infinite.”

- Karl Popper
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Author note

In May 2015 I was employed by the University of Liverpool Physics department as a research technician dedicated to the build of the E989 straw tracker modules, starting this PhD part time in early 2016 and becoming a full time student in December 2017. In that time I worked alongside both staff and students in the Liverpool Semiconductor Detector Center (LSDC) situated in Oliver Lodge Laboratory to help design, build, test and deliver 22 straw tracker modules for the E989 experiment at Fermi National Accelerator Laboratory (Fermilab) in Illinois, USA.

During the build I was working alongside my colleagues and also led numerous research and development experiments to optimise the design of the tracker modules including but not limited to: wire crimping and pulling tests, straw leak testing, straw hygroscopic testing, straw cutting repeatability, source and cosmic ray testing with the module, module leak testing, wire tension testing, pin annealing and straw build gluing trials. I created the risk assessments and liaised with radiation protection in making the source testing possible. I also aided numerous students who were either on work placement or conducting their undergraduate dissertation experiments in the LSDC.

Alongside the physical build of the straw tracker modules, during my role as a technician I was also leading the documentation of the testing during construction, compiled a comprehensive build manual for the modules for the design review with the E989 collaboration and created a manufacture database with the great help of Dr. Girish Patel. I also delivered a talk to the collaboration meeting at Fermilab on the production and status of the tracker module build.

Becoming a PhD student on the project also allowed me to be able to take part in the first three
Run shifts of the experiment, including the Run 1 shutdown where I assisted in the ring in preparing the tracker modules for the end of the run.

The work I have led and assisted with has now contributed to numerous papers being published for the E989 experiment, of which I am on the author list, on the build and data runs of the experiment. The documentation of the build that I made also has assisted in the continuation of module care and maintenance during the running of the experiment. The traceability of the components providing researchers and technicians at Fermilab to make informed decisions on module replacement and potential causes for wire or module failure and the repairs that could be conducted in the case of failures. This has been essential in maintaining the experiment for the length it has been running, providing a longer lifespan of the trackers than originally thought, hence providing more data than originally anticipated.

I count myself extremely fortunate to have played an instrumental role in the build, delivery and running of the E989 experiment; to have worked alongside such excellent people in very esteemed institutions was a pinnacle in my career I am grateful for.
Chapter 1

Introduction

The human mind’s requirement to quantify our surroundings, gives a basis for scientific theory and discovery. What are we made of? How are we here? These are questions that enter most minds from childhood and if we are lucky enough to have the ability to carry that curiosity through academia, are questions that we all have the ability to answer, at least partially ourselves. The most widely accepted model of the building blocks of the Universe, commonly known as the Standard Model, allows scientists of varying disciplines to interpret the behaviour either directly or indirectly of both nature and man-made experiments on the world around us. The law of conservation of energy, expressed by Albert Einstein as “Energy cannot be created or destroyed; it can only be changed from one form to another”, gives a fundamental basis to explain any discrepancies within the Standard Model, either observed through experimentation or theoretical calculation. That where there is a discrepancy, the possibility of new physics can arise.

1.1 The Standard Model

The Standard Model (SM) of particle physics, developed throughout the 20th century, classifies the fundamental constituents of matter, called fermions, and describes their interactions via force carrying particles, called bosons. Due to their quantum mechanical nature, despite being point-like, particles have an intrinsic angular momentum, called spin, which occurs in integer units of
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\( \frac{\hbar}{2} \), where \( \hbar \) is the reduced Planck’s constant. Fermions have fractional spin, whereas bosons have integer (including 0) spin. Every charged particle has an exact equivalent, but with an opposite charge, called an anti-particle. A table of particles is shown in figure 1.1.

There are 4 known fundamental forces of nature, 3 of which are described by the SM (gravity is not included). The most familiar, electro-magnetism, describes the interaction between charged particles, and is attractive or repulsive. The boson which mediates the interaction of charged particles is the photon. Because the photon is massless and neutral (it has no charge), the range of this force is infinite, although at distances larger than the ‘size’ of the particles, electro-magnetic forces are inversely proportional to the square of the distance. The force which binds protons and neutrons (which each consist of 3 quarks) together in the nucleus is the strong force. For this force, the equivalent of the electro-magnetic charge is called the colour charge, and there are 3 distinct colour charges, denoted red, green and blue. The mediating boson is the gluon, which itself can be colour-charged. This leads to confinement [1], which means individual quarks are never observed in nature, but come in multiples; pairs are called mesons, triplets are called baryons. Protons and neutrons are the most familiar examples of baryons. The colour-charge of the gluon limits the range of the strong force to very short distances. As the name suggests, at these scales this force dominates. The third force described by the SM is the weak force, which governs radio-active decay, and is mediated by the Z, W^+ and W^- bosons, where the W bosons are charged. These particles have masses of the order of 100 GeV, and thus the weak force is only noticeable over short distances of the order of an atom, and is much weaker than the strong force. The final boson is the Higgs boson, which was discovered in 2012 [2] [3]. It is the particle which gives mass to the other particles via electro-weak symmetry breaking.

The SM groups fermions together in families, or generations, and there are 3 generations each for the leptons and quarks. The different generations are often called flavours, and each flavour is identical to the other apart from the mass. For example, focusing on the charged leptons, the lowest mass, and therefore the first generation and the most common, is the electron. This is followed by the muon, which is \( \sim 200 \) times heavier than the electron. The third generation charged lepton is called the tau, which is another \( \sim 11 \) times heavier than the muon. Apart from

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1Natural units, with \( h^\prime = 1 \) and \( c = 1 \), which will be adopted throughout this document.
this mass difference these particles are thought to be identical. In fact testing whether they are indeed just heavy replicas of one another is one of the motivations behind many modern day physics experiments, including the Fermilab $g$-2 experiment.

1.2 The Muon

When Neddermeyer and Anderson’s discovery of the muon in 1936 using a cloud chamber experiment [4], after first being mistaken for the particle predicted by the Japanese physicist Yukawa Hideki in 1935, was later confirmed by Street and Stevenson [5] in 1937 with another cloud chamber experiment - it birthed a new era of particle physics experiments dedicated to measurements of the muon. It soon became clear that besides its mass, the muon had identical properties to the electron, and was the beginning of the generational structure of the Standard Model.

The muon, an unstable charged particle from the lepton family, with a relatively long mean lifetime of approximately $2.2\mu$s, has a much heavier mass than the electron, but much lighter than the tau, making them much more penetrating than other particles, aside from the neutron. The muon can be negatively or positively charged, and can decay via the weak force into electrons or positrons,
with their respective decays occurring as:

\[ \mu^- \rightarrow e^- + \nu\mu + \bar{\nu}_e \]  

(1.1)

\[ \mu^+ \rightarrow e^+ + \nu\mu + \bar{\nu}_e. \]  

(1.2)

1.3 The Anomalous Magnetic Moment of the Muon

Being a part of the lepton family, the muon may also be characterised by its spin or intrinsic angular momentum of \( \frac{1}{2} \). Equally important is the charge of the muon, which causes muons to align with an external magnetic field. The torque which causes this alignment is proportional to the magnetic field strength, but also the intrinsic magnetism of the muon, characterised by the magnetic moment, \( \mu \). The spin of the muon along with its electric charge, is related to the particle’s magnetic moment in Dirac’s relativistic theory [1][6], and yields an equation relating a fermion’s magnetic dipole moment to its spin:

\[ \vec{\mu} = g \frac{e}{2m} \vec{S} \]  

(1.3)

where \( g \) is the gyromagnetic ratio of the muon, \( e \) is the charge of the particle, \( m \) is the particle mass and \( \vec{S} \) is the directional spin.

The proportionality constant relating the magnetic moment of a particle to its spin, otherwise known as the \( g \) factor, was first postulated by Goudschmit and Uhlenbeck [7][8] which was then supported by Back and Landé in 1925 [9] [10] with a study of numerous experimental investigations on the Zeeman effect on the magnetic moment of the electron. In 1927 Pauli presented a quantum mechanical approach of the electron spin [9] and later, Dirac, using the relativistic theory he helped develop, famously predicted \( g = 2 \) [10][11][12].

Experimental studies of Dirac’s prediction of the value of \( g \) first began with Kusch and Foley in 1947 [13], finding the value of \( g_e \) to be greater than 2, later given as \( g = 2.00238(10) \) in 1948.
1.3. **THE ANOMALOUS MAGNETIC MOMENT OF THE MUON**

[14]. This discrepancy from Dirac’s theory, altered the value of $g$ to $g = 2(1 + \alpha)$, where $\alpha$ is the anomalous moment of the particle. Radiative corrections, which couple the lepton’s spin to virtual fields, introduce an anomalous magnetic moment defined by:

$$\alpha_l = \frac{g_l - 2}{2},$$

(1.4)

where the $l$ denotes any lepton.

This anomaly has prompted both theorists and experimentalists to study the anomaly of all the leptons, but the muon, $\alpha_\mu$, in particular. This is because the muon is 206 times heavier than the electron, and is therefore more sensitive to virtual corrections from as of yet undiscovered particles. The coupling of these new particles scales with the mass of the probe squared, so the muon is more sensitive than the electron by a factor of $\sim 40000$. Additionally the relatively long lifetime of the muon means that it can be stored (the tau decays too quickly). The long lifetime and increased sensitivity to new physics makes $\alpha_\mu$ an extremely interesting property to measure, but it also needs to be predicted extremely accurately.

Dissecting the Standard Model theoretical value of the muon is beyond the scope of this document. Taking the anomalous magnetic moment down to the quantum loop level, it can be presented in three parts:

$$\alpha_\mu^{SM} = \alpha_\mu^{QED} + \alpha_\mu^{EW} + \alpha_\mu^{HAD}$$

(1.5)

$\alpha_\mu^{SM}$ defines the Standard Model prediction of the anomalous magnetic moment of the muon, $\alpha_\mu^{QED}$ defines the quantum electrodynamic (QED) contribution, $\alpha_\mu^{EW}$ electroweak (EW) contribution and $\alpha_\mu^{HAD}$ gives the hadronic (HAD) contribution.

In 2020, the latest calculation from the Muon $g-2$ theory group presented $\mu^{SM} = 116591810(43) \times 10^{-11}$ [15]. Where the pure QED calculations has the largest contribution and the HAD terms give the largest contribution to the uncertainty. This uncertainty is smaller than the experimentally measured uncertainty, and interestingly a significant difference between the 2 values was observed,
as will be described in the next section.

### 1.4 Measurements of $a_\mu$

The technique for measuring $a_\mu$, first put forward by Francis Farley, has been refined over a number of experiments, and has grown increasingly precise, as demonstrated in table 1.1. It is described in detail in section 2.

Table 1.1: Summary of $a_\mu$ results from CERN and BNL, showing the evolution of experimental precision over time. Datasets are averages obtained in 1999, 2000 and 2001 only [16].

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Years</th>
<th>Polarity</th>
<th>$a_\mu \times 10^{10}$</th>
<th>Precision (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN I</td>
<td>1961</td>
<td>$\mu^+$</td>
<td>11450000(220000)</td>
<td>4300 [17]</td>
</tr>
<tr>
<td>CERN II</td>
<td>1962-1968</td>
<td>$\mu^+$</td>
<td>11661600(3100)</td>
<td>270 [18]</td>
</tr>
<tr>
<td>CERN III</td>
<td>1974-1976</td>
<td>$\mu^+$</td>
<td>11659100(110)</td>
<td>10 [19]</td>
</tr>
<tr>
<td>CERN III</td>
<td>1975-1976</td>
<td>$\mu^-$</td>
<td>11659360(120)</td>
<td>10 [19]</td>
</tr>
<tr>
<td>BNL</td>
<td>1997</td>
<td>$\mu^+$</td>
<td>11659251(150)</td>
<td>13 [20]</td>
</tr>
<tr>
<td>BNL</td>
<td>1998</td>
<td>$\mu^+$</td>
<td>11659191(59)</td>
<td>5 [21]</td>
</tr>
<tr>
<td>BNL</td>
<td>1999</td>
<td>$\mu^+$</td>
<td>11659202(15)</td>
<td>1.3 [22]</td>
</tr>
<tr>
<td>BNL</td>
<td>2000</td>
<td>$\mu^+$</td>
<td>11659204(9)</td>
<td>0.73 [23]</td>
</tr>
<tr>
<td>BNL</td>
<td>2001</td>
<td>$\mu^-$</td>
<td>11659214(9)</td>
<td>0.72 [24]</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>11659208.0(6.3)</strong></td>
<td><strong>0.54 [24]</strong></td>
</tr>
</tbody>
</table>

The uncertainty in the theoretical prediction has kept up with the experimental measurements. Figure 1.2 displays a history of the measurements from both CERN and the previous BNL E821 experiment of $a_\mu$ using measurements of both $\mu^+$ and $\mu^-$, the Kinoshita et al. theoretical prediction made in 1985 [25] and the subsequent theoretical predictions.

In an effort to improve the accuracy of the measurement on $a_\mu$, Brookhaven National Laboratory (BNL) in particular have ran numerous experiments, resulting in an increase in the significance of the discrepancy between the SM and experimental between 1997 and 2001. As can be seen from
Figure 1.2: A history of the individual E821 experiment measurements (a previous experiment studying $g-2$) of the anomalous magnetic moment, along with the CERN value and theory predictions (shown vertical lines dotted red [9]) prior to the running of the E989 experiment.

Figure 1.2, the experimental results have vastly reduced the error on the original measured value of $a_\mu$ by CERN in 1979; and the theoretical prediction has increased in accuracy since, however the discrepancy still exists, giving the motivation for an improvement on the E821 experiment and the creation of the E989 experiment.

Figure 1.3 presents a comparison of the values for $a_\mu^{\text{SM}}$ and $a_\mu^{\text{EXP}}$, with the predicted value for the new E989 $g-2$ experiment at FNAL. On this figure the $a_\mu$ central value for E989 is placed at the E821 measured value, but with reduced uncertainties which correspond to the expected fourfold factor of improvement in precision. The current discrepancy for $a_\mu$ between experimental and the SM predictions is 3.6$\sigma$ (from the E821 experiment) and may increase to 5$\sigma$ with expected reduction in the experimental uncertainty [16]. This has raised many questions of the implication of the discrepancy still apparent between SM and experimental results, arguing the case for new physics. With the refinement of the SM predictions of anomalous magnetic moment, there has still been this discrepancy of approximately 3$\sigma$ between the theoretical and experimental values. If the
E989 experiment at Fermilab can reproduce the result of the BNL E821 experiment, but with an improvement in accuracy by a factor of four, this could then potentially give evidence of physics beyond the Standard Model (BSM).

1.5 Straw Drift Chambers

Particle detectors exist in a variety of types and sizes, with a wide range of design purposes. One of the detectors for the E989 g-2 collaboration experiment is a straw tracking detector. This straw tracking detector, otherwise known as a straw drift chamber, will be the main hardware focus of this thesis as the author was one of the technicians to build and test the modules for the E989 experiment. This section will therefore give an introduction to the function and history of straw
drift chambers.

The basic concept involves using a gas tight cylindrical tube (historically made of metal) as a cathode, with an anode (sense) wire in the middle. The gas inside the tube will contain an ionising gas and a quencher gas, typically Argon:Ethane or Argon:Carbon Dioxide are used due to being highly efficient and low cost options. The wire will have a voltage applied across it to keep it at a higher potential than the straw walls. As a charged particle, in the case of E989 - a positron, passes through the tube, it ionises the Argon freeing an outer orbiting electron, which then "drifts" to the anode wire, see figure 1.4 and figure 1.5. The electrons that result from the interaction with the traversing charged particle are called primary electrons, in the sense that they come from primary ionisations, and typically several such primary electrons are present for a single crossing. These primary electrons are accelerated, and can themselves cause more ionisations, resulting in an avalanche of electrons drifting towards the sense wire. The induced charge difference is then recorded as a signal or a "hit".

![Figure 1.4: Drift circle diagram showing potential trajectory of 2 different positrons through a straw wall, their resulting ionisation points, from which drift circles give a potential electron drift radius to the sense wire.](image)

The positively charged ion, which has lost an electron as described above, will drift towards the straw wall. These ions are much heavier than the electrons, and so the drift velocity is much lower. When the ions hit the straw wall any electrons that are freed will of course drift back towards
the sense wire, a phenomenon called re-firing. The electrons from re-firing can be distinguished from the original avalanche electrons because they occur much later, and typically a “dead time” is applied in the software, so that once a hit has been recorded any subsequent hits from the same wire within a given time frame are ignored.

The quenching gas absorbs photons which are emitted from the Argon ions, preventing them from causing too many ionisations. The best absorbers are complex molecules, whose additional degrees of freedom can absorb photons over a wide range of wavelengths, hence the use of hydrocarbons. Depending on the gas choice, the correct operating voltage has to be applied for optimal efficiency. The permeation rate through the straw wall is also dependent on the gas used. Both the amplitude of the signal and the time can be recorded, the signal can be amplified, simplified and charge discriminated by an ASDQ board and the time stamp associated be encompassed to the signal using a TDC (Time to Digital converter) board. A high and low threshold is applied on the voltage of the signal giving a resulting ToT (Time over Threshold) result, which can be recorded and used to help discriminate between signal and noise.
Figure 1.5: Drift circle simulation using GARFIELD of an electron through a single straw of 5 cm diameter with a signal wire of 25 µm at 1800 V and magnetic field applied of Global $B_z = 1.4435$ T, Global $B_x = 0.1772$ T, Global $B_y = 0.0$ T with a gas choice of 50:50 Argon:Ethane. Simulation shows examples of tracks, clusters (red) and drift lines (yellow), with the points at which ionisation occurs (green dots).
The straw drift chamber is a popular choice for particle detectors for a number of reasons; minimal and low budget material makes them a cheaper alternative to silicon based detectors, isolated cells can minimize cross-talk and allow isolation and masking of any channels where sense wires are broken [26]. Early experiments used metal tubes, however the development and use of synthetic materials has allowed lower mass materials such as aluminized Kapton or Mylar BoPET (Biaxially-oriented polyethylene terephthalate), limiting scatter and potential noise from Bremsstrahlung radiation. Examples of experiments that use straw trackers include: NA62 [27], LHCb [28], ATLAS TRT [29] and E989’s sister project Mu2e [30] (see figure 1.6).

Figure 1.6: Mu2e’s straw tracker construction at Fermilab. Figure showing the same long straws used in the E989 tracker modules.
The Muon $g-2$ Collaboration Experiment (E989), installed at Fermi National Laboratory (FNAL), USA, aims to measure the muon anomalous magnetic moment, $a_\mu \equiv (g - 2)/2$, to unprecedented precision: the goal is 0.14 parts per million (ppm) [31]. The E989 experiment focuses on the use of multiple high precision detectors in an aim to close the discrepancy between the current Standard Model (SM) predictions and experiment results by improving the systematic contribution to the total uncertainty. The University of Liverpool constructed the tracking stations for the experiment whose role is to provide raw hit positions from muon decay products. This is accompanied by data from 24 calorimeters installed around the ring. Each tracker station contains eight identical straw drift chamber modules, with each module having 128 channels. The experiment and detector systems are described briefly in this chapter, with particular attention given to the systems that affect the straw trackers.
2.1 Accelerator

The storage ring is situated on the Muon Campus at FNAL (see figure 2.1), where the experiment measures positrons produced from polarised muons via decay.

\[ \mu^+ \rightarrow e^+ + \nu_\mu + \nu_e \]  

(2.1)

The neutrinos from the decay are not detected. The muons are produced by the accelerator infrastructure at FNAL, which is also used to provide beam for other experiments. A beam of collected protons from an 8 GeV Booster are aimed at a production target, producing pions with a momentum of \( \sim 3.11 \text{ GeV}/c \). These pions decay into muons, and those with a momentum of \( 3.094 \pm 0.3 \text{ GeV}/c \) (also known as the "magic momentum") are selected using a dipole magnet and collimator system. These are then sent to the Delivery Ring. The remaining pions decay
2.2. **STORAGE RING**

into muons after four orbits of the Delivery Ring, at which point they are injected into the Muon Storage Ring. Any remaining protons in the bunch travel slower around the Delivery Ring, and therefore are separated from the muon bunch and do not enter the storage ring [31].

## 2.2 Storage Ring

The muons arrive in bunches with a temporal width of \( \sim 120\text{ns} \), and are injected at an average rate of 12\( \text{Hz} \). The temporal intensity of the injected bunch, as measured by the T0 detector, a scintillating detector placed just in front of the beam injection point, is shown in Figure 2.2

![Intensity of beam arriving to the storage ring](image)

(a) Average beam intensity

(b) Beam intensity for each bunch

Figure 2.2: Intensity of beam arriving to the storage ring, as measured by the T0 detectors. Raw data provided by H. Binney [32].

Each injected bunch is called a fill, and yields approximately 10000 storeable muons. There is a small difference in the temporal width of each bunch, which repeats on an 8 bunch cycle. The storage ring has a vertical magnetic field of 1.45 Tesla (originally from BNL), which is cancelled at the point of injection by an inflector magnet, allowing the muons to enter the storage region. Details of the inflector are given in section 2.4.2. These muons which pass through the inflector are not at the correct orbit for storage. A pulsed magnetic field is applied to the muons by powerful "Kickers" to centralise the orbit of the muons. It takes 149.2 ns for the muons to orbit the ring, and this kick is only applied to the muons once, so needs to be finished by the time the muons circle back around. This is demonstrated in figure 2.3. The timing of the kicker pulses is tuned to each bunch in order to maximise storage. Details of the kicker magnet are given in section 2.4.4.
2.3 Field Measurements

Ideally the stored muons would all experience the same constant field, such that they precess at the same rate. The variation of the field azimuthally is 1 part per million, and is continuously monitored using a combination of fixed probes, which are permanently installed in the storage ring just outside the storage region, and trolley probes, which measure the storage region directly. These probes are mounted onto a ‘trolley’ which is pulled around the ring every 3 to 4 days. The field in between these measurements, when the muons are actually stored, is interpolated by combining the measurements from the fixed and trolley probes. The NMR probes measure $\omega_p$, the free proton Larmor precession frequency, which can be related to the magnetic field via

$$\omega_p = 2\mu_p B_z$$  \hspace{1cm} (2.2)

where $\mu_p$ is the magnetic moment of the proton. The absolute calibration of the NMR probes is obtained during dedicated calibration runs, where the trolley probes are compared with a re-
tractable water probe. This probe itself can then be cross referenced against other probes outside of the g-2 experiment, to ensure that the measured values of $\omega_p$ are consistent.

## 2.4 Measurement Principle

Figure 2.4 is a diagram demonstrating the spin precession of a muon in the g-2 storage ring. The spins of the muons are aligned when they enter the ring. Once a stable beam is achieved and all detectors are functioning, the following values are measured: $\omega_p$, the normalised magnetic field of a proton to Larmor frequency and $\omega_a$, the rate at which muon polarisation turns relative to the momentum. These 2 frequencies can then be combined to give a measurement of $a_\mu$. Firstly, the precession frequency for a charged particle in a magnetic and electric field is given by the BMT equation

$$\bar{\omega}_a = \frac{1}{m} \frac{Qe}{a_\mu B} \left[ a_\mu - \left( \frac{1}{\gamma^2} \right)^2 \beta \times E - a_\mu \left( \frac{V}{V^+} \right) (\beta \cdot B) \right]$$

(2.3)

where $\omega_a$ is calculated as the difference between the spin ($\omega_s$) and cyclotron ($\omega_c$) frequencies. The second term in equation 2.3 is the effect of the rest frame electric field being seen by the orbiting muons as a magnetic field, and thus affecting the precession rate. As would be expected, this is dependent on the velocity of the muons ($\beta$), hence the presence of $\gamma$, the Lorentz factor, which varies with $\beta$, in this part of the equation. There is a particular value of $\gamma$ where this term cancels, and the muons do not feel the effect of the motional magnetic field. This corresponds to $\gamma = 29.3$, which gives $p_\mu = 3.09$GeV, and is known as the magic momentum.

The final term in equation 2.3 is a reduction in the precession frequency which arises from the oscillating vertical component of the muons momentum. Due to the restoring force from the quadrupoles, the muons are not always travelling perpendicular to the field, and hence have a reduced precession frequency on average. Simplifying equation 2.3 by only considering muons at the ‘magic’ momentum, travelling perpendicular to the magnetic field gives:

$$\bar{\omega}_a = -a_\mu \frac{QeB}{m}$$

(2.4)
This can then be related back to the measured quantities giving

\[
\alpha = \frac{g_e}{\mu} \frac{m_\mu}{m_e} \mu_p \omega_a,
\]

where \(g_e\) is the gyromagnetic moment of the electron, which has been measured to 0.3 parts per trillion [34], \(m_\mu/m_e\) is measured to 22 parts per billion and \(\mu_p/\mu_e\) is known to 3 parts per billion [35].

The E989 experiment requires the precession of the muon to be measured to a statistical error of 100 ppb, while controlling systematic errors on \(\omega_a\) and \(\omega_p\) to the 70 ppb level [31], thus ensuring that these uncertainties dominate the \(\alpha\) measurement.

Of course, not all muons are at the magic momentum, and the correction due to the vertical component of momentum needs to be applied. Also the variation in the field, although very small, means that the path of the muons whilst orbiting needs to be measured, so that the field experienced by the muons before decay can be calculated. Moreover, the precession vector itself cannot be measured, but must be inferred from the direction of the decay positrons. As such detectors are placed around the ring to make these measurements. The tracking detector modules contribute to this measurement by providing precise reconstruction of the decay positron, inferring the positions of the stored muons without disturbing them. In an effort to achieve the required precision, the design of the modules attempts to minimize potential scattering by reducing the material budget of each tracking module and by having multiple straw layers in a UV configuration to obtain vertical as well as radial information.
2.4. MEASUREMENT PRINCIPLE

Figure 2.4: Spin precession in $g$-2 storage ring [9]
2.4.1 Magnet

The E898 magnet, repurposed from the E821 experiment and of Gordon Danby’s design, consists of 12 C-shaped yokes - three upper and three lower poles per yoke, giving a total of 72 poles and is powered by 3 superconducting NbTi/Cu coils. The poles are separated through use of shimming knobs, allowing for corrections of effects of pole tilts and non-flatness affecting uniformity, determining the field.

The magnet required extensive planning to move from Brookhaven laboratory to Fermilab (as seen in Figure 2.5). The magnet was moved 3200 miles across land and water often requiring closure of major roads. The “Big Move”, as it was named, began it’s journey from Brookhaven 22nd June 2013, finally arriving at Fermilab on 26th July 2013.

![Figure 2.5: “The Big Move” - showing the g-2 magnet’s final stage of moving from Brookhaven to Fermilab, with Wilson Hall at Fermilab in the background. [36]](image-url)
2.4. MEASUREMENT PRINCIPLE

2.4.2 Inflector

The inflector is a truncated, 1.7m superconducting magnet [37], which is placed at the point of injection in the storage ring, to counteract the magnetic field of the ring allowing the injection of the polarised muons. The inflector makes a 1.45 T uniform vertical field to cancel out the magnetic field in the injection channel and allows the muon beam to pass into the storage ring unperturbed [38].

![Inflector Diagram](image)

Figure 2.6: (a) Plan view of the beam entering the storage ring. (b) Elevation view of the storage-ring magnet cross section [31]

2.4.3 Quadrupoles

The central orbit has a radius of $R_0 \ 7.112 \ m$ and the cyclotron period is 149.2 ns. Four sections of pulsed high voltage electrostatic quadrupole (ESQ) plates provide weak focusing for vertical confinement of the beam [39] helping to achieve a stable orbit. This vertical focusing of the beam, is the cause of the final term in equation 2.3, and must be calculated and compensated for in what is called the ’pitch correction’ when calculating $\omega_a$.

Due to space withing the ring being constricted by the inflector, kickers and trolley garage; the number of quadrupoles able to be installed in the ring was limited - locations can be seen in Figure 2.7). Whilst this only allowed the quadrupoles a less ideal 43% geometric coverage of the storage ring, it did provide a four-fold symmetry in it’s coverage and gave space for additional detectors to be implemented.
2.4.4 Kickers

The purpose of the kickers is simply to correct the radial offset from $R_0$ at the injection point by using 3 kicker magnets located at 90° in the storage ring (see figure 2.7). By pulsing the magnet during the first orbit, a tangential force is applied to the circulating muons to ‘kick’ them onto their ideal orbit [41]. Another upgrade of the E821 experiment was the Kickers, this saw the introduction of three Blumlein pulsers to drive each of the 1.27-m-long non-ferric kicker magnets, which reside in the E989 storage ring vacuum (SRV) [42]. As opposed to the RLC PFNs used in E821, the Blumlein pulsars could be electrically grounded adding an extra safety measure to the experiment and simplifying the trigger electronics. The benefit of these new kickers is that they provide a more powerful kick while sustaining the increased repetition rate of the data runs.
2.4.5 Vacuum

The storage ring vacuum (SRV) is scalloped consists of 12 different chambers around the ring, joined by bellows, which are continuously monitored during data runs (see figure 2.8). Most of the chambers, with either quadrupole or kicker assemblies installed inside, were unchanged except the vacuum chambers which were modified from E821 in order to allow room for the NMR probes and straw tracker modules. The vacuum feed through was cooled with Fluorinert, rather than transformer oil, so that in advent of a leak to vacuum, the storage ring vacuum system would not be contaminated with oil [31]. To prevent the quadropoles from sparking, the maximum allowed SRV level was not to exceed $1 \times 10^{-6}$ Torr.

![Figure 2.8: E989 long term Storage Ring Vacuum (SRV) trend.](image)

The storage ring vacuum is monitored at different positions around the ring using ionisation gauges. Typical values from these are shown in figure 2.8. The interplay between the SRV and the permeation of gas through the straws was a significant challenge for the straw trackers to overcome.
CHAPTER 2. THE E989 COLLABORATION EXPERIMENT

2.5 Stored Muons

The path of an individual muon is not exactly circular, it oscillates radially about its ideal orbit, determined by its momentum. For example, a low momentum muon that, after the kicker pulse, is at a high radius will feel a restoring force pushing it back to its ideal orbit. When it gets there it will over shoot, and then feel a restoring force in the opposite direction. If the amplitude of this oscillation is low enough such that it doesn’t hit the storage ring walls it will be stored, and continue to oscillate about its ideal orbit radius until it decays. This effect means that the magnetic field focuses the beam radially.

The muons also have a vertical momentum component, which would cause them to hit the top or bottom of the storage ring. To prevent this, and maximise the number of stored muons, electrostatic quadrapoles are used. They provide a vertical force that pushes the muons to the centre of the storage region, focusing the beam vertically. This causes the beam to oscillate vertically in much the same way as the radial oscillations described above. The quadrapoles actually defocus the beam radially, such that the radial restoring force provided by the magnetic field is slightly reduced, but still provides overall focusing. The quadrapoles cannot be placed near the inflector, nor can they be placed in the kicker location. They also must be symmetric around the ring. This means there are 4 gaps in the storage ring, and that the quadrapoles only cover about 43% of the ring, as explained in section 2.4.3.

The higher momentum muons have a larger orbiting radius than the low momentum muons. This difference in path length slightly reduces the time for the lower momentum muons to orbit, which causes the beam to de-bunch, such that the muons eventually fill the entire storage ring.

2.6 Detector Systems

2.6.1 Calorimeters

There are 24 electromagnetic calorimeter stations positioned around the storage ring. These are located in the fringe field of the central storage ring, directly adjacent to the muon storage volume in a cutout of a scalloped vacuum chamber [31]. Each calorimeter comprises of a 54 lead flouride
2.6. DETECTOR SYSTEMS

crystals (PbF2) assembled as an array of 9 wide and 6 high, each of a volume of $25 \times 25 \times 140$ mm$^3$ [43]. Having an array of the Cherenkov crystals, was a design improvement with respect to the E821 experiment in that an array of crystals will allow for spatial resolution of pileup, providing an improvement on the systematic of E821. The calorimeters are dedicated to measuring the positron positions and time of decay by using large-area using silicon photo-multipliers (SiPMs) for absorber photodetection, high voltage (HV) bias and slow controls to digitize the signal with new 800 MHz waveform digitizers which must be synchronized through a distributed clock system [31]. From the number of decayed positrons detected by the calorimeters, $\omega_a$ (equation 2.3, 2.4 and 2.5) may be calculated.

The calorimeter crystals are thermally stabilised through the design of the enclosure providing sufficient cooling and the energy scale (gain) of each crystal is monitored in-situ and set using a laser calibration system. The calorimeter gain requires constant monitoring to ensure it remains stable over a 30-700 $\mu$s measurement period, with the laser calibration system being able to correct for residual gain instabilities to better than $4 \times 10^{-4}$ during the measurement period [43]. These requirements correspond to the systematic uncertainty on rate dependent gain effects of 20 ppb [31].

Two of the 24 calorimeters are placed behind the tracking stations (described below), such that the majority of positrons detected by these calorimeters will also have passed through the straws. In fact, the high momentum positrons have straighter tracks, and thus will traverse most of the tracking modules. This is the reason for the light weight straws used in the experiment, as we need to minimise energy loss due to scattering. Initially, it was unknown whether the effect of the tracking stations would compromise the calorimeters placed directly behind them. In fact, it was found that the only effect was on the phase of the detected positrons, and that these calorimeters were fine to be used in the final analysis [44][39].
Figure 2.9: Stacked calorimeter crystals connected to SiPM readout [43]
2.6. DETECTOR SYSTEMS

2.6.2 Trackers

There are three tracker stations positioned around the muon storage ring, with two stations currently occupied by eight modules each at 180° and 270° azimuthal angle $\Phi$ to the injection point in the ring. Only two stations are occupied due to the limited number of straw tracker modules built; the challenges of the build and time constraints prevented the build of spare modules. Therefore, only two stations were occupied to allow there to be spare modules in the case of module failure.

Figure 2.10: Image of Tracker Station 1 (eight tracker modules) within the ring at FNAL. The gold FLOBBERS with their associated cables and pipes can be seen protruding from the ring.

The tracker modules are straw drift chambers, these are essentially a design amalgamation of the early Multi Wire Proportional Chambers, where each signal wire is placed inside one drift tube (straw) with containing an ionising and quenching gas mix (50:50 Argon:Ethane). When the positron passes through the straw wall, the positron ionises a Argon molecule, releasing an electron from it’s orbit, this electron then drifts to the wire at the center of the straw, ionising other molecules in it’s path, which in turn release their own electrons that drift to the wire. It is this change in charge detected by the straw’s wire that is measured as a “hit”. The Ethan in
the gas mixture acts as a "quencher" to prevent a self-sustaining avalanche effect of hits within the straw. Signals from the wires are amplified, simplified and charge discriminated by ASDQ ASIC boards and their signals digitized with a time by Time to Digital Converter (TDC) boards implemented in a field-programmable gate array (FPGA). A new MIDAS-based data acquisition system (DAQ) was designed to collect the data from both the calorimeter and tracker modules [31].

Each tracker module, see Figure 2.11, consists of 128 of these straws made of aluminized Mylar, in four layers of two close-packed doublet planes, each plane containing 32 straws with the two doublet planes in a UV configuration at ±7.5° to the vertical. The signal wire strung at tension in the center of each of the straws, the wire is 25 µm in diameter and made of gold-plated Tungsten-Rhenium (used for the materials' high tensile strength and high melting point to prevent damage in use). The wire is held in place by two gold-plated copper pins and mechanically crimped to hold the tension, one of the pins acts as a signal readout to the ASDQ boards, the other is a 'dead end' acting simply for mechanical constraint of the wire. The module is designed to be vacuum sealed and leak resistance so as to function within the vacuum of the storage ring.

Signals from the tracker modules can be used for track reconstruction of the trajectory of the decay positrons, this can then be used to calculate the decay point of the muon, which can then also be used to monitor the profile of the muon beam inside the storage ring. These profiles determine the betatron oscillation parameters necessary for beam dynamics corrections and the precession data fits [39].
Figure 2.11: Section of an early drawing for the $g$ -2 tracking detector modules for the E989 experiment. In the top drawing the straws and manifolds, holding the 1st stage electronics, are highlighted, the Snouts which contain the Kapton flexi cables and the feed-through boards to the Flobber where the secondary electronics are held. The bottom image shows an ASDQ board arranged onto 16 of the 128 long pins.
Chapter 3

E989 Muon g-2 Tracker Modules

The E989 Muon g-2 Tracker Modules (see in Figure 3.3) were designed, built and tested at the University of Liverpool, in conjunction with the E989 collaboration. The University of Liverpool were responsible for the mechanical design, build, testing and commissioning of the module, University College London were responsible for the firmware design and Boston University designed the front end and back end electronics hardware.

During the initial stages of construction the design for the tracker modules underwent various changes with respect to the TDR [31], to meet the demands of other requirements of the experiment and to make production more feasible with the given time constraints. These are described in the following chapter.

The E989 experiment at FNAL, was designed with three slots in the ring to hold eight tracker modules per tracking station. This chapter will detail the design, construction, quality assurance and quality control tests of these modules before shipping to FNAL for commissioning, of which the author was one of the two technicians employed for the task.
Figure 3.1: The $g$-2 ring at FNAL
Figure 3.2: Engineering drawing of the $g$-2 experiment storage ring electrical grounding at the MC-1 building, on the Muon campus at FNAL. Supplied by Dr. Brendan Casey, drawn by Steve Chappa of FNAL.
Figure 3.3: $g$-2 tracker module 0, labelled according to the external mechanical parts.
Figure 3.4: g-2 technicians Kayleigh Thomson holding the Test Beam Tracker Module (left) and Dave Sim holding Module 00 before electronics installation (right) during production in the LSDC cleanroom at University of Liverpool
3.1 Final Tracker Module Design

The E989 tracker module (see Figures 3.3, 3.6 and 3.7) consists of two identical aluminium manifolds, held apart by an aluminium vacuum flange on one end and supported on the other end by a custom made carbon fiber post. Aluminium grade 6061 was used as it performs well in magnetic structures and an Allochrom coating was applied to prevent any corrosion. The manifolds, lids and flanges were made in the Oliver Lodge Laboratory workshop on a 5-axis CNC milling machine, the Snouts were cast and the FLOBBER was made by Boston University. 128 aluminized Mylar (TM) straws (see Figure 9) of equal length are potted into these manifolds as two close-packed doublet planes in a UV configuration (see figure 3.5) using a gas sealing glue (Araldite 2020), with each straw later strung with a 25µm gold-plated tungsten (sense) wire, pre-tensioned and then stretched to an average of 50 g. These wires are held in place by crimped gold-plated copper pins, seated in ABS injection molded inserts which are in turn held in place inside an aluminium insert either end of the straw. The aluminium inserts are attached to the straw using a silver electrically conducting epoxy to provide minimal electrical resistance and a source of electrical grounding to the aluminium manifolds, in an effort to minimize any potential electrical noise. The module was vacuumed sealed with the use of Viton (FKM - a fluorocarbon-based fluoroelastomer material) o-rings, either side of the vacuum flange, the straw side of the module used an o-ring groove and Dow Corning high vacuum grease to provide an adequate seal on compression. An o-ring groove and BNR o-ring with Dow Corning high vacuum grease applied was also used on bath manifold lids, the screws for the lids of the modules were also torqued to a maximum 80 cN (reduced from originally 120 cN to prevent thread stripping).
3.1. **FINAL TRACKER MODULE DESIGN**

Figure 3.5: Straw coordinate system UV layout orientation for E989 tracker modules [45]

Figure 3.6: Final drawing of the Stage 3 $g$-2 tracker module assembly (excluding the FLOBBER). Image credit design engineer John Carroll, University of Liverpool [46].
The aluminized Mylar straws (approx. 5 mm diameter) are originally 1.3 m in length, they are leak tested using CO\(_2\) with an acceptance maximum leak rate of \(40 \times 10^{-5}\) cc/min with a respective 1 atm pressure. Passed straws are then precisely cut to 90.6 mm lengths, with two aluminium end pieces, bonded to the straw ends with electrically conductive silver epoxy. The two end pieces, known as a “Top Hat” (see figure 3.8 and “Non-Top Hat” end piece, allows the straw to sit in the manifold hole when fed through one manifold and rest in the opposite hole. The aluminium end pieces allow an additional support for an injection moulded insert to seat a gold-plated copper pin, crimped and holding a gold coated tungsten-rhenium wire at tension, which acts as our signal wire. The Argon:Ethane gas is flowed through the module by use of a inlet situated at the top of the snout, the gas flows through the snout and into the manifold, the injection moulded inserts in the aluminium end pieces have a hole allowing ventilation of the gas through the straw. The gas...
then exits the straw to the bottom manifold and out via the bottom snouts gas outlet.

The U layer straws sit at $-7.5^\circ$ and the V layer straws sit at $+7.5^\circ$ with respect to the radial-vertical plane. The DC nature of the beam requires a tracker with multiple planes spread out over as long a lever arm as possible. Four layers of straws per module, minimizes multiple scattering. The requirement to place the detectors in the vacuum leads to the choice of straws since the circular geometry can hold the differential pressure with minimal wall thickness [31].

The straw wall is made of two layers of 6 $\mu$m Mylar, spiral wound, with a 3 $\mu$m layer of adhesive between. The total thickness of the straw wall is 15 $\mu$m. The inner surface has 500 Å of aluminium overlaid with 200 Å of gold as the cathode layer. The outer surface has 500 Å of aluminium to act as additional electrostatic shielding and aims to help to reduce the leak rate of the straw [31]. It is important that each assembled straw maintains a low resistance of approximately 30 $\Omega$ (as specified by Boston University) or lower to reduce the effect of noise within the data taken – assembled straws of a resistance greater than 40 $\Omega$ were not to be used for the production modules. This electrical resistance is measured using a digital multi-meter, probing either end of an assembled straw’s aluminium end piece.
Table 3.1: Summary of the properties of the tracking detectors [31]

<table>
<thead>
<tr>
<th>Feature</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straw material</td>
<td>Aluminized Mylar</td>
</tr>
<tr>
<td>Straw wall thickness</td>
<td>$15\mu m$</td>
</tr>
<tr>
<td>Wire</td>
<td>$25\mu m$ gold-plated tungsten</td>
</tr>
<tr>
<td>Straw length</td>
<td>97.5 mm</td>
</tr>
<tr>
<td>Stereo angle</td>
<td>$\pm 7.5^\circ$ from vertical</td>
</tr>
<tr>
<td>Gas Mixture</td>
<td>50:50 Argon:Ethane</td>
</tr>
<tr>
<td>Pressure</td>
<td>1 Atm</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>1625 V - 1650 V</td>
</tr>
</tbody>
</table>

The wire inside each straw is held in place by two of the gold-plated copper pins; a “long” pin and a “short” pin both with an manufacturer given tolerance of mean outer diameter (OD) between 0.94-1.00 mm and a mean hole diameter or inner diameter (ID) between 0.06-0.10 mm, with mean lengths between 17.8-18.2 mm for the long pin and 15.8-16.2 mm for the short pin. The long pin provides the electrical connection to the first stage electronics within the manifolds by connecting to the sockets via the ASDQ boards, the short pin acts as a “dead” end and is covered with insulating caps to prevent electrical discharge between the short pins and the underside of the ASDQ boards. The long pins are crimped on a material tester, see figure 3.9, at a given load and the short pins are annealed to enable crimping by hand. Adequate crimping is essential to both the accuracy of the tracking by ensuring the wire is held as central as possible with minimal sag, and for the lifetime of the module - any wire that slips through a crimp or is fractured by over crimping, will render that channel unusable - often resulting in a rewire of that section of the module.

Each manifold is sealed with a lid and o-ring and has an aluminium irregular shaped tube or “Snout” connecting the flange to the second stage electronics (see figures 3.3 and 3.7) held in the “FLOBBER” - Frontend Low voltage Optical Box to BackEnd Readout. A gasket provides a gas seal between the Snout and the feedthrough boards. Dow Corning High Vacuum grease is applied.
3.1. **FINAL TRACKER MODULE DESIGN**

Figure 3.9: Long pin crimping in the Lloyds LRX Plus materials tester, using the custom wire eroded jaws giving a set crimp depth, an extensometer (Epsilon) was used to monitor the jaw movement during crimping.

The first stage electronics include: eight Amplifying Simplifying Charge Discriminating Boards (ASDQ) with their respective flexi cables (4 per manifold), 8 HV internal cables (4 cables connected by a central board - one assembly per manifold) and two feed-through boards (one per manifold). The ASDQ boards sit onto 16 of the long pins (giving 16 channels per ASDQ board), each board is supported by ABS plastic 3D printed mounts and covered by two Teflon heat pads (one on each of the ASDQ chips) with a copper heat sink placed on top, is designed to redistributed any localised heat created by the first stage electronics to the manifold. The ASDQ boards are in turn connected to the feed-through boards via a Kapton flexi cable and high voltage (HV) internal supply cable through the Snouts. The original snout was designed with all angles at 90°, however, was later modified to have a graduated slope to the feed-through boards, to allow for the bend angle of the flexi cables (see figure 3.3).

The second stage electronics include: 2 logic boards (one per manifold), 2 high voltage (HV) external power boards (one per manifold) and 4 Time to Digital Converter (TDC) boards (2 per manifold). The TDCs communicate the simplified charge signal from the ASDQ boards and convert to a timed digital signal. The power supply used for the eight HV channels that supply voltage
to the 128 straw wires is a CAEN 40 channel high voltage system - model SY 127 (provided by Fermilab) is used to test the modules at Liverpool in final quality control testing. There are 8 HV channels, one per ASDQ board. A Graphical User Interface (GUI) has been created by UCL members of the tracking team to monitor and control these channels, providing safety features for high current trips and power outages.

The HV supplied to the module is typically at a voltage of 1500 V for a gas mixture of Argon and Carbon Dioxide (Ar:CO$_2$ at an 80:20 ratio respectively) and current at 1 $\mu$A. Up to 1650 V will be used in the final experiment, which will run using an Argon Ethane gas mixture (50:50 ratio respectively). For testing the modules at Liverpool, two Thandor TS1542S power supply crates are used to provide a low voltage supply to the second stage electronics, these typical run at a voltage of 5.000 V with 0.737 A and 3.000 A current. Ar:CO$_2$ was used at the University of Liverpool as procedures were already in place to be able to use the gas safely within the LSDC and was easily available, gas mixtures with Ethane required an additional level of health and safety procedures which would have taken time better used for production. The electronics are kept cool by two methods: a long hole drilled inside each manifold to allow a continuous flow of water in the manifold via a pipe inlet and outlet, the water is flowed and is treated with bacterial and corrosion inhibitors to prevent galvanic corrosion inside the manifold. The pipes were original made of copper but later replaced with plastic to prevent any oxidisation of the copper contaminating the cooling system. A negative pressure fan system is situated on the FLOBBER electronics which is located outside the ring, providing an extra method of cooling. Dust protectors are also placed onto the FLOBBERS to prevent dust getting inside.
3.2 Tracker Module Production

The straws for the tracking detectors of the E989 experiment are composed of several layers of alternating adhesive and aluminized Mylar, manufactured by Dupont in the USA before being delivered to the University of Liverpool. Several batches were made, shipped to the University of Liverpool and inspected before use. This section details those procedures for quality assurance and quality control testing to assure suitability for the experiment.

Each straw assembly consists of, in addition to a wire later threaded and crimped per straw:

- 1 x 90.6 mm length aluminized Mylar straw
- 1 x aluminium top hat end piece
- 1 x aluminium non-top hat end piece
- Tra-Duct 2902 silver epoxy
(a) Highlighted in red the location of the gluing well  
(b) Silver Epoxy, pre-mixing

Figure 3.10: Images showing the silver epoxy used for gluing the aluminium end pieces to the straw and the location of the gluing well which the adhesive was applied to.

The straw tracking detector consists of the aluminized Mylar straws of a 90.6 mm length and 5 mm diameter, with 2 aluminium end pieces, bonded to the straw ends with electrically conductive silver epoxy in the gluing well - see figure 3.10.

The two end pieces are a Top Hat and Non-Top Hat end piece, for which the Top Hat allows the straw to rest in the manifold hole and will provide the pin for the electronic readout end of the wire. The straw wall is made of two layers of 6 µm Mylar, spiral wound, with a 3 µm layer of adhesive between layers. The total thickness of the straw wall is 15 µm. The inner surface has 500 Å of aluminium overlaid with 200 Å of gold as the cathode layer. The outer surface has 500 Å of aluminium to act as additional electrostatic shielding and improves the leak rate. A material budget for the straw may be seen in table 3.1. It is important that each assembled straw maintains a low resistance of approximately 30 n or lower to reduce the effect of noise within the data taken - assembled straws of a resistance greater than 30 n will not be used for the production modules.
3.2. TRACKER MODULE PRODUCTION

3.2.1 Straw Identification

In order to better identify straws within the detectors in case of failure, each straw tested was individually named to provide traceability. The convention for this is described below. The straws used for the experiment were delivered at an uncut length of approximately 1270 mm, wrapped in an anti-static sheet inside a long reinforced plastic tube. These were causally known as the “long straws”, which were later cut to the desired length. For the purpose of identification of each cut straw once installed into the detector, the long straws were first numbered by the following convention. Each tube was a different batch and designated a ‘GS’ number, for example the first batch was GS1. All straws within that batch had a designation prefix of GS1, followed by their individual number. Therefore, the first long straw, randomly selected from the first delivered tube had the designation GS1-1. Once the long straw was cut to the desired length, each “short straw” would then follow the convention GS1-1-1, GS1-1-2 etc.

3.2.2 Long Straw Inspection

Long straws were transported to Liverpool with an internal paper to hold their structure, wrapped in anti-static bags and placed in large cylindrical protective case. When they arrived at Liverpool, the straws were removed from their packaging and inspected in rounds of 20. Custom trays were made to hold both long straws before and after testing and short straws prior to building. Initial inspection of the long straw included visual and physical tests to assess suitability for production. The visual inspection consisted of checking either end of each straw for potential “unravelling”, where the adhesive at the seam of the straw had been insufficient to hold its cylindrical form and instead was unravelling to a single strip. Any straws which appeared to have physical damaged of a kink or a hole, were recorded and discarded, even in the case of it passing other tests, it was decided there was still potential for that straw to fail later in the experiment with any apparent structural weakness. Every long straw also had its length recorded with a ruler and electrical resistance recorded with a digital multi-meter and a probe at either end, touching the internal straw surface. Only straws from batch PPG4 and PPG3 were used to build the detectors: straw lengths measured an average of 1269.2 mm +/-0.5 for PPG3 straws with average resistance of 196.64 n +/-0.01 before paper removal and 185.21 n +/-0.01 after paper removal and and average of 1296.3 mm +/-0.5
for PPG4 straws with average resistance of 185.72 n +/-0.01 before paper removal and 182.82 n +/-0.01 after paper removal (see figure 3.11 for spread of PPG3 and PPG4 length measurements and figure 3.12 for their spread of resistances. Each batch presented a slightly different internal diameter, with PPG3 being wider than PPG4, for which different batches of aluminium end pieces were made to match after measuring with precision gauges.

![Figure 3.11: Long straw length measurements used in production, includes both PPG3 and PPG4 batches.](image1)

![Figure 3.12: Long straw measured resistances per unit length measured.](image2)
3.2.3 Long Straw Leak Test

In order to minimise any potential of failure of straws within the g-2 ring vacuum, each long straw that passed visual inspection was individually leak tested to assess if it could hold a gas under pressure for an extended amount of time. The leak test equipment and test code was provided to the University of Liverpool g-2 team by the Mu2e collaboration who were using the same straws [47]. The equipment consisted of: a testing chamber – a metal pipe with an air ball valve shut off switches and gas detector (the leak rate is calculated from the PPM/s slope recorded from the detector), Arduino Uno readout and Raspberry Pi Interface for reading the results with code pre-written by a Mu2e collaborator. The code was modified to suit the requirements of the E989 straw testing [41]. In preparation for the long straw leak testing, the long straw internal paper was carefully removed and at either end, a custom made injection moulded insert was adhered inside of the straw using Araldite 5050 and left to cure overnight. The injection moulded straw inserts were designed to fit the internal diameter of the straw and provide an inlet for the gas. Tubes of soft Viton were placed over the gas inlets to allow the straws to be connected to the leak test equipment easily and with minimal movement of the straw.

The straws for the tracker module have Argon:Ethane gas flowing through them whilst the module is under vacuum, therefore only straws that leak the minimum amount of gas are to be used in production. The straws are leak tested at UoL using a 50:50 Argon:Carbon Dioxide gas mixture (±2% uncertainty of Argon), where a maximum leak rate of Carbon Dioxide at $10^{-4}$ cc/min is allowed. Carbon Dioxide is used at UoL to test the straws to reduce the risk of explosive gas in the atmosphere and that with a smaller molecule of CO$_2$ in comparison C$_2$H$_6$ (Ethane) it would theoretically be quicker to detect a leak in the straw wall.

The test chamber used for leak testing consists of a copper piping in a circuit with two ball valves, a fan with a CO$_2$ detector controlled by an Arduino UNO. At UoL the detector was connected to a Raspberry Pi which enabled leak test data to be automatically pushed to an elog for traceability. The code was modified from the Mu2e test to suit the gas used at UoL by S. Charity [41].

To remove the internal paper, roll the straw very gently between 2 fingers to lose the paper adhering to the straw inner wall (very minimal compression to prevent damage to the straw). It
is possible for a section of the internal paper to dislodge when doing this, making it relatively easy to remove the paper with a pair of tweezers. Gently and slowly pulling the paper out from the inside of the aluminized Mylar. There have been straws where it is more difficult to remove the paper; it is suspected that the paper remains adhered to the inside of the straw. Pulling the paper out in such situations will kink the straw if pulled with too much force, rendering the straw unusable after. It is therefore recommended that the straw is rolled very slightly along its full length, in an effort to prevent this. Paper removed should be kept and inspected afterwards for contaminants. Labelling each paper strip with its straw counterparts name after removal, helps with good practice in documenting anything observed later on. The straw is prepared by removing the paper, measuring the resistance of the straw, and gluing in an injection molded gas feed into either end of the straw using 5 minute Rapid Araldite adhesive. Approximately 60 mm length of Viton is then attached onto the gas feed inserts either end of the long straw and a layer of Rapid
Araldite is applied over the seam to provide an extra gas seal. The straws are left to cure overnight in the black × 10 straw trays see figure 3.14.

Figure 3.14: Straws curing with Rapid Araldite bonding Viton attached to injection molded gas inlets.

Results of the PPG3 and PPG4 leak testing can be seen in figures 3.15, 3.16, 3.17 and 3.18. As can be seen in the PPG4 straw results, the average leak rate was much higher than that of the PPG3 batch of straws. It can be assumed this was due to the PPG4 straws having a thinner straw wall making it easier for gas molecules to permeate. After consultation with the vacuum and tracker teams in the collaboration, it was decided that the acceptance straw leak rate could be raised from a maximum of $10 \times 10^{-5}$ cc/min to $40 \times 10^{-5}$ cc/min, which still gave an acceptable permeation rate within the SRV, whilst maximising the amount of long straws that could be used for production.
CHAPTER 3. E989 MUON G-2 TRACKER MODULES

Figure 3.15: PPG3 Straw Leak Rates - Straw PPG3-38 to PPG3-199.

Figure 3.16: PPG3 Straw Leak Rates - Straw PPG3-200 to PPG3-298.
3.2. TRACKER MODULE PRODUCTION

Figure 3.17: PPG4 Straw Leak Rates - Straw PPG4-1 to PPG4-104.

Figure 3.18: PPG4 Straw Leak Rates - Straw PPG4-106 to PPG4-196.
3.2.4 Straw Cutting

The straws received from FNAL for the straw tracker detector were referred to as “full length” straws. The straw length designed for the tracking detectors to provide optimum detector space in the given dimensions from the rest of the experiment was 90.6 mm. To achieve precise, repeatable lengths with a quick production turnaround, a custom guillotine was made and maintained by the University of Liverpool Physics Department Workshop. Each long straw was cut roughly into 11 segments of 120 mm and then inserted with a cylindrical internal support, wrapped with the straw’s original paper. The straw was then inserted into the guillotine and cut to the final length in preparation for “Top Hat” and “Non-Top Hat” gluing. The two blades in the guillotine were checked and replaced regularly to ensure quality of cutting was maintained.

Figure 3.19: Guillotine for straw cutting to 90.6 mm.
3.2.5 Aluminium Top Hat and Non-Top Hat De-Burring

The aluminium straw ends were manufactured externally and therefore require cleaning of contaminants and manual removal of internal burrs. This procedure can be done with batches of end pieces to reduce time. After the de-burring process, the ends are then sent externally for Allochrome coating to prevent corrosion and provide a better electrical grounding, reducing potential noise in the data from the straws. The batch number assigned to the ends is the date they are received from coating, e.g. date received 1st June 2016 were given a batch number of 010616 (DDMMYY) [48].

Materials required include:

- Isopropanol alcohol (undiluted)
- De-ionized water
- Q-Tips
- Small, soft grinding stone – conical shape, in pin chuck barrel
- Small, hand grinding stone
- Rounded tweezers
- Small pyrex beakers
- Ultrasonic bath with fine mesh metal basket
- Batch of top hat and non-top hat aluminium end pieces

Using a soft grinding stone (see figure 3.37) any internal burrs are removed - minimal force is to be applied when inserting the grinding stone into the end piece. A slight rotational movement of the grinding stone whilst holding the end piece, helps to remove any burrs. This is then repeated for the other side of the end piece. Batches of at least 40 top hats and 40 non-top hat end pieces should be done at one time, to ensure enough are available for at least one tray of straws. The end pieces are then inspected after de-burring using a jeweller’s loupe or other available magnifier for visual inspection.

Once the end pieces have been de-burred, they are placed into a small clean glass beaker (pyrex
or borosilicate) with isopropanol alcohol and stirred using a glass rod. The isopropanol alcohol is drained from the end pieces using a metal sieve, dried and place into fine metal mesh basket for the ultrasonic bath. The basket is placed into the ultrasonic bath, which is filled with deionized water to just above the top of the aluminium ends. A 10 minute period of the ends being agitated in the ultrasonic bath is sufficient without any temperature increase.

After the ultrasonic bath cycle, the aluminium ends are dried and cleaned once again in a glass beaker of isopropanol alcohol. The ends are removed and the inner diameter cleaned with a new Q-Tip. The batch is placed in the fume cupboard to air dry once complete (the time may be reduced by using the air line in the fume cupboard to dry them). They are then sealed in clean container or bag, ready for Alochrome coating [48] - this coating produces an electrically conductive surface coating, providing a grounding route to the manifold and in turn to the g-2 ring.
3.2.6 Straw Build

The final straw build consisted of adhering a “Top Hat” and “Non-Top Hat” aluminium end, one into either end of a guillotined straw. Prior to the straw build, the aluminium ends were de-burred. The Non-Top Hat end of the straw was designed to slide through a manifold hole, allowing the Top Hat end to then sit within the rim of that hole without sliding through. The aluminium ends were adhered to the internal diameter of the straw using a silver based epoxy - Loctite Hysol Tra-Duct 2902 [49]. Figure 3.22 shows a non-top hat end piece prepared with the silver based epoxy, ready for short straw gluing. This epoxy then provided good electrical contact and adhesion to the straw. The adhesive does not come pre-mixed and has a short working time with a full cure of 24 hours in a 25°C environment. Therefore, practice and technique studies were conducted to decide the final method of application.

Once cured, each built straw electrical resistance was checked, the limit being 30 n using a digital multi-meter and two probes in contact with the aluminium ends adhered to the straws. Failed straws were removed immediately, so as not to be accidentally used. Care had to be taken not to accidentally damage the thin straw wall whilst taking the resistance measurement with the DMM probes, hence using the aluminium ends as the probe region.

Figure 3.22: Non-top hat on orange 3D printed mount, prepared with silver based epoxy for short straw gluing.
3.2.7 Manifold Inspection and Assembly

Coordinate Measuring Machines or CMM, are a widely used tool in metrology to inspect the physical geometry of an object through the use of a contact probe. The probe can either be manually moved or navigated through a programme on the CMM software to inspect a part or many parts in production and cross-check their geometry with the given CAD design or specification in X, Y and Z. The probe often consists of a pivoting and/or rotating arm on a gantry, with a precision cut synthetic ruby sphere of varying diameters dependant on the application. The synthetic ruby used on the CMM probe is used as a datum as the surface can be optically well-defined surface. Rubies are selected by CMM manufacturers as they are relatively inexpensive and resistant to physical or chemical damage. The measurement surface for the object is usually an accurately flat granite base, with a location hole for a reference sphere to be mounted for calibration.

The manifolds and flanges for the tracker modules were all inspected on the CMM in the LSDC. This was to ensure that the hole locations for the straws in the manifolds were within specification, the flanges were also within specification, and to the measure the separation between the manifolds when assembling and jacking apart the module.

It was essential that these parts met specification. Firstly if the flanges were out of specification, i.e. the flange to vacuum chamber face was not flat enough - not only would they not effectively seal the module for vacuum in the SRV but if the slots for the manifolds were out of alignment, the straws would twist and be out of alignment. Secondly, if the hole locations were out of specification – this would potentially affect the straw location and angle enough to put a systematic offset into the tracking data. Knowing the manifold hole locations and their respective positions to the Top and Bottom manifolds, allows the tracking analysers to compensate for these systematic offsets and compare the positions of the straws in the tracking reconstruction with the measured positions on the CMM.

A programme to measure each manifold was created using the 3D CAD model of the tracker modules. Each module was mounted in a holder onto the granite base of the CMM, the coordinate system was established using the holder. In order to allow quick and repeatable measurements of all the manifolds, a pallet coordinate system was set up and used each time to allow the probe to
automatically locate the holder. This is carried out using the 3-2-1 (or Plane-Line-Point) method: i.e. a plane of three points on the surface of the holder giving primary direction set along z axis, a line of two points on side face of the holder giving the secondary direction along the y-axis and a single point on the remaining face giving the origin in the x-axis (see figure 3.23). Therefore the part coordinate system was created using a corner of the manifold end using the 3-2-1 method. The 128 straw holes measured were established in the program as cylinders and then intersected with the bottom pocket plane to create an intersection point. A loop for each plane of each of the 32 holes was used to measure the cylinder, the intersection was then obtained for the first hole, and then the coordinate system was relocated by 6.052 mm (distance between the middle of two neighbouring points) [50].

Figure 3.23: 3D CAD representation of the CMM coordinate system on tracker manifold [50]

The following gives the CMM surveys of the manifolds, representing the hole location variations by straw number in the top and bottom manifolds in both the x (perpendicular to the flange interface) and y direction (parallel to the flange face).

Figure 3.24 gives examples of the surveyed top manifold hole locations in all 4 layers in X (see the Appendix for other module results). A drift in the hole locations from the vacuum flange at straw 1 to straw 32 is observed of approximately 25 \( \mu m \), this could either be a systematic from the CMM tolerance or an offset with the CNC 5-axis milling machine used to manufacture the
manifolds. Figure 3.27 compares the average of those 4 layers for the top and bottom manifolds of those modules, the 25 $\mu$m drift across the manifold, can again be observed. Figure 3.28 shows the manifold hole location measurement in Y for the top and bottom manifolds, these results are much improved on the X axis measurements, giving an indication that it was the CNC milling tool potentially creating the X axis hole drift. Figure 3.29, summarises these results for modules 5 and 9, figure 3.30 does likewise for modules 3 and 16. The results see for module 3 and module 16 in figure 3.25 and 3.26 show outliers in the CMM hole position measurement, these anomalies we would expect to see in the tracking data, however as they have not been see in the run data we can attribute them to a potential error in the CMM measurement.
Figure 3.24: CMM measurements of manifold hole location variation in X for the top manifolds, showing for all four layers - Modules 5, 8 using PPG3 straws and Module 13 and 16 using PPG4 straws.
Figure 3.25: Average CMM measurements of manifold hole location variation in X for top and bottom manifolds - Modules 5 and Module 8, using PPG3 straws and Modules 13 and 16, using PPG4 straws.
Figure 3.26: CMM measurements of manifold hole location variation in Y for the top and bottom manifolds, showing all four layers - Modules 5, 8 using PPG3 straws and Module 13 and 16 using PPG4 straws.
Figure 3.27: Histograms of CMM measurements of manifold hole location showing the average variation in the hole positions in x and y for both top and bottom manifolds - Module 5 and Module 8, using PPG3 straws.
3.2. TRACKER MODULE PRODUCTION

Figure 3.28: Histograms of CMM measurements of manifold hole location showing the average variation in the hole positions in x and y for both top and bottom manifolds - Module 13 and Module 16, using PPG4 straws.
3.2.8 Straw Potting

128 built straws of 30 n or under are chosen and then potted into the assembled g-2 manifolds. To allow full cure of the straws to ensure the module is fully electrically grounded and vacuum sealed, they are potted 2 layers at a time. 64 straws will first be inserted through the top of the manifold using the non-top hat end of the straw first, allowing the top-hat end of the straw to sit inside the top manifold with the non-top hat end resting inside the corresponding hole in the bottom manifold. The straws are inserted a layer at a time and fully recorded to allow traceability in the case of any leaks when pressure testing the closed module.

![Figure 3.29: Module with V layer populated ready for potting.](image)

Once the two layers of straws are insert, they are given an additional layer of silver conducting adhesive around the aluminium ends to the manifold. Once the conductive layer has cured, the gas sealing adhesive (Araldite 2020 [51]) is gradually injected into the well of the manifolds using a fine gauge needle, surrounding the aluminium ends of straws. A green dye is applied to the Araldite 2020 during the mixing process, to allow the technician to better fix the adhesive across the well (see figure 3.30). The entire process take up to four days, allowing for a full 24 hours curing of the gas seal adhesive per manifold: day one - top manifold layers UA and UB, day two - bottom manifold layers UA and UB, day three - top manifold layers VB and VA, day four - top manifold layer VB and VA. This process is essential to ensure the module is full vacuum compatible for the experiment.
3.2.9 Wire Crimping

Inside each straw is a 25 µm gold-plated tungsten wire, suspended and held centrally inside the straw by two gold coated copper pins of different lengths. These pins sit within injection moulded plastic inserts (see figure 3.31), which in turn sit inside each of the aluminium ends bonded to the aluminized Mylar straws. These wires are tensioned to a minimum of 30 g in order to remain central within the straw so a single drift time to distance parameterisation can be used along the length of the straw, prevent electrical discharge that would damage the channel and to receive signal for hits. The ASDQ cards then sit on top of the long readout pins – see bottom of figure 3.33, the short pins act as a non-readout end. The system will operate with a 50:50 Ar-Ethane gas mix at 1 Atm pressure at 1650 V for operating voltage [31].

The wire used for the g-2 tracker modules is made of gold-plated tungsten with a nominal 25 µm diameter, purchased from Luma. Each wire spool is typically 300 m in length with the wire having a Young’s Modulus of 2985 N/mm². For the module straws to be strung with this wire, 128 wires are threaded and crimped with a long pin and plastic insert. One in every ten wires are pull tested (pulled until breaking point) in the current QA of the wires. These pull tests and the crimping of the long pins are performed on the Lloyds LRX Plus Materials tester, situated in the ISO class
CHAPTER 3. E989 MUON G-2 TRACKER MODULES

Figure 3.31: Long pin machine crimped with 25 \( \mu \)m wire in injection moulded insert (with gas inlet) - imaged using Leica MZ12 microscope

5 clean room at Oliver Lodge Laboratory. The short pins are later hand crimped with the wire pre-tensioned at 30 g during the module stringing, see figure 3.32.

Figure 3.32: Tracker module in stringing process - thin white plastic rod used to feed the signal wire through the straw, held at a tension of 30 g pre module stretching.

Long pin threading requires a 1 m length of the 25 \( \mu \)m wire with plastic insert threaded onto the wire first and then the long pin. The long pin is fixed into the insert using cyanoacrylate adhesive and left to cure. A set of custom made, hardened steel jaws with precision wire eroded notches of varying depths on one side and a flat face on the other. These jaws are then clamped onto
the Lloyds LRX Plus and the crimping test is set as a compression test at a speed of 2 mm/min. A 1 kN load cell is used in the test, no pre-load value is used at the beginning of the run. The pre-threaded pin is sat in the 0.575 mm notch in the custom jaws and the test runs by closing the jaws with increasing load until the machine registered the safety load limit of the cell. The result of the run leaves the pin flattened, crimped, holding the wire inside. These pin crimp depths are measured with vernier calipers after the run and recorded to monitor any potential tool wear or misalignment in the test setup, potentially affecting the quality of the crimping on the pin.

The average crimp depth of the pin, measured across the flats is $0.633 \pm 0.042$ mm from a sample of 228 crimped long pins, with the pin deforming approximately at 500 N during compression. The machine extension is measured by an Epsilon Extensometer, this allows precise in-situ measurements of the extension to sub-millimeter accuracy.

The wires selected for pull testing ensure that the pin crimping has performed as expected. The manufacturer gives a Young’s Modulus of the wire to be 2985 $N/mm^2$, making the breaking load of the wire to be 1.2 N. 128 wires are required per module and 12 wires out of every 120 will be
pull tested. This is also performed on the LRX Plus machine, however with a 100 N instead and a pre-crimped wire of 150 mm with a board soldered onto the end is mounted into the materials tester. The test conditions are changed from compression to pull, this test is destructive to the sample and will continue to extend the wire until either breaking point or the wire slips - indicating a failed crimp. Wires breaking at 100 g (approximately 1 N) or above are accepted. Any result below this value would indicate the wire has been damaged in soldering, or in crimping and so has a low breaking point (shorter elastic limit) than expected, or has slipped through the crimp. Wires crimped before or after a failed pull test would then be pull tested to eliminate anymore failures before stringing. Figure 3.34 gives examples of different pin crimps with wires being pulled on the materials tester, failures can be seen at 50 g, 100 g and 120 g depending on the crimp used and type of failure, for example sharp drops in load indicate wire breakage and gradual drops indicate a wire slipping through the crimp (suggesting a greater crimp depth needed on the wire eroded crimping jaws).

Figure 3.34: Example sample of failed and passed pull test graphs overlayed with key limits of 50 g, 100 g and 120 g approximately, highlighted.
3.2.10 Module Stringing and Tension Testing

After the module is has been populated with all 128 straws and left for the required curing time of the Araldite 2020, it is then mounted into the the stringing jig (see figures 3.37, 3.38 and 3.39). The stringing process requires a thin, rounded plastic rod with a hole in one end which resembles a blunt plastic needle to thread a length of wire through each straw. The end of wire away from the crimped pin was fed into the hole of the plastic rod and tied off. The plastic rod then feeds the wire through the straw until the plastic insert sits into the Top Hat aluminium end, on the opposite side of the straw a plastic insert would be fed onto the over hanging wire into the Non-Top Hat aluminium end and then a short pin would be threaded to sit in the plastic insert. The wire is then pre-tensioned with a 30 g mass and crimped using a custom hand crimp tool (see Figure 27). The short pins have been annealed by the manufacturer prior to gold-plated and so require less force to crimp the pin (typically 400N as measured on the materials tester). This process is then repeated for all remaining 127 straws. On completion of the stringing process a continuity check is performed on the wires from pin to pin using a digital multi-meter (DMM) - each wire should measure between 10 Ω and 13 Ω typically. The jacking system is then used to move the manifolds apart by 70 µm to induce an extra 20 g tension in the wire, whilst tensioning the straws simultaneously. The new manifold separation distance is checked using the CMM, the carbon fiber post is secured between the manifolds to hold them in place and the jacks are removed.

![Figure 3.35: Module during stringing process - the feeding rod with signal wire attached is being fed through one of the straws in the module. The module is mounted in the custom made stringing jig.](image)
Each wire tension is recorded post stretching to monitor any wire failures in moving the manifolds apart. Wires above 25 g are generally accepted so as not to be affected by any gravitational sag of the wire, with a preferable tension being 50 g (which is just shy of half way to the breaking point load of the wire).

The tension tester (see figure 3.35 [52]) requires, the two crocodile clips of the tester being secured onto either side of the wire - onto the long and short pin. A reasonably strong magnet is placed above the test straw, supported by a thin sheet of perspex. A pulse is sent down the wire, the
magnet “kicks” the wire with its magnetic field and the frequency induced along the wire is displayed on the tension tester screen, followed by the tension in grams. When a resonant frequency is hit, it is interesting to hear the different pitches produced according to the different tensions. The tension tester calculates the wire Tension using equation (5), where \( f_1 \) is the frequency in Hertz, \( T \) is the tension in Newtons (later converted to grams), \( m \) is the mass of the wire in kilograms and \( L \) is the length of the wire in meters. The recorded wire tensions for all the modules for Tracker 1 pre-vacuum testing at Liverpool and post-restringing, can be seen in figure 3.39. The histogram shows a Gaussian type distribution of the tensions, centering over 45 g to 50 g as desired. Number of wires that have required to be restrung due to failed crimps during production of the modules - is seen in Table 3.2, modules 10 to 21 experienced no needed for repeat crimping due to failed crimps at the production stage, this can be attributed to the procedure in use being perfected over time.

\[
f_1 = \frac{T}{2L}
\]  

(3.1)

Table 3.2: Number of wires requiring restring post-stretching and tension testing, due to failed crimps during production of first 9 modules

<table>
<thead>
<tr>
<th>Module No.</th>
<th>No. of wires restrung</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
</tr>
</tbody>
</table>
Tension Tester

**MAGNET**

**MODULE 00**

**PROBE TO PIN**

**TENSION TESTER (Arduino Uno)**

**STRINGING JIG**

Figure 3.38: Labelled diagram of the tension tester with module in-situ testing.
Final module wire tensions before vacuum testing

Figure 3.39: Histogram of all recorded wire tensions in grams for the first nine modules constructed, pre-vacuum testing at Liverpool and post-restringing.
3.2.11 Electronics Insertion

Subject to the tension testing being successful, or after successful restringing is completed; the manifold electronics are inserted. This requires eight ASDQ boards, four HV internal connectors (four cables per connector), eight flexi cables, 64 insulating end caps, eight ASDQ supports, 16 PTFE thermal heat pads, conformal coating and eight copper heat sinks (see figure 3.40).

Figure 3.40: Components for an E989 tracker module includes flange, lid, manifold (top to bottom, left hand side), snout (top middle), Kapton flexi cables (four on right hand side), ASDQ board, 3D printed ASDQ board support, copper heat sink, aluminized Mylar straw with pins, aluminium ends and plastic inserts (bottom of figure, left to right). Image credit: Mike Wormald, University of Liverpool.

Insulating end caps first are adhered to the short pins (the “dead ends”) to prevent electrical
discharge between the short pins and underside of the ASDQ boards. ASDQ boards are then inserted onto the long pins, there are four per manifold - the 3D printed board supports between the underneath of the board and the inside of the manifold. PTFE thermal heat pads are placed onto the two ASDQ chips on the board to transfer the heat produced by the board to the copper heat sink which sit on top of the ASDQ board (see figure 3.42), the copper heat sink in turn transfers that heat to the aluminium manifold.

The copper heat sinks are secured to the ASDQ boards and manifold using brass screws. A conformal coating is applied to these screws due to close proximity with the HV internal cables, this is to prevent any potential electrical discharge within the manifold.

The flexi cables and HV internal connectors are fed into the manifold through the snout and inserted into their respective ASDQ boards. Both flexi and HV internal cables have different lengths to reach their board within the manifold. The cables are connected to the feedthrough board at the Snout end of the module simultaneously (see figure 3.42), and the feedthrough board is connected to the Snout with a gasket in between and screws tightened to maintain a gas seal. At this point an o-ring for the manifold can have vacuum grease applied to it and the lid will seal the manifold using a torque wrench set to 80 cNm.
CHAPTER 3. E989 MUON G-2 TRACKER MODULES

Figure 3.42: Stage 1 - ASDQ insertion onto manifold long pins
(a) ASDQ card fitting to long pins on
(b) PTFE heat sink pads placed on chips?

Figure 3.43: Stage 2 - Heat sink fitting with Teflon pads to ASDQ boards
(a) All PTFE pads fitted to one layer ASDQ boards
(b) Copper heat sinks placed on top of ASDQ boards - one per board

Figure 3.44: Cable fitting - flexi cable and HV cables
(a) HV cable insertion - one to each ASDQ board
(b) Flexi cable insertion - one to each ASDQ board
3.3 Tracker Module Quality Testing

Each stage of the production of the E989 tracking modules underwent vigorous quality assurance and quality control testing; with every straw and every wire in every module constructed we are able to trace it’s measured results in the g-2 tracker database, created by Dr. Girish Patel and Kayleigh Thomson, both of University of Liverpool [53] The location of the electronics of each module as commissioned from the University of Liverpool also being assigned within the database. Straw leak test, wire resistance or tension and manifold CMM data are all located within the database [53] in order to provide traceability in the event of a straw or wire failure of the module during final commissioning assessment or running in Fermilab. The following sections will detail those quality control and assurance measures taken at each stage of the production.

3.3.1 Vacuum Testing

The first vacuum tests of the E989 tracker modules are performed in the clean room at Oliver Lodge Laboratory, University of Liverpool. The modules are installed horizontally into a custom made vacuum tank to allow for the maximum rate of cosmic hits in Data Acquisition (DAQ) testing. The module is mounted onto a dummy flange, which is then bolted to the outer shell of the vacuum tank using a vacuum-greased o-ring to seal the mating surfaces. Module gas is connected with the inlet into the top manifold snout and outlet from the bottom manifold snout to a bubbler. The gas used to test the modules in Argon:Carbon Dioxide 80:20 ratio with an in-line oil and particle contamination filter. The rate of flow of the gas is set to 0.1 LPM (liters per minute). The vacuum pump used in test is a Oerlikon Leybold model with a CenterOne gauge, the gauge is connected by serial port to a computer and live output of the vacuum data is read out using plot.ly. The vacuum pump kicks in with the rougher pump initially to bring the tank to approximately $10^{-3}$ mbar, before the turbo pump reduces the vacuum tank pressure down, see Figure 32.

Live plot.ly output of the vacuum pump down can be monitored remotely, see figure 3.48. If a module does not pump down to below $10^{-3}$ mbar within the first 24 hours, this indicates there is a module leak. A pressure of below $10^{-6}$ mbar is for the $g$-2 ring vacuum level. Table 3 displays the final vacuum pressure measurements from using the plot.ly live output setup. Note Module 8 being the best performing module in terms of vacuum pump down at a value of $4.54 \times 10^{-7}$ mbar and the
least performing module being Module 9 at $1 \times 10^{-5}$; Module 1 was made with PPG3 straws and Module 9 with PPG4, therefore Module 9 straws on average permeate at a higher rate than Module 1 due to the batch used to make the module. Both modules however are now installed at the ring at FNAL and are performing at an acceptable vacuum pump down rate for the experiment.
Table 3.3: Asymptotic vacuum test limits for the E989 tracker modules at Liverpool before shipping.

<table>
<thead>
<tr>
<th>Module No.</th>
<th>Final vacuum test reading (mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$1.25 \times 10^{-6}$</td>
</tr>
<tr>
<td>2</td>
<td>$1.52 \times 10^{-7}$</td>
</tr>
<tr>
<td>4</td>
<td>$8.04 \times 10^{-6}$</td>
</tr>
<tr>
<td>5</td>
<td>$1.46 \times 10^{-6}$</td>
</tr>
<tr>
<td>6</td>
<td>$1.05 \times 10^{-6}$</td>
</tr>
<tr>
<td>8</td>
<td>$4.54 \times 10^{-7}$</td>
</tr>
<tr>
<td>9</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td>10</td>
<td>$3.27 \times 10^{-7}$</td>
</tr>
<tr>
<td>11</td>
<td>$1.64 \times 10^{-8}$</td>
</tr>
<tr>
<td>12</td>
<td>$6.82 \times 10^{-8}$</td>
</tr>
<tr>
<td>13</td>
<td>$9.23 \times 10^{-8}$</td>
</tr>
<tr>
<td>14</td>
<td>$8.66 \times 10^{-6}$</td>
</tr>
<tr>
<td>15</td>
<td>$8.27 \times 10^{-6}$</td>
</tr>
<tr>
<td>16</td>
<td>$2.64 \times 10^{-6}$</td>
</tr>
<tr>
<td>17</td>
<td>$7.92 \times 10^{-6}$</td>
</tr>
<tr>
<td>18</td>
<td>$4.84 \times 10^{-8}$</td>
</tr>
<tr>
<td>19</td>
<td>$2.91 \times 10^{-8}$</td>
</tr>
<tr>
<td>20</td>
<td>$2.76 \times 10^{-8}$</td>
</tr>
<tr>
<td>21</td>
<td>$3.31 \times 10^{-8}$</td>
</tr>
</tbody>
</table>
Figure 3.46: Tracker module 0 - initial vacuum pump down.

Figure 3.47: Tracker module 1 - initial vacuum pump down.
3.3. TRACKER MODULE QUALITY TESTING

Figure 3.48: Tracker module 1 - stable vacuum achieved 24th November 2016.

Figure 3.49: Tracker module 5 - vacuum 10th April 2017.
Figure 3.50: Tracker module 5 - vacuum pump down and release.

Figure 3.51: Tracker module 9 - best vacuum achieved 21st December 2016.
3.3. TRACKER MODULE QUALITY TESTING

3.3.2 Cosmic and Source Data Testing

The E989 modules were assessed using the DAQ system created primarily by Boston University (BU) and University College London (UCL). Once low voltage noise scans, high voltage noise scans and vacuum tests proved acceptable, cosmic and in some module’s cases beta source testing, was performed. These tests provided data on each wire individually, giving raw data indicating if there was a poor connection to a wire or a contamination on a wire.

The general procedure, was to allow the module to pump down to sufficient vacuum (1 × 10⁻⁵ cc/min) and then perform noise scans and HV ramping, including any required HV training. Using MIDAS (data acquisition software package) the module could then perform a data taking run, this could be either using a beta emitting source such as Strontium 90 or cosmics; provided the module was mounted horizontally - with the straw length facing vertically. A four hour continuous run was performed on the modules, the minimum allowed time to ensure all wires received hits during a cosmic run. Once adequate hits are achieved across all active channels, a long term run of minimum eight hours was performed. These runs were also monitored remotely.

The Data Quality Management (DQM) page is an invaluable tool for in-situ observation of module runs. During production it has provided an extremely useful source of identifying “dead channels” quickly and also by identifying “noisy” channels and their HV training. Examples of cosmic and beta source data runs will be shown in the following sections.

Module 00, the first prototype module after the test beam module, was primarily DAQ tested using a 37 MBq (last measured current activity 32 MBq) activity beta-emitting source. Perspex shielding was provided around the modules and above the straws to limit the amount of possible Bremsstrahlung emittance from the aluminium based module. A full risk assessment was conducted by Kayleigh Thomson and approved by Dr. Tim Jones and Professor Pete Cole of University of Liverpool, prior to these tests. Tongs for moving the enclosed source, training to all users and eye protection was provided. The tests included moving the source along intervals of the straws and taking MIDAS runs. Figure 3.52 displays an example of a data run taken at Liverpool with members of University of Liverpool, Boston University and University College London. The image shows the position highlighted in red of the position of the source during the run and the
graph above the results of that position. It is seen clearly the peak of the emittance in the amount of hits per channel. This first test not only provided information that all channels were present and receiving hits, but also that the data was being recorded where expected in the module to ROOT output of the data.

Figure 3.52: Strontium 90 source testing with module 00, image credit Dr. Tom Stuttard [54]. The straw convention running from left to right in the graphs with the first straw located at the flange end of the module.
3.4 Evolution of the E989 Tracker Module Design

There were several design iterations before the final tracker module design was approved. The original design of the tracker stations consisted of nine modules of three different designs. The three different module designs, seen in the schematic Figure 3.54(a) and Figure 3.55 consisted of modules of three different manifold lengths. Whilst this would have optimised the amount of material overall for each tracker station, it limited the flexibility of using the modules due to the shape and size of the beam, modules would not be able to be swapped and interchanged to different positions in the event of failures. It was therefore ascertained that for longevity of the modules in the experiment to have the ability to change with any other modules, that a uniform design for each station was required. This also allowed production of the modules to be more efficient as the same processes and measuring techniques could be used for all of the modules, instead of three different methods depending on the length of the module, the resulting tracker station design can be seen in Figure 3.54(b).

With different length modules considered, different length straws were also considered to optimise the height of the modules to the shape of the beam. Figure 3.56 is an early drawing of one of the straw lengths proposed. This would have also further complicated the production procedure, requiring different cutting tools for each length and different stringing jigs to have the signal wires in the center of the straws at the right tension (see Section 3.3 for detail on the production procedures). It was therefore decided the the straws also should be of uniform design.

The ASDQ boards situated on the readout pins of the straws went through several design iterations by Boston University. Firstly, the design was made uniform to match the new lengths of the final module design, secondly the connecting sockets to the readout pins were changed to allow ease of insertion and removal of the boards (see section 3.5.5). The readout pins also underwent design changes - the “dead end” pin became shorter than the readout pin (known as the “long pin”) to minimise material and this shorter pin also became annealed before coating with gold to enable the technician to hand crimp the wire at tension easier (see section 3.5.4).

Cooling pipes were added to the manifold design, so that the module manifolds could be water cooled with a continuos flow through pipes spiral wound with a thin nylon wire, without adding any
moisture inside the module. These copper pipes were swapped to plastic to prevent contamination from any potential corrosion. This was especially important as the original design included a cooling bar between the flexi cables and the ASDQ boards, which had to be omitted due to limited space and a danger of damaging the surrounding electronics when closing and torquing the manifold lid. The carbon fiber post was also added to support the two manifolds and induce a tension into the straws to maintain their shape.

3.5 Preliminary Tests for Tracker Module Production

Prior to the building of E989 tracker modules, a variety of tests were conducted to assess the best methods for production using data from the beam module and mechanical tests with a “mini-module” to produce the first production module - Module 00. The following details some of those pre-production tests and inspections performed.

3.5.1 Straws

Before using the straws for production, visual inspections were carried out using the SmartScope of the straw internal and external walls and straw seam. This was required as a quality inspection after initial inspections of the first batch of straws after delivery, indicated some damage and out of specifications anomalies. Examples of damage observed include kinks in the straw wall, holes in the straw wall and unravelling of the long straw ends. Figures 3.62, 3.67, 3.69 give examples of such damage. These sorts of damages made the straw unusable - straws with kinks or any other kind of visual damage were removed and not used. Even small kinks may create surface micro-fractures or sub-surface damage to the straw material – potentially increasing the overall electrical resistance of the straw, see figure, or creating a hole in the straw which would present a problem with gas leaking into vacuum.

The potential route of permeation of gas could also be seen when back lighting a cut straw at the seam, this can be seen in figures 3.68. There was a concern with the PPG4 batch of straws which a larger percentage of straws leaking. Upon visual inspection of the straw seam, it was seen that some display an amount of “feathering” (see figures 3.60 and 3.61), where the straw seam did
not seal flat against the straw wall. Measurements of the straw wall thickness were taken using a
digital micrometer which showed the straw walls measuring at a thickness of 3 µm thinner than
expected. The discrepancy in thickness was determined to be an insufficient layer of glue, resulting
in a thinner straw wall and inadequate sealing of the straw seam.

Several methods of building the module straws were suggested and tested to find the optimal
procedure that minimized electrical resistance of the built straw and gas leakage. Several theories
for high straw resistance included: feathering at the straw seam where bonding the aluminium ends
did not allow for proper contact with the adhesive (see figure 3.68 and 3.69), inadequate mixing
of the adhesive and inconsistent application of the adhesive in glue well of the aluminium inserts
providing insufficient contact to the inner straw wall.

### 3.5.2 Straw Build Tests

Several methods of building the module straws were suggested and tested to find the optimal
procedure that minimized electrical resistance of the built straw and gas leakage. Several theories
for high straw resistance included: “feathering” where the straw seam did not lie flush at the straw
seam where bonding the aluminium ends did not allow for proper contact with the adhesive (see
figures 3.60, 3.61 and 3.62) or the blade on the guillotine blunting prematurely, creating a kink in
the straw end, which would not allow effective bonding to the aluminium end.

Varying weld line “structures” and widths – these were observed between straws during visual
inspections on the Smartscope, the internal and external seam widths appeared to vary between
straws and closer visual inspection of the seam could also identify structures of the seam welding
– suspected to be residual adhesive from straw manufacturing with an enhanced profile due to the
coating over the top.
Areas of inconsistent spluttering or perhaps coating removal when internal paper removed, proper identification of the material was not made due to lack of resources. Physical damage to the straw creating microfractures in the straw coating – creating a greater straw resistance. As the weld line of the straw, inside and out, was not electrically conductive (tested with a digital multimeter), this indicated that the weld line was not conductive with the rest of the straw. Therefore damage at any location along the straw is detrimental as the conductive path of the straw could not cross the weld line and must follow the spiral route of the straw.
3.5. PRELIMINARY TESTS FOR TRACKER MODULE PRODUCTION

Figure 3.53: Production flowchart - Tracker Module Assembly Document [48]
Figure 3.54: Sections of two different engineering drawings of the g-2 trackers - (a) shows the three module type tracker design in the ring and (b) shows the one module type tracker design in the ring which is used today.

Figure 3.55: 3D CAD model of the 3 module type design of the tracker - from John Carroll, HEP, University of Liverpool [46]
3.5. PRELIMINARY TESTS FOR TRACKER MODULE PRODUCTION

Figure 3.56: Section of an early drawing of an assembled g -2 straw - drawing NP63-01-05[5]. Label 1 indicating the Top Hat Aluminium end piece, Label 2 indicating the aluminized Mylar (TM) straw and Label 3 indicating the Non-Top Hat end piece. Units associated with shown numbers are in millimeters. The length of this design was later modified [46]

Figure 3.57: The Example of a straw seam - image taken at x40 magnification on OGP Smartscope CNC625.

Figure 3.58: The Example of a straw seam with "feathering - image taken at x40 magnification on OGP Smartscope CNC625.
Figure 3.59: Example of a straw seam with "feathering - image taken at x287 magnification on OGP Smartscope CNC625.

Figure 3.60: Example of a straw end kinked after cutting - image taken at x40 magnification on OGP Smartscope CNC625.

Figure 3.61: Example of a straw seam - image taken at x287 magnification on OGP Smartscope CNC625.
Figure 3.62: Example of a straw seam with possible structures from over coated seam adhesive residual - image taken at x287 magnification on OGP Smartscope CNC625.
Figure 3.63: Example of a internal straw wall with possible coating anomaly circled - image taken at x40 magnification on OGP Smartscope CNC625.

Figure 3.64: Example of a internal straw wall with possible coating anomaly circled (same straw as figure 3.63)- image taken at x287 magnification on OGP Smartscope CNC625.
Figure 3.65: Example of an internal straw wall with possible damage to the Mylar under the coating - image taken at x287 magnification on OGP Smartscope CNC625.
Figure 3.66: Example of an internal straw wall at seam - image taken at x287 magnification on OGP Smartscope CNC625 with backlighting in green visible light.

Figure 3.67: Example of an internal straw wall with adhered to the coating, presenting a microfracture in the coating - image taken at x40 magnification on OGP Smartscope CNC625.

Finally, migration of the silver in a silver based epoxy, this may occur if not effectively mixed - varying the conductive properties of the epoxy [55][56] (see figure 3.71). Oxide layers may also
3.5. **PRELIMINARY TESTS FOR TRACKER MODULE PRODUCTION**

Figure 3.68: Example of an internal straw wall coating, presenting a microfracture in the coating (same straw area as figure 3.67)- image taken at x287 magnification on OGP Smartscope CNC625.

develop at exposed sites. An increase in resistance of the initially high resistance straws over time was also observed, the low resistance straws however, remained the same. Mielke describes that factors such as the epoxy, solvent used for aspects such as cleaning, cure time, environment and surface preparation can significantly influence the electrical properties of the bonded junction [55].

Therefore, as the previous anomalies with straw structures could not be wholly controlled once the straws were delivered to Liverpool and time constricted sourcing straws from elsewhere, the only factor that could be investigated and controlled effectively once visibly damaged straws were removed, was the straw adhesive mixing and application. Excluding the frequent inspection and replacement of the guillotine blades.

Loctite (Hysol) TRA-DUCT 2902 was the epoxy chosen to bond the Top Hat and Non-Top Hat aluminium ends to the precision cut, leak tested straws - once these two ends were bonded, the straw was defined as “built”. The epoxy was chosen for its excellent designed properties for electronic bonding and sealing applications that require a combination of good mechanical and electrical properties. TRA-DUCT 2902 passes NASA out-gassing standards ISO-10993-5, as well as it being tested to and passed the requirements of ISO 10993-5 for cytotoxicity. With the silver epoxy not
being pre-mixed, there were suspicions that the method of adhesive mixing and applying in the straw build was greatly varying the built straw resistance. The silver epoxy (TRA-DUCT 2902) comes in a sachet with two compartments sealed in the middle of the sachet and held separate by a plastic clip. The two compartments, containing separately the resin (a silver-based epoxy with 2,3-epoxypropyl o-tolyl ether) and hardener (triethylenetetramine with substituted aminophenol) required mixing prior to use and then had an approximate one hour work time with a 24 hour full time at 25°C. Therefore, a potential issue of human error in mixing, whether it was not mixed thoroughly within the sachet, mixed for too little or too long a time, could have had a potential to affect the properties of the epoxy and so the built straw’s repeatability.

Another factor that may have affected the epoxy’s properties was that for this silver epoxy’s storage the optimal temperature was at 27°C; however, the ISO Class 5 cleanroom the tracker modules were built in required a lower ambient temperature. Therefore, there is a possibility that this also affected the properties of the batch TRA-DUCT 2902 we used. Epoxy mixing tests performed by D. Sim, K. Thomson and M. Wormald of University of Liverpool included: mixing the epoxy within the packet (as recommended by the manufacturer), mixing the epoxy freehand using a foam swab for a set time onto a flat surface (cleanroom grade Q-Tip) and mixing the epoxy using a vortex mixer to keep the mixing at a consistent known rate. It was found that using the vortex
mixer was not effective in that the epoxy was over-mixed and had started curing even on the lowest setting. Mixing within the packet was effective but no consistent as the shape of the packet (rectangular with sharp corners), meant parts of the resin or hardener were trapped in the corners and unable to be mixed effectively. Free-hand mixing, required removed the compartment clip and seal, then cutting the top of the tube with sharp scissors before squeezing all the contents of both compartments onto a mixing mat; the contents was then mixed by hand using a foam swab for 30 seconds timed. The free-hand mixing was found to be the most consistent and effective at mixing the epoxy as it enabled the user to remove as much of the resin and hardener as possible and mix in a timed controlled manor, approximately 2 strokes a second were used.

Application of the epoxy to the aluminium ends posed another potential for error in the straw build procedure. Previously the mixed epoxy was being applied using a 3ml syringe with a fine gauge needle. Whilst this method certainly gave a quicker and visually neater result, the application could be tricky and not all of the gluing well of the aluminium end was always filled adequately for repeatable electrical contact. It was therefore decided, after trialling several methods, that application of the epoxy to the gluing well was more effective using a cleanroom grade foam swab, with the removal of excess epoxy from the straw outer surface using a foam swab soaked in isopropanol alcohol.

The methods of straw building trialled for the module were:

- Option 1 – Resin and hardener was mixed inside package as described by the manufacturer

- Option 2 – Resin and hardener was emptied separately into a vortex mixer and mixed for 3 minutes

- Option 3 - Resin and hardener was emptied from packaging via the resin side onto a mixing pad and mixed for 30 seconds by hand using a foam swab until a consistent silver colour.

Option 3 was used in production as it gave the most consistent results for built straw resistances.
3.5.3 Pin Inspections

The pins were made in a single batch by the same manufacturer. They were made in a similar method in that the copper material would be stretched into a long cylinder until the desired outer was reached, cut to the specified length and then coated. Due to the nature of this process, the pins were found under inspection of the CNC Smartscope (see figure 3.70), to be slightly inconsistent in hole diameter in both shape and size (see figure 3.74), they also presented blockages (see figure 3.75) which required cleaning using a citric acid solution in an ultrasonic bath, followed by isopropanol alcohol to clear the remaining debris and then threaded with wire to ensure the blockage was clear (see figures 3.72 and 3.73).

Whilst the pins arrived in two batches (one for the short pins, one for the long pins). It was clear upon attempting to insert the pins into the injection molded inserts, that there was a variation in the long pin batch. Figure 3.76 displays the results of measuring 420 long pin outer diameters using a digital micrometer, it shows a two-peak distribution of the measurements - one at the lower tolerance specified, one at the upper tolerance specified. This could indicated that the pins were actually made in two batches, hence the variation in outer diameters. As a result of this, the upper tolerance pins were too wide for the injection molded inserts and had to be discarded.
Figure 3.70: Measuring pin hole diameters using Measure X software with OGP Smartscope CNC 625
Figure 3.71: Pin 1 - top view taken on OGP CNC625 Smartscope with two different magnifications

Figure 3.72: Pin 23 - top view taken on OGP CNC625 Smartscope with two different magnifications with 25µm wire through pin hole

Figure 3.73: Pin 24 - top view taken on OGP CNC625 Smartscope with two different magnifications with 100µm wire through pin hole
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Figure 3.74: Two different pins- top view taken on OGP CNC625 Smartscope both x148 magnification, showing different size holes. Pin 28 (b) also shows a hole blockage.

Figure 3.75: Two different pins- top view taken on OGP CNC625 Smartscope both x287 magnification, showing different size holes. Irregularity also seen with hole shape.
Figure 3.76: Measurements of long pin outer diameters using digital micrometer.
### 3.5.4 Pin annealing

Both short and long pins for the tracker modules, prior to production, were originally both of the same material, same coating and both not annealed. The long pins were machine crimped to ensure a successful and uniform crimp to hold the gold-plated tungsten wire under tension. The long pins were pre-crimped with the wire on an LRX Plus material tester to a set depth, however, due to the geometry of the pins within the manifold, it was not possible to machine crimp the short pin when inserted into the module. It was also found that attempting to hand crimp these original short pins did not apply enough force to crush the pin to hold the wire in place. Therefore, it was investigated as to whether annealing the short pins would make them malleable enough for a sufficient hand crimp of the pin to hold the wire at tension without slipping. As the short pins did not hold the ASDQ card and were effectively “dead ends”, it was deemed that annealing would be a possible avenue and would not affect the performance of the module, providing that the pins were not crimped at too great a force to fracture the wire inside. As the department workshop hand designed a hand crimp tool with accurate crimp depth using wire erosion on the tool to create a depth of 0.97 mm, they were able to replicate this tool as an adaption to the LRX Plus materials tester to crush the pins to the same depth to test crushing pins with a measurable force.

Using a furnace at the University of Liverpool, a batch of short pins (originally not-annealed) were annealed at 700°C for one hour. These annealed pins along with a batch of short pins that were not annealed, were crushed at the set depth on the LRX Plus materials tester and the force applied measured. It can be seen in figure 3.79 that the load required to crush the annealed pins at the set depth was less that of the non-annealed pins. Both batches of pins presented a linear elasticity where the annealed pins reached a level of perfect plasticity at the crimp depth and the non-annealed pins had a more gradual non-linear elasticity before a plasticity region before the crimp depth was reached.

Handcrimping a batch of annealed pins also confirmed the use of less force on the annealed pins to achieve the required crimp depth, achieving an average crimp depth of 0.715 mm +/- 0.03 mm across the flats of the crimp using an RS Pro 150 mm digital vernier caliper.

The initial investigation to achieve an effective crimp with annealed pins was successful. However,
it was seen that the gold coating was damaged during the annealing process at the University of Liverpool. Therefore, an alteration to the specification for the manufacturers to anneal the pins prior to coating with gold was made.

### 3.5.5 ASDQ card extraction and insertion

In the event of a channel not registering hits in a module cosmic run quality test, several reasons are considered as to the cause. A process was designed and followed to find the cause of the channel failure, with minimal disturbance to the module as possible. In the event that all the electronics connections have been checked and deemed working (by way of ASDQ pulse testing, rotating the module, changing connections to the FLOBBER); a channel failing to register hits could be due to a wire failure - a break or a slip in the crimp of the pin, this would be a “worst case scenario” requiring the module to be disassembled down to removing one or several ASDQs to restring the failed wire.

ASDQ removal from a module was tried and tested prior to production for use in the event of a wire failure, requiring module restringing. Due to the shape of the ASDQ boards in the manifolds, it
was deemed too difficult to remove by hand and posed too great a risk of disturbing multiple wires instead of one that required restringing. This resulted in an card extraction tool being designed and built by the University of Liverpool Physics department engineering design team and workshop team, the tool being used and assessed by the technicians in the LSDC cleanroom. The notion of a card insertion tool was also investigated to assess the possible risk of damaging the cards when inserting.

The initial card extraction tests were performed using a spare dummy manifold, pre-populated with top hat aluminium ends, in turn populated with injection moulded inserts with crimped long pins. The pins were secured to the injected moulded inserts (as per production) and the aluminium ends were secured to the manifold with rapid Araldite. Two ASDQ board designs were compared with two different contact sockets onto the pins (see figures 3.78 and 3.79) with a view that the “new socket” would improve contact to the pin with minimal effort of removal. The purpose of the test was to firstly, establish if the new sockets selected by Boston University for the ASDQ boards were suitable for production and secondly to devise a method of ASDQ card extraction that minimised any potential damage to the surrounding pins.

![Old socket](image1) ![New socket](image2)

Figure 3.78: Old socket versus new socket for ASDQ card connectors - taken on OGP CNC625 Smartscope at x110 (old) and x178 (new) magnification

The ‘old socket’ on board 1 required 24 N of force to remove the card (1.5N per pin) and the “new socket” on board 0435 required 8.0 N of force to remove the card (0.5 N per pin), according to the manufacturer’s specification. The “old sockets” on version3 ASDQ card were using the using
MillMax 02 multi-finger contact sockets and the ‘new sockets’ on version4 ASDQ card were using the MillMax 03 multi-finger contact sockets.

For the first test, using the LRX Plus Material Tester, a card was mounted onto 16 pins dummy manifold and four long steel wires connected between the card (one connection at each corner) and the material tester. The card is manually inserted onto the pins. Wire is secured at each corner of the card and then secured to the central probe. This wire was measured in length to ensure even force was applied. The probe would lift, firstly taking the slack of the wire. It would then continue to lift with an increasing force until there was a sharp drop in load — indicating the card was extracted from the pins. This was done using an automated program. The material tester would pull the card from the pins in a vertical direction, the fail load was set to 50 N. The test was time limited, so was repeated 5 times on each card.

Due to the pins being angled to ±7.5° to the vertical, in order to not damage the pins in the test,
and better represent how we wish to do design the extractor, the manifold was mounted at 7.5° on a 5" sine bar using precision slip gauges (16.58 mm stacked height) and clamped to the material tester base to prevent movement during the extraction.
Figure 3.80: ASDQ card extraction tests using the LRX Plus Materials Tester in the LSDC with sine bar and dummy manifold.
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Figure 3.81: Version 3 card extraction on LRX Plus materials tester

Figure 3.82: Version 4 card extraction on LRX Plus materials tester
Using the same mount on the LRX Plus materials tester with the sine bar, slip gauges, manifold, the motion of the probe was reversed to simulate ASDQ insertion.

The ASDQ card was aligned onto the pins but not inserted, the probe was then carefully driven down onto the center of the cards and the force required for proper insertion was monitored see figure 3.83.

![Diagram](image)

Figure 3.83: Version 4 card insertion on LRX Plus materials tester compared with manufacturer model of the sockets

The manufacturer states that the values given in the catalogue were taken using bullet shaped gauge pins. As the pins used for the modules are not bullet shaped, it can be assumed the flat
edge of the pin is creating the greater load seen at the beginning of the graph in figure 3.83 for initial insertion. However, this force is significantly reduced later to an average of 18.8 N for the OLD 02 sockets and 14.7 N NEW 03 sockets as the contacts begin to open. The sharp rise at the end of the graph indicates the card is inserted fully.

The conclusion is the version 4 card with 03 sockets are more easily extracted and inserted than the version 3 card 02 sockets from 16 pins. The shape of the pins creates an initial higher insertion force, which decreases for the majority of the card insertion. These initial insertion forces match to those shown in the manufacturer’s data. The extraction forces also match closely to that of the manufacturer data. The maximum load for insertion on the NEW 03 sockets from these tests is 21.2 N and for the extraction is 15.1 N. As a result of these tests, conducted by the author, the procedure adopted was that the cards are inserted manually and extracted using an extraction tool.
3.5.6 Electronics Testing

First tests of the Data Acquisition (DAQ), require testing the readout electronics for their level of residual noise, the threshold being 200 mV. Each of the 16 channels on the ASDQ board are thus tested at low voltage and high voltage at values of 1000 V, 1250 V and at the gas operating voltage for Ar:CO$_2$ of 1500 V. The behavior for all channels at all voltages should be identical, showing a small rise before 200 mV in the mean number of hits per trigger for that channel, and then a return to zero. Typically 2000 mean hits are expected below 200 mV in noise scan testing, see Figure 3.86. Any channel not following this behavior would indicate a faulty connection to the wire or a requirement for high voltage training of that wire due to potential contamination.

![Figure 3.84: Noise scan result at low voltage for TDC0 (one of two TDC chips on TDC motherboard) Logic Board 1 Module 5](image)

High voltage training of a wire is only required when it has failed the noise scan section of the DAQ QA, see figures 3.86 and 3.85. This is evidence when noise is apparent above the 200 mV of the readout electronics from the ASDQ board. High voltage training requires using the CAEN power supply as the supply for the module and ramping up the voltage for each of the module’s eight HV channels firstly in 100 V increments to indicate where the HV channel trips. At this stage only a 1 µA current is required until a channel trip is evident. If a channel trip occurs, the current can be raised to a maximum of 3 µA and left for a minimum of one hour. Wire training may be required, due to contamination on the wire.

Temperature readouts from the ASDQ boards were also performed to check the effectiveness of the
Figure 3.85: High voltage wire training on 3 wires for module 6 shown in the DQM.

Figure 3.86: High voltage wire training on 3 wires for module 6.

heat sinks. Figure 3.87 shows the readout from module 15 ASDQs every 30 seconds.
Figure 3.87: Temperature readout of the top manifold ASDQs from module 15 - readout every 30 seconds.
Chapter 4

E989 Muon g-2 Tracker Module Performance

4.1 Module Performance at University of Liverpool

A total of 22 tracker modules were built by the University of Liverpool for the E989 experiment. Modules 00, 0, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 and 21; were all successfully built and quality tested at Liverpool before shipping to Fermilab, only module 3 failed quality testing.

Module 3 failed at the module pressure testing stage, where multiple leaks were observed around the straws. Submersion of the module in de-ionised water whilst flowing gas through the sealed module confirmed this, as gas bubbles leaking from the module were clearly visible. Multiple leaks were detected, but their locations were difficult to identify. It was decided not to use this module as it became far too time consuming to locate the individual leaks for repair. Module 3 has instead been used as a dummy module for alignment techniques by technicians at Fermilab (under non-vacuum conditions, without electronics or sense wires). It has also been useful for testing whether the tracking modules will fit into certain positions, for example when designing the transport devices around the Fermilab campus.
Only one module needed HV training on multiple wires. Module 6 had three wires that were successfully HV trained in this manner and found to have a normal noise scan on re-testing. The Data Quality Management tool (DQM) was used during a cosmic data run of Module 6, and showed the impact of the wire training over time, with the amount of hits per noisy channel decreasing the AMC13 event size with a high, constant current over time (see figure 4.3). These wires were not apparent in the initial noise scans and only later found during a cosmic data run. In a cosmic data run all 128 channels should present approximately the same amount of hits over a minimum of four hours. Noisy channels can present 1000 times the amount of the normal channel cosmic hit rate (see Figure 3.85 for a typical noisy channel display).

The DQM displays were not only useful when testing the modules at Liverpool, but also enabled...
the users to become familiar with the MIDAS software, and monitoring pages which were to be used when running the main experiment. Many of the histograms used to monitor the health of the installed modules at Fermilab were developed during the testing at Liverpool.

### 4.2 Cosmic Data Tests

Where possible, the modules underwent cosmic data tests, where the modules were orientated inside the vacuum tank such that the plane of straw face was pointing vertically, so that vertical cosmics would pass through all the layers. The modules were typically left overnight, with the HV on and the readout connected to the MIDAS software, so that the data was recorded. If time did not allow for this simple source tests were performed to ensure that all channels were reading out properly. The overnight tests were preferable as it also gave us confidence that the straws could continue to operate, holding their voltage, under vacuum for long periods of time. The vacuum level was recorded after each of these tests. A description of the results from the cosmic tests from 5 modules is given below.

Module 4, run number 1753 in MIDAS was a cosmic data run under vacuum, for approximately 11 hours. 40213 events were recorded by the AMC13 for the whole module during that time with all HV channels holding at 1496 V and at 1 µA. The vacuum pressure in the tank recorded at the end of this run was at 8.6 \times 10^{-6} \text{ mbar}. Figure 4.2 displays the ROOT output of the data from MIDAS, the x axis providing each channel number (wire within the module on one row of 32 channels, with three more rows behind (4 x 32 channels = 128 wires per module for U and V layers). A relatively even number of cosmic hits can be seen across all channels with a mean in Y axis for cosmic hits being 1.429 with a standard deviation of 1.095σ. This is an example of a typical cosmic run and constitutes a fully functioning module, that is ready for shipment to Fermilab.

Module 5 was placed into the vacuum tank for run number 1781 in MIDAS, which is another cosmic data run under vacuum, for approximately 9.5 hours. 34418 events were recorded by the AMC13 for the whole module during that time with all HV channels holding at approximately 1496 V and at 1 µA. The vacuum pressure in the tank recorded at the end of this run being at 1.9 \times 10^{-6} \text{ mbar}. The difference in this vacuum level as compared to the previous module is within
the typical observed difference for different pump downs, and can be attributed to the temperature variation and out gassing of the tank. It is not entirely due to a lower leak rate of the straws.

Figures 4.3 display the ROOT output of the data from MIDAS taken during a cosmic data. A relatively even number of cosmic hits can be seen across all channels, although a slight increase towards the flange end (channel 0) of the module, with a mean in Y axis for cosmic hits being 1.448 with a standard deviation of 1.133σ. This is still an acceptable variation, consistent with all straws behaving correctly.
Module 6, run number 1784 in MIDAS provides a cosmic data run under vacuum, for approximately 8.25 hours. 25497 events were recorded by the AMC13 for the whole module during that time with all HV channels holding at 1497\(\text{V}\) and at 1\(\mu\text{A}\). The vacuum pressure in the tank recorded at the end of this run was at 1.55\(\times 10^{-6}\text{mbar}\). The number of hits across all channels is consistent with a flat distribution, with a mean in Y axis for cosmic hits being 1.485 with a standard deviation of 1.119\(\sigma\), seen in figure 4.4.

![Figure 4.4: Tracker module 6 cosmic data result - run 1784.](image)

Module 8, run number 1803 in MIDAS provides a cosmic data run under vacuum, for approximately 8 hours. The vacuum pressure in the tank recorded at the end of this run being at 5.1\(\times 10^{-7}\text{mbar}\). Figure 4.5 displays ROOT output of the data from MIDAS. Once again, a relatively even spread in the number of cosmic hits can be seen across all channels with a mean in Y axis for cosmic hits 1.484 with a standard deviation of 1.115\(\sigma\).

Module 9 run number 1718 in MIDAS provides a cosmic data run under vacuum, for approximately 10 hours. The vacuum pressure in the tank recorded at the end of this run being at 2\(\times 10^{-6}\text{mbar}\). Figure 4.6 displays ROOT output of the data from MIDAS. A relatively even number of cosmic hits can be seen across all channels with a mean in Y axis for cosmic hits 1.498 with a standard deviation of 1.115\(\sigma\).

The cosmic tests were the final stage of testing at Liverpool. After these successful tests the module were cleaned, and packed into the dedicated pelicases for shipment to Fermilab. The pelicases were
just small enough so that the modules could be taken on as hand luggage. Where possible a single flight was booked, to minimise the risk of damaging the modules during take off and landing. The cabin pressure is kept fairly constant, but can drop as much as 20%. When packing the modules for shipment the gas inlets and outlet were covered to prevent dust entering the modules, but not sealed, so that the straws were never in danger of being under-pressured with respect to their surroundings. The straws themselves were kept from harm via custom built perspex cases. The pelicases were also packed with cushioning to minimise the impact of any potential environmental
4.3. MODULE PERFORMANCE AT FERMILAB

When the modules arrived at Fermilab they were taken to Lab 3, a clean room located near the Warrenville entrance to Fermilab, for testing. The author was not directly involved in the testing, although was consulted with any problems observed with the modules, and helped set up the procedures used for handling and testing the modules. Unlike at Liverpool, Fermilab was able to test the modules with a 50 : 50 mixture of Argon Ethane, and even compare the performance of Argon Ethane with the Argon Carbon dioxide.

Figure 4.8 shows a voltage scan of Module 00, the first to arrive at Fermilab. The module was filled with both gases in turn, ensuring that 3 hours of flow between swapping the gases to ensure that the modules were completely filled with the new gas. The Voltage on the wires was varied from 1000V up to 1800V in steps of 20V. A Sr$^{90}$ source, which emits positrons, was placed near the straws. For the purposes of this test only one straw is shown, although data was recorded for more straws. The modules were connected to the full DAQ, in a similar setup to the one at Liverpool, and the hits recorded. As the voltage increases, the number of electrons that make it to the sense...
wire increase. The current caused by these electrons is detected, and registers a hit. Focusing first on the $\text{Ar} : \text{CO}_2$ result, as the voltage is increased from 1000V to 1380V the number of hits per trigger increases, due to the increased current. Initially not all primary ionisations cause enough current to be detected above the threshold, which is set by the user to be just above the noise level, at 200mV. Above 1380 V the number of hits starts to level off. This is because the detector is operating near 100% efficiency; every primary ionisation is causing enough current in the wires to be detected. As you increase the voltage, you are only amplifying the signal. Going beyond 1450 V however the number of hits starts to increase again. This is thought to be due to refiring - where a single hit causes multiple currents, and is read out as 2 separate hits. This can occur when the positive ion (which has lost an electron as the positron passed through) drifts to the straw wall, and causes more ionisations, which create their own signal. Operating in this voltage region is not desirable. The same thing can be observed when the module is filled with $\text{Ar} : \text{C}_2\text{H}_6$, only the 100% efficiency region is more obvious. Figure 4.8 demonstrates a fully working module, and
also shows how the operating voltage range of $1625 - 1650 \text{V}$ was determined, as this is the 100\% efficiency region.

### 4.4 Module Installation at Fermilab

Of the 22 modules that were made at Liverpool, 16 of these modules occupy 2 tracking stations inside the ring in MC-1 at Fermilab. The remaining station has been used for another detector, allowing the remaining 6 modules to act as “spares” in the events of gas leaks, sense wires breakages or readout electronics failures.

For the purposes of record keeping, the installation dates and corresponding muon g-2 elog entries are given here. In general, when deciding which modules went into each slot the straws with the same radii were kept together, although this was not crucial.

The following 16 modules were installed into the E989 experiment on 13th November 2017: in station location C7 there were modules 16, 13, 11, 14, 15, 12, 9 and 17, in station location C10 there were modules 5, 7, 8, 1, 4, 6, 0 and 2 installed and running.

After running all 16 modules it was found that module 1 gave too much noise in it’s data, therefore was replaced by module 18. Module 6 was found to have a leaking straw, so was replaced by module 19. These replacements were made prior to Run I. The following modules were therefore used throughout Run I data taking: in location C7 there were modules 16, 13, 11, 14, 15, 12, 9 and 17, in location C10 there were modules 5, 7, 8, 18, 4, 19, 0 and 2.

Since Run I, two more modules have been replaced at C10 due to minor leaks: module 4 was replaced by module 20 and module 0 was replaced by module 21. As of 15th January 2021, the following modules have been taking data in the ring: in location C7 there are modules 16, 13, 11, 14, 15, 12, 9 and 17 and in location C10 there are modules 5, 7, 8, 18, 20, 19, 21 and 2.

Once the modules were installed into the ring, and the beam was stable, all the modules could be tested at once. Figure 4.9 shows straw hits from all 16 modules. It should be noted that besides the 5 straws which were observed to leak at Liverpool, and were plugged up or removed, all the straws successfully read out hits. The lack of noisy straws is a testament to the design and care
CHAPTER 4. E989 MUON G-2 TRACKER MODULE PERFORMANCE
Figure 4.10: [45] The time taken for the electrons to drift to the sense wire against distance of closest approach of the incident particle. A distribution of the measured drift time for different distances of the track from the wire. This distance is estimated using interpolated tracks that do not use the straw hit. An entire layer of 32 straws is shown in this plot, whereas the time-to-distance parameterization used in the reconstruction is performed on a straw-by-straw basis.

time is 60ns, which is what is expected for Ar : C₂H₆. The DCA on the x axis is the distance of closest approach, which is determined from by the tracking software, which is described in detail in [45].
Figure 4.11: Tracking detector data from a three-day period during Run 1. A cross-section of the stored muon beam from extrapolated tracks after the start of the measurement time at 30 µs. The radial position is measured relative to the design radius of 7112 mm.[45]
Figure 4.12: Tracking detector data from a three-day period during Run 1. The radial and vertical projections, respectively, of the beam cross-section.[45]
Chapter 5

Impact of Measured Straw Angles on the Pitch Correction

The pitch correction was introduced in section 2.4 and chapter 5, and arises due to the non-zero vertical component of the stored muons momenta. It is a beam dynamics related quantity, and since the trackers measure the stored beam during the fills, the trackers are the principle detector used in determining the pitch correction. The author did not directly calculate the pitch correction, details of which can be found in [59]. However, the CMM measurements can be used to place a limit on the maximum angle that the straws can make with the vertical direction, which in turn can be used to constrain the uncertainty in the pitch correction calculation associated with the assumption that the straw angle is at exactly $7.5\degree$. The uncertainty in the straw pitching angle also contributes elsewhere, but the largest impact is in the pitch correction.

Firstly, a look at the impact that changing the straw angle can have on the measured quantities, namely the mean vertical position and mean vertical width of the beam. In order to determine this, the angle of the straws was modified in the GEANT geometry, which is used in the reconstruction for both simulation and data. The vertical distance between the top and bottom manifolds is $L\cos(\theta)$, where $\theta = 7.5\degree$, and $L$ is the straw length, approximately 90.6 cm. Assuming a hole position error of 200 $\mu$m, the corresponding change in the straw angle is $0.1\degree$. This sets the scale
for the variation of straw angle, because we don’t expect the hole position to deviate as much as 200µm, and as such 5 different angle were used, corresponding to the range ±0.15° from nominal. A larger value in angle variation was used to ensure the variation in vertical mean and RMS could be observed. The data were reconstructed separately for each of these different straw angles, and the variation in the vertical width and mean position are given in figures 5.1 and 5.2 respectively.

Figure 5.1: Change in the RMS of the vertical position of the beam for different straw angles, (nominal 7.5°) to the vertical for both stations. Image from Dr. James Mott [60]

The data used in this study corresponds to a full run (a 2 hour period of data taking), taken in 2017, run 15922. This run was used for a variety of different systematic studies, and is actually part of run 1a in the g-2 PRL [39]. The uncertainties are statistical, and give an indication of the agreement between the 2 stations, but it should be noted that since it is the same data for each point (just a slightly different reconstruction) the points are correlated. As might be expected, the change in the average vertical position is negligible. This is because the beam is fairly well
centred vertically, and an increase in the angle affects the vertical position of the higher and lower muons by the same amount, but in opposite directions (it moves the higher hits higher and the lower its lower), such that the mean is fairly constant. With this in mind, it is not surprising that the largest effect is seen on the vertical width of the beam, as characterised by the RMS. A change in straw angle of 0.3° gives a change in width of 0.6 mm. The pitch correction is approximately related to the beam width via

\[ C_p = \frac{\Delta \omega_a}{\omega_a} = -\frac{n}{2R_0^2} < y^2 >. \]  

(5.1)

Here \( n \) is the field index, and is related to the quadrupole strength. For run 15922 this was \( n = 0.108 \). \( R_0 \) is the radius of the storage ring, so the prefactor is approximately \( 1.06 \times 10^{-9} \text{mm}^{-2} \). The typical beam width is 12.5 mm, so inputting this into equation 5.1 gives \( C_p = 167 \text{ ppb} \), which is
Table 5.1: Average straw angle as measured by the CMM, and RMS of the straw angle distribution for each module.

<table>
<thead>
<tr>
<th>Module</th>
<th>$&lt;\Delta \theta&gt;$ [degrees]</th>
<th>$\Delta \theta$ RMS [degrees]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UA</td>
<td>UB</td>
</tr>
<tr>
<td>1</td>
<td>0.011</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
<td>-0.041</td>
<td>-0.065</td>
</tr>
<tr>
<td>5</td>
<td>0.044</td>
<td>0.035</td>
</tr>
<tr>
<td>6</td>
<td>-0.021</td>
<td>-0.034</td>
</tr>
<tr>
<td>7</td>
<td>0.036</td>
<td>0.031</td>
</tr>
<tr>
<td>8</td>
<td>0.016</td>
<td>0.011</td>
</tr>
<tr>
<td>10</td>
<td>-0.028</td>
<td>-0.028</td>
</tr>
<tr>
<td>11</td>
<td>0.002</td>
<td>-0.001</td>
</tr>
<tr>
<td>12</td>
<td>0.036</td>
<td>0.037</td>
</tr>
<tr>
<td>13</td>
<td>-0.025</td>
<td>-0.014</td>
</tr>
<tr>
<td>14</td>
<td>-0.020</td>
<td>-0.018</td>
</tr>
<tr>
<td>15</td>
<td>-0.007</td>
<td>-0.013</td>
</tr>
<tr>
<td>16</td>
<td>-0.002</td>
<td>0.014</td>
</tr>
<tr>
<td>17</td>
<td>0.002</td>
<td>0.016</td>
</tr>
<tr>
<td>18</td>
<td>-0.001</td>
<td>-0.007</td>
</tr>
<tr>
<td>19</td>
<td>0.067</td>
<td>0.051</td>
</tr>
<tr>
<td>20</td>
<td>-0.075</td>
<td>-0.087</td>
</tr>
<tr>
<td>21</td>
<td>-0.143</td>
<td>-0.124</td>
</tr>
</tbody>
</table>

A typical value for the pitch correction. This equation can also be used to determine the impact of a mis-measurement of the straw angle on the pitch correction, $\Delta C_p = 8\, \text{ppb}$ for a change in straw angle of 0.3. This in turn yields $\Delta C_p / \Delta \theta = 27\, \text{ppb per degree}$. The error budget for the pitch correction, for the final dataset is actually only 10ppb, although for the limited statistics of run 1 anything under 30ppb was acceptable. The CMM data can now be used to measure the deviation in hole positions, and corresponding change in the straw angle. This is only possible because the hole positions in each manifold were measured separately, and the manifolds used for each module were recorded. The straw angle was determined by taking the central hole position for each straw of the top and bottom manifold for each module. The variation in the straw angles is displayed in figures 5.3, 5.4 and 5.5, and summarised in table 5.1.

Ideally, these data could be inputted into the GEANT model, so that each straw was rotated to the as measured value for the straw angle. However, due to the uniformity of the distributions, and the precision to which the manifolds were made, this was deemed unnecessary. The observed deviation in straw angles, neglecting the sign, is covered by 0.17.5. This corresponds to a change
in the pitch correction of only 2.7 ppb, well below the budgeted uncertainty. It must be kept in mind that this is the impact of all straws moving by the same amount, whereas in real life there is a spread around the average straw angle of 7.5°, which will reduce this uncertainty even further.
CHAPTER 5. IMPACT OF MEASURED STRAW ANGLES ON THE PITCH CORRECTION

Figure 5.3: Straw angle variation for modules 1 to 8, as determined by measurements from the CMM.
Figure 5.4: Straw angle variation for modules 10 to 15, as determined by measurements from the CMM.
CHAPTER 5. IMPACT OF MEASURED STRAW ANGLES ON THE PITCH CORRECTION

Figure 5.5: Straw angle variation for modules 16 to 21, as determined by measurements from the CMM.
Chapter 6

Current Status and Outlook

22 tracker modules were built and tested at the University of Liverpool, which were transported to Fermilab by aeroplane, tested and commissioned for the E989 muon g-2 experiment located in MC-1 building at Fermi National Accelerator Laboratory, Illinois, USA. Of the 22 modules built, 16 at any one time were occupied and collecting data within the ring and are still. Of the 22 modules built, 4 have required replacing in the ring over the last 4 years due to faults: module 1 due to noise, module 6 due to a leaking straw, module 4 due to minor gas leaks and module 6 due to minor gas leaks. All of these modules were early modules made with PPG3 ‘old’ straws. The cause behind these failures are unclear, but it would be reasonable to assume that ageing of the signal wires may have contributed to the noise in module 1. All of the leak failures occurred in station located at Chamber 10, however, as these were all early built modules, it could be assumed that the life span of the straws, or indeed the straw to gas seal glue seam, had reached its limitations.

7th April 2021 saw the unveiling of the Run I data unblinded result giving the E989 current measurement of the positive muon anomalous magnetic moment to 0.46 ppm [39]. Three data runs have now been completed, with Run IV coming to the end of data taking see Figure 6.1. The result published by the E989 collaboration was given as $a_\mu(\text{FNAL})=116592040(54)\times10^{-11}$ (0.46 ppm), $3.3\sigma$ greater than the standard model prediction and is in agreement with the previous Brookhaven National Laboratory (BNL) E821 measurement - combining previous measurements of both $\mu^+$
and $\mu^{-}$, gives the experimental average of $a_\mu(\text{Exp}) = 1.1592061(41) \times 10^{-11}$ (0.35 ppm), this has increased the tension between experiment and theory to 4.2 standard deviations [39].

The E989 Collaboration continues to work on improving this result through the analysis of the future data Runs. The so-far improved accuracy of the result can be attributed to the improvement on the systematic uncertainties as required by the E989 Technical Design Report [31]. Precision manufacture, build and test of the new detectors in this upgrade experiment from E821, such as the introduction of the straw tracker modules, has helped make this possible, by meeting the specifications of the build.

![Figure 6.1: E989 current status and run data projection [39]](image)

Each metrology result, from the centrality of the pin holes to the CMM measurement of the manifold hole positions, contributes to the systematic uncertainty being better understood in the tracking data. Thorough quality assurance and testing procedures helps to ensure longevity of the tracker modules installed, improving hardware reliability for the experiment. Documentation of
each of these procedures through accessible database then allows for traceability and evidence for potential future improvements on the experiment.

The unblinding of the Run 1 data gives great anticipation for potential new physics and release of the subsequent run data, will only look to improve of the current published systematic result. [39].

Figure 6.2: Statistical comparison of the standard model prediction compare to the experiment average of E989 and E821 $a_\mu$ result from E989 Run I [39]
The ultimate precision of the experiment would not have been achieved without the precision build and rigorous quality testing of the tracker modules. The author was dedicated to this task from the prototype build through to commissioning and first 3 data runs of the experiment, having written the build procedures, built the modules, performed the quality testing on each module built in Liverpool and then delivering the modules for commissioning at FNAL. The author also took part in several data run shifts at FNAL when the modules were installed, including being on shift for the first milestone of meeting the same collection of raw positron data as BNL E821.

The quality control and quality assurance tests described in this thesis, which were either led by the author or assisted by, played a vital role in optimising the design and build of the experiment to achieve high performing modules which have exceeded expectations on their lifespan and data acquisition. The work of the author has also added a layer of traceability to the data enabling technicians and research staff at Fermilab to repair or replace modules with confidence in the case of failures.

The comprehensive and in depth testing of each component, which the author has done at every stage of the module build, has therefore produced modules of a high performance rate and reliability, enabling the experiment to achieve the data run milestones required for successful analysis of the data obtained.
Bibliography


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