Fermi National Accelerator Laboratory

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Final Report

Measurement of the gas gain and understanding the gas flow in the Mu2e Tracker

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Abstract

The Mu2e experiment will search for the charged-lepton flavor violating (CLFV) neutrinoless conversion of a negative muon into an electron in the field of an Aluminum nucleus $\mu^- N \rightarrow e^- N$. The signature of this process is the emission of a monochromatic electron with an energy of 104.97 MeV. The Mu2e Tracker is a low mass straw tube detector, whose aim is to measure the position and the momentum of the electron.
In past measurements, high values of currents were found in some panels of the Tracker in absence of any radioactive sources. In this report new measurements of currents, that were taken with the panel MN084 of the Mu2e Tracker are described. Moreover, the addition of a small amount of water vapour in the gas mixture and the influence of the environmental conditions on the currents of the panel are studied.

Contents

Introduction

Theoretical Background

According to the Standard Model (SM), muons decay into electrons with the emission of two neutrinos: $\mu \rightarrow e\nu_\mu\overline{\nu}_e$ in a decay time of $2.2\,\mu s$. In this process both the individual and the total lepton numbers between the initial and final states are preserved.
The individual lepton number is an accidental conserved quantity in the SM with strictly massless neutrinos. However, several experiments have established that neutrinos do oscillate from one flavor to another. This implies that neutrinos have masses different from zero and the lepton number can be violated[4].
The Mu2e experiment will search for the charged-lepton flavor violating (CLFV) neutrino-less conversion of a negative muon into an electron in the field of an Aluminum nucleus $\mu^- N \rightarrow e^- N$ by measuring the ratio

$$R_{\mu e} = \frac{\mu^- N \rightarrow e^- N}{\mu^- N \rightarrow \text{all muon captures}} \tag{1}$$

Even introducing neutrino masses, the probability for this process to happen is $< 10^{-54}$, since it is suppressed by terms proportional to $\left(\Delta_{ij}{}^2/M_W{}^2\right)^2$, where Δ_{ij} is the ratio of the mass-squared difference of neutrinos and M_W is the mass of the W boson[1]. Other theoretical models beyond the SM estimate this conversion to happen with a higher probability. Therefore, the observation of this decay at the sensitivity of today's experiments can be related to New Physics.
The best experimental limit on muon-to-electron conversion, $R_{\mu e} < 7 \cdot 10^{-13}$ (90% CL), is from the SINDRUM II experiment[3]. The expected single-event sensitivity probed by Mu2e is $R_{\mu e} = 3 \cdot 10^{-17}$, almost a 4 orders of magnitude improvement over the existing limit[1].

Overview

The aim of this report is to summarize the results I have obtained in the 2-month internship at Fermilab working with the Mu2e Tracker group.
This report is divided into 4 chapters: in the first one the Mu2e experiment is described, with a particular focus on the Tracker and its smallest module: the panel.
In the second chapter, the main topic of this report is introduced, that is the presence of high currents observed in the panel MN084 when no source is present. Besides this, the way in which a measurement of a current is performed in a panel of the Mu2e Tracker is described.
In the last chapter, the data I have collected at Fermilab are shown together with the description of the effects caused on the currents by the environmental conditions and the introduction of water vapour in the gas mixture.
In the end, some conclusions and perspectives are outlined

Chapter 1

Mu2e Experiment

1.1 Mu2e at Fermilab

Muons are unstable particles that can be obtained as decay products of pions. Hence, in order to produce a beam of muons, a complex system of solenoids is required.
Mu2e will use a proton pulsed beam, with which $3.9 \cdot 10^7$ protons with a kinetic energy of 8 GeV will enter in the Production Solenoid (PS) every 1.7 ns, the revolution period in the Fermilab Delivery Ring[1].
Protons will strike a radiatively cooled tungsten target (Production Target), leading to the production of charged and neutral pions, among others. Backwards-going charged pions will mainly decay into muons: $\pi^- \to \mu^- \overline{\nu}_\mu$, that will compose the final Mu2e muon beam[1].
The S-shaped Transport Solenoid (TS) provides additional length for pions to decay and it is used in order not to transmit photons, positive muons, and high momentum particles[2]. The muon beam finally reaches the Detector Solenoid (DS), where it hits an Al target (Stopping Target) (Fig. 1.1).

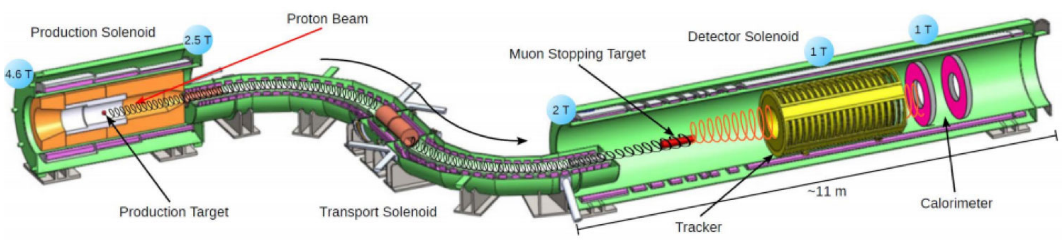


Figure 1.1: Experimental setup of Mu2e

Once the muon is stopped in the target, a muonic atom is formed with the muon in the 1S orbital. When this happens, three outcomes are possible

- The muon decays in orbit ($\approx 40\%$)
- The muon is captured by the nucleus ($\approx 60\%$)
- The muons converts into an electron

The signature of the last process is the emission of a monochromatic electron with an energy of

$$E_e = m_\mu - B_\mu - E_{\text{rec}} = 104.97\,\text{MeV} \tag{1.1}$$

where m_μ is the muon mass, B_μ is the binding energy of the muon and E_{rec} is the nuclear recoil energy.

The emitted electron will be eventually detected by the Tracker and the Calorimeter.

[1] The latter are related to beam flash. to be deepened

1.2 The Mu2e Tracker

The Mu2e Tracker is designed to accurately measure the trajectory of electrons in a uniform magnetic field of 1 T in order to determine their momenta. The Tracker is a low mass straw tube detector with a required momentum resolution of less than 180 keV/c [1]. The detector is still under construction at Fermilab.

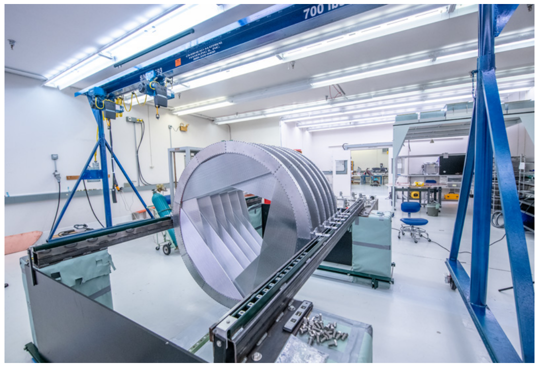


Figure 1.2: Mu2e Tracker in the cleanroom at Fermilab

1.2.1 The panel

The smallest module the Tracker is composed of is called the "panel" (Fig. 1.3). One panel has 96 aluminized Mylar straws with a 5 mm diameter and 15 μm walls. The straws are positioned in a layered configuration and cover a 120° arc. A 25 μm tungsten sense wire is centered in each straw.

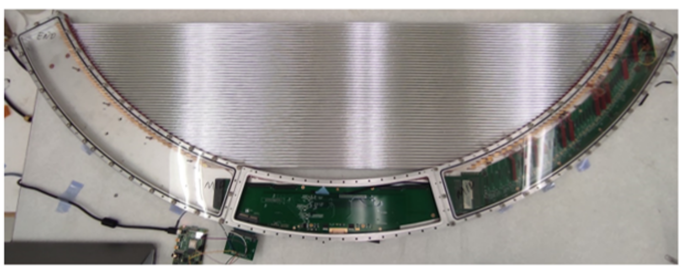
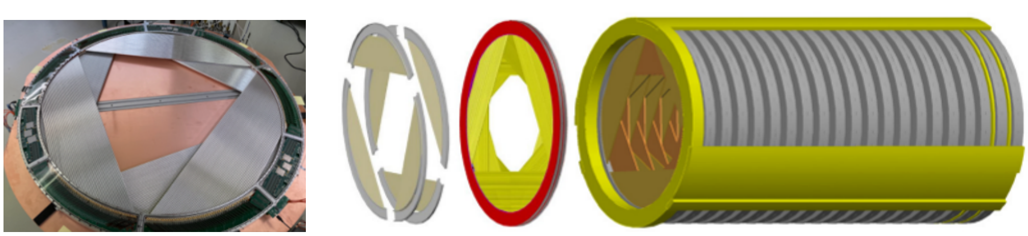


Figure 1.3: Panel MN084 of the Tracker

Six panels rotated by 30° form one plane (Fig. 1.4a). Two assembled planes form one station and the final Mu2e Tracker will host 18 stations, equally spaced along the beam axis, resulting in 20736 straws (Fig. 1.4b). Straws cover the radial area from 300 mm to 700 mm where the detector is sensitive to conversion electrons, whereas most of the electron coming from the decay in orbit (DIO) are not detected. The used gas mixture is made of Ar-CO_2 (80:20) at 15 psid and the detector will operate at 1.5 kV.



(a) A plane of the Tracker

(b) Scheme of a panels, planes, stations

Figure 1.4

Chapter 2

High currents in the panel MN084

In any gaseous detector, the increase of the voltage between the cathode and the anode implies the increase of the gain of the detector, up to a certain limit. This means that for each electron-ion pair created in the ionization process of the medium, secondary electrons are produced by an avalanche process.
However, if one performs measurement without any sources, that means no electron-ion pairs in the medium are supposed to be produced, very small currents are expected to be measured, regardless of the value of the gain. Unexpected high currents were measured in the panels of the Mu2e Tracker in absence of sources. An example of this can be seen in Fig. 2.1.

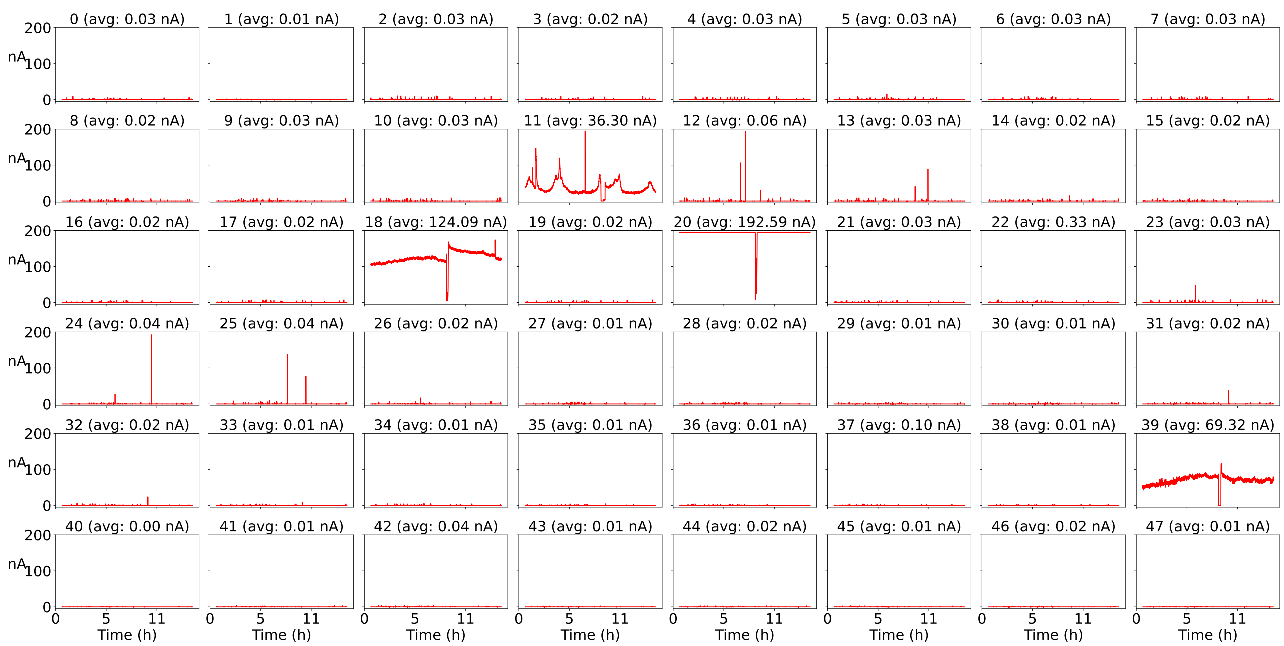
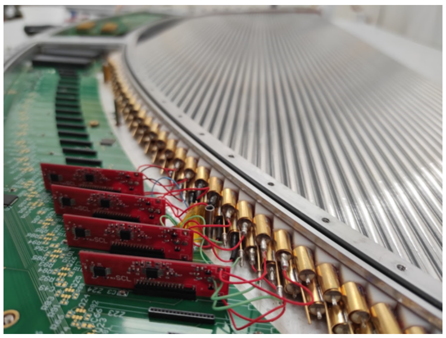


Figure 2.1: 48 currents of Panel MN084 measured in February 2022

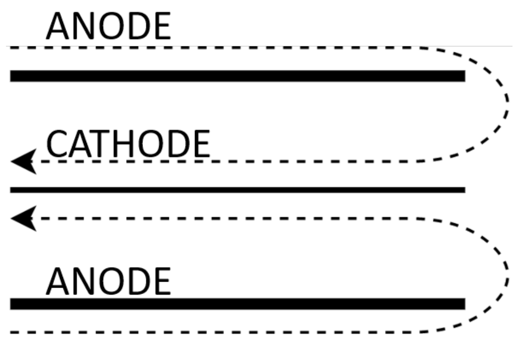
This measurement was taken in February 2022 and shows the 48 currents running in the panel MN084 in a 16 hours long measurement. Above each current the average value is written. The way by which a measurement like this is performed will be explained in the next section.
As one can see, most of the currents have a stable average close to zero, usually of few pA. However, some currents have an unexpected behaviour, this can be seen in currents 11, 18, 20 and 39.

2.1 How to measure the current

In a panel of the Mu2e Tracker, the straws are organized in two rows (Fig. 2.2a). Between these two rows containing the sense wires, a row of grounded cathode is present. One upper and one lower anode are connected to the same cathode in pairs.
The measurement of the currents is always performed on the cathode, since this is at low potential and this is what the electronics at our disposal allows us to do. Because of this, one can understand why in all the datasets that will be shown in this report, 48 currents are measured even if 96 Mylar straws are present in each panel.
Two anodes giving contribution to the same current form one *doublet*



(a) A panel seen from the left hand side with 4 slow amplifiers connected



(b) Measurement of one current from two anodes

Figure 2.2

The doublets are numbered from 0 to 47 starting from the farthest from the middle of the panel.
Each straw is in turn numbered in the following way: the upper row of straws has even numbers increasing from the longest to the shortest (0, 2, 4, ...), the lower row has odd numbers increasing in the same way (1, 3, 5, ...). As an example, the straws 0 and 1 form the first doublet.

2.2 Experimental Setup

The experimental setup I have used is composed by the following elements:

- Panel MN084
- Gas Flowmeter
- HV supplier
- 24 Slow amplifiers
- Raspberry Pi

Besides this, two sensors of humidity, temperature, and pressure and additional gas flowmeters were used.

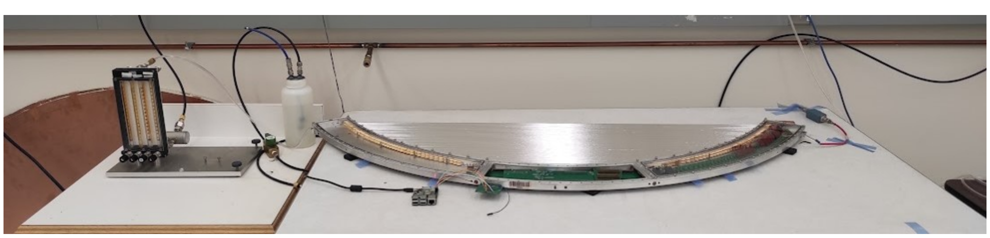


Figure 2.3: Panel MN084 with the gas flowmeter on the left

The working principle is the following: the Ar-CO_2 gas flows from the gas cylinder to the right hand side[1] of the panel passing through the gas flowmeter. The flow rate used is 0.14 SCFH. Then, the gas reaches the left hand side of the panel passing through the straws.
Here, the slow amplifiers are connected to the AMB (Analog Motherboard) and the signal is digitalized, amplified and finally transferred to the DMB (Digital Motherboard), in the middle part of the panel.
In the end, the data are collected and stored by a Raspberry Pi.

The High Voltage (HV) is provided by an HV supplier to the AMB: all the current measurements that are presented in this report are performed at 1450 V subtracting a *pedestal measurement*. The latter consists in a measurement of the currents when the voltage supplied is equal to zero[2]

Each slow amplifier has two independent circuits that can measure two currents and this is the reason why only 24 slow amplifiers are needed to measure 48 currents. They are connected to the DMB and to four anodes and two cathodes of the panel, providing the required HV for the circuit.
Before taking any measurement after a long time in which the gas was not flowing in the panel, a flushing time of nearly one hour is usually waited.

[1]The convention used is opposite with respect to the orientation of Fig. 2.3

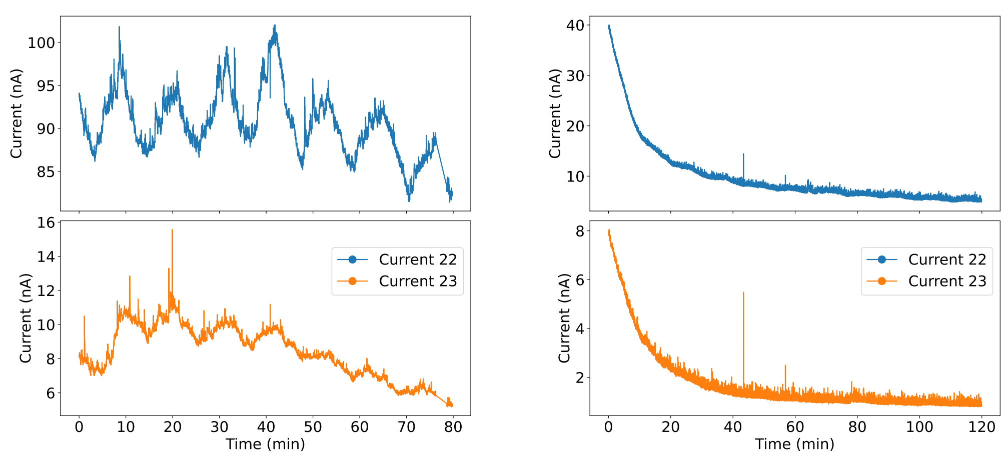
[2]A pedestal measurement is long enough to have a negligible error on the average value, that is usually 10 minutes. The average value of each current when the voltage is zero is subtracted to the data when HV is supplied

Chapter 3

Results

3.1 Initial measurements

In this section, new data collected between July and September 2022 are presented. During the first month a limited number of slow amplifiers was available, this is the reason why an initial complete measurement of all the 48 currents is missing.
In Fig. 3.1a two currents measured on 05^{th}August 2022 for nearly 90 minutes are shown. As one can see, high values of currents were measured in these two doublets taken into account and these values are much higher than the corresponding ones measured in February 2022 (Fig. 2.1).
Besides this, some periodic fluctuations can be seen, this topic will be deepened in Chapter 3.5.
In the next measurements a perceptible decreasing of these currents was observed. The two same currents measured on 10^{th}August are plotted on the right (Fig. 3.1b) and a clear exponentially decreasing trend can be seen.
This effect is referred to as *conditioning effect* and consists in having very high currents the first time HV is supplied and observing a decrease in the currents as the time goes on if the HV is constantly supplied.



(a) 5^{th}August (b) 10^{th}August

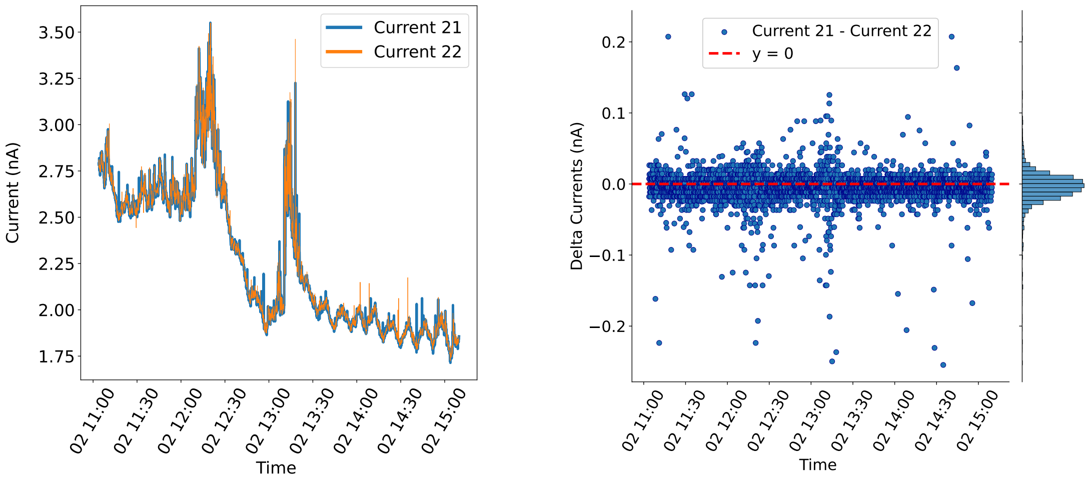
Figure 3.1: Currents in doublets 22 and 23 measured in two different dates

3.2 Two cases of interest

In the first month of internship the panel became well conditioned, reaching a stable situation in the beginning of September. Throughout this interval time, some behaviours of particular currents were investigated and are presented here.

3.2.1 Identical values in neighboring doublets

In several datasets, the two neighboring doublets 21 and 22 have the same identical current as a function of the time as shown in Fig.3.2a. From the plot on the right (Fig. 3.2b), one can see that the difference between the currents running in the two doublets is centered at 0 nA.



(a) Current 21 and 22 as functions of time

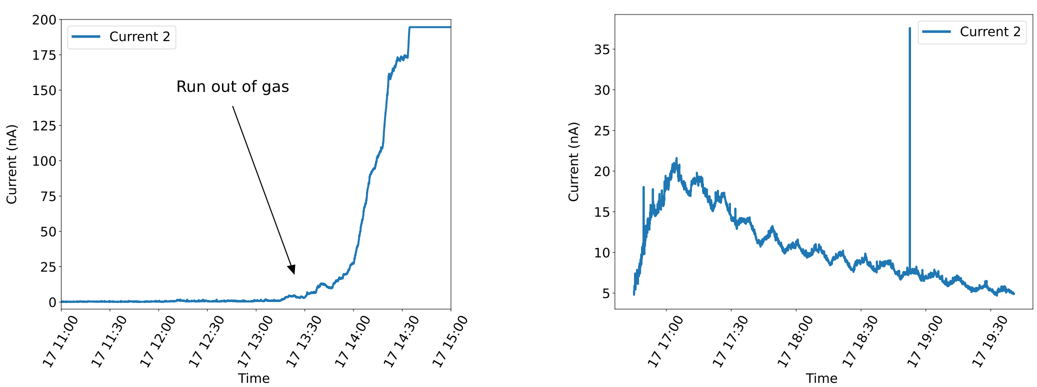
(b) Difference between Current 21 and 22

Figure 3.2: Measurement performed on 2$^{\text{th}}$September

It turned out that the two circuits were shorted due to a component called "ground clip" not well fixed. The latter is silver-epoxied to a pair of neighboring straws forming one doublet. If the ground clip is not stable, it can touch the next cathode, causing the observed short. After fixing this, different currents were correctly measured.

3.2.2 Running out of gas

On 24$^{\text{th}}$August the gas mixture of Ar-CO_2 inside the gas cylinder was consumed. This was an opportunity to see the behaviour of the currents when this happens. In the plots shown below, one can see an increase in the currents rapidly reaching the maximum value (Fig.3.3a), and after the gas cylinder was changed a new shorter phase of reconditioning is observed (Fig. 3.3b). It is noteworthy to say that not all the doublets showed the same rise in the data collected. However, the doublets in which a rise was observed are the same that in future datasets (Fig. 3.4 or Fig. 3.5) continue to show high currents.[1]



(a) Current 2 before running out of gas

(b) Current 2 after the gas cylinder was changed

Figure 3.3: Measurement performed on 24$^{\text{th}}$August

[1]The doublets in which a rise like the one shown was observed are 2, 3, 5, 8, 9, 18, 21, 22. The doublet 14, that will be the one drawing the highest current was disconnected

3.3 Complete measurements

On 30thAugust a complete measurement with all 24 slow amplifiers connected was done (Fig.3.4). Here, the panel is still under a conditioning phase as one can infer looking at the decreasing values of the currents in most of the doublets. One can also recognize that current 21 and 22 are shorted as previously explained.

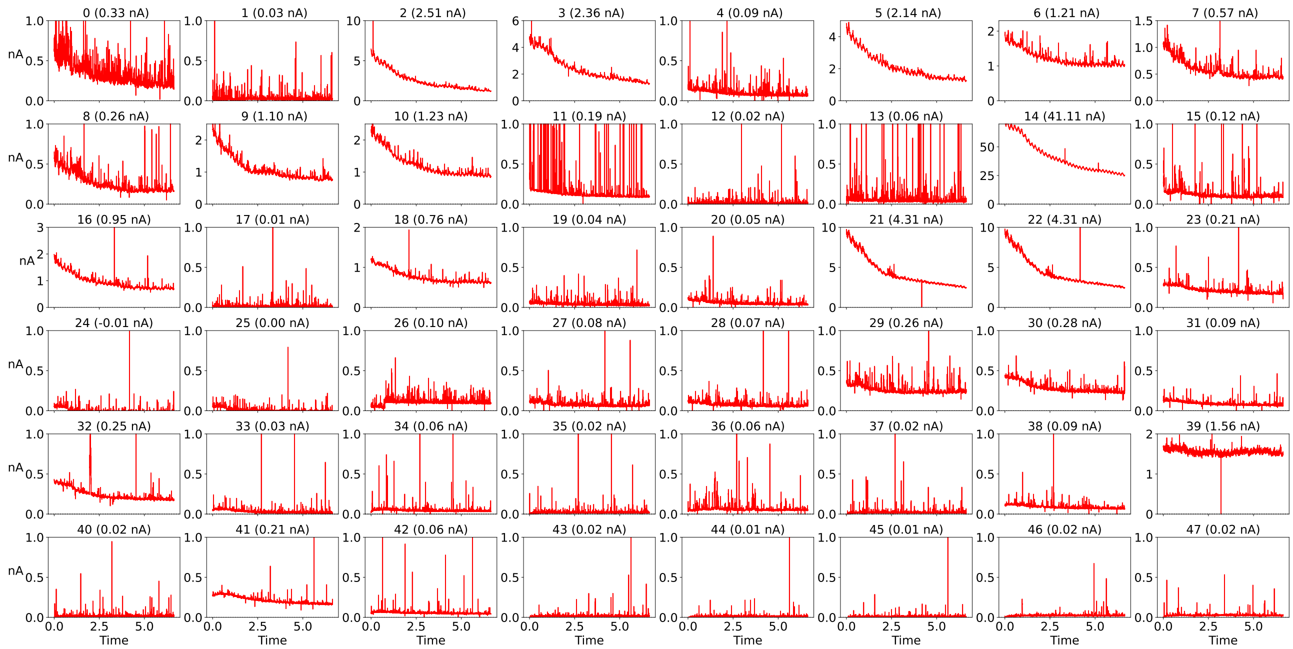


Figure 3.4: 48 currents measured on 30thAugust

A more steady situation was reached on 07 thSeptember and it is presented below in Fig. 3.5. The fluctuations that can be seen in doublets like 5, 10 and 14 are due to environmental effects as it will be shown in Chapter 3.5. The panel is now well conditioned.

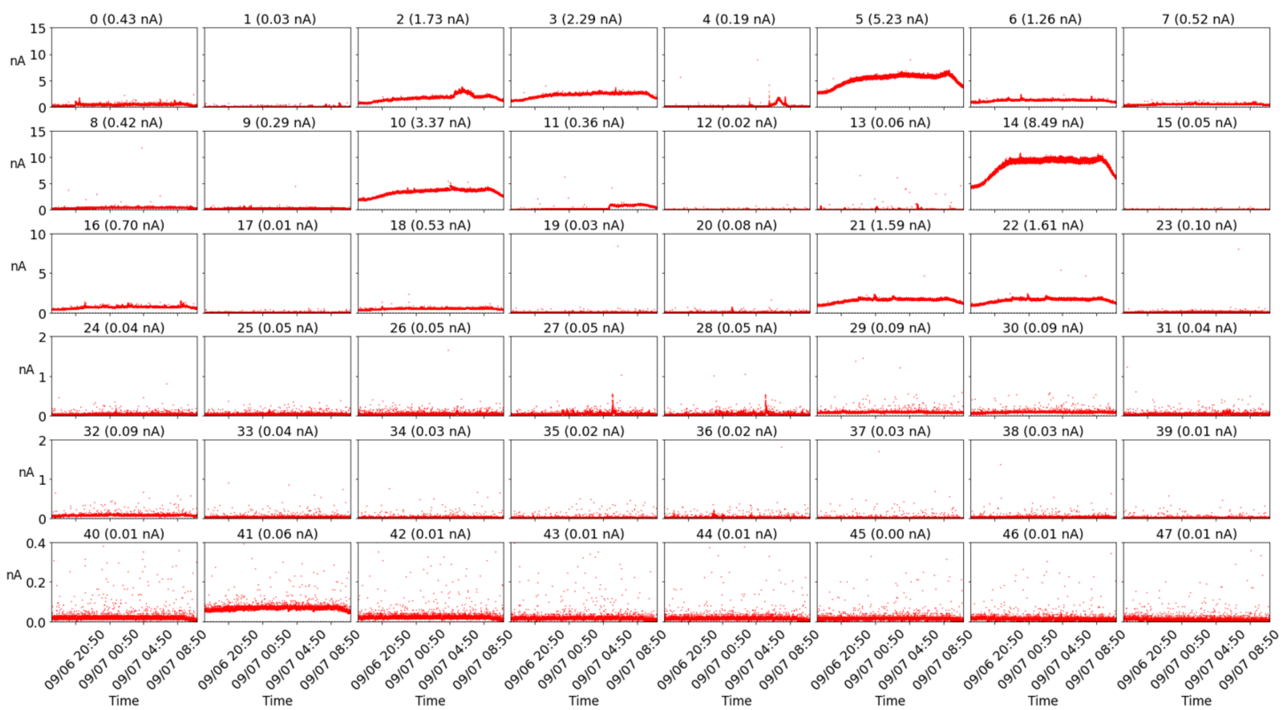


Figure 3.5: 48 currents measured on 7thSeptember. The same y-axis is used for currents in the same row

Now we want to compare the currents measured on the 7^{th}September with the ones measured in February 2022. The result is presented in Fig. 3.6. Currents in red are measured in September and are the ones shown in Fig. 3.5, currents in blue are the ones measured in February 2022 and shown in Fig. 2.1.

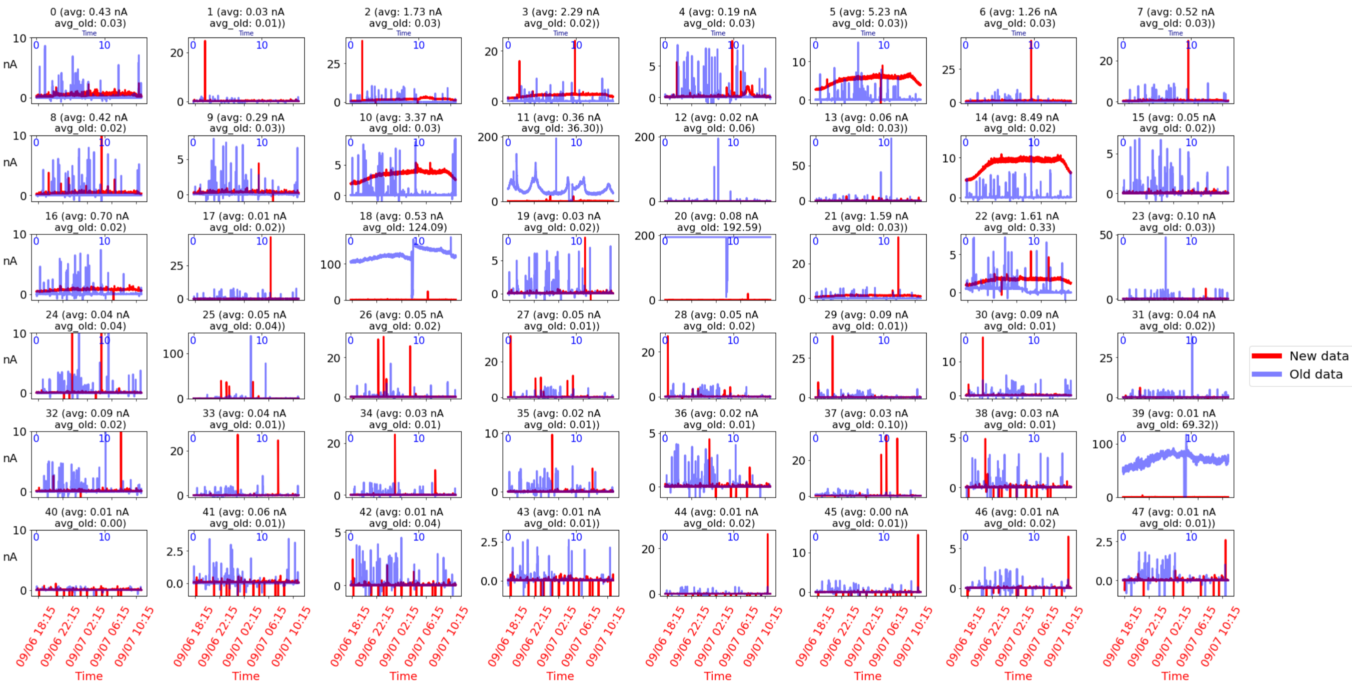


Figure 3.6: Comparison of the previous dataset with measurement of February 2022. The red x-axis refers to the date and time of the data of September, the blue x-axis on top of each subplots refers to data of February and it is expressed in hours from the start of the measurement. The average values of both the datasets are written on top of each subplots

The 4 high currents 11, 18, 20 and 39 are now much smaller, but other doublets draw higher currents than previously measured (5, 10, 14). In order to have a more clear visualization of the improvements, the comparison of the average values is presented (Fig. 3.7).

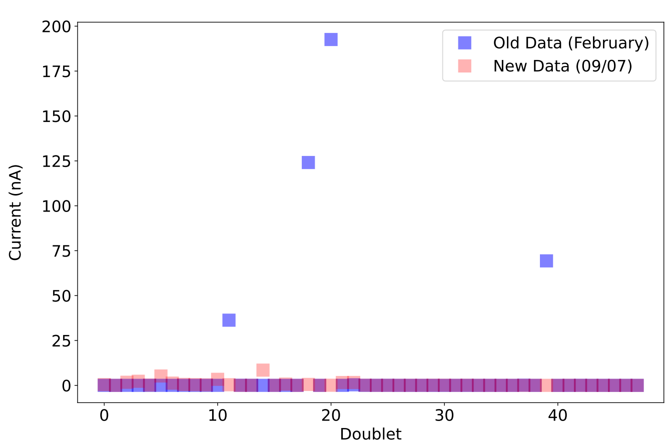


Figure 3.7: Comparison of averages of the dataset of September with the one of February

3.4 Effect of the water vapour

After reaching a stable situation, we studied the consequences of introducing a small percentage of water vapour (1%) in the gas mixture. The flow rate of the water vapour was set to 0.1 SCFH.
In the plot presented below (Fig. 3.8), the region highlighted in light blue corresponds to the time in which this percentage of water vapour was flushing as component of the gas mixture. In this interval of time, all the currents drastically increased. What we are most interested in is the effect that the flushing has, after the original gas mixture is restored.

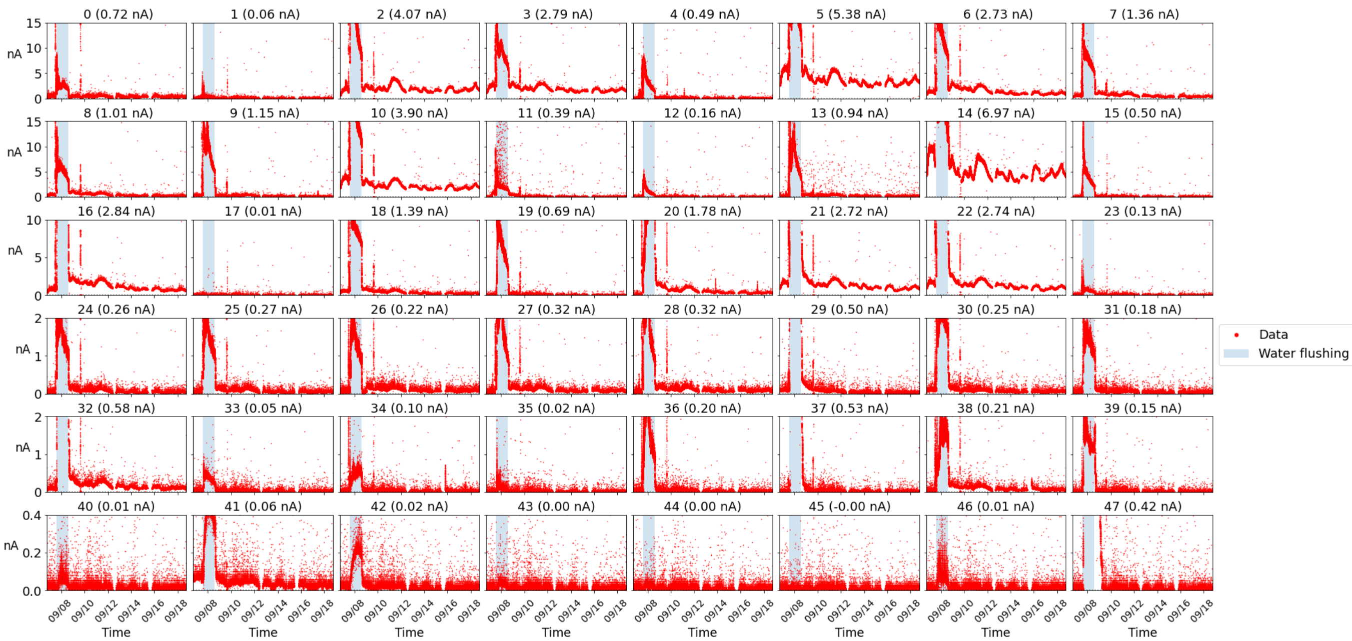


Figure 3.8: 48 currents measured for 10 days before, during and after the addition of water vapour

A comparison of averages between the night before the water vapour was introduced (7thSeptember) and the night of 18thSeptember is shown in Fig. 3.9. As one can see, the highest currents dropped down. Yet, these currents do not reach a value of the order of picoamperes like the others.

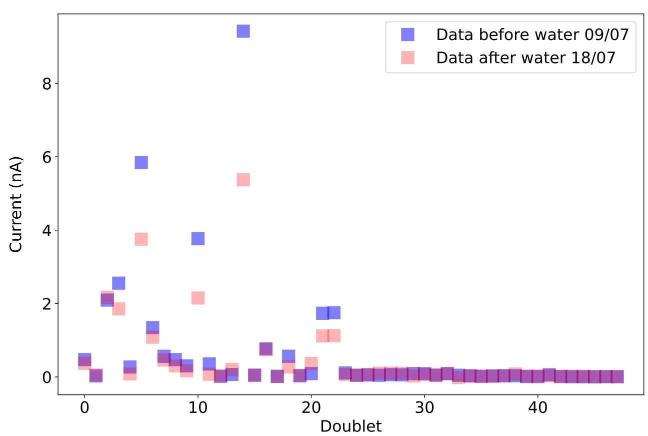


Figure 3.9: Comparison of averages of currents over night before and after the addition of water vapour

3.5 Environmental Conditions

Besides the introduction of the water vapour, in the measurement taken from 07thSeptember to 17thSeptember presented in Fig. 3.8, two important features can be observed:

- A daily oscillation (Fig. 3.10 on the left), that was already mentioned related to Fig. 3.5
- A secondary oscillation (Fig. 3.10 on the right), with a period of 15 minutes, that was already mentioned related to Fig. 3.1a

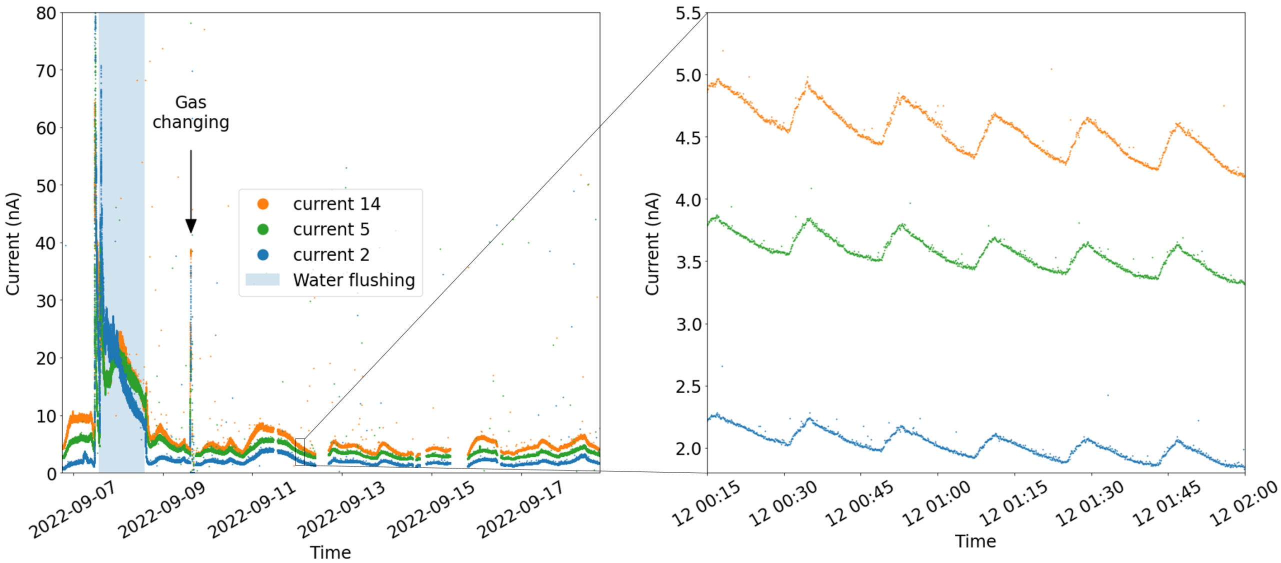


Figure 3.10: Three currents as reference in which the daily oscillations and 15-min oscillations are visible. The plot on the right is a zoom in the box of the plot on the left

Since no electronic component is supposed to be responsible for fluctuations with such a long period, we studied a possible dependence of currents in humidity, temperature and pressure, both inside and outside the panel.
To do this, two sensors were installed in the experimental setup: one inside the panel, the other one outside the panel. The panel was sealed using an appropriate metallic cover to have a more accurate estimate of the environmental condition inside the panel.
In Fig.3.11 the humidity measured by the sensor outside the panel and three of the highest currents are plotted as a function of the time. The scale for the y-axis of humidity is on the left, the one for the currents is on the right. The humidity inside the panel is also plotted with the same scale of the one outside.

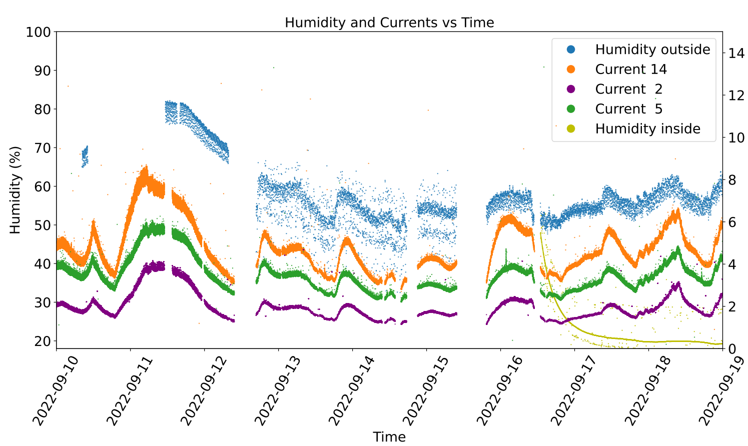


Figure 3.11: Humidity outside and inside the panel with three currents as reference

It is evident that the currents plotted here as examples follow the same trend of the humidity outside the panel, that is the humidity of the cleanroom. Moreover, the humidity measured inside the panel is does not go to zero as one would expect knowing that there is a constant flow rate of Ar-CO_2.
The curve of the humidity inside the panel was fitted with an exponential function plus a constant term (Eq. 3.1), where the latter represents the residual humidity measured inside the panel. It turned out that a residual 20% of humidity is found in the panel.

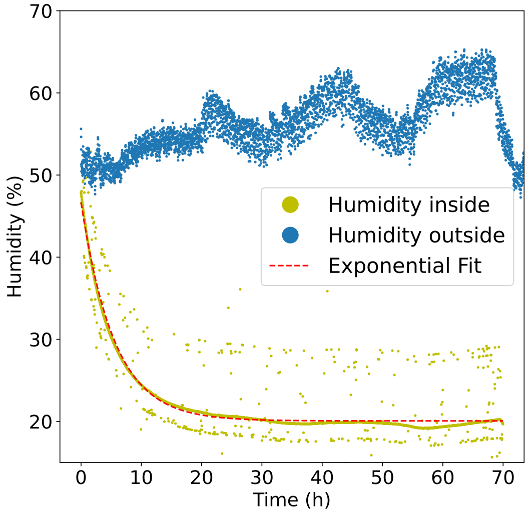


Figure 3.12: Fit of the humidity inside the panel

$$H = A \cdot e^{\frac{-t}{\tau}} + B \tag{3.1}$$

A (%)	τ(hours)	B (%)
26.61 ± 0.02	5.533 ± 0.003	20.064 ± 0.003

Table 3.1: Parameters of the fit

3.5.1 Residual Humidity equal to 20%

We tried to explain the reasons of the unexpected results presented in the previous section. We took into account the following possibilities:

1. The sensor does not go to lower values than 20%
2. The sensor is working properly but a leak can be present in the setup.
3. The sensor is broken or does not work properly in a low humidity environment.
4. The humidity is actually 20%

The first three possibilities were rejected performing the following measurements:

1. Increasing the flow rate to nearly 0.3 SCFH, the sensor was measuring lower values.
2. Measuring the flow rate coming out from the panel and the rate flowing in the panel with an additional flowmeter, the result is the same. Therefore, no leak is supposed to be present
3. Placing the sensor inside a sealed Tupperware where the gas was flowing in, a humidity level of 0% was quickly reached.

A final measurement placing the sensor in a sealed Tupperware with gas flowing in with the same rate used for the panel (0.14 SCFH) showed values of humidity lower than 7% and still decreasing.
We conclude that there is a residual humidity of 20% in the panel, since both the sensor and the panel behave correctly.

3.6 Secondary oscillation

For what regards the secondary oscillations introduced in the previous section, it turned out that both the temperature and the humidity have the same period that the currents have (Fig. 3.13). No dependence on pressure was observed in the currents.

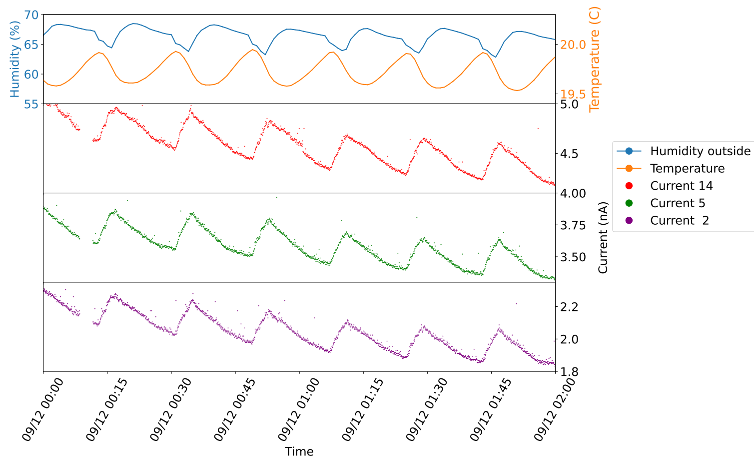


Figure 3.13: Oscillations of currents, temperature and humidity. The y-scale for the humidity in blue on the left, the y-scale for the temperature is in orange on the right

These fluctuations can only be seen in the environmental conditions outside the panel and only in the highest currents. It is relevant to say that in Fig. 3.1a, when these oscillations were seen for the first time the period was shorter ($\approx$ 10 minutes) but no measurement of the environmental conditions of the cleanroom is available for that date.

Conclusions

To sum up the work presented in this report, three main key points have been arisen:

- The conditioning effect has played by far the most dominant role on the reduction of the currents.
- The introduction of water vapour has had a little effect on reducing small currents of the order of nA. More measurements are needed to evaluate further reductions.
- Environmental conditions of the cleanroom, humidity in particular, strongly affect the currents of the panel.

Moreover, an unexpected residual humidity of 20% was found inside the panel. Further measurements are needed to confirm this. A possible idea is to change the panel to check if any defects are present in the panel MN084 or in the connections used.

Bibliography

[1] L. et al. Bartoszek. Mu2e technical design report, 2015.

[2] Robert H. Bernstein. The mu2e experiment. *Frontiers in Physics*, 7, jan 2019.

[3] Wilhelm Bertl, Roland Engfer, Erwin Hermes, G. Kurz, T. Kozłowski, John C. Kuth, G. J. Den Otter, F. Rosenbaum, N. Ryskulov, Arjen van der Schaaf, Peter Wintz, Izabella Zychor, and The Sindrum II Collaboration. A search for μ-e conversion in muonic gold. *The European Physical Journal C - Particles and Fields*, 47:337–346, 2006.

[4] P.Q. Hung, Trinh Le, Van Que Tran, and Tzu-Chiang Yuan. Muon-to-electron conversion in mirror fermion model with electroweak scale non-sterile right-handed neutrinos. *Nuclear Physics B*, 932:471–504, 2018.