Mu3e: Cooling of ultra-thin monolithic pixel sensors with gaseous helium

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Overview

Introduction to Mu3e

What governs the detector design?

Mu3e detector concepts

Pixel detector mechanics
  Layers 1/2
  Layers 3/4

Mu3e pixel cooling

Helium plant

Conclusions
Introduction to Mu3e

Mu3e is an experiment to search for

\[
\mu^+ \rightarrow e^+ e^- e^+
\]

A very rare decay.

We’re in an unusual regime, hence allow for some physics background.
Introduction to Mu3e

$\mu \to eee$ in the standard model.
Introduction to Mu3e

\[ \mu \rightarrow eee \] in the standard model.

SM: \(< 1 \times 10^{-54}\)

The suppression comes from the neutrino masses.

Current best limit: \(< 1 \times 10^{-12}\)

(SINDRUM 1988)

Alternative models predict BR within reach of Mu3e \(< 1 \times 10^{-16}\).
Introduction to Mu3e — Signal in $r\phi$-view

$e^+ e^- e^+$

Signal
SM: $< 1 \times 10^{-54}$
Introduction to Mu3e — Signal in $r\phi$-view

$e^+$ $e^-$ $e^-$ $e^+$

Signal
SM: $< 1 \times 10^{-54}$

$\sum p_i = 0$
Signal
SM: $< 1 \times 10^{-54}$

$\sum p_i = 0$

$m_{\text{inv}} = m_\mu$
Introduction to Mu3e — Signal in $r\phi$-view

Signal
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\[ \sum p_i = 0 \]

\[ m_{\text{inv}} = m_\mu \]

\[ t_i = t_j \quad \forall \, i, j \]
Introduction to Mu3e — Signal in $r\phi$-view

Signal
SM: $< 1 \times 10^{-54}$

$$\sum p_i = 0$$

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$$t_i = t_j \quad \forall i, j$$

common vertex
Introduction to Mu3e — Signal in $r\phi$-view

Signal
SM: $< 1 \times 10^{-54}$

\[ \sum p_i = 0 \]
\[ m_{\text{inv}} = m_\mu \]
\[ t_i = t_j \ \forall \ i, j \]
common vertex

Radiative decay
SM: $3.4 \times 10^{-5}$

\[ \sum p_i \neq 0 \]
\[ m_{\text{inv}} < m_\mu \]
\[ t_i = t_j \]
common vertex
Introduction to Mu3e — Signal in $r\phi$-view

Signal
SM: $< 1 \times 10^{-54}$

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SM: $3.4 \times 10^{-5}$

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$m_{\text{inv}} < m_{\mu}$
$t_i = t_j$
common vertex

Accidental background

$\sum p_i \approx 0$
$m_{\text{inv}} \approx m_{\mu}$
$t_i \approx t_j$
"bad vertex"
Introduction to Mu3e

Full Geant4-based detector simulation

Expected SM background

Prospects for \( \mu \rightarrow eee \) signal at various branching fractions

\[ m_{\text{rec}} [\text{MeV/c}^2] \]

- \( 10^{15} \) muon stops at \( 10^8 \) muons/s
- \( \mu \rightarrow eee \)
  - at \( 10^{-12} \)
  - at \( 10^{-13} \)
  - at \( 10^{-14} \)
  - at \( 10^{-15} \)

- \( \mu \rightarrow eee eee! \)

New Physics in Mu3e
What governs the detector design?

Hence we need:

- Precise tracking (vertexing and momentum) ⇒ pixels
- Good timing (coincidence, event separation) ⇒ scintillators
- Minimal material budget design (background suppression, multiple scattering) ⇒ solutions...

Note: Muons are stopped on a target. No bunch structure.

Rad-hard electronics is not that important.
Mu3e detector concepts
Mu3e detector concepts

Phase-I configuration:
Mu3e detector concepts

Phase-I configuration:

- High rate: $10^8$ muon stops on target per second
- Time resolution (pixels): 20 ns
- Vertex resolution: about 200 $\mu$m
- Momentum resolution: about 0.5 MeV
- All inside a cryogenic 1 T magnet, warm bore I.D. 1 m
Mu3e detector concepts

Let's focus on the pixels. Monte-Carlo studies led to the following geometry:

\((B = 1 \, T, x/X_0 = 0.1\% \text{ per layer})\)
Identical copies of layers 3/4 will extend the detector in $z$ to extend coverage for recoiling tracks.
Mu3e detector concepts

Ok, we got the geometry. But what about the material budget of the pixel layers?

Let’s put this into perspective:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Ref.</th>
<th>$x/X_0$ per layer [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS IBL</td>
<td>[1]</td>
<td>1.9</td>
</tr>
<tr>
<td>CMS Phase I</td>
<td>[2]</td>
<td>1.1</td>
</tr>
<tr>
<td>ALICE upgrade</td>
<td>[3]</td>
<td>0.3</td>
</tr>
<tr>
<td>STAR</td>
<td>[4]</td>
<td>0.4</td>
</tr>
<tr>
<td>Belle-II IBL</td>
<td>[5]</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Mu3e</strong></td>
<td></td>
<td><strong>0.1</strong></td>
</tr>
</tbody>
</table>
Pixel detector mechanics
Inner modules have ladders of 6 chips each. Observe: No V-folds here.
Pixel detector mechanics – Layers 1/2

Modules layer 2 design (1 is similar, one facet less)

Exploded view of same part.
Pixel detector mechanics

Cut in the $r - \phi$ plane.

Yellow: active pixel matrix
Red: periphery, non-sensitive but has material and source of heat.

The gap (light blue) will be used for the cooling (see later).
Pixel detector mechanics

Shown: One one module per layer inserted.
Pixel detector mechanics
Pixel detector mechanics

- Ladder
- Interposer
- Endpiece
- Flexprint
- MuPix chips
- Polyimide V-fold
- Cooling gas inlet
- Push-down lid
- Contact matrix to interposer
Pixel detector mechanics

Mupix sensor 50µm
HDI ~100µm
polyimide 15µm
SpTAB bonds
Mupix periphery

Radiation length: \( \approx 0.1\% \frac{x}{X_0} \)
Mu3e pixel cooling

Cooling needs:

- 2844 chips \( \times \) 20 \( \times \) 20 mm\(^2\) active area \(\Rightarrow\) 1.14 m\(^2\) instrumented
- 250 mW/cm\(^2\) heat dissipation \(\Rightarrow\) about 3 kW
- Upper temperature governed by glue \(\Rightarrow\) \(<\)60 °C
- Temperature gradient along ladders acceptable
- Stability over time is crucial, not absolute temperature
Why helium at ambient pressure?

- Radiation length $\approx 17 \times$ larger than air
- Large speed of sound: 980 m/s
- Spec. heat capacity 5.2 kJ/(kg K) (air: 1 kJ/(kg K))
- Inert
- Affordable
The low-mass paradigm doesn’t allow for traditional liquid cooling. Hence we switch to Helium, the lowest mass gas.
Mu3e pixel cooling

Figure 2.2: Helium cooling system of the silicon chips with detail of the centre part.
Summary of results of G12

Table 4.5 shows the summary of all relevant results obtained for the gap flow between layers 1 & 2. The solid column is indicating the defined material of the MuPix chip. Unequal heat dissipation indicates if the MuPix chip was divided into two parts with different heat dissipation or set to the equal value of 400 mW/cm² (see section 4.1.5). The Benchmark was used to compare the heat transfer with the estimation and to provide a benchmark for the further simulations. It shows that the higher heat dissipation in the periphery is causing an increase of around 30 K. For the original and optimised version the increase is lower but in a similar range. The optimisation is also decreasing the temperature of the MuPix by around 10 K both with and without the higher heat dissipation in the periphery.

The elongation and outer tube showed different effects in terms of cooling. The elongation increased the temperature by approximately 40 K which is not suitable. On the other hand the outer tube decreased the maximum temperature by 40 K which is far below the maximum of 70°C.

Example CFD simulation result for vertex detector.

\[ P/A = 400 \text{ mW/cm}^2, \] unequally distributed among periphery and pixel matrix

Chip size 20 × 23 mm²
Simulation is nice. Measuring something in the lab is **nicer**.
Mu3e pixel cooling

We started with tape heater ladders...

Aluminium-polyimide laminate, stainless steel plates ($d = 50 \mu m$). All dimensions match current detector design.
Mu3e pixel cooling

...assemble them to a L1/2 mockup...

Again everything matches specs, especially mechanical structure is final. Electrical connections using Samtec ZA8H interposers.
Mu3e pixel cooling

...integrate it into a test stand...

Low-mass thermocouples added to mockup structure.
Mu3e pixel cooling

5.1 Measurement model

- Pressure
- Mass flow
- Temperature
- Various Measurement points

- Electrical
- Cooling gas
- Leakage gas

Legend

- Process media
- ... that offers all the diagnostics needed.

This setup can be operated with air and helium.
NB: One bottle of 50 L helium at 200 bar offers 12 min of measuring time with 2 g/s mass flow.
Mu3e pixel cooling

Heat maps in simulation suggested the formation of a vortex.

Do we see it in the lab?

(a) Measurement - optimised inflow geometry.
(b) CFD - original inflow geometry.
(c) CFD - optimised inflow geometry.
Mu3e pixel cooling

Heat maps in simulation suggested the formation of a vortex.

Yes. Views of simulation match view of IR camera.

NB: Hot zones to left and right are from power feeds.
Mu3e pixel cooling

Figure 4.43: Velocity and temperature profile of part A with optimised geometry.

Part A-B-C

The results of the simulation with all three parts are shown in figure 4.45 with the MuPix and global flow temperatures. The MuPix of part B show again an increase in temperature resulting from the missing interface. All three parts show a different MuPix temperature behaviour, for part A the temperature increases with $z$, which can be expected, because the cold flow enters at $z = 580 \text{ mm}$ and flows along $z$ where it gets heated up. Part B has flows coming from both sides resulting in a maximal temperature somewhere around $z = 0 \text{ mm}$. Part C has the maximum temperature of layer 3 at low $z$ because the inlet is at $z = 580 \text{ mm}$ and is heated up to $z = 200 \text{ mm}$. On the other hand, layer 4 has the maximum temperature at higher $z$ because the global flow is flowing in the opposite direction.

Simulation of full detector, central part shown.

Observe the temperature at low radii where the SciFi will be.

No significant heat influx to SciFi.
The full detector needs the following helium circuits:

<table>
<thead>
<tr>
<th>No.</th>
<th>ID</th>
<th>Description</th>
<th>#</th>
<th>Mass flow g/s</th>
<th>Inlet pressure mbar</th>
<th>Outlet pressure mbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GL12</td>
<td>Gap flow vertex detector</td>
<td>1</td>
<td>2.0</td>
<td>+40</td>
<td>-40</td>
</tr>
<tr>
<td>2</td>
<td>GL3S</td>
<td>Gap flow between SciFi and L3</td>
<td>1</td>
<td>6.9</td>
<td>+25</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>GL3T</td>
<td>Gap flow between SciTile and L3</td>
<td>2</td>
<td>5.7</td>
<td>+28</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>GL34</td>
<td>Gap flow between L3 and L4</td>
<td>3</td>
<td>7.6</td>
<td>+25</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>VL3</td>
<td>Flow in V-folds L3</td>
<td>3</td>
<td>1.3</td>
<td>+90</td>
<td>-90</td>
</tr>
<tr>
<td>6</td>
<td>VL4</td>
<td>Flow in V-folds L4</td>
<td>3</td>
<td>1.5</td>
<td>+80</td>
<td>-80</td>
</tr>
<tr>
<td>7</td>
<td>GLF</td>
<td>Global flow, $D \approx 300$ mm</td>
<td>1</td>
<td>4</td>
<td>+0.03</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>14</td>
<td>56</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

How to create that flow with $4 \, ^\circ \text{C}$ at inlet?
Helium plant

We have three distinct circuit types foreseen...
Helium plant

Closed circuit, e.g. for He in V-folds
Helium plant

Open circuit, e.g. volume between L3 and L4 vents to large volume
Helium plant

Global flow: prevention of hot pockets and exhaust
Critical flows and pressures: instrumented volume of pixels. Differential pressures between neighbouring volumes under **tight control** in all operation modes (ramp-up, steady operation, ramp-down, off).

$\Delta p$ limit to be determined on mock-up, estimated to be $O(1 \text{ mbar})$
Helium plant

Constraints:

- Very restricted space inside magnet \(d = 1\,\text{m}, \, l \approx 2.8\,\text{m}\)
- Magnetic field of 1 T ⇒ solenoid valves or motors won’t work inside
- Helium atmosphere everywhere
- All material must be non-magnetic
- Openings in magnet shield doors limit space for feed-throughs
Helium plant—options

- **High pressure** using screw compressors.
  - Standard solution e.g. for helium liquefaction plants. Reliable.
  - Monoatomic gas, almost adiabatic compression, $\kappa = \frac{5}{3} \Rightarrow$ energy loss, power $\approx 250$ kW
  - Flow control using precision valves and flow-meters
  - Cost driver: power consumption, flow-meters
Mu3e helium gas cooling system – concept

Environment:
- 10-35°C (not controlled, PSI experimental hall)
- ambient pressure
- RH not controlled

Important note:
This is a conceptual sketch to develop the full cooling system
Order of equipment, number of circuits etc. may change

Note: indicative, more than 3 circuits will be needed.
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Mu3e experiment

Flow direction

Pressure vessel(s) at low pressure

Water cooling circuit

Chiller (existing)

Heat exchanger (existing)

Gas purification system (to remove air, humidity and organic residues)

Storage vessel

He replenishment

Some connections need to be flexible as needed to move experiment

Outlet T: 30-60°C (varying)

Inlet T: ~4°C

0 mbar (= ambient)

Mu3e experiment

Average pressure inside experiment: ambient
Passive pressure control needed, e.g. rupture disc

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Helium plant

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10-35°C

-100 mbar

flow direction

+8 bar (!)

+5 bar (!)

+200 bar

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10-35°C

-100 mbar

flow direction

+8 bar (!)

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+200 bar

Note: indicative, more than 3 circuits will be needed.
Helium plant—options

- **Low pressure** using turbo compressors
  - Not off-the-shelf, requires ultra-highspeed compressors
  - Limited compression ratio per stage $< 1.2$
  - Flow control via compressor speed, flow-metering via pressure drop along pipes
  - Power consumption: a few kW
Helium plant— options

Such compressors offer limited mass flow and compression ratio but are energy efficient (6 kW for full system). Cost: comparable to screw compressor (!).

We perform a feasibility study. Stay tuned.

Plot courtesy Celeroton, 8604 Volketswil, Switzerland. Used by permission.
Helium atmosphere

One more thing...
Helium atmosphere

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- Sometimes last autumn in Morris, IL, all of a sudden, Apple iPhones died in a hospital
Helium atmosphere

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- Sometimes last autumn in Morris, IL, all of a sudden, Apple iPhones died in a hospital
- Reason: Helium vented during installation of a new MRI system
- Helium got distributed over A/C
Helium atmosphere

One more thing…

- Sometimes last autumn in Morris, IL, all of a sudden, Apple iPhones died in a hospital
- Reason: Helium vented during installation of a new MRI system
- Helium got distributed over A/C
- Apple iPhones use a MEMS device instead of a quartz as base clock oscillator
Helium atmosphere

The MEMS device in question is an SiT512 32 kHz oscillator.

„Tuning fork“ inside silicon box, BGA grid to chip with electronics (maybe PLL?) and another BGA for PCB mounting.

Helium diffuses through silicon and stays trapped for a while.

For more background, see e.g.

- https://ifixit.org/blog/11986/iphones-are-allergic-to-helium/
- https://www.youtube.com/watch?v=vvZWaVvB908
Conclusions

- Mu3e uses gaseous helium as coolant of the pixel tracker

NB: All studies available on our website https://www.psi.ch/mu3e/theses
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- Mu3e uses gaseous helium as coolant of the pixel tracker
- Concept proven in simulation and in mockup studies
- Design studies for helium plant started
- Helium has surprises...

**NB:** All studies available on our website [https://www.psi.ch/mu3e/theses](https://www.psi.ch/mu3e/theses)
References

ENCORE
Adiabatic compression

Helium is a monoatomic gas, hence the adiabatic exponent is

$$\kappa = \frac{3}{5}$$

The temperature of a gas under adiabatic compression goes as

$$T_2 = T_1 \cdot \left( \frac{p_1}{p_2} \right)^{\frac{1-\kappa}{\kappa}}$$

Example: Helium with a compression ratio of 8 and starting at 293 K heats up to

$$T_2 = 293 \, \text{K} \cdot \left( \frac{1}{8} \right)^{-\frac{2}{5}} = 673 \, \text{K} = 400 \, ^\circ\text{C}$$

This is realised in e.g. piston compressors. Screw compressors work differently and work almost isothermic.
Okay, this looks all fine. And you know why our detector lives in helium. But what could go wrong?
Okay, this looks all fine. And you know why our detector lives in helium. But what could go wrong?

We have Helium (inert, dry) and radiation...
Inert Helium atmosphere

The MEG experiment at PSI decommissioned its phase-I detector recently.

- Search for $\mu \rightarrow e\gamma$ at same beamline.
- Similar radiation dose, same particle spectrum as Mu3e.
- Observed degradation of polyimide films. They became very brittle.
- Other polymers degraded as well but this was more expected. Polyimide has this reputation of being the rad-hard polymer.
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- Other polymers degraded as well but this was more expected. Polyimide has this reputation of being the rad-hard polymer.
- What could be the cause? Inspiration came from our scintillator colleagues

Inert Helium atmosphere

Polyimide
Inert Helium atmosphere

Polyimide

Polystyrene
Let’s illustrate our hypothesis.

Without radiation, the radical concentration in a polymer stays low.
Inert Helium atmosphere

Now we turn on radiation.

The concentration of radicals inside the polymer rises.
Inert Helium atmosphere

![Diagram]

If we keep the material in an inert atmosphere, the radicals stay there.

The only chemical reaction possible: with the polymer itself. This leads to structural damage.
Inert Helium atmosphere

If exposed to oxygen, radical concentration drops to safe levels.
Inert Helium atmosphere

If under radiation and oxygen presence, radical level saturates at much lower levels, ageing is much slower.
Inert Helium atmosphere

- This explains observed behaviour of polyimide
- Opens a door to mitigation options
- Needs verification
- Backed by papers on similar observations with plastic scintillators
Inert Helium atmosphere

We’ve started an irradiation campaign.

$^{90}$Sr source in inert atmosphere, targetting samples.

Analytics of samples: visual aspect, mechanical parameters, spectra (IR, $^1$H-NMR, $^{13}$C-NMR)
Inert Helium atmosphere

This is the **Michel spectrum**, i.e. the energy spectrum of the positrons of muons decaying at rest.

Much lower than what e.g. LHC experiments see.

Source: https://doi.org/10.1016/j.physrep.2013.07.002
Inert Helium atmosphere

Irreducible BG: radiative decay with internal conversion (IC)

\[ e^+ + e^- + \nu + \nu \text{ missing energy} \]

steeply falling!

very good momentum / total energy resolution required!

R.M. Djilkibaev, R.V. Konoplich

PRD79 (2009)

\[ B(\mu^+ \rightarrow e^+e^+e^-\nu\nu) = 3.4 \times 10^{-5} \]
Inert Helium atmosphere

Interposer Samtec Z-Ray

Pitch: 0.8 mm

<table>
<thead>
<tr>
<th>Model</th>
<th>Compressed height</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZA8H</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>ZA8</td>
<td>1 mm</td>
</tr>
</tbody>
</table>

Industry standard component, cost 5–10 € a piece.

Allows use of flexes instead of cables.
We’ve prepared single silicon heater assemblies.

Consists of heater (sputtered aluminium on silicon, thinned down to 50 µm) and a flex HDI (2 layers Al/polyimide). Very close to final design.

Heater designed to dissipate up to 400 mW/cm².

Has a 1000 Ω RTD on it

Next set of slides: graph paper viewed reflected on back of silicon heater
Analog pixel electronics floats on sensor diode: **monolithic design**

Analog pixel electronics floats on sensor diode: **monolithic design**

Industry standard HV CMOS process allows for E-field across diode ⇒ **depletion zone** of about 15 µm

⇒ drift dominates
Inert Helium atmosphere

The MuPix chip is such a **depleted MAPS**, thinned to 50 µm ≈ 0.05% x/X₀