Mechanics, readout and cooling systems of the **Mu3e** experiment

Frank Meier
Paul Scherrer Institute

17 October 2019

Prelude

—

What is Mu3e about?

Introduction to Mu3e

Mu3e is an experiment to search for

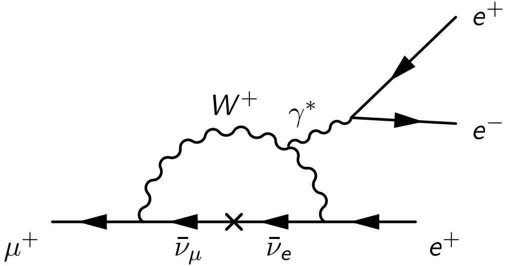
$$\mu^+ \rightarrow e^+ e^- e^+$$

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.



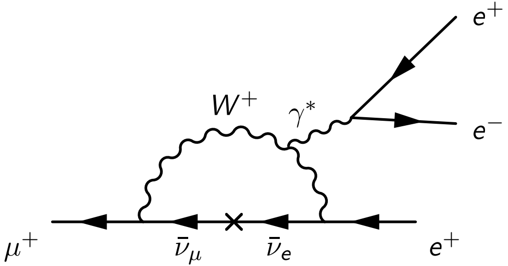
Introduction to Mu3e

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

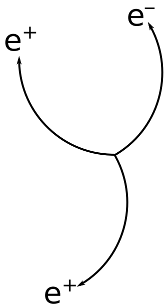
SM: $< 1 \times 10^{-54}$
The suppression comes from the neutrino masses.

Current best limit: $< 1 \times 10^{-12}$
(SINDRUM 1988)

Alternative models predict BR within reach of Mu3e ($< 1 \times 10^{-16}$).



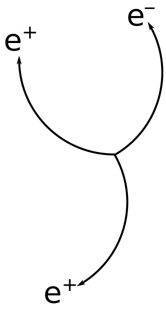
Introduction to Mu3e — Signal in $r\phi$-view



Signal

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

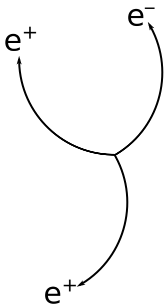
Introduction to Mu3e — Signal in $r\phi$-view



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

$\sum p_i = 0$

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



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$m_{\text{inv}} = m_\mu$

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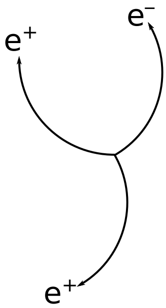

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$t_i = t_j \quad \forall\, i, j$

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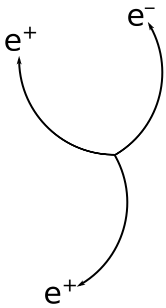

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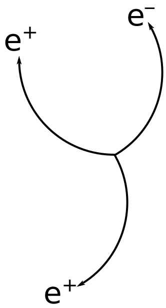

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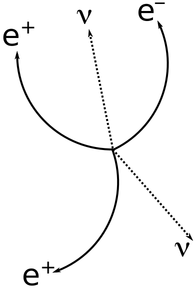
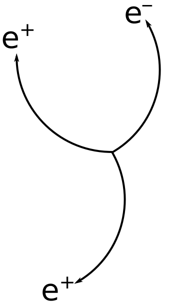


Radiative decay
SM: 3.4×10^{-5}

$\sum p_i \neq 0$
$m_{\text{inv}} < m_\mu$
$t_i = t_j$
common vertex

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



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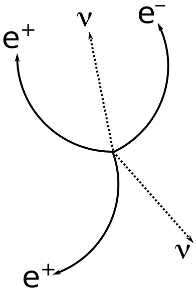

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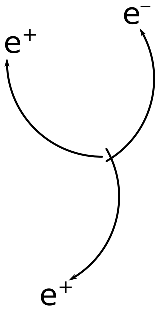
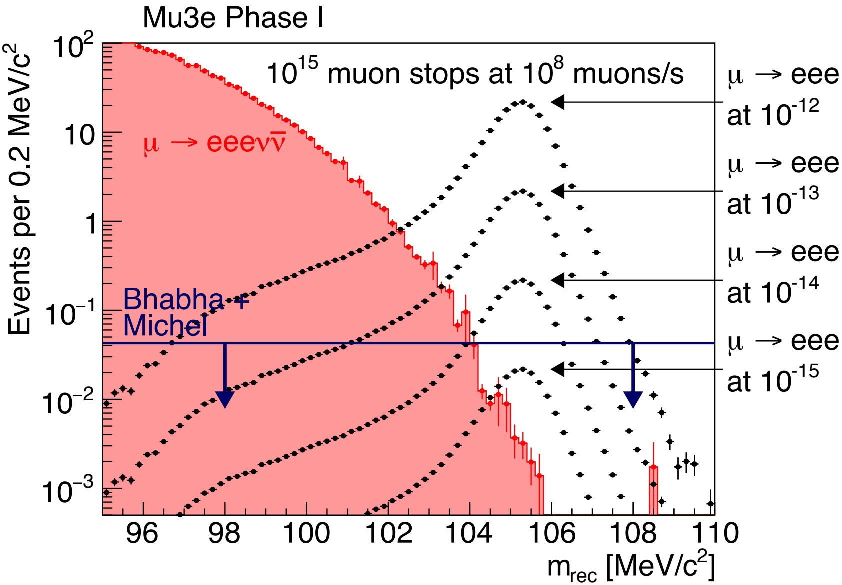


Accidental background

$\sum p_i \approx 0$
$m_{\text{inv}} \approx m_\mu$
$t_i \approx t_j$
“bad vertex”

Introduction to Mu3e – hypothetical signal responses



Part I

Search for $\mu \to eee$ with pixels.

Mu3e detector concepts

We are facing the following challenges:

- Low momentum electrons, $p_e \leq 53\,\text{MeV}$
- μ decay whenever they will.
- No trigger.

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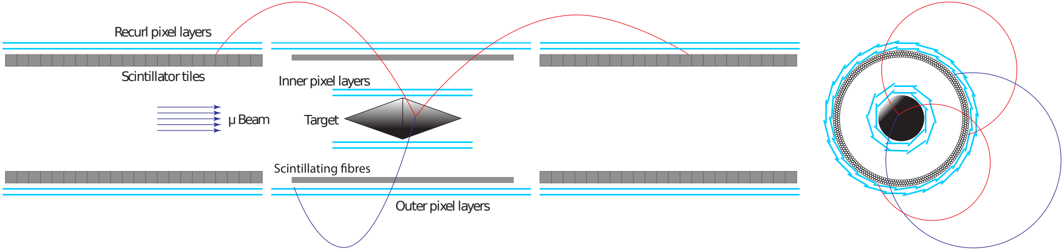
Mu3e detector concepts

We are facing the following challenges:

- Low momentum electrons, $p_e \leq 53\,\text{MeV}$ $\Rightarrow$ **low material design**
- μ decay whenever they will. $\Rightarrow$ **Always on.**
- No trigger. $\Rightarrow$ **Capture all hits.**

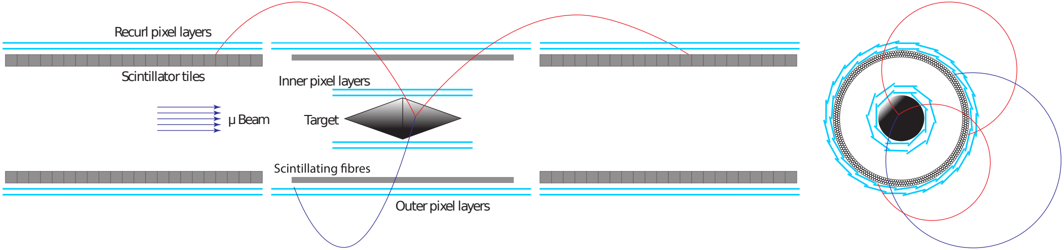
Mu3e detector concepts

Phase-I configuration:



Mu3e detector concepts

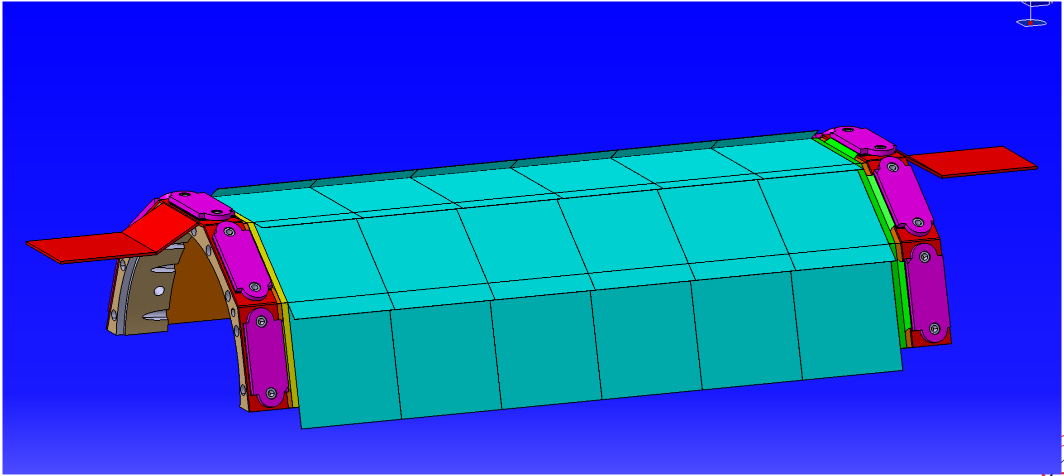
Phase-I configuration:



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

Mu3e detector concepts – Layers 1/2

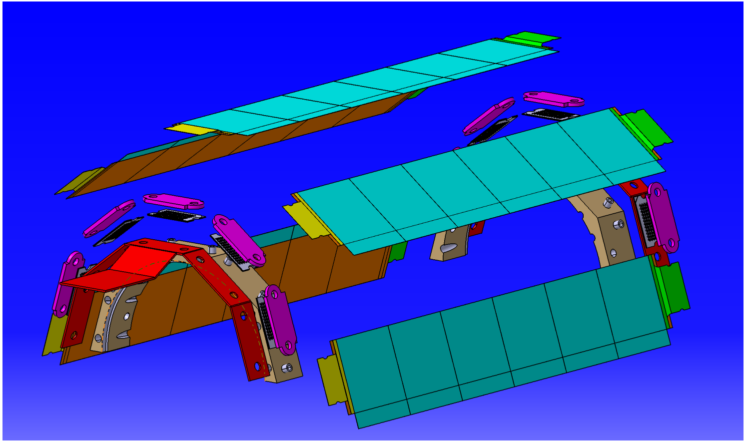
Modules layer 2 design (1 is similar, one facet less)



Inner modules have ladders of 6 chips each. Observe: No V-folds here.

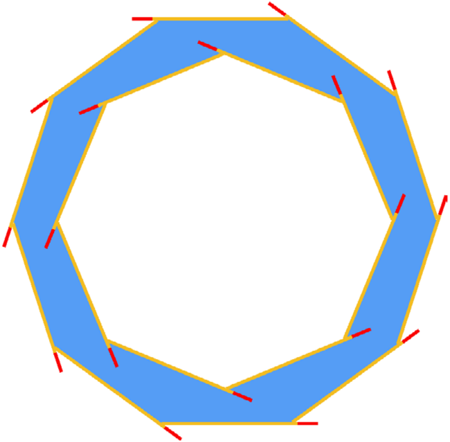
Mu3e detector concepts – Layers 1/2

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



Exploded view of same part.

Mu3e detector concepts



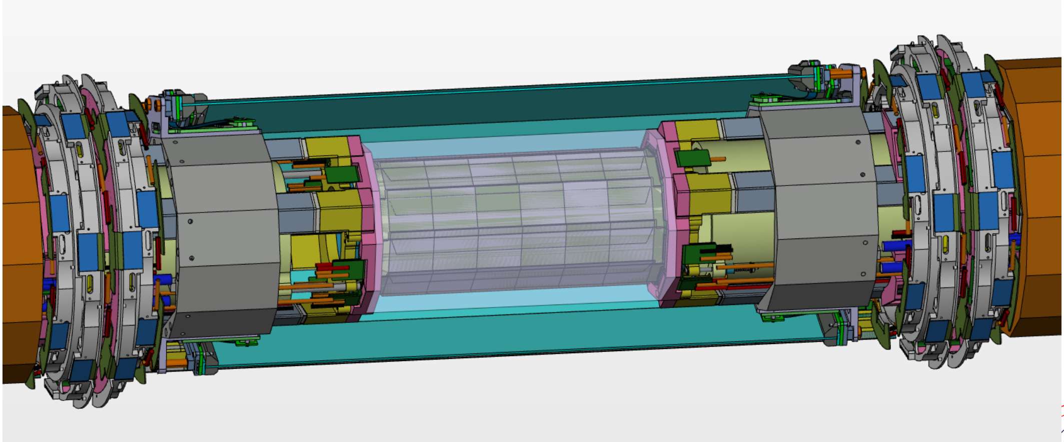
Cut in the $r - \phi$ plane.

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

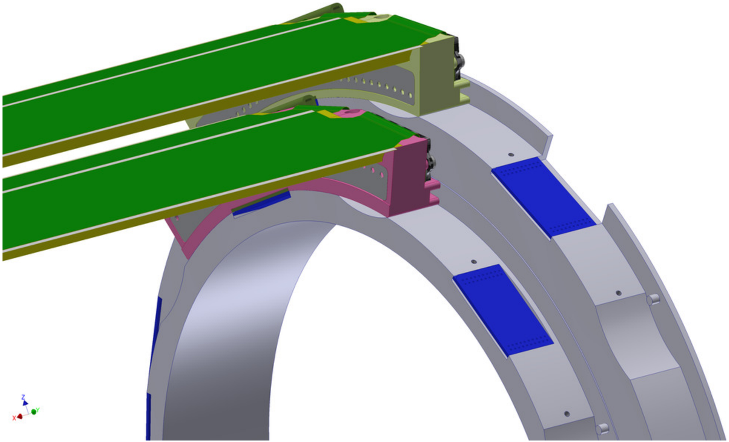
The gap (light blue) will be used for the **cooling** (see later).

Mu3e detector concepts

To briefly put that into perspective:

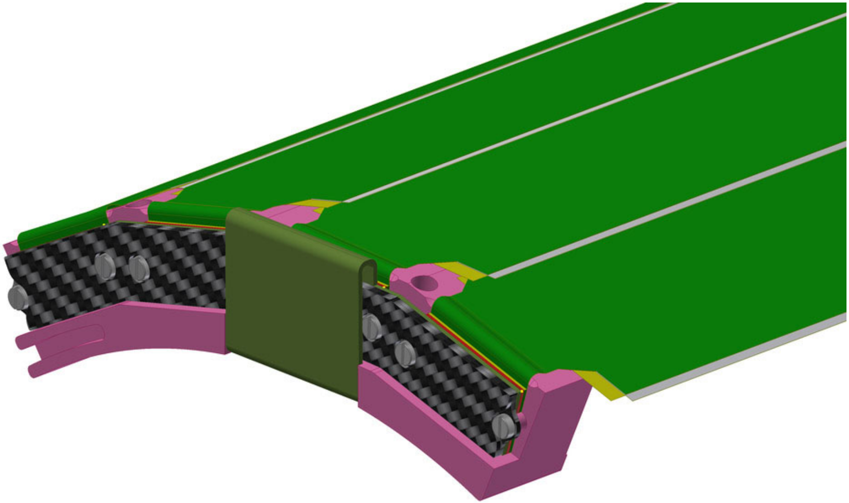


Mu3e detector concepts

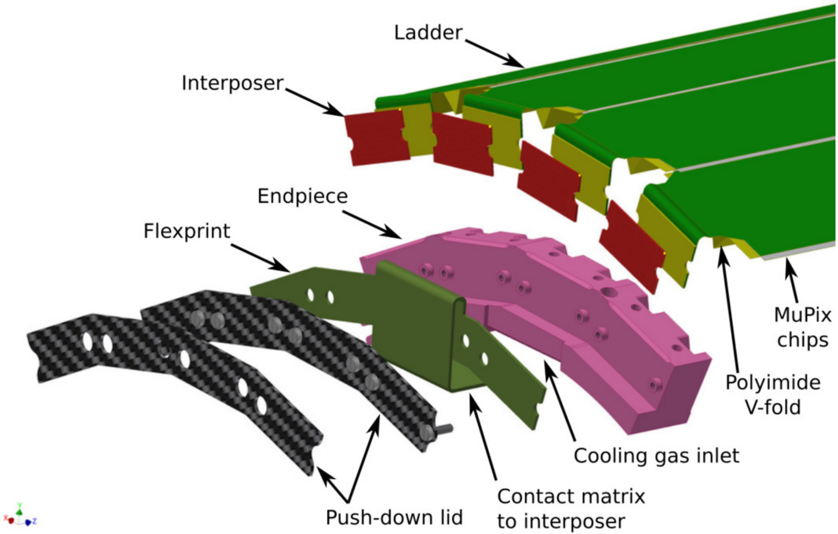


Shown: One one module per layer inserted.

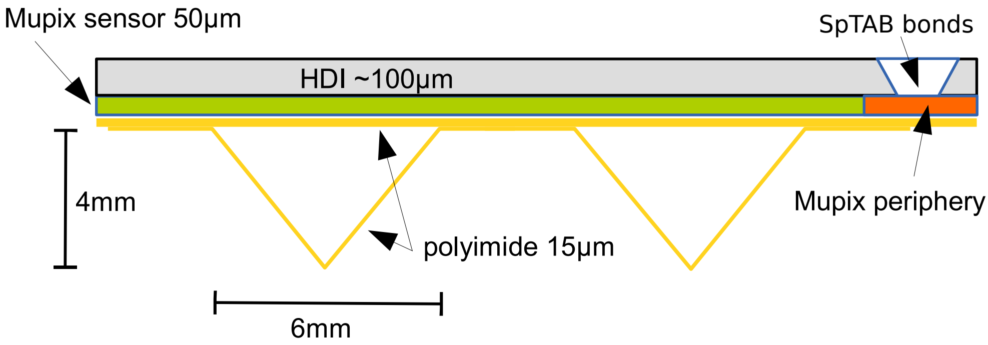
Mu3e detector concepts



Mu3e detector concepts



Mu3e detector concepts



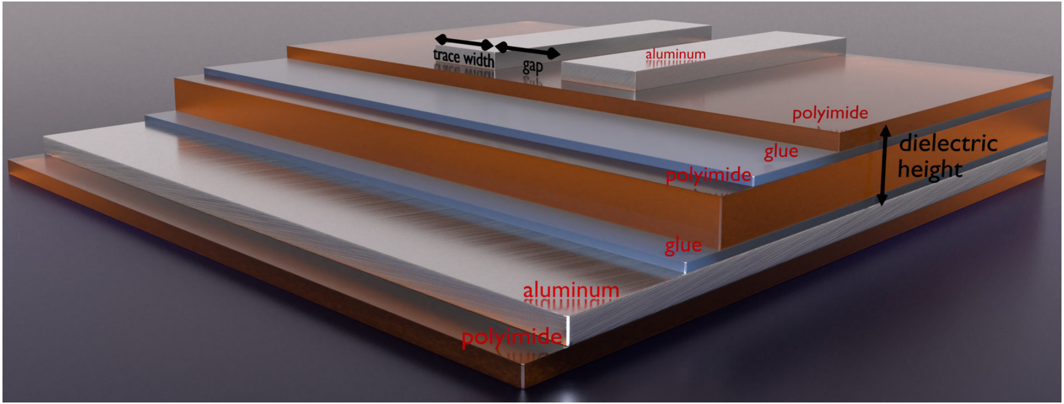
Radiation length: $\approx 0.1\% \, x/X_0$

Part II

Reading out data with aluminium HDI.

Reading out over an aluminium HDI

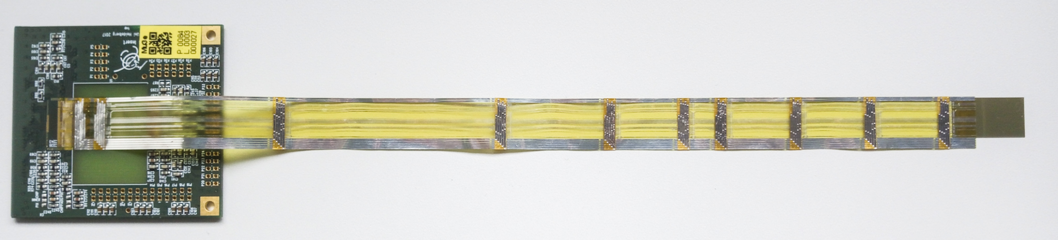
Our HDI stack:



Aluminium thickness: 12 µm. Why? Reduce material.

Reading out over an aluminium HDI

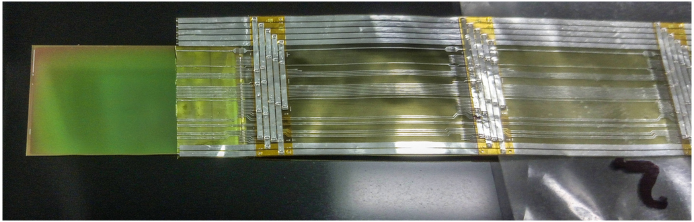
Test setup with 24 cm long HDI (conservative, detector will use 18 cm):

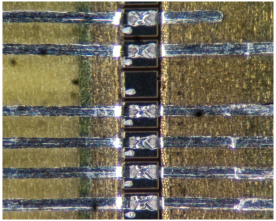


Board on the left is our standard single chip board. HDI acts as an „expandion cord".

Reading out over an aluminium HDI

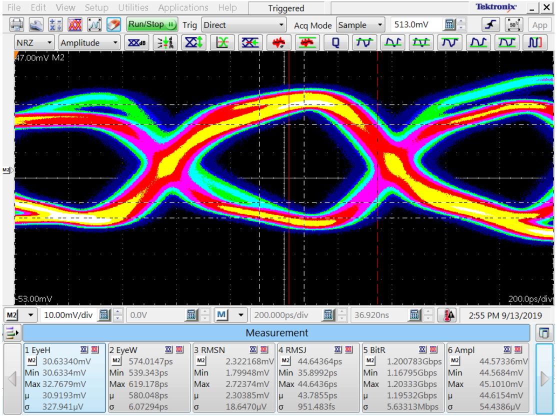
A closer look to the chip:



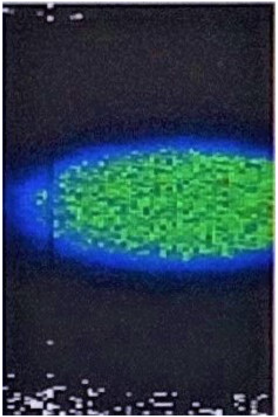


Connections are made using *single point tape automated bonding* (SpTAB), bonding the aluminium trace directly to the chip pad (no wire).

Reading out over an aluminium HDI



Eye diagram at 1.25 GHz



^{90}Sr source

It works well! BER $\leq 1.5 \times 10^{-15}$ (measurement ongoing as we speak)

Part III

Cooling of a pixel detector with gaseous helium.

Cooling a pixel detector with helium

Cooling needs:

- 2844 chips à $20 \times 20\,\mathrm{mm}^2$ active area $\Rightarrow$ $1.14\,\mathrm{m}^2$ instrumented
- $250\,\mathrm{mW/cm}^2$ heat dissipation $\Rightarrow$ about $3\,\mathrm{kW}$
- Upper temperature governed by glue $\Rightarrow$ $<60\,^\circ\mathrm{C}$
- Temperature gradient along ladders acceptable
- Stability over time is crucial, not absolute temperature

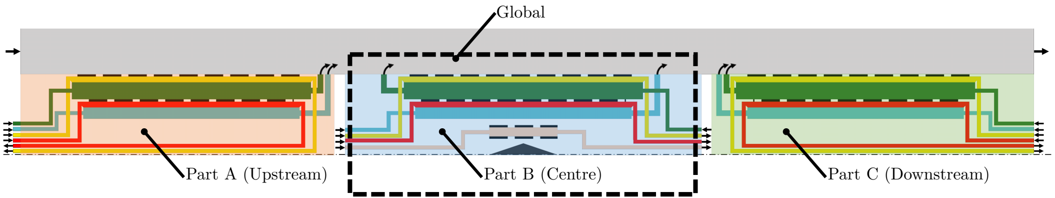
Cooling a pixel detector with helium

Why helium at ambient pressure?

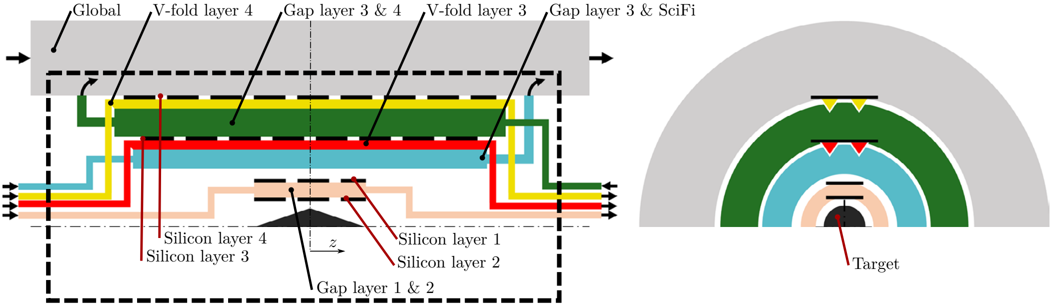
- Radiation length $\approx 17\times$ larger than air
- Large speed of sound: 980 m/s
- Spec. heat capacity 5.2 kJ/(kg K) (air: 1 kJ/(kg K))
- Inert
- Affordable

Cooling a pixel detector with helium

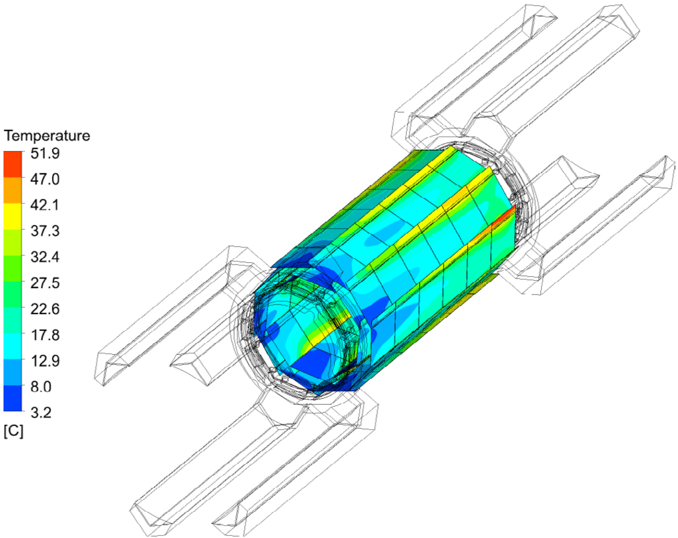
The low-mass paradigm doesn't allow for traditional liquid cooling. Hence we switch to Helium, the lowest mass gas.



Cooling a pixel detector with helium



Cooling a pixel detector with helium



Example CFD simulation result for vertex detector.

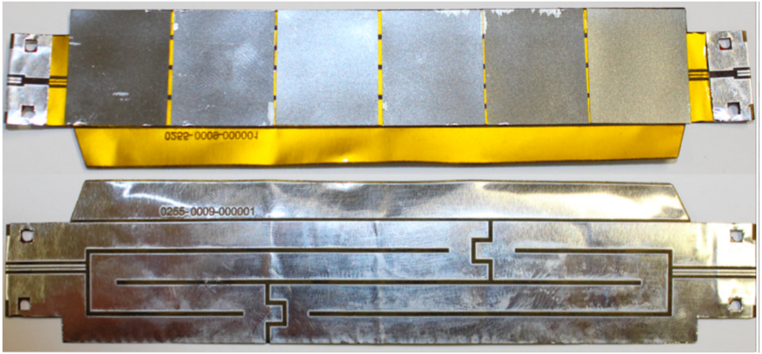
$P/A = 400\,\mathrm{mW/cm^2}$, unequally distributed among periphery and pixel matrix

Chip size $20 \times 23\,\mathrm{mm}^2$

Cooling a pixel detector with helium

Simulation is nice. Measuring something in the lab is **nicer**.

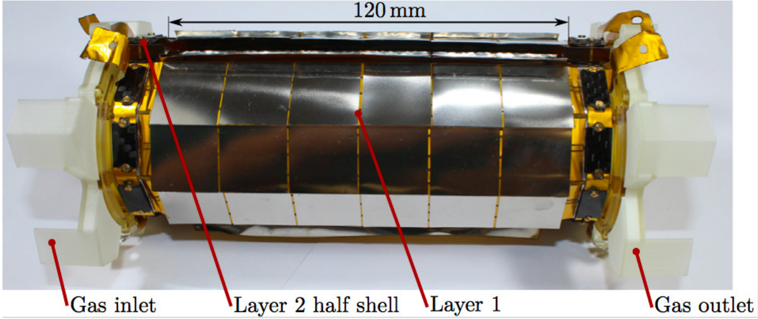
Cooling a pixel detector with helium



We started with tape heater ladders. . .

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

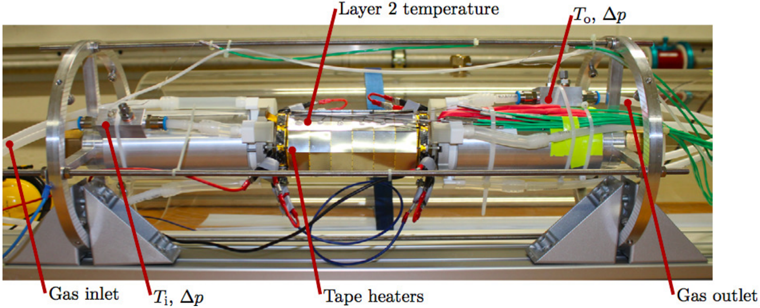
Cooling a pixel detector with helium



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

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

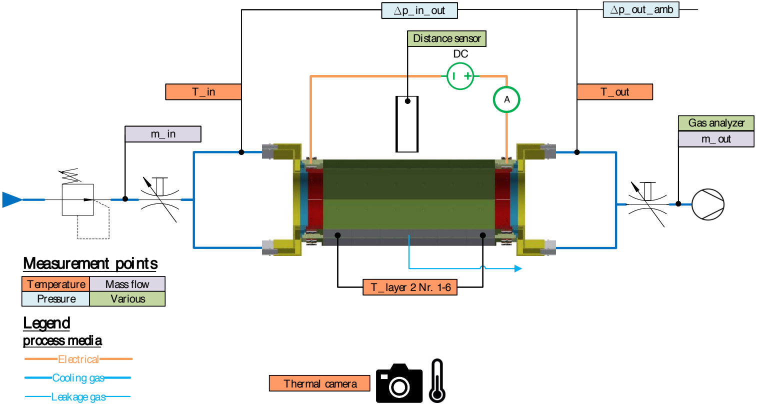
Cooling a pixel detector with helium



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

Low-mass thermocouples added to mockup structure.

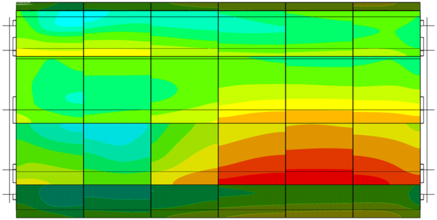
Cooling a pixel detector with helium



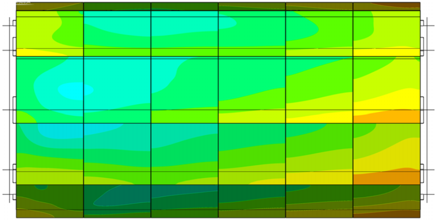
. . . that offers all the diagnostics needed.

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.

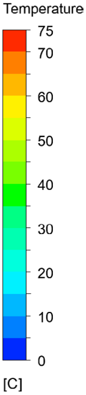
Cooling a pixel detector with helium



(b) CFD - original inflow geometry.



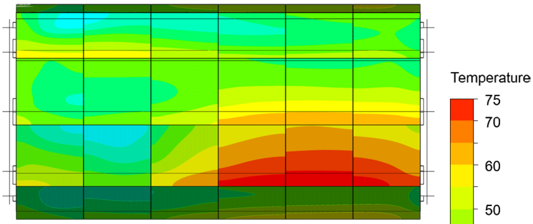
(c) CFD - optimised inflow geometry.



Heat maps in simulation suggested the formation of a vortex.

Do we see it in the lab?

Cooling a pixel detector with helium



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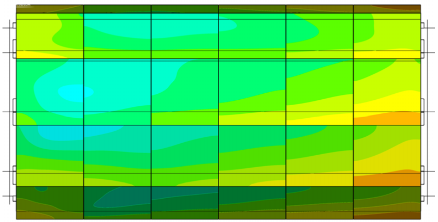
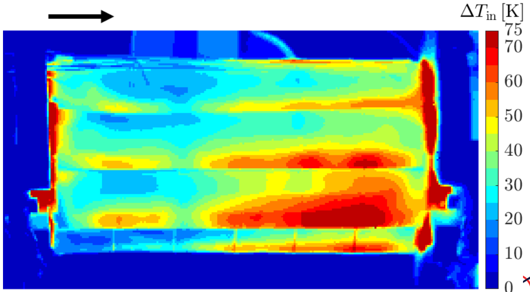


(c) CFD - optimised inflow geometry.

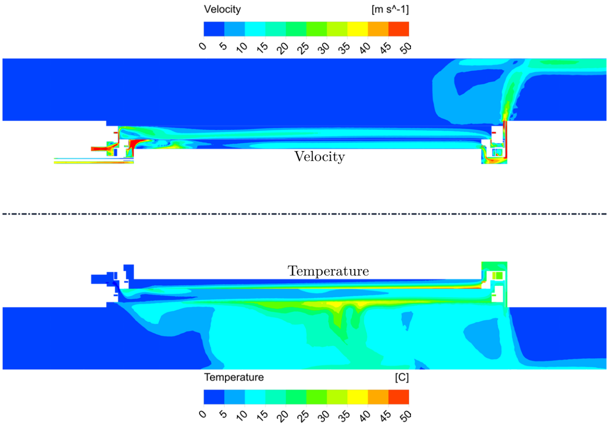
Heat maps in simulation suggested the formation of a vortex.

Yes. Views of simulation match view of IR camera.



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

Cooling a pixel detector with helium



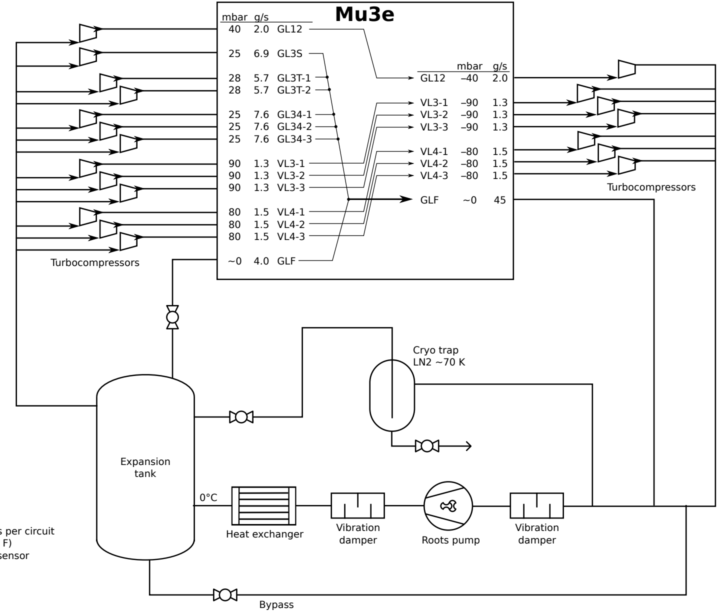
Simulation of full detector, central part shown.

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

No significant heat influx to SciFi.

Mu3e helium cooling – miniature turbo compressor option

Simplified conceptual sketch



Not shown:
- Control valves per circuit
- Sensors (p, T, F)
- Gas analysis sensor

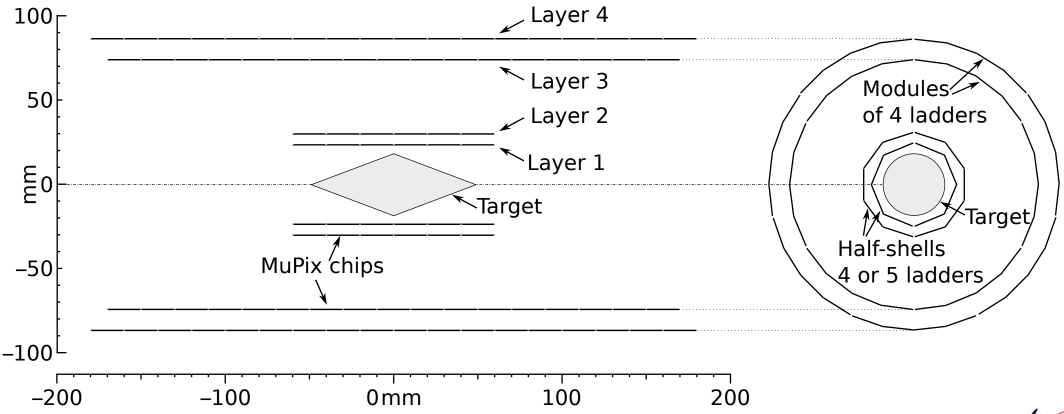
25.9.19, F. Meier

Conclusions

- Low momentum tracking with thin pixels is possible, but poses **unique challenges** in detector design.
- You have to leave the **comfort zone** of past experience in detector construction.
- Thin aluminium HDI work, 1.25 Gbit/s demonstrated.
- Gaseous helium cooling demonstrated in simulation and in the lab.
- Next steps: MuPix10 (see talk by A. Schöning), helium plant

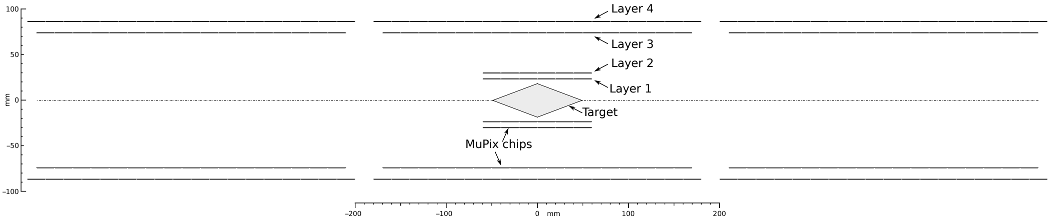
ENCORE

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



($B = 1\,\mathrm{T}$, $x/X_0 = 0.1\%$ per layer)

Identical copies of layers 3/4 will extend the detector in z to extend coverage for recoiling tracks.



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

Let's put this into perspective:

Experiment	Ref.	x/X_0 per layer [%]
ATLAS IBL	[?]	1.9
CMS Phase I	[?]	1.1
ALICE upgrade	[?]	0.3
STAR	[?]	0.4
Belle-II IBL	[?]	0.2
Mu3e		**0.1**

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