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

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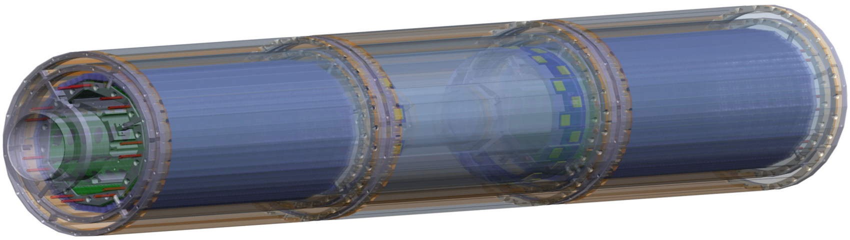
Overview

Introduction to Mu3e

Mu3e is an experiment to search for

$$\mu^+ \to e^+ e^- e^+$$

A very rare decay.



We're in an unusual regime, hence allow for some physics background.

Introduction to Mu3e

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

Introduction to Mu3e

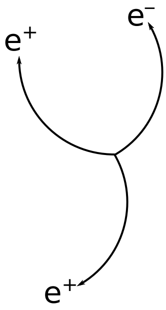
$\mu \rightarrow eee$ in the standard model.

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



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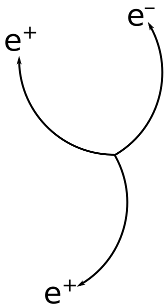
Introduction to Mu3e — Signal in $r\phi$-view



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$\sum p_i = 0$

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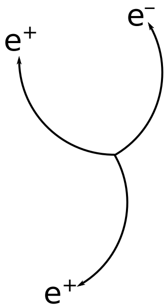

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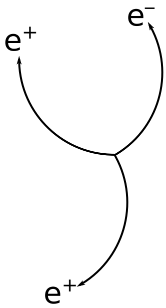

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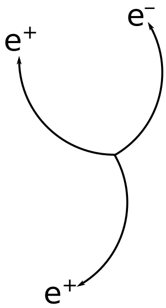

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common vertex

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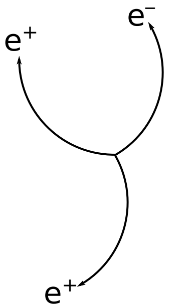

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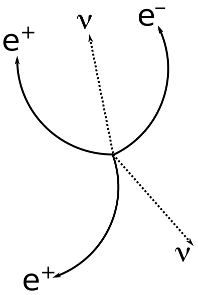
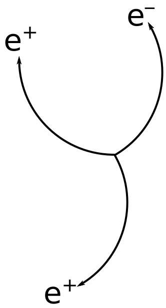


Radiative decay
SM: 3.4×10^{-5}

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

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



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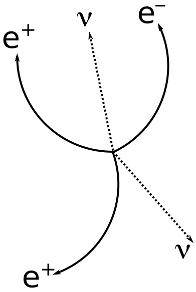

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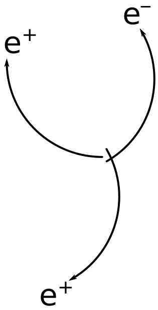
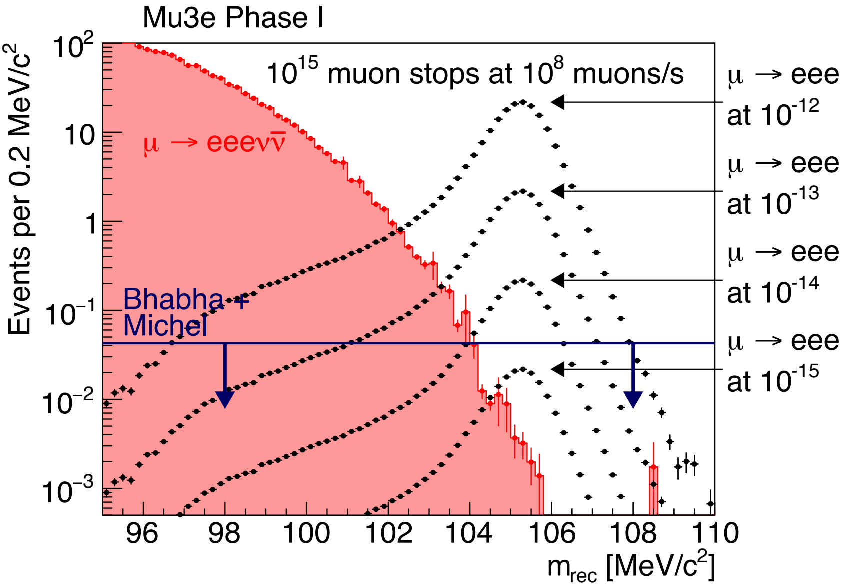


Accidental background

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

Introduction to Mu3e



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. . .

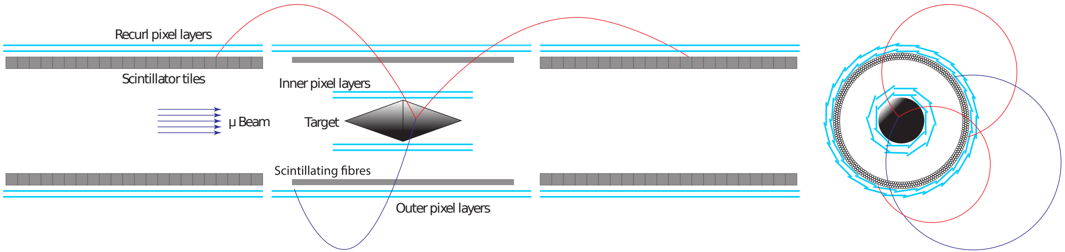
Note: Muons are stopped on a target. No bunch structure.

Rad-hard electronics is not that important.

Mu3e detector concepts

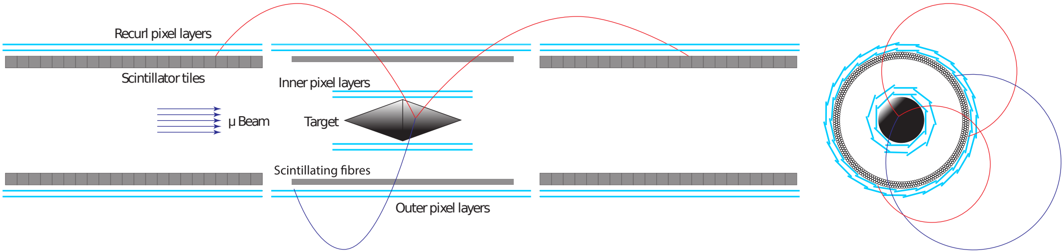
Mu3e detector concepts

Phase-I configuration:



Mu3e detector concepts

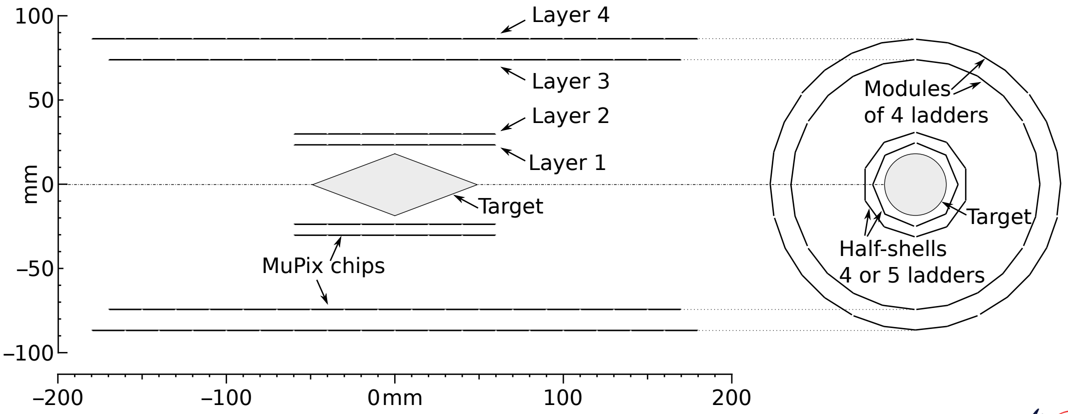
Phase-I configuration:



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

Mu3e detector concepts

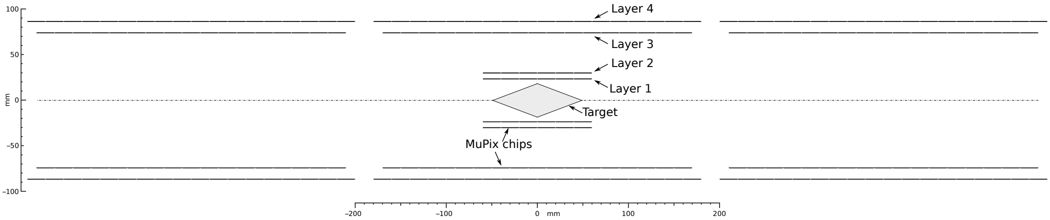
Let's focus on the pixels. Monte-Carlo studies led to the following geometry:



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

Mu3e detector concepts

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?

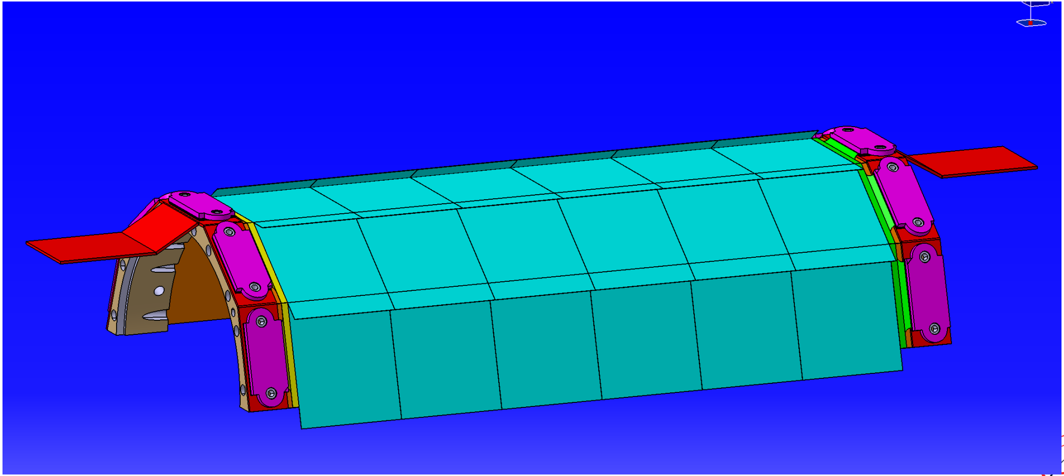
Let's put this into perspective:

Experiment	Ref.	x/X_0 per layer [%]
ATLAS IBL	[1]	1.9
CMS Phase I	[2]	1.1
ALICE upgrade	[3]	0.3
STAR	[4]	0.4
Belle-II IBL	[5]	0.2
Mu3e		**0.1**

Pixel detector mechanics

Pixel detector mechanics – Layers 1/2

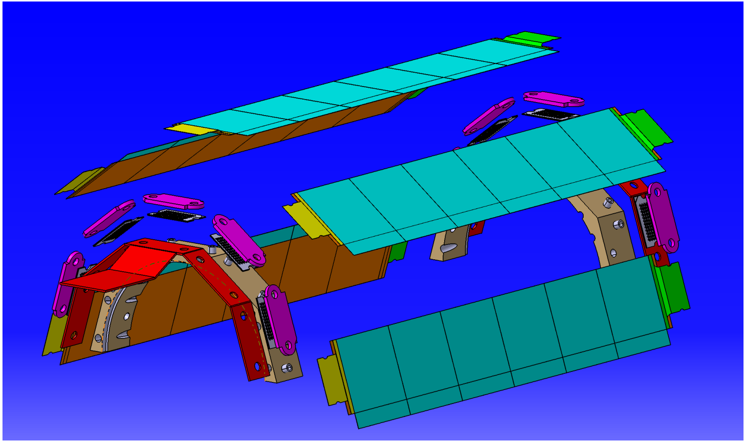
Modules layer 2 design (1 is similar, one facet less)



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

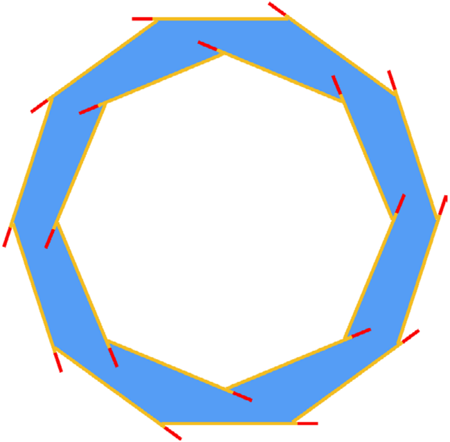
Pixel detector mechanics – Layers 1/2

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



Exploded view of same part.

Pixel detector mechanics

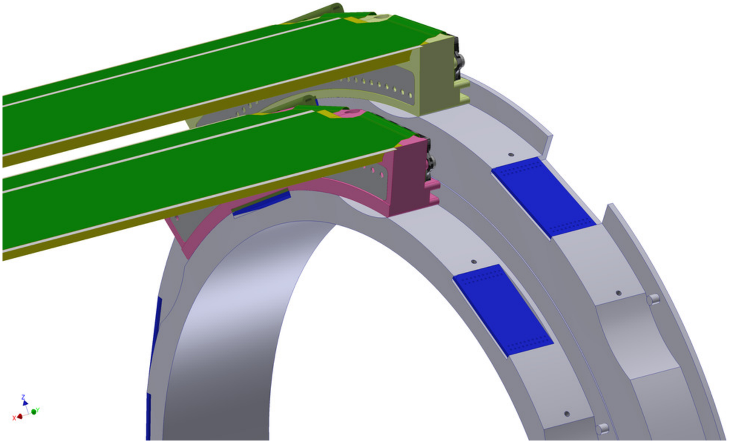


Cut in the $r - \phi$ plane.

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

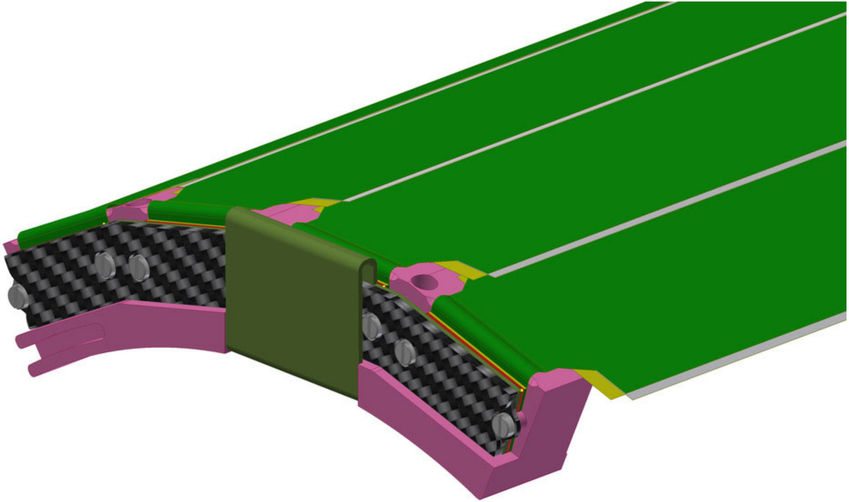
The gap (light blue) will be used for the coolling (see later).

Pixel detector mechanics



Shown: One one module per layer inserted.

Pixel detector mechanics



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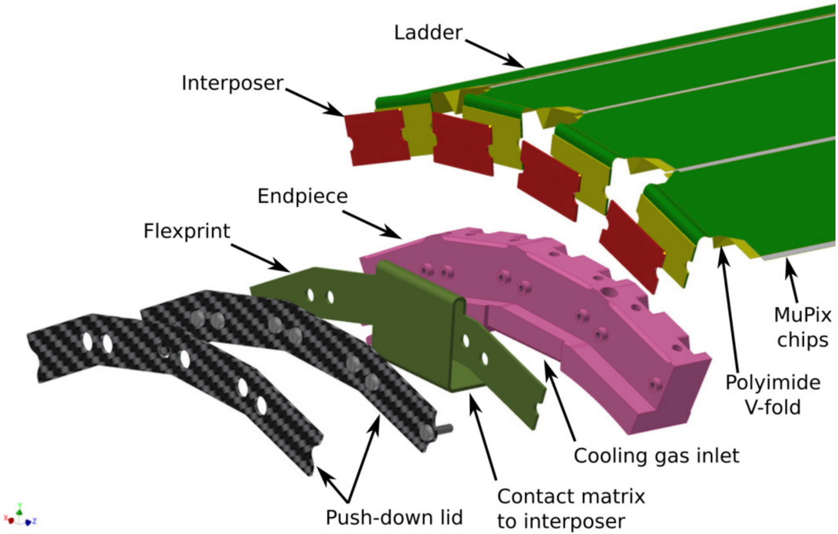

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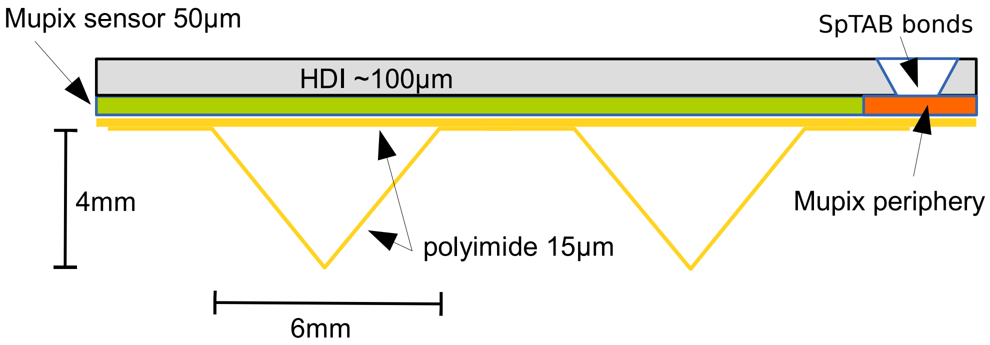


Radiation length: $\approx 0.1\% \, x/X_0$

Mu3e pixel cooling

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

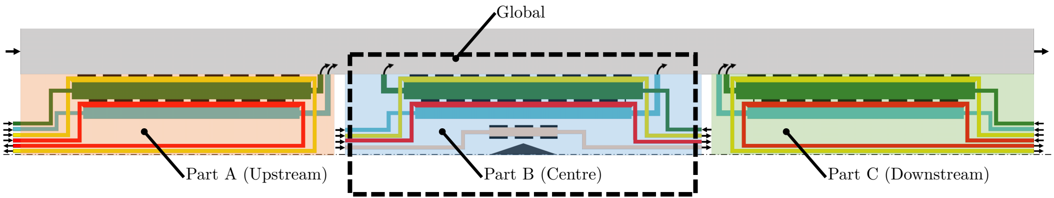
Mu3e pixel cooling

Why helium at ambient pressure?

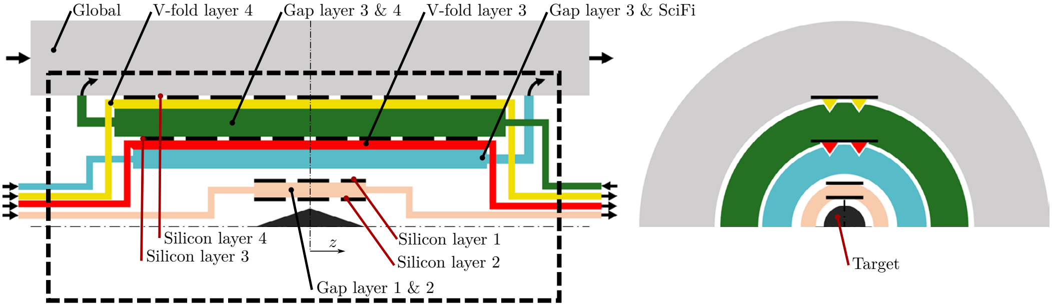
- Radiation length $\approx 17\times$ larger than air
- Large speed of sound: 980 m/s
- Spec. heat capacity 5.2 kJ/(kg K) (air: 1 kJ/(kg K))
- Inert
- Affordable

Mu3e pixel cooling

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



Mu3e pixel cooling



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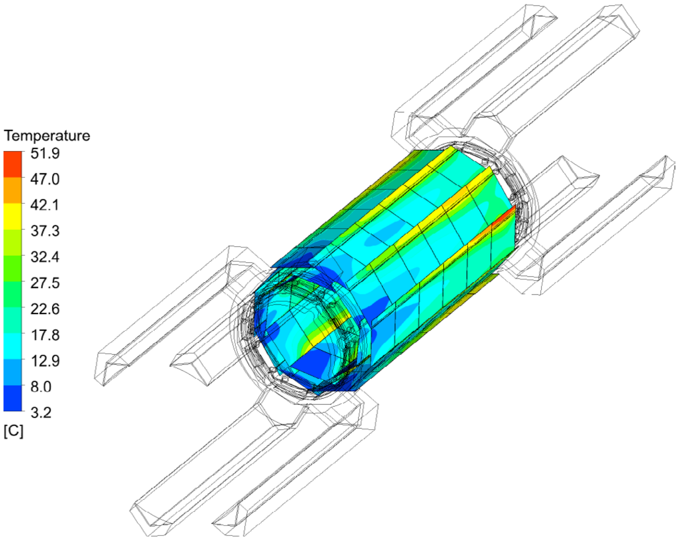


Example CFD simulation result for vertex detector.

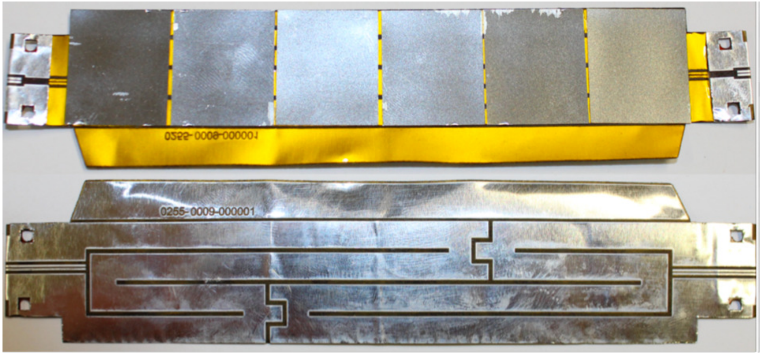
$P/A = 400\,\mathrm{mW/cm^2}$, unequally distributed among periphery and pixel matrix

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

Mu3e pixel cooling

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

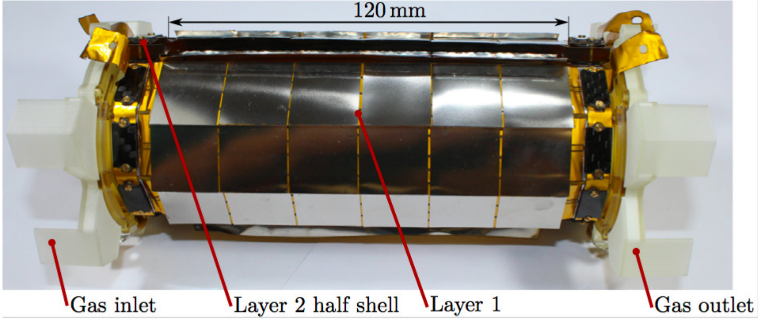
Mu3e pixel cooling



We started with tape heater ladders. . .

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

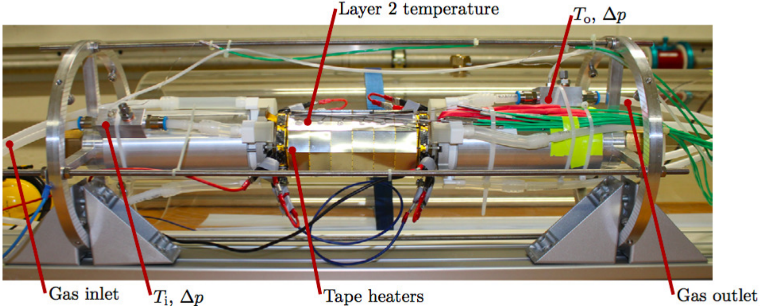
Mu3e pixel cooling



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

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

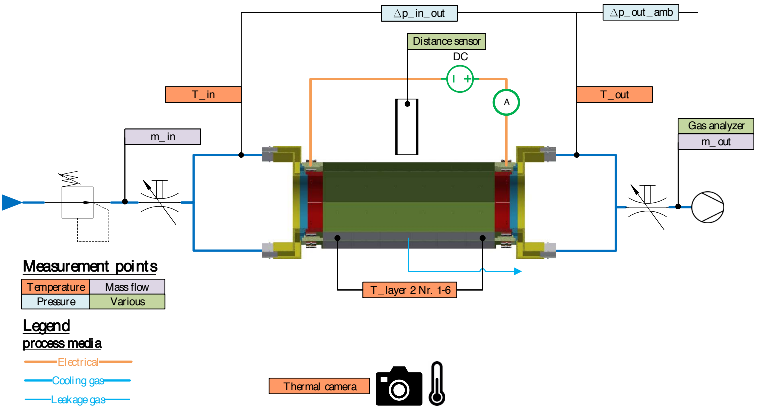
Mu3e pixel cooling



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

Low-mass thermocouples added to mockup structure.

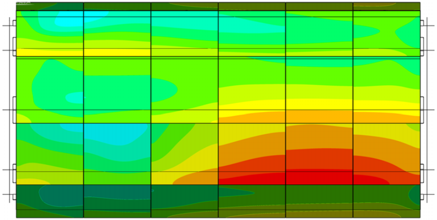
Mu3e pixel cooling



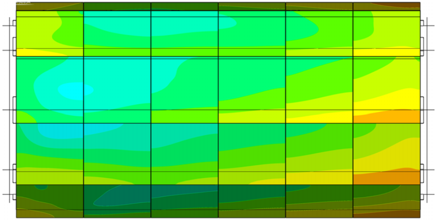
. . . that offers all the diagnostics needed.

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.

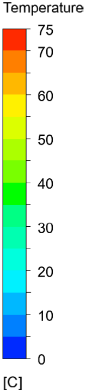
Mu3e pixel cooling



(b) CFD - original inflow geometry.



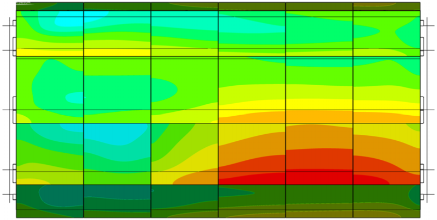
(c) CFD - optimised inflow geometry.



Heat maps in simulation suggested the formation of a vortex.

Do we see it in the lab?

Mu3e pixel cooling



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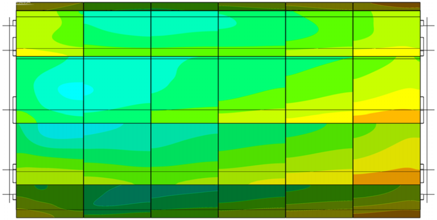

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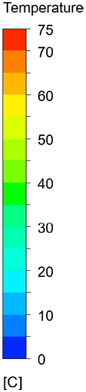
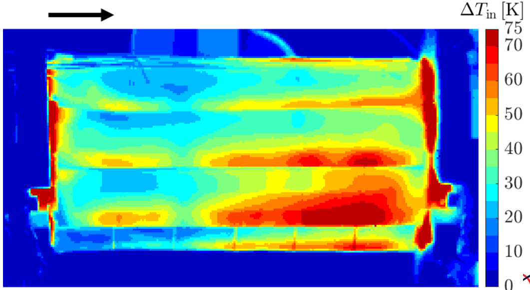


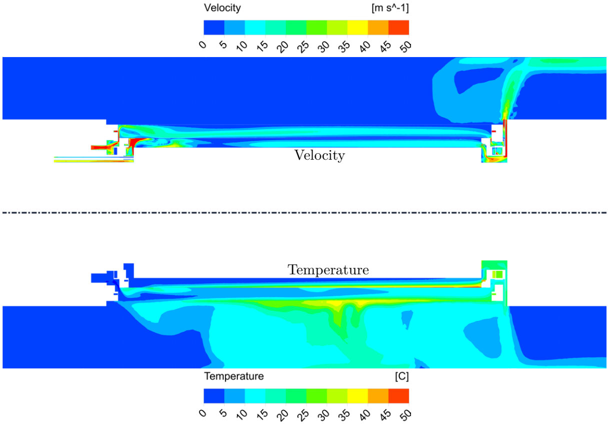
Heat maps in simulation suggested the formation of a vortex.

Yes. Views of simulation match view of IR camera.



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

Mu3e pixel cooling



Simulation of full detector, central part shown.

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

No significant heat influx to SciFi.

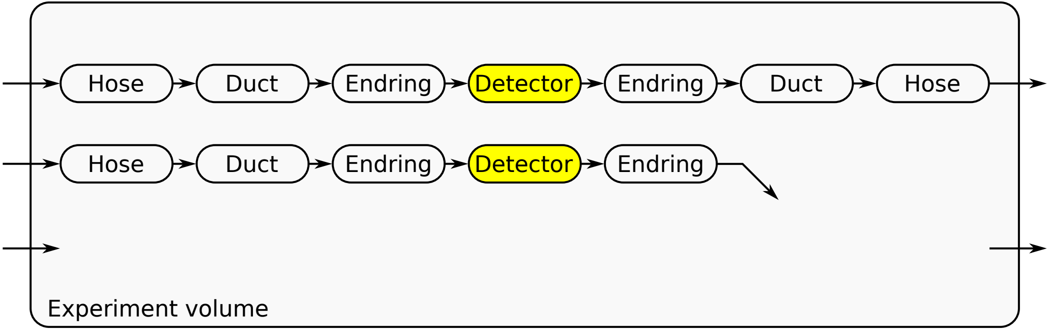
Helium plant

The full detector needs the following helium circuits:

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

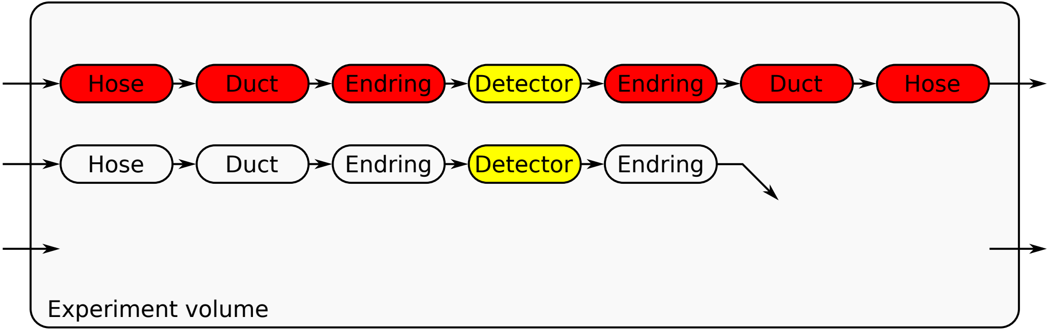
How to create that flow with 4 °C at inlet?

Helium plant



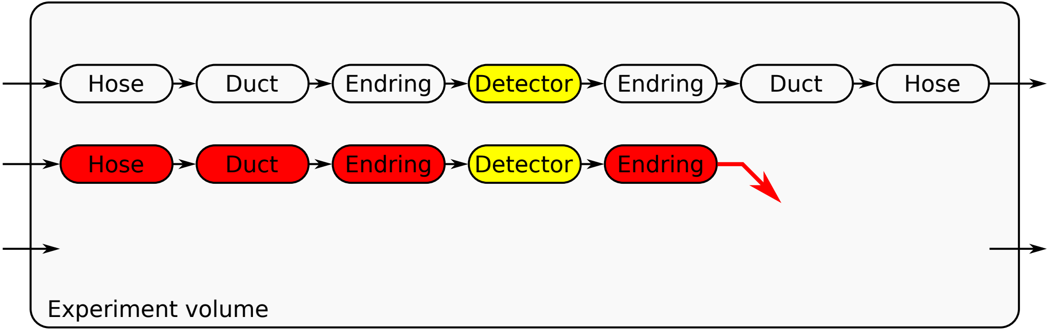
We have three distinct circuit types foreseen. . .

Helium plant



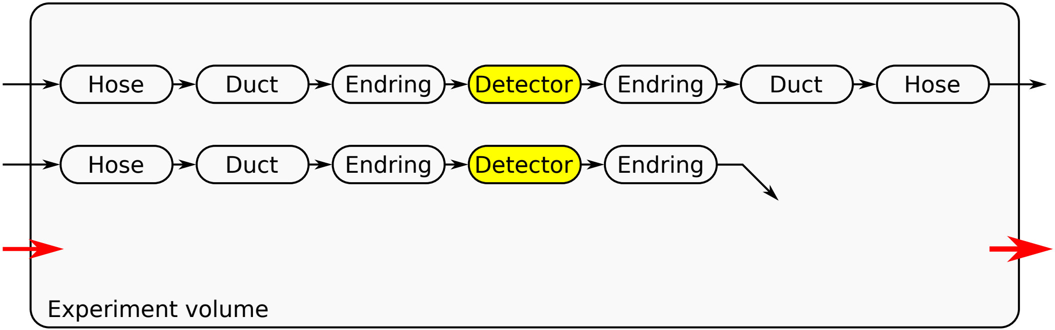
Closed circuit, e.g. for He in V-folds

Helium plant



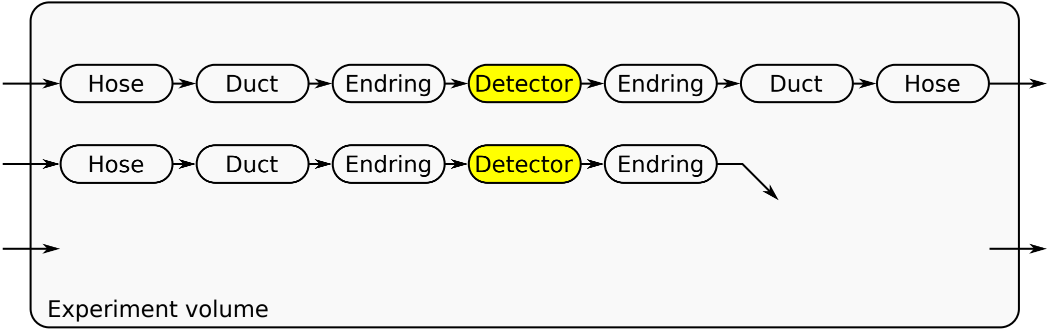
Open circuit, e.g. volume between L3 and L4 vents to large volume

Helium plant



Global flow: prevention of hot pockets and exhaust

Helium plant



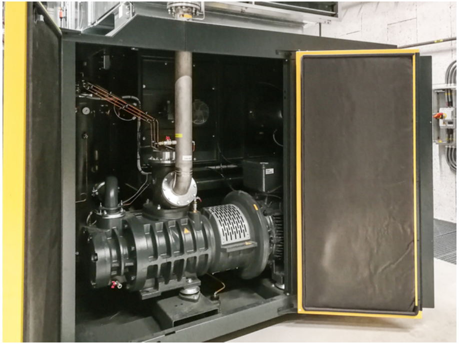
Critical flows and pressures: instrumented volume of pixels. Differential pressures between neighbouring volumes under **tight control** in all operation modes (ramp-up, steady operation, ramp-down, off).
Δp limit to be determined on mock-up, estimated to be $O(1\,\text{mbar})$

Helium plant

Constraints:

- Very restricted space inside magnet ($d = 1\,\mathrm{m}$, $l \approx 2.8\,\mathrm{m}$)
- Magnetic field of $1\,\mathrm{T} \Rightarrow$ 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

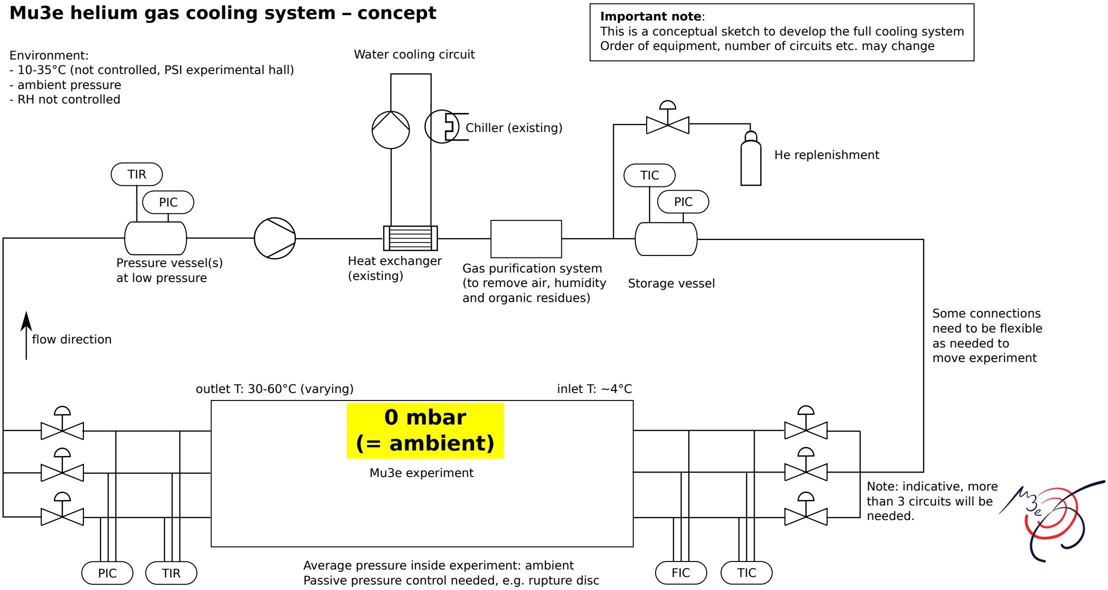
Helium plant— options



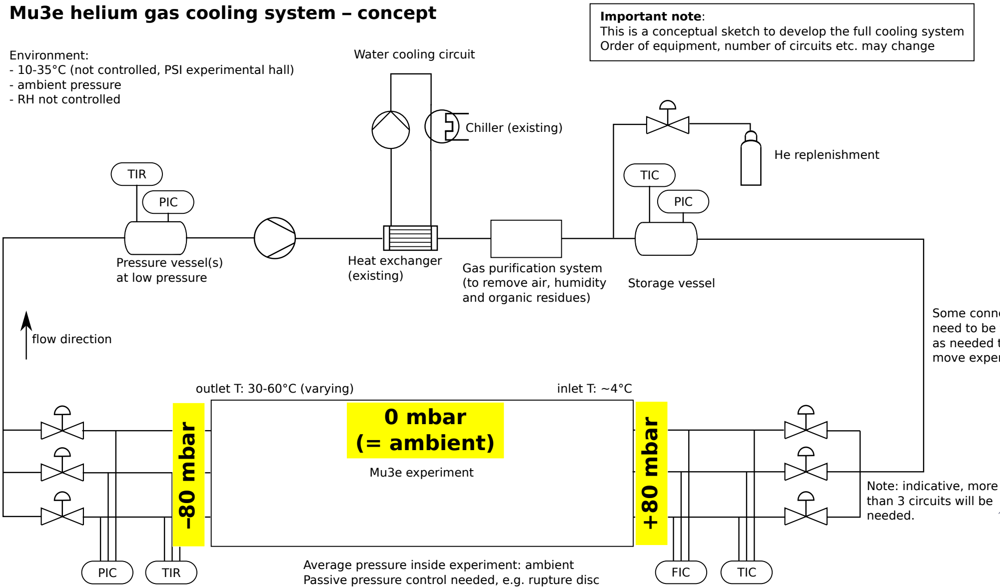
High pressure using screw compressors.

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

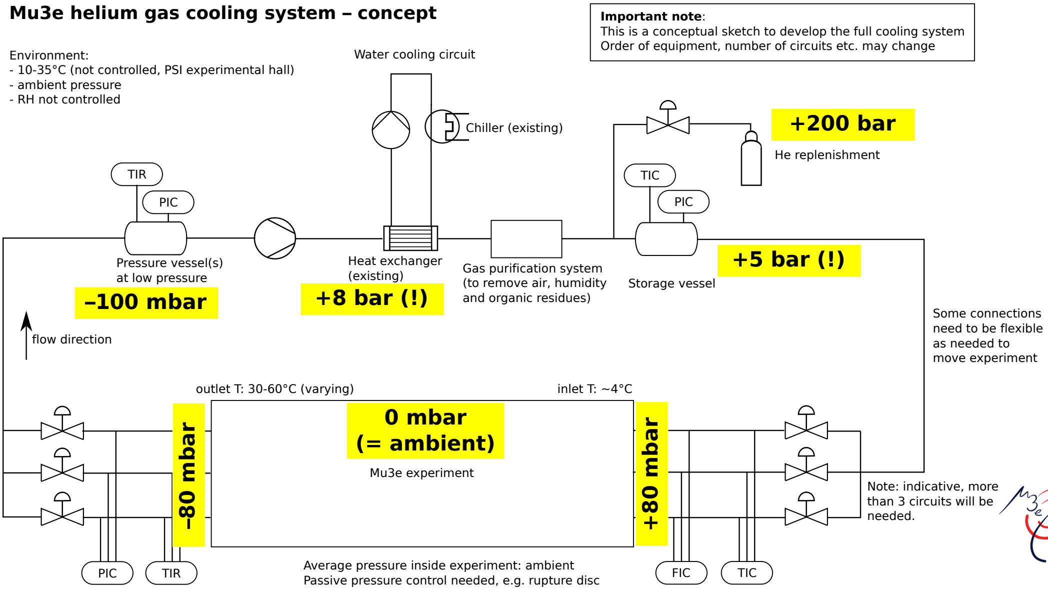
Helium plant



Helium plant

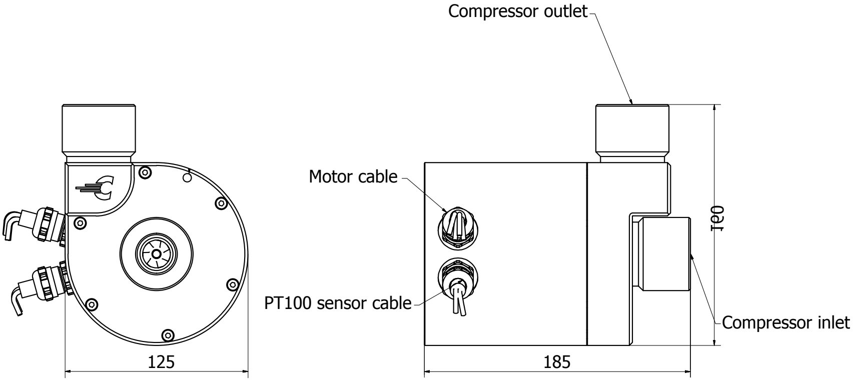


Helium plant

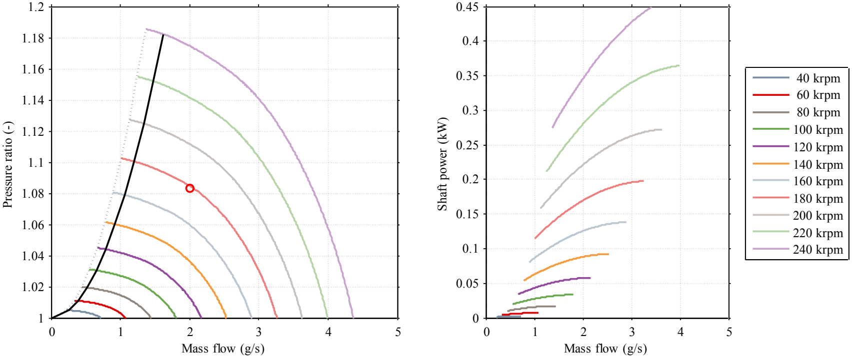


Helium plant— options

- **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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- Reason: Helium vented during installation of a new MRI system
- Helium got distributed over A/C

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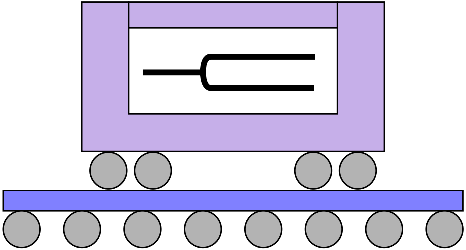
- Reason: Helium vented during installation of a new MRI system
- Helium got distributed over A/C
- Apple iPhones use a MEMS device instead of a quartz as base clock oscillator

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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Conclusions

- 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`

References

[1] ATL-INDET-PROC-2015-001

[2] CERN-LHCC-2012-016, CMS-TDR-11

[3] arXiv:1211.4494v1

[4] G. Contin, talk at PIXEL2016

[5] C. Koffmane, talk at PIXEL2016

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

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

This is realised in e.g. piston compressors. Screw compressors work differently and work almost isothermic.

Inert Helium atmosphere

Okay, this looks all fine. And you know why our detector lives in helium. But what could go wrong?

Inert Helium atmosphere

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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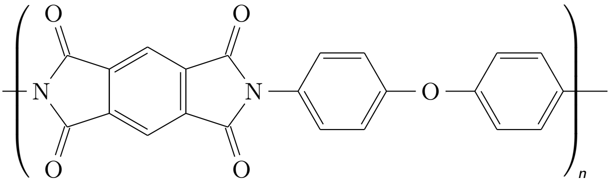
- Other polymers degraded as well but this was more expected. Polyimide has this reputation of being **the** rad-hard polymer.
- What could be the cause? Inspiration came from our scintillator colleagues

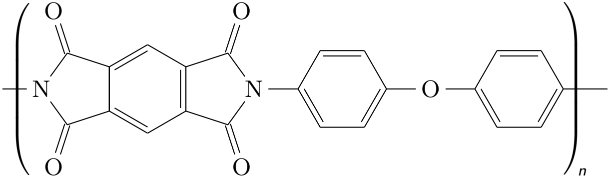
Busjan, Wick, Zoufal 1999, https://doi.org/10.1016/S0168-583X(98)00974-4

Inert Helium atmosphere

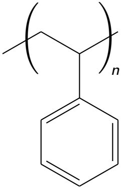


Polyimide

Inert Helium atmosphere

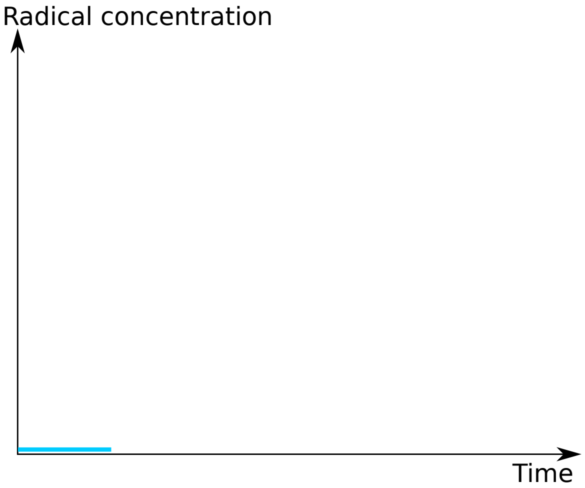


Polyimide



Polystyrene

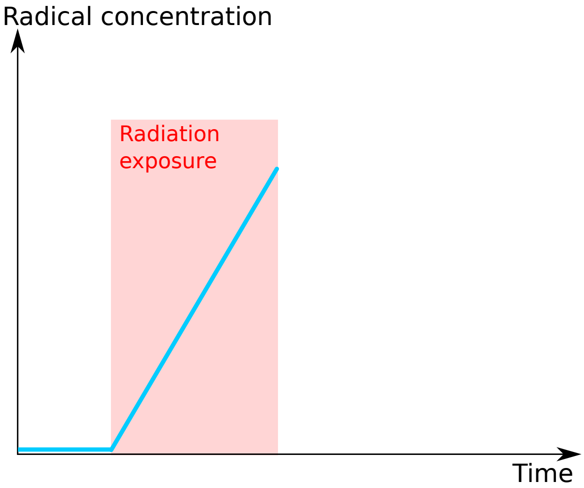
Inert Helium atmosphere



Let's illustrate our hypothesis.

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

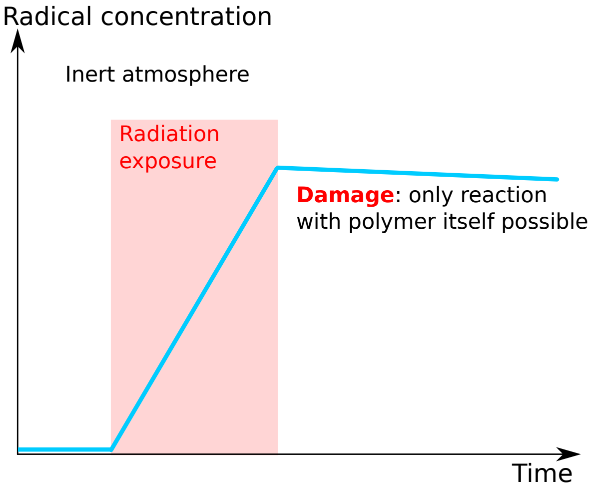
Inert Helium atmosphere



Now we turn on radiation.

The concentration of radicals inside the polymer rises.

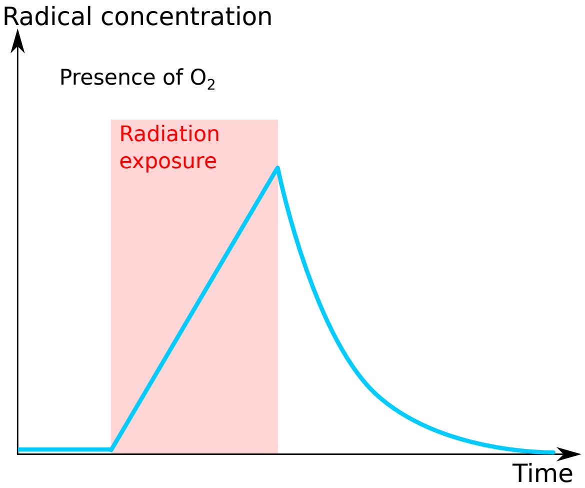
Inert Helium atmosphere



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

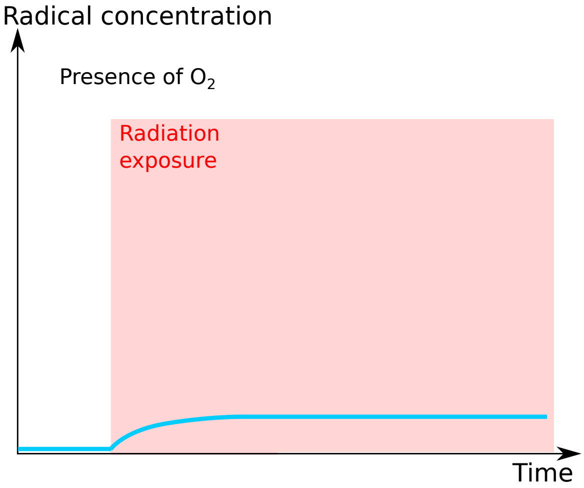
The only chemical reaction possible: with the polymer itself. This leads to structural damage.

Inert Helium atmosphere



If exposed to oxygen, radical concentraion drops to safe levels.

Inert Helium atmosphere

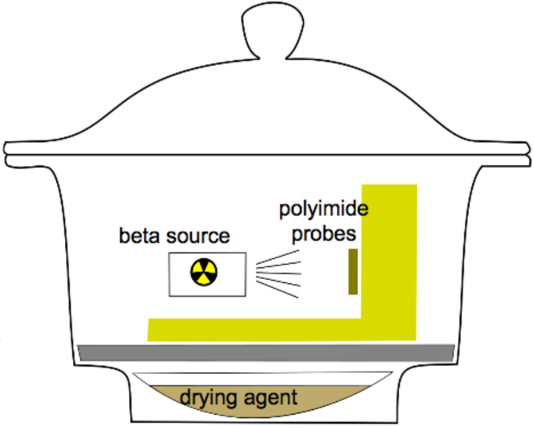


If under radiation **and** oxgen presence, radical level saturates at much lower levels, ageing is much slower.

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

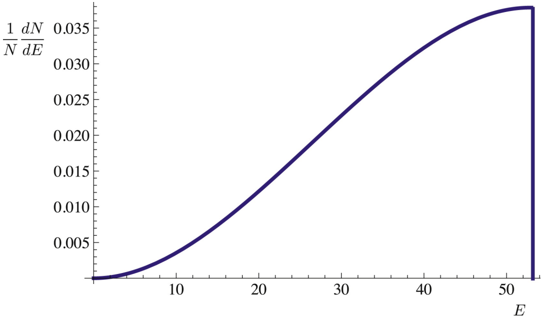


We've started an irradiation campaign.

^{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

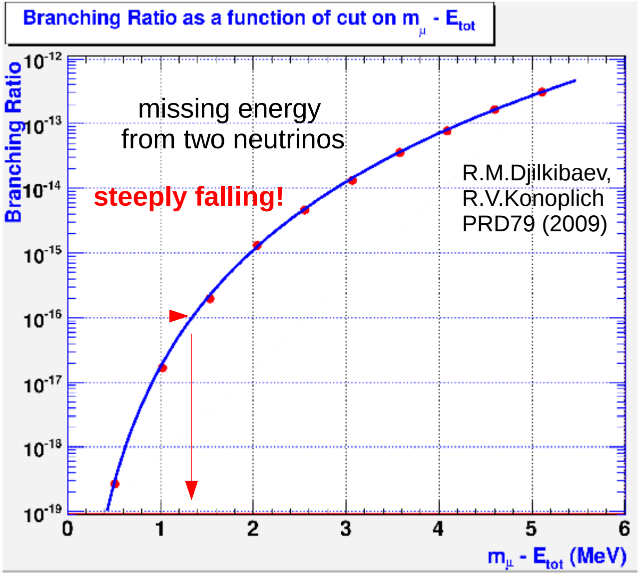


Source: `https://doi.org/10.1016/j.physrep.2013.07.002`

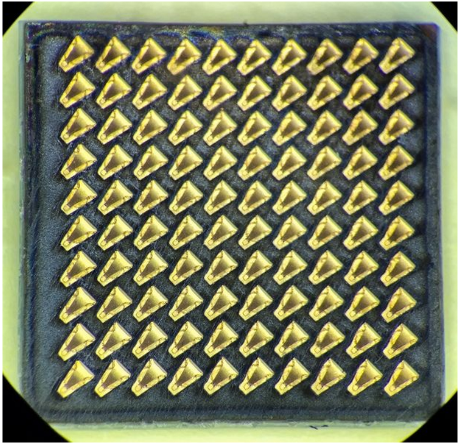
This is the **Michel spectrum**, i.e. the energy spectrum of the positrons of muons decaying at rest.

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

Inert Helium atmosphere



Inert Helium atmosphere



Interposer Samtec Z-Ray

Pitch: 0.8 mm

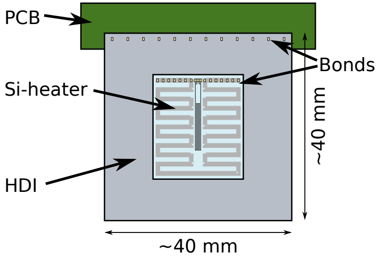
Model	Compressed height
ZA8H	0.3 mm
ZA8	1 mm

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

Allows use of flexes instead of cables.

Inert Helium atmosphere

- 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). **Veryclose to final design.**
- Heater designed to dissipate up to 400 mW/cm^2.
- Has a 1000 Ω RTD on it
- Next set of slides: graph paper viewed reflected on back of silicon heater



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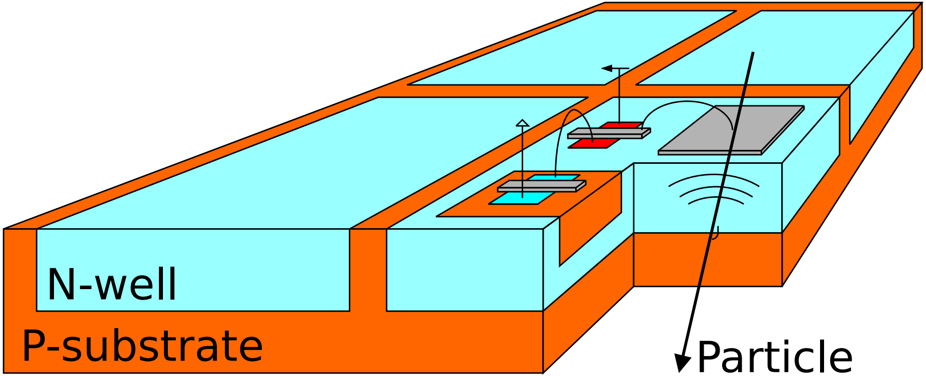
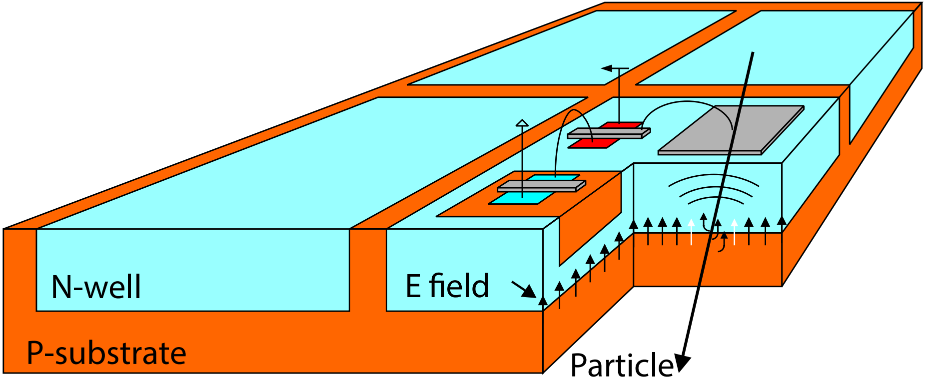


Ivan Perić, Nucl.Instrum.Meth. A582 (2007) 876-885

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

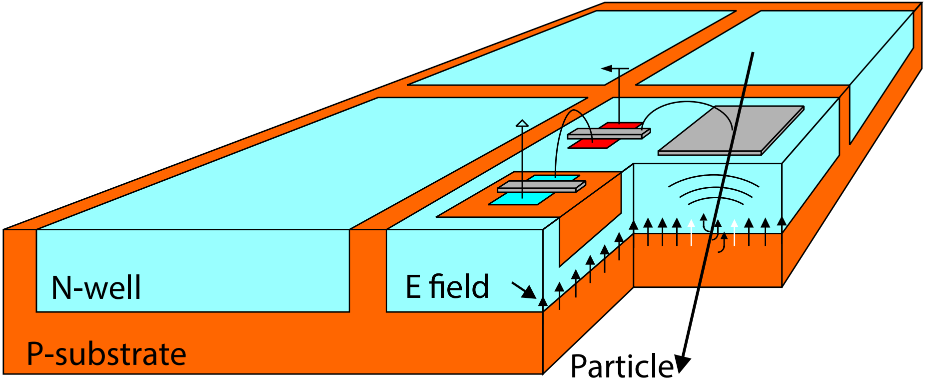
Inert Helium atmosphere



Ivan Perić, Nucl.Instrum.Meth. A582 (2007) 876-885

- 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



Ivan Perić, Nucl.Instrum.Meth. A582 (2007) 876-885

The MuPix chip is such a **depleted MAPS**, thinned to 50 µm $\approx 0.05\% \; x/X_0$