Detector degradation in Helium atmosphere
or
what we have to consider for Mu3e

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Overview

Introduction to Mu3e

What governs the detector design?

Mu3e detector concepts

Mu3e pixel cooling

Inert Helium atmosphere

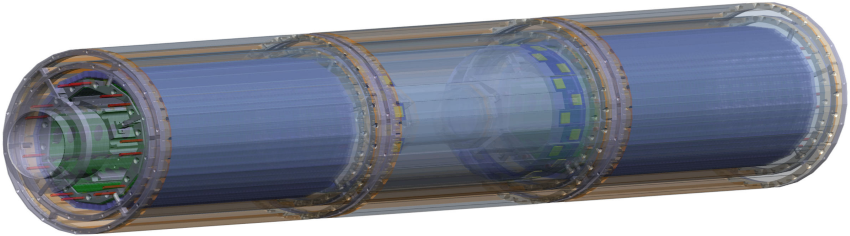
Conclusions

Introduction to Mu3e

Mu3e is an experiment to search for

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

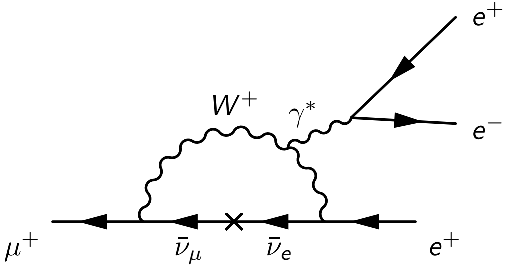
A very rare decay.



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

Introduction to Mu3e

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



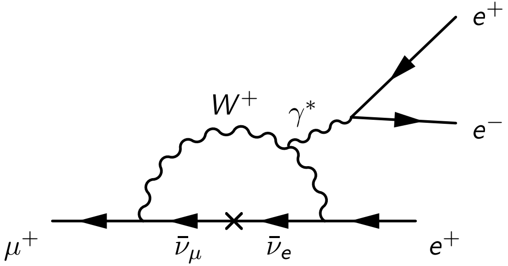
Introduction to Mu3e

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

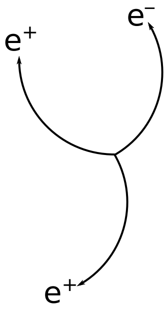
SM: $< 1 \times 10^{-54}$
The suppression comes from the neutrino masses.

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



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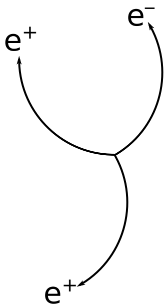

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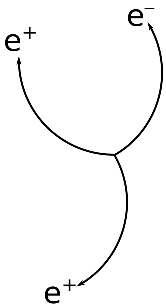
$\sum p_i = 0$

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



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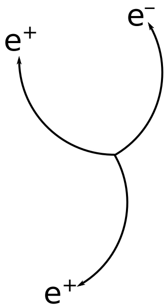

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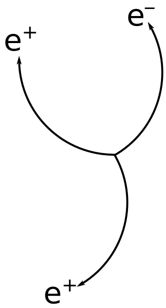

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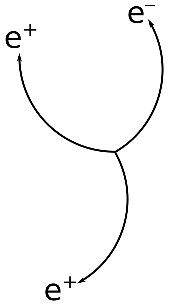

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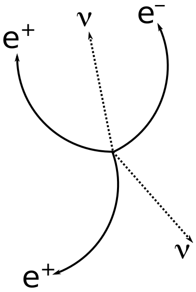
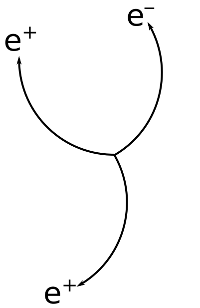


Radiative decay
SM: 3.4×10^{-5}

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

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



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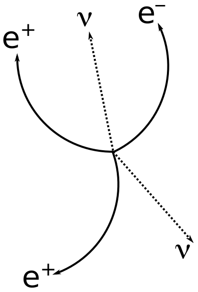

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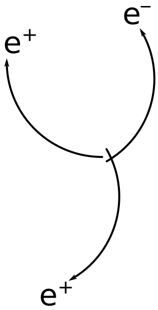
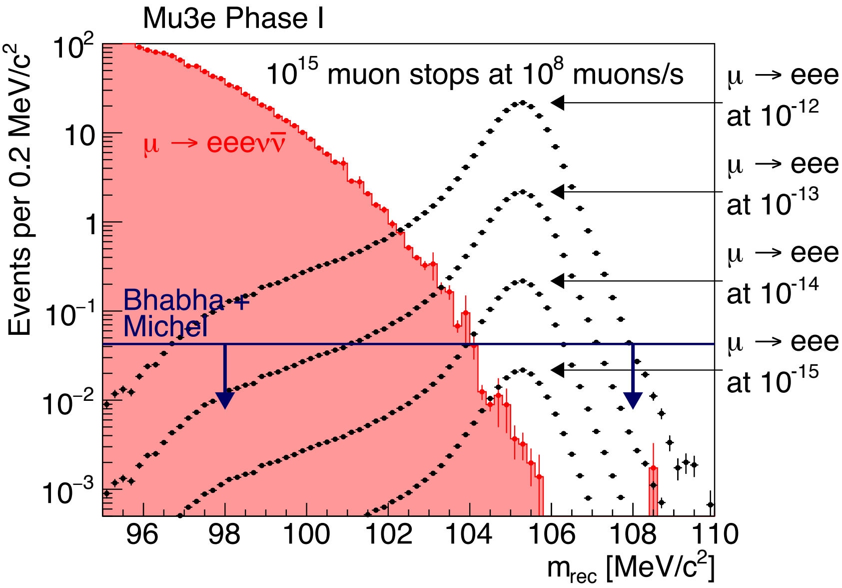


Accidental background

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

Introduction to Mu3e



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. . .

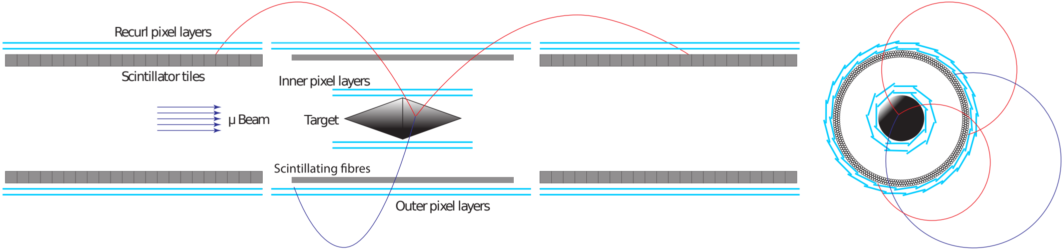
Note: Muons are stopped on a target. No bunch structure.

Rad-hard electronics is not that important.

Mu3e detector concepts

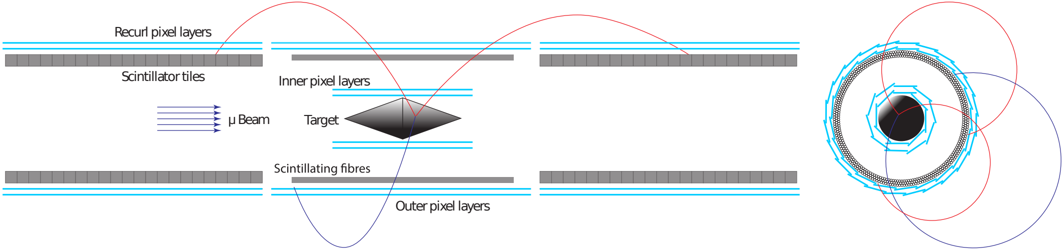
Mu3e detector concepts

Phase-I configuration:



Mu3e detector concepts

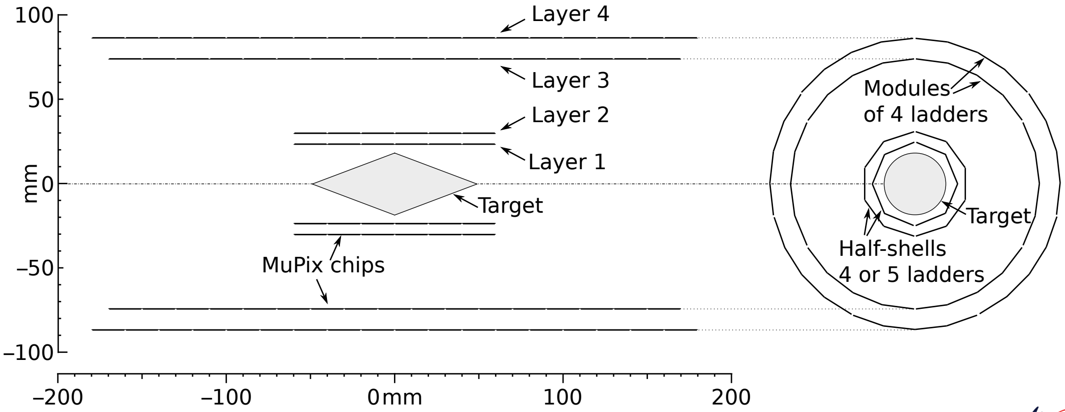
Phase-I configuration:



- 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

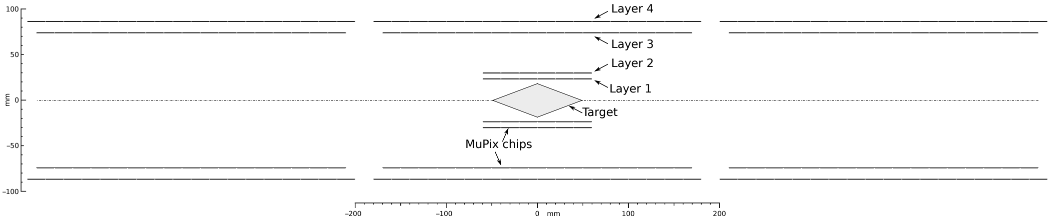
Let's focus on the pixels. Monte-Carlo studies led to the following geometry:



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

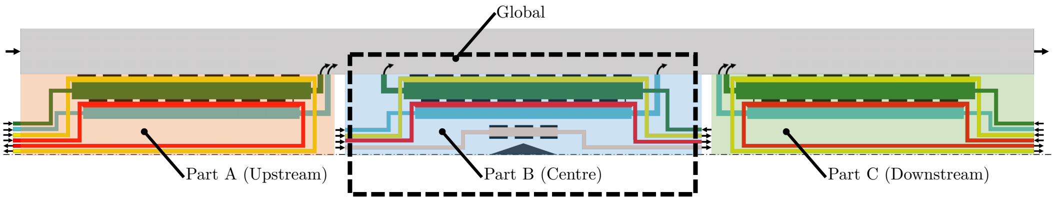
Ok, we got the geometry. But what about the material budget of the pixel layers?

Let's put this into perspective:

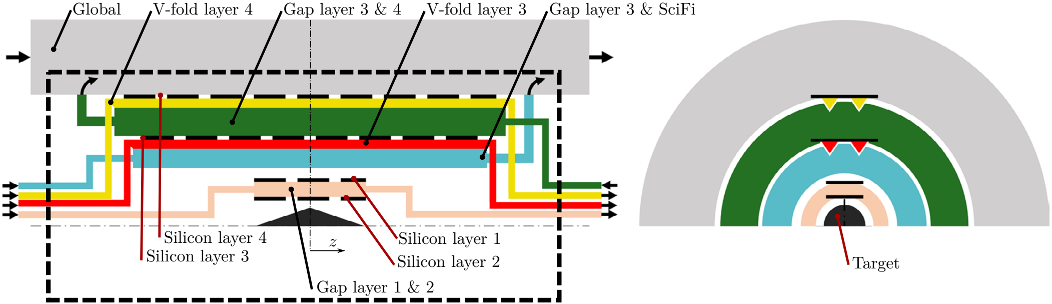
Experiment	Ref.	x/X_0 per layer [%]
ATLAS IBL	[1]	1.9
CMS Phase I	[2]	1.1
ALICE upgrade	[3]	0.3
STAR	[4]	0.4
Belle-II IBL	[5]	0.2
Mu3e		**0.1**

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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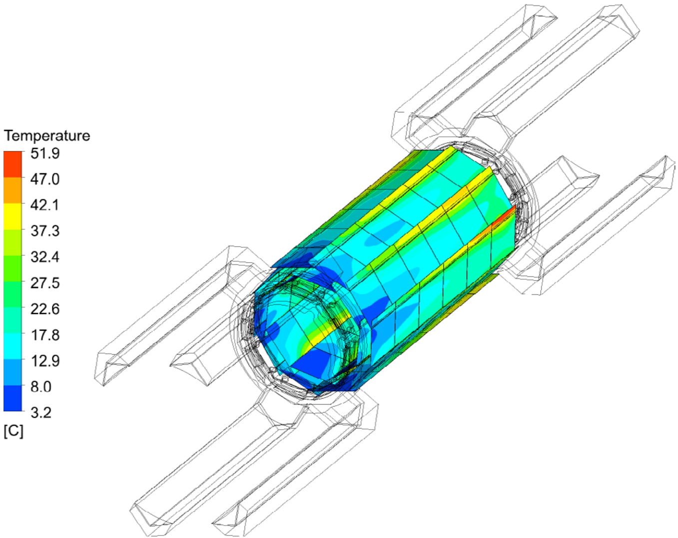


Example CFD simulation result for vertex detector.

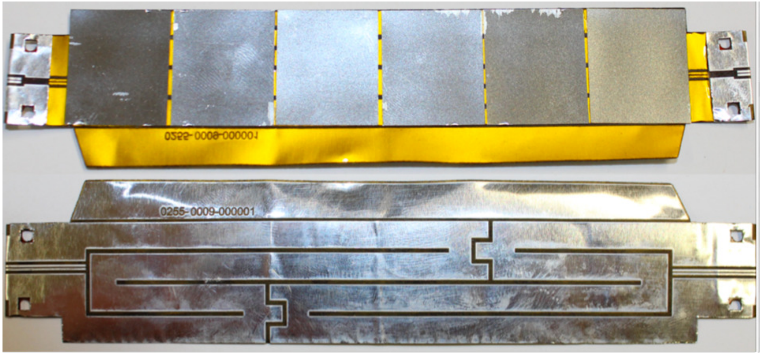
$P/A = 400\,\mathrm{mW/cm^2}$, unequally distributed among periphery and pixel matrix

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

Mu3e pixel cooling

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

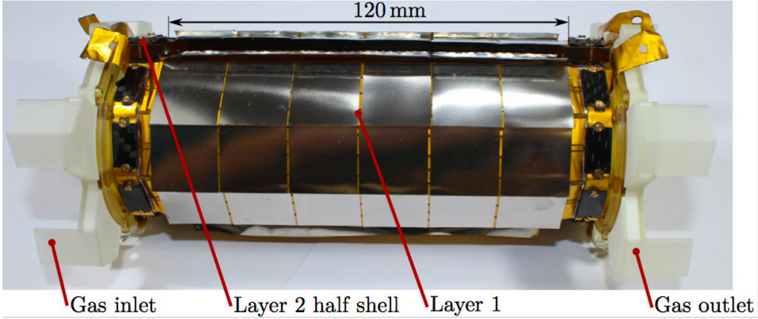
Mu3e pixel cooling



We started with tape heater ladders. . .

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

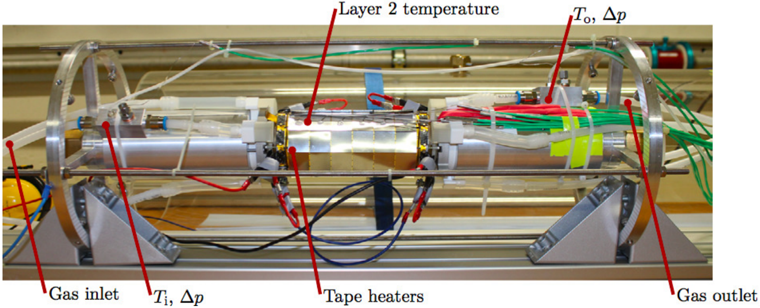
Mu3e pixel cooling



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

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

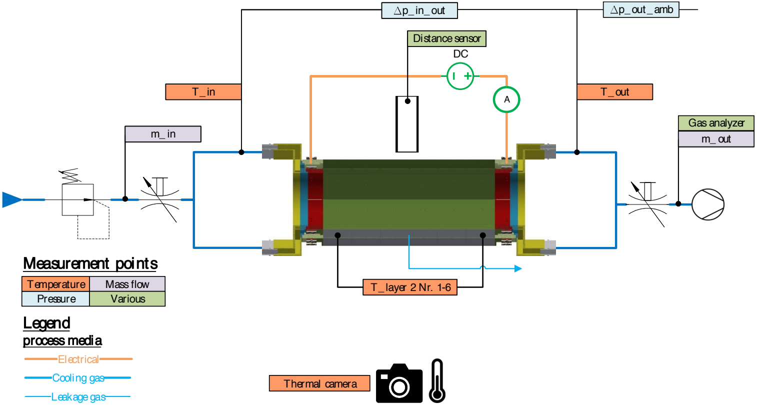
Mu3e pixel cooling



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

Low-mass thermocouples added to mockup structure.

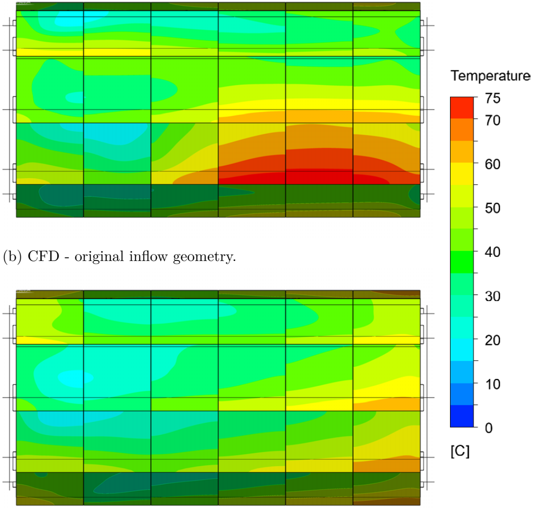
Mu3e pixel cooling



. . . 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 4 g/s mass flow.

Mu3e pixel cooling



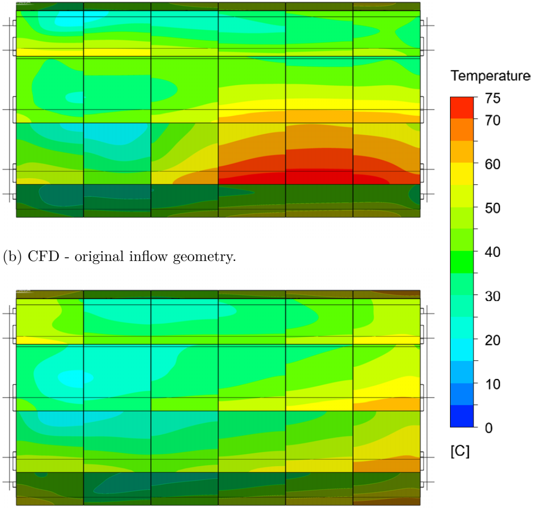
(b) CFD - original inflow geometry.

(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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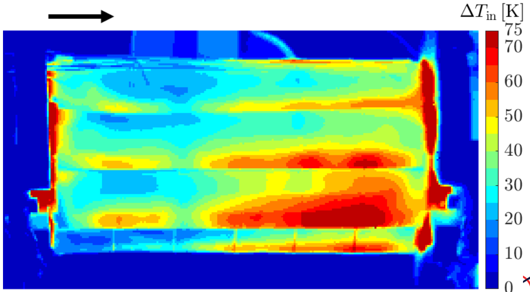
Heat maps in simulation suggested the formation of a vortex.

Yes. Views of simulation match view of IR camera.



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

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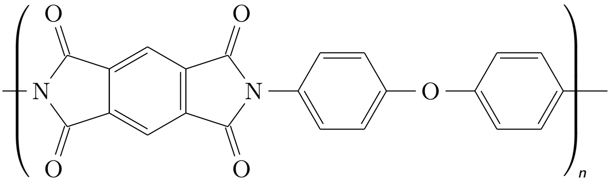
- Other polymers degraded as well but this was more expected. Polyimide has this reputation of being **the** rad-hard polymer.
- What could be the cause? Inspiration came from our scintillator colleagues

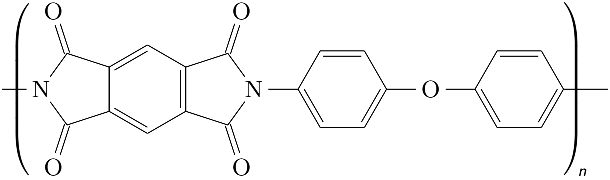
Busjan, Wick, Zoufal 1999, https://doi.org/10.1016/S0168-583X(98)00974-4

Inert Helium atmosphere

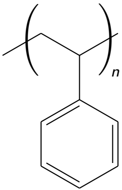


Polyimide

Inert Helium atmosphere

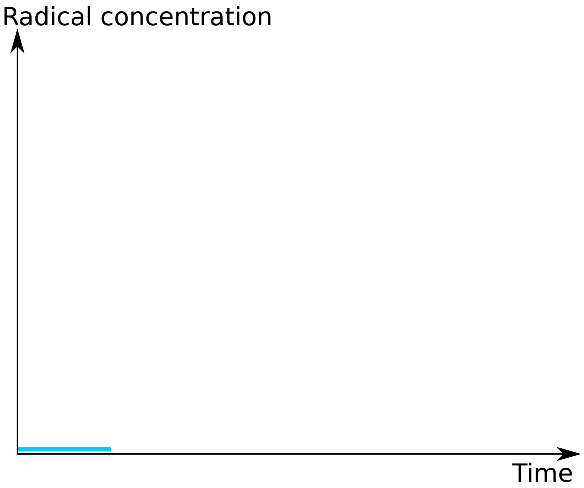


Polyimide



Polystyrene

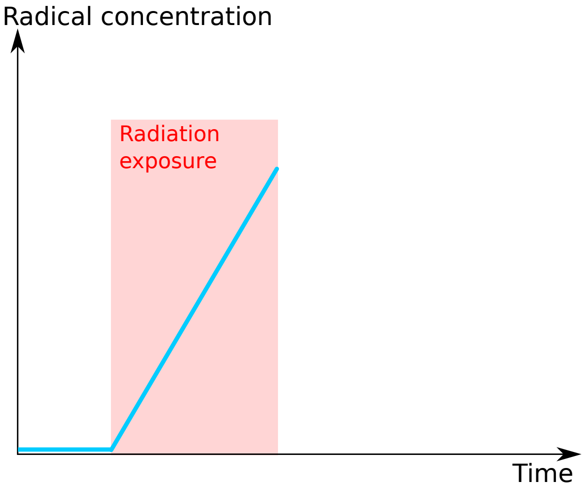
Inert Helium atmosphere



Let's illustrate our hypothesis.

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

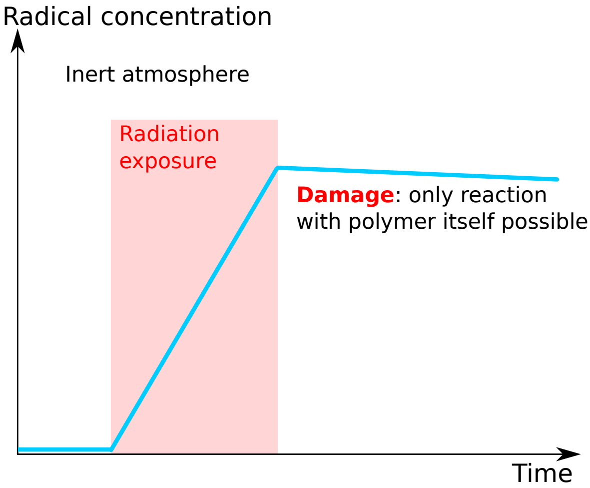
Inert Helium atmosphere



Now we turn on radiation.

The concentration of radicals inside the polymer rises.

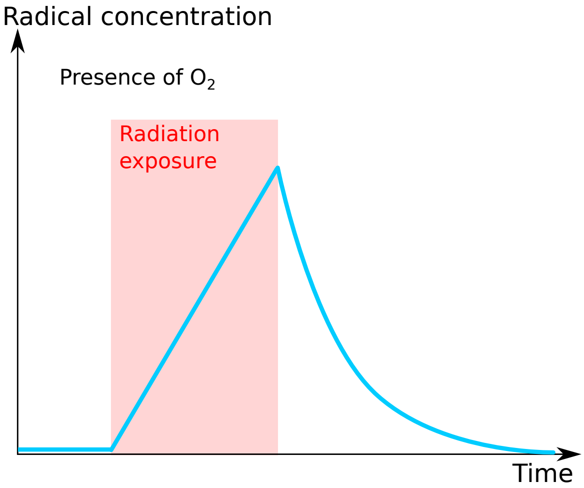
Inert Helium atmosphere



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

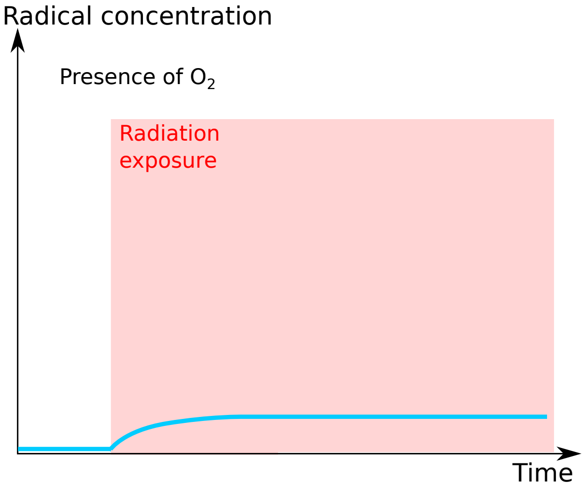
The only chemical reaction possible: with the polymer itself. This leads to structural damage.

Inert Helium atmosphere



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

Inert Helium atmosphere

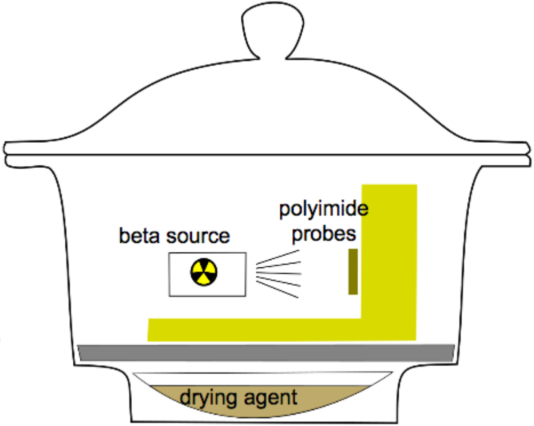


If under radiation **and** oxgen presence, radical level saturates at much lower levels, ageing is much slower.

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

One more thing. . .

Inert Helium atmosphere

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Inert Helium atmosphere

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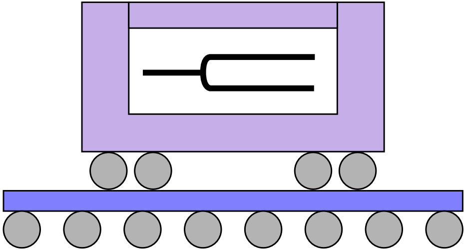
- Sometimes last autumn in Morris, IL, all of a sudden, Apple iPhones died in a hospital
- Reason: Helium vented during installation of a new MRI system
- Helium got distributed over A/C

Inert 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

Inert 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

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  - Polyimide becomes more susceptible to radiation[1]
  - Electronic components may fail

[1] other polymers affected as well, of course

Conclusions

- Mu3e uses gaseous helium as coolant of the pixel tracker
- Concept proven in simulation and in mockup studies
- Dry helium atmosphere poses surprising challenges:
  - Polyimide becomes more susceptible to radiation[1]
  - Electronic components may fail
- Mu3e takes this seriously and performs studies:
  - Irradiation studies with search for mitigating conditions
  - Tests of curcial electronics components in dry helium

[1] other polymers affected as well, of course

References

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

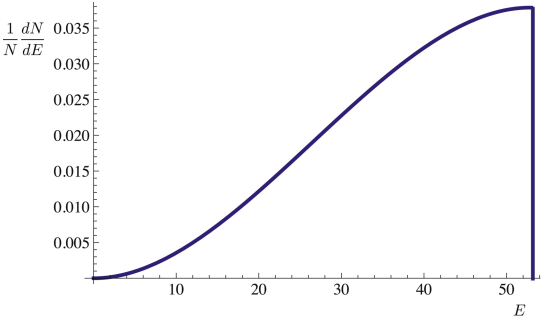
[2] CERN-LHCC-2012-016, CMS-TDR-11

[3] arXiv:1211.4494v1

[4] G. Contin, talk at PIXEL2016

[5] C. Koffmane, talk at PIXEL2016

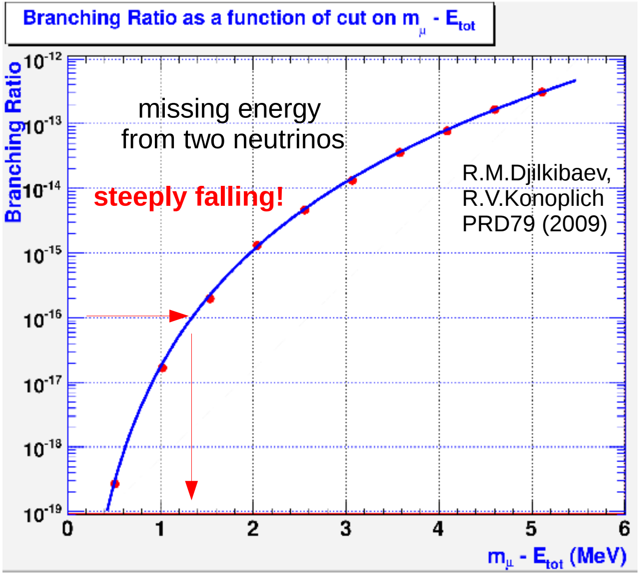
ENCORE

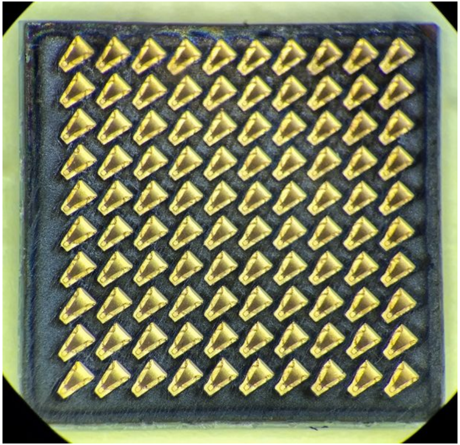


Source: `https://doi.org/10.1016/j.physrep.2013.07.002`

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.


Branching Ratio as a function of cut on $m_\mu - E_{tot}$
Branching Ratio
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
0
1
2
3
4
5
6
$m_\mu - E_{tot}$ (MeV)
missing energy
from two neutrinos
steeply falling!
R.M.Djilkibaev,
R.V.Konoplich
PRD79 (2009)



Interposer Samtec Z-Ray

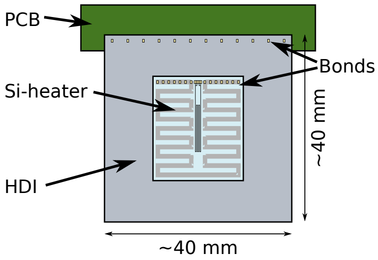
Pitch: 0.8 mm

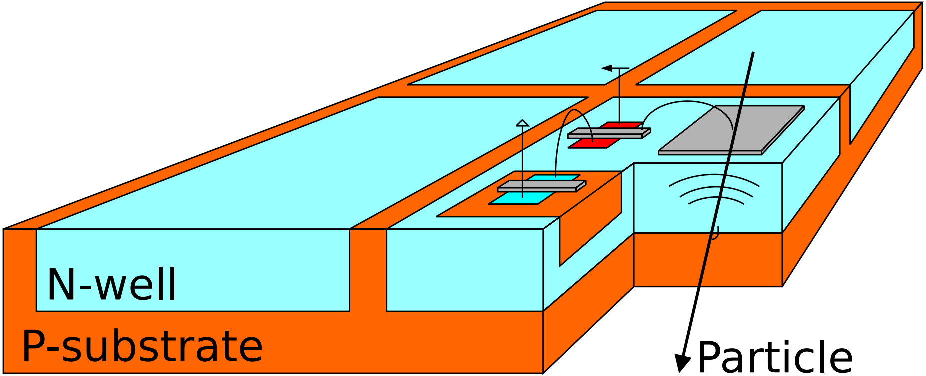
Model	Compressed height
ZA8H	0.3 mm
ZA8	1 mm

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

Allows use of flexes instead of cables.

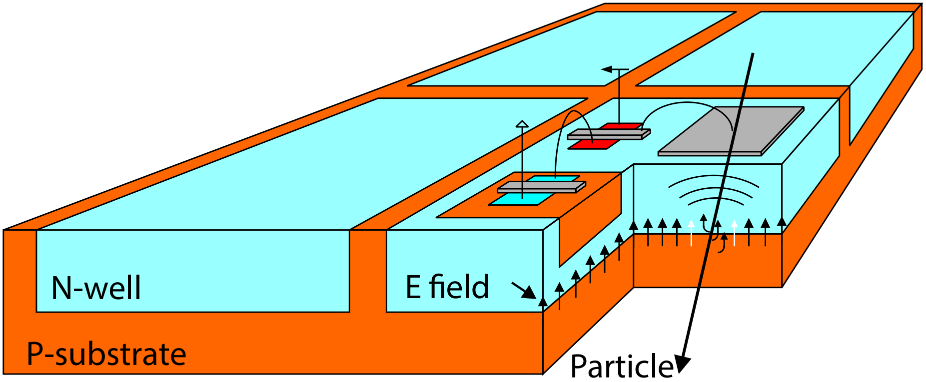
- We've prepared single silicon heater assemblies.
- Consists of heater (sputtered aluminium on silicon, thinned down to 50 µm) and a flex HDI (2 layers Al/polyimide). **Veryclose to final design.**
- Heater designed to dissipate up to 400 mW/cm^2.
- Has a 1000 Ω RTD on it
- Next set of slides: graph paper viewed reflected on back of silicon heater





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

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



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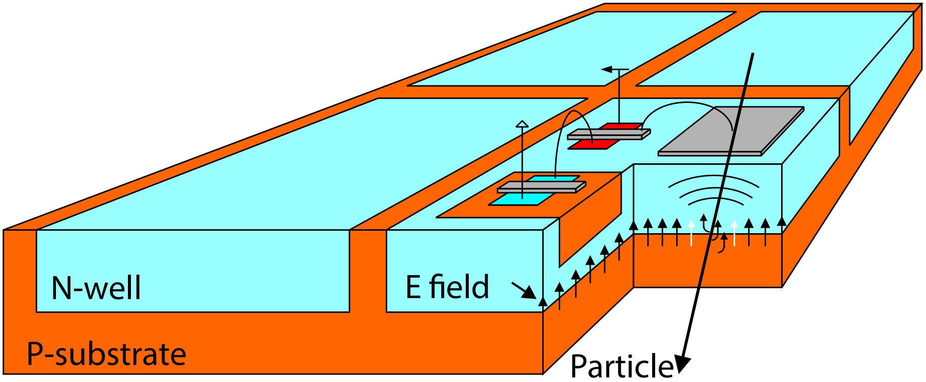
- Analog pixel electronics floats on sensor diode: **monolithic design**
- Industry standard HV CMOS process allows for E-field across diode ⇒ **depletion zone** of about 15 μm



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

The MuPix chip is such a **depleted MAPS**, thinned to 50 µm ≈ 0.05% x/X_0