The Mu3e ultra-low-mass tracker

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for the Mu3e collaboration

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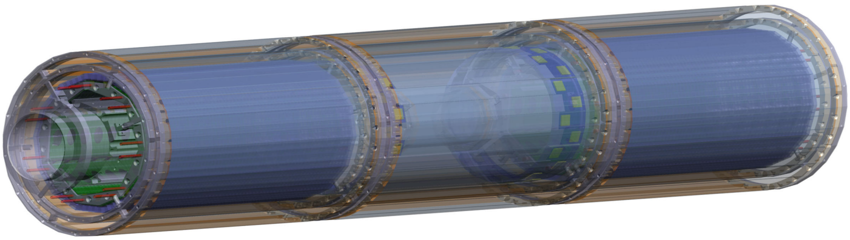
Introduction to Mu3e

Mu3e is an experiment to search for

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

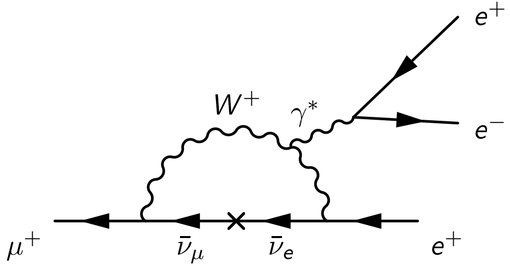
A very rare decay.



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

Introduction to Mu3e

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



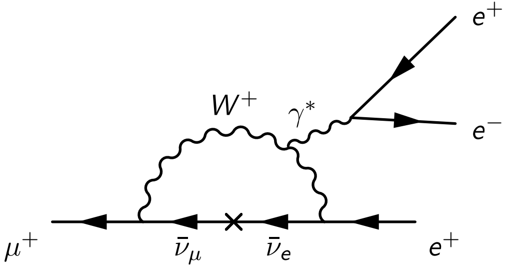
Introduction to Mu3e

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

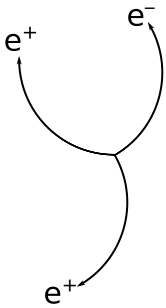
SM: $< 1 \times 10^{-54}$
The suppression comes from the neutrino masses.

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

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

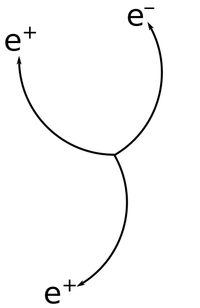


Introduction to Mu3e — Signal in $r\phi$-view



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

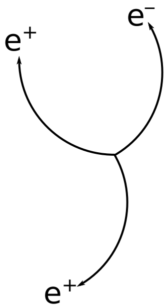
Introduction to Mu3e — Signal in $r\phi$-view



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

$\sum p_i = 0$

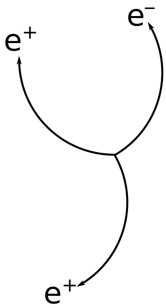
Introduction to Mu3e — Signal in $r\phi$-view



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

$\sum p_i = 0$
$m_{\text{inv}} = m_\mu$

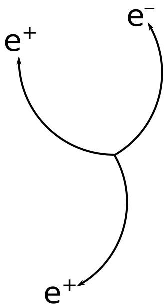
Introduction to Mu3e — Signal in $r\phi$-view



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

$\sum p_i = 0$
$m_{\text{inv}} = m_\mu$
$t_i = t_j \quad \forall\, i, j$

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



Signal

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

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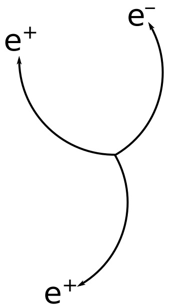
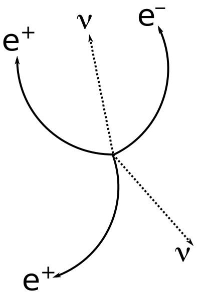
common vertex

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





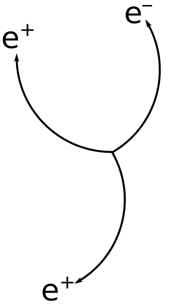
Signal
SM: $< 1 \times 10^{-54}$

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

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



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

$\sum p_i = 0$
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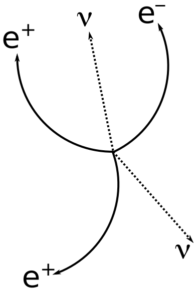
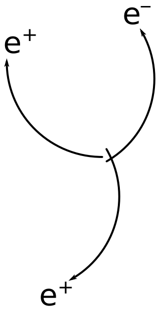
$t_i = t_j \quad \forall\, i, j$
common vertex



Radiative decay
SM: 3.4×10^{-5}

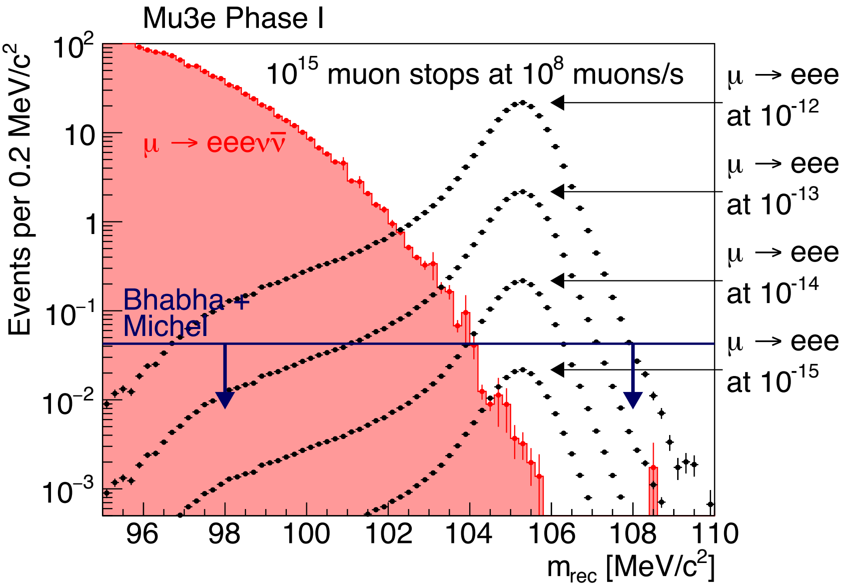
$\sum p_i \neq 0$
$m_{\text{inv}} < m_\mu$
$t_i = t_j$
common vertex



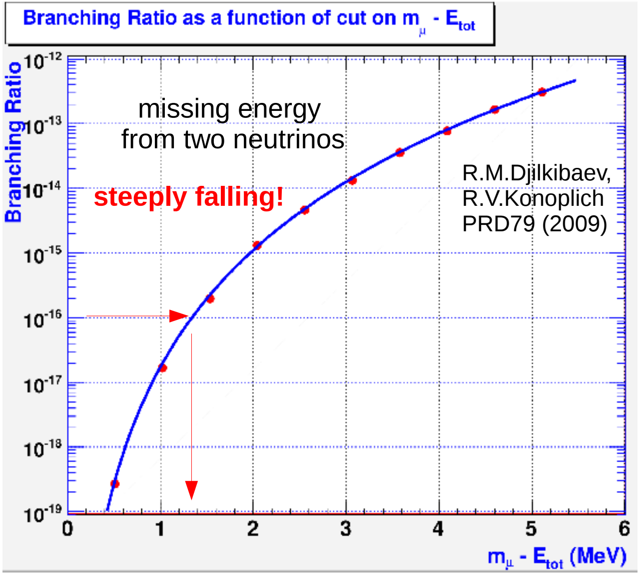
Accidental background

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

Introduction to Mu3e



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. . .

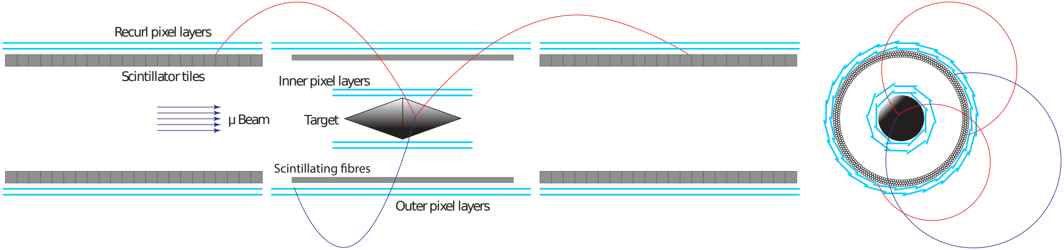
Note: Muons are stopped on a target. No bunch structure.

Rad-hard electronics is not that important.

Mu3e detector concepts

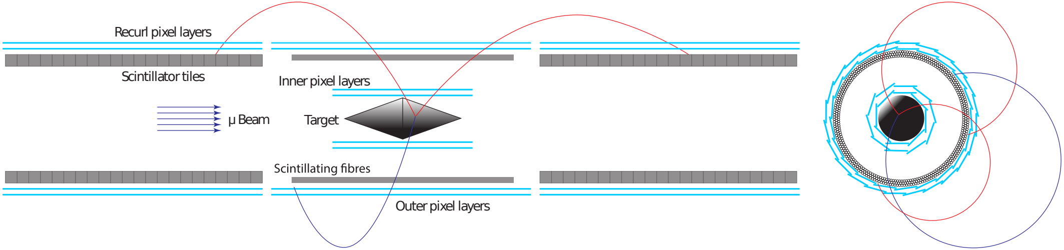
Mu3e detector concepts

Phase-I configuration:



Mu3e detector concepts

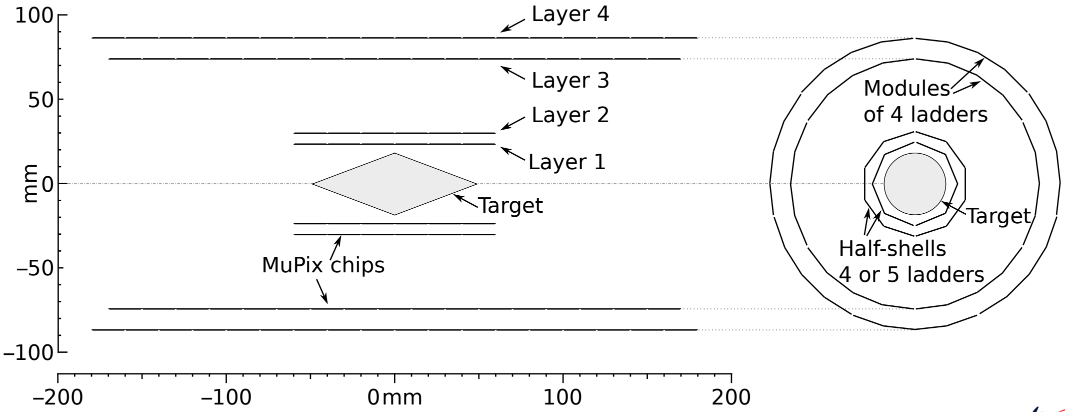
Phase-I configuration:



- 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

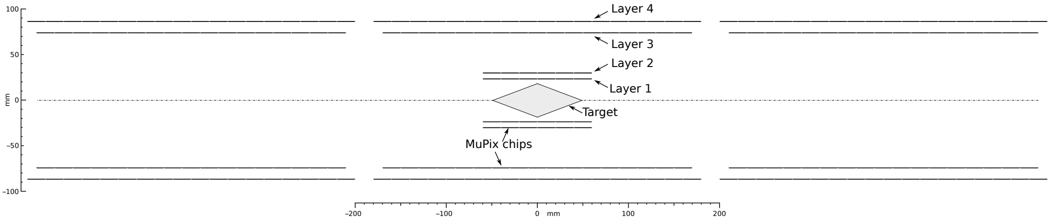
Let's focus on the pixels. Monte-Carlo studies led to the following geometry:



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

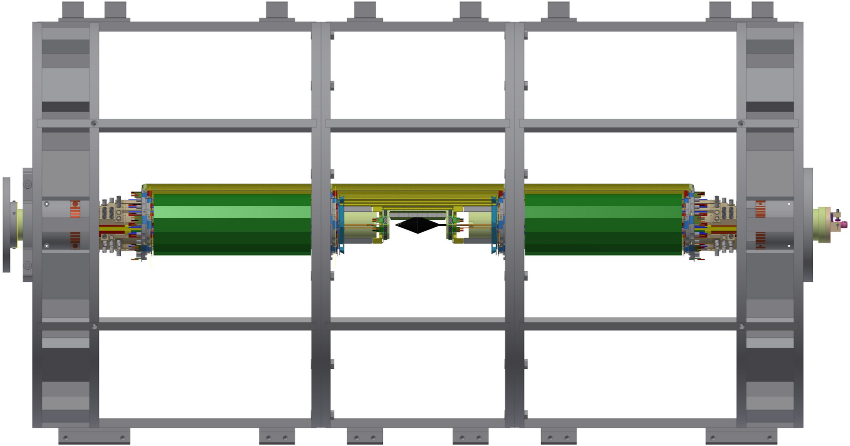
Experiment	Ref.	x/X_0 per layer [%]
ATLAS IBL	[1]	1.9
CMS Phase I	[2]	1.1
ALICE upgrade	[3]	0.3
STAR	[4]	0.4
Belle-II IBL	[5]	0.2
Mu3e		**0.1**

Mu3e detector concepts

Coming back to the solutions I will talk about

- **Low-material mechanics** based on polyimide film
- **Aluminium flexes** to reduce Z
- **Interposers** to save space
- **Stuffing all together** to make it work

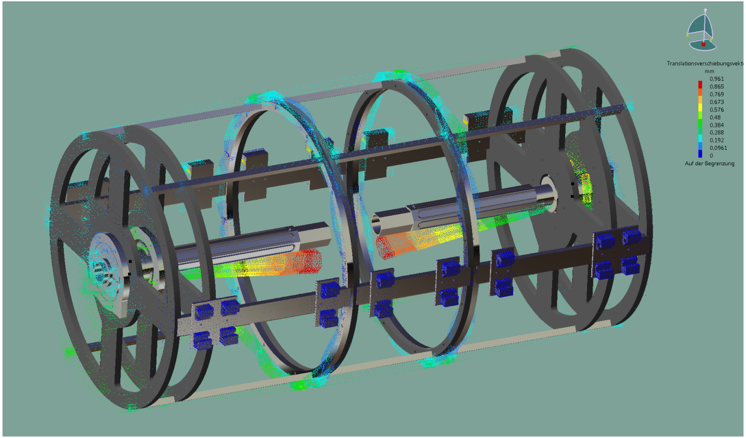
Mu3e mechanics – Mounting structure



Top view of experiment frame, diameter $\approx 1\,\text{m}$.

Mu3e mechanics – Mounting structure

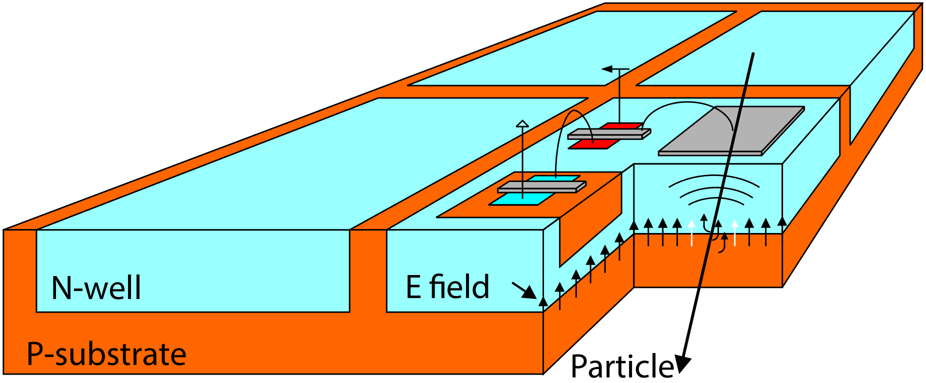
It needs to take the load:



Deformation 100× exagerated. Matches measurements on a mock-up well.

Pixel modules

Mu3e mechanics



We use a monolithic, depleted pixel sensor, thinned to 50 µm. Active chip size $20 \times 20\,\mathrm{mm}^2$, power dissipation $\leq 250\,\mathrm{mW/cm}^2$ (confirmed by measurements).

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

Mu3e mechanics

Central station:

Layer	Unit	units/layer	ladders/unit	chips/ladder	#chips	#links
1	half shell					
2	half shell					
3	module					
4	module					
Total						

Mu3e mechanics

Central station:

Layer	Unit	units/layer	ladders/unit	chips/ladder	#chips	#links
1	half shell	2				
2	half shell	2				
3	module	6				
4	module	7				
Total						

Mu3e mechanics

Central station:

Layer	Unit	units/layer	ladders/unit	chips/ladder	#chips	#links
1	half shell	2	4			
2	half shell	2	5			
3	module	6	4			
4	module	7	4			
Total						

Mu3e mechanics

Central station:

Layer	Unit	units/layer	ladders/unit	chips/ladder	#chips	#links
1	half shell	2	4	6		
2	half shell	2	5	6		
3	module	6	4	17		
4	module	7	4	18		
Total						

Mu3e mechanics

Central station:

Layer	Unit	units/layer	ladders/unit	chips/ladder	#chips	#links
1	half shell	2	4	6	48	
2	half shell	2	5	6	60	
3	module	6	4	17	408	
4	module	7	4	18	504	
Total					1020	

Mu3e mechanics

Central station:

Layer	Unit	units/layer	ladders/unit	chips/ladder	#chips	#links
1	half shell	2	4	6	48	144
2	half shell	2	5	6	60	180
3	module	6	4	17	408	408
4	module	7	4	18	504	504
Total					1020	1236

Mu3e mechanics

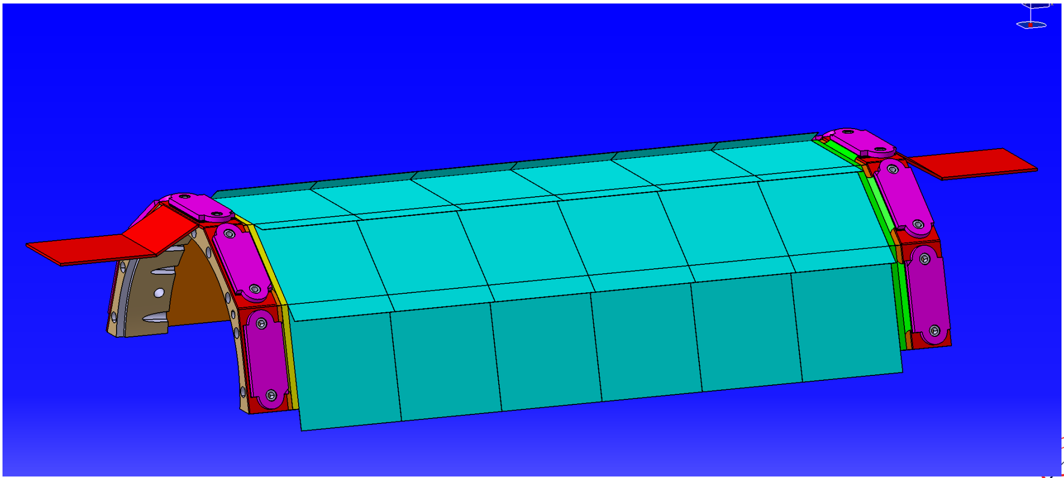
Central station plus two recurl stations:

Layer	Unit	units/layer	ladders/unit	chips/ladder	#chips	#links
1	half shell	2	4	6	48	144
2	half shell	2	5	6	60	180
3	module	6	4	17	1224	1224
4	module	7	4	18	1512	1512
Total					2844	3060

One chip dissipates about 1 W $\Rightarrow$ about 3 kW of heat.

Mu3e mechanics – Layers 1/2

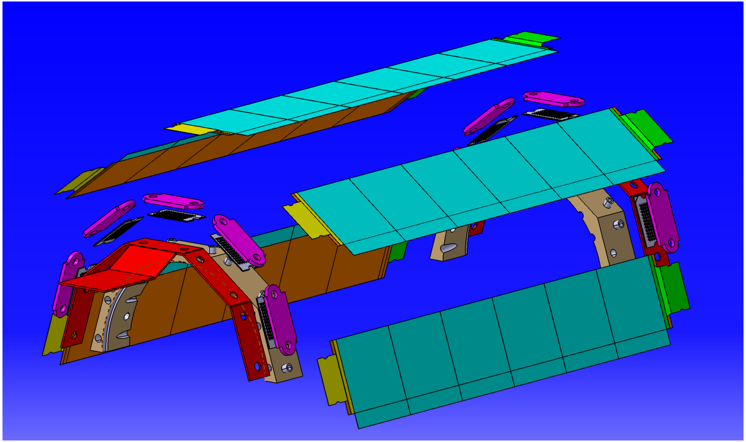
Modules layer 2 design (1 is similar, one facet less)



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

Mu3e mechanics – Layers 1/2

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

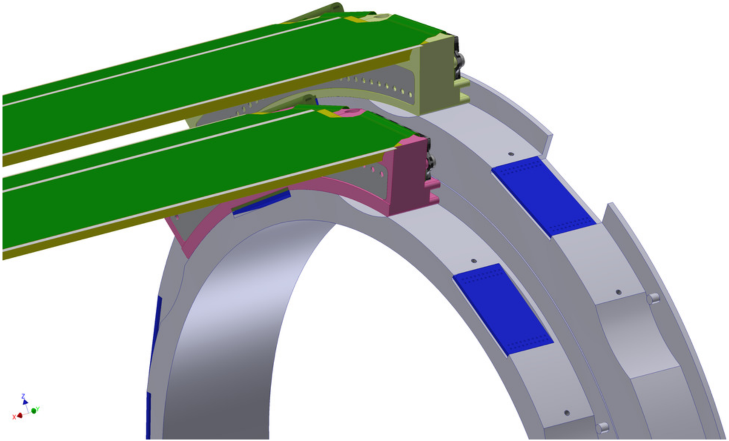


Exploded view of same part.

Mu3e mechanics – Layers 1/2

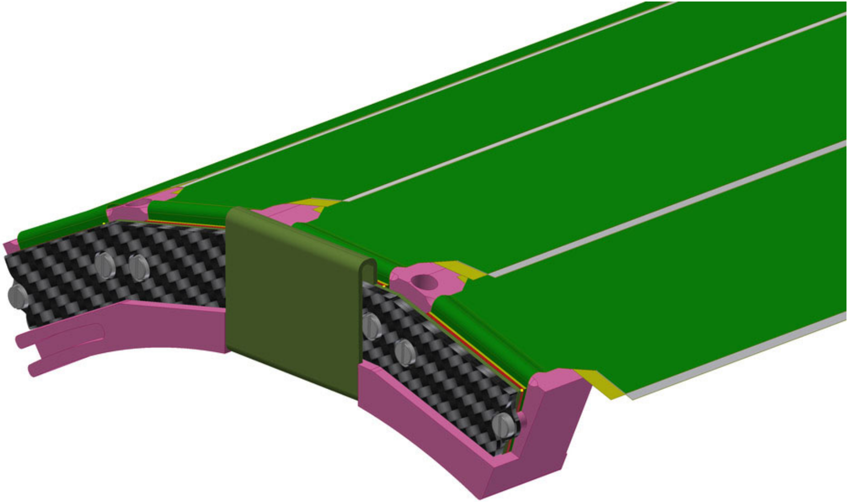
More on this: see poster by Simon Muley.

Mu3e mechanics

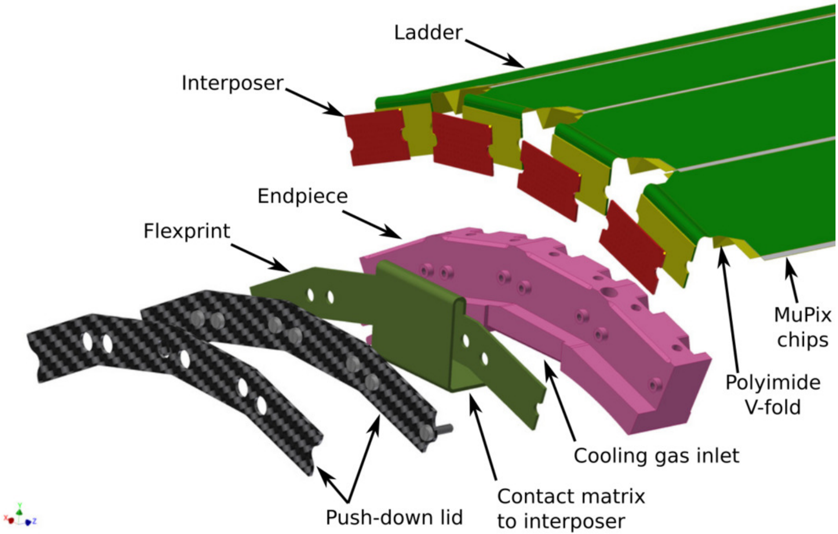


Shown: One one module per layer inserted.

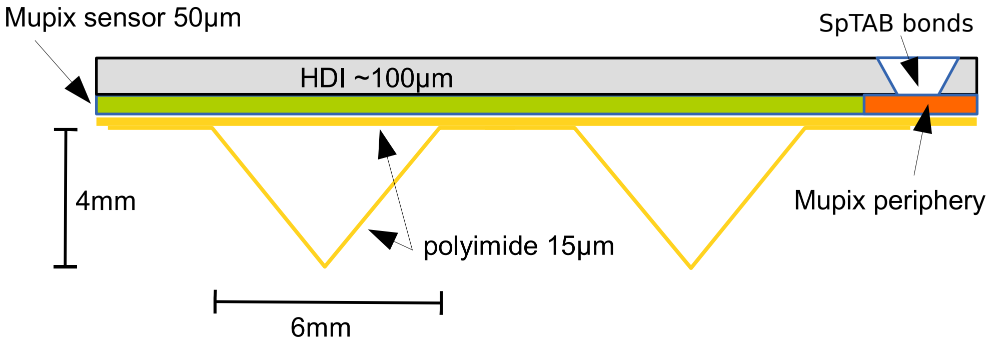
Mu3e mechanics



Mu3e mechanics



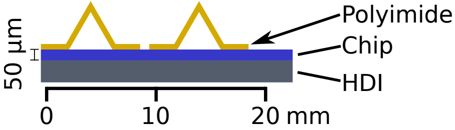
Mu3e mechanics



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

Mu3e mechanics – V fold gluing

Let's have a look at gluing V-folds on ladders. This is the outcome:

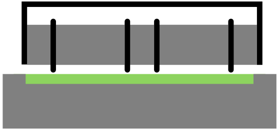


Mu3e mechanics – V fold gluing

1.

Fill reservoir with 50 µm layer of glue

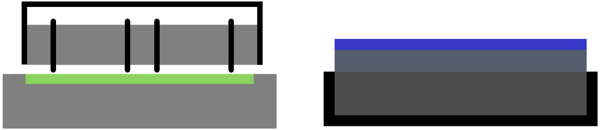
Mu3e mechanics – V fold gluing



2.

Dip stamp
into reservoir

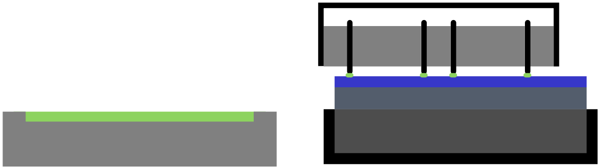
Mu3e mechanics – V fold gluing



3.

Place bare ladder on jig

Mu3e mechanics – V fold gluing



4.

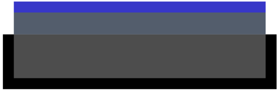
Apply glue

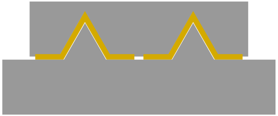
Mu3e mechanics – V fold gluing

5.

Place V-folds
on jig

Mu3e mechanics – V fold gluing





5.

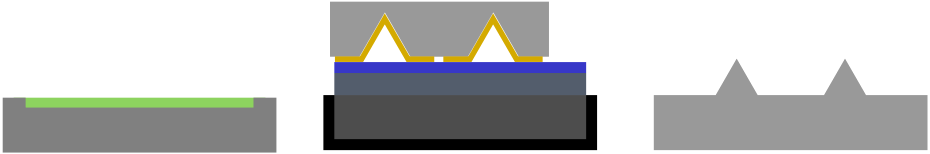
Place V-folds on jig

Mu3e mechanics – V fold gluing

6.

Pick V-folds

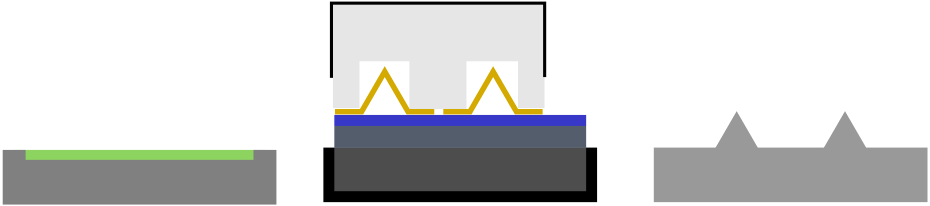
Mu3e mechanics – V fold gluing



7.

Lower V-folds down

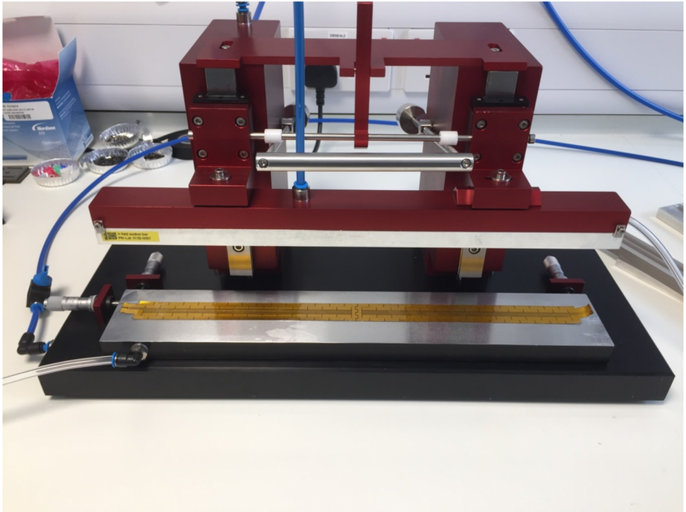
Mu3e mechanics – V fold gluing



8.

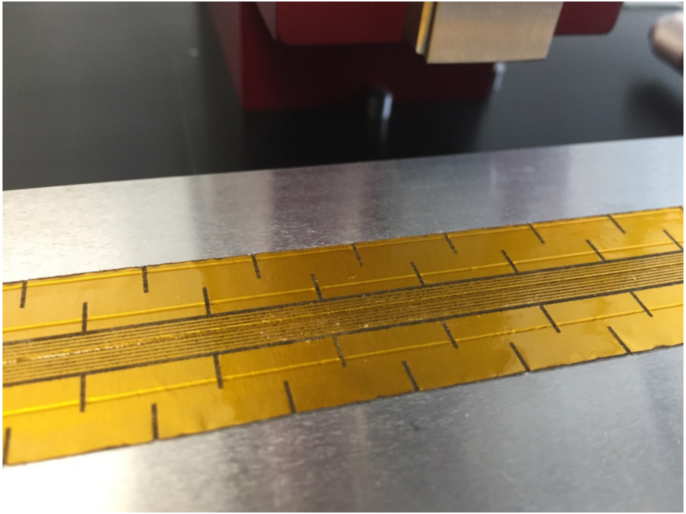
Place curing weight
Let glue cure

Mu3e mechanics



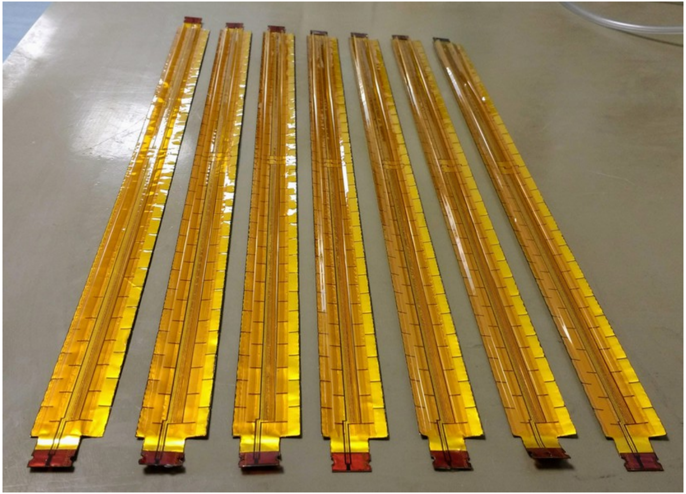
Setup for gluing

Mu3e mechanics



Closeup view. Here, dispensing robot was used as an alternative approach.

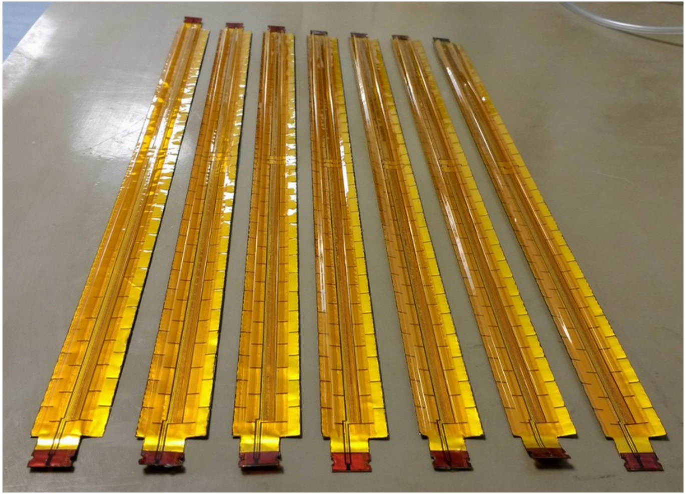
Mu3e mechanics



Mock-up ladders made of tape heaters

Made of aluminium-polyimide laminate (25 µm thickness each), laser structured meander for heating and temperature measurement.

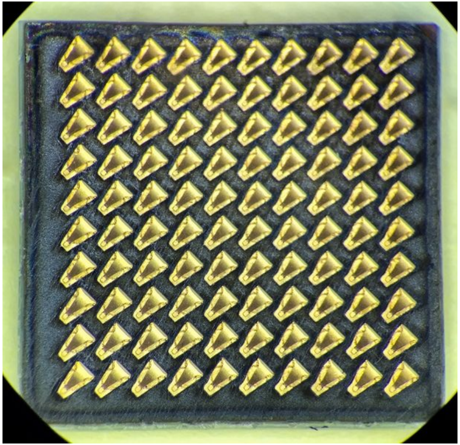
Mu3e mechanics



Mock-up ladders made of tape heaters

Electrical connectivity

Electrical connectivity



Interposer Samtec Z-Ray

Pitch: 0.8 mm

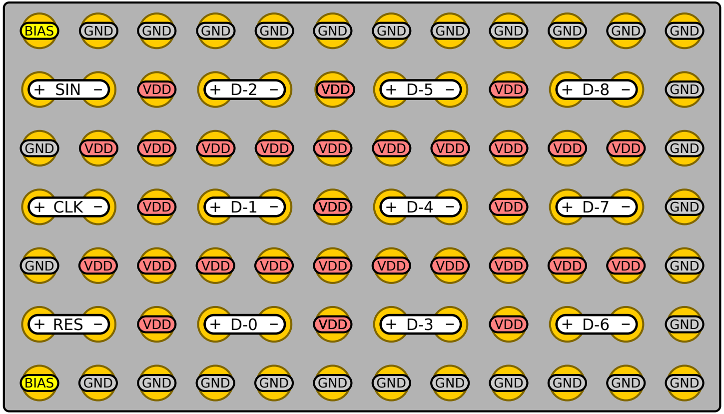
Model	Compressed height
ZA8H	0.3 mm
ZA8	1 mm

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

Allows use of flexes instead of cables.

Electrical connectivity

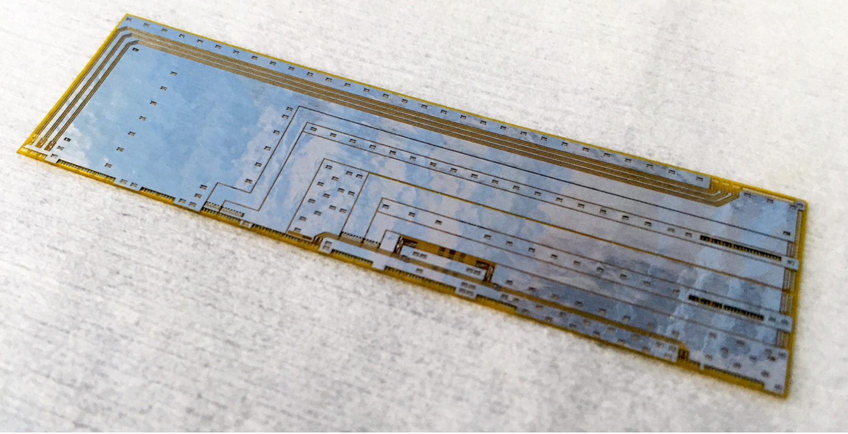
The nice feature: many connections on a small area.



One stave has 9 data links. Current limit per pin: 0.8 A. This will work.

Electrical connectivity

For the HDI, we go for aluminium/polyimide:

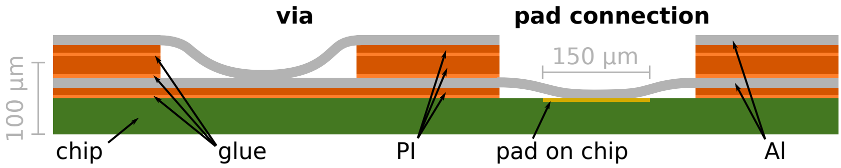


Made by LTU (Kharkiv, Ukraine), used in e.g. ALICE pixels for power strips.

Electrical connectivity

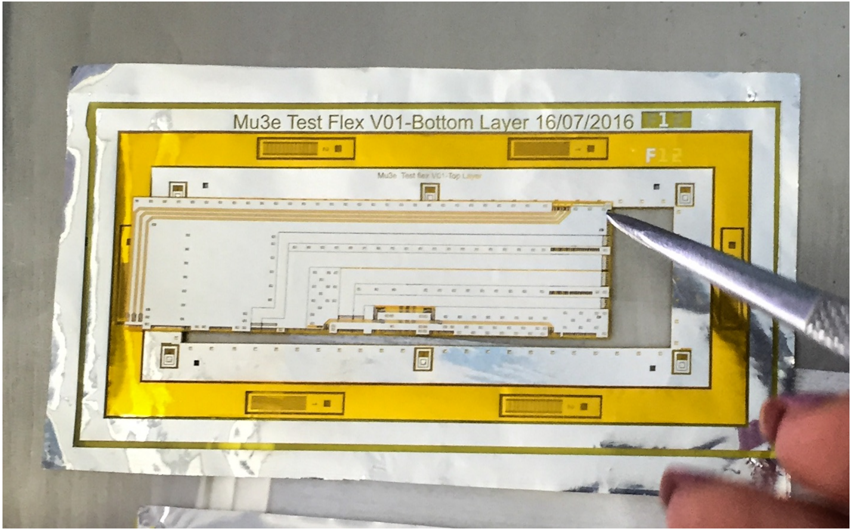
Process steps:

1. Starts with **aluminium foil**, thickness of 12.5 µm or 25 µm
2. Create **polyimide** layer: spinning of primer, drying and polimerisation
3. **Photolithographic etching** of aluminium traces
4. **Etching** of polyimide
5. **Glueing** of layers to form a stack
6. Additional polyimide foil for added dielectric, if needed
7. **Tab bonding**. Bonds aluminium traces directly, no wire.

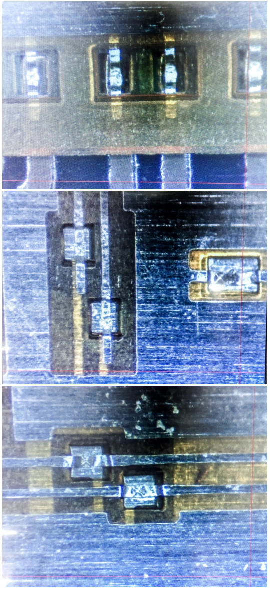


Electrical connectivity

Flex when cut out from panel:



Electrical connectivity



Some bond examples under a microscope:

Top: Bond to PCB
PCB is visible on the bottom edge of the image

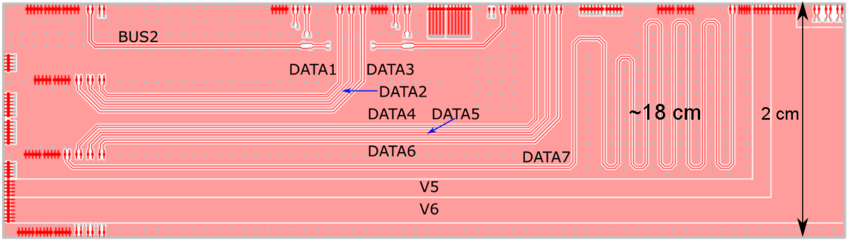
Center: Connecting layers (via)
The visible misalignment is a shrinking effect from polymerisation at 350 °C. One trace needs to be wider to absorb the tolerances.

Bottom: Vias for a bus

Electrical connectivity

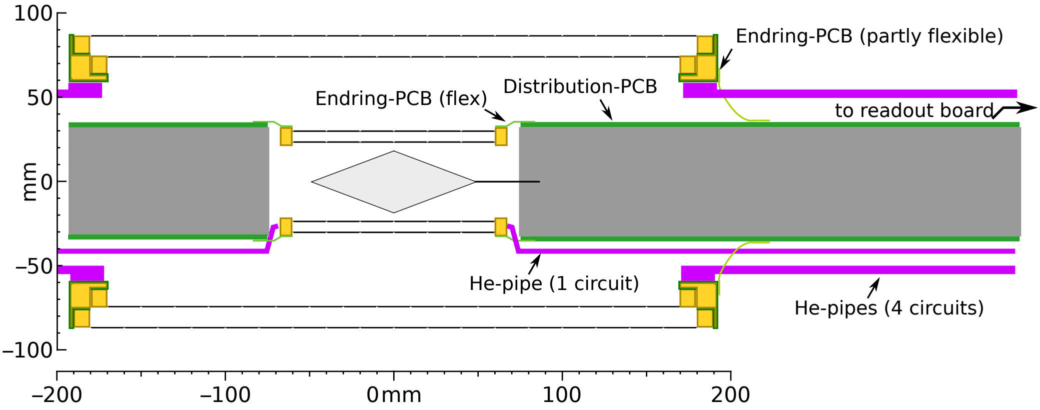
Bit error rate tests:

Rate Gb/s	Line	BER (95% C.L.)
1.25	all	$\lesssim 5.5 \times 10^{-13}$
2.5	all	$\lesssim 5.9 \times 10^{-13}$
3.2	short ones	$\lesssim 4.1 \times 10^{-13}$
	18 cm	fail
4.0	all	fail



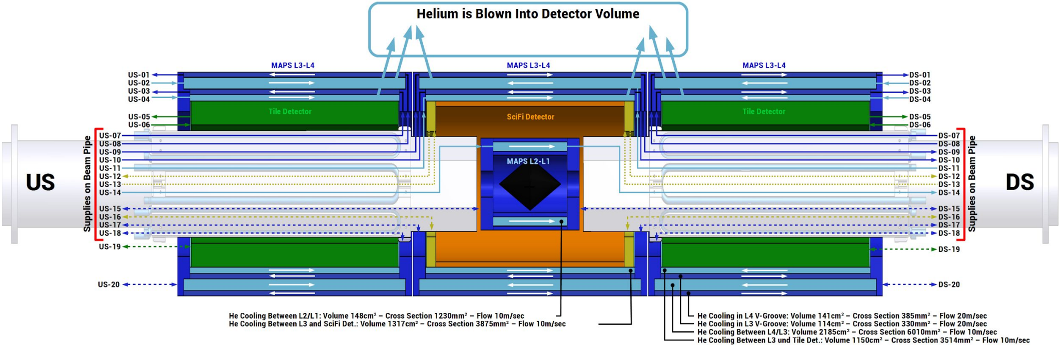
Pixel detector cooling

Pixel detector cooling



Sketch of supplies: electrical connectivity and cooling circuits.

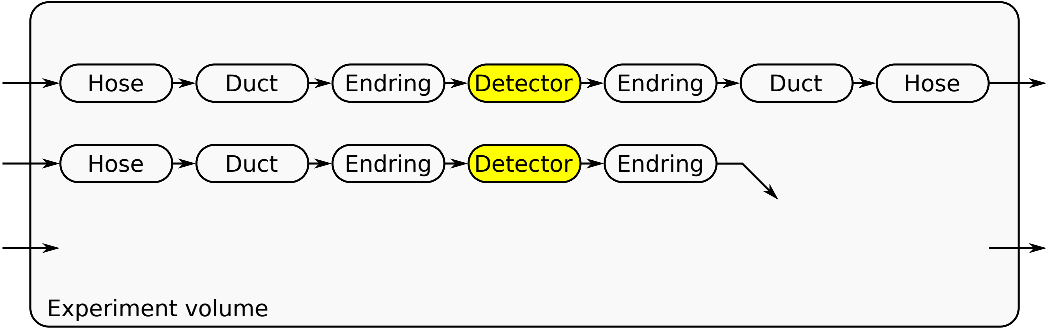
Pixel detector cooling



A busy sketch showing all connections

Line styles: solid = He, dotted = water, dashed = power/signal

Pixel detector cooling



Three helium circuit types

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

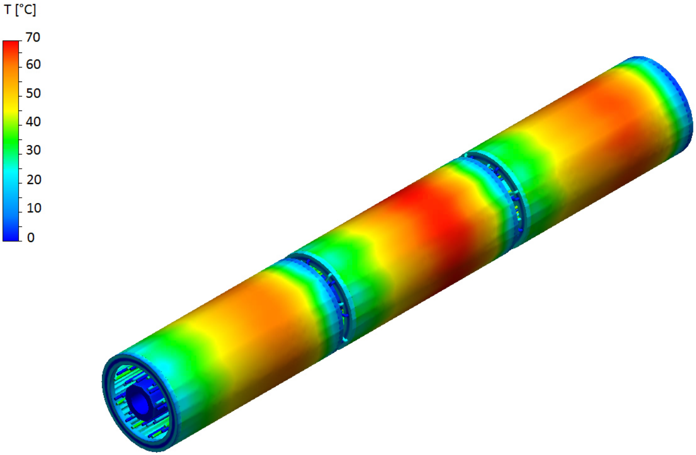
Pixel detector cooling

Constraints;

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

Pixel detector cooling

The V-folds not only give mechanical strength but are used for cooling with gaseous Helium. Simulation results:



Pixel detector cooling –

Required target flows per helium circuit:

Volume	He flow speed m/s	Cross-section cm^2	Volume cm^3	Occurence times	Volumetric flow m^3/min
Gap L1/L2	10	12	148	1	0.72
Gap SciFi/L3	10	39	1320	1	2.3
Gap Tile/L3	10	34	1150	2	4.2
V-folds L3	20	3.3	114	3	1.2
Gap L3/L4	10	60	2185	3	10.8
V-folds L4	20	3.9	141	3	1.4
Global flow	0.5	7600	912000	1	23
Total		7750			43

$\Rightarrow$ Volumes differ up to factor ≈ 20

Cooling simulations

Cooling simulations

- Cooling simulations have been repeated
- Two power dissipation cases:
  - 400 mW/cm^2 (pessimistic)
  - 250 mW/cm^2 (realistic)
- The two cases scale linearly, hence show 400 mW/cm^2 only
- Also pressure drop across ducts and detector volumes have been simulated

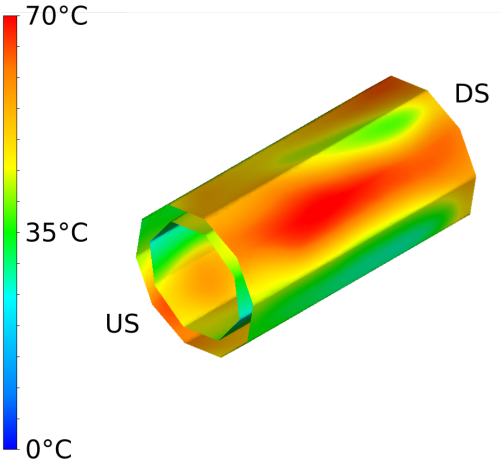
Cooling simulations

Simulated flows:

Volume	Flow speed (m/s)	Direction
Gap L1/L2	10	DS $\rightarrow$ US
Gap SciFi/L3	5	US $\rightarrow$ DS
V-folds L3/L4	20	DS $\rightarrow$ US
Gap L3/L4	10	DS $\rightarrow$ US
Global	0.5	US $\rightarrow$ DS

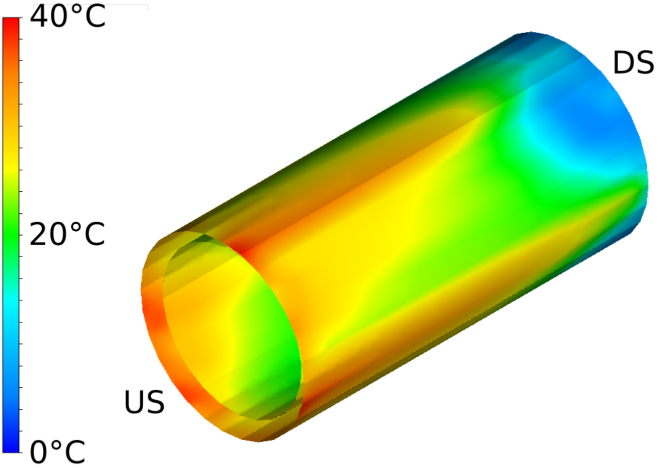
Following pages show temperature of silicon as heat maps. Other parts removed for clarity.

Cooling simulations



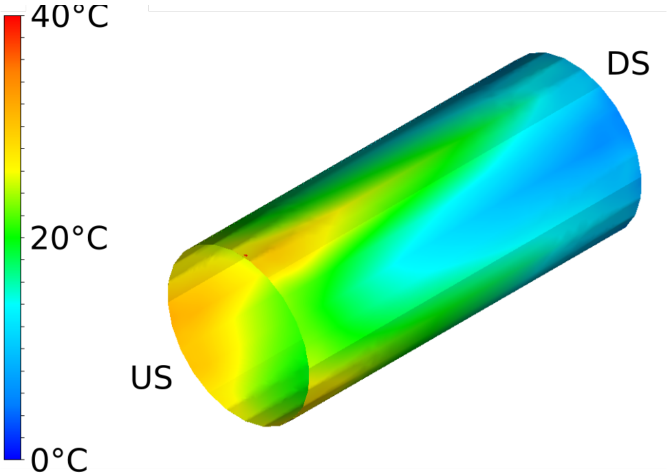
L1/2

Cooling simulations



L3/4

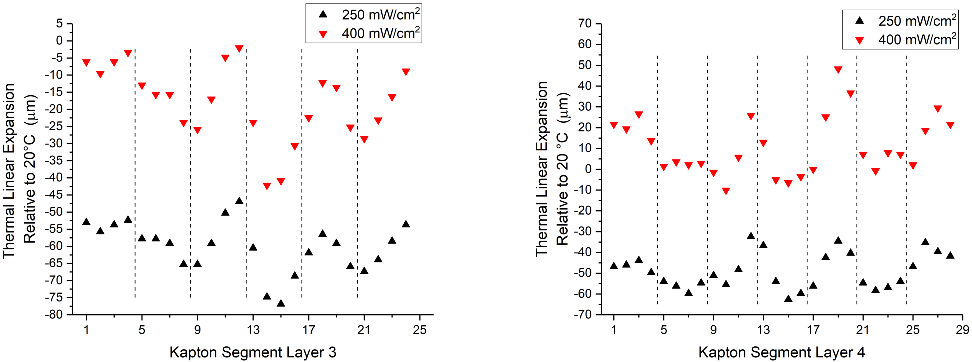
Cooling simulations



L3 only

Cooling simulations

Average temperature of ladder translated into thermal expansion of polyimide:



Note: This is a result calling for more studies. Plan is to optimise gas inlets. Interplay with duct layout, hence non-trivial.

Cooling simulations

Expected **pressure drops** in the circuits from same simulation:

Circuit	Duct IN	Flange	**Detector**	Flange	Duct OUT
Gap L1/L2	25	7	$< \mathbf{1}$	9	24
Gap SciFi/L3	6	< 1	**3**	28	–
V-folds L3	25–50	80–90	**10–20**	50–70	25–25
Gap L3/L4	8	25	$< \mathbf{1}$	11	–
V-folds L4	30–50	60–70	**10–20**	50–70	20

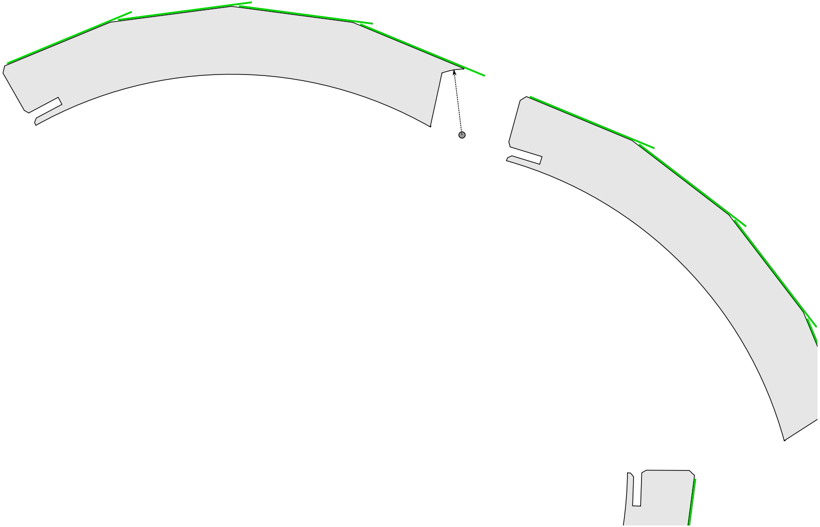
All pressure values in mbar. If range given: min/max observed per compartment.

Some gaps vent to global volume.

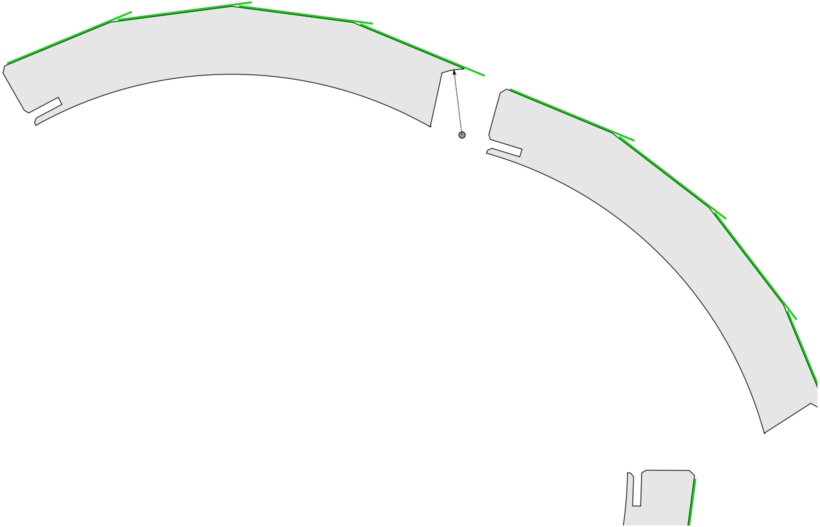
This seems manageable and the detector shouldn't „pump up".

Pixel module insertion

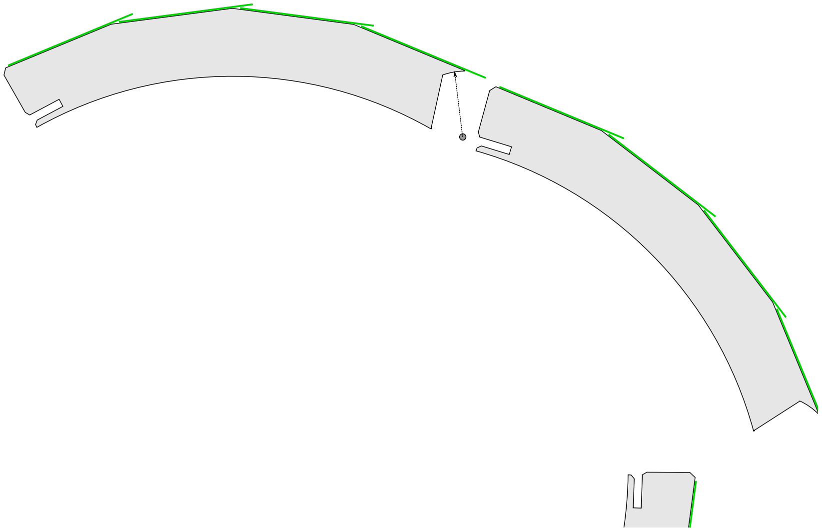
Pixel module insertion



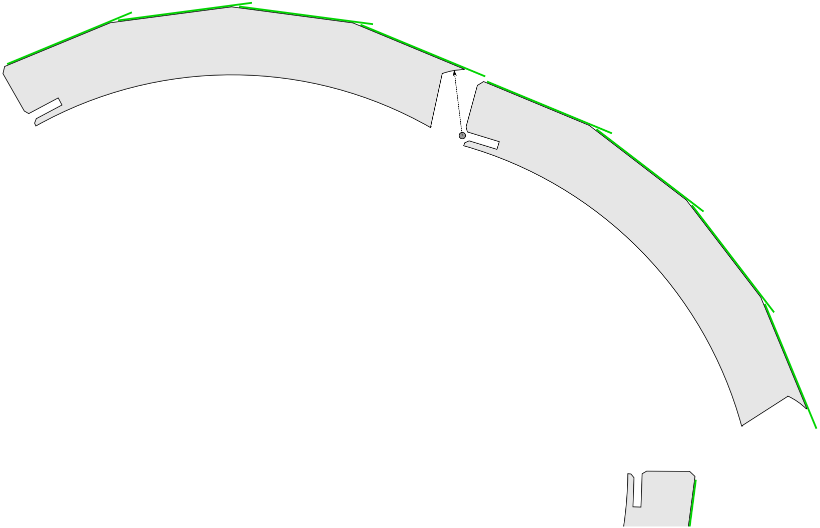
Pixel module insertion



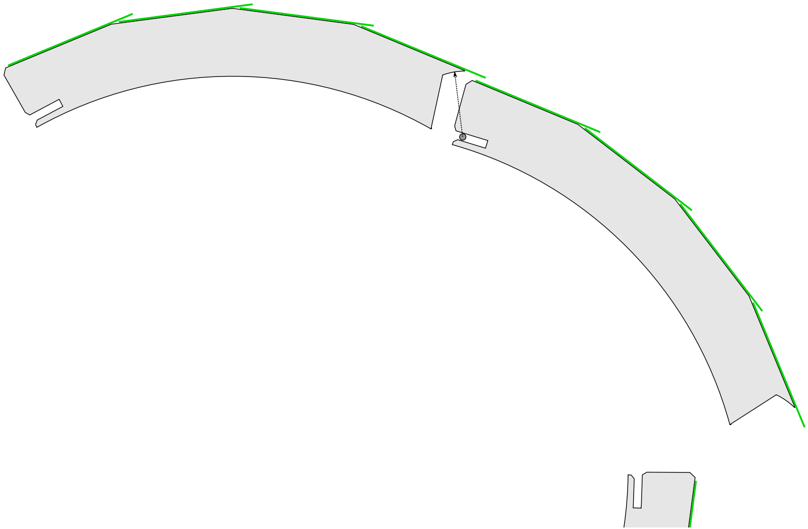
Pixel module insertion



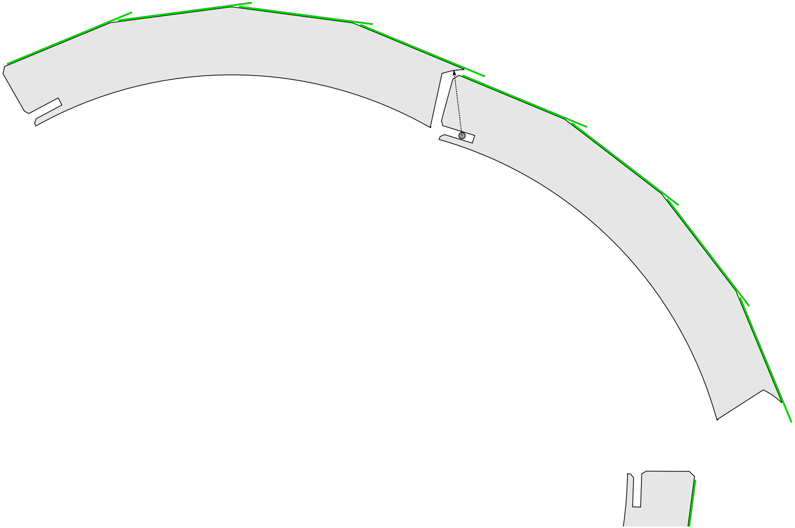
Pixel module insertion



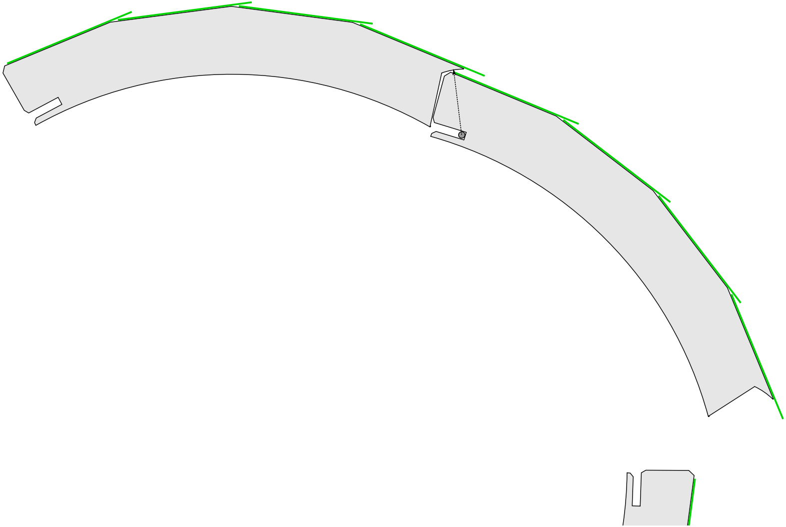
Pixel module insertion



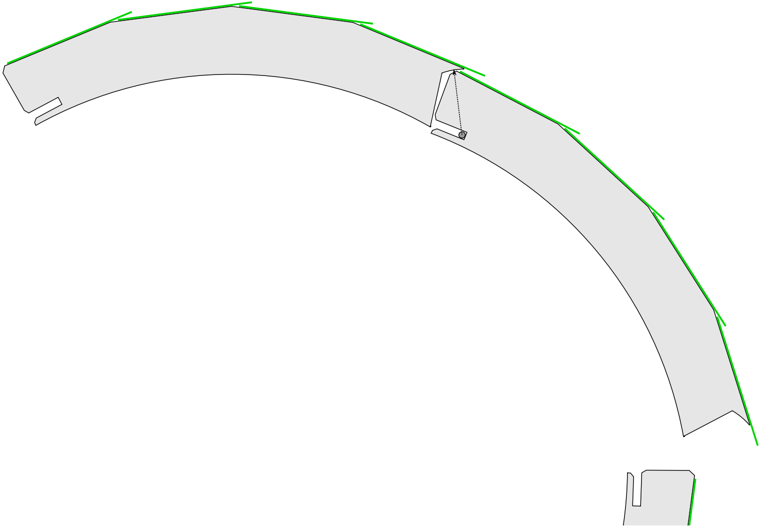
Pixel module insertion



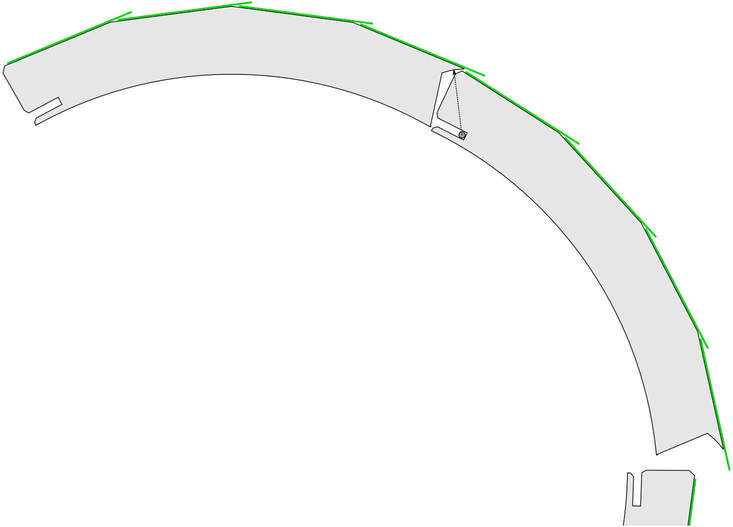
Pixel module insertion



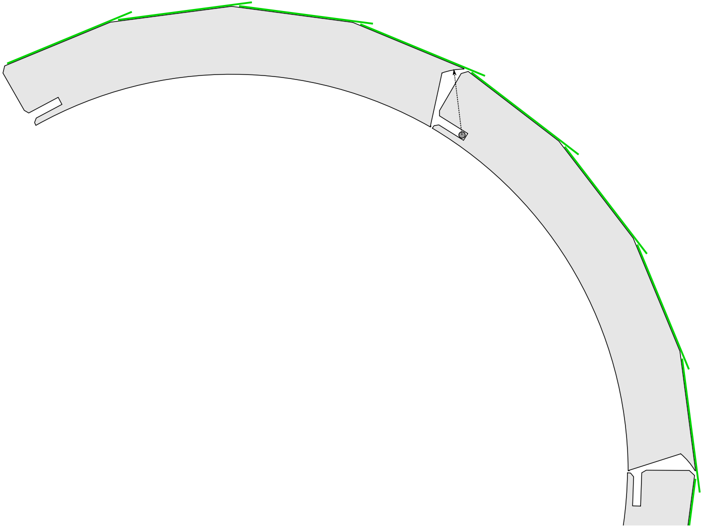
Pixel module insertion



Pixel module insertion



Pixel module insertion



Conclusions and outlook

- We have a challenging but exciting detector project:
  - Thinned silicon pixel, monolithic, self-triggered pixels
  - Scintillating detectors for timing (not shown here, sorry...)
  - Ultra-light weight mechanics
- Gaseous helium cooling
- Readout using Aluminium flexes and micro-twisted pair cables (not shown again...)
- Plans:
  - Building a full thermo-mechanical mock-up using silicon chip heaters
  - Implementing module fabrication workflows
  - Further electrical integration

References

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

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

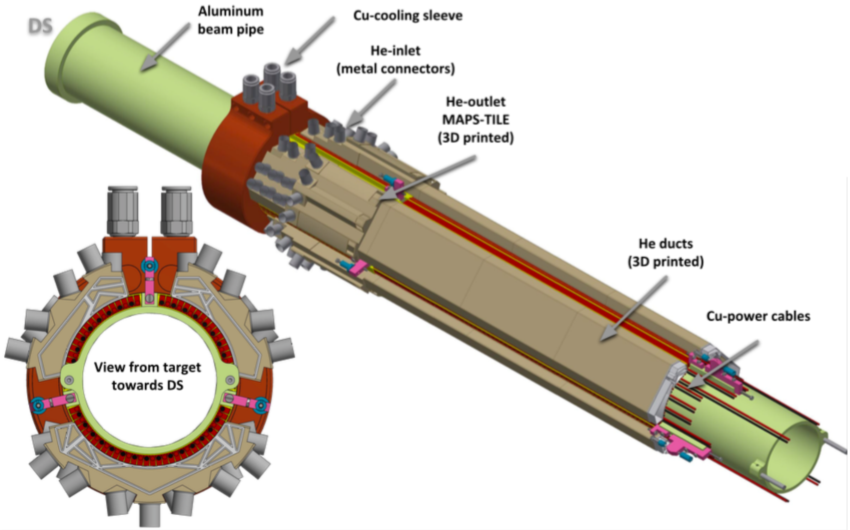
[3] arXiv:1211.4494v1

[4] G. Contin, talk at PIXEL2016

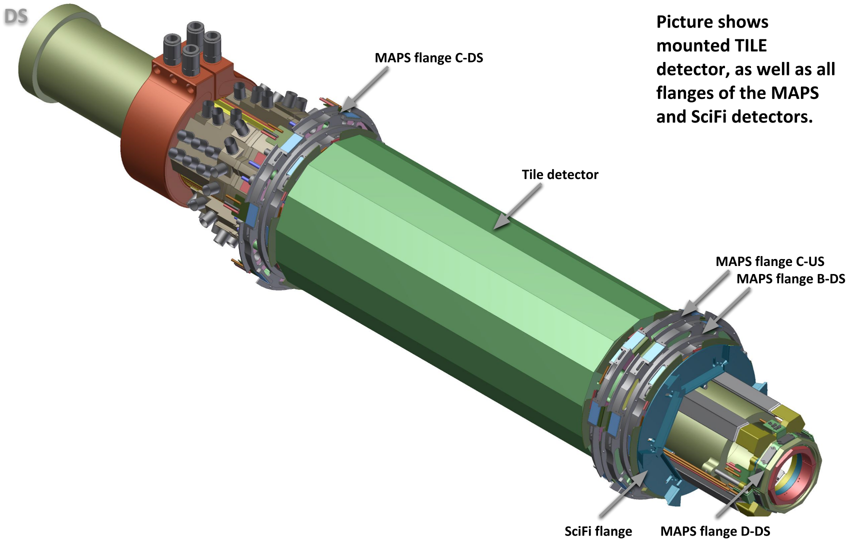
[5] C. Koffmane, talk at PIXEL2016

ENCORE

Assembly procedure

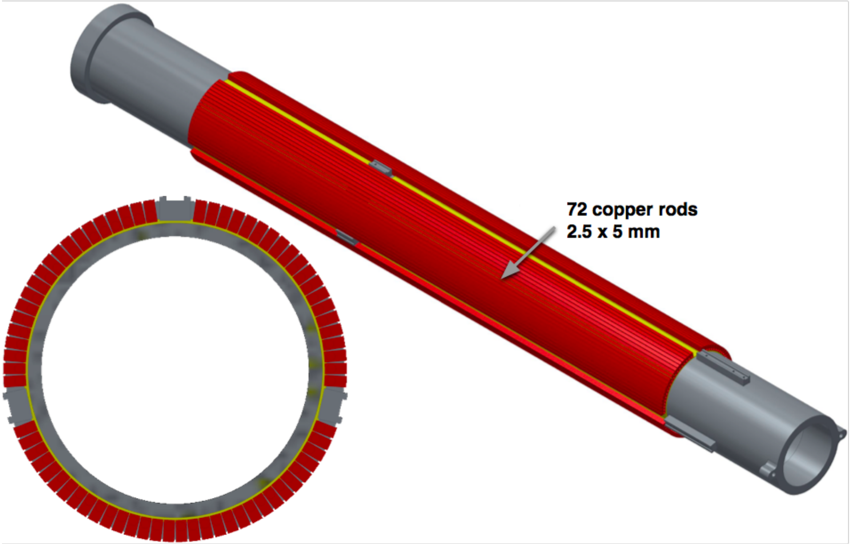


Assembly procedure

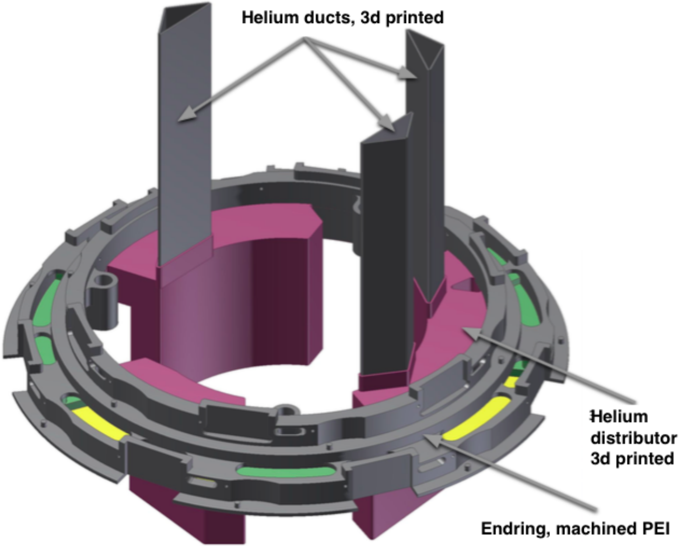


Picture shows mounted TILE detector, as well as all flanges of the MAPS and SciFi detectors.

Assembly procedure



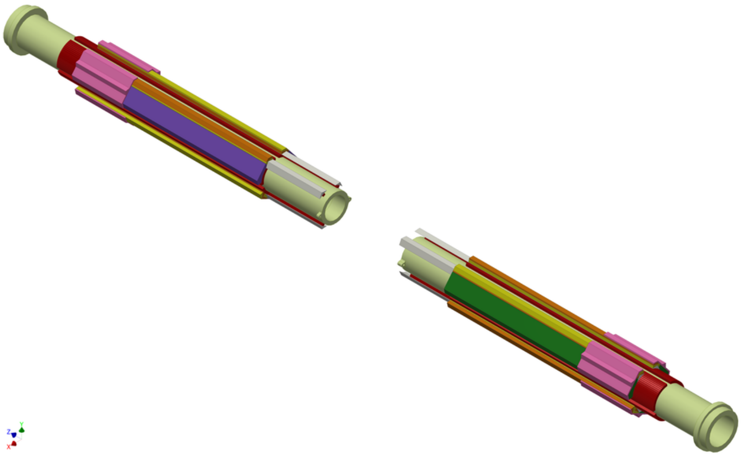
Assembly procedure



Assembly procedure

- The following slides show a step-by-step mounting procedure
- Order of sequence has certain freedoms. This is one possible choice.

Assembly procedure

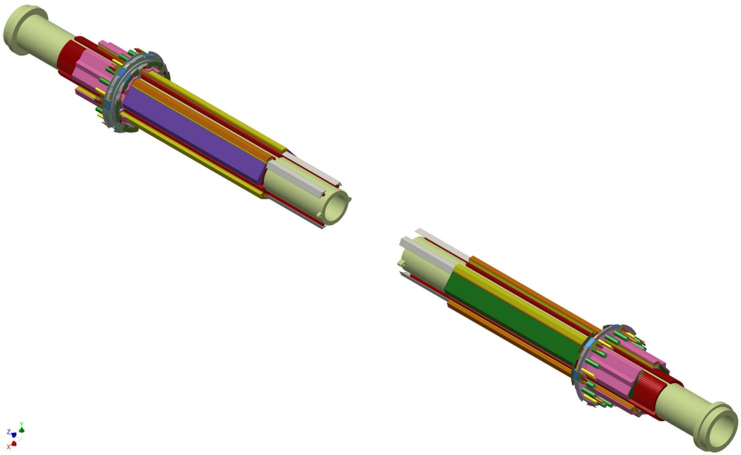


We start with the two beampipes.

Already mounted:
copper bars and helium ducts.

Two beampipes still allowed to be mechanically independent for first few steps.

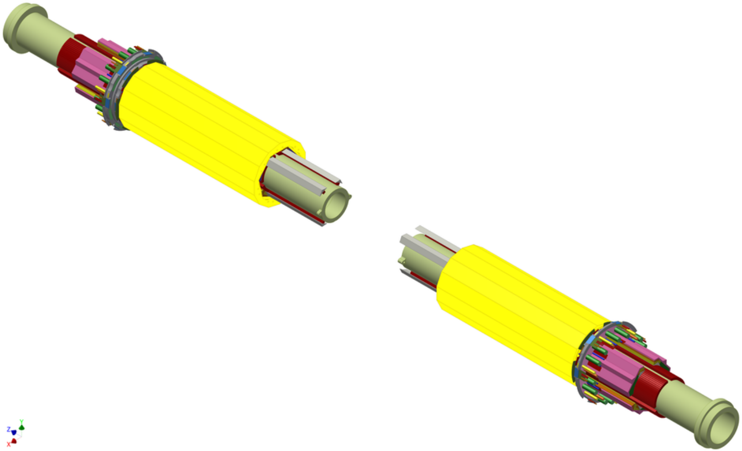
Assembly procedure



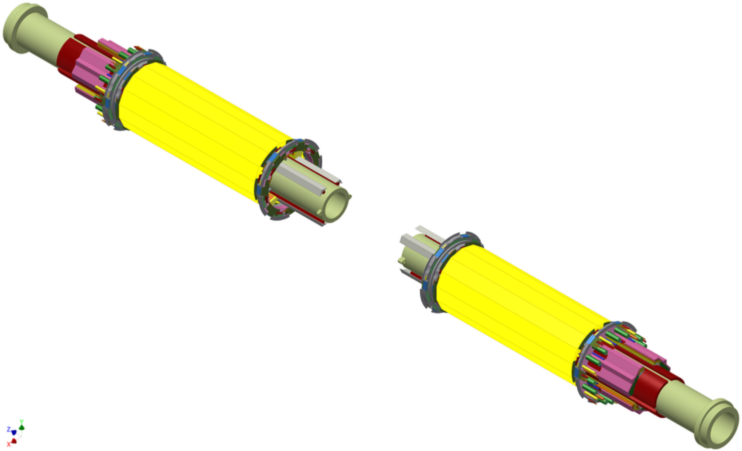
Outermost endrings

Assembly procedure

Tile detectors

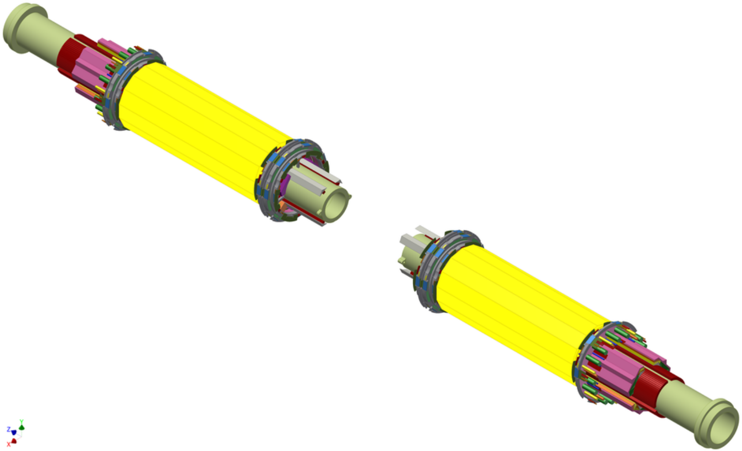


Assembly procedure



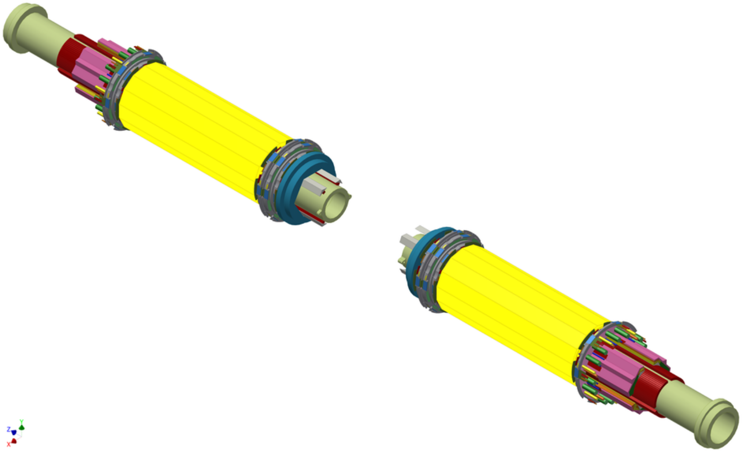
Second endrings for recoil stations

Assembly procedure



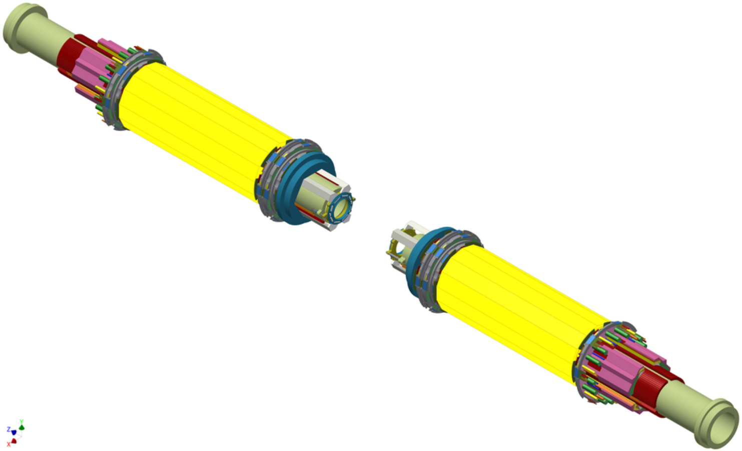
Endrings for central station

Assembly procedure



Mounting frame for SciFi

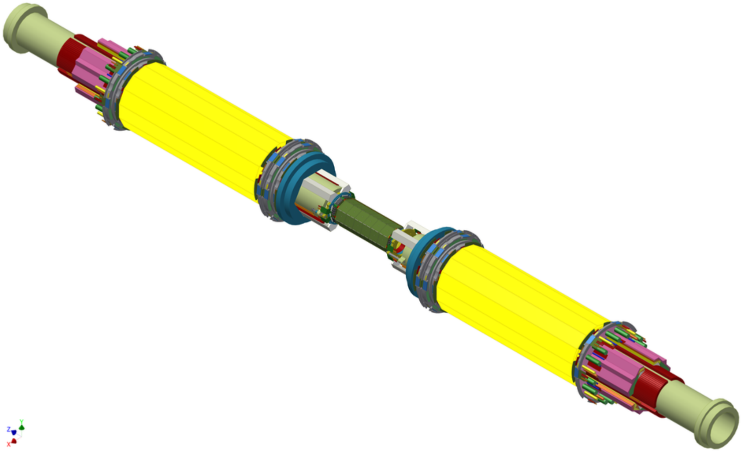
Assembly procedure



Endrings for L1/2

Note: Until now, no mechanical connection between US/DS.

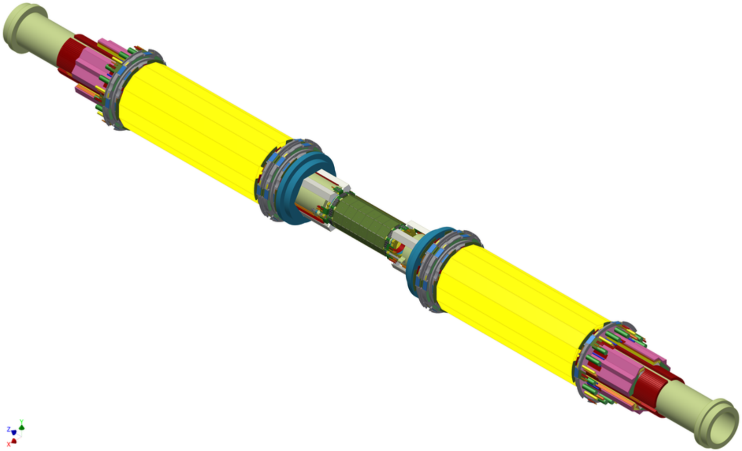
Assembly procedure



Two half-shells for L1

Note: From now on everything is in experiment frame and beampipes must be aligned.

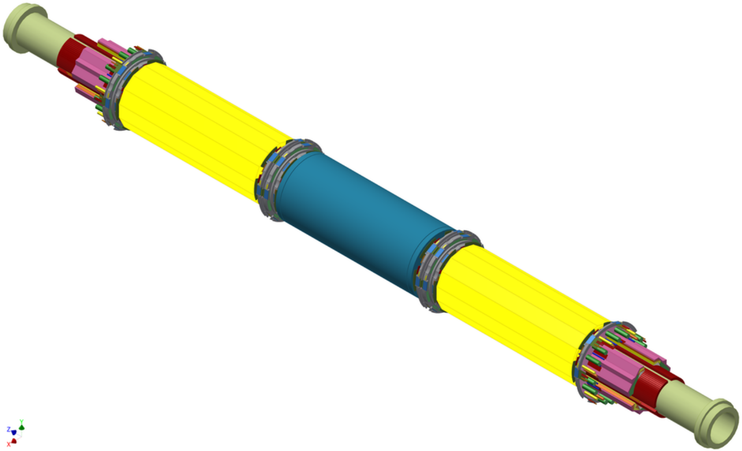
Assembly procedure



and same for L2

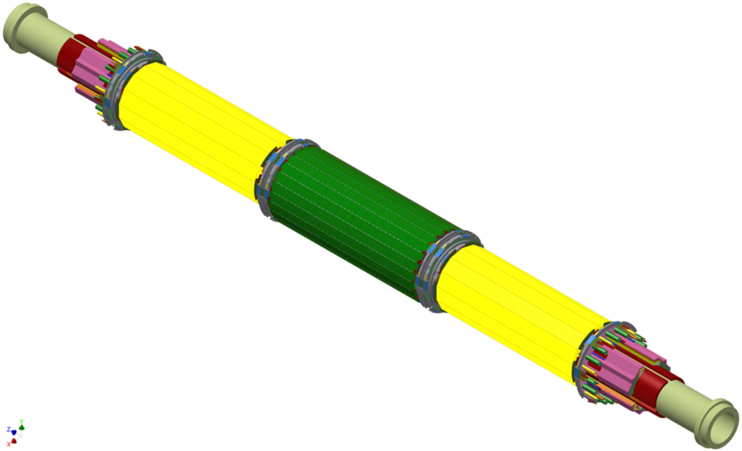
Assembly procedure

Insert SciFi modules



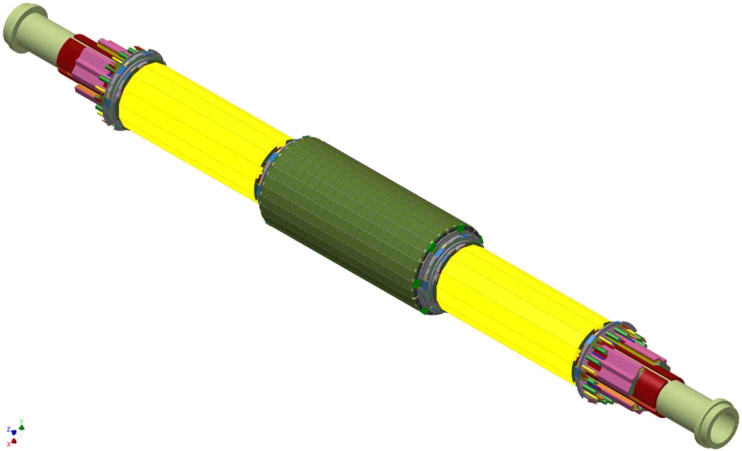
Assembly procedure

Insert pixel L3 modules



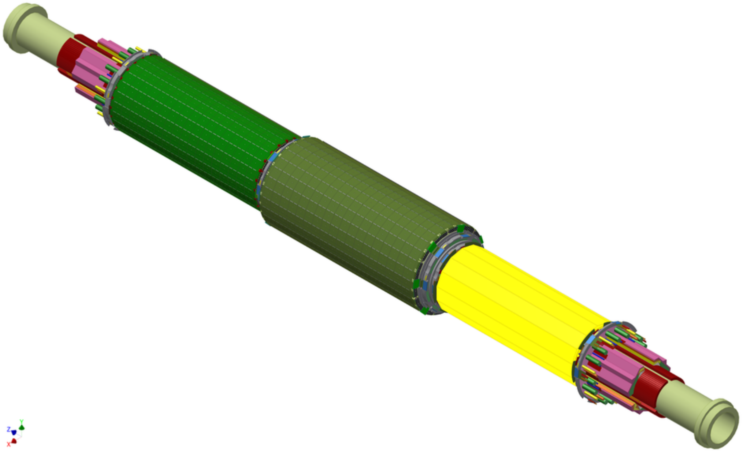
Assembly procedure

and L4



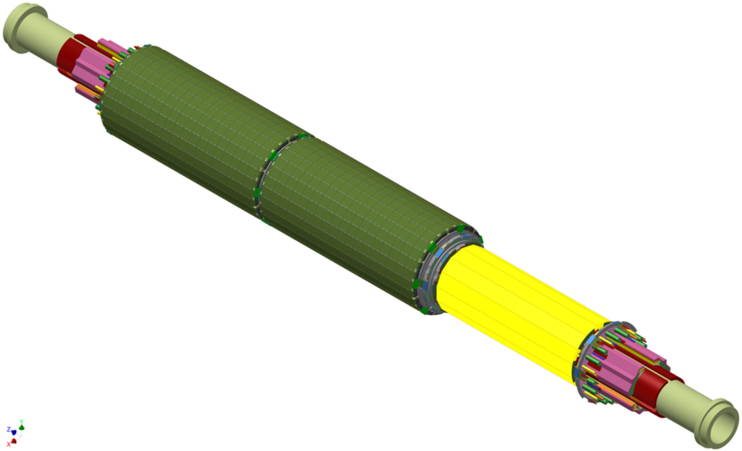
Assembly procedure

L3 of US recoil station

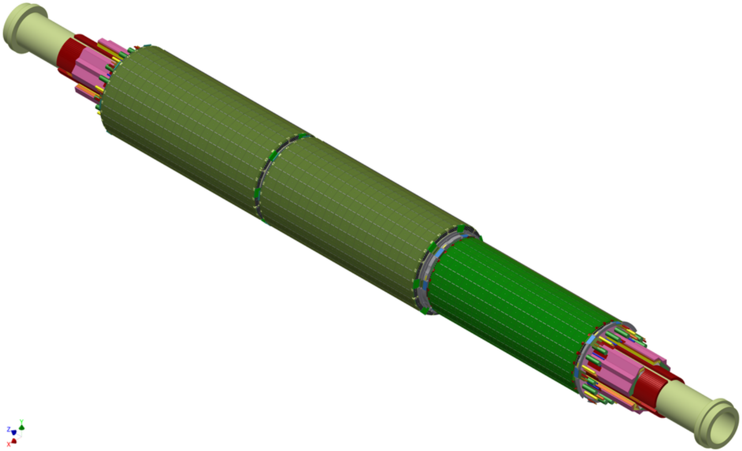


Assembly procedure

L4

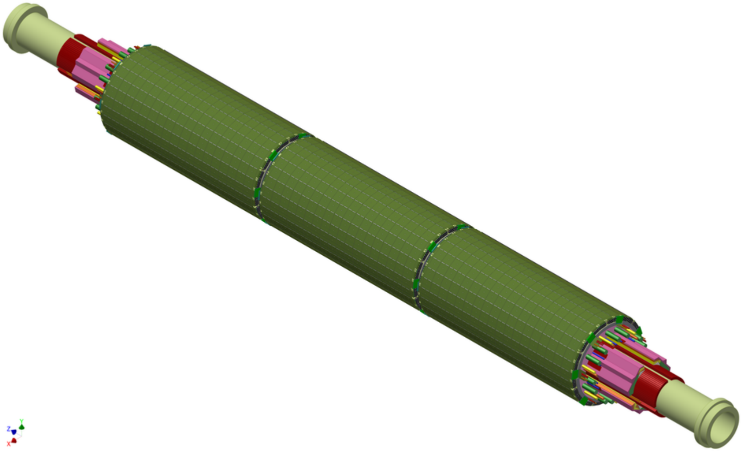


Assembly procedure



L3 of DS recoil station

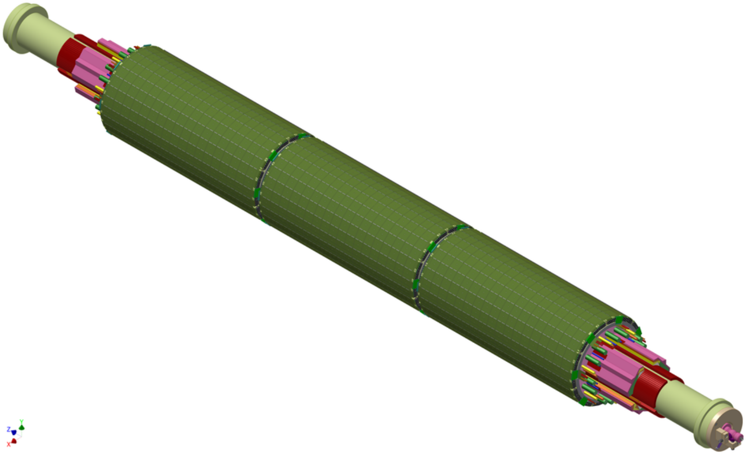
Assembly procedure



L4

Now detector is in principle ready for insertion into magnet.

Assembly procedure



And finally: insert target from DS

Multiple scattering

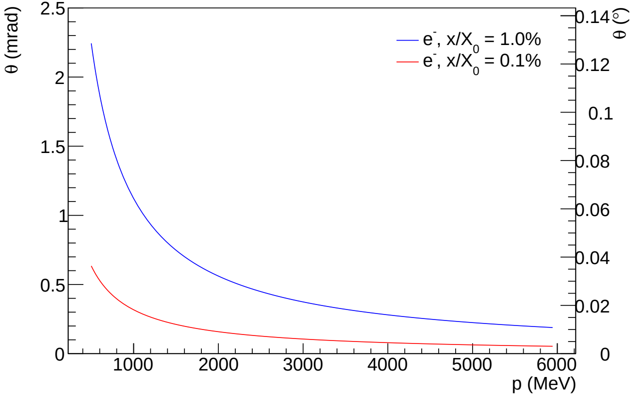
As you know, PDG gives you the following formula:

$$\theta = \frac{13.6\,\text{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\left[1 + 0.038 \ln\left(x/X_0\right)\right]$$

Allow me to illustrate that a bit...

Multiple scattering

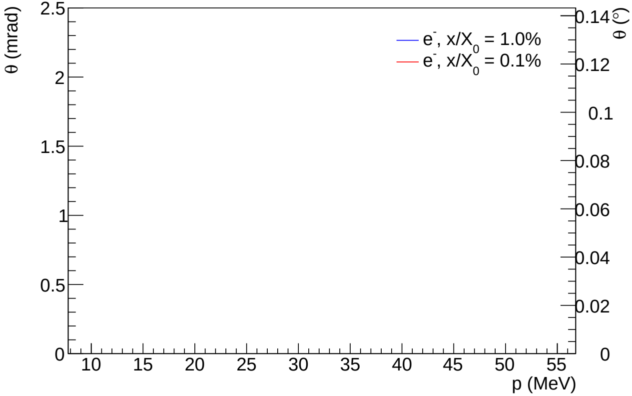
Multiple scattering at LHC energies for an electron:



Thinner detector layers is a nice-to-have, but 1% x/X_0 is ok.

Multiple scattering

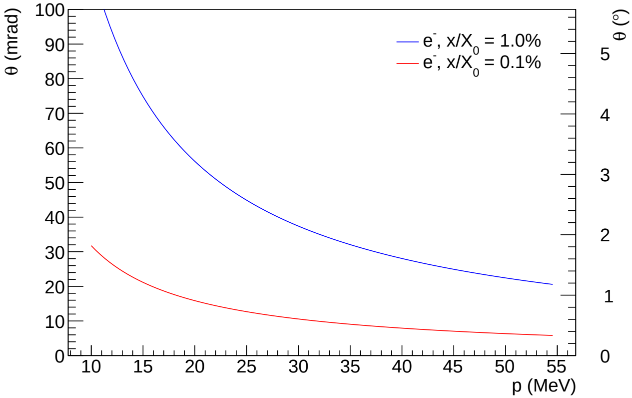
Multiple scattering at Mu3e energies for an electron:



Ooops. Did we loose the curve. . . ?

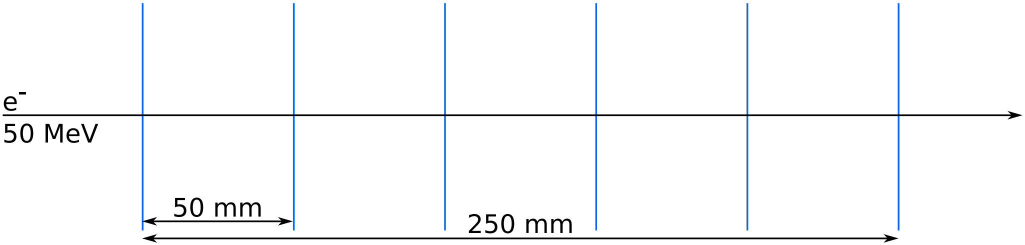
Multiple scattering

Multiple scattering at Mu3e energies for an electron:



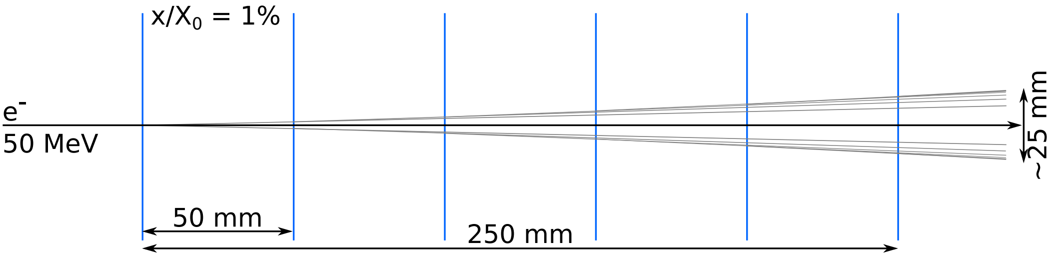
40× scale increase. At low energies, matter matters.

Multiple scattering



The stage is a simple toy tracker. Particle enters from the left.

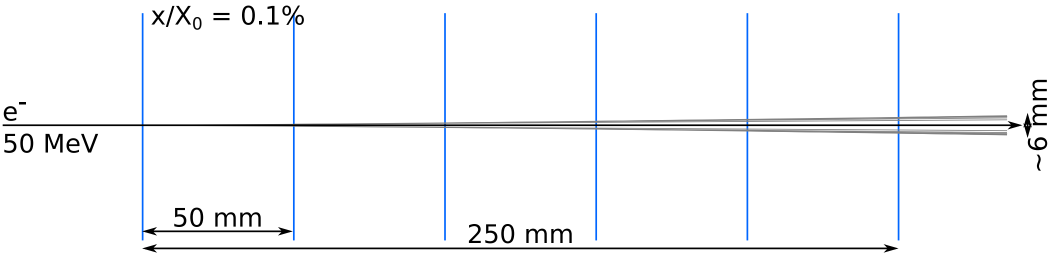
Multiple scattering



Let's take pixel layers with $x/X_0 = 1\%$ each. Observe the substantial scattering at such low momenta.

Note: This sketch is to scale. Per-layer contribution added in quadrature.

Multiple scattering



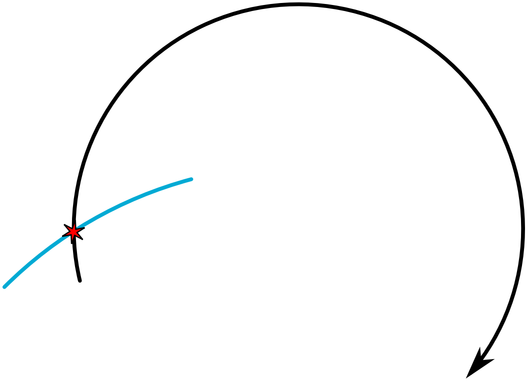
Reducing x/X_0 to 0.1% helps.

Multiple scattering

To measure the momentum, a B-field is present. Hence tracks are helices.

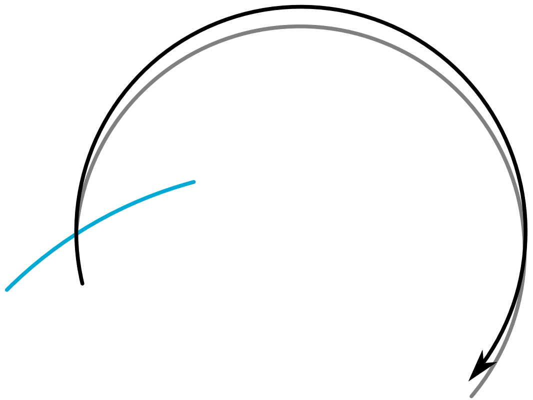
How can we take this to our advantage?

Multiple scattering



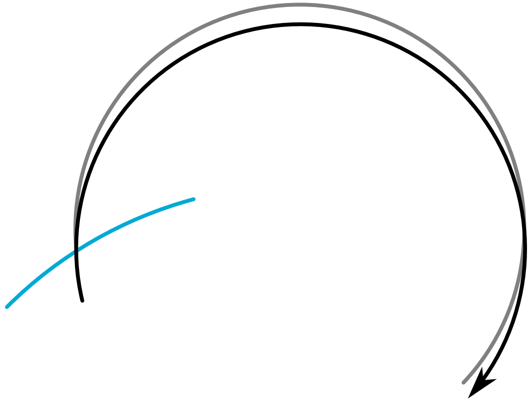
Assume a particle in a B-field scatters at some detector layer (blue)

Multiple scattering



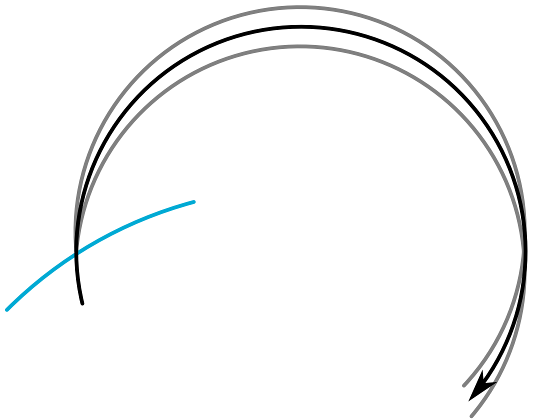
Let it scatter to the right...

Multiple scattering



. . . or to the left. . .

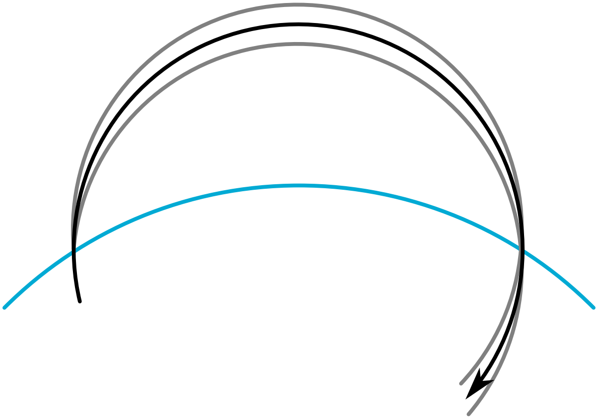
Multiple scattering



Observe the magic point where the scattering effect cancels.

It is after a half turn.

Multiple scattering



Choose radii wisely for best preformance.

Multiple scattering

Ok, now you know our basic ingredients to do our job:

- Optimise the radii of the detector
- Minimise the material per detector layer

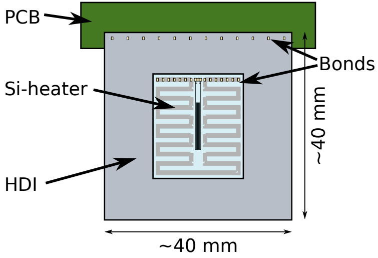
Multiple scattering

Ok, now you know our basic ingredients to do our job:

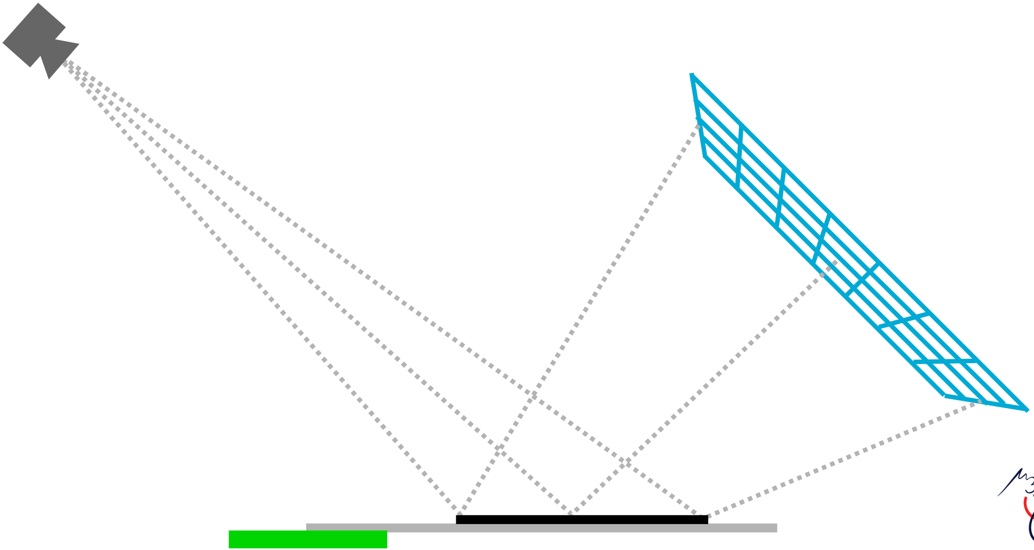
- Optimise the radii of the detector
- Minimise the material per detector layer
  - Pixel sensor: MuPix
  - Mechanics
  - Readout
  - Cooling

Silicon heaters

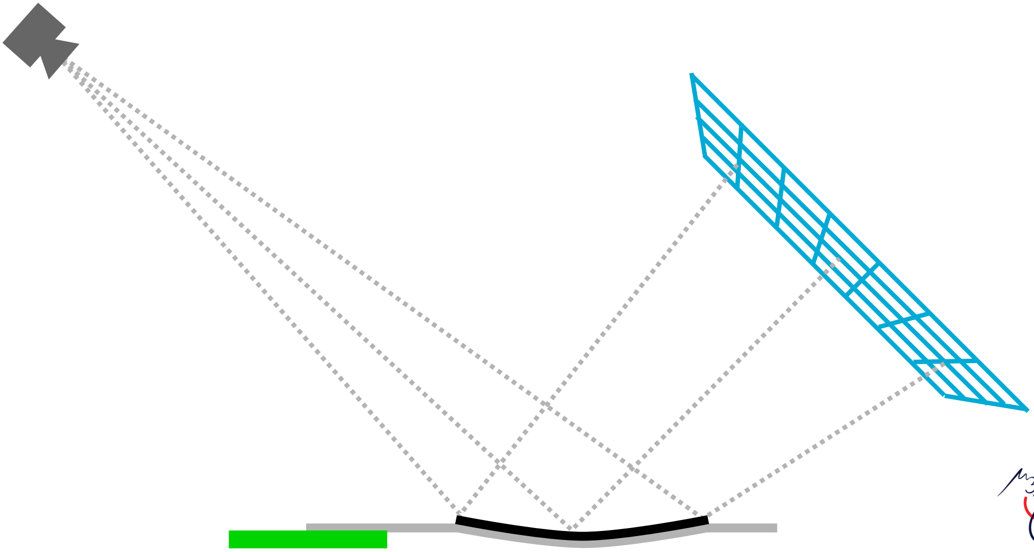
- We've prepared single silicon heater assemblies.
- Consists of heater (sputtered aluminium on silicon, thinned down to 50 µm) and a flex HDI (2 layers Al/polyimide). **Veryclose to final design.**
- Heater designed to dissipate up to 400 mW/cm^2.
- Has a 1000 Ω RTD on it
- Next set of slides: graph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



Silicon heaters

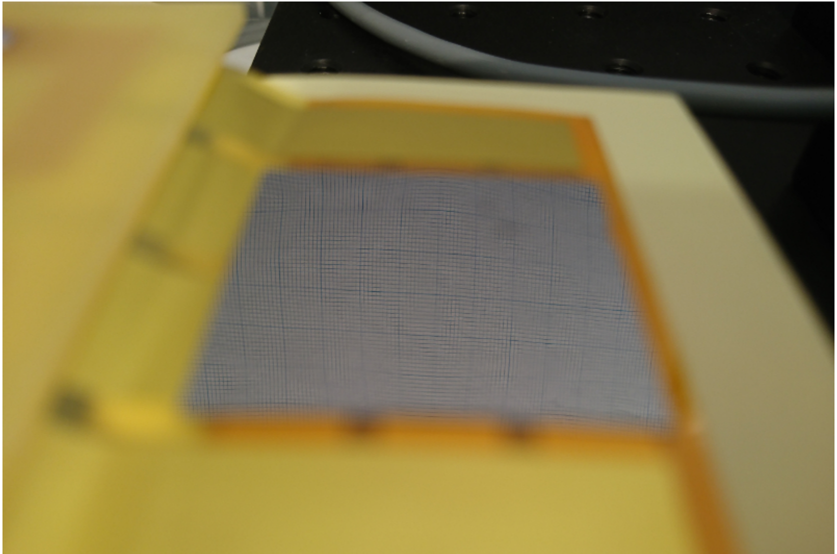


Silicon heaters



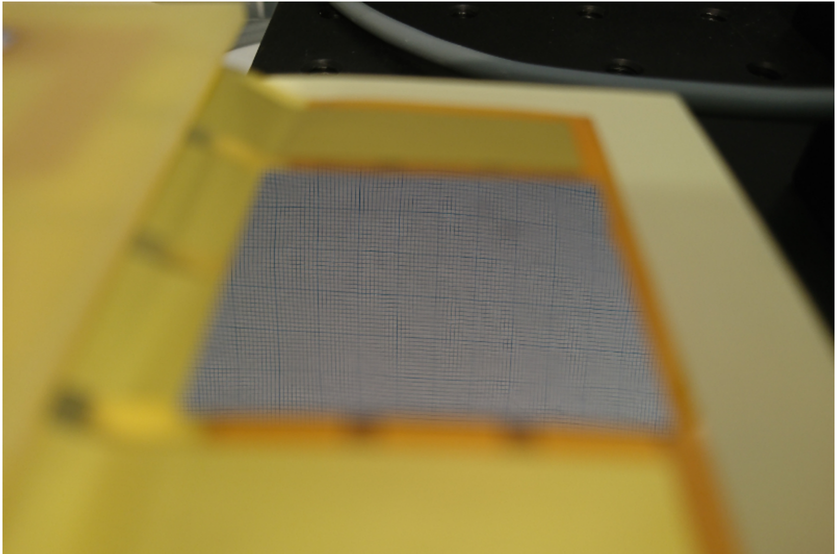
Silicon heaters

$\vartheta = 30\,°\mathrm{C}$



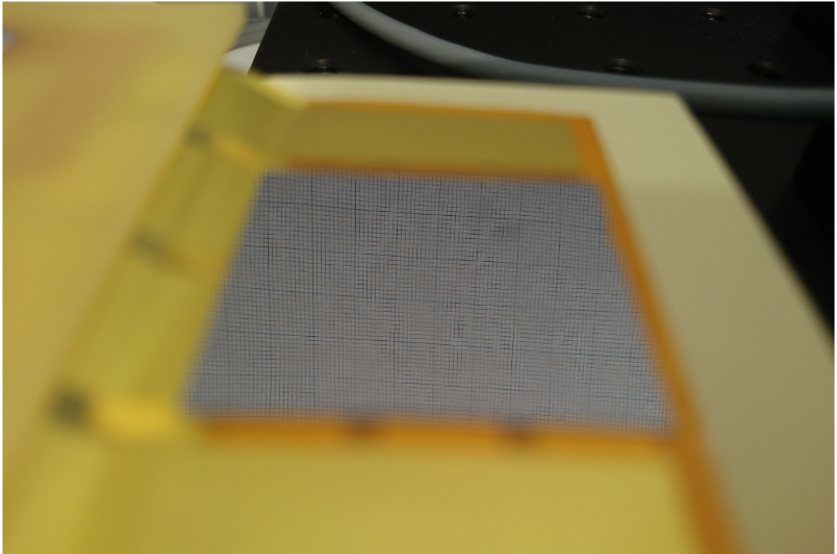
Silicon heaters

$\vartheta = 40\,^{\circ}\mathrm{C}$



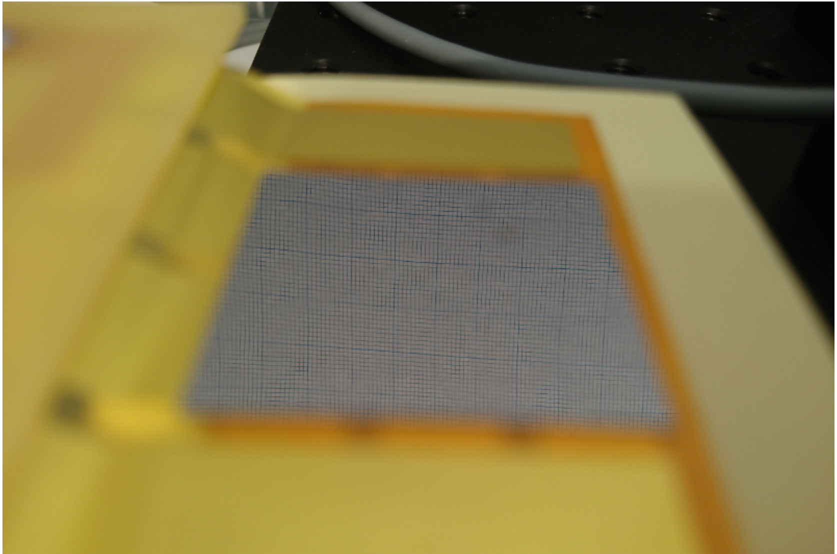
Silicon heaters

$\vartheta = 50\,°C$



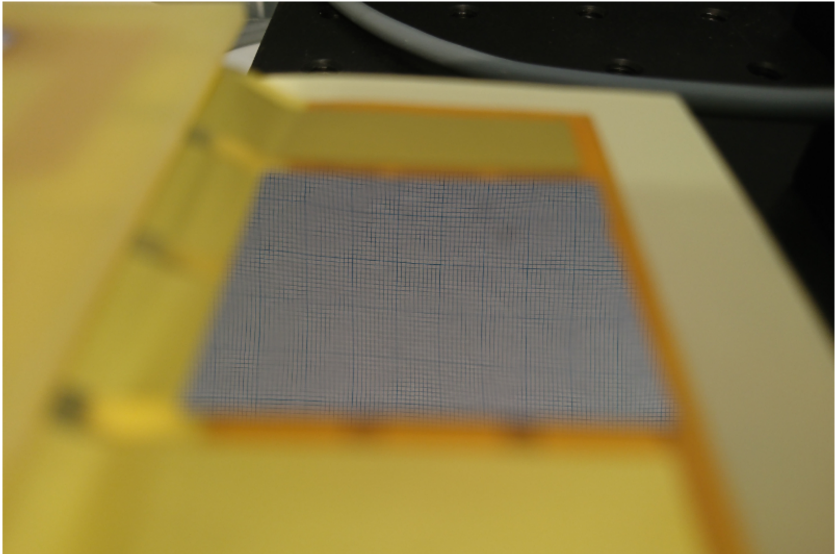
Silicon heaters

$\vartheta = 60\,^\circ\mathrm{C}$

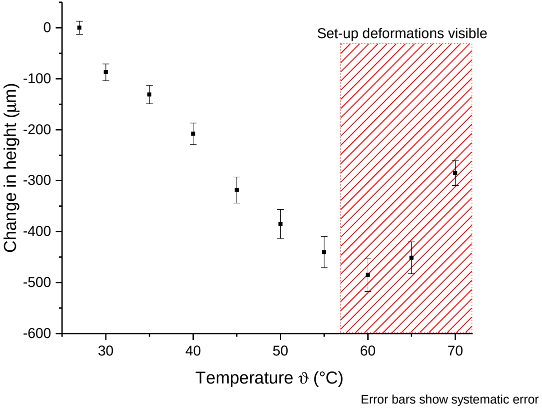


Silicon heaters

$\vartheta = 70\,°\mathrm{C}$



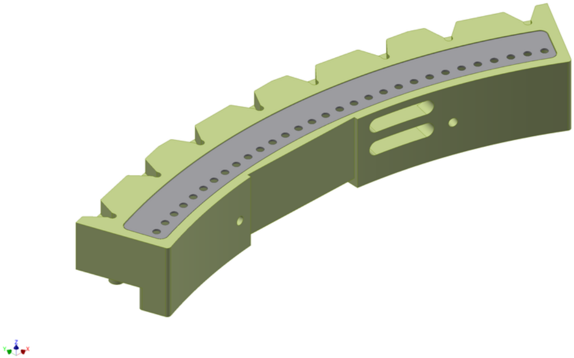
Silicon heaters



Before you get too shocked:

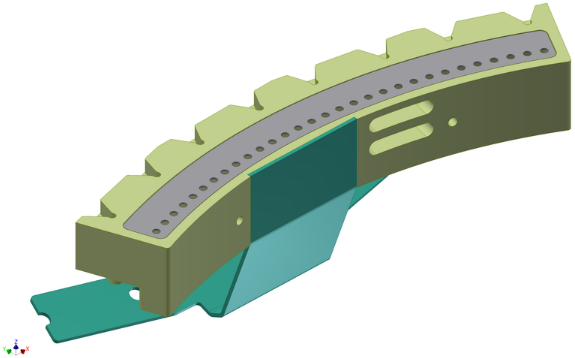
- About the magnitude expected from **CTE mismatch polyimide-silicon**.
- Glue pattern has **not been optimised** yet.
- Will calibrate finite element simulations and optimise glue pattern in simulation.
- If detector is in thermal equilibrium and stable over time, **track-based alignment can handle this**.
- Thermal mass is small, hence equilibrium will be reached fast.

Module assembly procedure



Take endpiece. Glue gas cavity lid.

Module assembly procedure

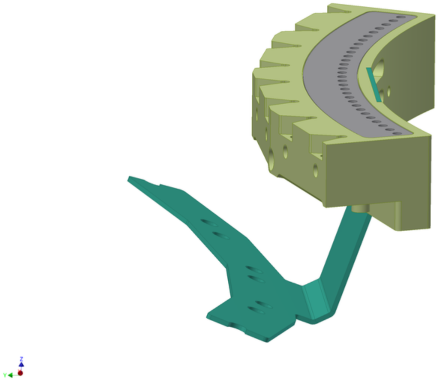


Pre-fold flexprint, glue it to endpiece. Let glue cure.

Note: Flexprint has nothing mounted on it. All you see are traces and the BGA-arrays.

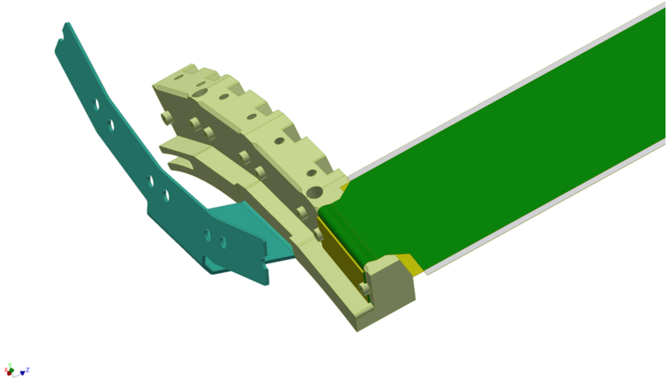
Gluing must be to precision $< 100\,\mu m$ w.r.t. endpiece reference.

Module assembly procedure



Turn it and . . .

Module assembly procedure

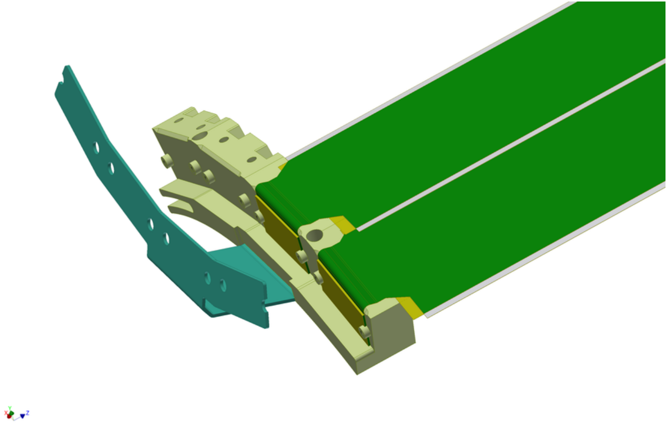


. . . place it on mounting jig (not shown). Secure with two screws (big holes).

Apply glue, place first ladder.

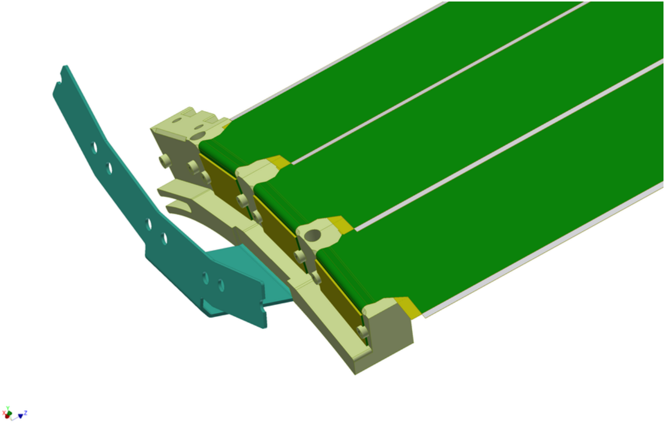
Remember: Ladder has a small flex at both ends with BGA array for interposer.

Module assembly procedure



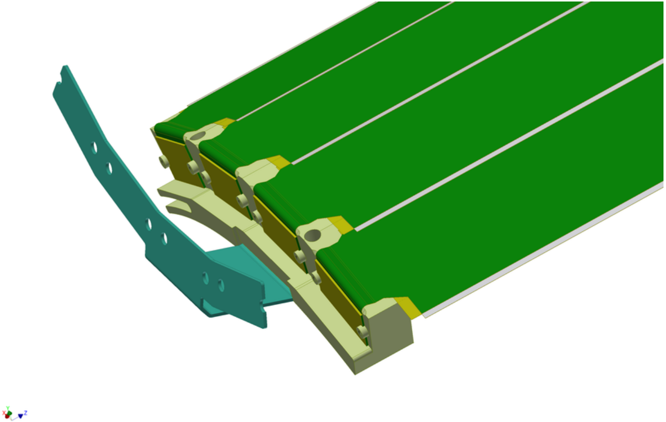
Repeat for second ladder. . .

Module assembly procedure



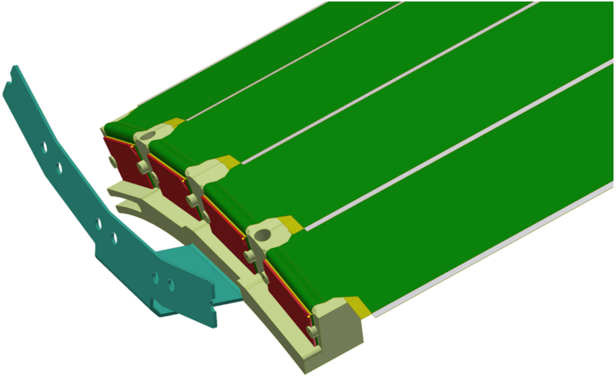
. . . third, and. . .

Module assembly procedure



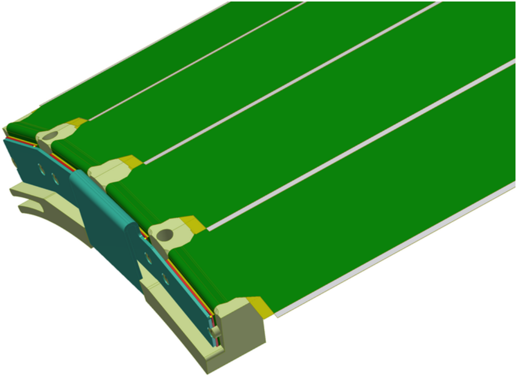
fourth ladder.

Module assembly procedure



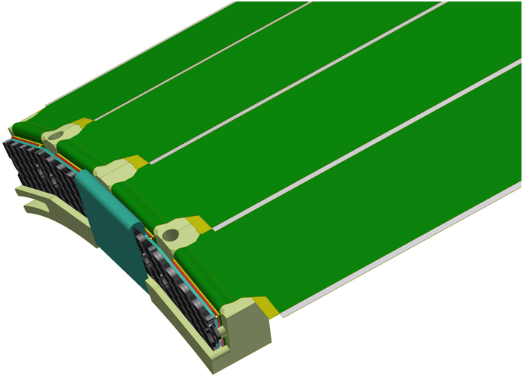
Place interposer (4 times).

Module assembly procedure



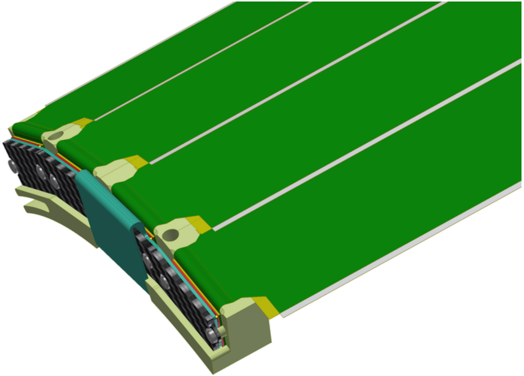
Fold in flexprint.

Module assembly procedure



Add compression bar (slides in from left under hair-pin loop)

Module assembly procedure

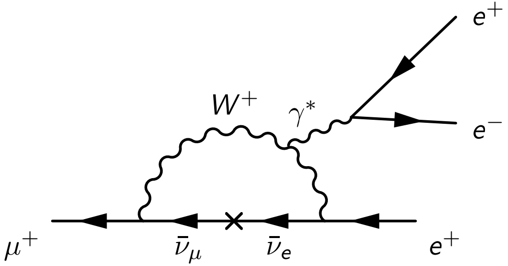


Secure everything with screws, 8 in total.

Seal V-folds from back side.

Mu3e physics

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



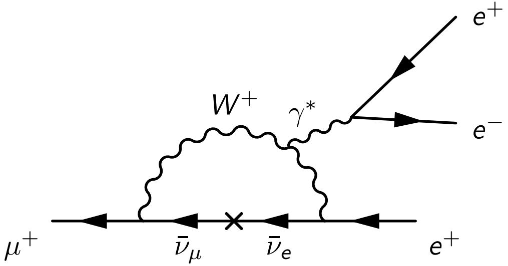
Mu3e physics

$\mu \rightarrow eee$ 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)

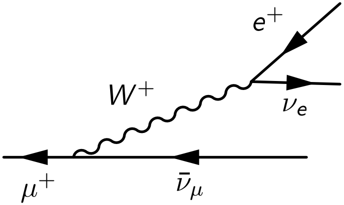
Alternative models predict BR within reach of Mu3e ($< 1 \times 10^{-16}$).



Mu3e physics

The standard Michel decay

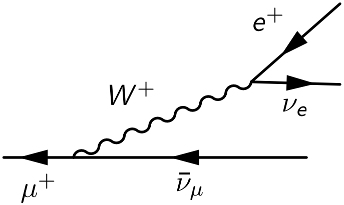
SM: $\approx 99.997\%$



Mu3e physics

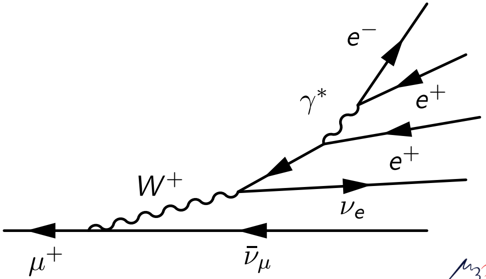
The standard Michel decay

SM: $\approx 99.997\%$

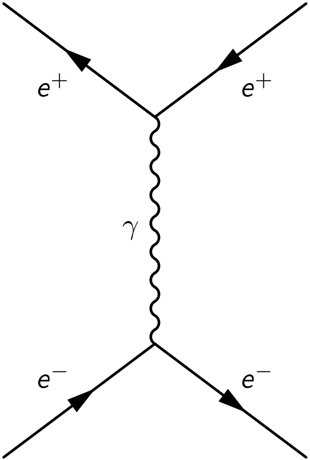


The radiative SM decay

SM: $(3.4 \pm 0.4) \times 10^{-5}$



Bhabha scattering

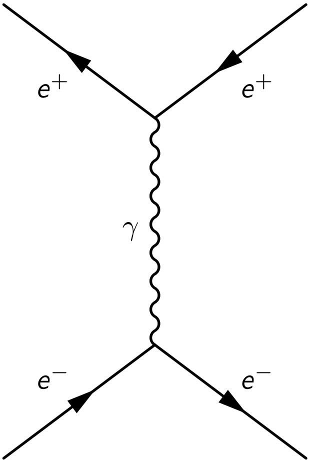


A well-known process.

Sources of particles:

- e^+: Michel decay, beam impurities
- e^-: Material in experiment

Bhabha scattering



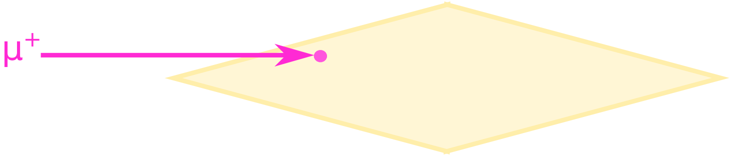
A well-known process.

Sources of particles:

- e^+: Michel decay, beam impurities
- e^-: Material in experiment

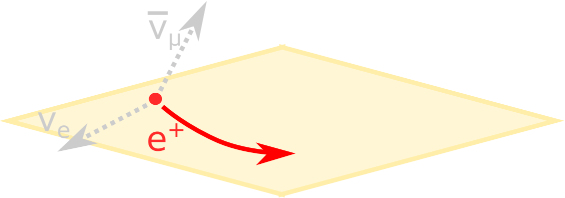
Mitigation:
Reduce material, improve resolution.

Mu3e physics



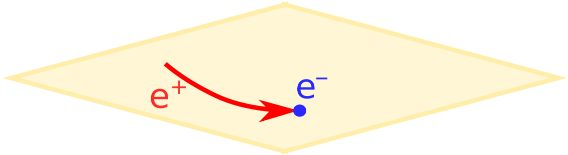
A muon from the beam stops on the target. . .

Mu3e physics



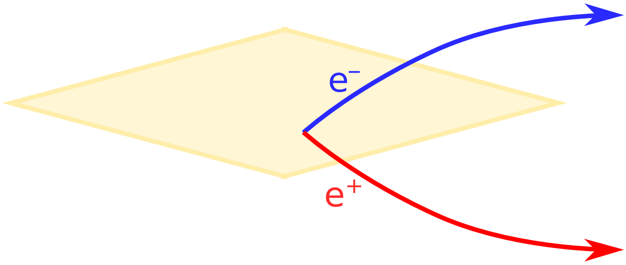
...and it makes a Michel decay.

Mu3e physics



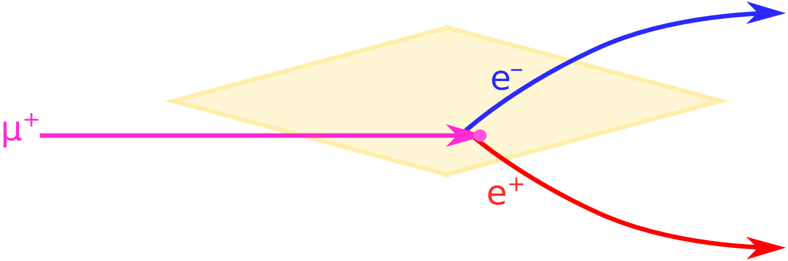
The positron hits an electron. . .

Mu3e physics



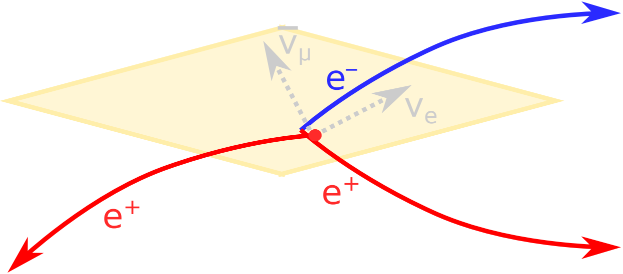
. . . undergoing Bhabha scattering and we have an electron track.

Mu3e physics



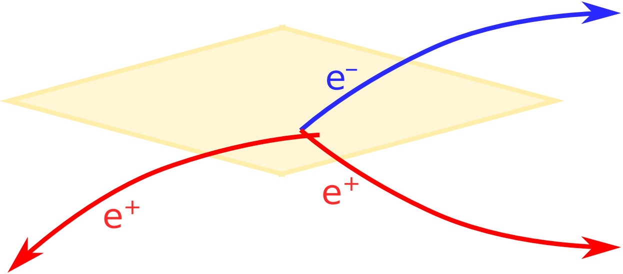
If another muon stops nearby…

Mu3e physics



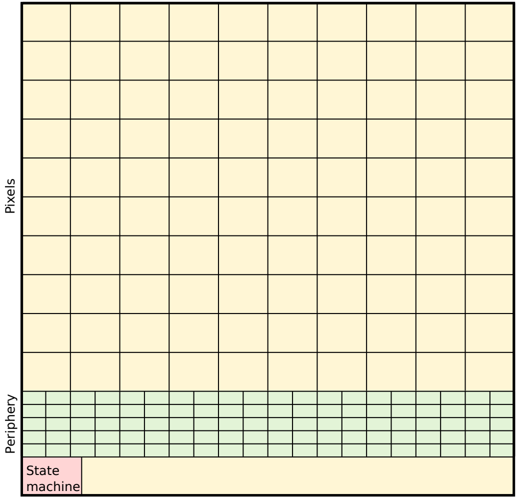
...and makes a Michel decay...

Mu3e physics



. . . you get the besic signature of our signal event.

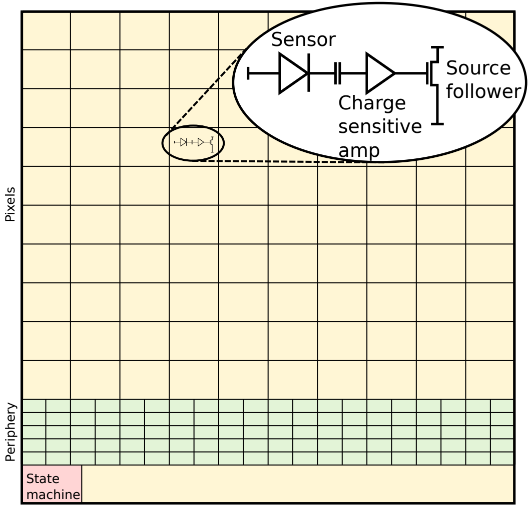
MuPix principle



The MuPix 7 chip is a DMAPS chip and consists of

- Active pixel matrix
- Mirror pixel in periphery
- State machine
- Plus support circuitry (VCO, PLL, etc., not shown)

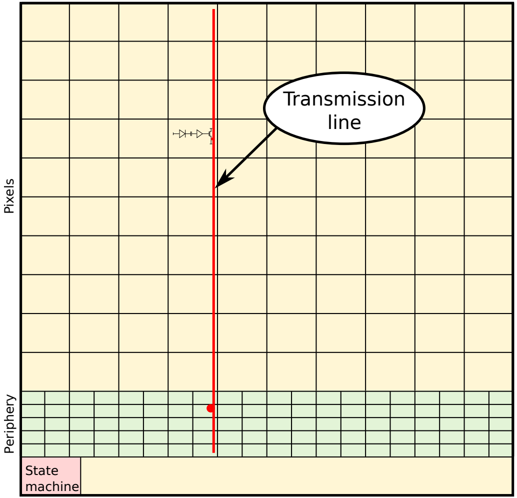
MuPix principle



The **analog cell** has

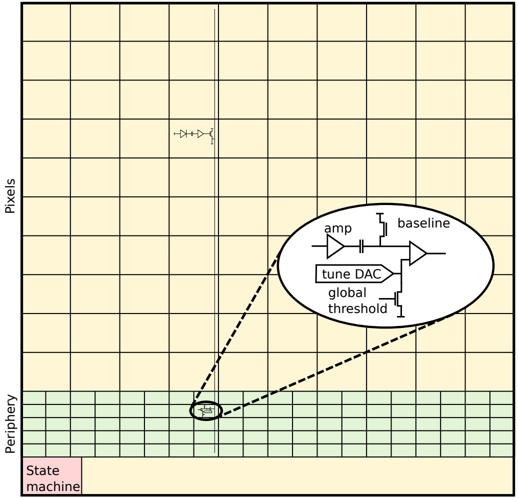
- a reverse biased sensor ($\approx -85\,\mathrm{V}$)
- a charge sensitive amplifier
- a source follower to drive. . .

MuPix principle



the **transmission line** to the corresponding partner cell in the periphery.

MuPix principle

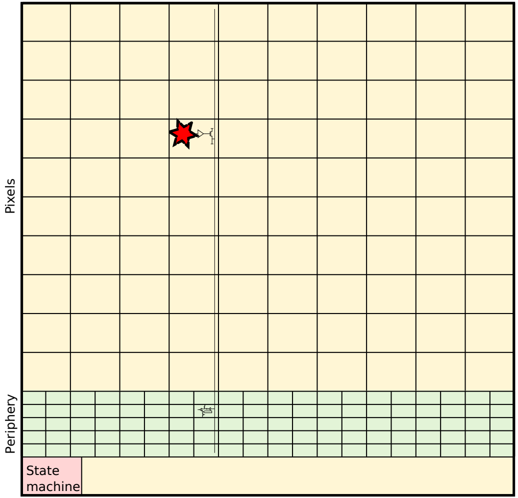


In the **partner cell**, the transition from analog to digital happens:

- an amplifier
- a comparator
- tuning capabilities

This separation protects the analog cell from digital crosstalk.

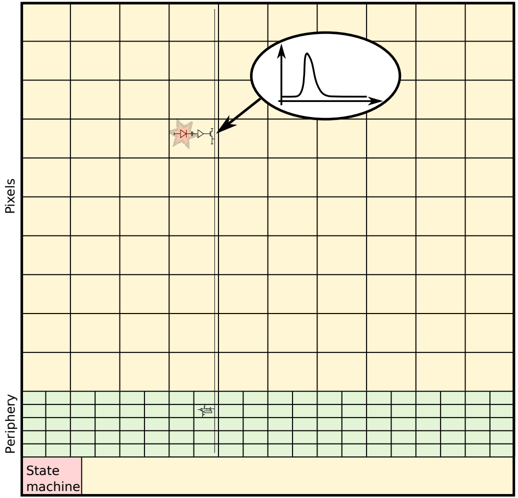
MuPix principle



All this results in a **non-shuttered**, **self-triggered** monolithic pixel chip.

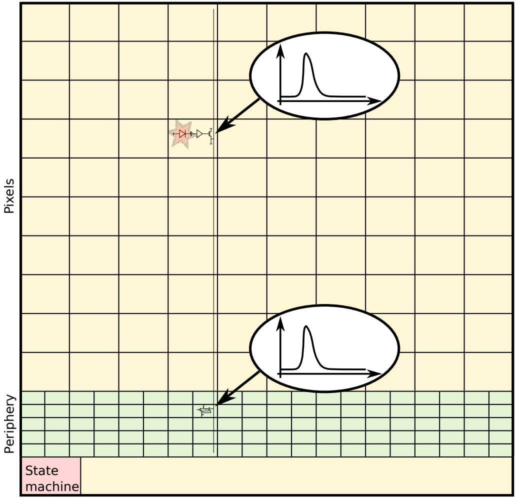
Upon a hit. . .

MuPix principle



. . . the charge sensitive amplifier sends a pulse proportional to the charge. . .

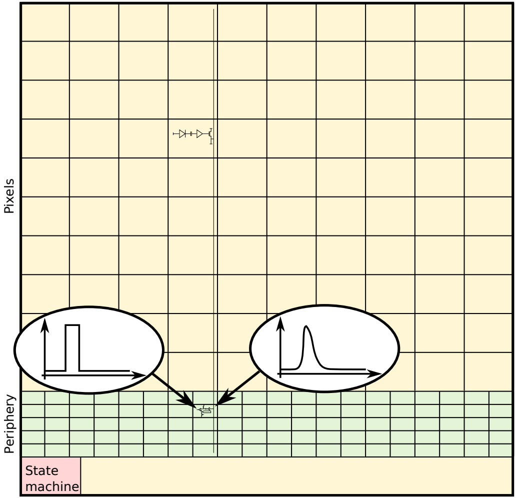
MuPix principle



. . . across the transmission line . . .

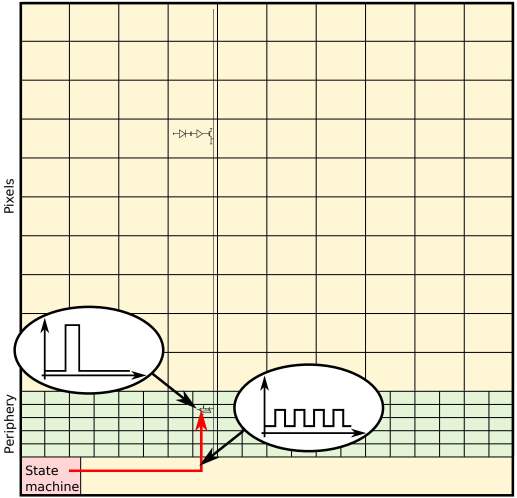
BTW: every pixel has its own transmission line

MuPix principle



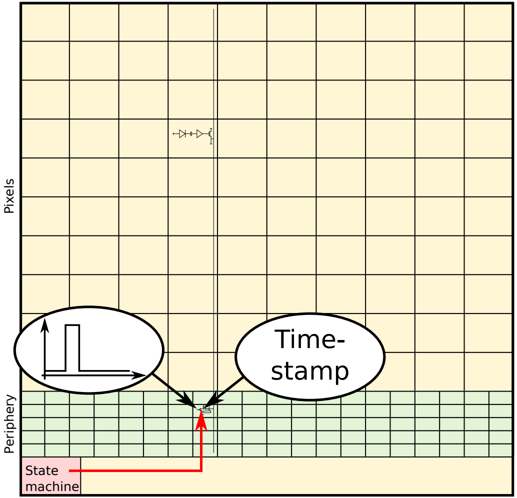
. . . and the comparator in the periphery creates a digital signal, if above threshold.

MuPix principle



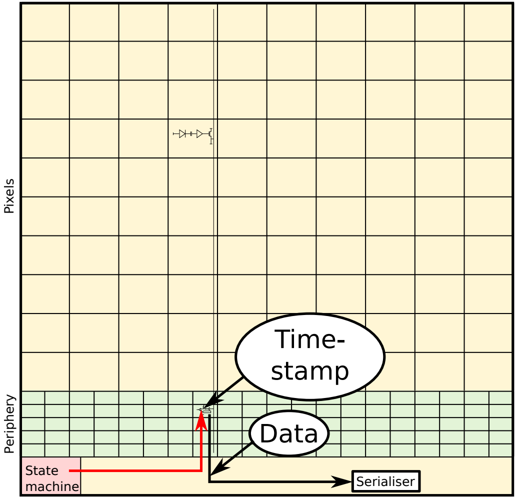
The state machine provides clock for a counter. . .

MuPix principle



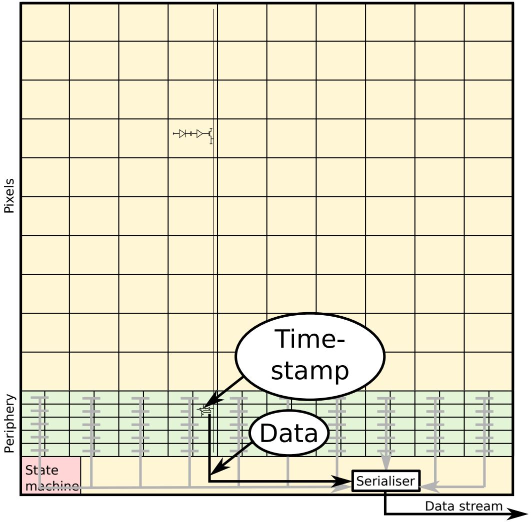
. . . in order to create a timestamp.

MuPix principle

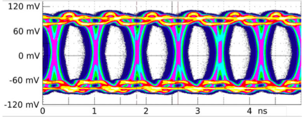


The data (pixel location, timestamp) goes through the serialiser. . .

MuPix principle



. . . and all the data is transmitted to the data stream at 1.25 Gbit/s.



MuPix principle

This design choice results in a

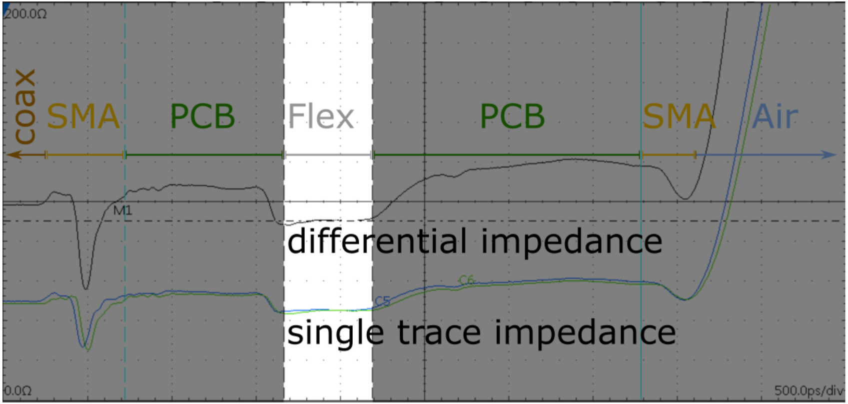
- pixel unit cell, that is always sensitive ⇒ „self-triggered“ and non-shuttered
- time-stamp allows event formation

This is tailored to our needs because we have

- no bunch structure
- no possibility for a reliable trigger with almost no material
- monolithic chips can be thinned to about 50 μm

MuPix principle

Time domain reflectometry of LTU HDI differential lines



MuPix principle

Several generations of MuPix chips realised:

Version	Year	Main features
MuPix1/2	2011/12	Analog prototype chips
MuPix3	2013	First digital readout
MuPix4	2013	Working digital readout and timestamping
MuPix6	2014	Readout bugs fixed, double-staged preamplifier
MuPix7	2014	Fast serial readout (1.25 Gbit/s), internal state machine, internal clock generation

MuPix3–7 have an active area of $3.2 \times 3.2\,\mathrm{mm}^2$, chip size is $\approx 3.5 \times 4\,\mathrm{mm}^2$.
MuPix7 pixel size: $103 \times 80\,\mu\mathrm{m}^2$, making up a 32×40 matrix.

Will this pixel detector work?

- The concepts we have and they look ok
- The detector geometry is optimised for our case
- But: can we reach the permille in radiation length?
- And what abozt the performance of the detector?

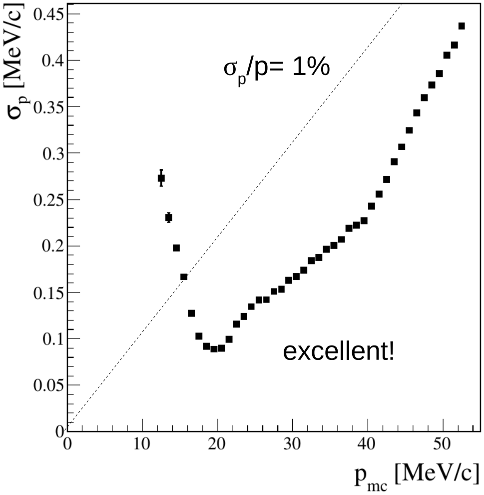
Will this pixel detector work?

Here is a material budget drilldown for pixel layers:

	Layer 1-2		Layer 3-4	
	thickness [μm]	X/X_0	thickness [μm]	X/X_0
MuPix Si	45	0.48×10^{-3}	45	0.48×10^{-3}
MuPix Al	5	0.06×10^{-3}	5	0.06×10^{-3}
HDI polyimide & glue	45	0.18×10^{-3}	45	0.18×10^{-3}
HDI Al	28	0.31×10^{-3}	28	0.31×10^{-3}
polyimide support	25	0.09×10^{-3}	≈ 30	0.10×10^{-3}
adhesives	10	0.03×10^{-3}	10	0.03×10^{-3}
total	158	1.15×10^{-3}	163	1.16×10^{-3}

We miss the target a bit. But after we built that detector we will elarn where we can optimise more.

Will this pixel detector work?



Our simulation lets us expect good performance.

Will this pixel detector work?

x/X_0: Fraction of radiation length

Defined by

- mean distance an electron looses $1/e$ of its energy by bremsstrahlung
- $7/9$ of the mean free path for pair production

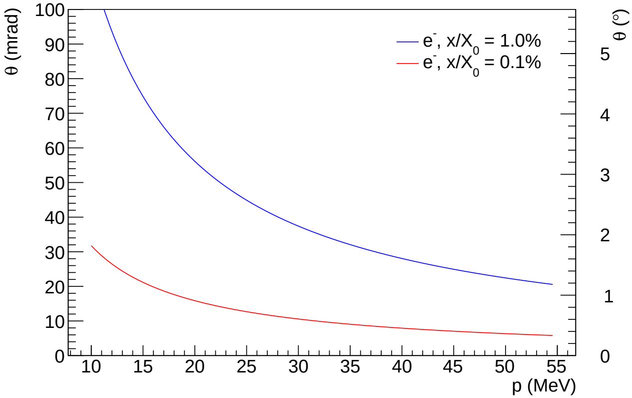
Used in estimating the expected scattering angle of a particle traversing matter:

$$\theta = \frac{13.6\,\mathrm{MeV}}{\beta c p}\, z\,\sqrt{x/X_0}\,[1 + 0.038\ln(x/X_0)]$$

Take-away: Material with larger X_0 create less scattering. Goes with charge number Z of nucleus.

Will this pixel detector work?

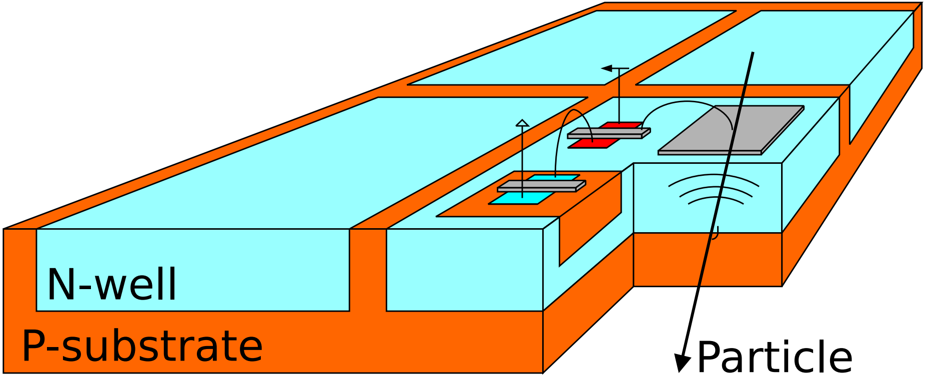
Multiple scattering at Mu3e energies for an electron:



Tracking detectors in this energy regime need to be as thin as possible.

Pixel sensor

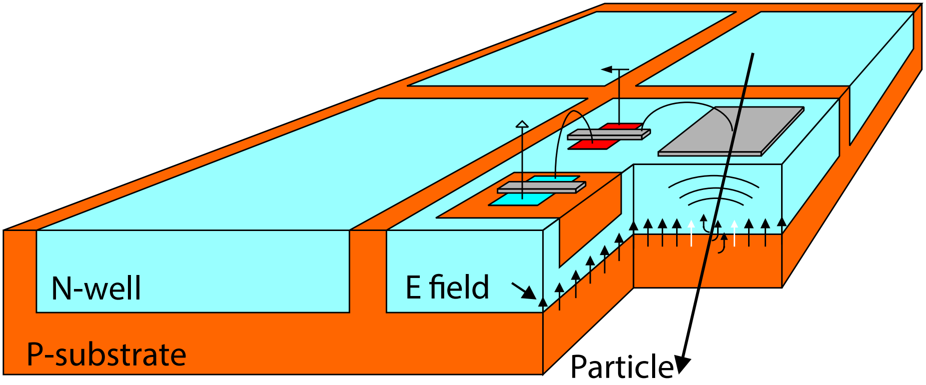
Pixel sensor



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

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

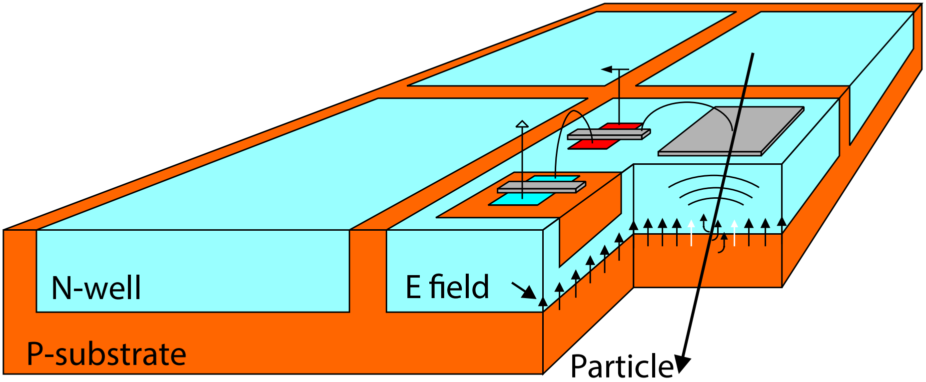
Pixel sensor



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

Pixel sensor



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

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