psi.ch/mu3e

Mu3e – ultra-thin pixel tracker using HV-CMOS

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Universität Heidelberg
on behalf of the **Mu3e** collaboration

April 13, 2017

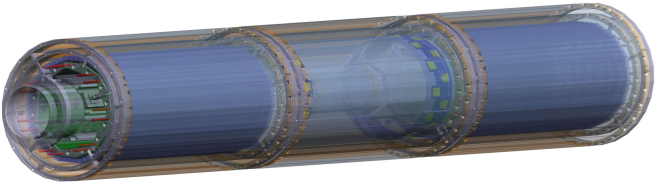
Mu3e

Mu3e is an experiment to search for

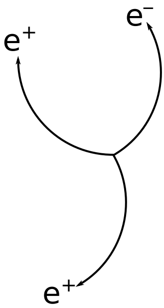
$$\mu^+ \rightarrow e^+ e^- e^+$$

A very rare decay.

- Hosted at Paul Scherrer Institut (PSI), Switzerland
- Collaborative effort amongst KIT, U Mainz, U Heidelberg, U Geneva, ETH Zürich and PSI. (UK institutes interested to join)

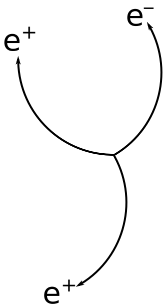


Mu3e physics



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

Mu3e physics

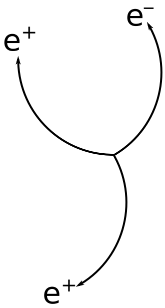


Signal

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

$\sum p_i = 0$

Mu3e physics



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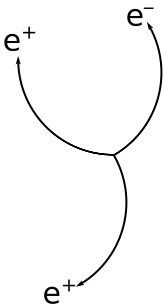
Mu3e physics



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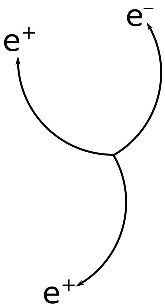
$t_i = t_j \quad \forall\, i, j$

Mu3e physics



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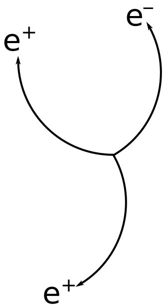
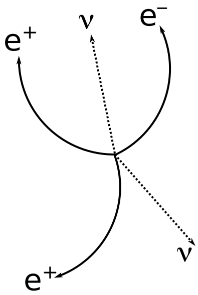
$t_i = t_j \quad \forall\, i, j$
common vertex

Mu3e physics





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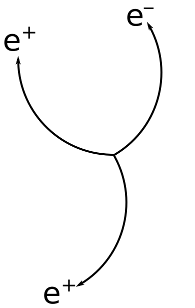
common vertex

Radiative decay
SM: 3.4×10^{-5}

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

Mu3e physics



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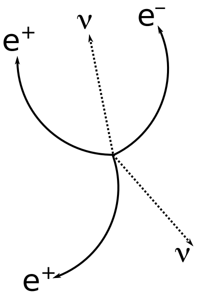

Radiative decay
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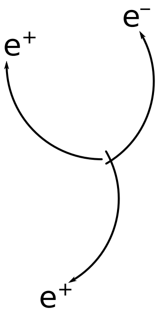
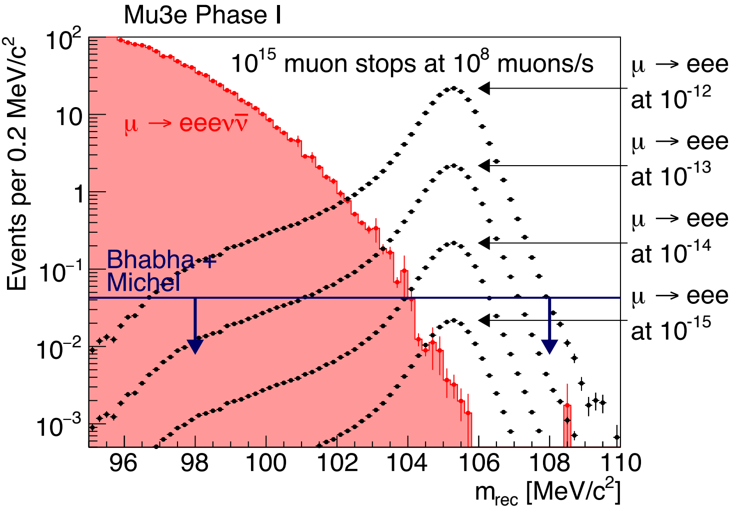
common vertex



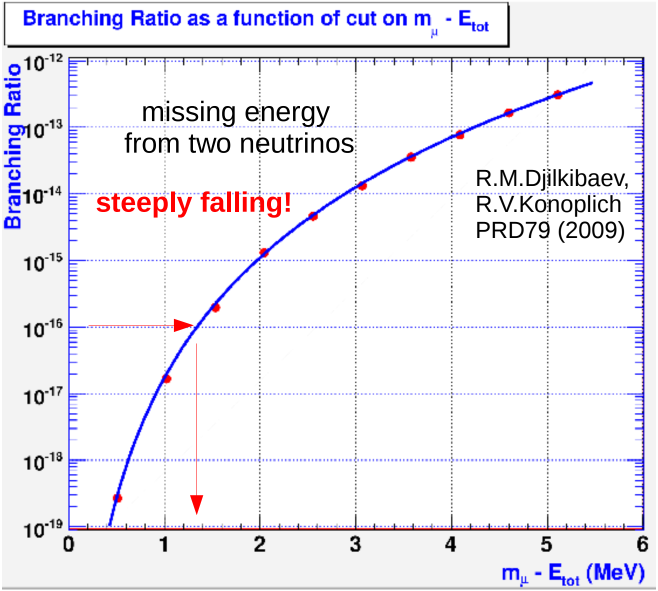
Accidental
background

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

Mu3e physics



Mu3e physics



Mu3e physics

Hence we need:

- Precise **tracking** (vertexing and momentum)
- Good **timing** (coincidence, event separation)

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

Interesting fact:
Last measurement done by SINDRUM in 1988 (!) at PSI
(BR $< 1 \times 10^{-12}$, 95% C.L.). We want to reach BR $< 1 \times 10^{-16}$

Material effects

Material effects

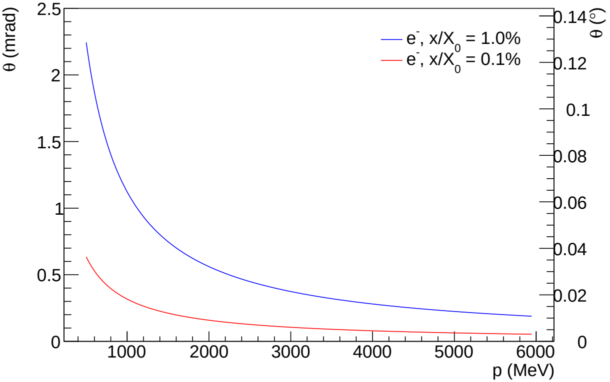
As you know, PDG gives you the following formula:

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

Allow me to illustrate that a bit...

Material effects

Multiple scattering at LHC energies for an electron:

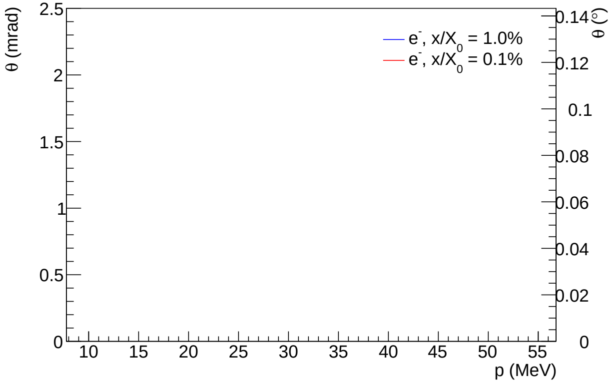


Thinner is a nice-to-have, but 1% x/X_0 is ok.

How does this looks like at Mu3e energies?

Material effects

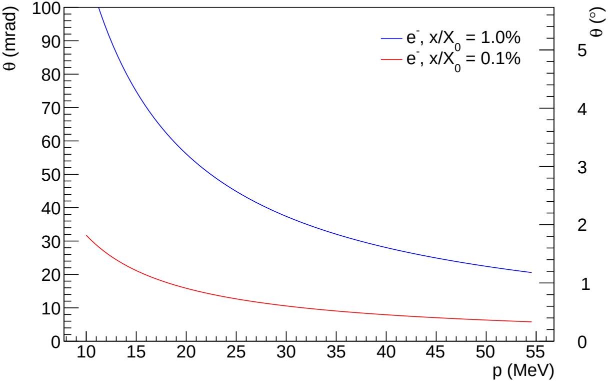
Multiple scattering at Mu3e energies for an electron:



Ooops. Did we loose the curve. . . ?

Material effects

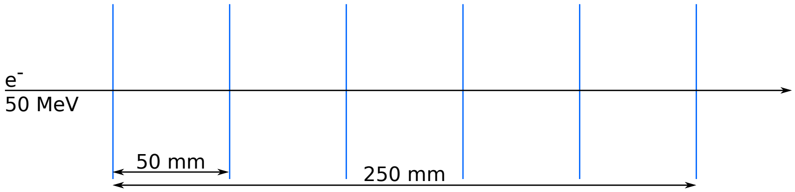
Multiple scattering at Mu3e energies for an electron:



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

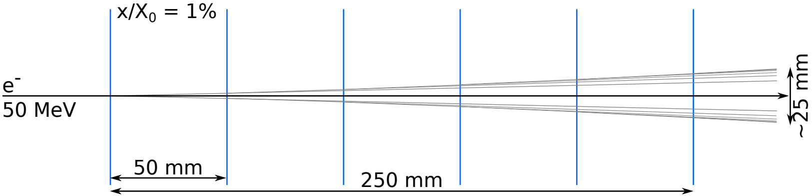
What does that mean for a tracking device?

Material effects



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

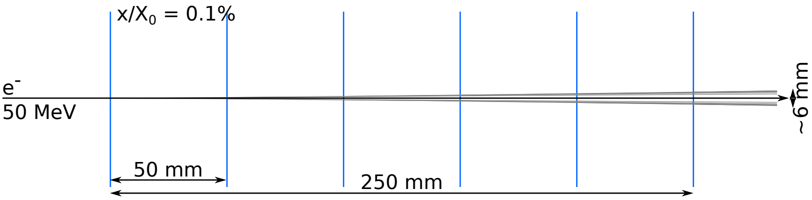
Material effects



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.

Material effects



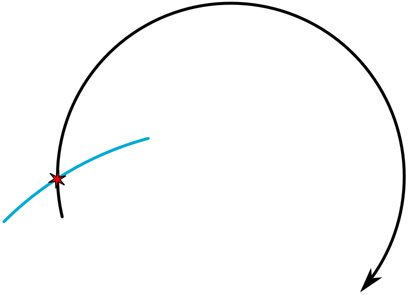
Reducing x/X_0 to 0.1% helps.

Material effects

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

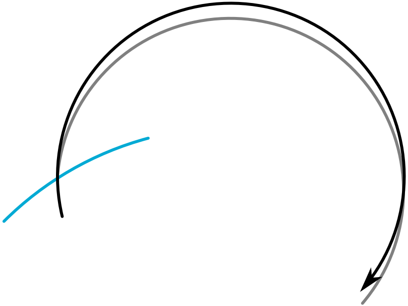
How can we take this to our advantage?

Material effects



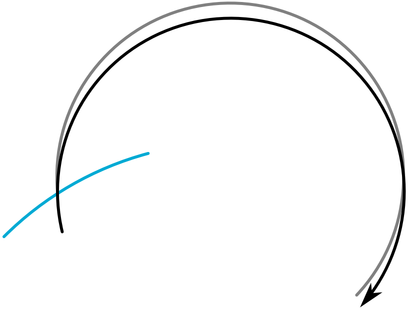
Assume a particle in a B-field scatters at some detector layer (blue)

Material effects



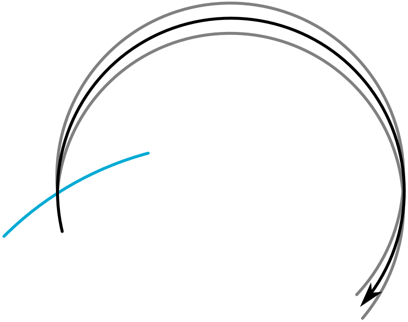
Let it scatter to the right. . .

Material effects



. . . or to the left. . .

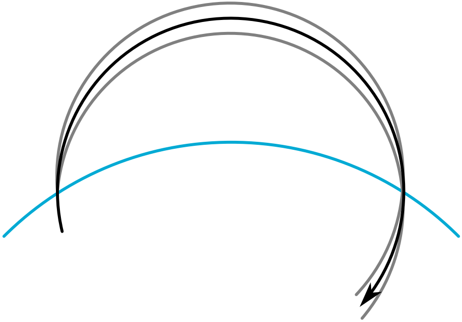
Material effects



Observe the magic point where the scattering effect cancels.

It is after a half turn.

Material effects



Choose radii wisely for best preformance.

Material effects

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

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

Material effects

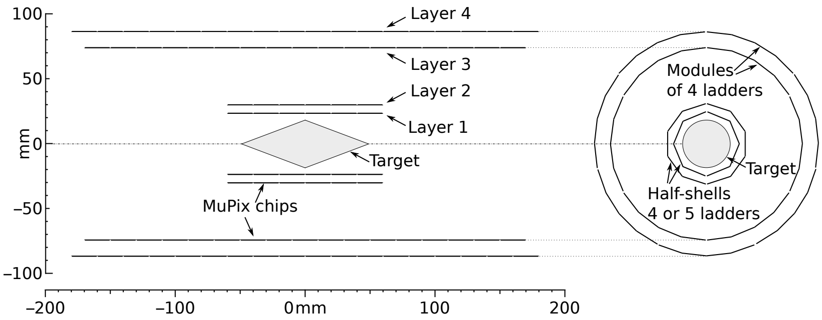
Ok, now you know our basic ingredients to do our job:

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

Detector geometry

Detector geometry

Monte-Carlo studies were performed. This led to the following geometry: ($B = 1\,\mathrm{T}$, $x/X_0 = 0.1\%$ per layer):



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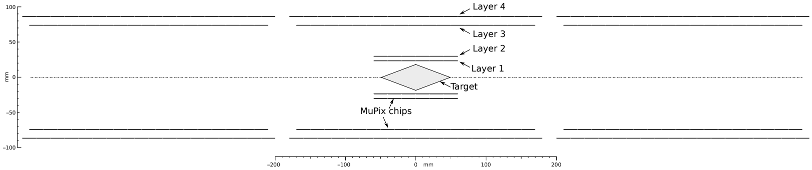


Identical copies of layers 3/4 will extend the detector in z to extend coverage for recoiling tracks.

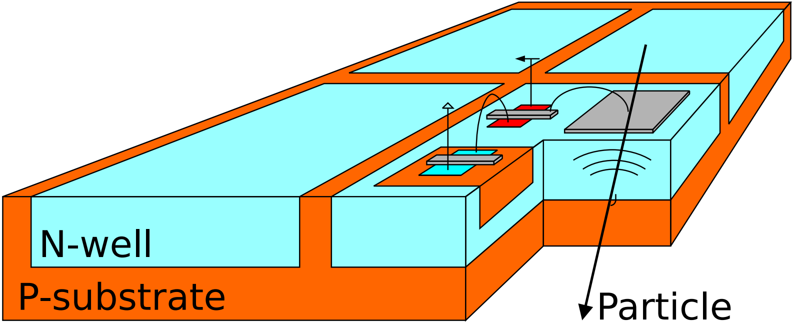
Detector geometry

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 sensor

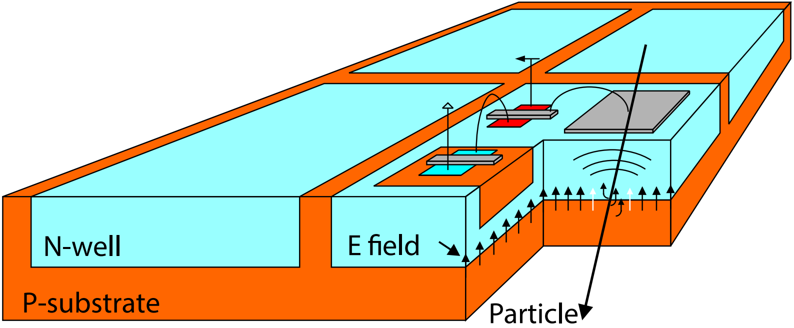
Pixel sensor



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

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

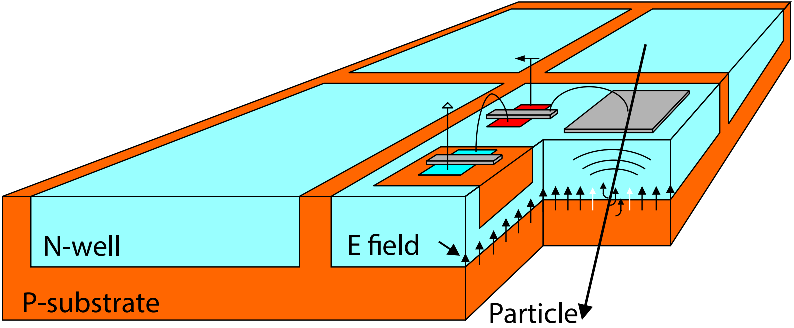
Pixel sensor



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 → drift dominates.

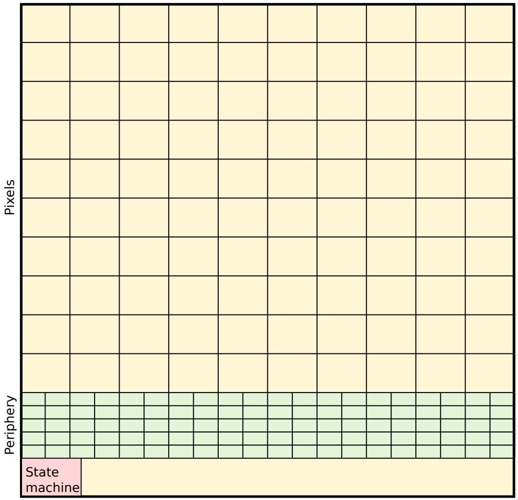
Pixel sensor



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

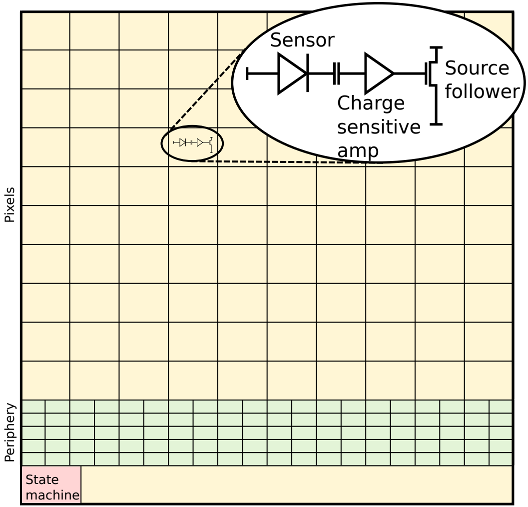
MuPix principle



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)

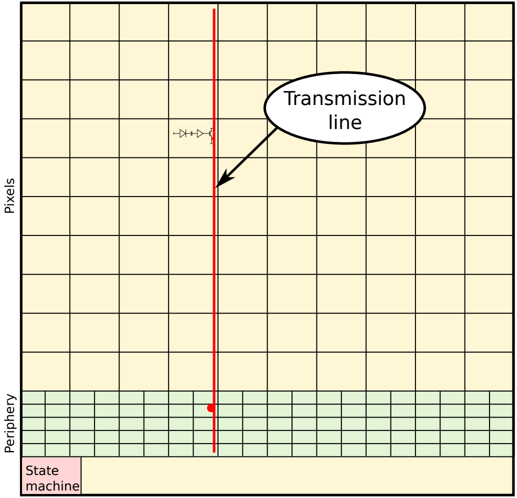
MuPix principle



The **analog cell** has

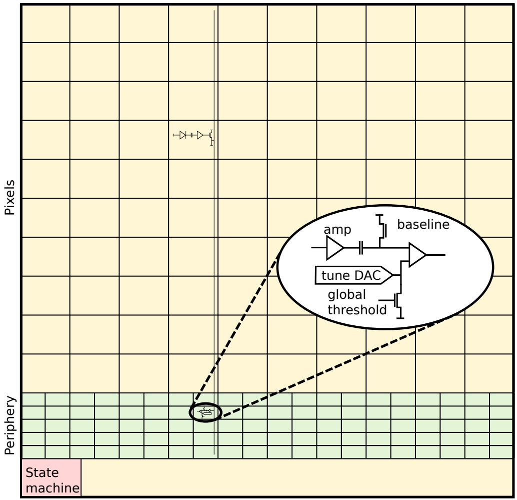
- a reverse biased sensor ($\approx -85\,\mathrm{V}$)
- a charge sensitive amplifier
- a source follower to drive...

MuPix principle



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

MuPix principle

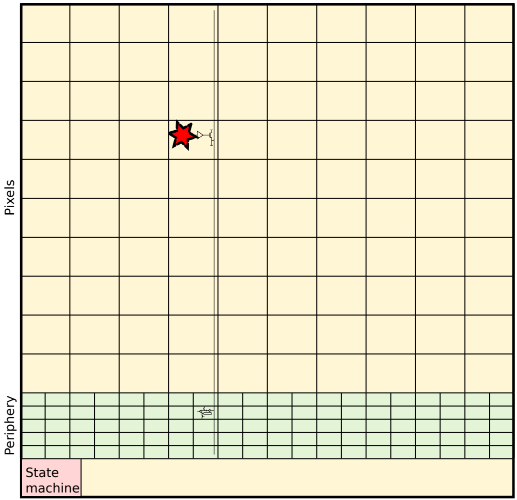


In the **partner cell**, the transition from analog to digital happens:

- an amplifier
- a comparator
- tuning capabilities

This separation protects the analog cell from digital crosstalk.

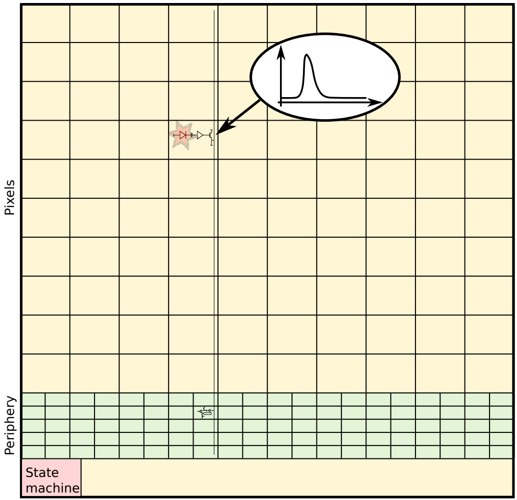
MuPix principle



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

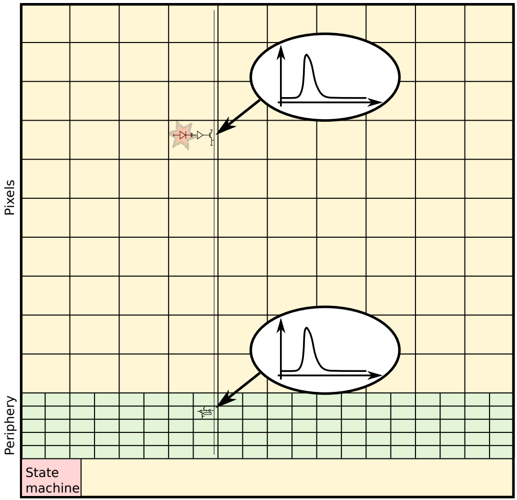
Upon a hit. . .

MuPix principle



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

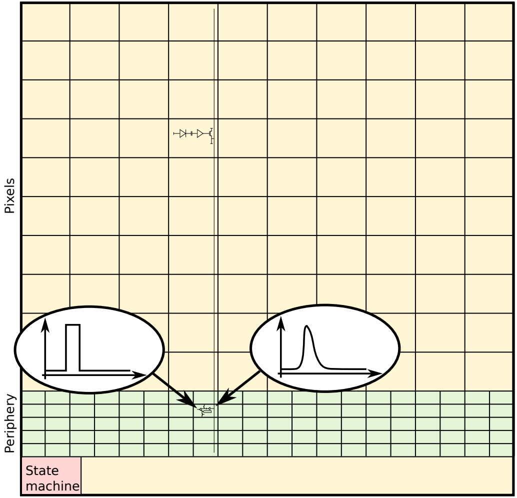
MuPix principle



. . . across the transmission line . . .

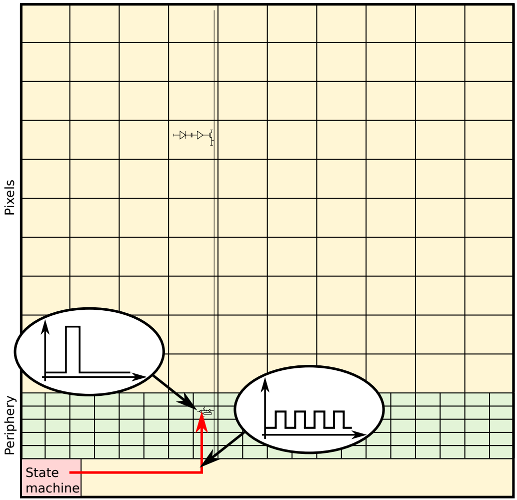
BTW: every pixel has its own transmission line

MuPix principle



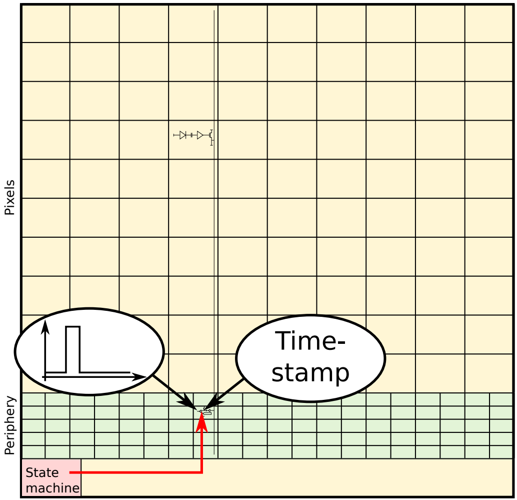
. . . and the comparator in the periphery creates a digital signal, if above threshold.

MuPix principle



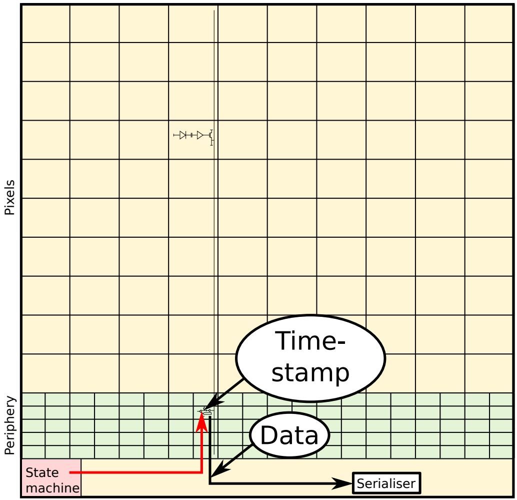
The state machine provides clock for a counter...

MuPix principle



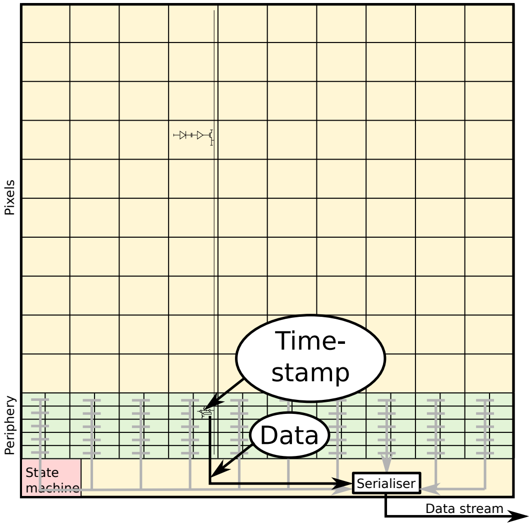
. . . in order to create a timestamp.

MuPix principle

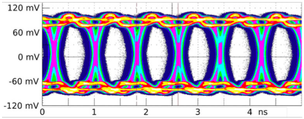


The data (pixel location, timestamp) goes through the serialiser. . .

MuPix principle

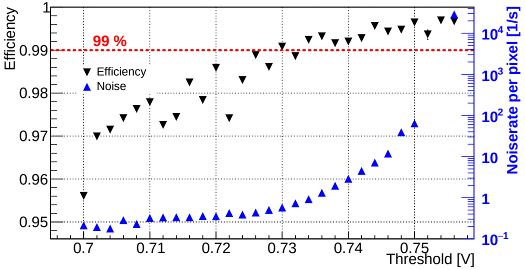


. . . and all the data is transmitted to the data stream at 1.25 Gbit/s.



MuPix7 performance

MuPix7 performance

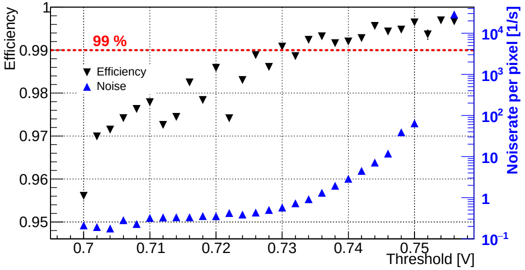


Efficiencies are very good at settings where power dissipation is 300 mW/cm^2

Beam: 4 GeV e^+ (DESY)

Top: 90° incidence

MuPix7 performance



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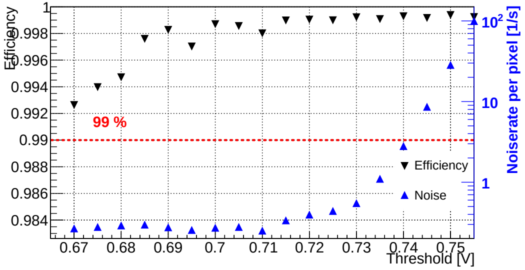
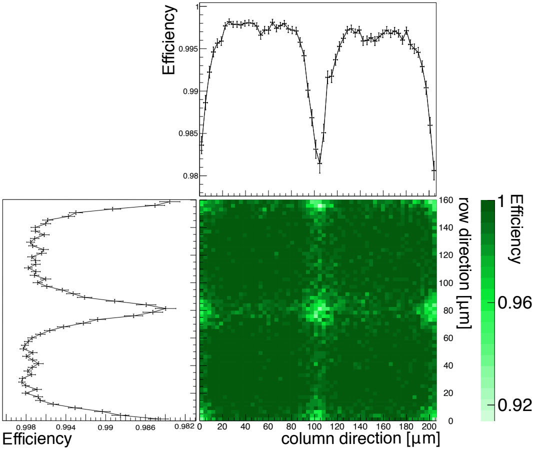


Bottom: 30° incidence
(i.e. sensor tilted by 60°)

MuPix7 performance

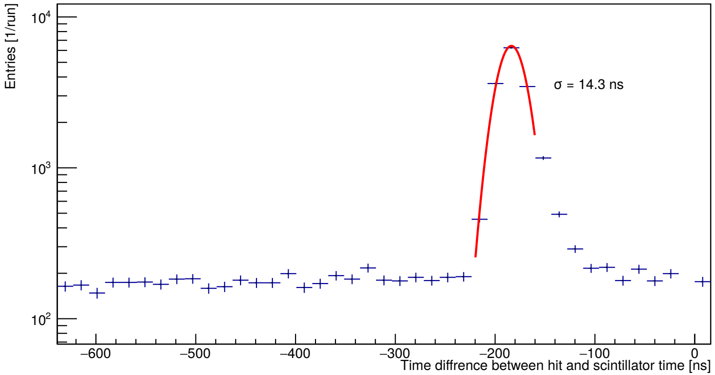


Sub-pixel efficiency study using EUDET telescope at DESY.

Threshold intentionally adjusted to 735 mV for lower overall efficiency to enhance effects. Bias: 85 V.

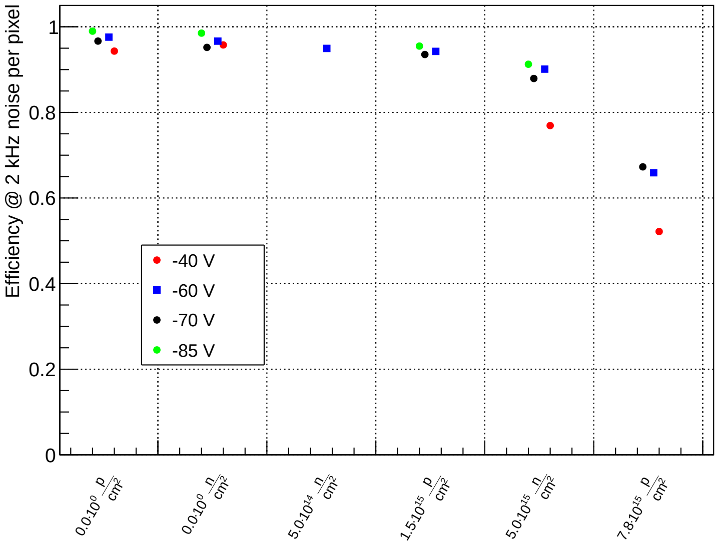
MuPix7 performance

Time resolution at same power settings are very good:



MuPix7 performance

MuPix7 is quite radiation hard:

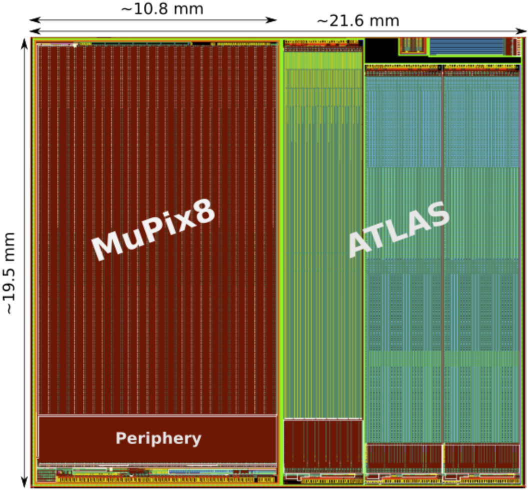


MuPix8

- Results shown were from MuPix7.
- $3 \times 3\,\mathrm{mm}^2$ active area, fully functional chip, e.g. used for making telescopes

- MuPix8 chip currently in production, expected next week
- Pixel size $80 \times 80\,\mu\mathrm{m}^2$ achieved
- Higher resistivity substrate: $80\,\Omega\,\mathrm{cm}$ instead of $20\,\Omega\,\mathrm{cm}$
- Power reduction expected
- Timewalk correction using time-over-threshold

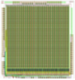
MuPix8



MuPix8 currently in production

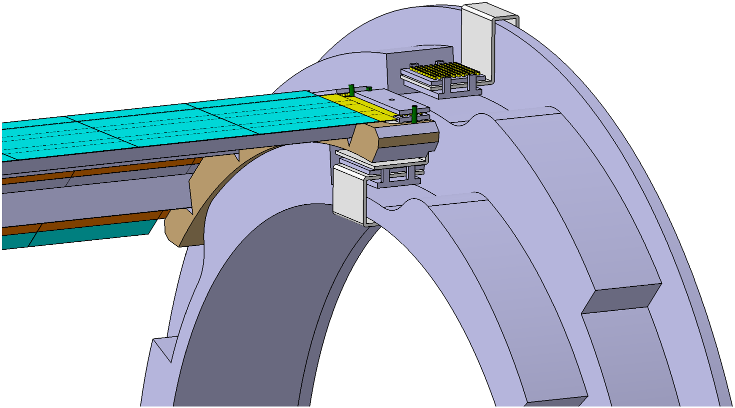
The chip will almost match full target size for the experiment but active area is smaller.

MuPix7 for comparison:



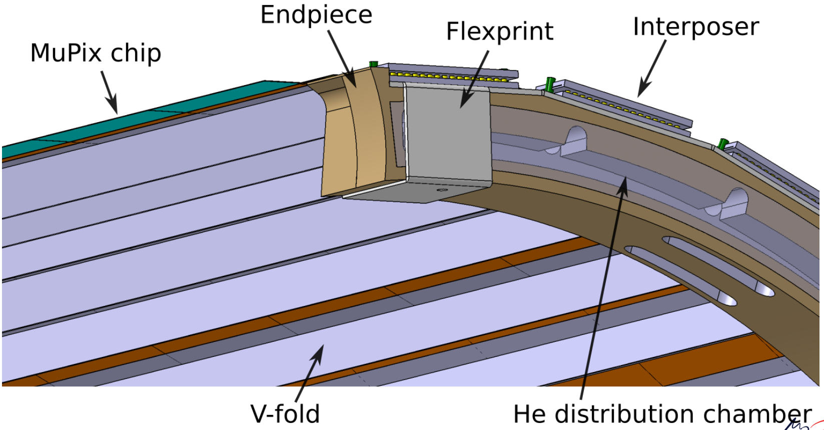
Pixel detector mechanics

Pixel detector mechanics

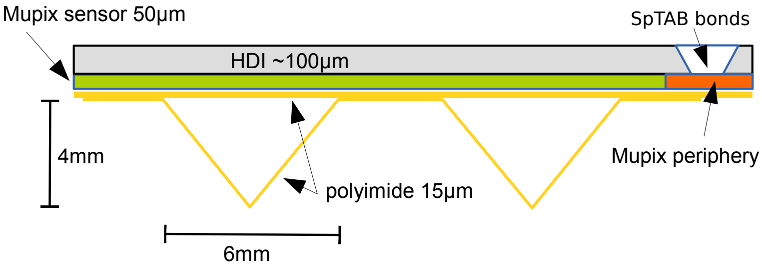


Shown: One layer 3 module inserted.

Pixel detector mechanics

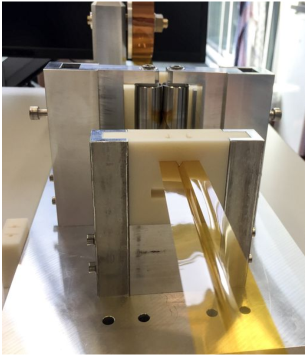


Pixel detector mechanics



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

Pixel detector mechanics



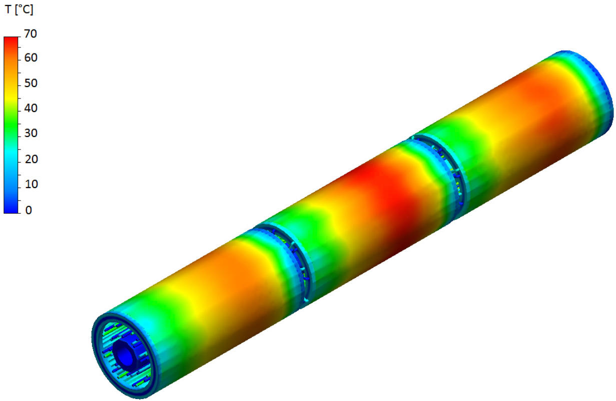
We developed a machine to make V-folds into polyimide film.

Film thickness: 25 µm

Pixel detector cooling

Pixel detector cooling

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

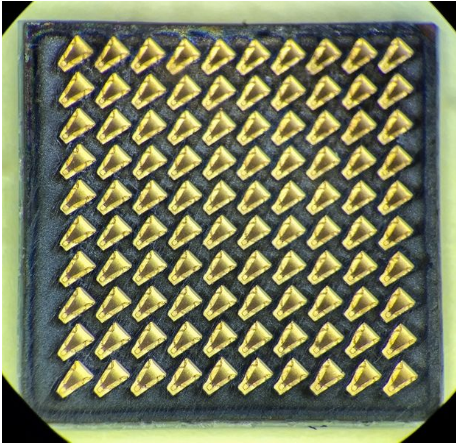


$\frac{P}{A} = 400\,\mathrm{mW/cm^2}$ All pixel layers, no target or SciFi

$v_{\mathrm{global}} = 0.5\,\mathrm{m/s}$ $v_{\mathrm{gap}} = 10\,\mathrm{m/s}$ $v_{\text{v-fold}} = 20\,\mathrm{m/s}$

Electrical connectivity

Electrical connectivity



Interposer Samtec Z-Ray

Pitch: 0.8 mm

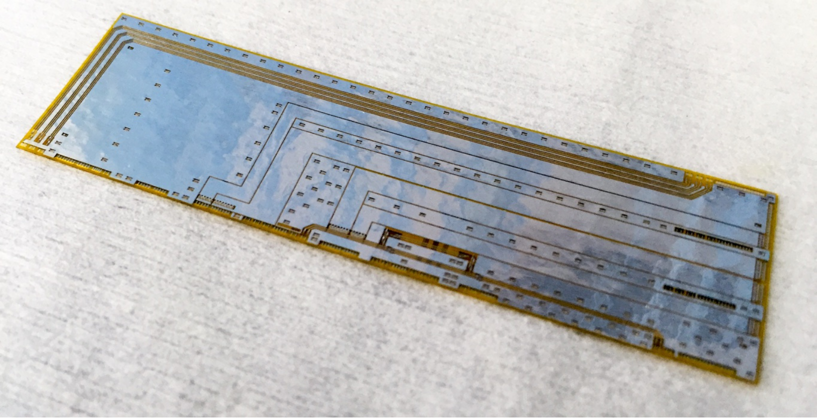
Model	Compressed height
ZA8H	0.3 mm
ZA8	1 mm

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

Allows use of flexes instead of cables.

Electrical connectivity

For the HDI, we go for aluminium/polyimide:

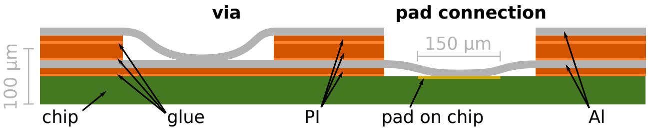


Made by LTU (Kharkiv, Ukraine), used in e.g. ALICE pixels for power strips.

Electrical connectivity

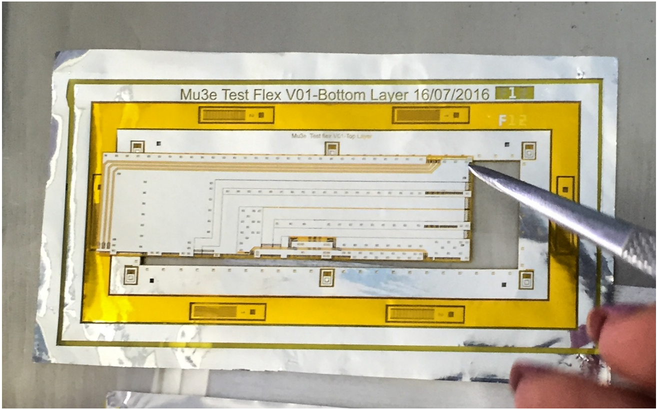
Process steps:

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.

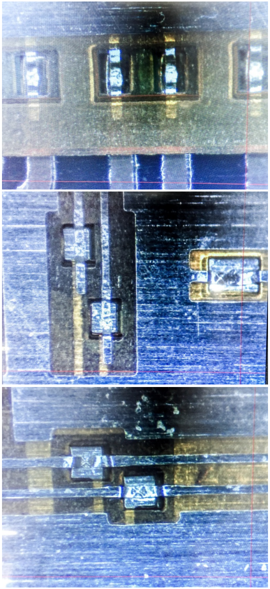


Electrical connectivity

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

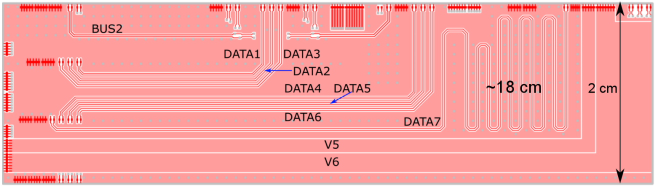
Center: Connecting layers (via)
The visible misalignment is a shrinking effect from polymerisation at 350 °C. One trace needs to be wider to absorb the tolerances.

Bottom: Vias for a bus

Electrical connectivity

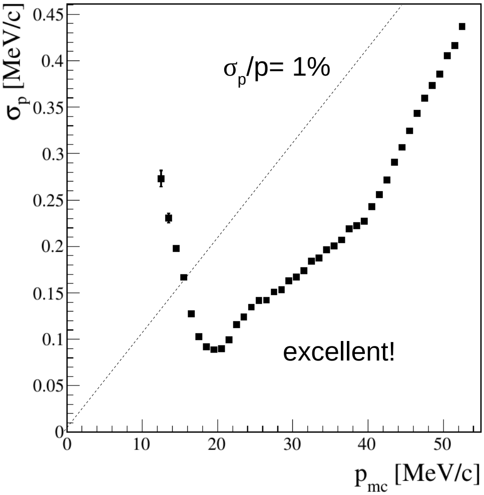
Bit error rate tests:

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



Will this pixel detector work?

Will this pixel detector work?



We will see.

But our simulation lets us expect good performance.

Summary

- The **Mu3e** experiment is a challenging effort.
- Novel technologies for 0.1% x/X_0 (per layer):
  - Thinned chip (50 μm)
  - Support structure made of polyimide film
  - HDI made of polyimide and aluminium, SpTAB bonding
  - Small sized industry-standard parts (interposer)
- MuPix7 is a full working monolithic DMAPS chip
  NB: Our workhorse since about 2 years
- Clever detector layout mitigates multiple scattering effects (half-turns)
- Note: We have additional timing detectors, not covered for brevity

We'd like to acknowledge generous support at test beam facilities at **DESY** Hamburg (Germany), a member of the Helmholtz Association (HGF), **PSI**, **MAMI** and **CERN**.

References

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

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

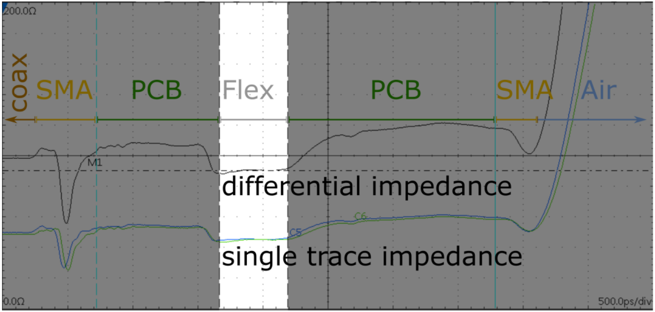
[3] arXiv:1211.4494v1

[4] G. Contin, talk at PIXEL2016

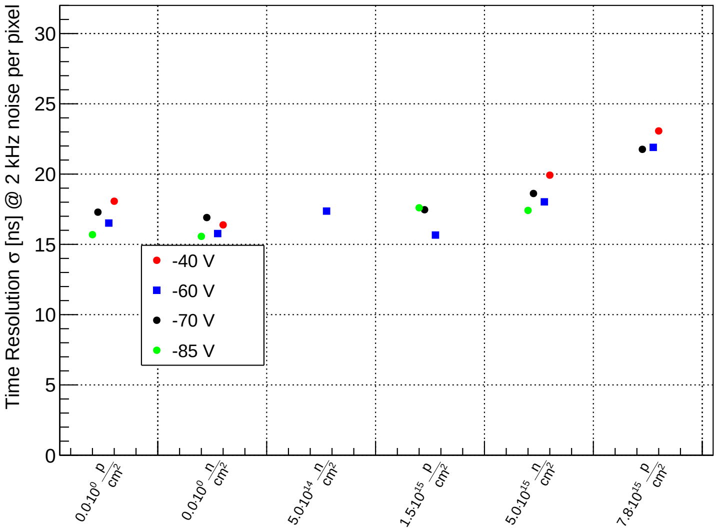
[5] C. Koffmane, talk at PIXEL2016

ENCORE

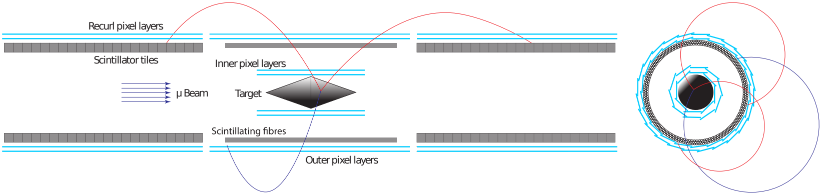
Time domain reflectometry of LTU HDI differential lines



MuPix7 is quite radiation hard:



The Mu3e experiment, Phase-I configuration:



Key requirements:

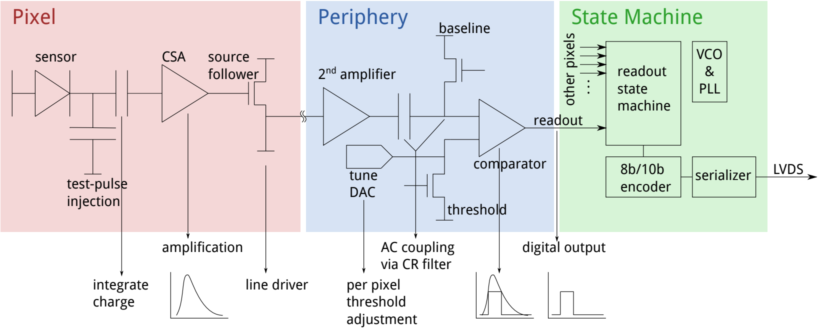
- High rate: 10^8 muon stops on target per second
- Time resolution (pixels): 20 ns
- Vertex resolution: about 200 μm
- Momentum resolution: about 0.5 MeV
- Low material budget: 1‰ X_0 per pixel layer

This translates to the following chip requirements:

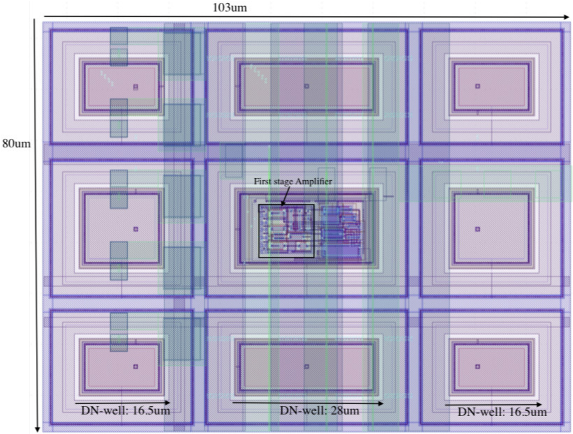
	Requirement	MuPix7	Conclusion
Pixel size (μm^2)	80×80	103×80	$\rightarrow$ MuPix8
Sensor size (mm^2)	20×20	3×3	$\rightarrow$ MuPix8
Thickness (μm)	50	50	ok
Bandwidth per chip (Gbit/s)	3×1.25	1×1.25	$\rightarrow$ MuPix8
Hit rate (MHz/cm^2)	2.5	5.5	ok
Spatial resolution (μm)	< 100	$103/\sqrt{12}$	ok
Time resolution (ns)	< 20	11	ok
Efficiency (%)	> 99	99.5	ok
Power (mW/cm^2)	≤ 300	≤ 300	ok

More on material budget and cooling requirements in the talk by S. Dittmeier tomorrow.

MuPix7 block diagram

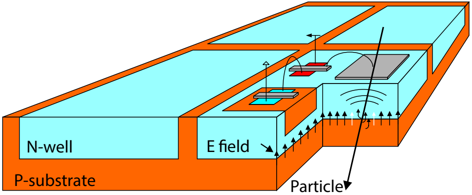


Pixel unit cell



Observe the 3 × 3 diode design. The analog electronics is on top of the center diode.

We use a High-Voltage **Monolithic** Pixel Sensor (HV-MAPS):



- HV CMOS technology used automotive and audio industry
- Reverse biasing up to −85 V routinely (−93 V tested)
- Thinning to 50 μm possible and done
- Self-triggered, continuous readout (no shutter, darkframe etc.)

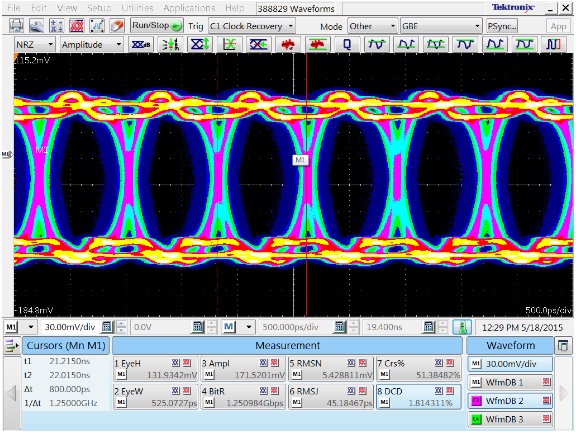
Several generations of MuPix chips realised:

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.

MuPix7: Fast serial readout signal

Signal quality of fast readout signal at 1.25 Gbit/s is very good:

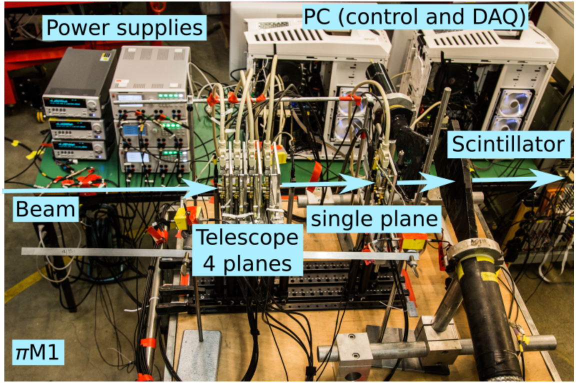


Clock is at 125 MHz, high speed clock internally generated.

Measured on test bench using chip on standard test board.

MuPix7: Telescope

Telescope setup, e.g. at PSI πM1:



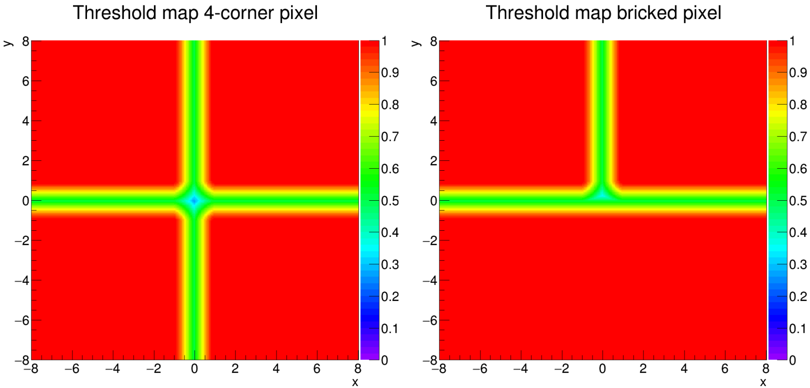
Telescope with 4 MuPix7 planes, 1 plane elected as DUT

MuPix7

Integration studies:

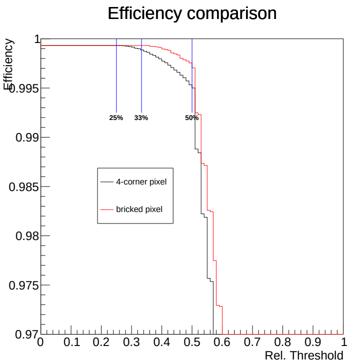
- Build a **prototype of an inner layer module**: 2×3 chips.
- Studies with different **flex print options** (1 signal layer, 2 power layers):
  - **Traditional:** 3 layer copper: conservative but reliable, too much material for final design (2‰ X_0)
    $\Rightarrow$ Electrical integration studies
  - **Baseline:** 1 copper layer (signal), 2 aluminium layers (power/GND), sandwiched (1.2‰ X_0 possible)
    $\Rightarrow$ Copper technology has nice spacing (10 µm feature sizes available)
  - **Optimal:** 2 layer Aluminium, if necessary with one additional layer. Uses pad-bonding (1‰ X_0)
    $\Rightarrow$ Technology implemented by ALICE. Riskier approach, new territory but promising.

Efficiency of 4-corners vs. bricked layout



ToyMC for a sample charge cylinder with unit radius. Shows fraction of charge seen in the pixel under the impact center. Range $[-8, 8]$ corresponds to a pixel of 80 µm size and 5 µm charge radius.

Efficiency of 4-corners vs. bricked layout

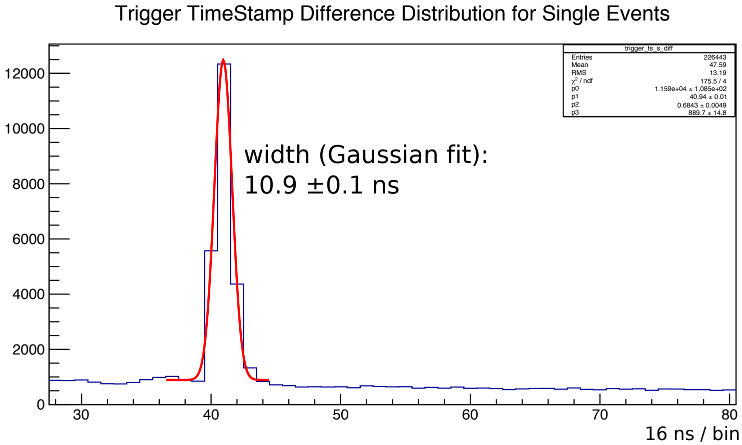


Efficiency vs. threshold (arbitrary units).

A 4-corner pixel starts to loose hits if threshold is above 25% of full charge generated.

Bricked pixel gives some headroom.

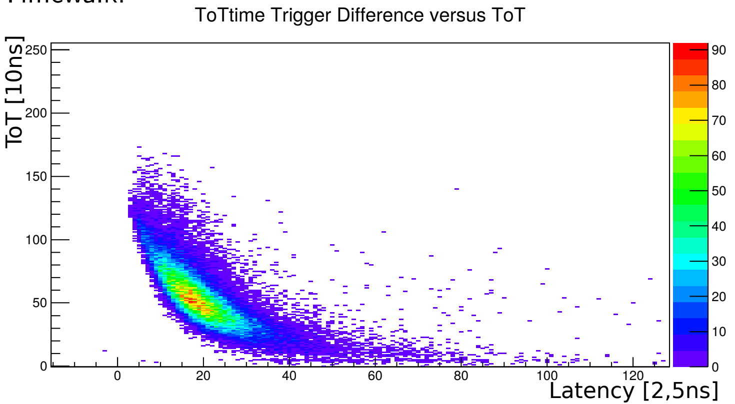
MuPix7: Time resolution



Technique: Scintillator coincidence signal as reference. Plotted timestamp scintillator − timestamp MuPix7 (Settings used: $1000\,\mathrm{mW/cm^2}$)

MuPix7: Time resolution

Timewalk:



ToT can be measured for one selected pixel. Anticorrelation clearly visible (Settings used: 1000 mW/cm^2).

MuPix7: DAQ performance

- **CERN SPS**: MuPix7 run successfully at rates of about **500 kHz** (on chip)[1].
- Speed limit of MuPix7 telescope: about **1 million tracks per second**. Can be increased by optimising DMA transfer.
- Fast data transfer and reconstruction demonstrated (simulation and at DESY).
  - Hits sorted on FPGA
  - Transferred to memory using DMA
  - Processed in GPU for track reconstruction.

  300 MB/s with simulated data achieved[2].

[1] Exact rate determination difficult due to saturated DAQ.

[2] This is processing speed, not write to disk.

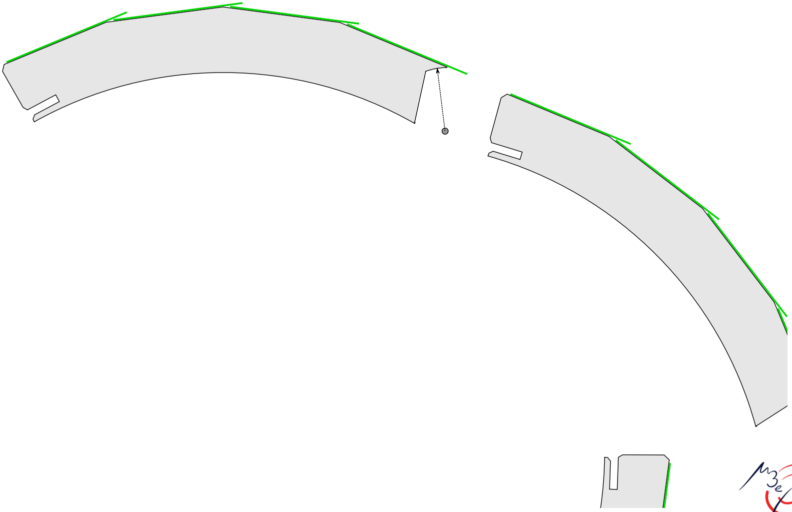
MuPix7

How does the insertion mechanism work?

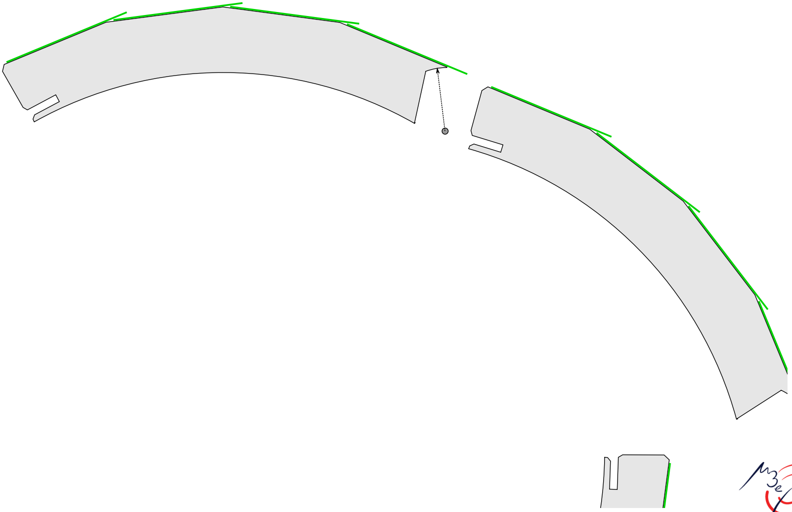
Next few slides show an animation.
Mechanically tested using 3d printed model.

Note: Endpiece shape more matured meanwhile.

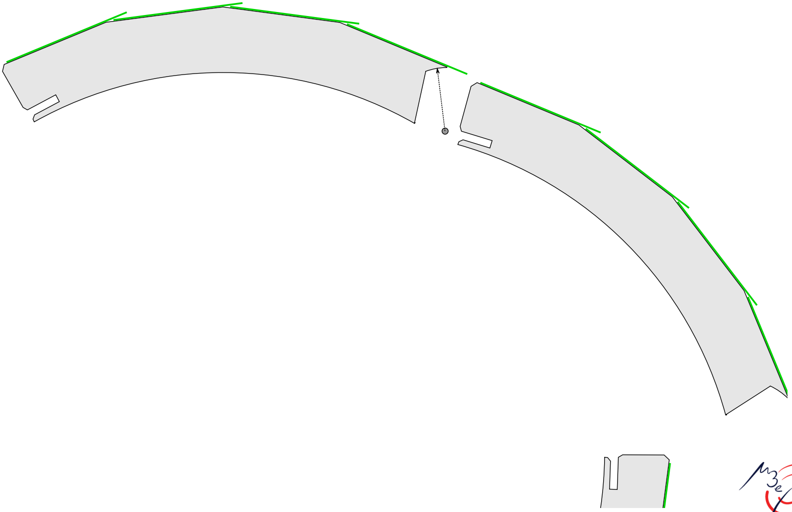
MuPix7



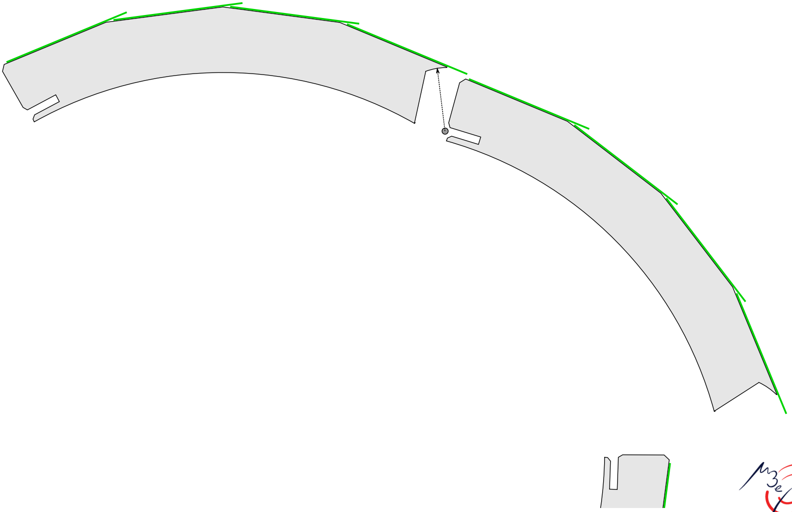
MuPix7



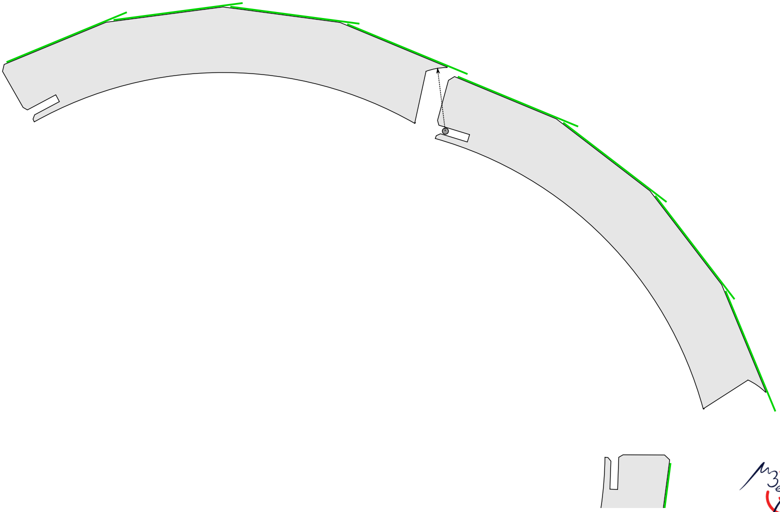
MuPix7



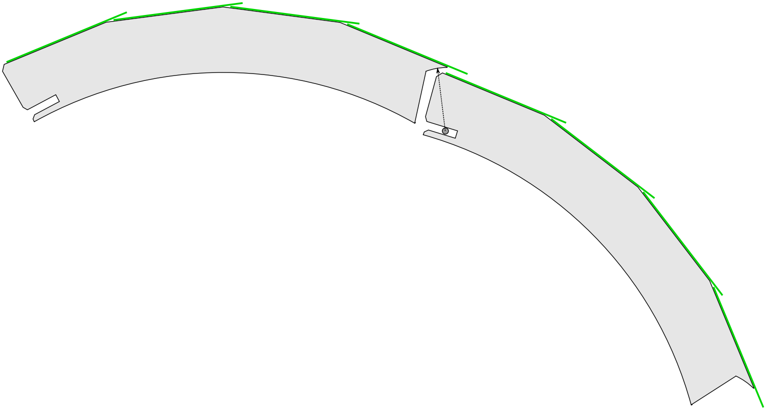
MuPix7

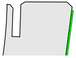


MuPix7

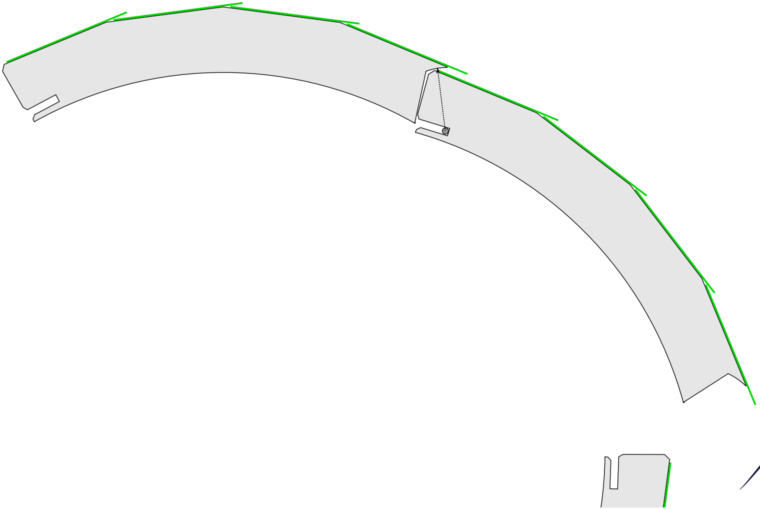


MuPix7

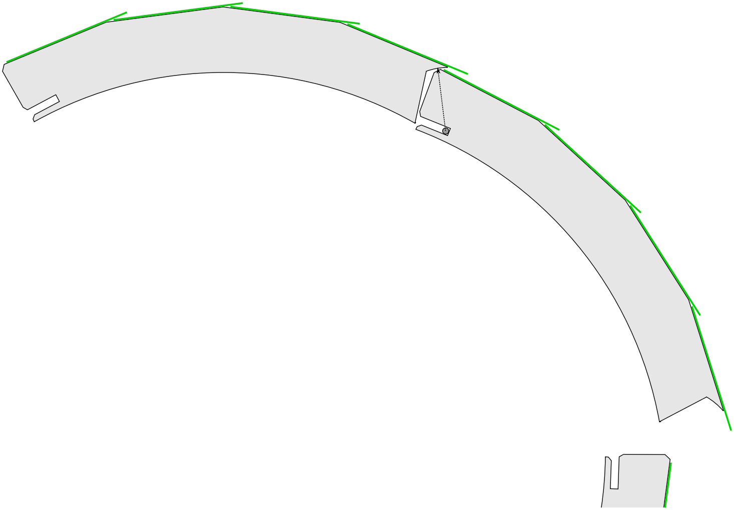




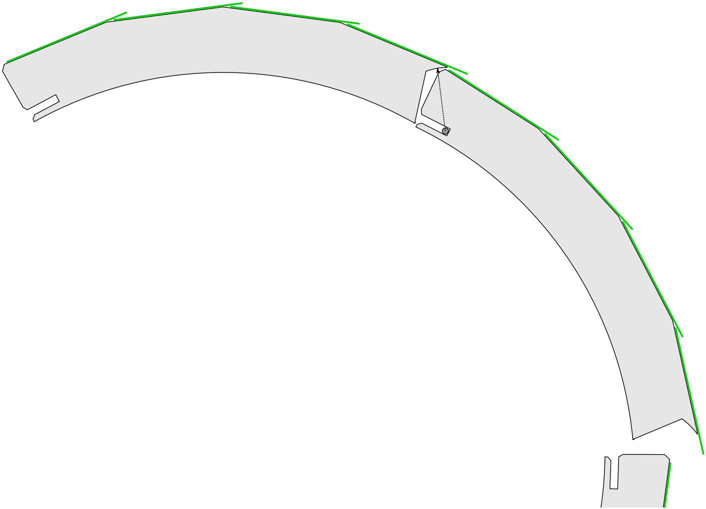
MuPix7



MuPix7



MuPix7



MuPix7