# Construction of the Mu3e inner tracking detector

Thomas Rudzki - 22.7.2020 - HighRR seminar

# Introduction

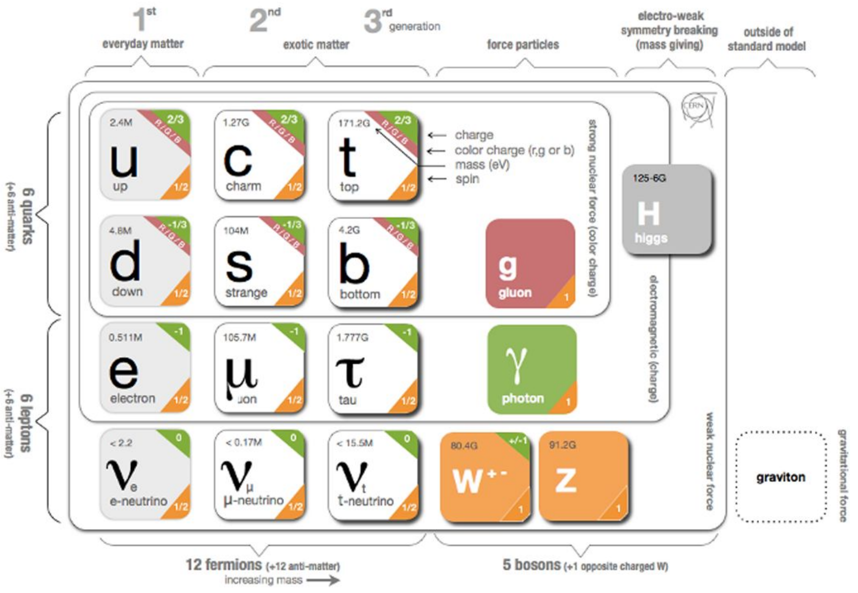
# The incomplete Standard Model

The Standard Model (SM) provides no explanation for:

- Gravitation
- Origin of the neutrino masses
- Dark Matter

2 hints in leptonic sector for potential extensions of the SM:

- Neutrino oscillations
- Anomalous magnetic dipole moment of the muon



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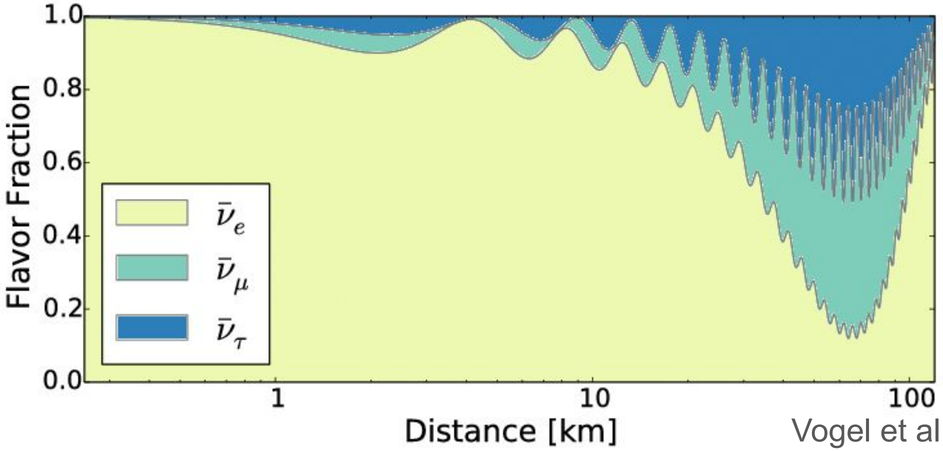


Vogel et al.

# The incomplete Standard Model

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- Gravitation
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$\alpha = (g - 2) / 2$

2 hints in leptonic sector for potential extensions of the SM:

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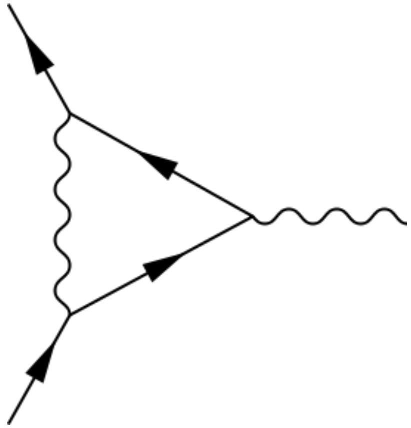


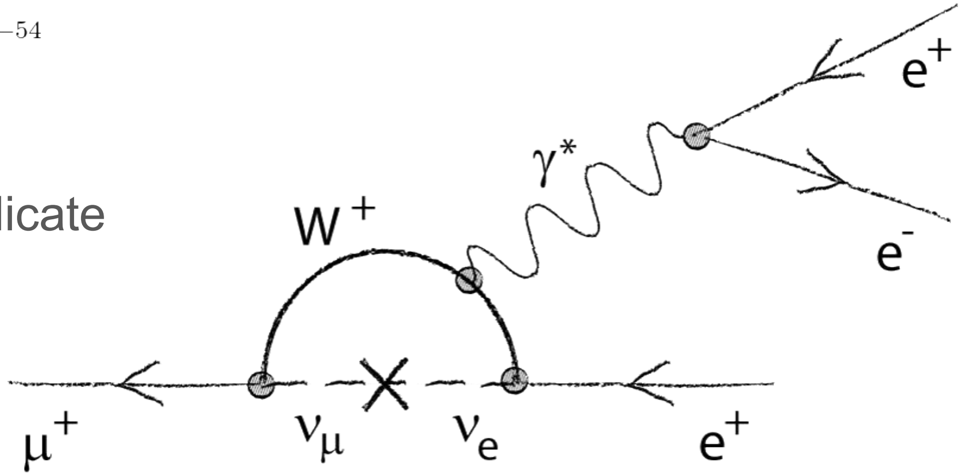
# The decay μ→eee

This decay is strongly suppressed in the SM:

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left(\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right)^2 < 10^{-54}$$

An observation of this decay would indicate physics beyond the SM

- Enters via additional couplings
- Would increase cross section significantly

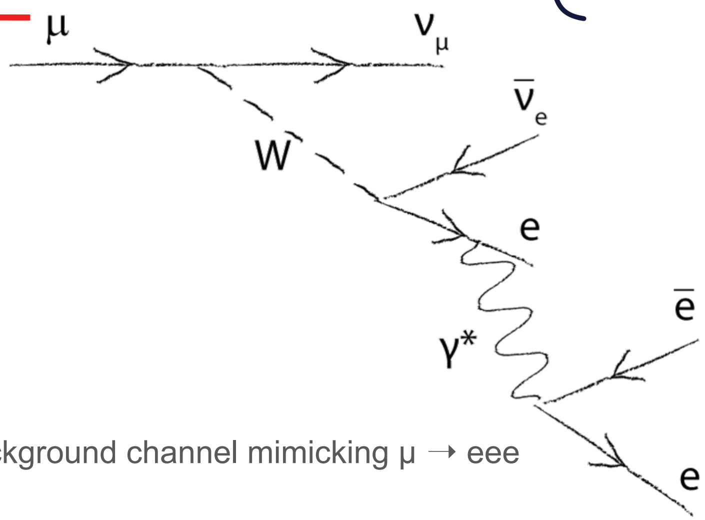


# Experimental challenges

Goal: improving limits set by SINDRUM (1988)

$$\mathcal{B}\left(\mu \rightarrow eee\right) < 1 \cdot 10^{-12}$$

➔ High muon rate required
➔ Fast detection and readout
➔ Excellent background suppression

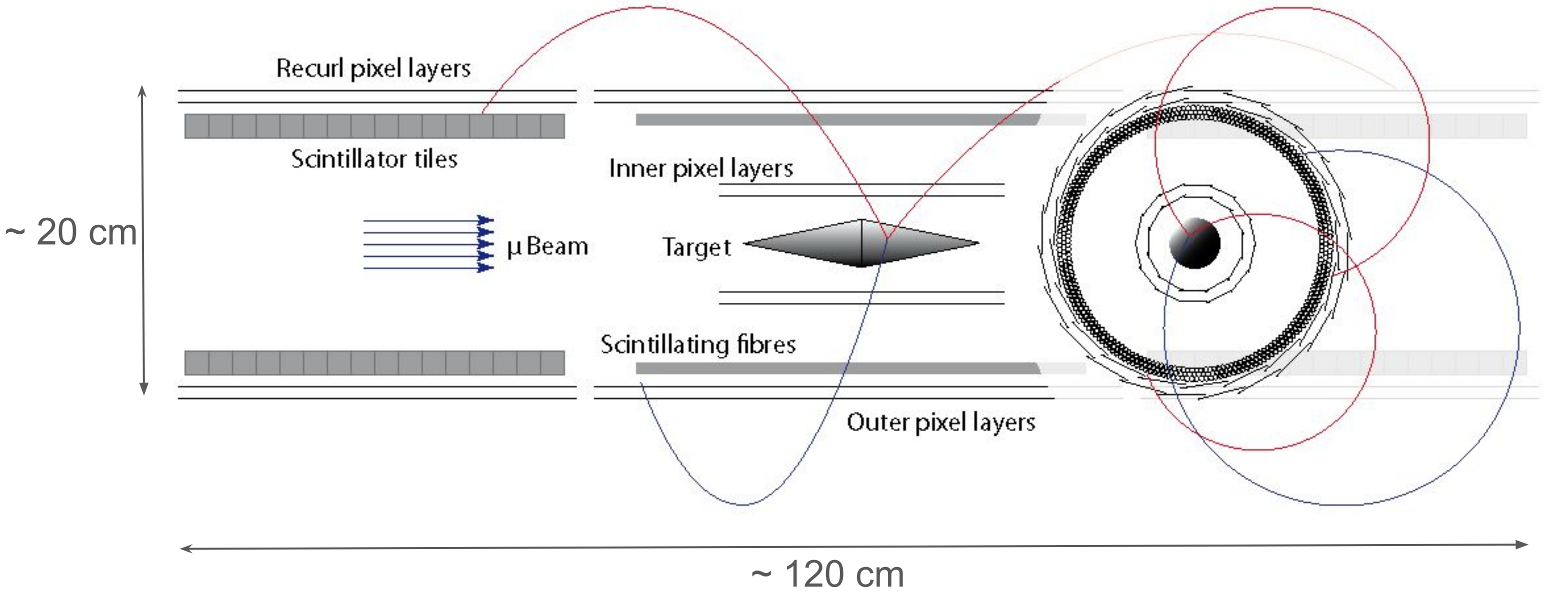



Background channel mimicking μ → eee

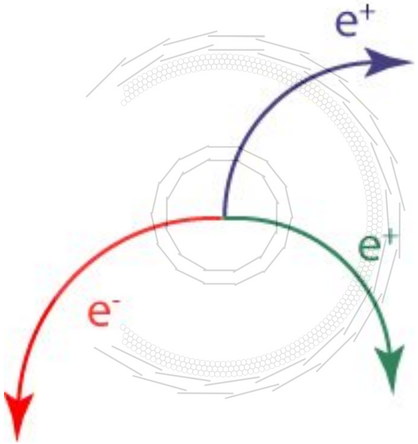
2 phases foreseen:

I. Using an existing beam line: $\mathcal{B}\left(\mu \rightarrow eee\right) \leq 10^{-15}$
II. Upgrading detectors + new beamline: $\mathcal{B}\left(\mu \rightarrow eee\right) \leq 10^{-16}$

# The Mu3e experiment

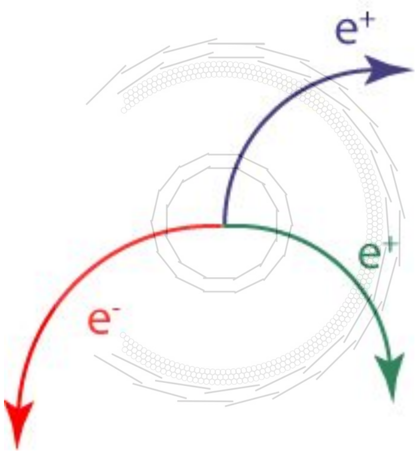


# Discriminating signal and background

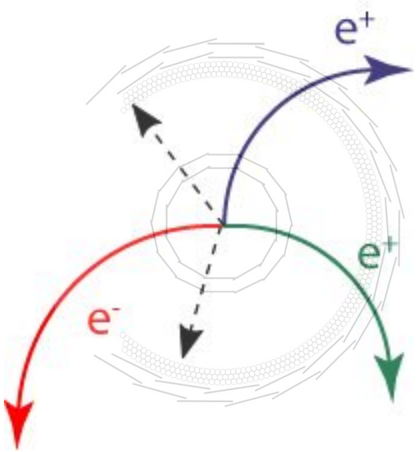



**Signal channel**

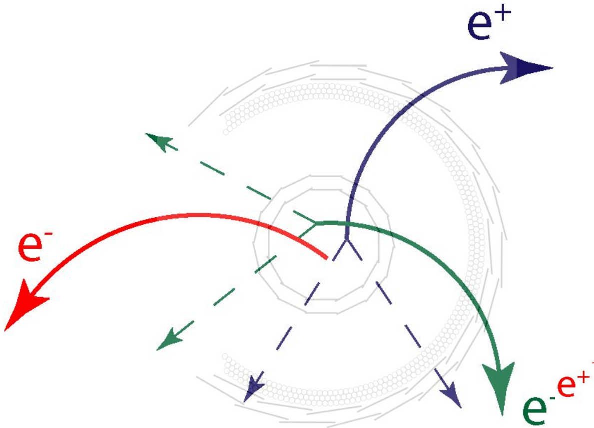
# Discriminating signal and background



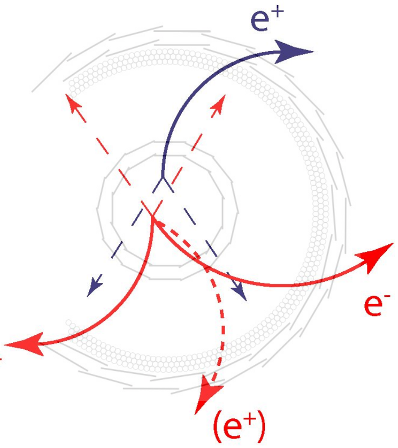

**Signal channel**




Missing momentum
carried away by neutrinos




Accidental background I
3 uncorrelated sources,
e.g. 2x $e^+$ from $\mu \rightarrow e\nu\nu$ &
1x $e^-$ from Bhabha scatt.




Accidental background II
$e^+ e^-$ pair from $\mu \rightarrow ee e\nu\nu$
&
1x $e^+$ from $\mu \rightarrow e\nu\nu$

# Discriminating signal and background

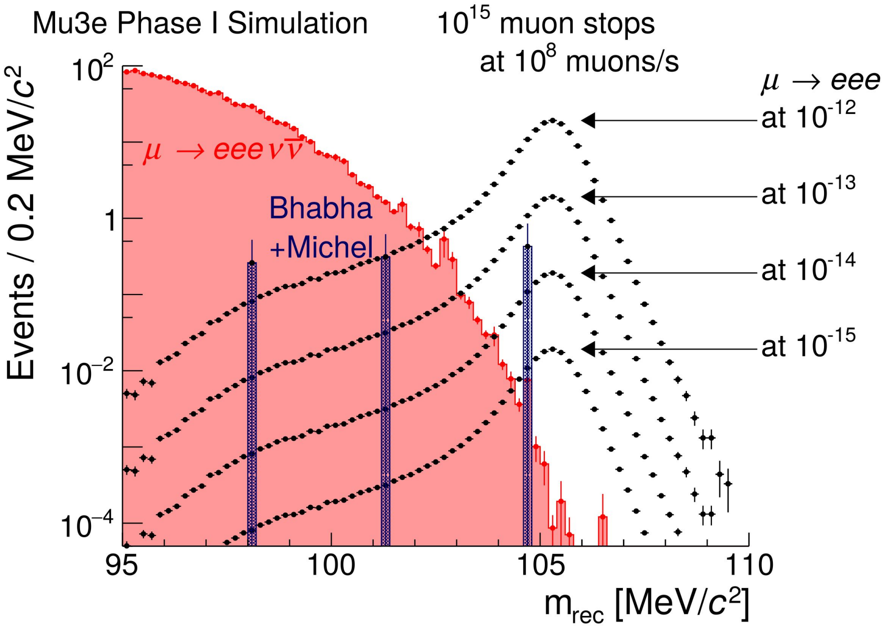
- Resolution of invariant mass
  - Suppression of the decay μ → eeevv
  - Resolution of < 1 MeV required
  - Dominated by multiple Coulomb scattering

➪ **less material**

- Suppression of accidental background

➪ **fast detectors**

➪ **less material**

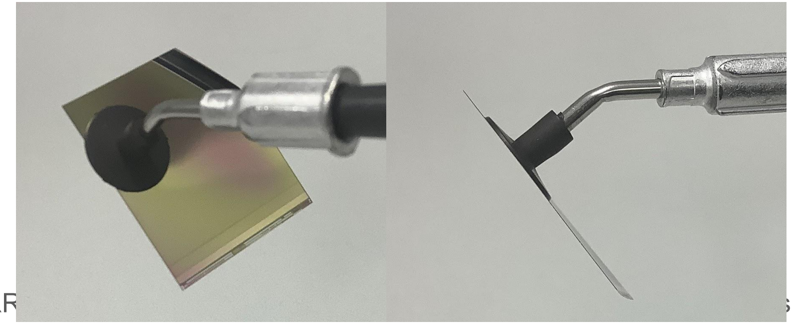



Preliminary sensitivity study from the to-be-published Mu3e TDR

# How to realize low material budget

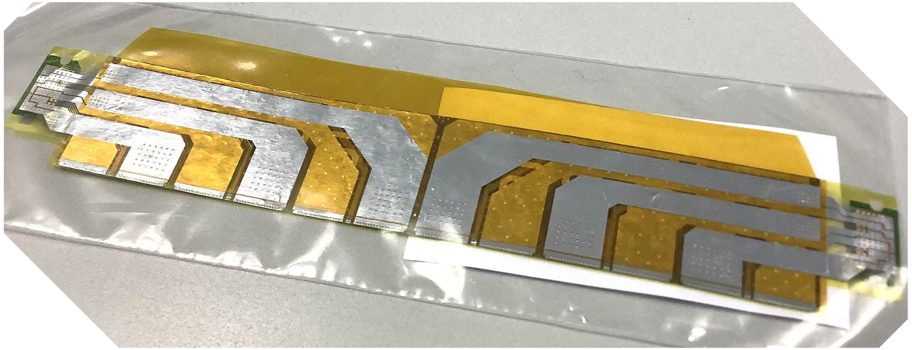
**Monolithic pixel sensors**

- HV-MAPS (high-voltage monolithic pixel sensors)
- 50 µm thin
- Efficiency > 99 %
- Time resolution < 20 ns

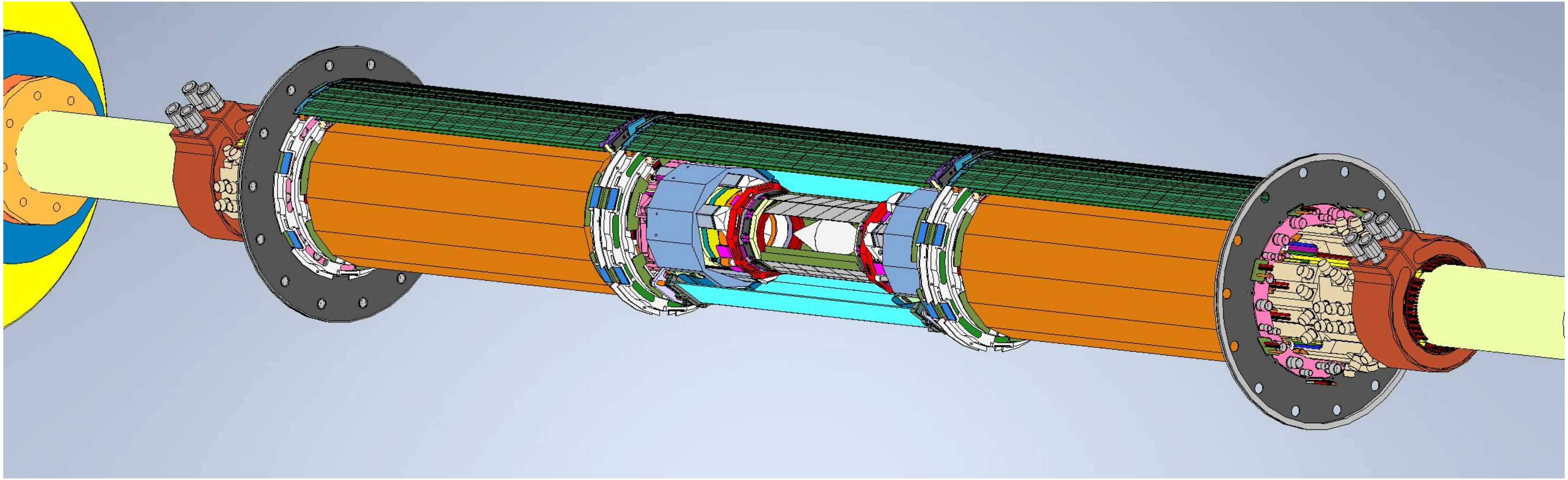


**Ultra-thin support structure**

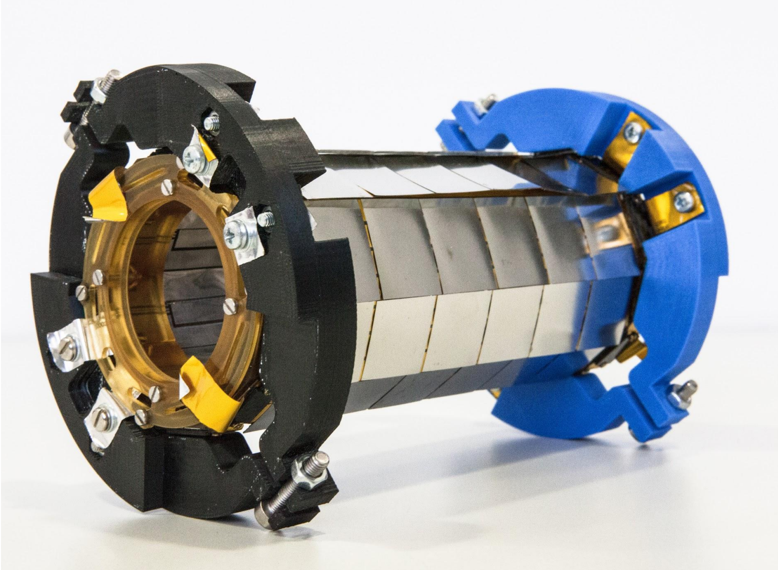
- High-density interconnects (HDI)
- 50-80 µm thin Kapton-aluminum flexprints
- Guide signals and power lines



# Nice CAD drawing



# The Mu3e inner tracking detector



Thermal-mechanical mockup

# The Mu3e inner tracking detector

| | | | |
|---|---|---|---|
| MuPix sensors | HDIs | Mechanical support | Helium cooling |

# The Mu3e inner tracking detector

MuPix sensors

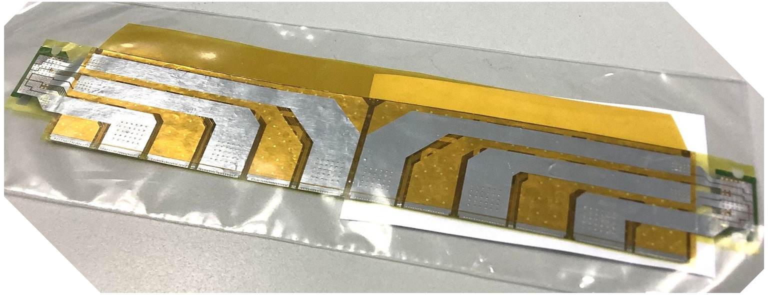
HDIs

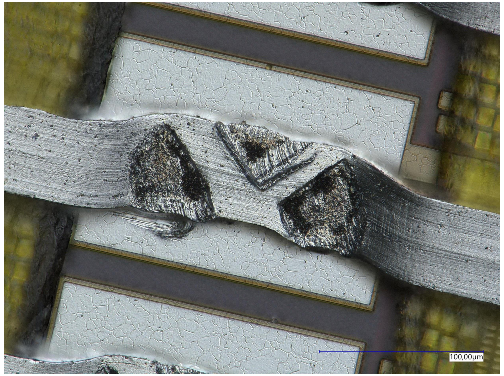
Mechanical support

Helium cooling

# HDIs

- ~80 µm thin flexprints
- Guide power, HV, and signals
- Sensors are glued on one side
- Electrical connection via spTAB bonding


High-density interconnect for Si heater chips


spTAB bond

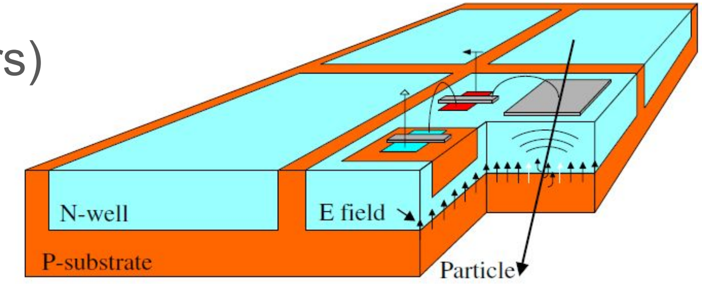
Layer stack of LTU hdi

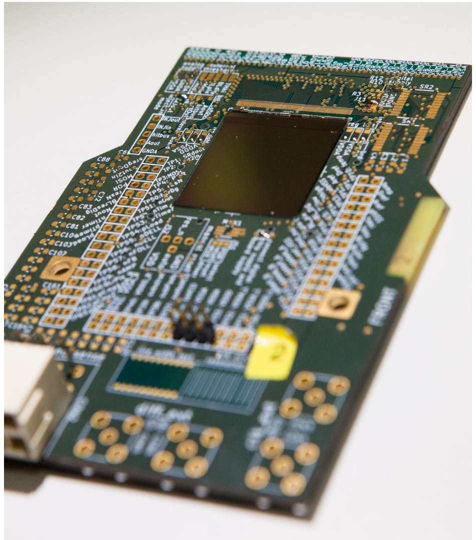
# The Mu3e inner tracking detector

| MuPix sensors | HDIs | Mechanical support | Helium cooling |
| --- | --- | --- | --- |

# MuPix10/11 sensor

- HV-MAPS (high-voltage monolithic pixel sensors)
- 256x250 pixels (~2x2 cm²)
- 80x80 µm² pixel size
- Minimalist approach of needed connections:
  - 1 HV line
  - 1 power input
  - 1 reference clock
  - 1 slow control
  - 1 to 3 data outputs
- Design and characterization by HighRR fellows: Alena Weber, David Immig, Heiko Augustin



# The Mu3e inner tracking detector

MuPix sensors

HDIs

Mechanical support

Helium cooling

**POWERING &**
**SIGNAL TRANSMISSION**

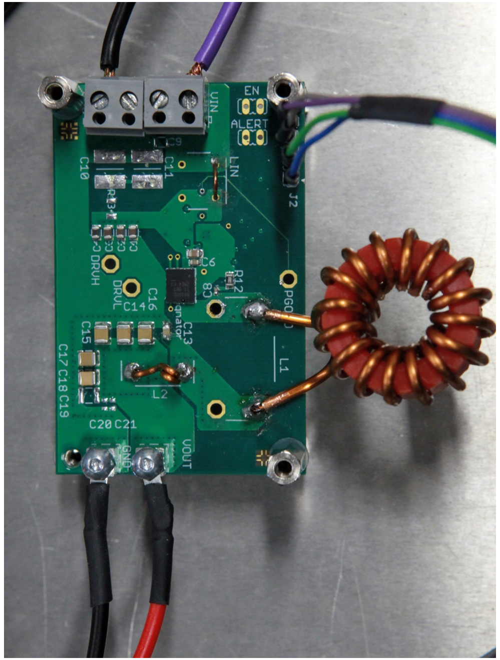
# Powering concept

**Situation:**

- Power supplied by custom DC-DC converters (Uni Mainz)
  ⇨ Intrinsic ripple on power input (10-20 mV, 1 MHz)
- No space for filter components
- Distance to sensor: 50-100 cm
- 12/15 sensors powered by 1 DC-DC converter

**Questions**:

- Sensors working despite ripple?
- Sensors disturbing each other?




DC-DC board prototype

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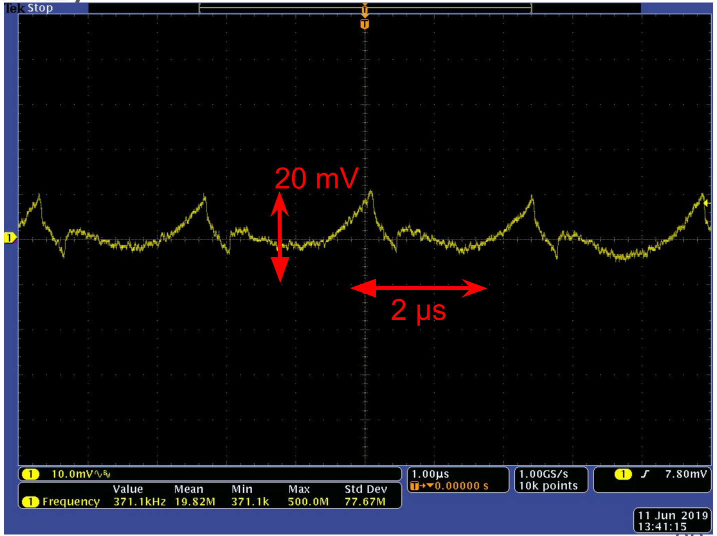



Output ripple of DC-DC prototype

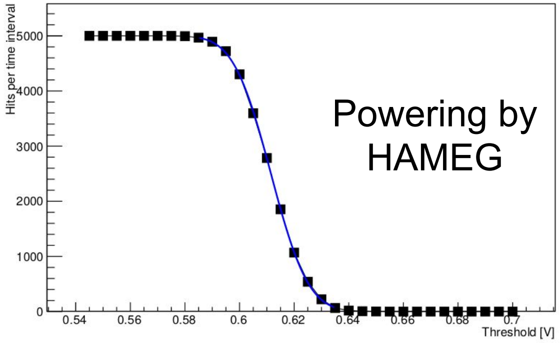
# Powering studies

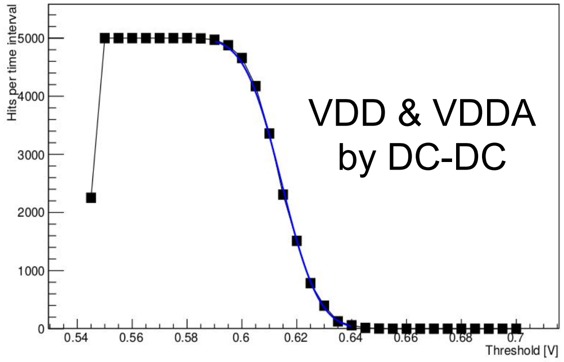
- MuPix test boards optimized for development
  - A lot of filtering on the boards
  - HAMEG power supply
  - Supply voltages are 1.8/1.0 V
  - MuPix prototypes have 3 individual supply voltages
    ⇨ Only 1 channel for final sensor
- Remove all filter components
- Supply all power via 1 DC-DC converter only
- Test
  - sensor operationable?
  - Noise and efficiency behaviour

# Powering studies

Laboratory measurements

- Sensor working without filter components on board
    - Noise stable
    - Eye diagrams of data output fine
    - Running at low thresholds

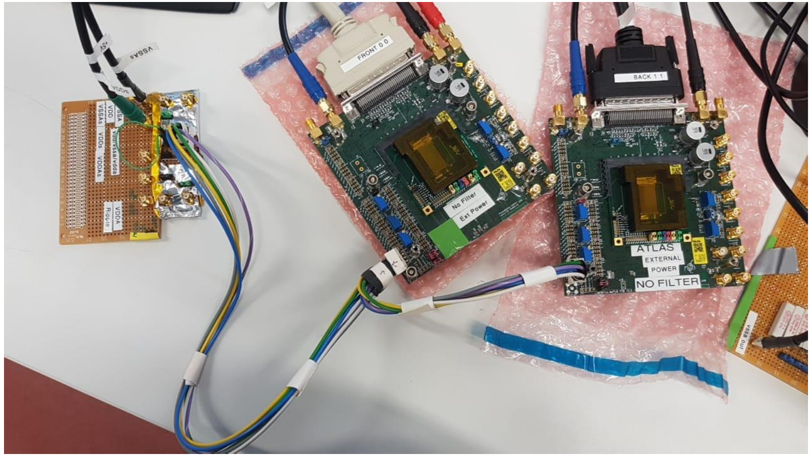


# Powering studies

## Laboratory measurements

- Sensor working without filter components on board
  - Noise stable
  - Eye diagrams of data output fine
  - Running at low thresholds
- Two sensors powered in parallel also working fine
- Ready to test efficiency and noise in testbeam at DESY




Two MuPix8 sensors powered in parallel by 1 DC-DC converter

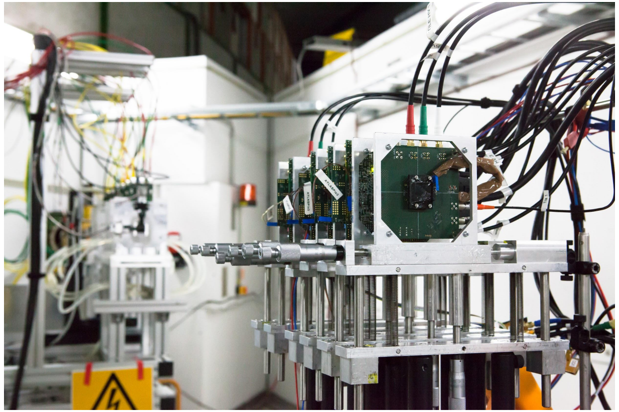
# Powering studies

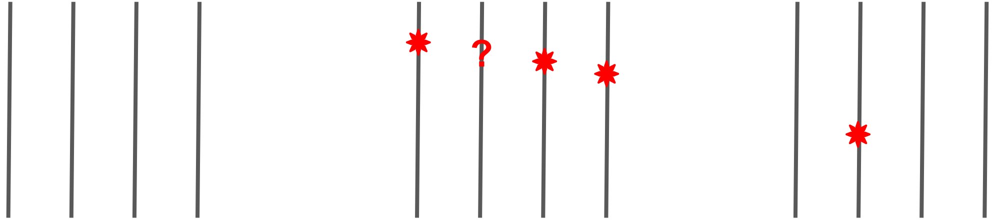
Testbeam campaign in December 2019

# Powering studies

## Testbeam campaign in December 2019

**Testbeam intermezzo:**






4 sensor layers
+
2 timing layers

hits in reference layers; device under test (DUT) as well?

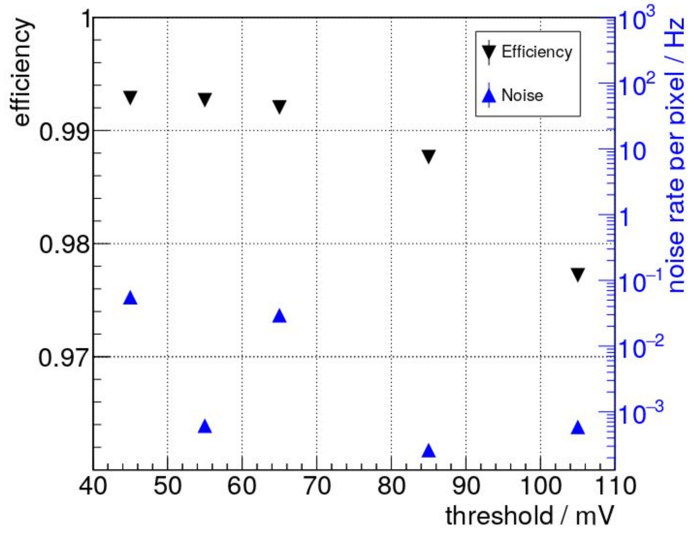
➪ **efficiency**

hit only in DUT

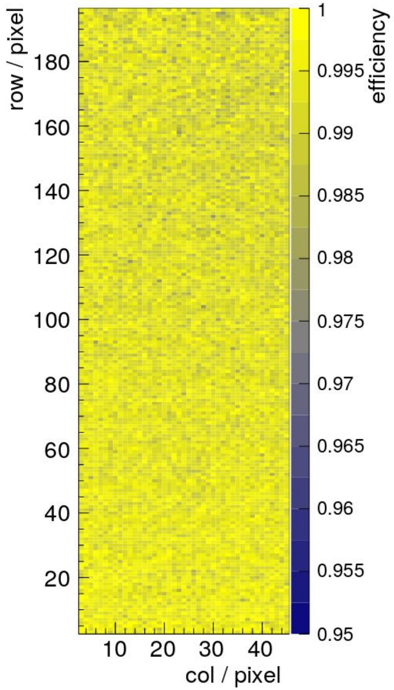
➪ **noise**

# Powering studies

Testbeam campaign in December 2019




Threshold scan for DC-DC powered MuPix8 sensor

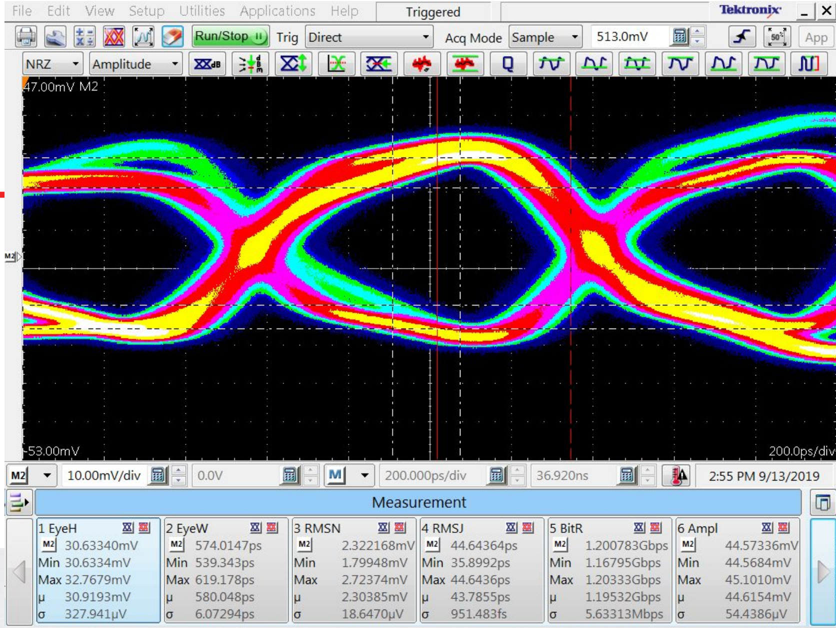


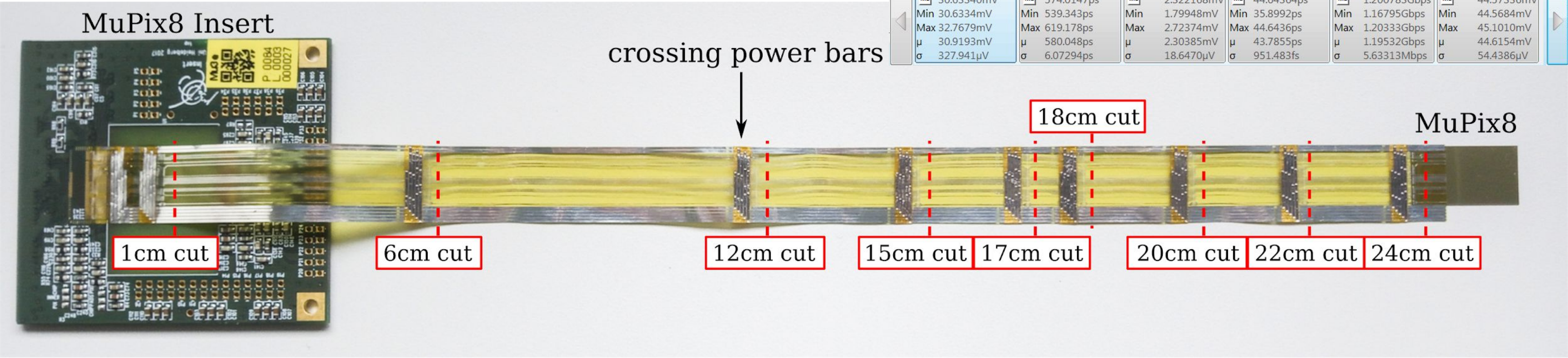

Efficiency map at 45 mV threshold

# Data transmission

Studies last winter by Lars Noehte (arXiv:2003.11077)

Data output could be retrieved after a 24 cm long HDI (max. for outer tracking layers)



# Powering & data transmission summary

**Studied:**

- MuPix8 can be operated being powered by the DC-DC converter
- MuPix8 can be operated on HDI
- Two sensor do not disturb each other

**To be studied:**

- Power sensor on HDI by DC-DC converter
- Operate multiple sensors on HDI (autumn 2020)
- Operate final sensor (has to be submitted)
- Frequency behaviour of final supply chain

# The Mu3e inner tracking detector

| MuPix sensors | HDIs | Mechanical support | Helium cooling |
|---|---|---|---|

# Gaseous helium cooling

**Reason for choice:**

- Low material budget
- High thermal conductivity (i.e. 5x higher than air)

**Requirement:**

- Max. temperature 70°C
  ➪ glass transition of glue

# Gaseous helium cooling

**Realization:**

- 2 g/s helium flow for inner tracker
  ➪ velocity = 10 m/s
- Allows for heat dissipation of 400 $mW/cm^2$
  ➪ ~2 Watt per sensor ➪ >200 Watt only for inner tracker
- Periphery of sensor dissipates more heat than active pixel matrix

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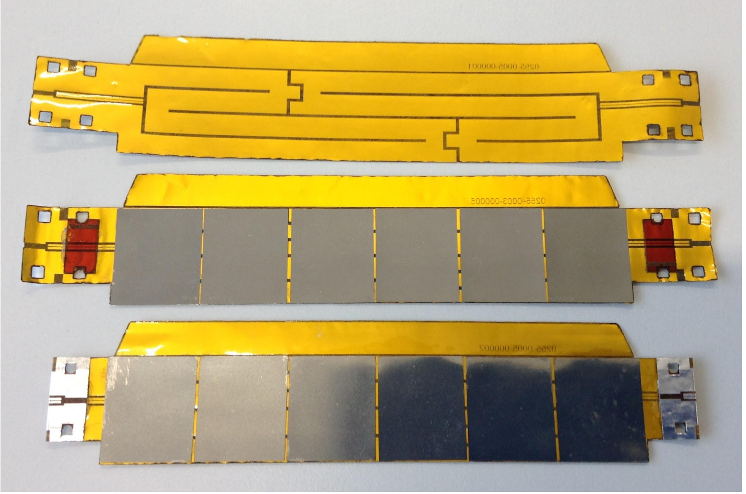
- Periphery of sensor dissipates more heat than active pixel matrix

For the **outer tracking** layers
Max. 6 kW heat dissipation

# Tapeheater program

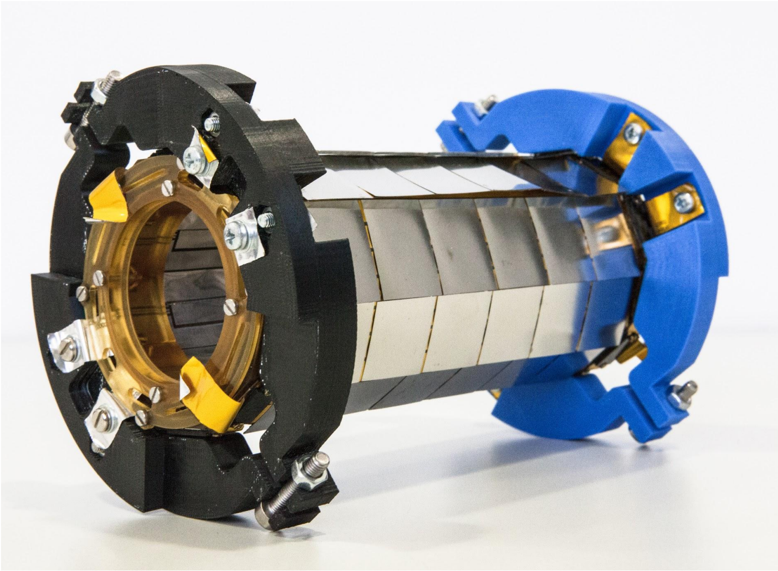
- Construction of inner tracker mockup to study cooling concept
- Aluminized polyimide tapes equipped with 50 μm thin steel plates
- Heating loop engraved with laser cutter



# Tapeheater program

- Construction of inner tracker mockup
- Aluminized polyimide tapes equipped with 50 µm thin steel plates
- Heating loop engraved with laser cutter

- Mockup constructed and tested in Heidelberg
- Cooling studies performed at FHNW in Brugg (Switzerland) by Marin Deflorin

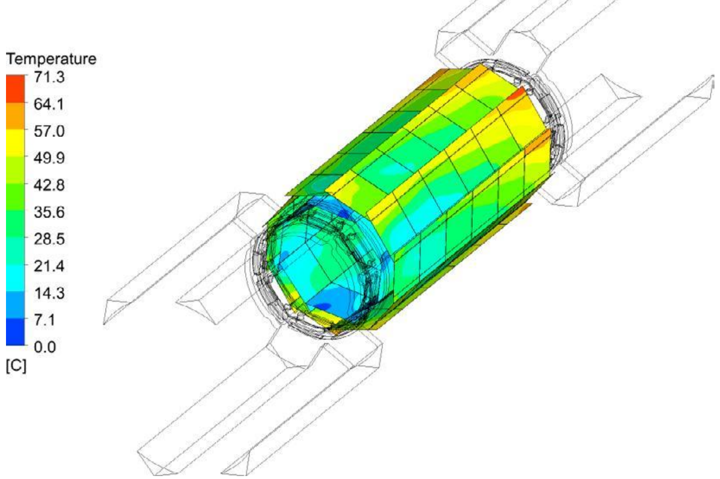


# Tapeheater program

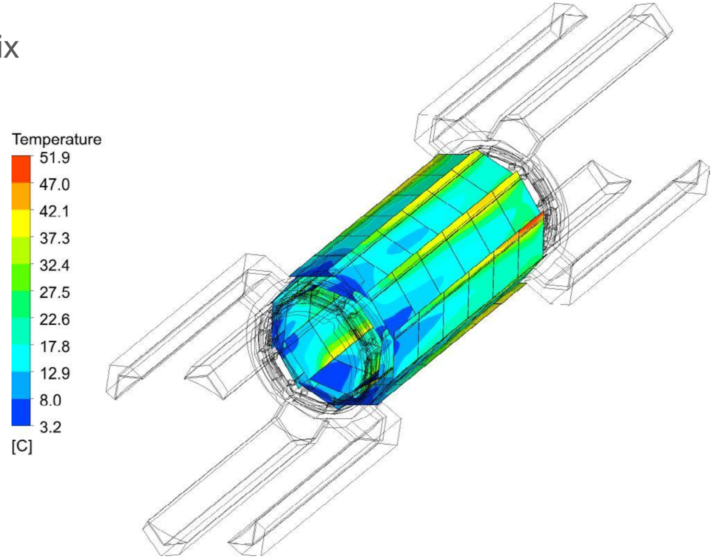
Simulations were carried out for baseline geometry

Heat dissipation = 400 mW/cm²

Heat dissipation in periphery ~10x higher than in pixel matrix




Helium flow only between layer 1 & 2




Additional helium flow around layer 2 using a mylar tube

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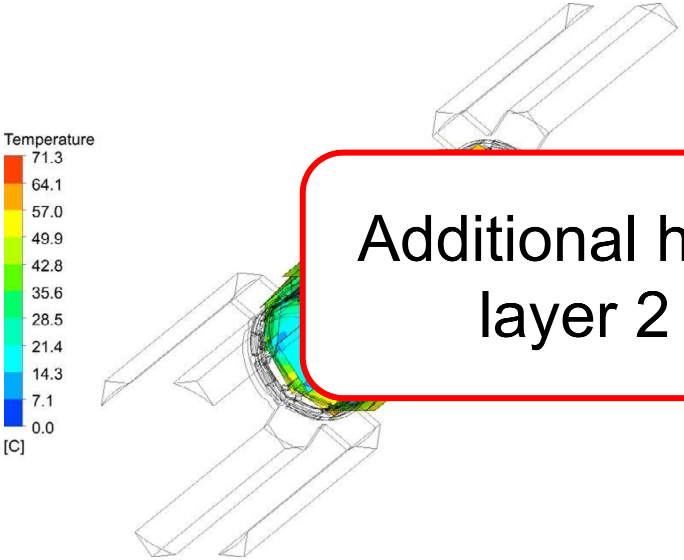
Simulations were carried out for baseline geometry

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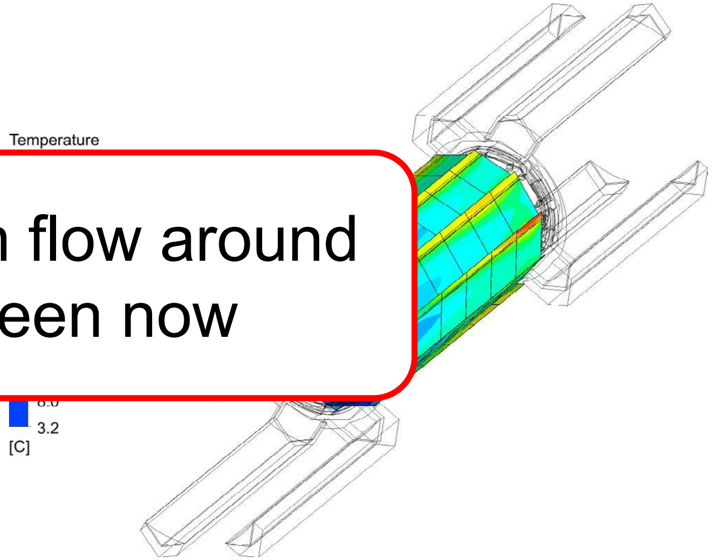


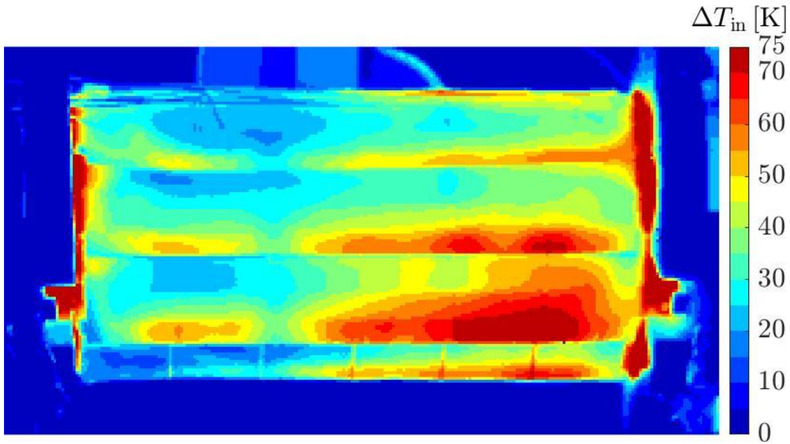

Additional helium flow around layer 2 using a mylar tube

**Additional helium flow around layer 2 foreseen now**

# Tapeheater program

Simulations were verified with the thermal-mechanical mockup

- Temperatures in simulation and measurement do agree
- Underlines necessity of additional helium flow



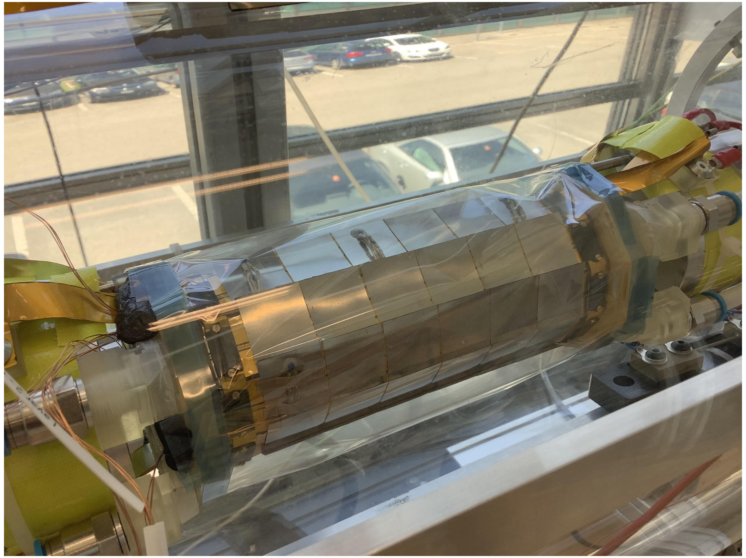

Mockup heated with 390 mW/cm², cooled with helium.
Measurement with thermal camera

# Current status of helium cooling

- Last month, durable cooling with circulating helium was realized in Brugg
  - Stable operation
  - Maximum temperature difference of inlet to sensors around 50 K
- Test of another mockup (silicon heater) foreseen in September/October

*…more on this later…*

- Transfer of helium cooling system to PSI after this study



# The Mu3e inner tracking detector

MuPix sensors

HDIs

Mechanical support

Helium cooling

**RADIATION TOLERANCE**

# Irradiation studies

**Motivation**:

Polyimide is deemed to be a radiation-hard material

*But*...

Observations of brittle polyimide in particle physics experiments and aerospace application

➔ Either in inert atmosphere (e.g. helium) or vacuum + ionizing radiation

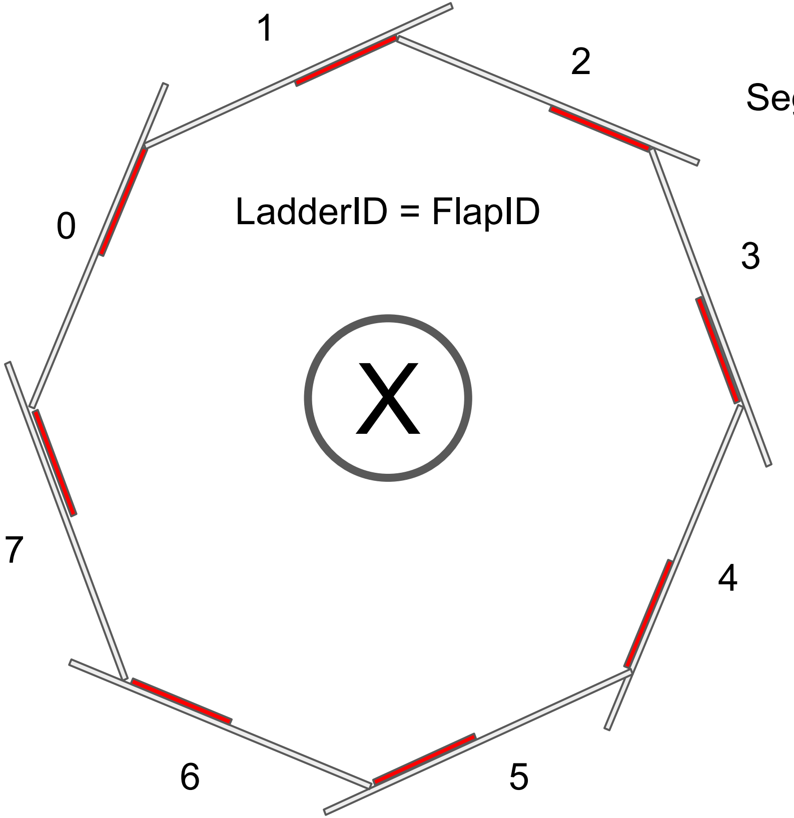
**Mu3e:**

➔ Polyimide serves as support structure of tracking detector
➔ Inert atmosphere (helium) surrounding the material
➔ Irradiation by low-energetic electrons (few MeV)

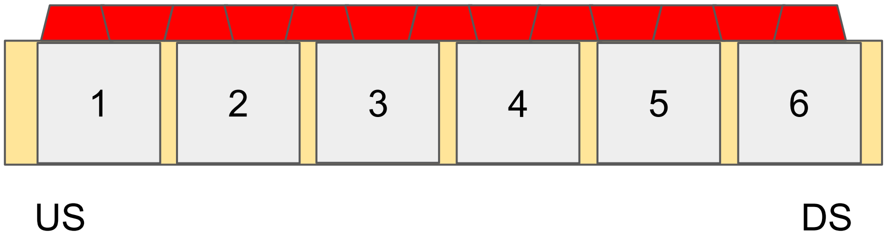
# Estimated dose in polyimide

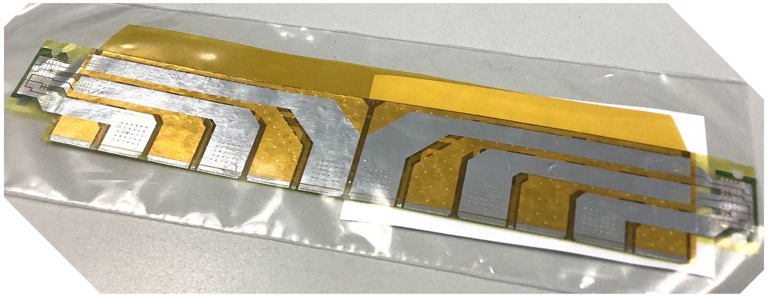
- Simulate absorbed dose in innermost tracking layer
  - Using Geant4
  - Updated the tracker and beampipe geometry of the mu3e simulation
- Dose normalized to $10^{15}$ stopped muons on target (full phase I)
- Expected beam profile from simulations

# Dose map terminology

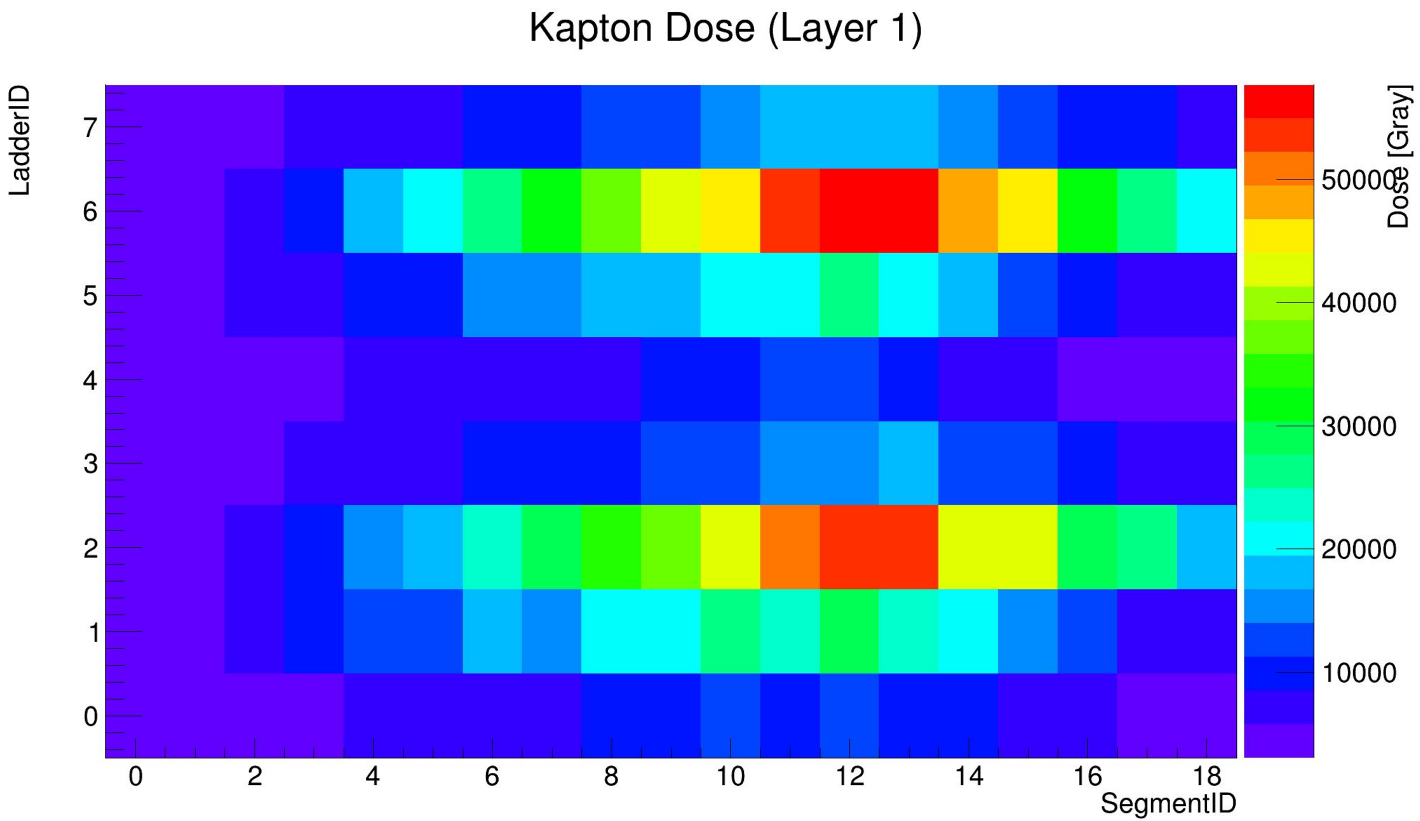



SegmentID = 0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18

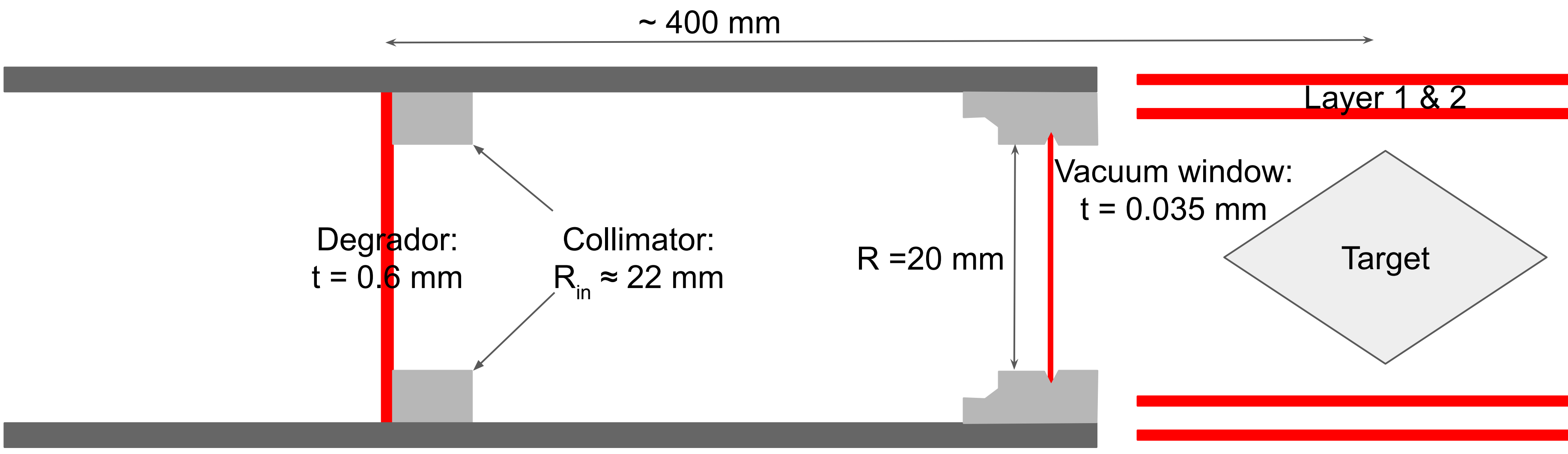


# Dose map for Layer 1



# Beam pipe & target



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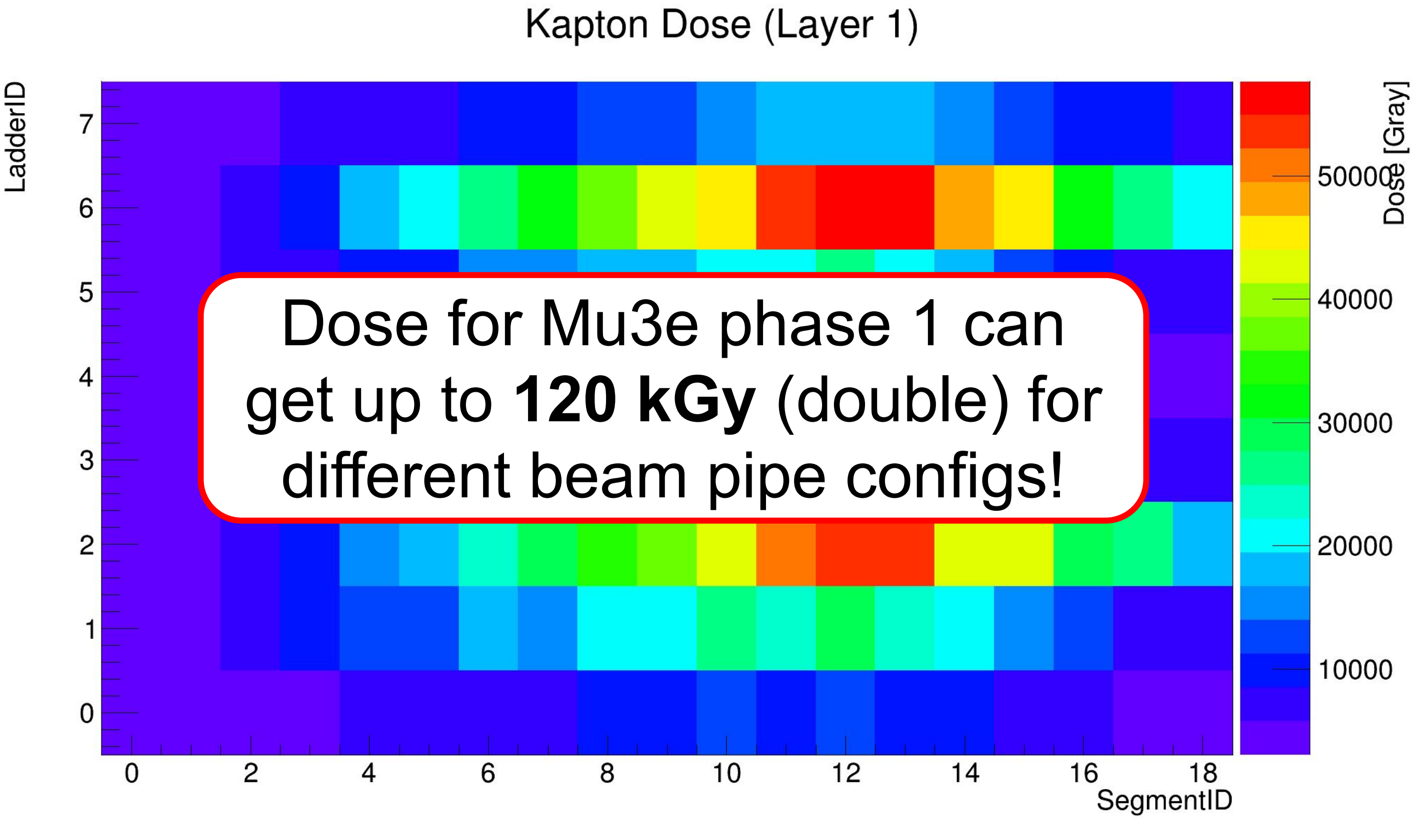
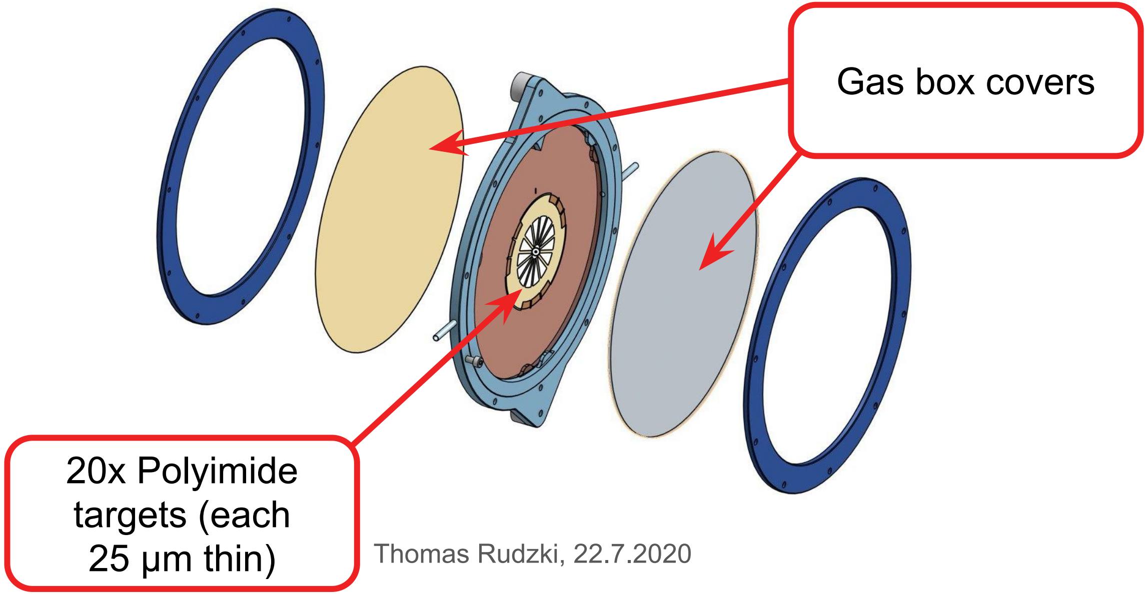



Dose for Mu3e phase 1 can get up to **120 kGy** (double) for different beam pipe configs!

# Setup

- Parasitic testbeam during aging studies of SiPMs for Mu3e
- Box with 20x polyimide targets flushed with helium
- Polyimide only material inside box to minimize remnants



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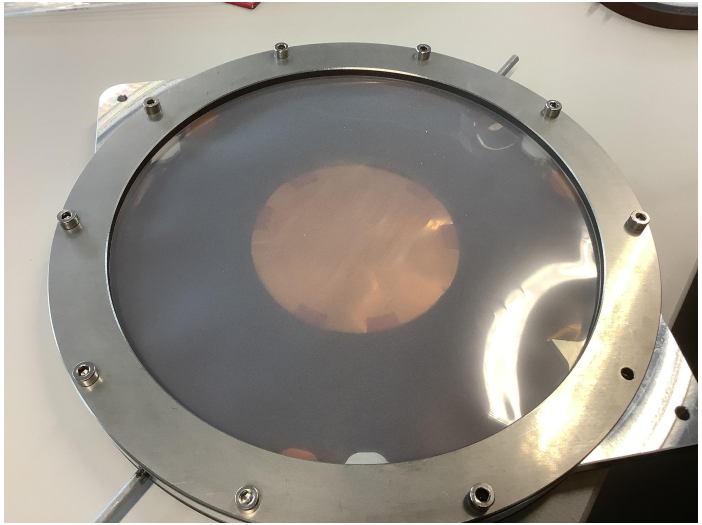
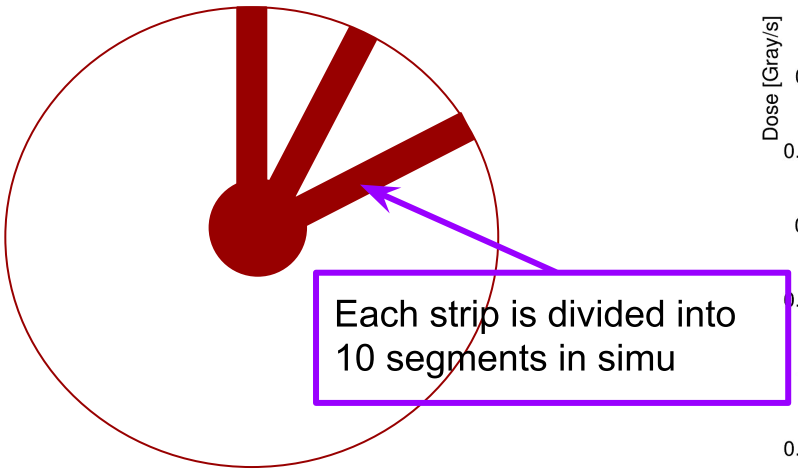
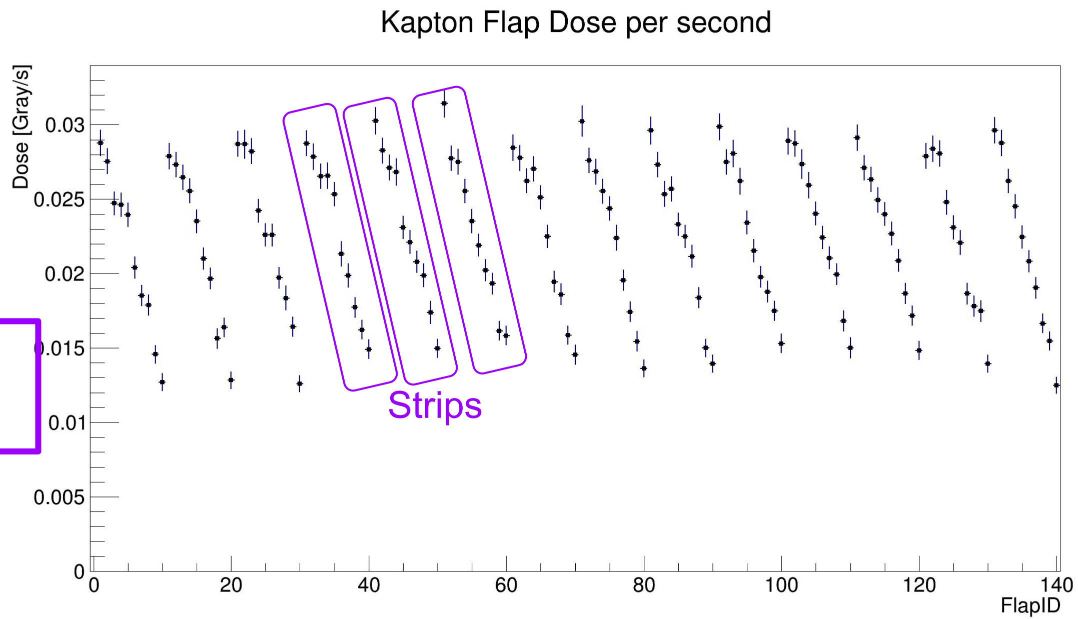


# Expected dose for 3 weeks of beamtime

14 strips (2 x 20 mm²) of 25 μm thick Kapton



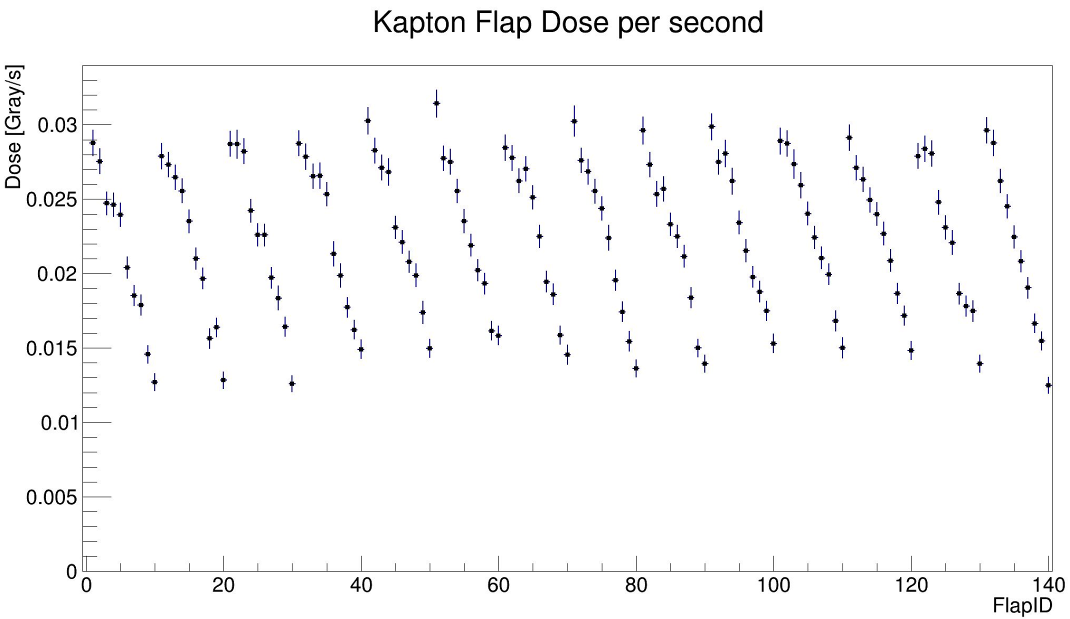
# Expected dose for 3 weeks of beamtime

Geant4 simulations to estimate dose rate:

Last layer of polyimide gets up to ~0.025 Gy/s

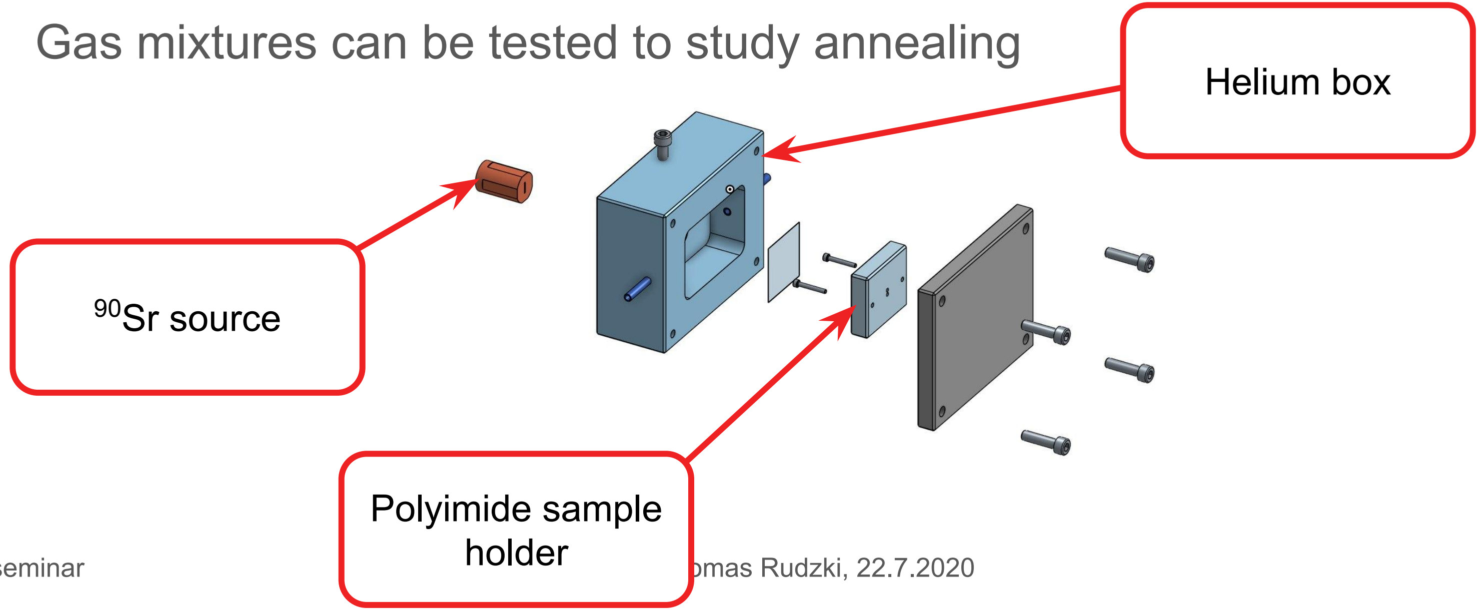
3 weeks
⇨ 45 kGy maximally achievable

Up to 60 kGy expected for Mu3e phase I



# Outlook on irradiation study

- Ongoing irradiation campaign as calibration for Mu3e-like irradiation
- Higher doses achieved by strong beta source at PSI
- No strict time limitations
- Gas mixtures can be tested to study annealing



# From preparation to construction

# Main challenges

- Placement precision (chip-to-chip distance)
  - 80 µm for Si heater / 40 µm for MuPix sensors (optimised for smallest possible gap)
  - 5 µm precision required
- Glue thickness
  - As little material budget as possible
  - Goal: 5 µm glue thickness
- All bonds working
  - SpTAB bonding has to work for each connection
- Glue ladders together to barrel
- Establish all connections to the outside world

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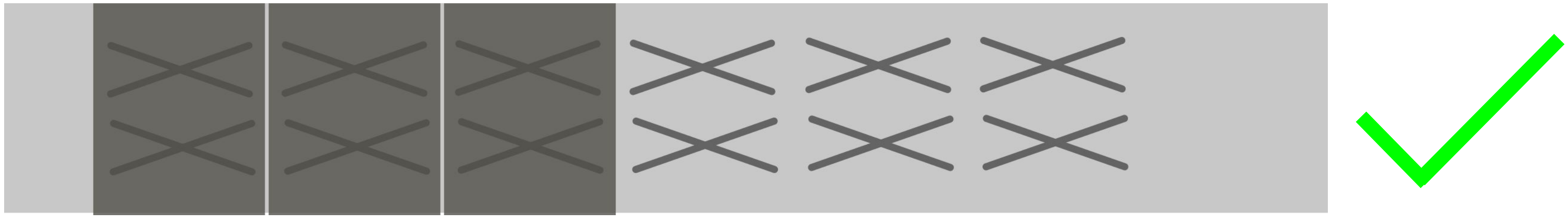
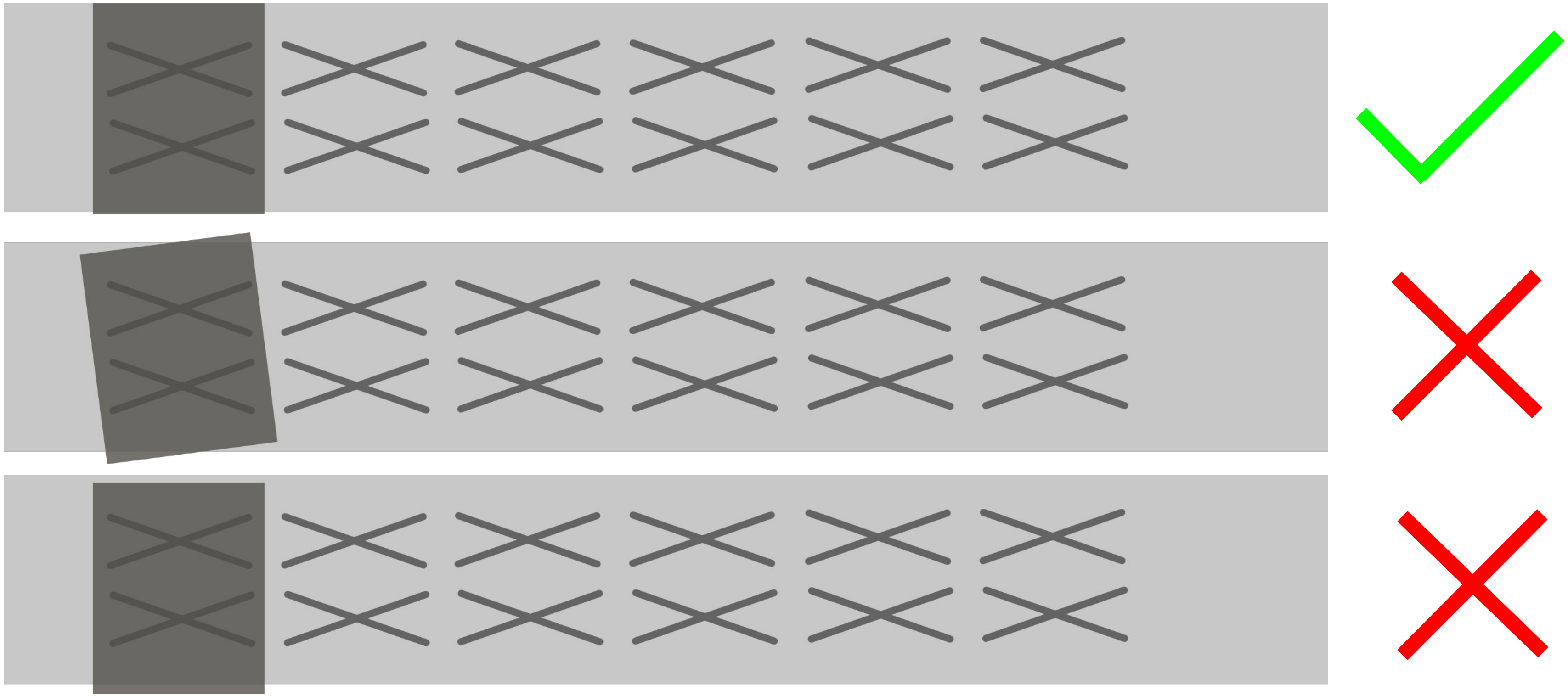
# Sensor placement



- Chip confinement while placing on chuck necessary
- Gap between chips: 80 ± 5 µm (Si heater)
  40 ± 5 µm (MuPix)

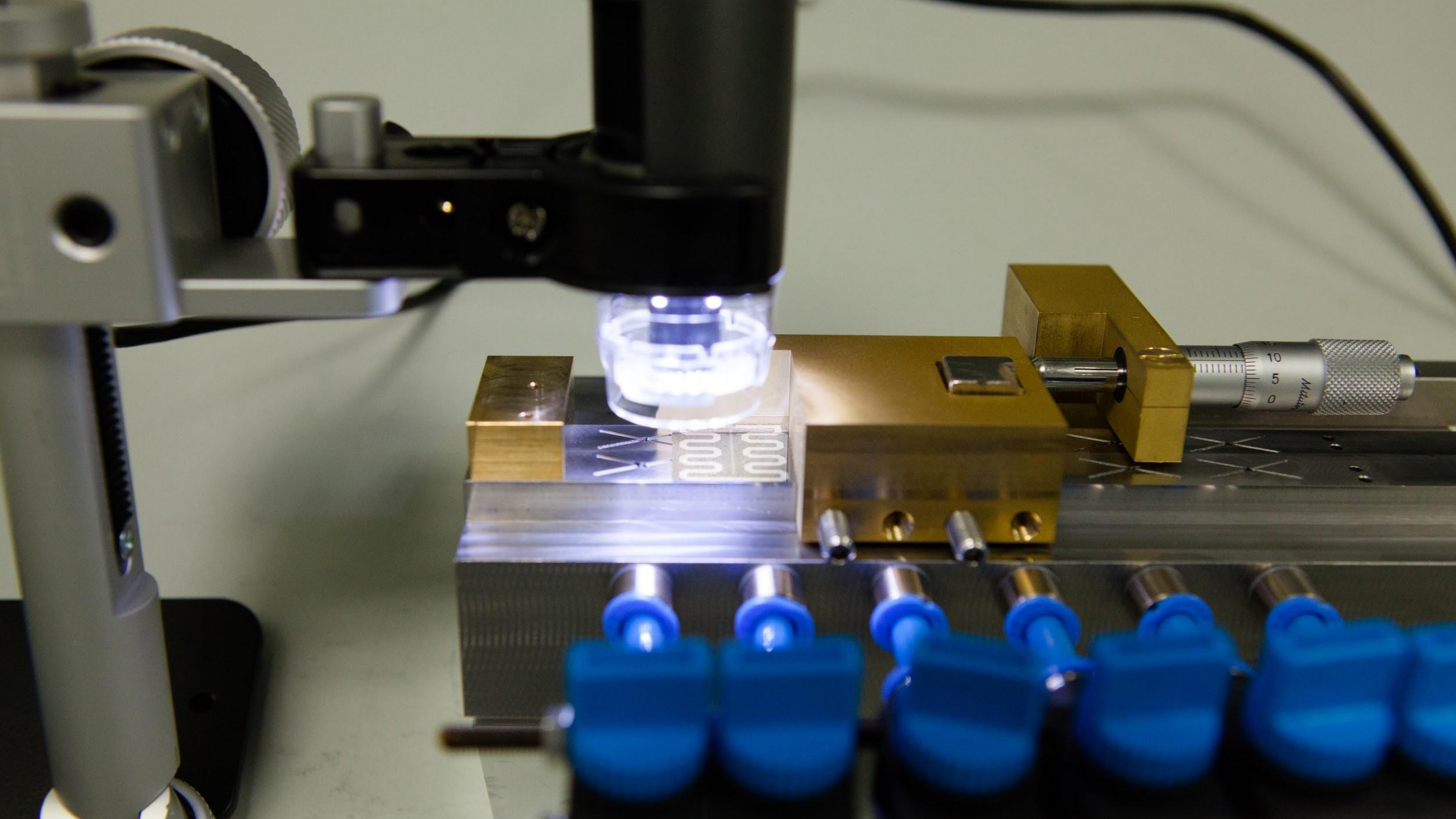
# Sensor placement



# Some time for my YouTube career

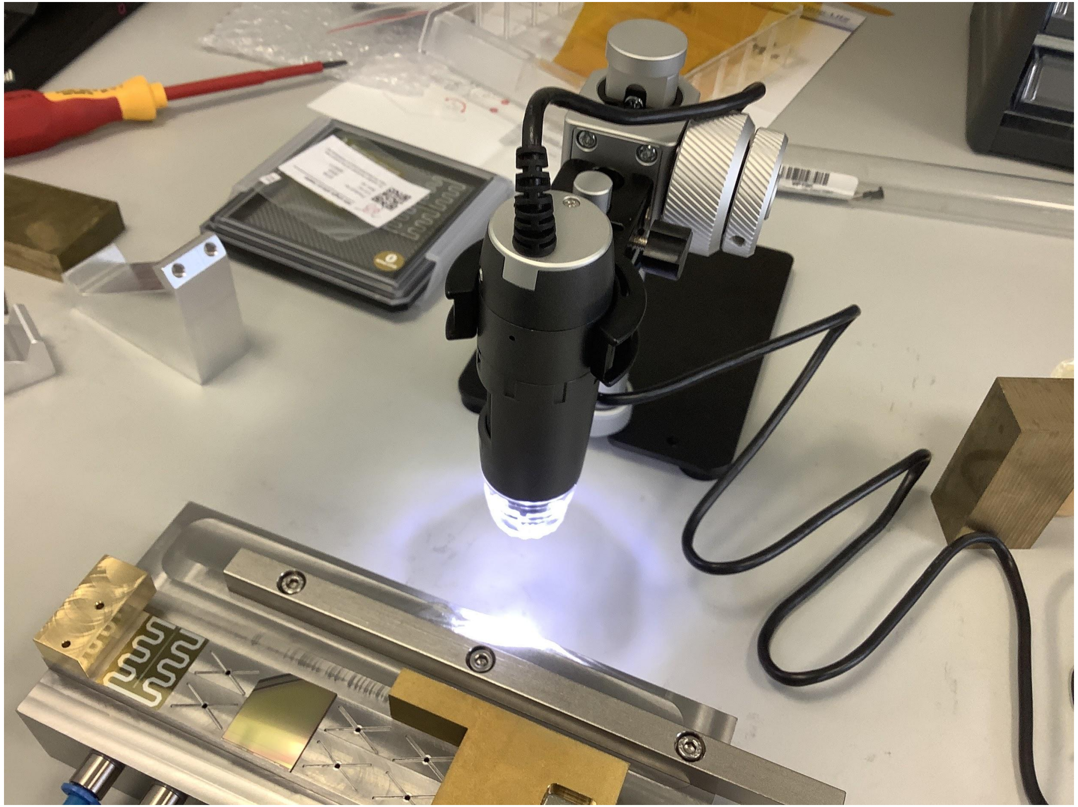
https://www.youtube.com/watch?v=0SYqHSbH3U4&
feature=emb_logo

# Precision?

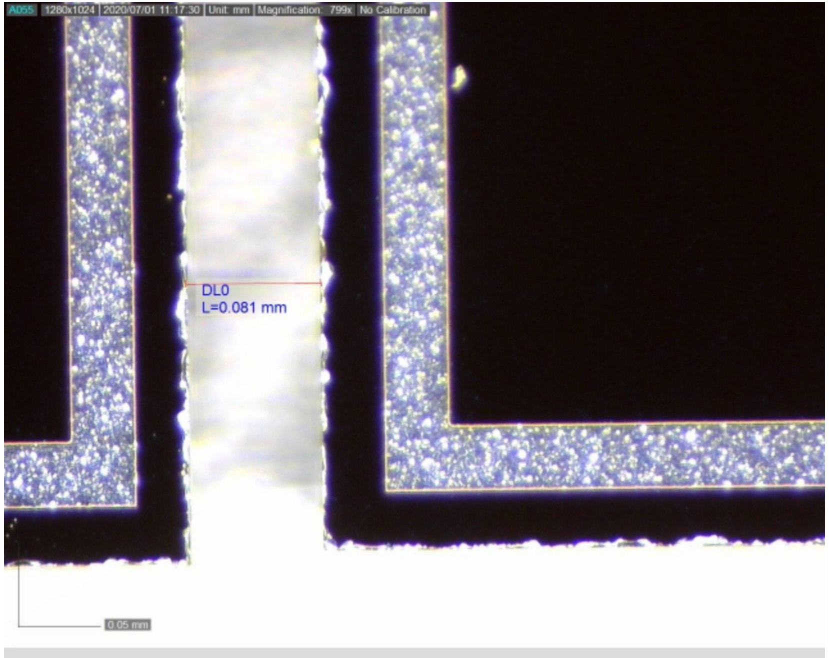

10
5
0

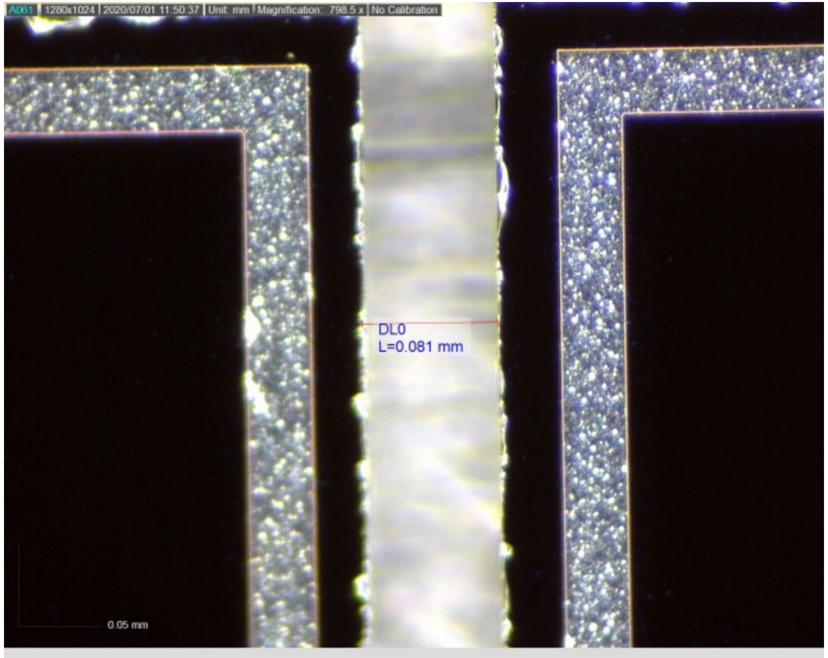
# Measuring the gap size

- Digital microscope
- Resolution: 1.5 µm
- Costs ~ 700-800 €
- USB interface



# Measuring the gap size



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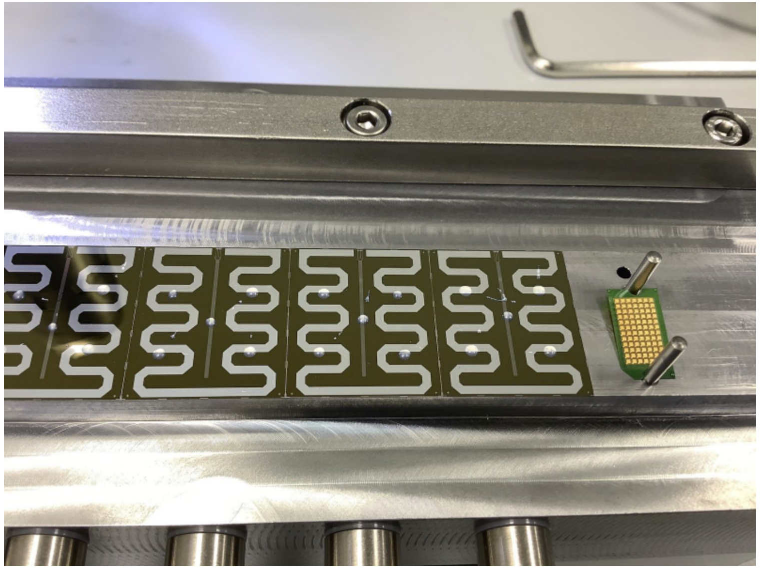
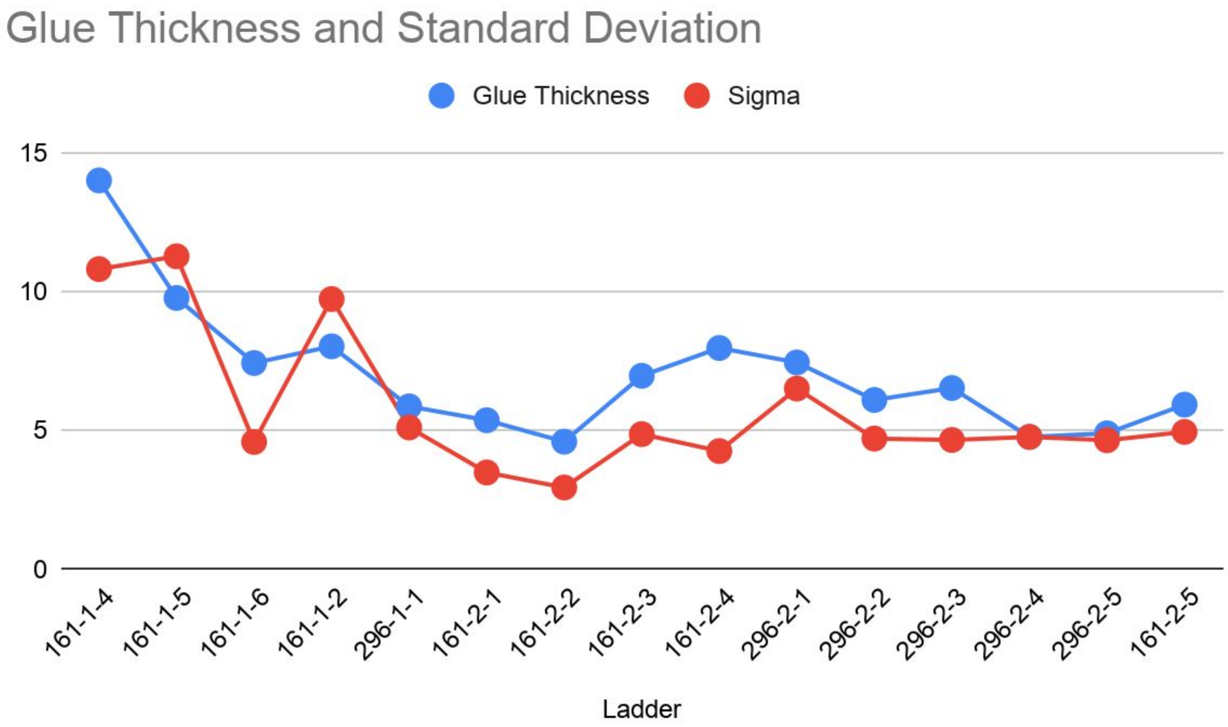


# The Hammer & The Dance



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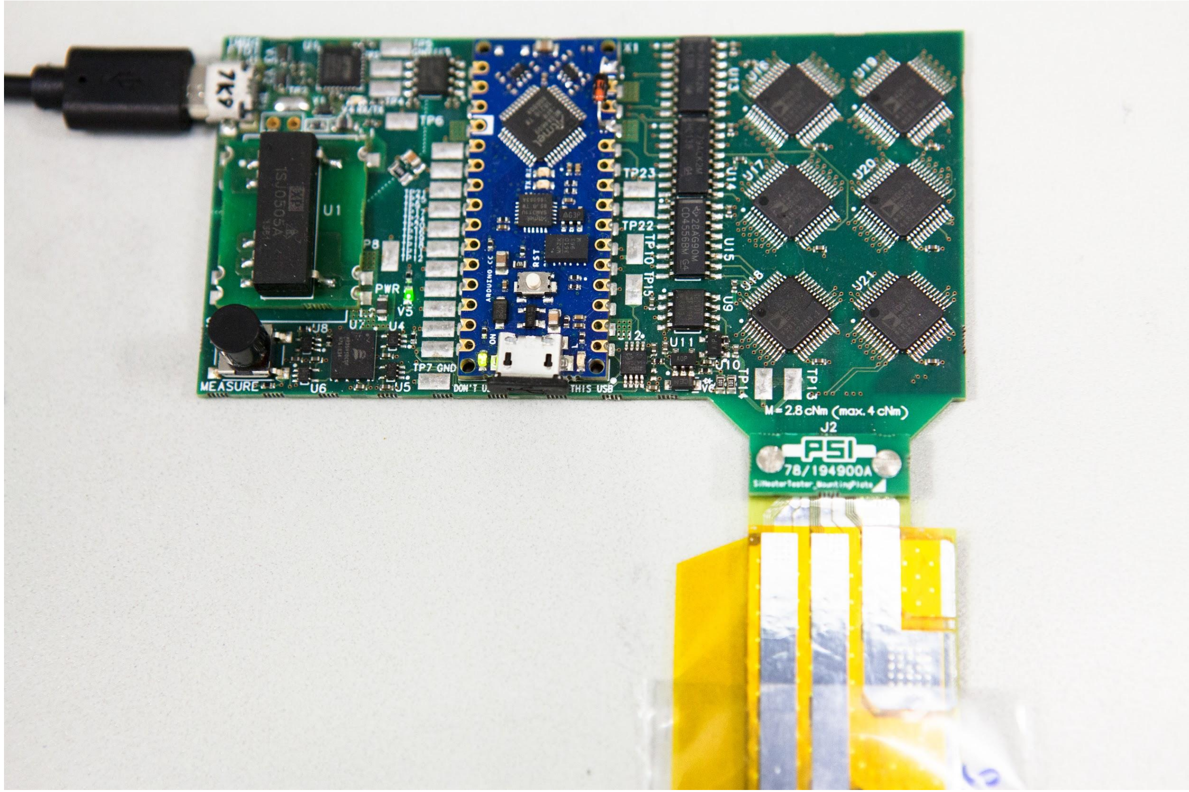
# Si heater tester



| ladder | General remarks | thickness | distances | bad bonds |
|---|---|---|---|---|
| 161-1-3 | Some Si broke off at 1 sensor (maybe usable) | No Q&A | ~ 100 µm | 2x Power #1 |
| 161-1-4 | Good to use | µ = 14 µm | ~ 100 µm | Temp. #1 |
| 161-1-5 | Two broken sensors | µ = 10 µm | ~ 80 µm | Not tested |
| 161-1-6 | Good to use | µ = 7 µm | ~ 80 µm | - |
| 161-1-2 | Good to use | µ = 8 µm | ~ 80 µm | - |
| 161-2-1 | Good to use | µ = 5 µm | ~ 80 µm | - |
| 161-2-2 | Good to use | µ = 5 µm | ~ 80 µm | - |
| 161-2-3 | Good to use | µ = 7 µm | ~ 80 µm | - |
| 161-2-4 | #1 broken (might be usable) | µ = 8 µm | ~ 80 µm | - |
| 161-2-5 | Good to use | µ = 6 µm | ~ 80 µm | Temp. #4 (#37) |
| 161-2-6 | | | | |
| 161-2-7 | | | | |
| 161-2-8 | | | | |
| 161-2-9 | | | | |
| 161-2-10 | | | | |
| 161-2-11 | | | | |
| 296-1-1 | Good to use | µ = 6 µm | ~ 80 µm | - |
| 296-2-1 | Two broken sensors | µ = 7 µm | ~ 80 µm | Not tested |
| 296-2-2 | Good to use | µ = 6 µm | ~ 80 µm | - |
| 296-2-3 | Good to use | µ = 7 µm | ~ 80 µm | - |
| 296-2-4 | #6 broken (might be usable) | µ = 8 µm | ~ 80 µm | Temp. #6 |
| 296-2-5 | In production | | ~ 80 µm | |

# Main challenges

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- Placement precision (chip-to-chip distance)
  - 80 µm for Si heater / 40 µm for M... mise
  - 5 µm precision ...
- Gl...
- A...
  - ...pTAB bonding has to work for each connection
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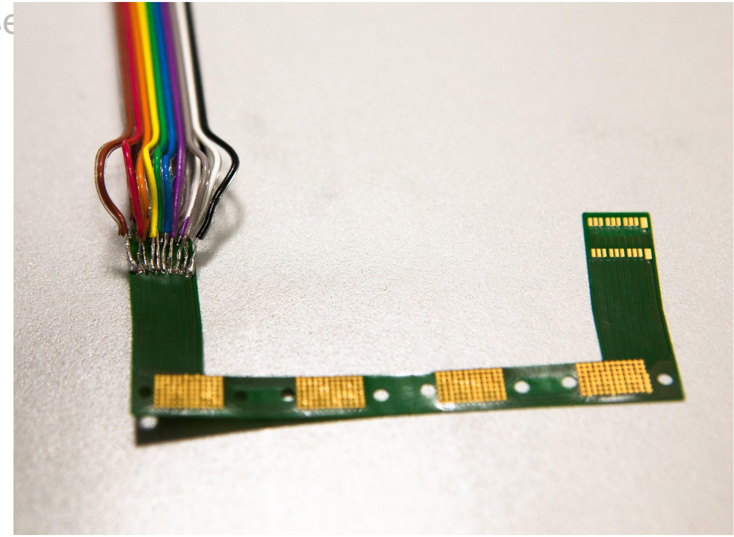
**After summer holidays :-)**



# Outlook

2020:

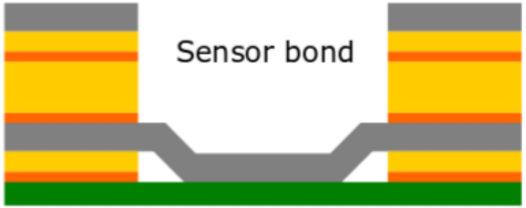
- 6x MuPix10 on HDI (flexes will arrive late summer/autumn)
- Construct an inner tracker out of test PCBs carrying 6x MuPix10
    - Demonstrator for test run in Mu3e magnet in December

2021:

- Construction of final inner tracker with MuPix11

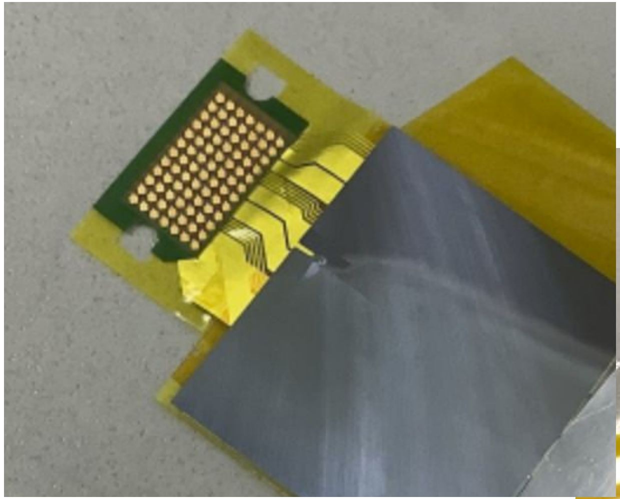
# backup

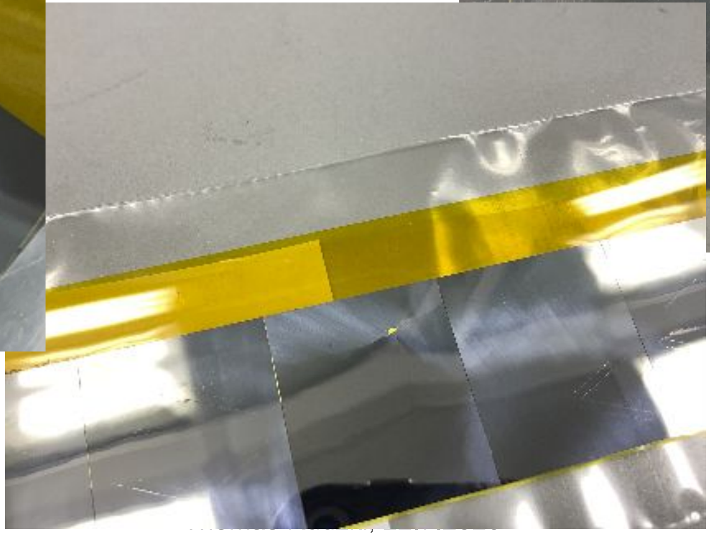

Via

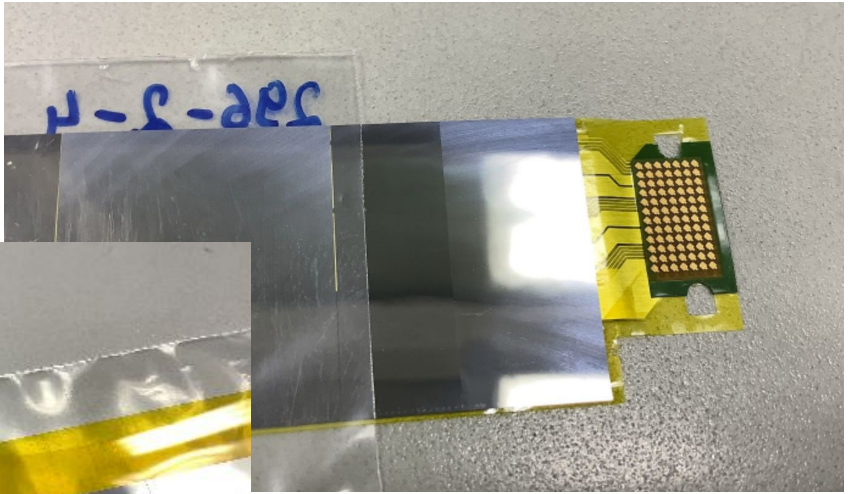

Sensor bond

# Broken sensors

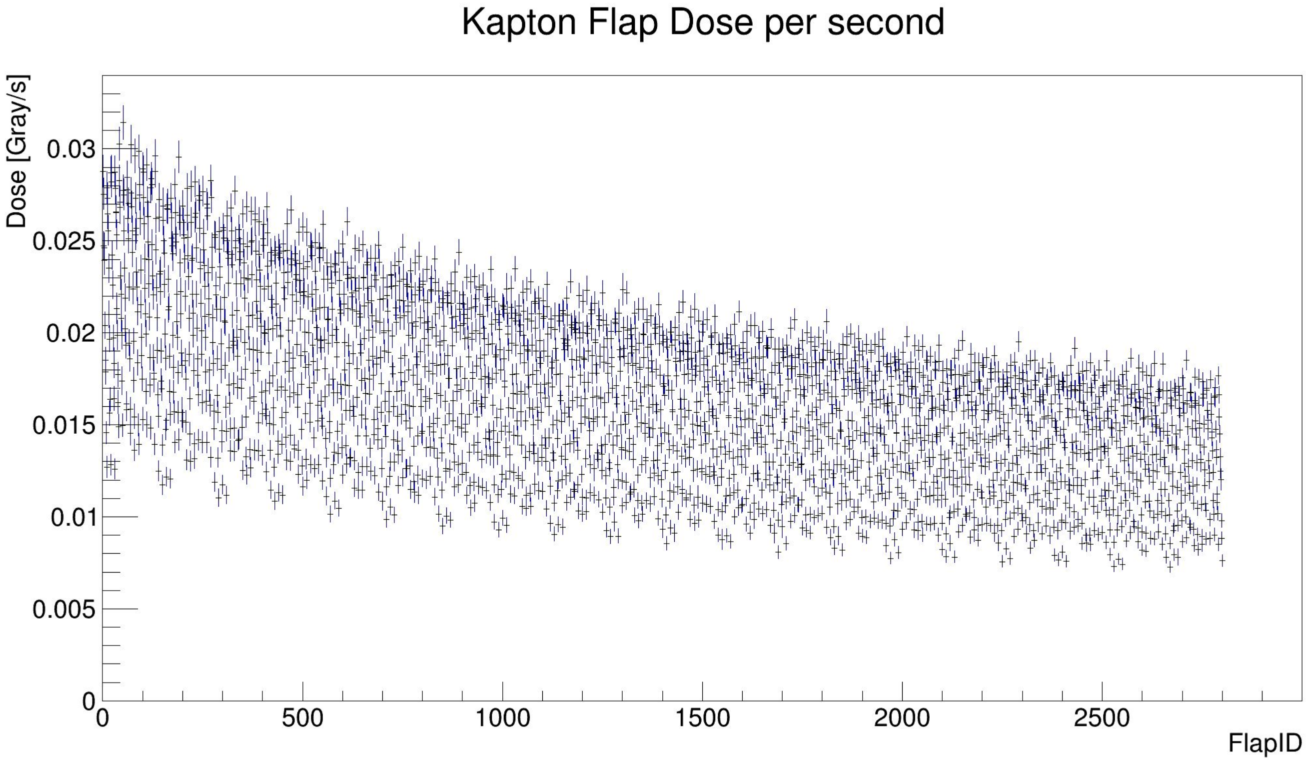
Very delicate sensors!



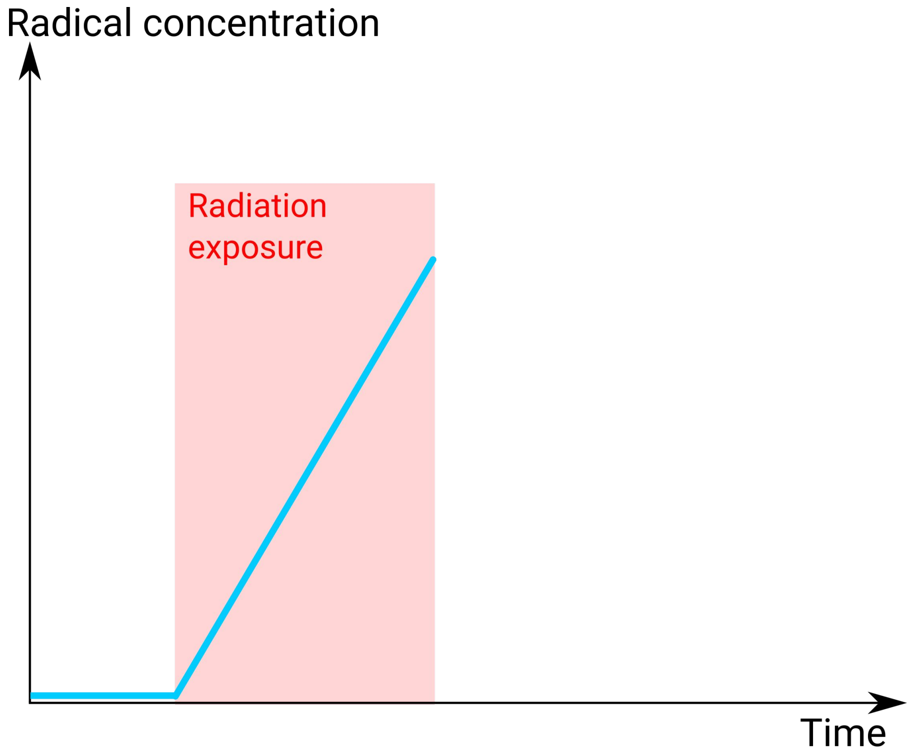




# Dose rate for all polyimide layers (irrad setup)

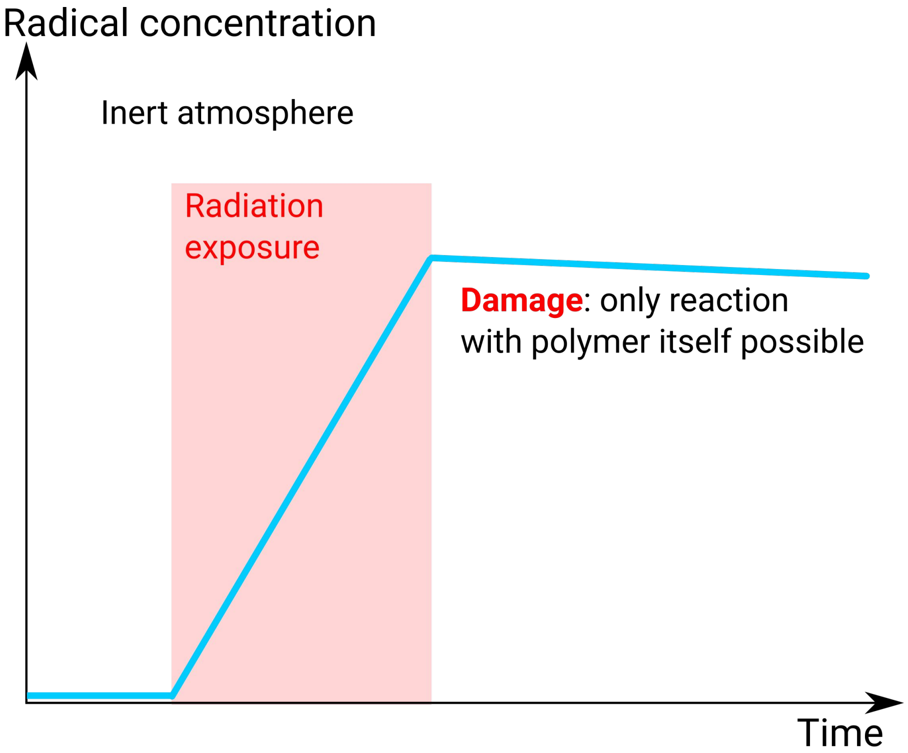


# Hypothesis for radiation damage




1. Formation of radicals in irradiated material

# Hypothesis for radiation damage




1. Formation of radicals in irradiated material
2. Reaction of radicals

   **Inert atmosphere:**
   Radicals decompose material and/or creates cross-links

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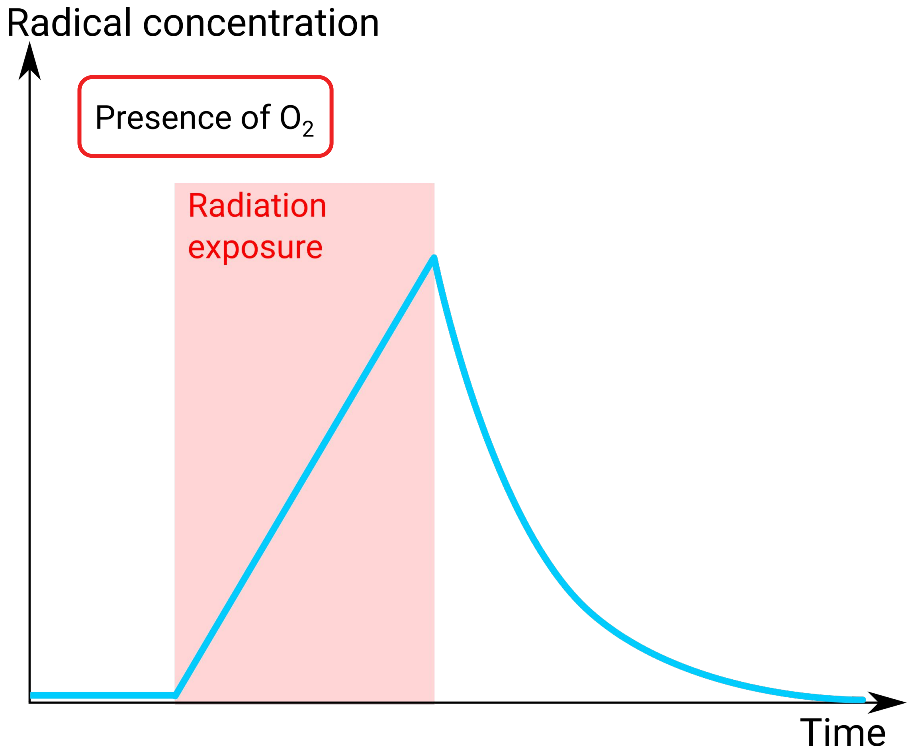


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   **Oxygenic atmosphere:**
   Radicals react with $O_2$, annealing effect, no decomposition

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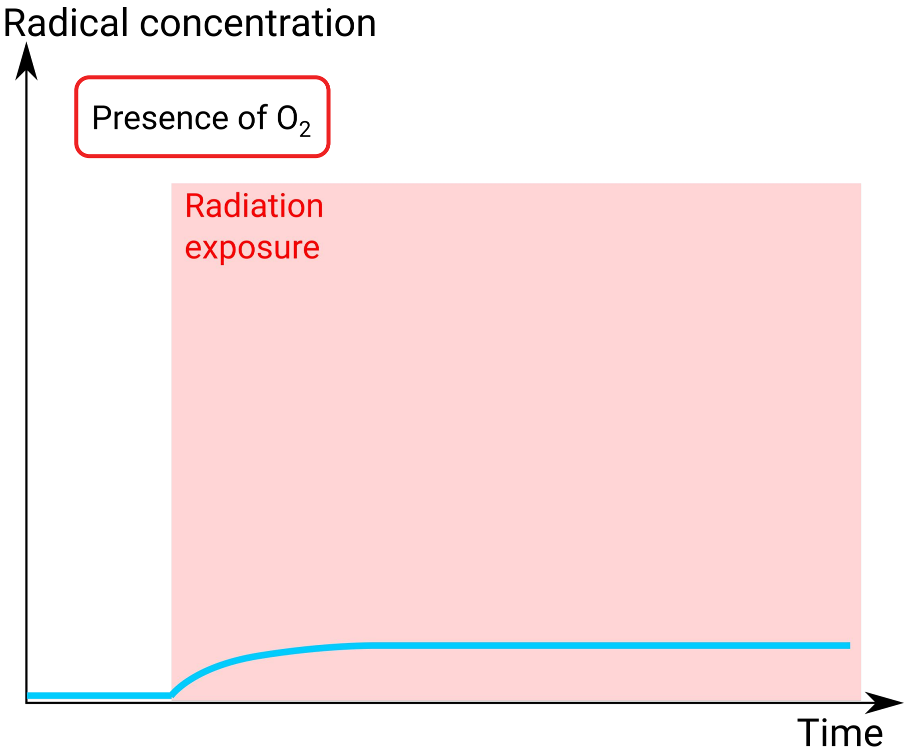


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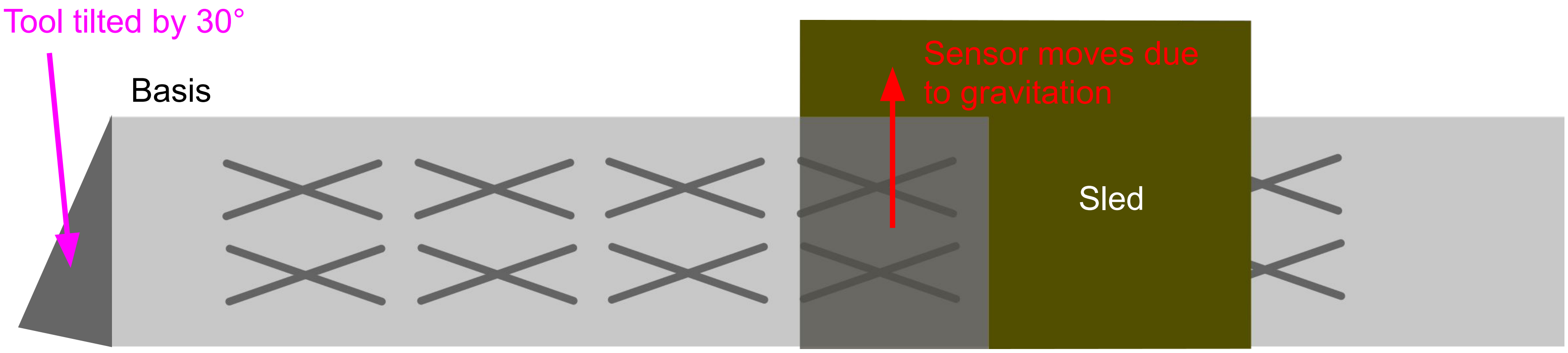
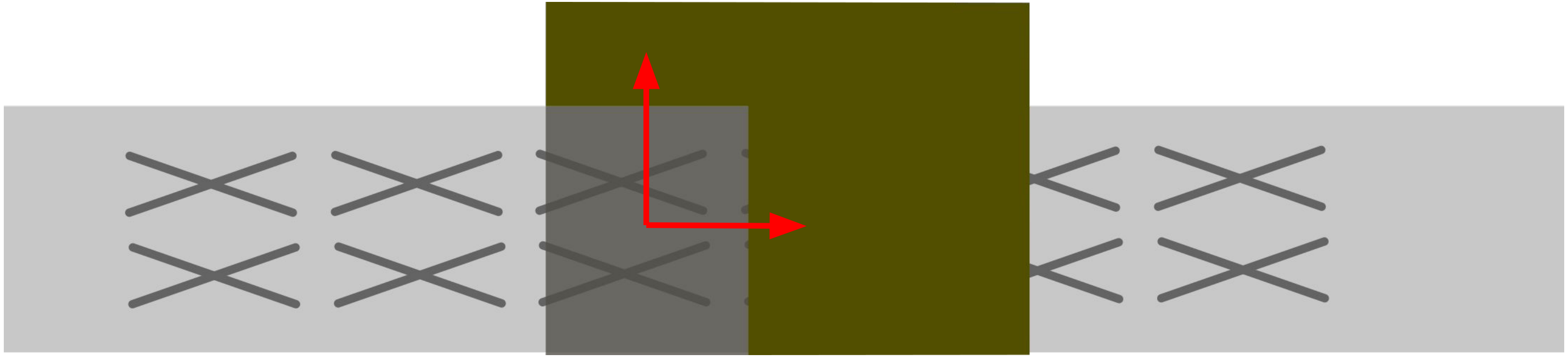
# Realization




Tool is tilted

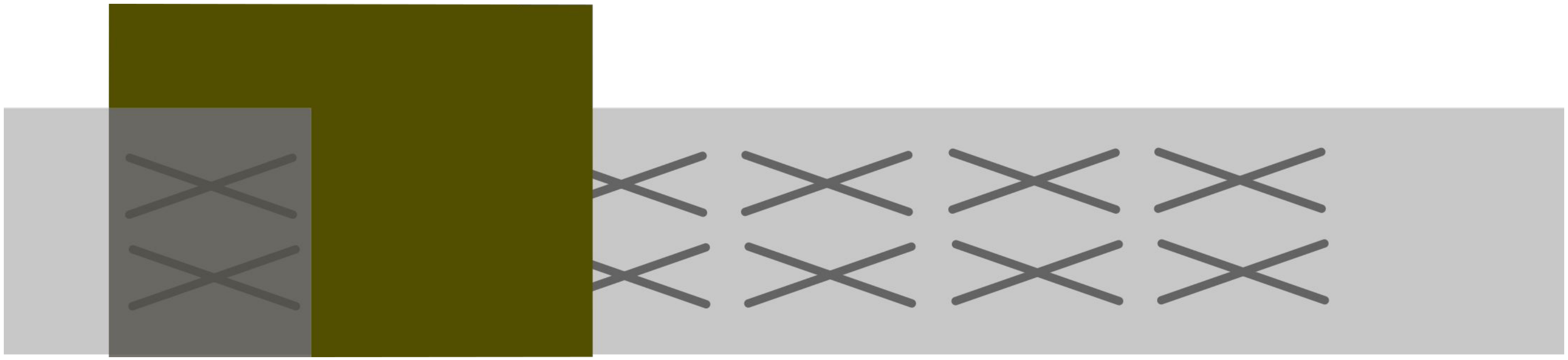
➡ Gravitation helps to confine chip in one direction

# Realization



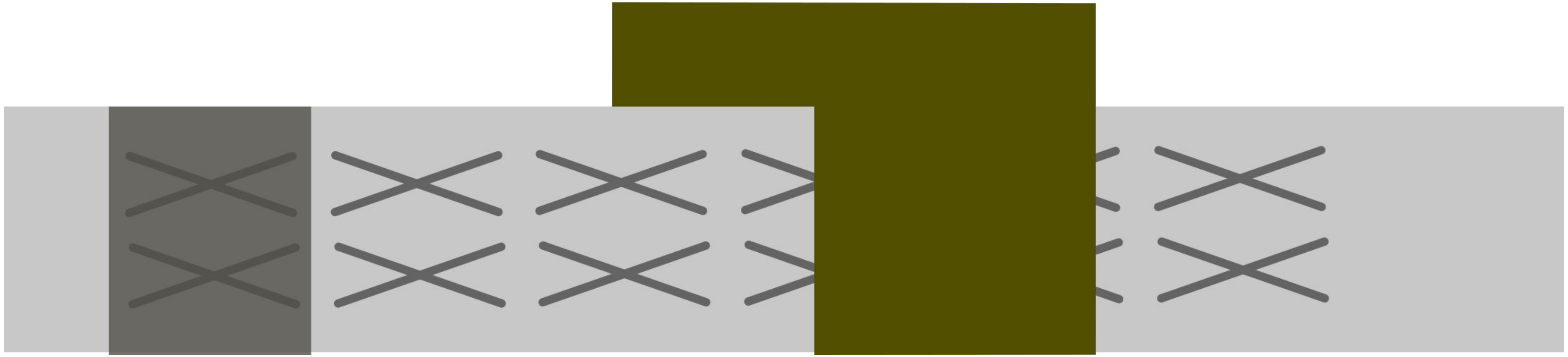
Chip is moved to desired position (confined by sled)

# Realization

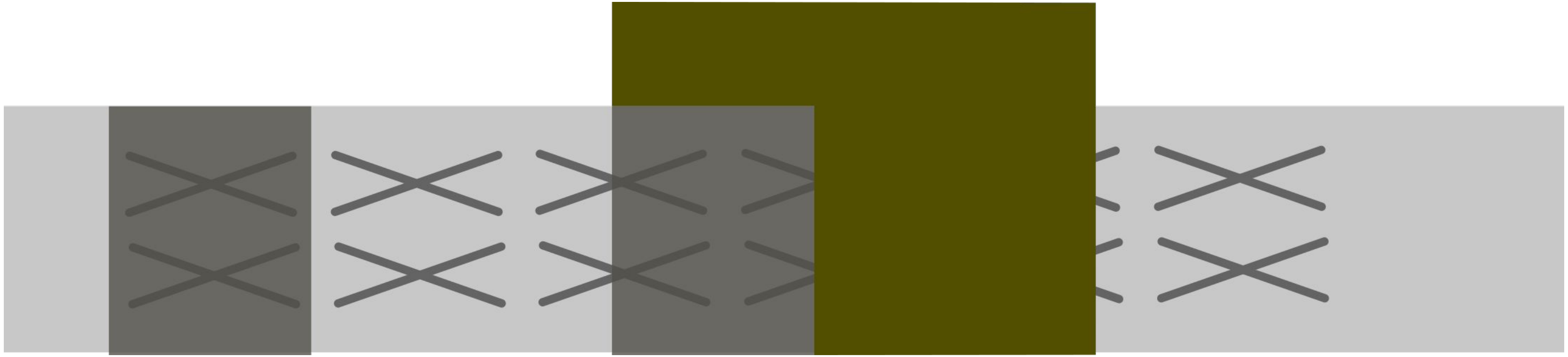


Chip is fixed by vacuum

# Realization

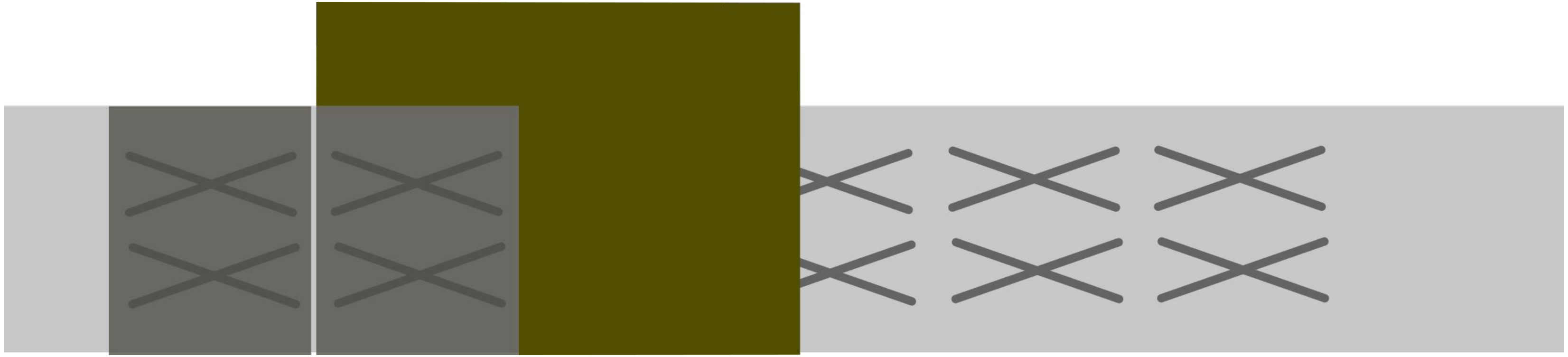


# Realization



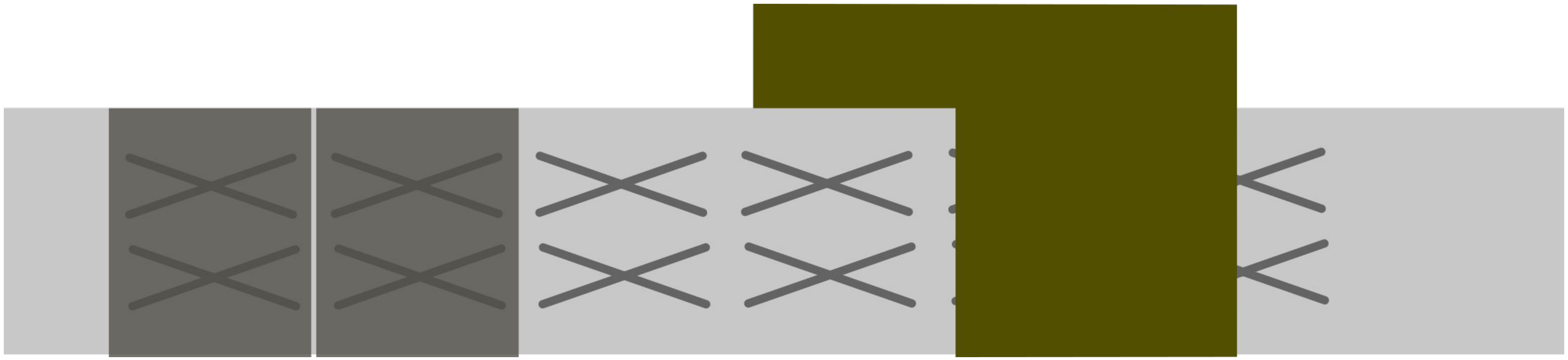
2nd chip is placed on tool

# Realization



Chip is fixed by vacuum

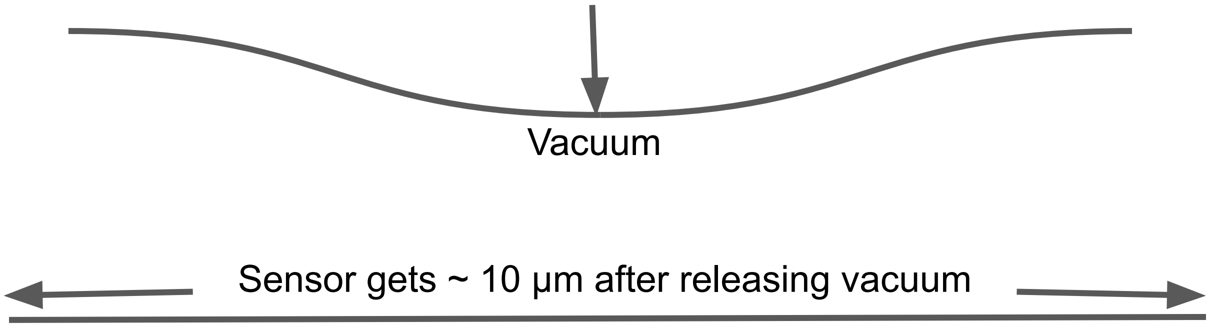
# Realization



and so on ...

# Measuring the gap size

- Measurement revealed that chips are too wide by ~25 μm
- Gap shrinks after glueing by 5 μm
- Effect is reproducible



# The Mu3e inner tracking detector

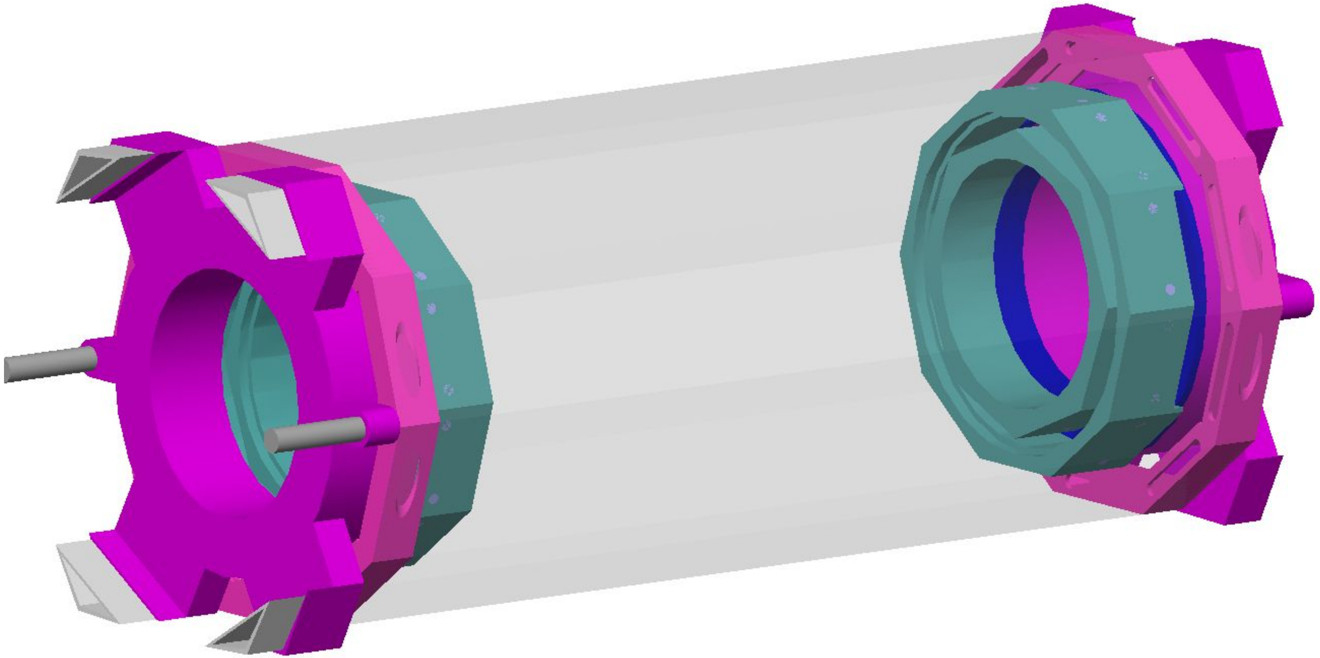
MuPix sensors

HDIs

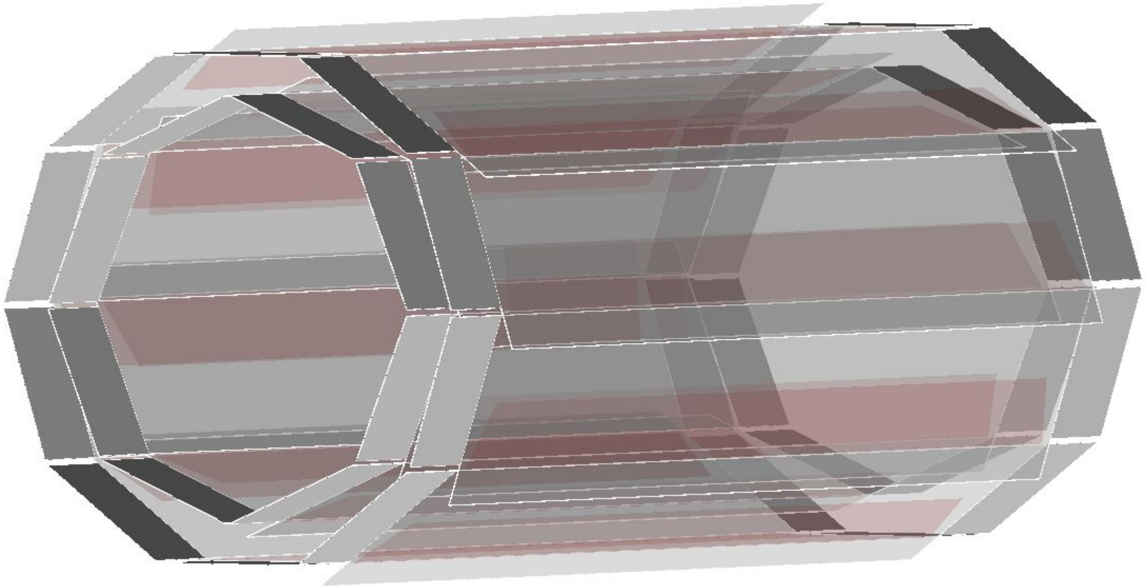
Mechanical support

Helium cooling

# Inner tracker support



# HDIs



# MuPix sensors