Mupix: Monolithic sensors for the Mu3e experiment

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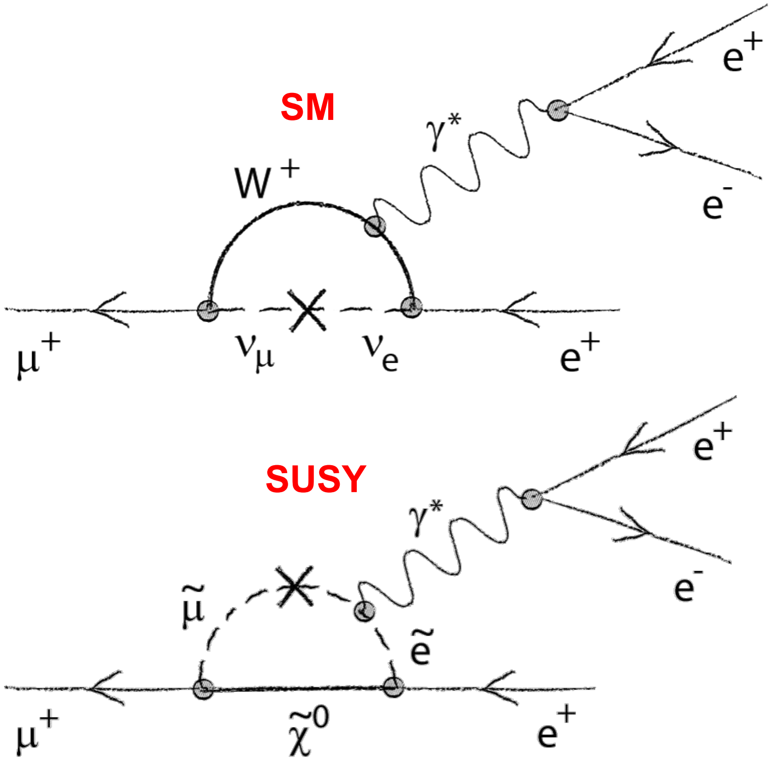
Mu3e: Physics Motivation

- Search for $\mu \to eee$
  - Standard Model: BR ($\mu \to eee$) < 10^{-54}
- New physics might enhance BR
- Current limit:
  - BR ($\mu \to eee$) < 10^{-12} (SINDRUM, 1988)
- Aimed single-event sensitivity:
  - BR ($\mu \to eee$) < $2 \cdot 10^{-15}$ (Phase 1)
  - BR ($\mu \to eee$) < 10^{-16} (Phase 2)
- Phase 2: PSI High Intensity Muon Beamline
- Phase 1 pre-production starting by end of the year

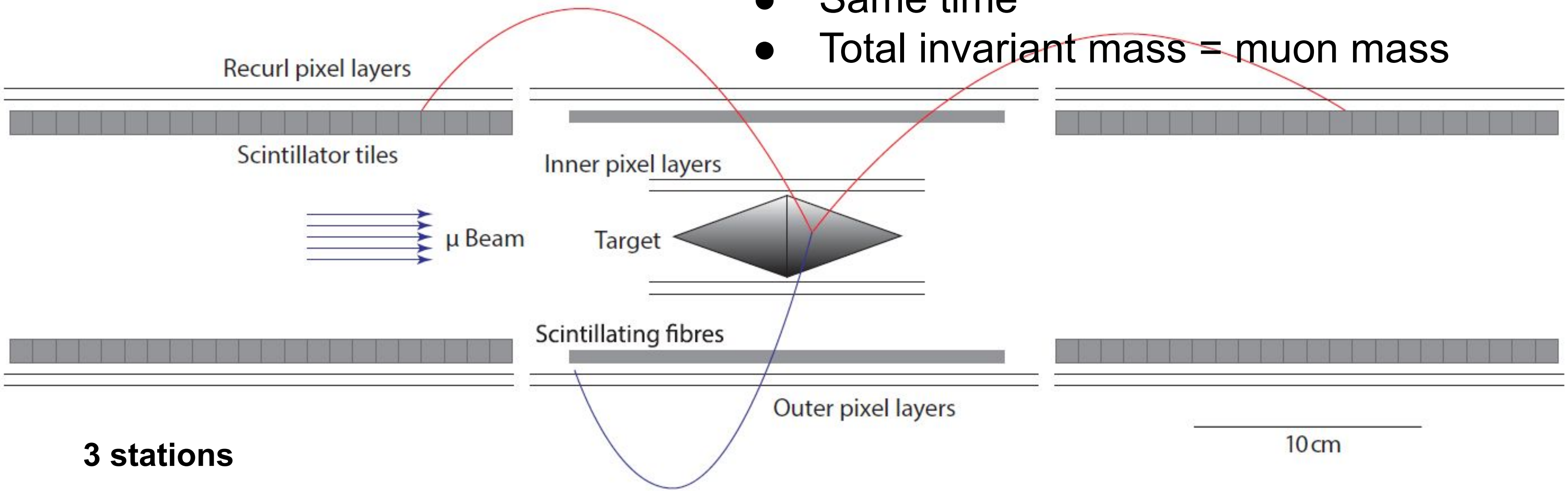


Experimental concept

- Tracking electrons coming from muon decays at rest (~10^8 Hz in Phase I)
- Magnetic field (1 T)

3 electrons

- Same vertex
- Same time
- Total invariant mass = muon mass



3 stations

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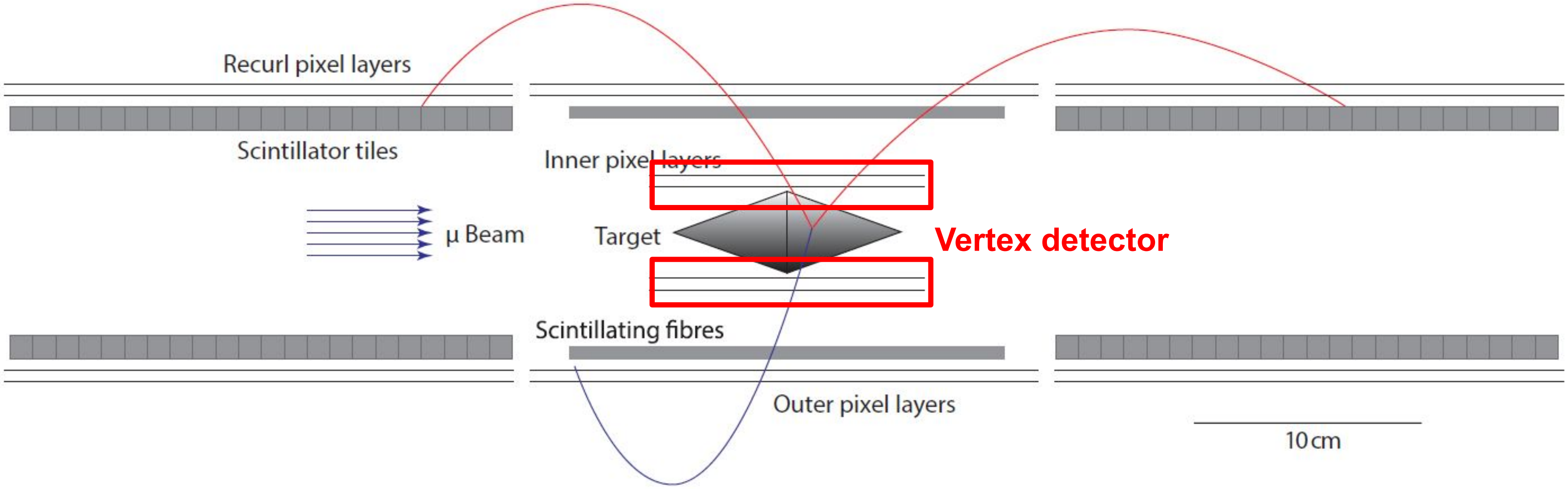

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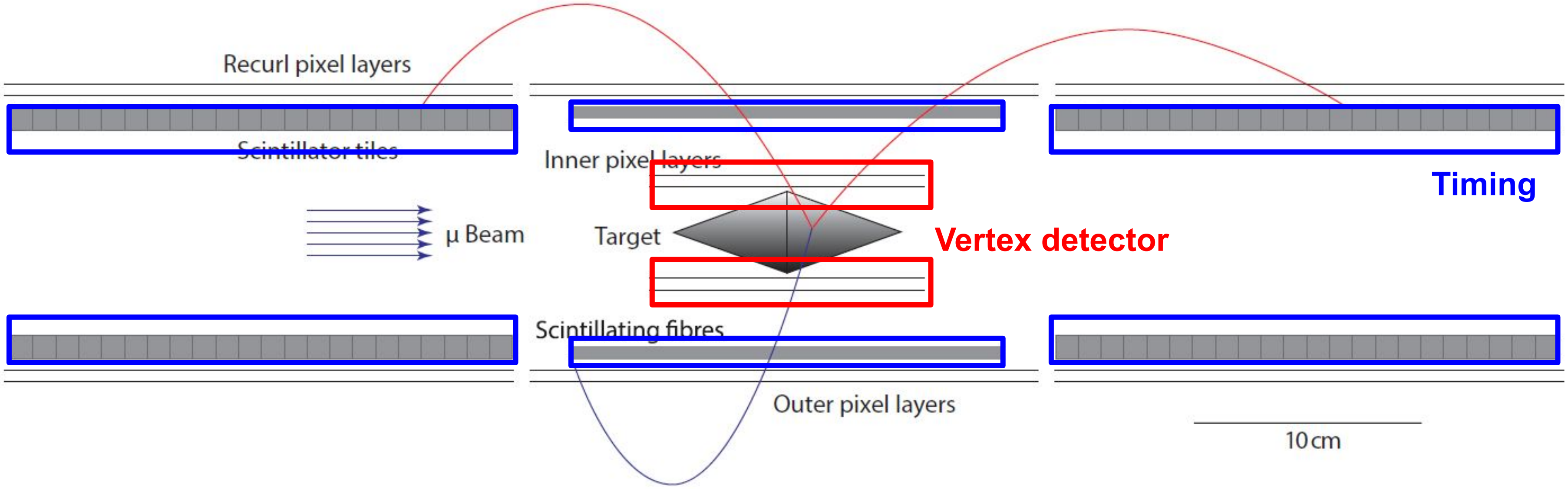

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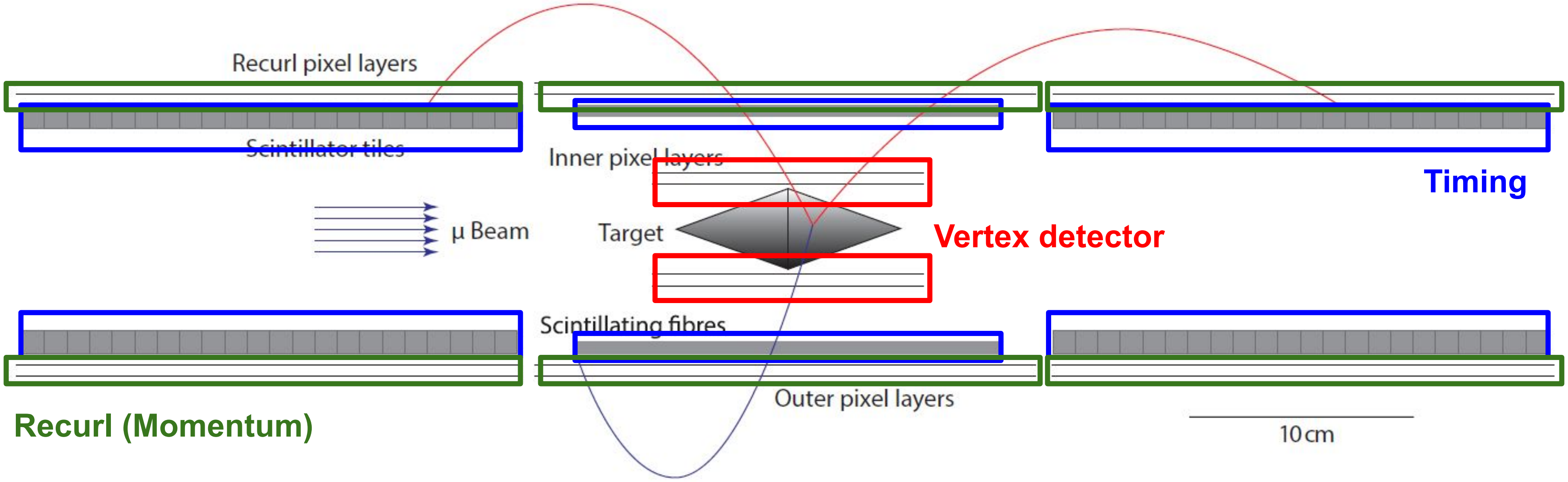

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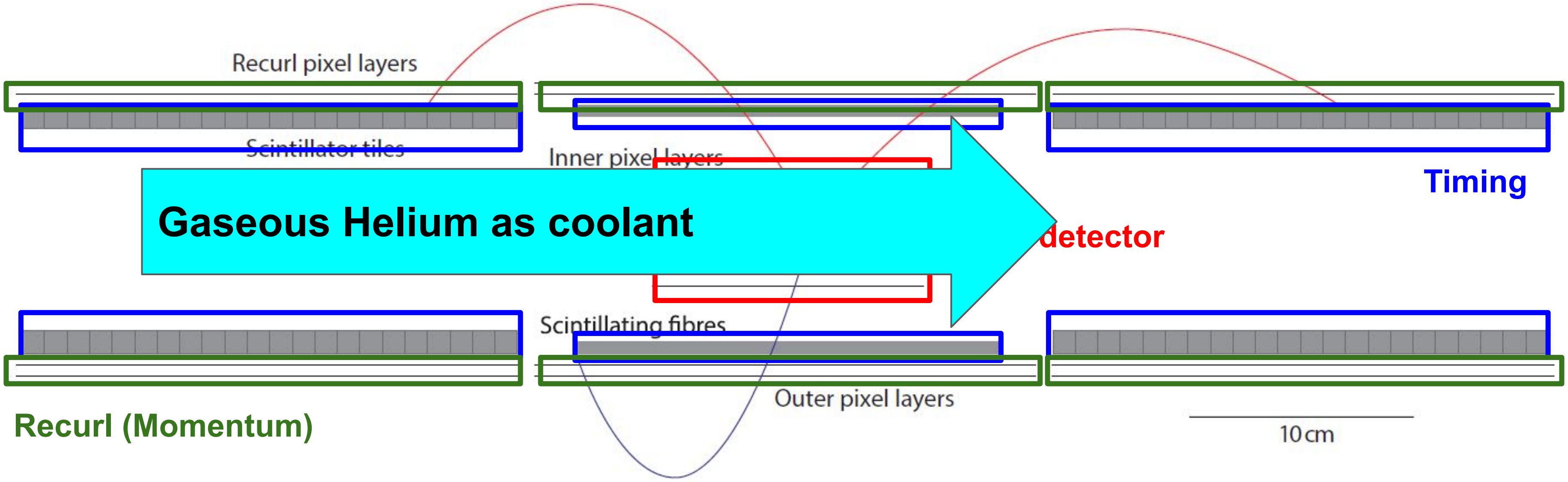

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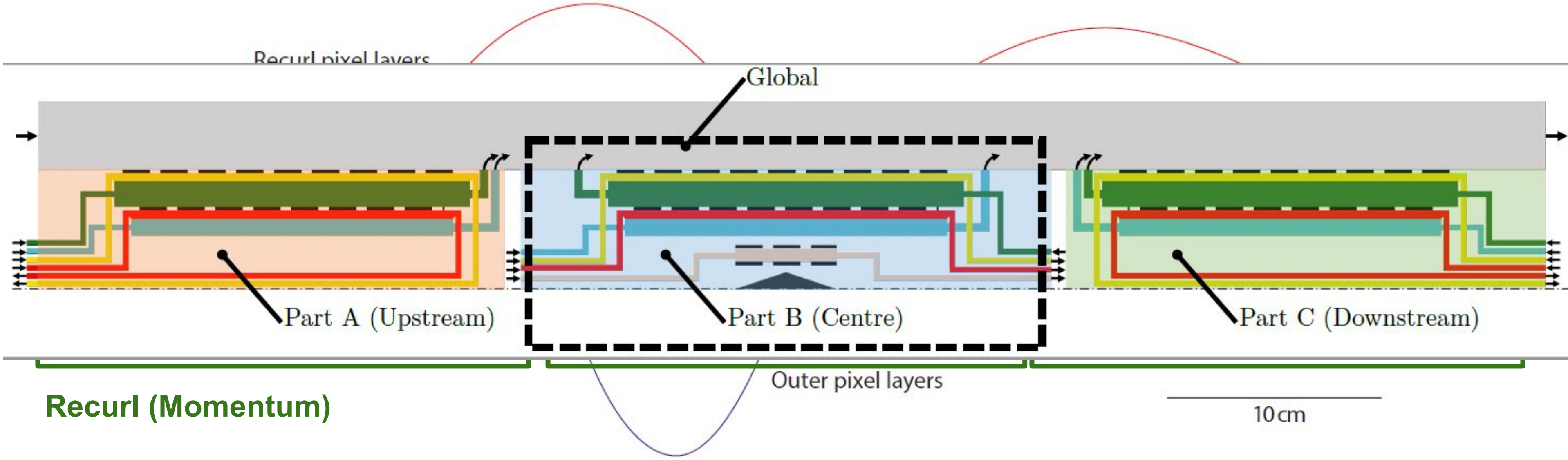
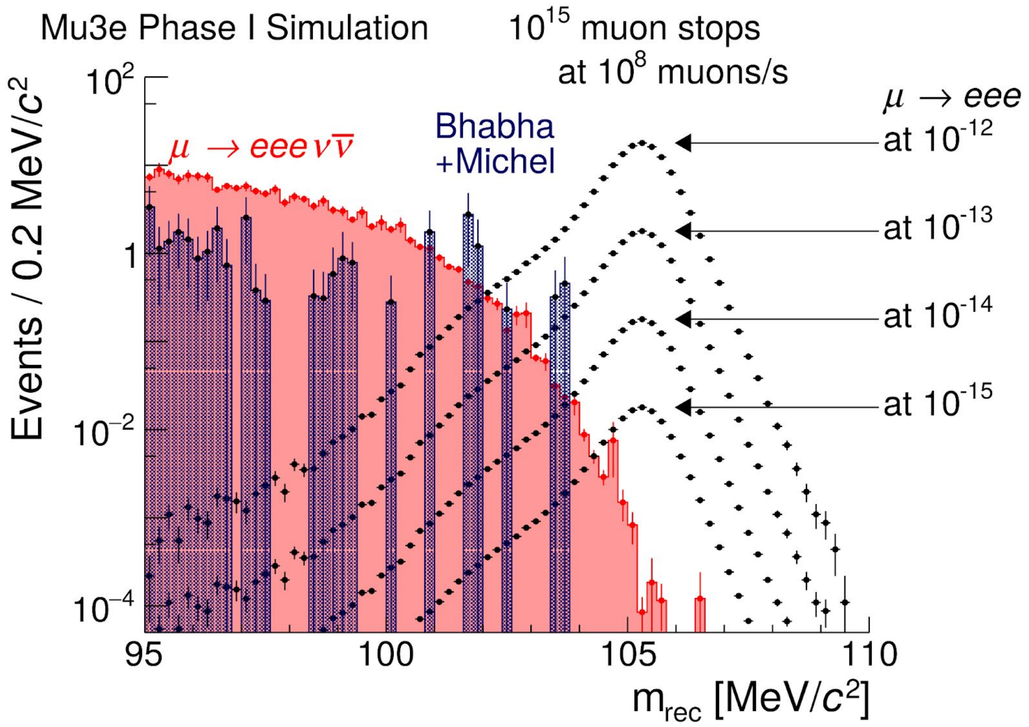


Recurl (Momentum)

Complex cooling system

Experimental sensitivity



Invariant mass of signal decay, radiative decay and accidental background (Bhaba+Michel)

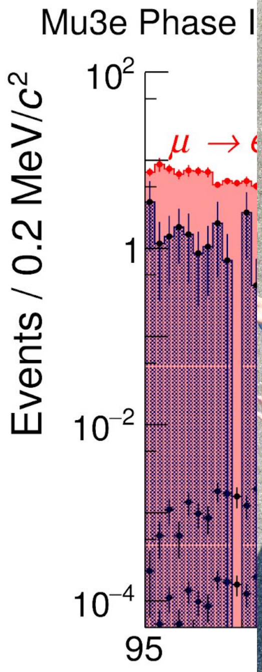
Momentum resolution crucial for detecting the peak at muon mass…

Material budget is key factor!

1 MeV resolution with 0.1% * X/X_0 per layer

Mu3e TDR at *Nucl.Instrum.Meth.A* 1014, 165679

Experimental sensitivity



Invariant mass
background (Bl

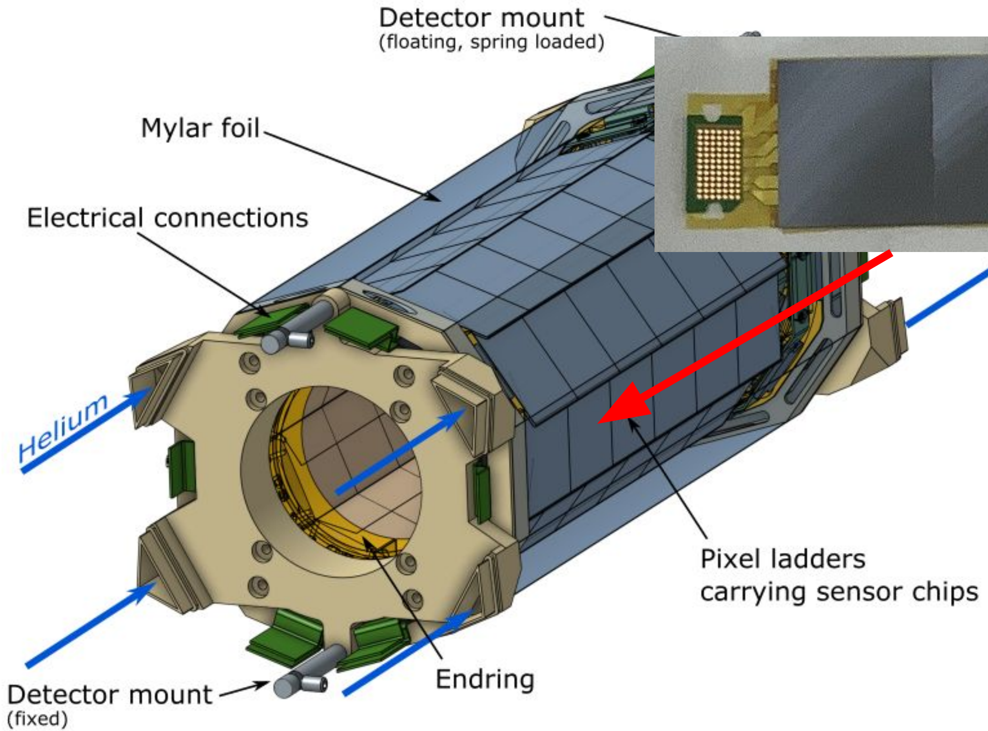
Momentum resolution

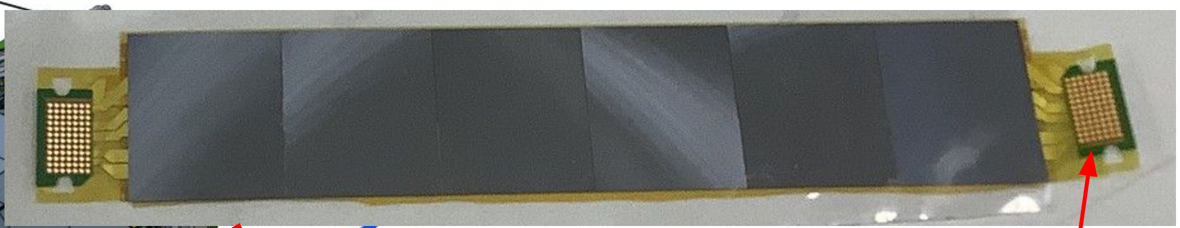
All done by a collaboration of 12 institutes in 3 countries

Mu3e Collaboration Meeting PSI 2022

Tracking System

Layer 0/1





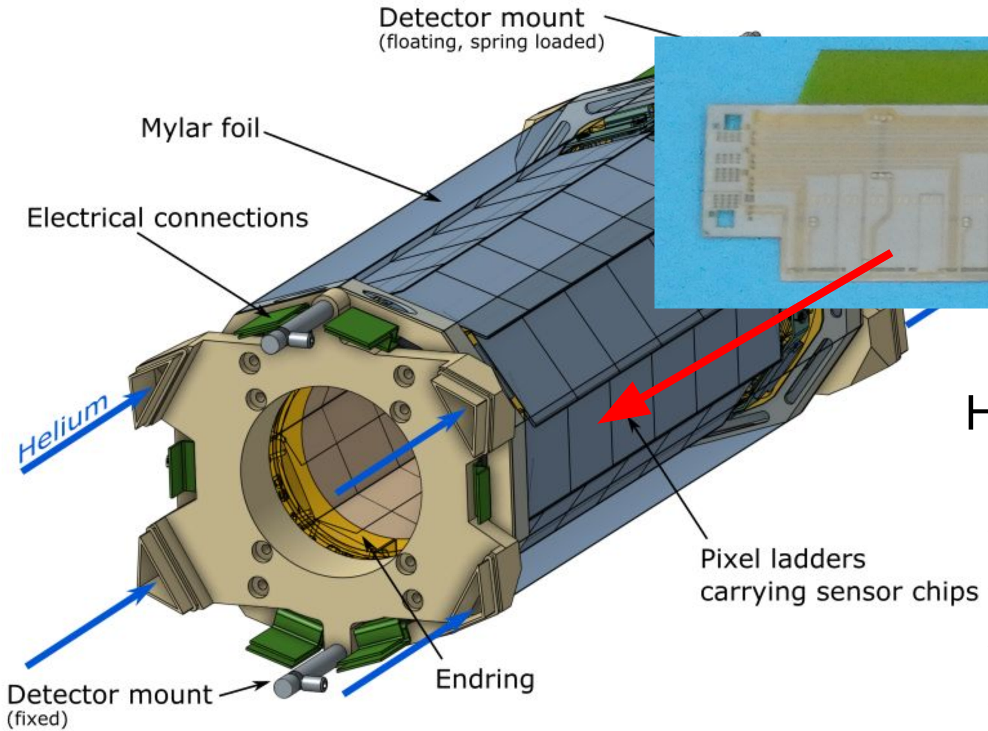
(Thermomechanical mockup)

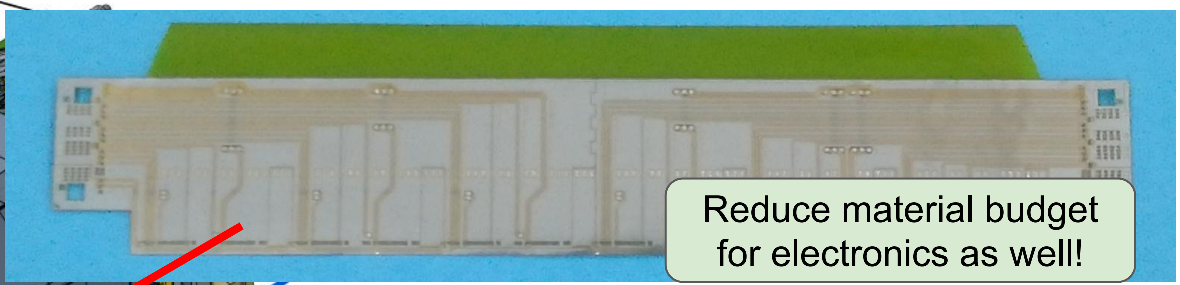
Chips glued on High Density Interconnects (HDIs)

- 6 for layer 0 and 1
- 17/18 for layer 2 and 3
- 50 µm thin
- Connection via interposers (pressed against RO flexes)

Tracking System

Layer 0/1



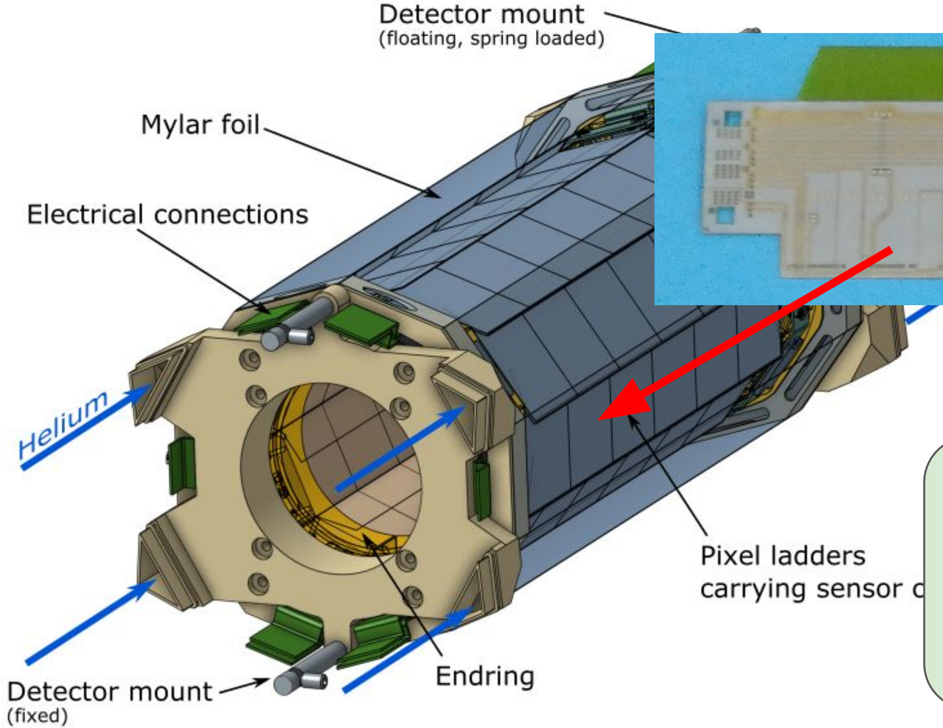


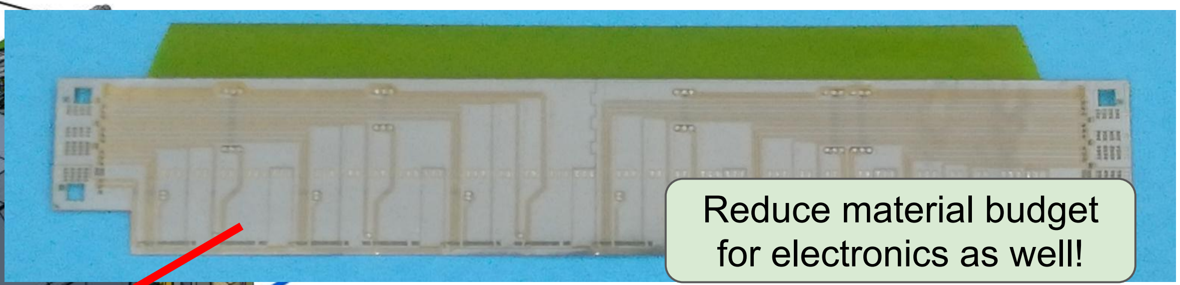
HDIs:

- Kapton/Aluminum foils
- Serve as mechanical support
- Electrical traces
- Produced by LTU (Ukraine)
- No extra components

Tracking System

Layer 1/2



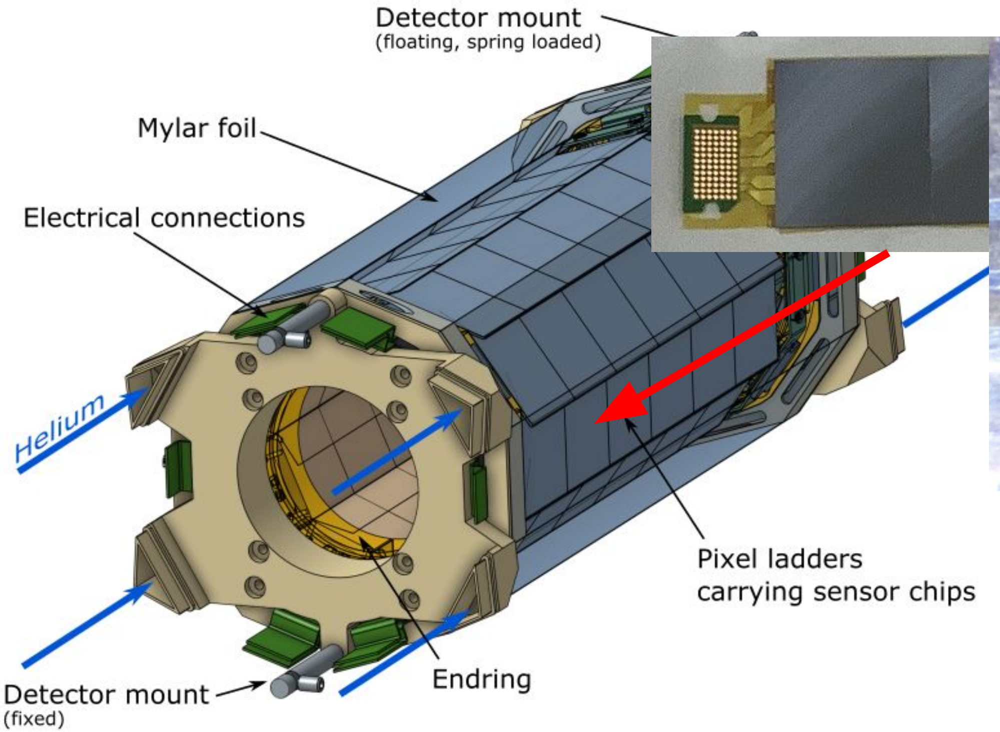


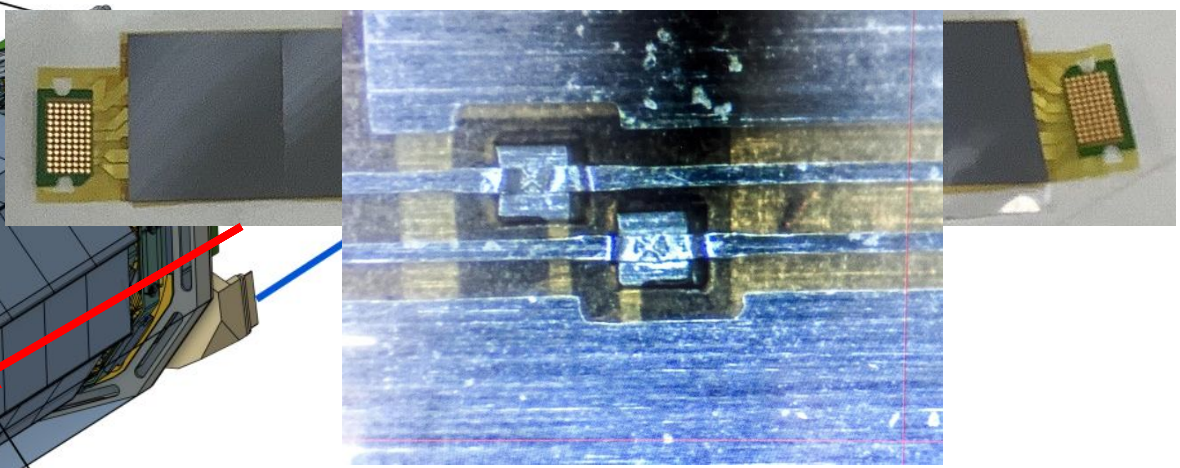
HDIs

Very limited amount of lines for each ladder
All going to the service area (~2 m away)

Tracking System

Layer 1/2

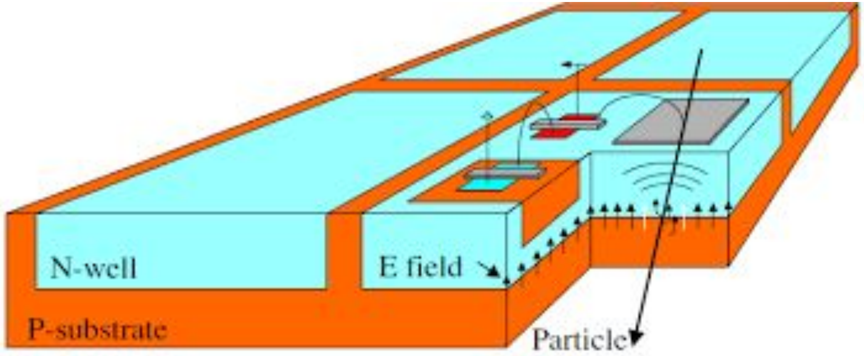




Electrical connections with Singe Point Tape Automated Bonding (SpTAB)

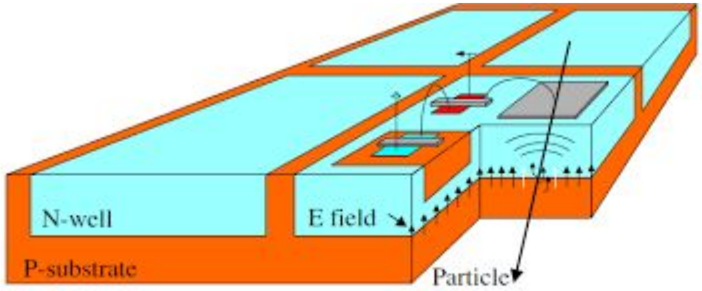
MuPix sensors

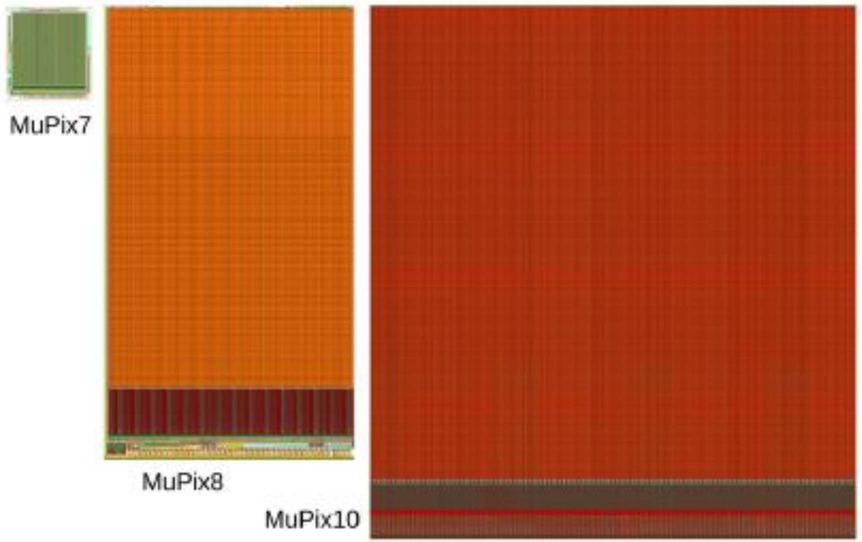
- Monolithic HV-CMOS
  - Readout electronics embedded inside silicon bulk
    - In deep n-well
  - No need for hybridization
  - Can be thinned while maintaining high performance



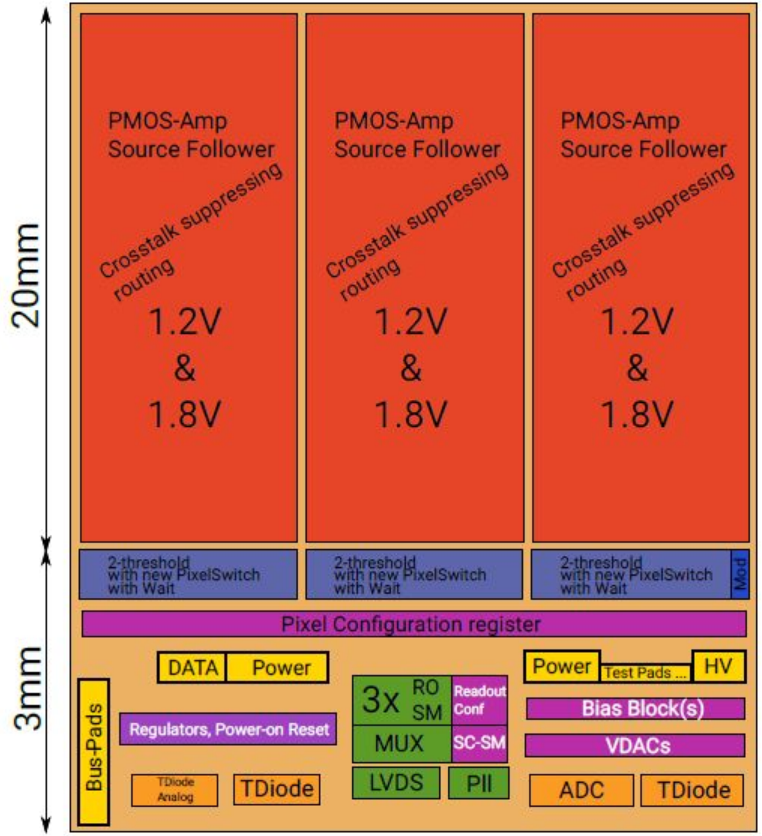
MuPix sensors

- Monolithic HV-CMOS
  - Can be thinned while maintaining high performance
- 180 nm H18 technology derived from IBM
  - AMS until 2018
  - TSI afterwards
- Long R&D campaign
  - Mupix7 first fully monolithic
  - Mupix8 first large area
  - Mupix9 implemented slow control
  - Mupix10 with final size
    - Used for prototyping
  - Mupix11 final chip
    - Characterization ongoing



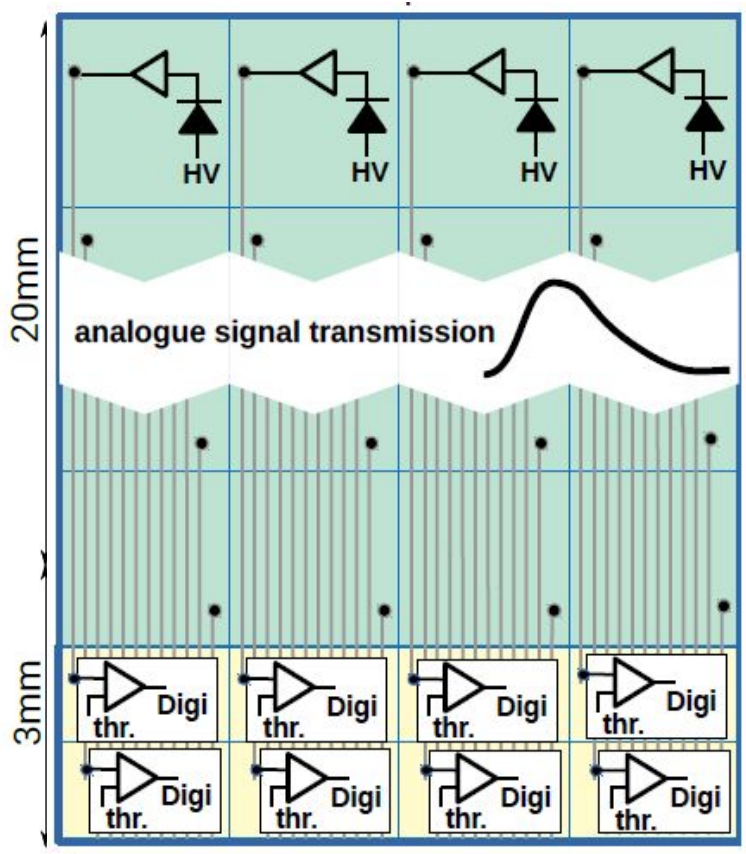


MuPix sensors: MuPix10/11



- ~2x2 cm^2 active area
- Chip periphery on bottom
- 250 mW/cm^2 power consumption

MuPix sensors: MuPix10/11



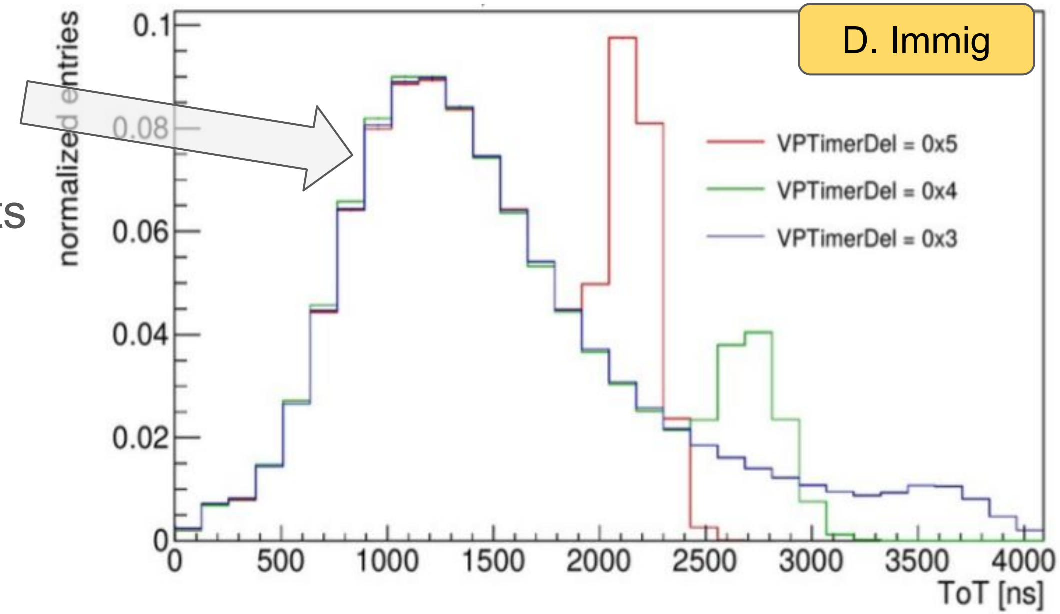
- ~2x2 cm^2 active area
- Chip periphery on bottom
- 250 mW/cm^2 power consumption
- Signal collected and amplified by pixels
- Analogue signal driven to periphery
- Each pixel mirrored in periphery
  - Analogue signal digitized
- State machine collects hits from double columns
- Continuous read-out!
- 4 LVDS link
  - 3 per matrix (inner trackers)
  - 1 mulitplexed (outer layers)

MuPix sensors: design challenges

- 2 LVDS input lines as bus lines (common to 3/9 chips)
  - Clock and Serial input
  - 125 MHz clock
- 9 Data lines
  - 3x3 inner layers or 1x9 outer layers (multiplexed)
  - 1.25 Gbit/s
- 3 DC lines per ladder
  - VDD+GND sense ⟹ Recover voltage drops
  - Temperature sense ⟹ Hardware interlock
- Slow control
  - ADC to read internal voltages and temperature
  - Readings sent out via data links
  - Extra temperature diode (analogue output)

MuPix sensors: design challenges

- Hit-delay circuit
  - Hit recorded after a fixed delay from ToA
  - Easier time sorting procedure
  - Incidental effect: max value on ToT
- No active or passive components to “help” on flexes
- Proved to work until 1 MHz particle rate
  - Within specs



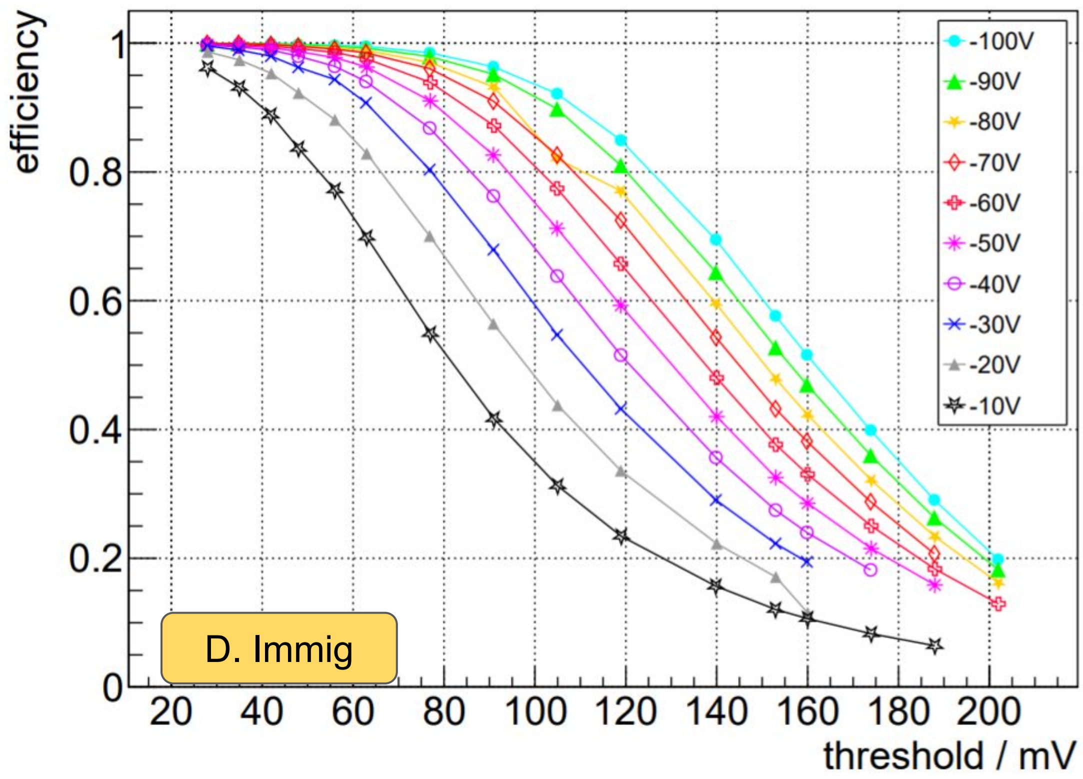
Experiment's validation

- Prove performance requirements
  - Lab tests
  - Testbeams
- Operate with HDIs
- Operate in experimental conditions
  - Prototyping
  - Beam, target, magnet
  - Cosmic only
- Thermo-mechanical mockup
  - See backup

MuPix sensors: requirements

pixel size [μm^2]	80×80
sensor size [mm^2]	20×23
active area [mm^2]	20×20
active area [mm^2]	400
sensor thinned to thickness [μm]	50
LVDS links	$3 + 1$
maximum bandwidth§ [Gbit/s]	3×1.6
timestamp clock [MHz]	≥ 50
RMS of spatial resolution [μm]	≤ 30
power consumption [mW/cm^2]	≤ 350
time resolution per pixel [ns]	≤ 20
efficiency at 20 Hz/pix noise [%]	≥ 99
noise rate at 99 % efficiency [Hz/pix]	≤ 20

MuPix10: results

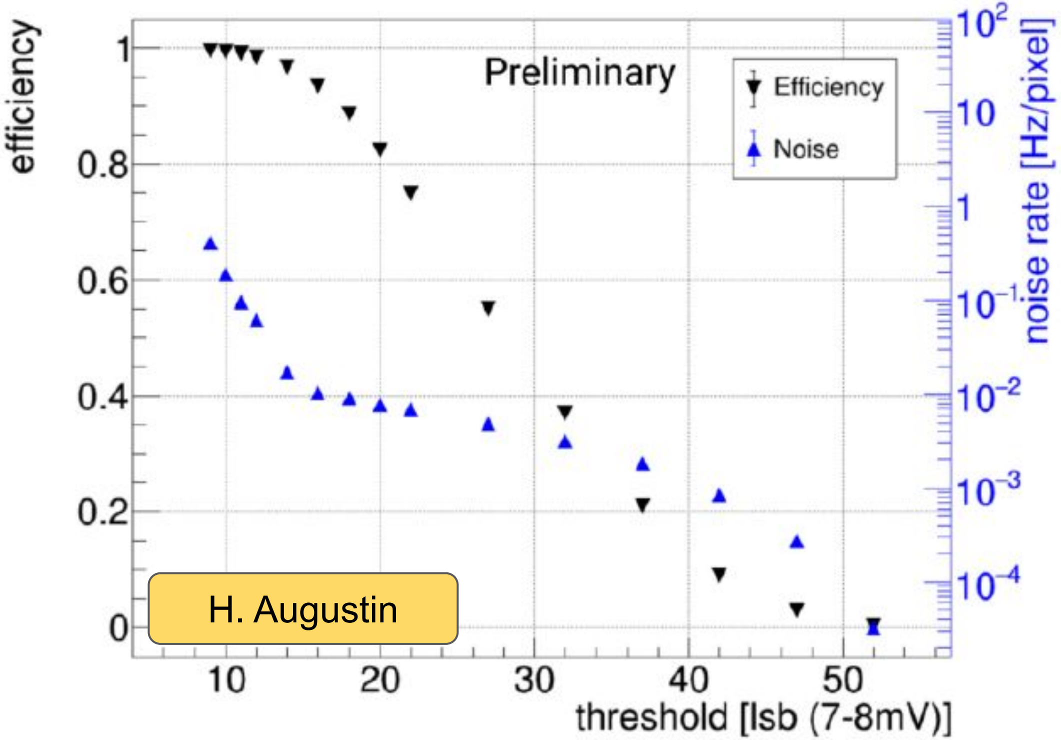


100 µm thickness

110 V breakdown

Efficiency plateau well defined above 20 V

MuPix10: results



50 µm thickness

20 V (see later why)

Efficiency and noise requirements met

Mupix10 detailed studies

Testbeam at DESY

Alpide telescope

6 layers

5 µm resolution

EuDAQ + Corryvreckan

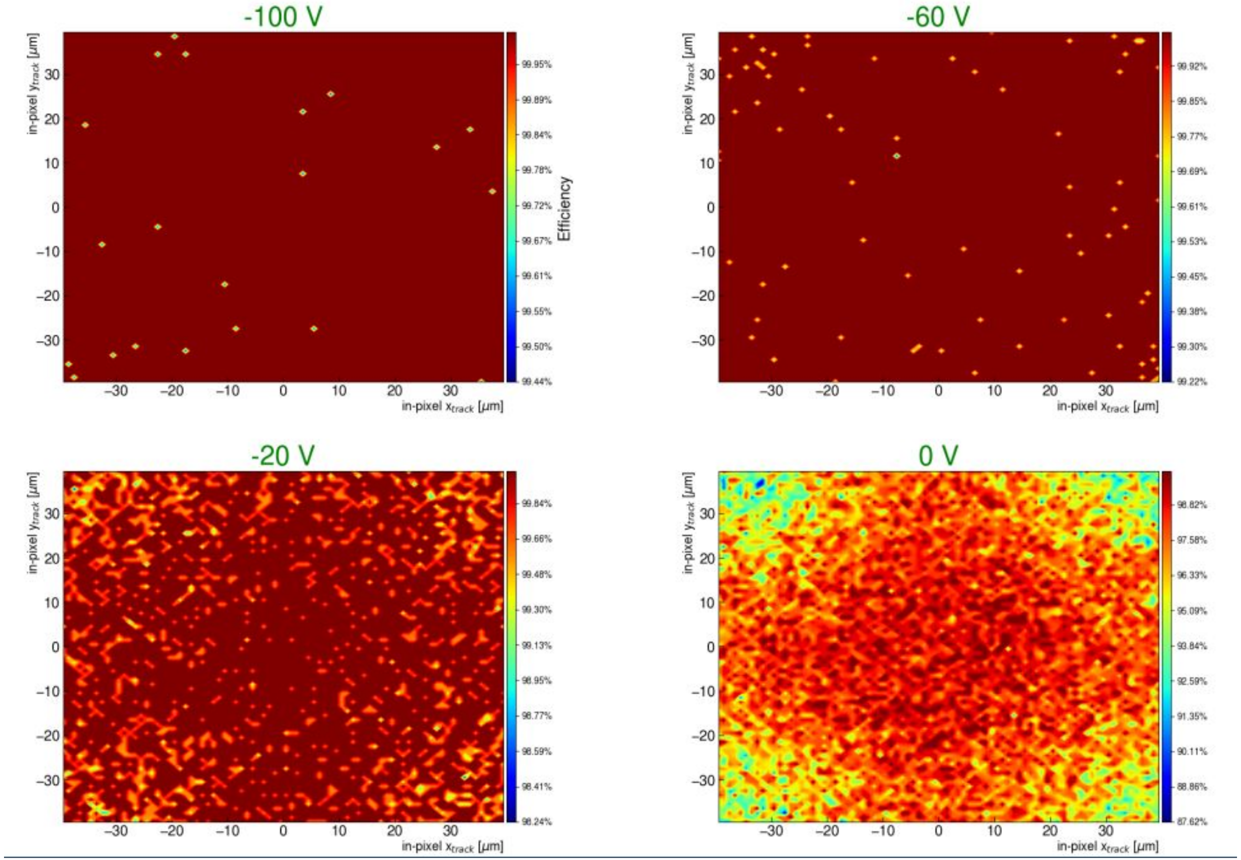
Mupix10 detailed studies

In-pixel efficiency

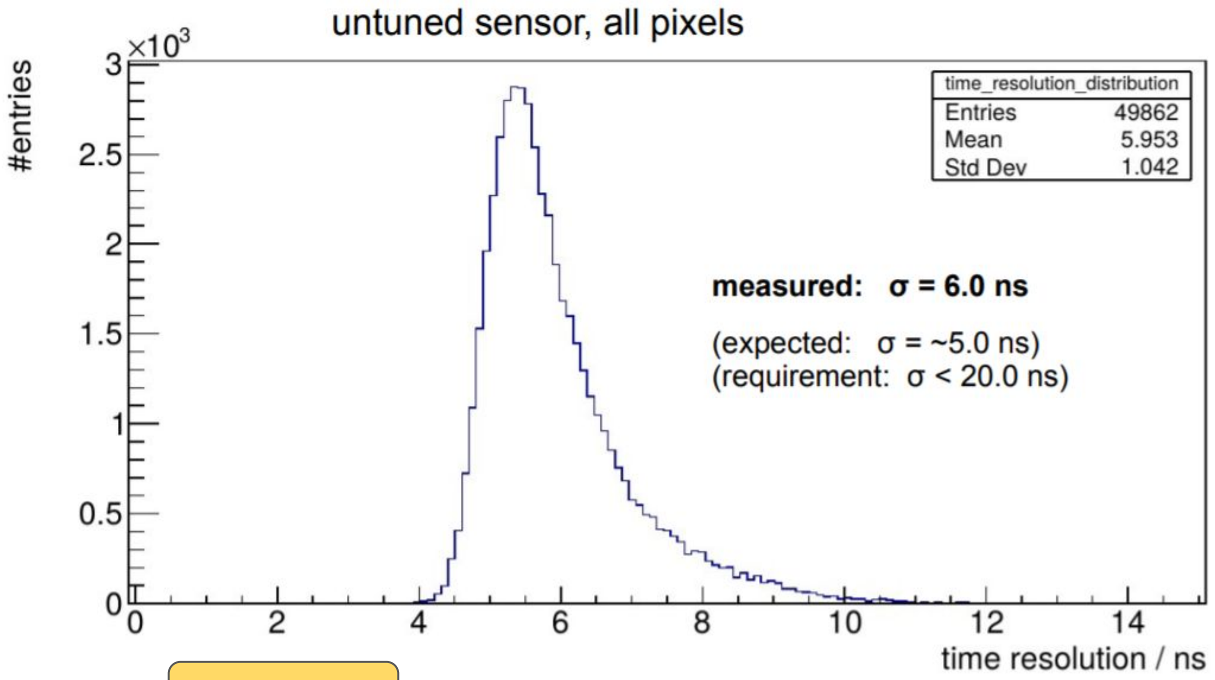
100 µm thick

43 mV threshold

A.M. Gonzales



MuPix10: results



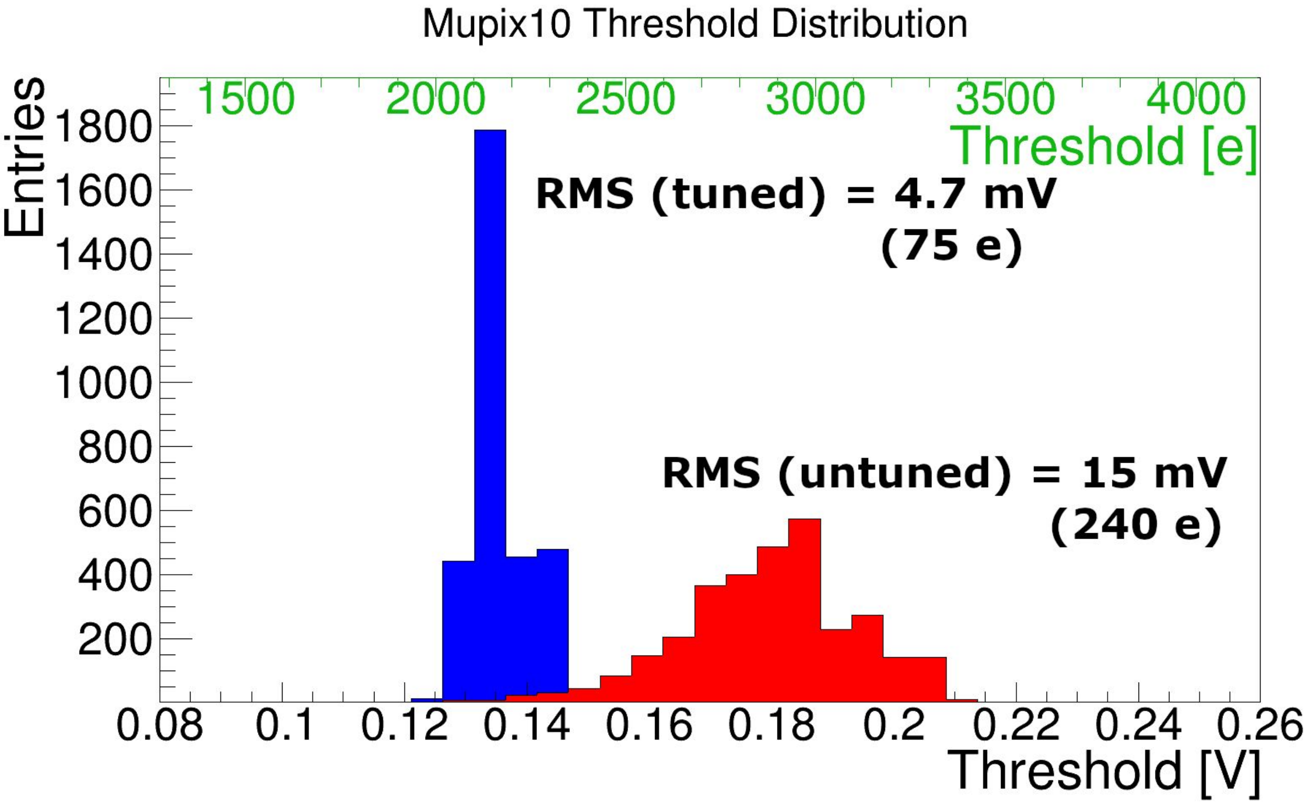
F. Frauen

Time resolution well within specifications

~15 ns without corrections

6 ns after row and time-walk corrections

MuPix10: results



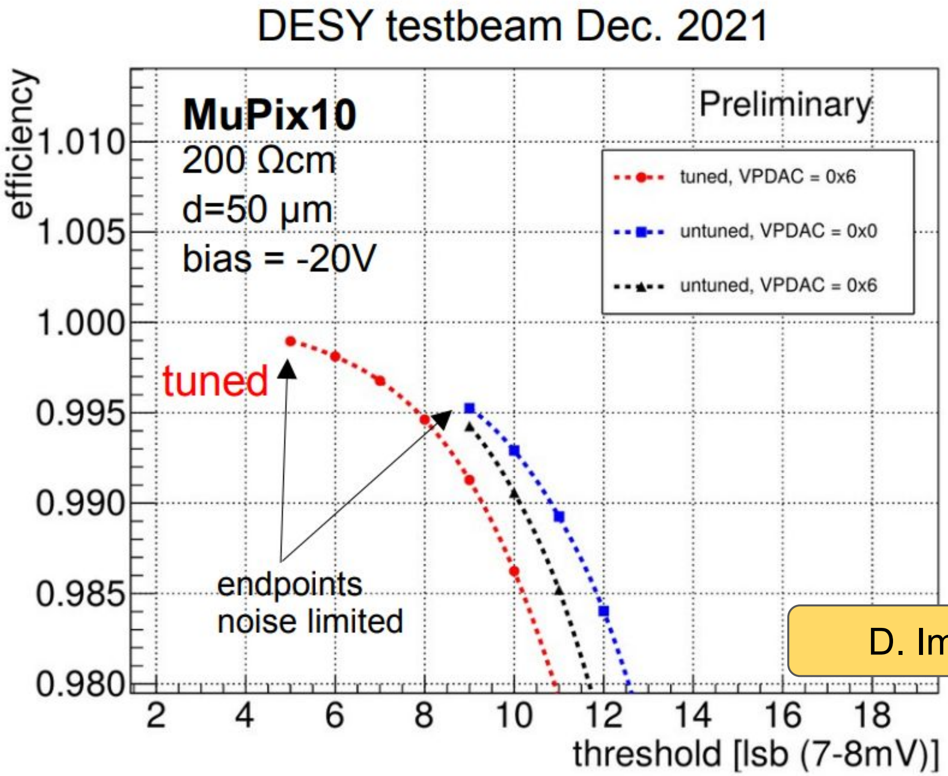
Tunable threshold for each pixel

Tuning with threshold scans:

Low threshold dispersion

M. Menzel

MuPix10: results



Tuning by lowering threshold while keeping noise constant: maximize efficiency!

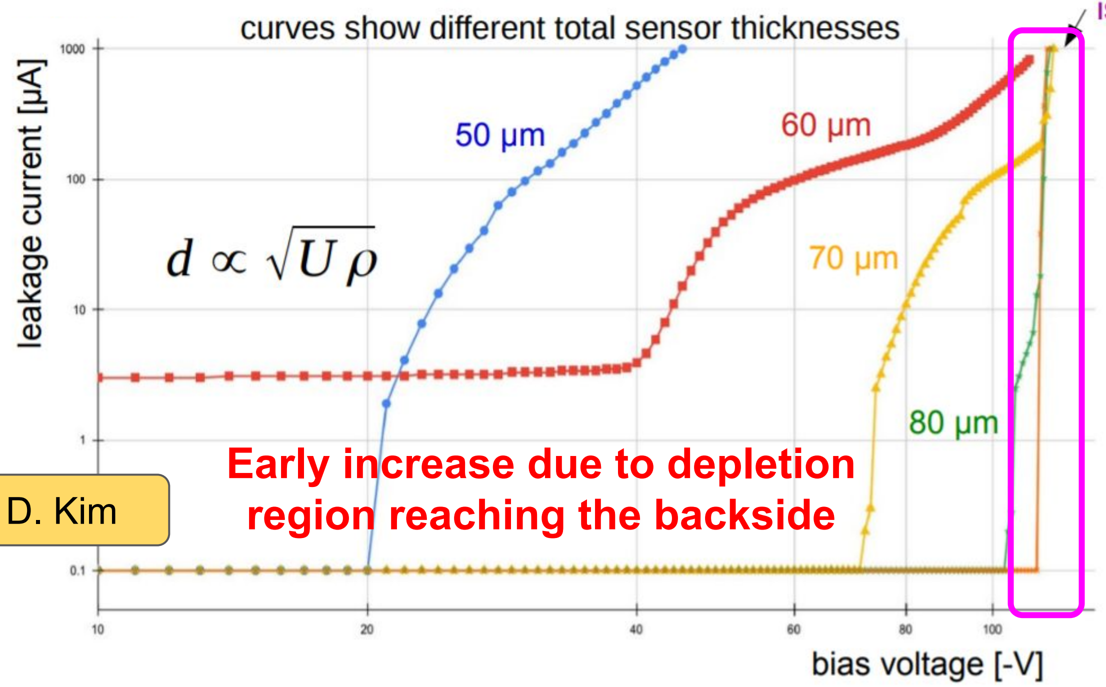
D. Immig

Mupix10: thinning

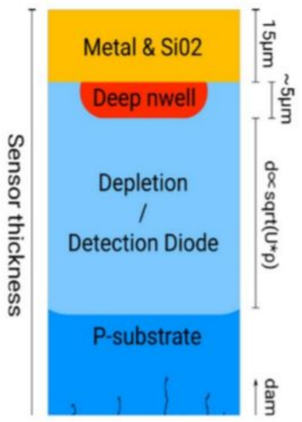
MuPix10 devices thinned at different thicknesses (by mechanical grinding only)

IV curves affected

breakdown is at ~110V



D. Kim



Full depletion compatible with 400 Ωcm resistivity (nominal: 200 Ωcm Measured: 370 Ωcm)

Thinning

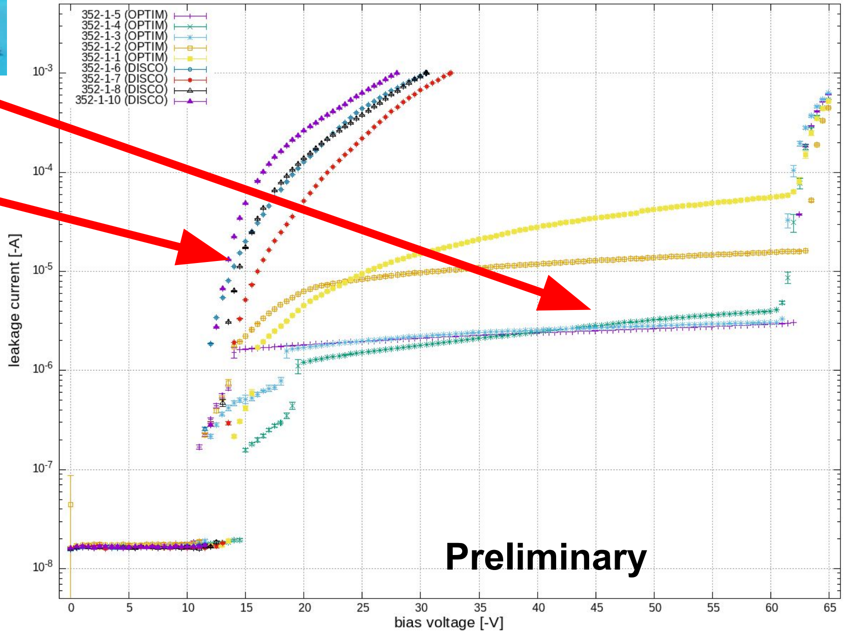
Investigated thinning with AtlasPix3.1: with and without plasma etching

W/O **W/**

50 µm thin

Plasma etching shows significant improvement both mechanically and electrically (IV curves)

80-100 Ωcm wafers will reach 50 µm full depletion at ~100 V

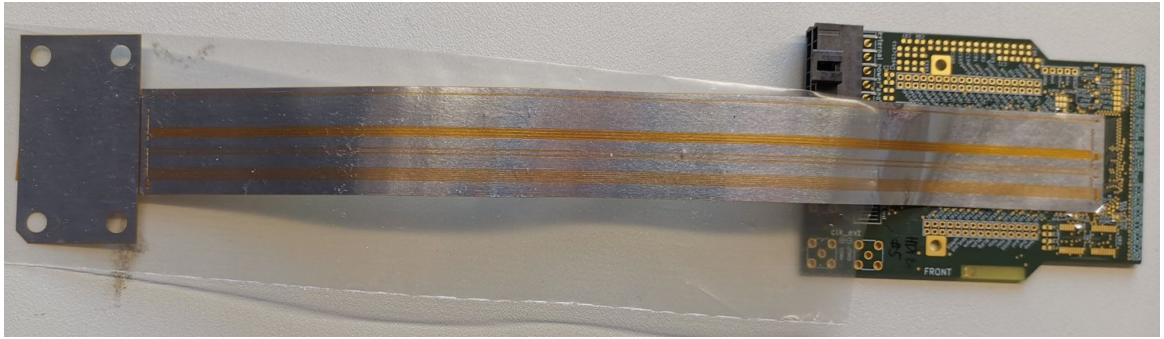


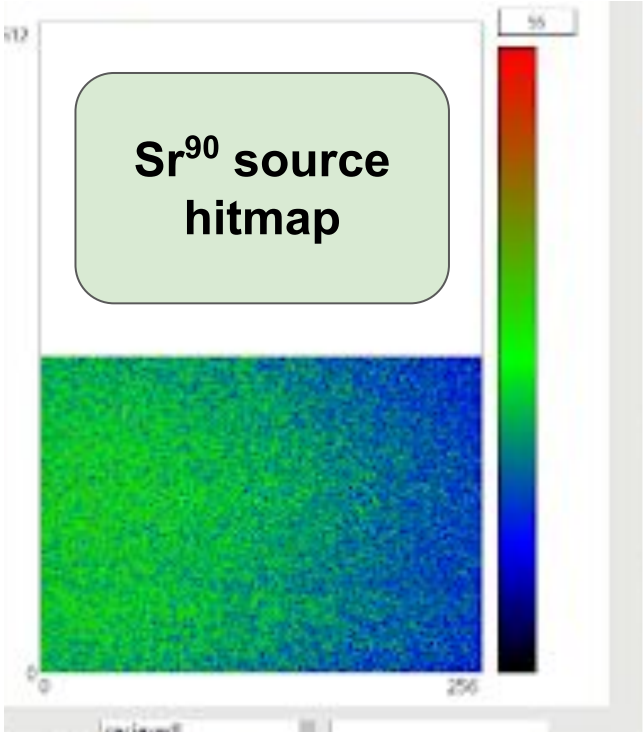
Mupix10 with HDIs

Aluminum HDis tested with Mupix10

Differential impedance matching (100 Ohms)

Tested with long single chip HDI

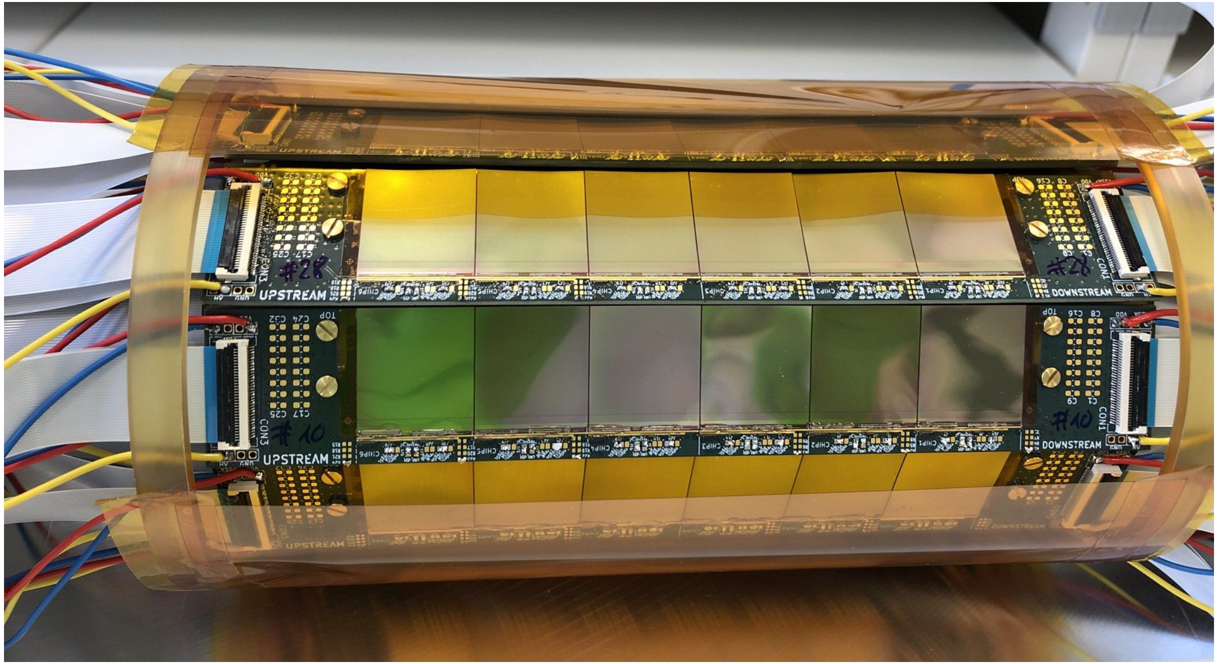




Length: 24 cm. Max length in experiment: 18 cm

Operation in experimental conditions

DAQ and experimental concept



Prototype of vertex detector

Jun/Jul 2021 and 2022

50 µm-thin chips mounted on katpon foils

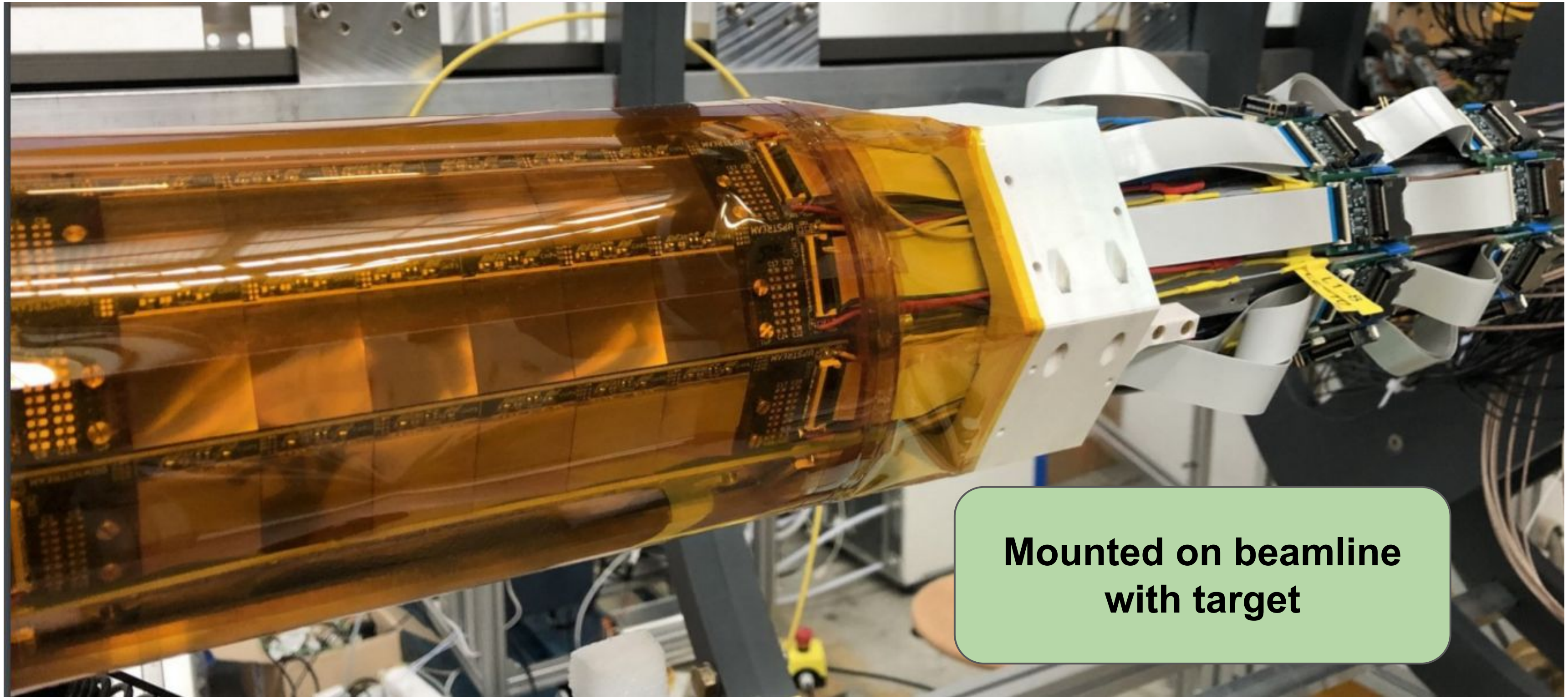
Connected to ladder-boards

Same shape as inner tracker, slightly larger radii

External connection with ribbon cables

Operation in experimental conditions

DAQ and experimental concept

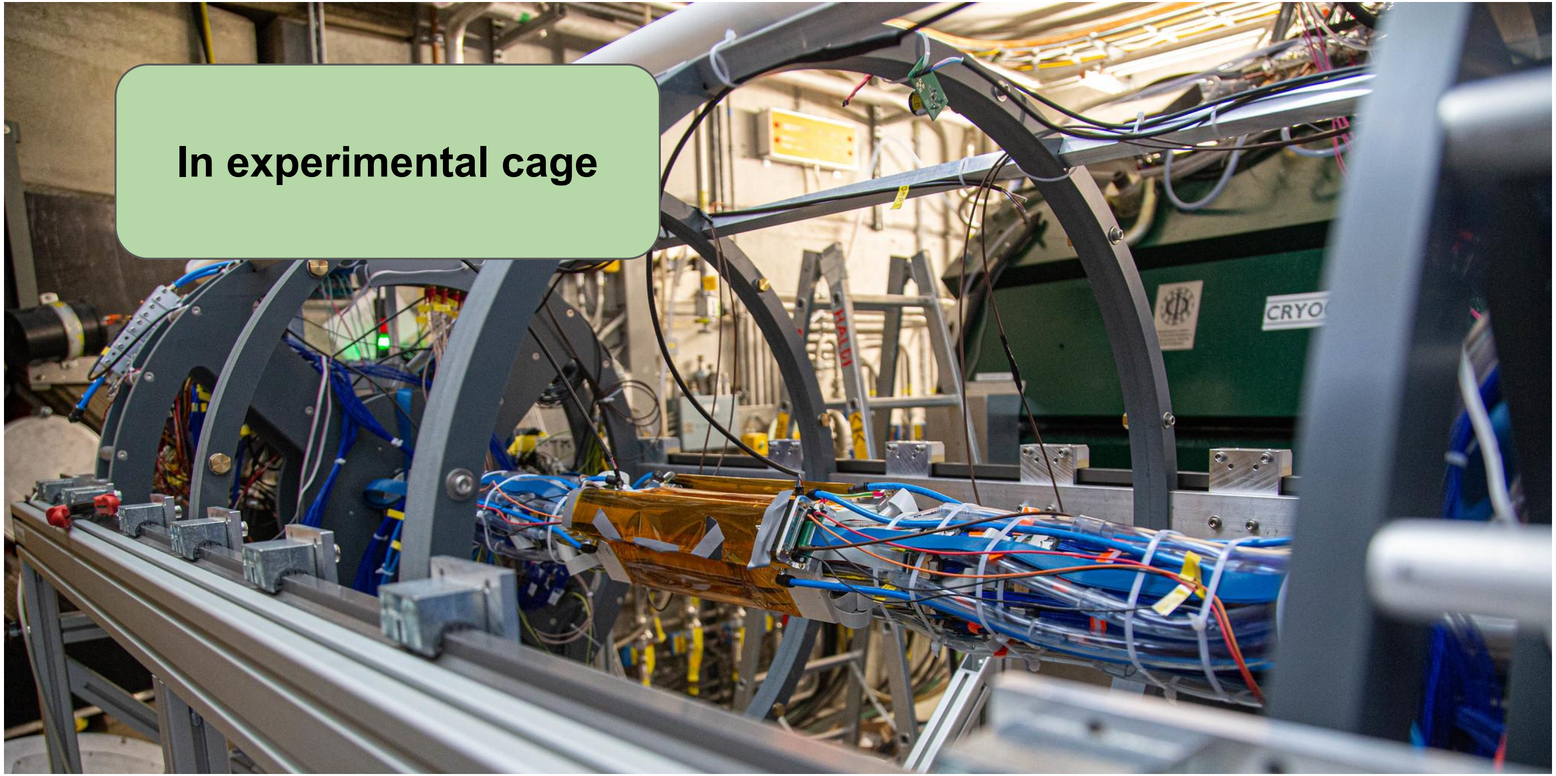


Mounted on beamline with target

Operation in experimental conditions

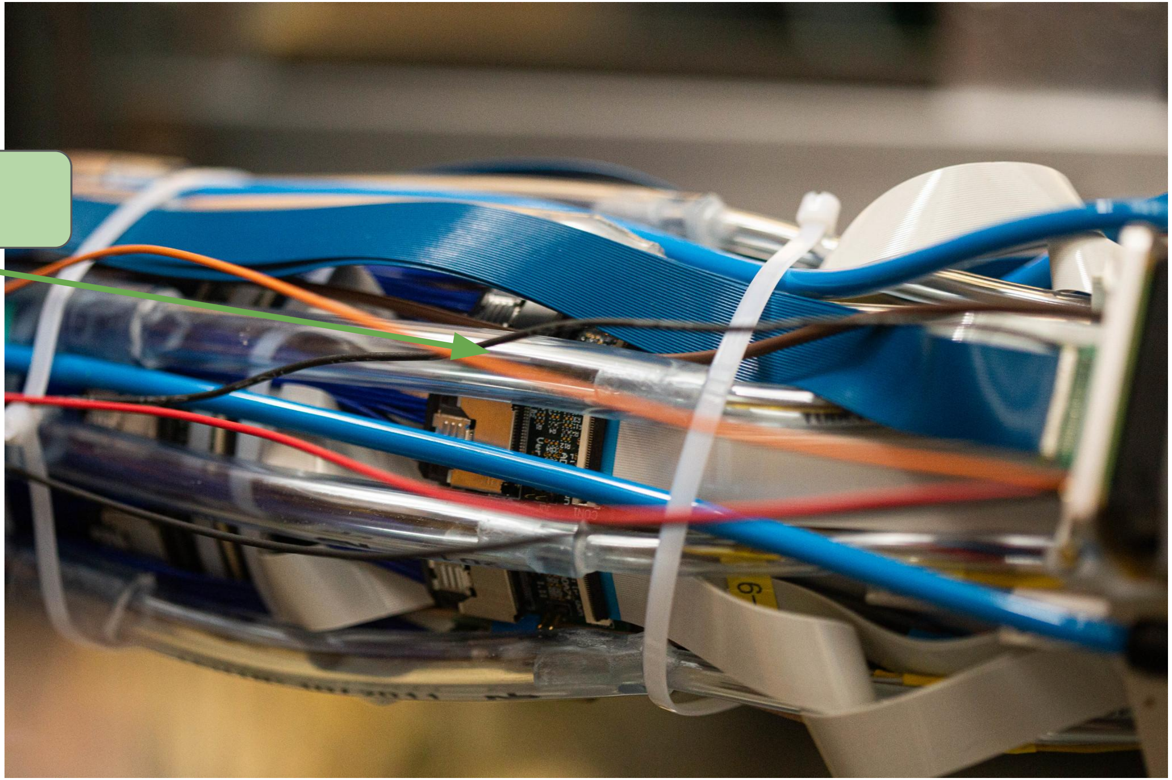
DAQ and experimental concept

In experimental cage



Operation in experimental conditions

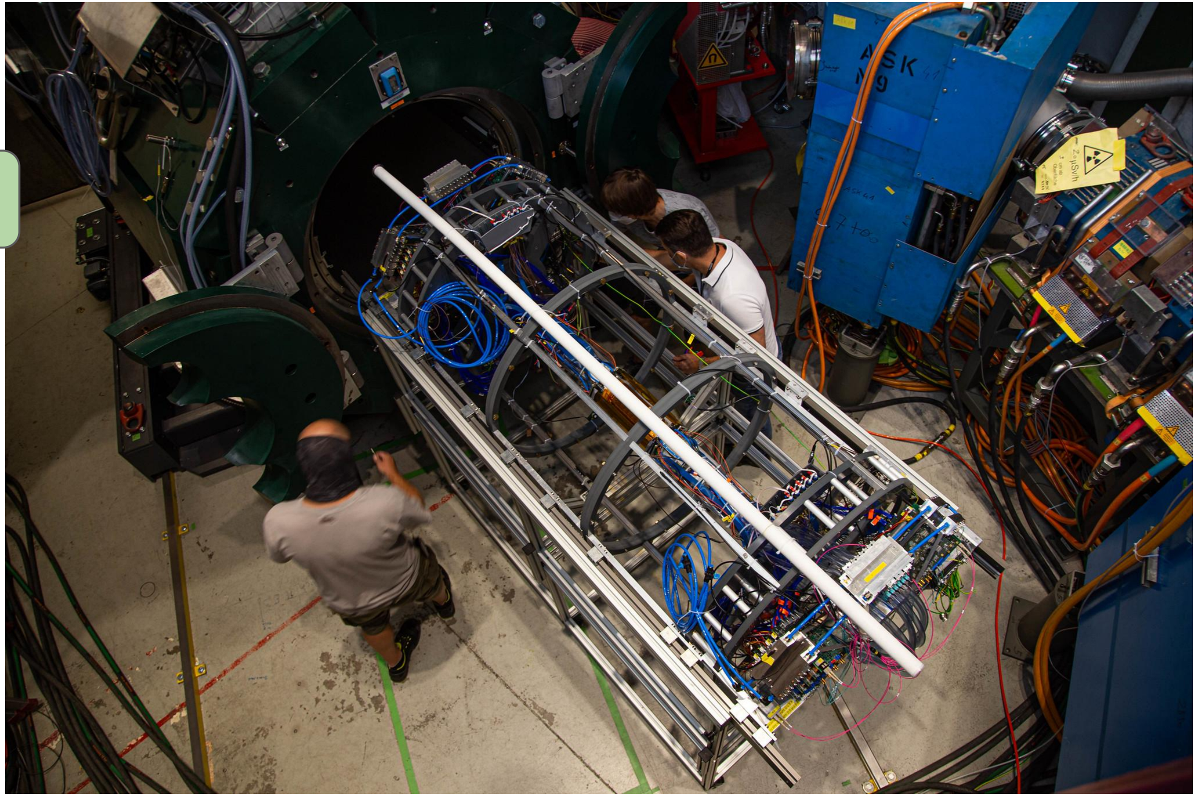
DAQ and experimental concept



Operation in experimental conditions

DAQ and experimental concept

Inside Magnet

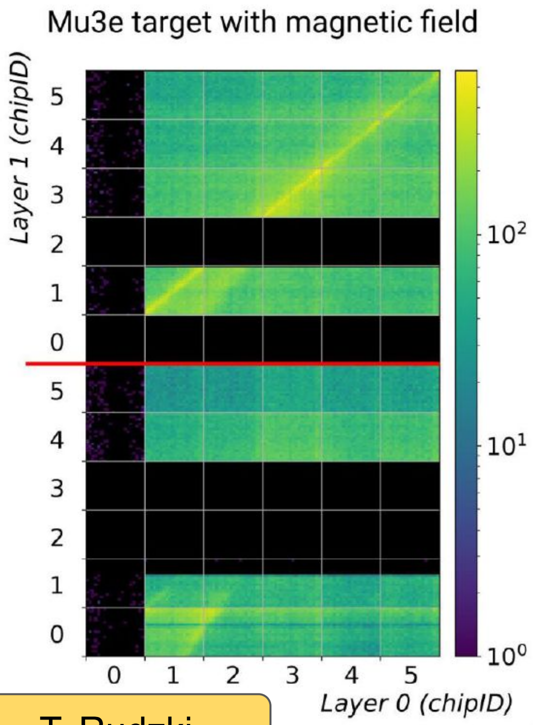


More pics at
https://www.flickr.com/photos/nberger/albums/72157719305216074/page1/

Operation in experimental conditions

Results

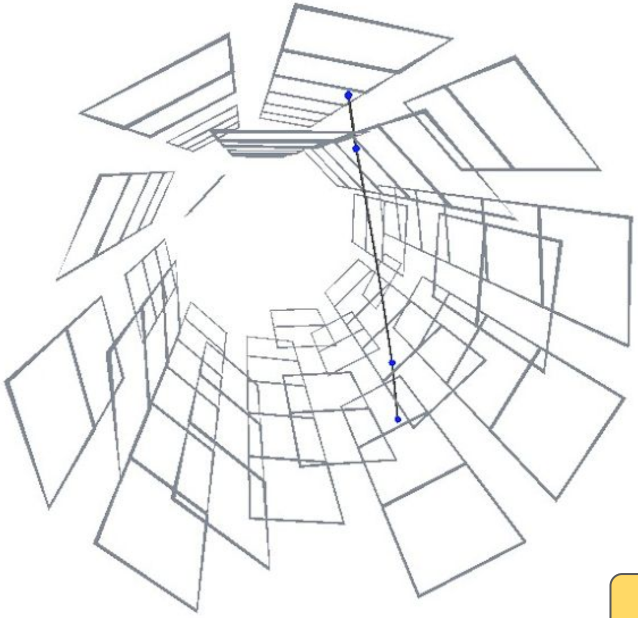
With beam (2021)



Layer 0-1 correlation!

T. Rudzki

With cosmics (2022)



More analysis ongoing

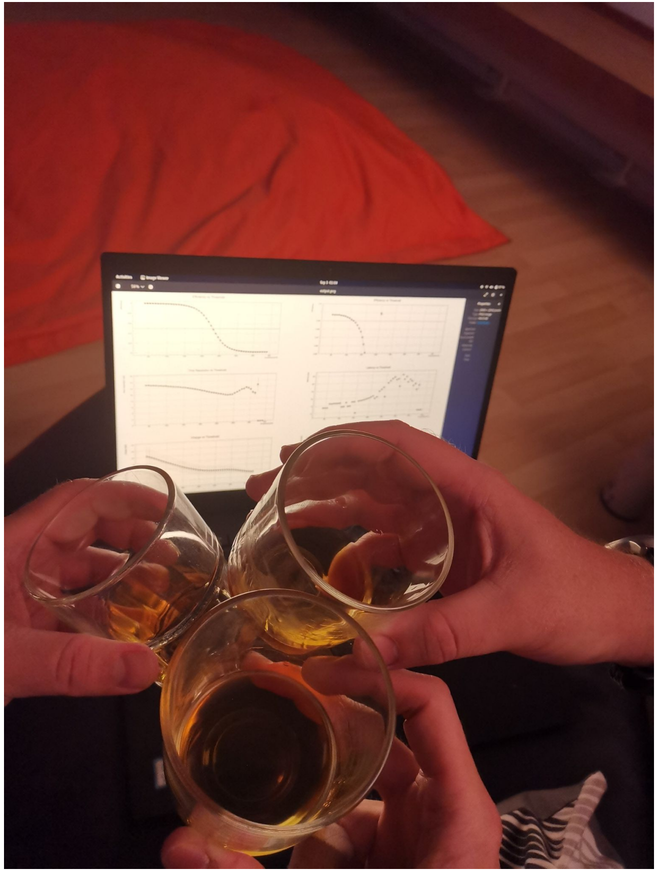
B. Gaygther

Conclusions

- Mu3e is a CLFV experiment which uses HV-MAPS to track electrons and positrons from muon decays
  - High rates
  - Low energy
- Tight experimental constraints on pixels ⟶ HV-CMOS!
- MuPix development at the forefront of HV-CMOS R&D
- MuPix10 satisfies most of experimental requirements
- Prototype of vertex detector successful
- MuPix11 testing ongoing
- Pre-production of Mu3e starting by end of the year

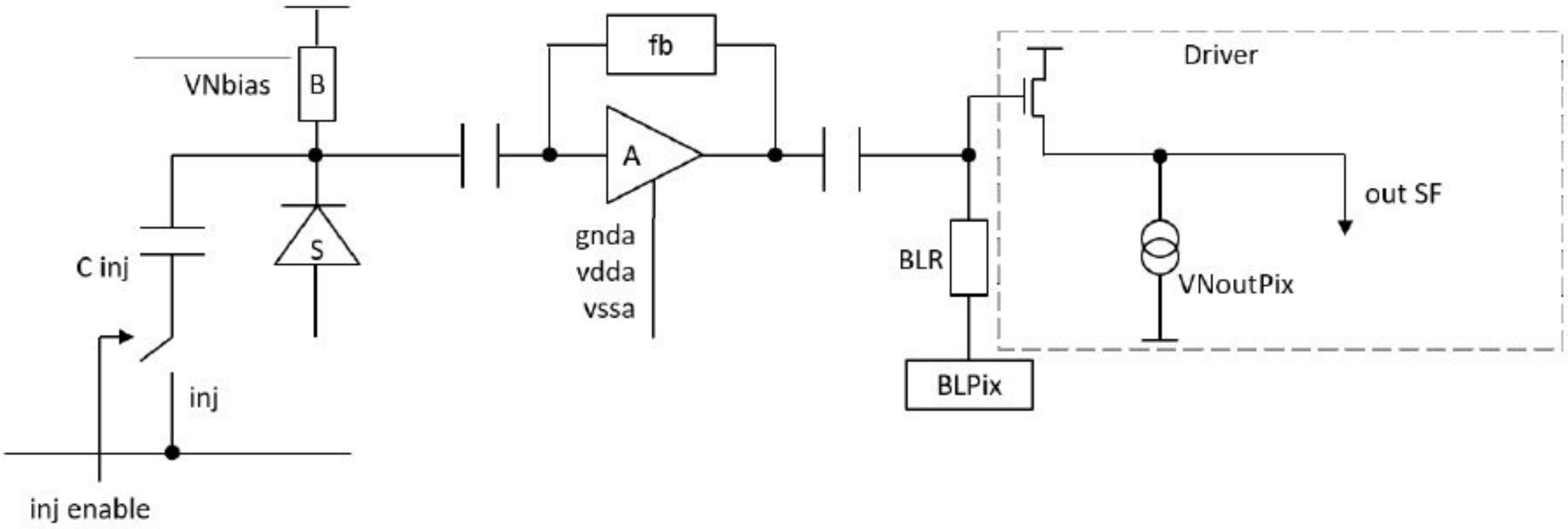
Backup

Mupix11 results (preliminary)



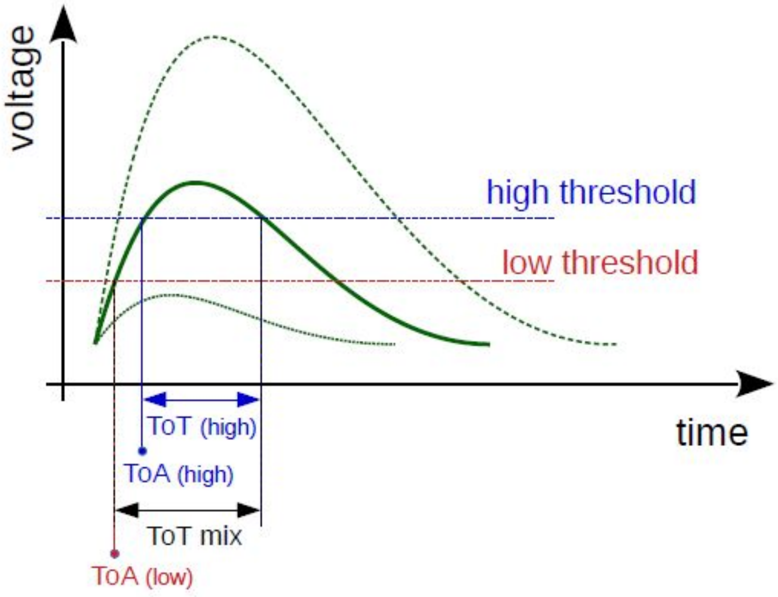
MuPix sensors: MuPix10

Single pixel read-out: in-cell



MuPix sensors: MuPix10

Single pixel read-out: periphery



Comparator in digital cell

Records Time-of-Arrival (ToA)

Records time of falling edge

Time-over-Threshold (ToT) computed

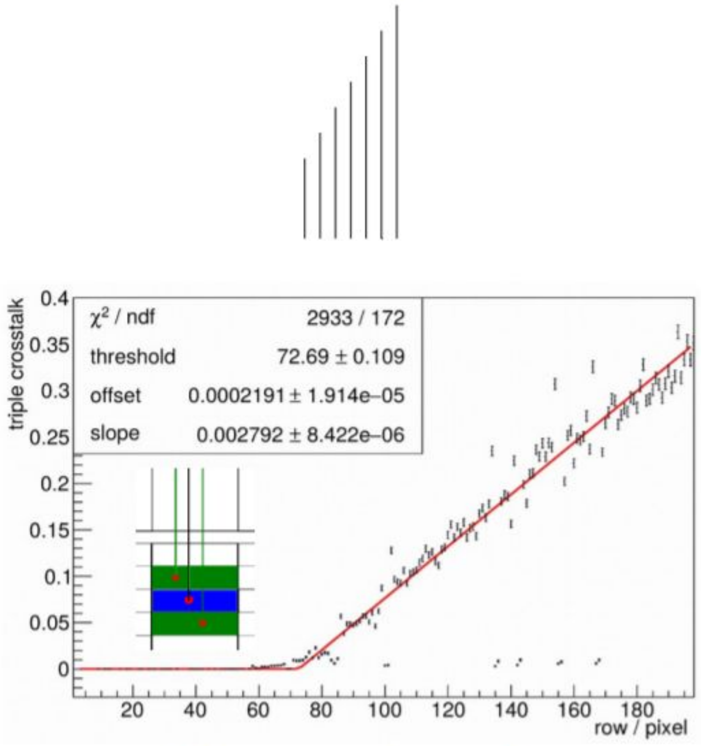
2 threshold mode:

- hit flag raised with high threshold
- ToA recorded with low threshold
- Falling edge on high threshold

Decreases time-walk

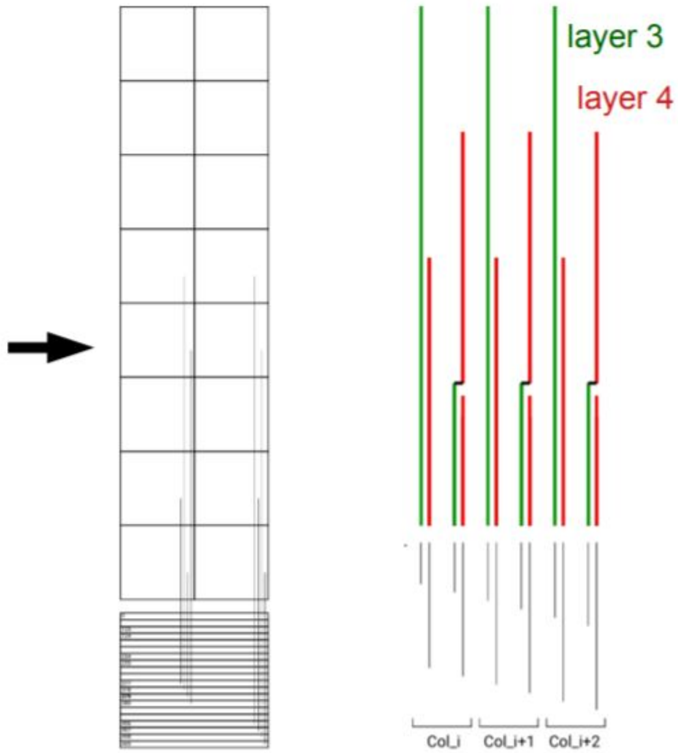
Backup: crosstalk

Mupix8 Layout



Triple cross talk probability

New Mupix10 Layout

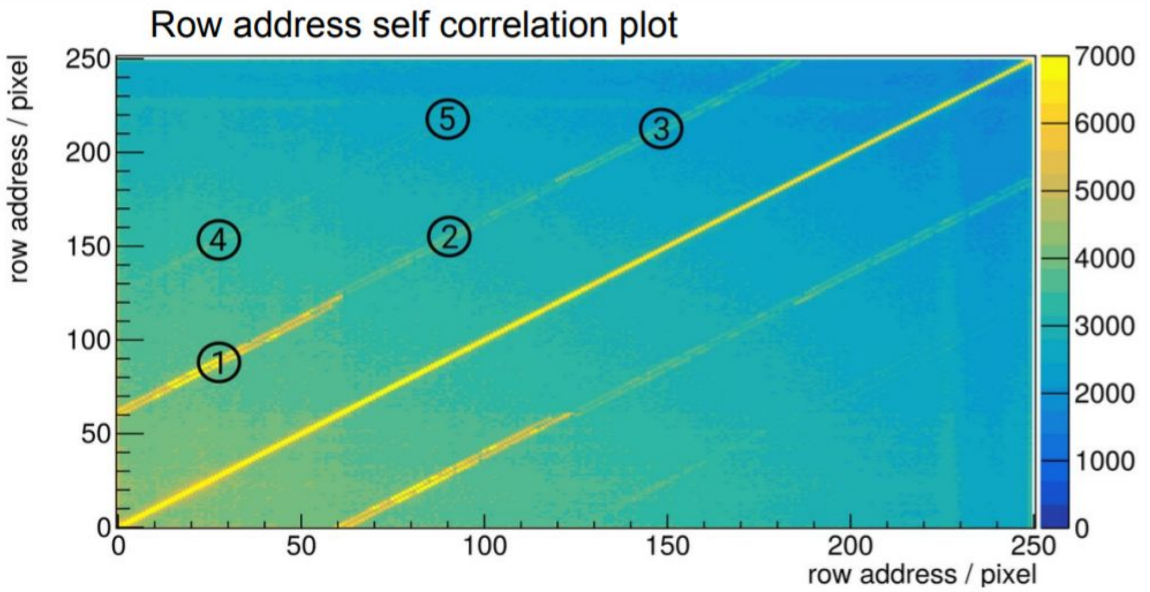


double column

2-metal layers

MuPix10: results

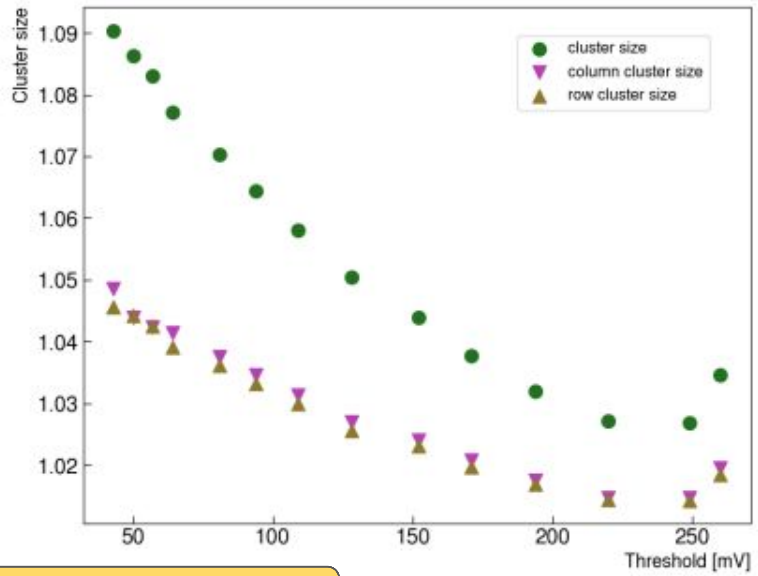
Cross-talk

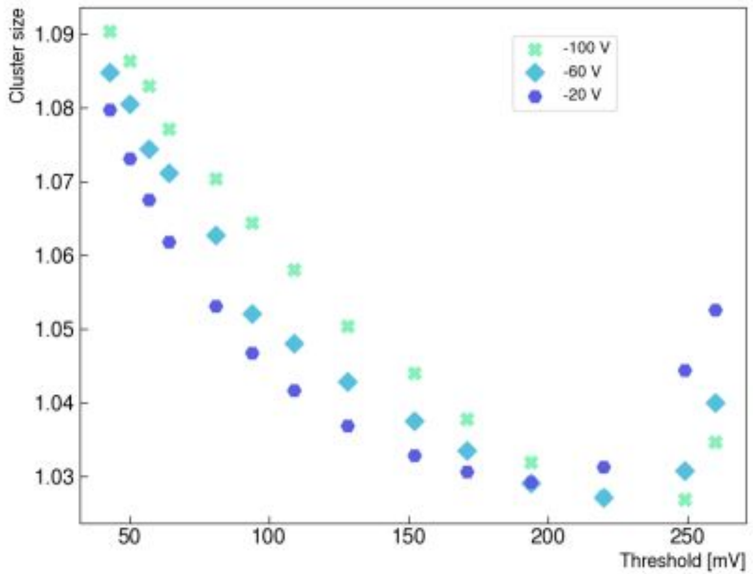


Multiple metal layers (TSI specific) used to minimize inter-line capacitances.
Cross-talk probability < 1.5%

Neighbouring pixels are routed on different lines: cross talk distinguishable from charge sharing

Mupix10 detailed studies





A.M. Gonzales

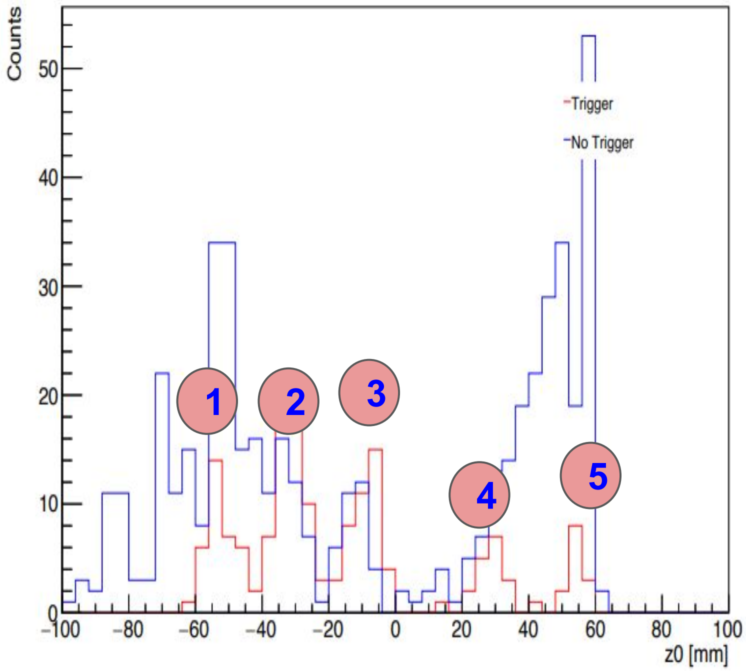
Cluster size vs threshold
Large threshold -> bias towards delta rays

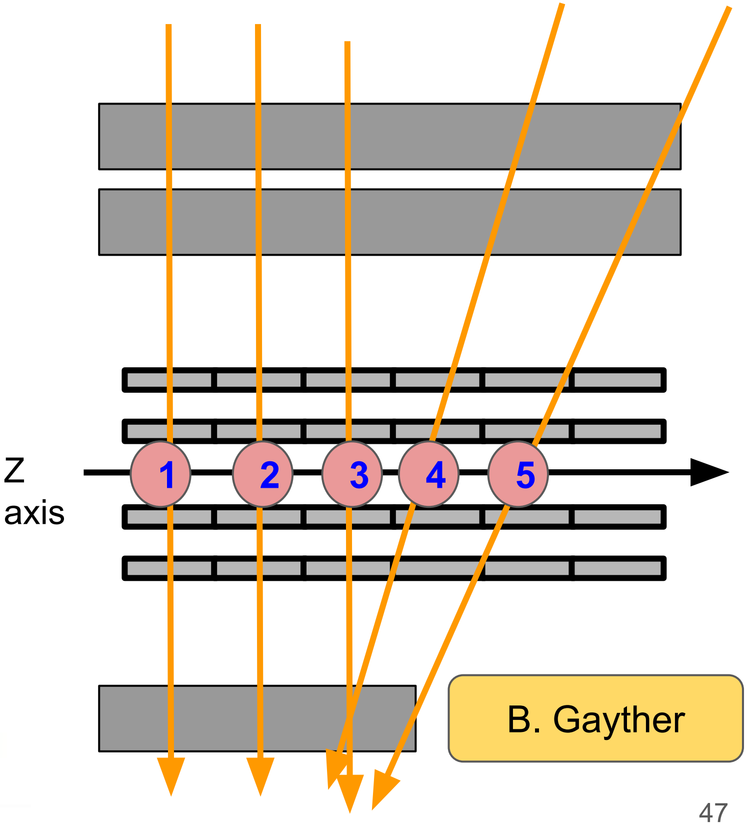
Operation in experimental conditions

Results

With cosmics

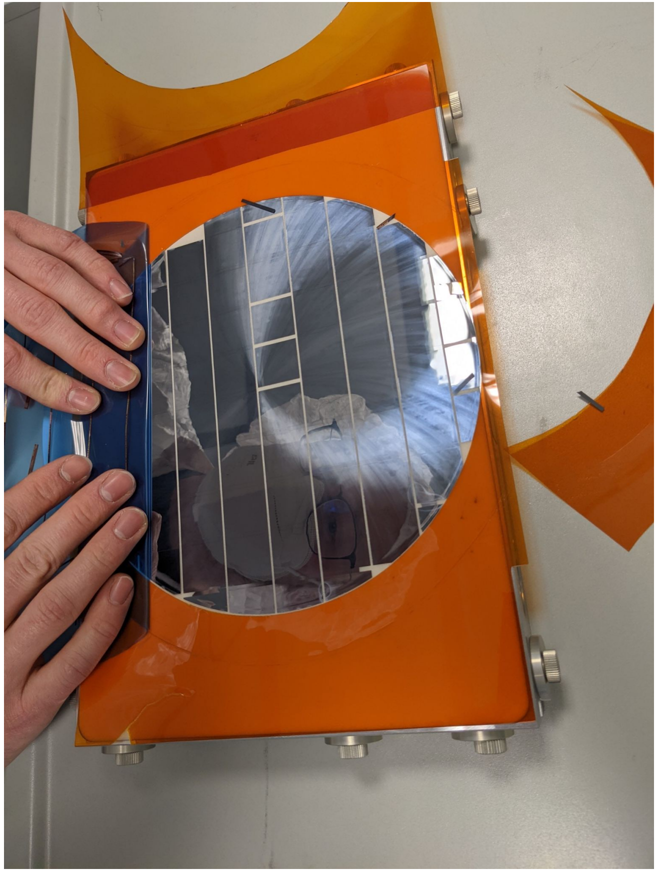
Distribution of z0: closest point of approach along z axis

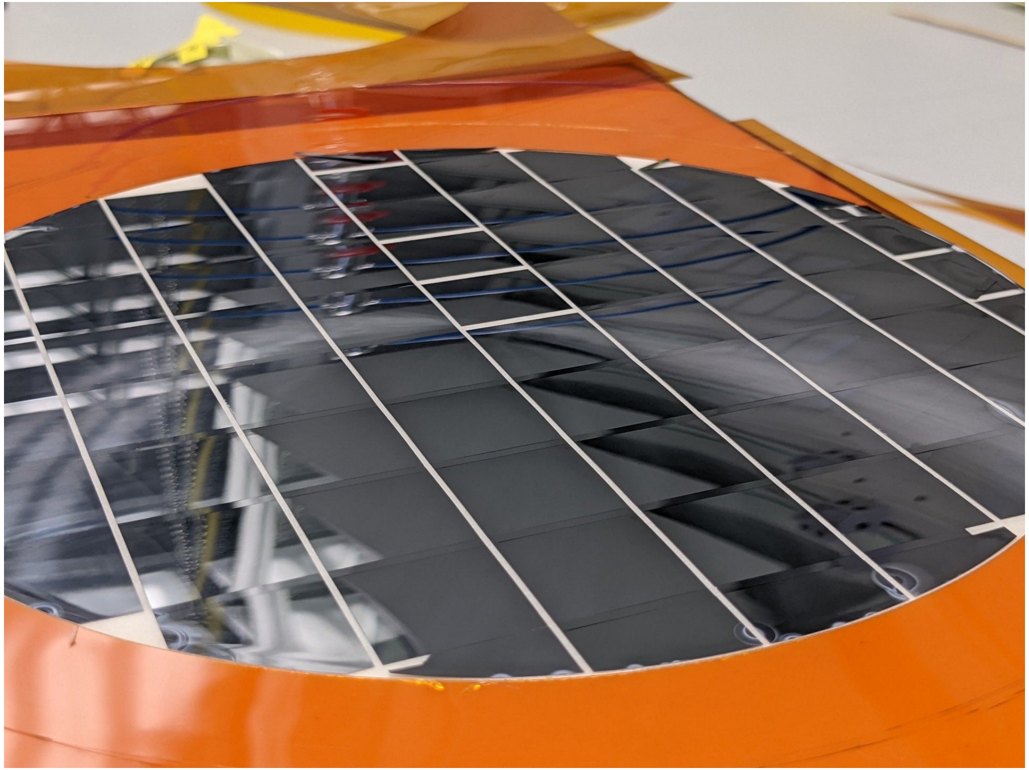




B. Gayther

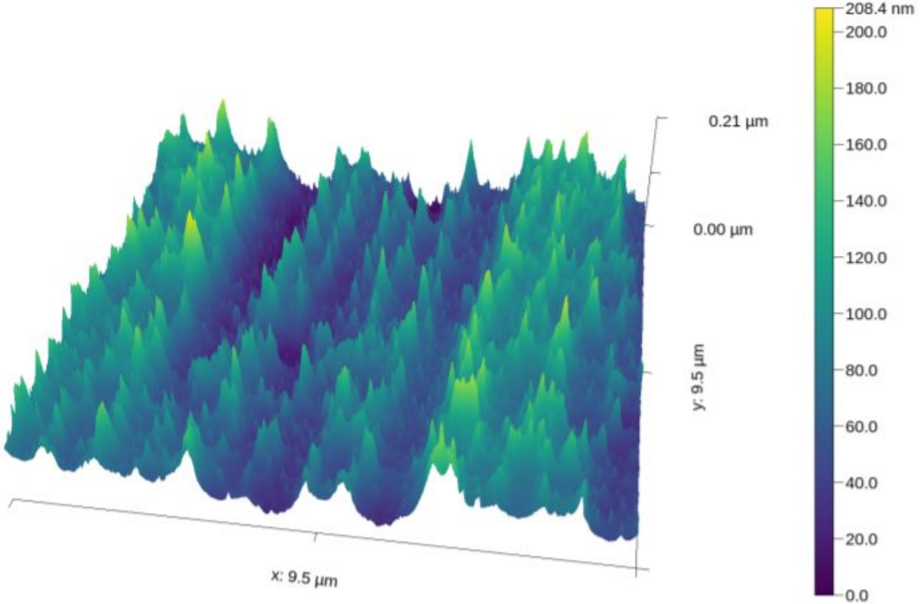
Backup: chip picking

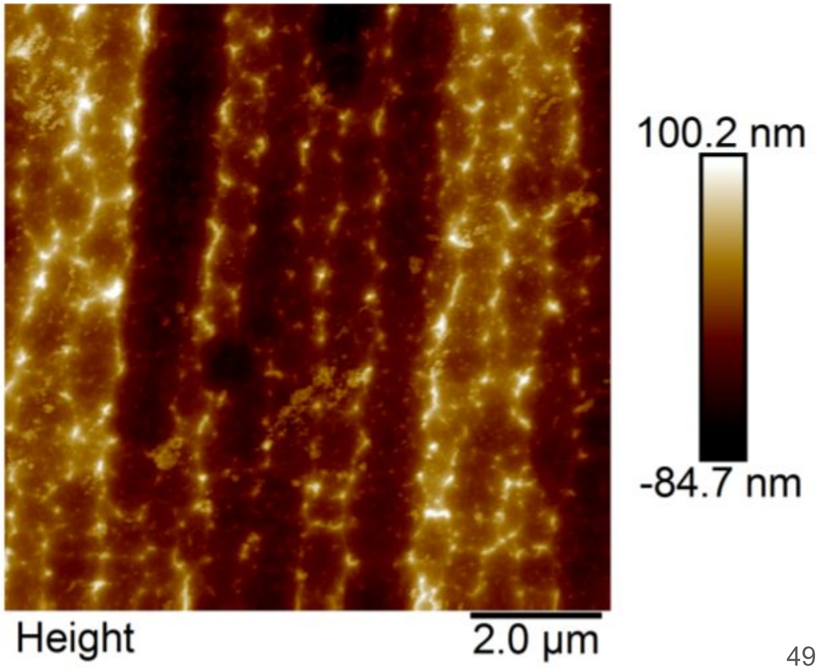




Backup: thinning issue

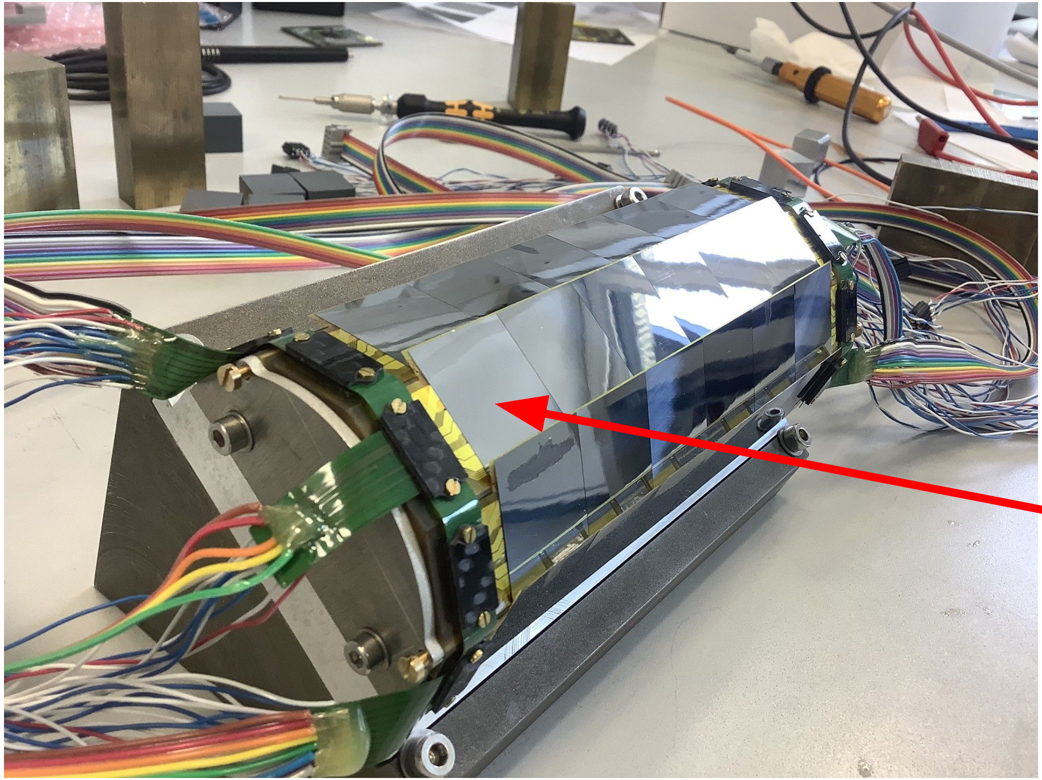
Atomic force microscopy on backside





Backup: Prototyping

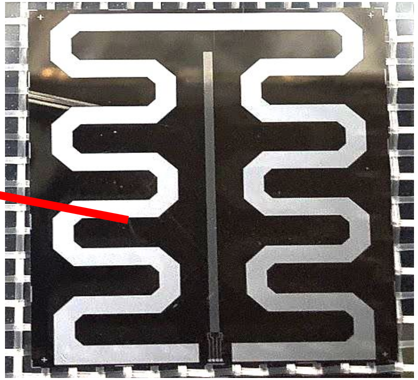
Thermo-mechanical stability



Silicon heater prototype

Reproduction of inner tracker with same materials and connections

Chips are just passive silicon heaters

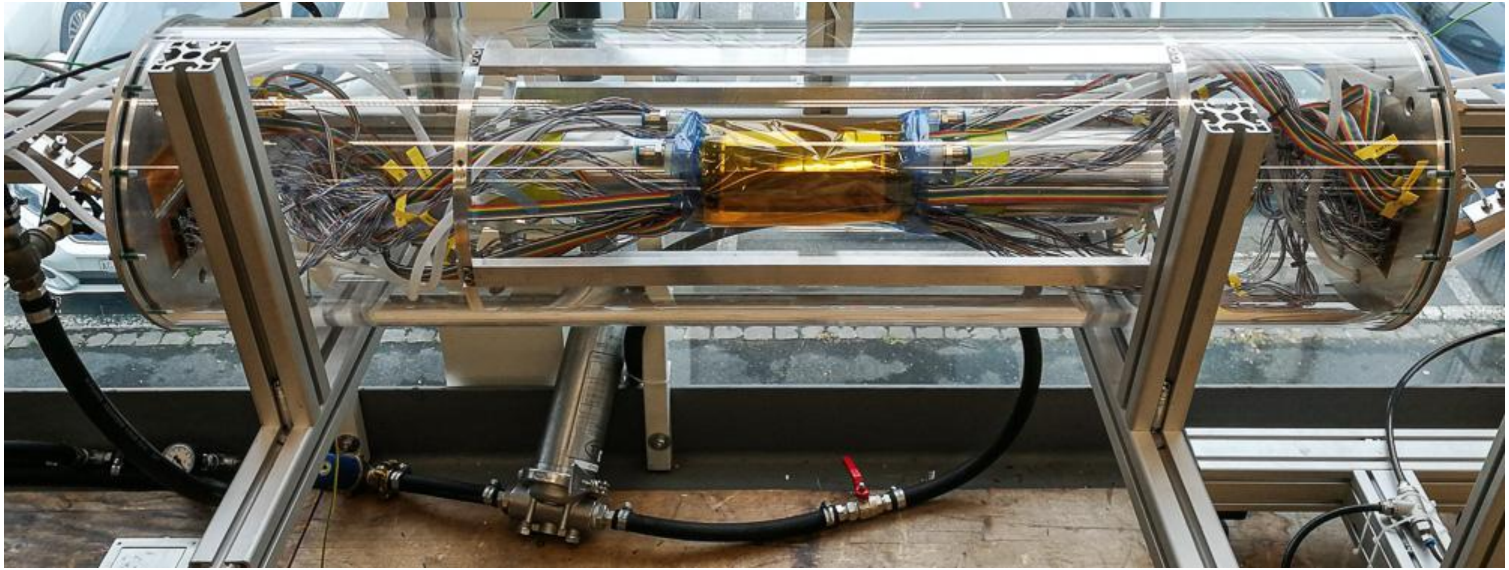


Backup: Prototyping

Thermo-mechanical stability

Silicon heater prototype

Test stand
with Helium
cooling
system

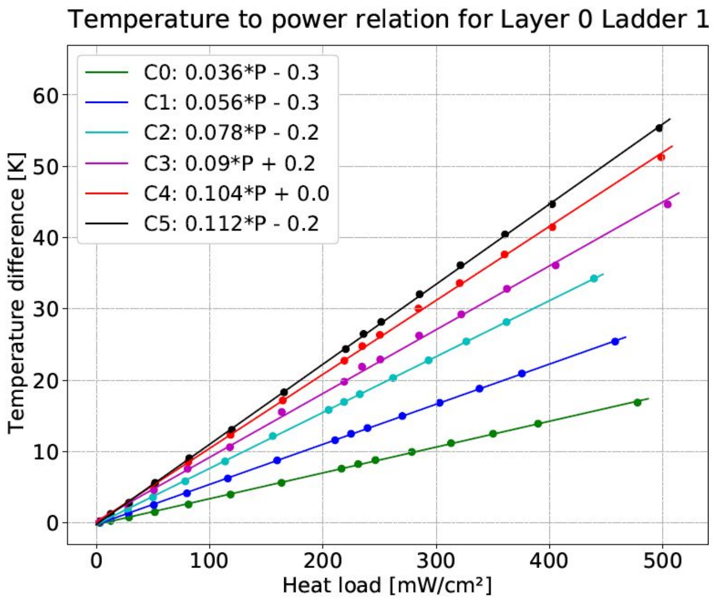


Backup: Prototyping

Thermo-mechanical stability

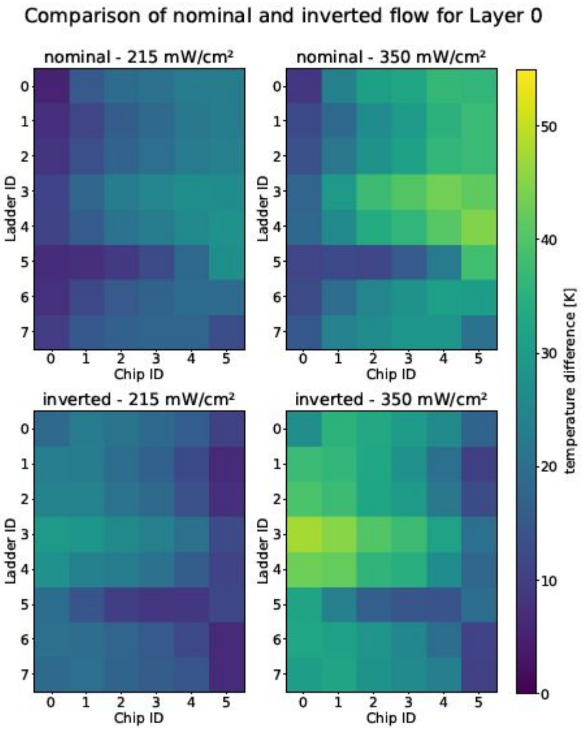
Silicon heater prototype

- Measurement of temperature-to-power relation
- Temperature difference linearly depending on heat dissipation
- Expected ΔT < 70 K for 350 mW/cm² (conservative limit)
- Cooling concept works ✅
- More detailed studies to come

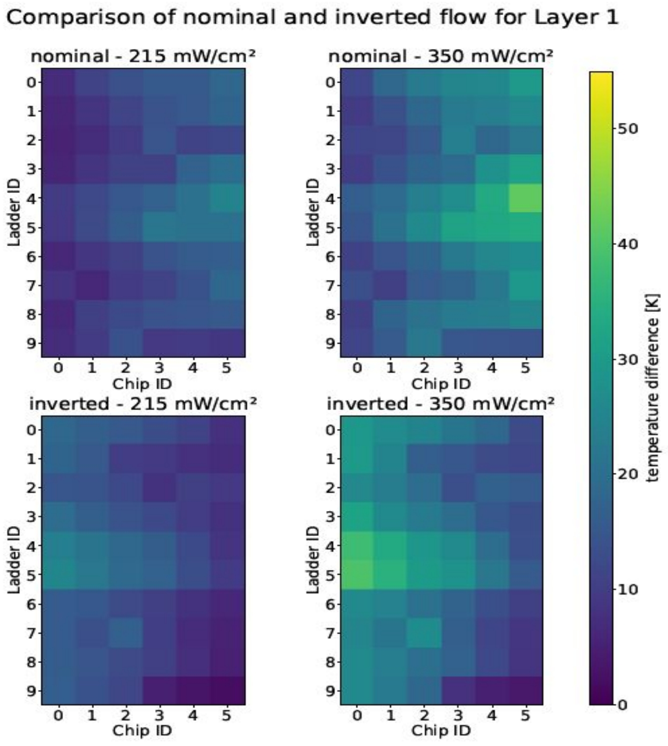


Backup: Prototyping

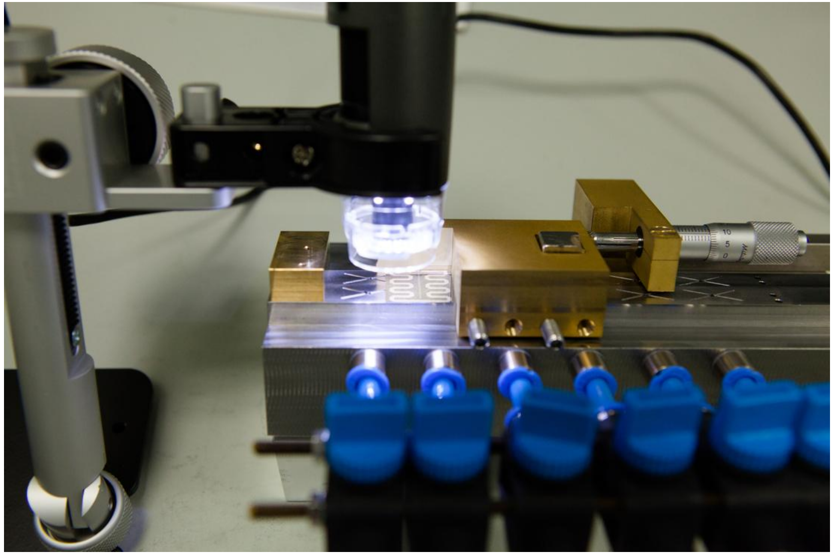
Thermo-mechanical stability



Silicon heater prototype



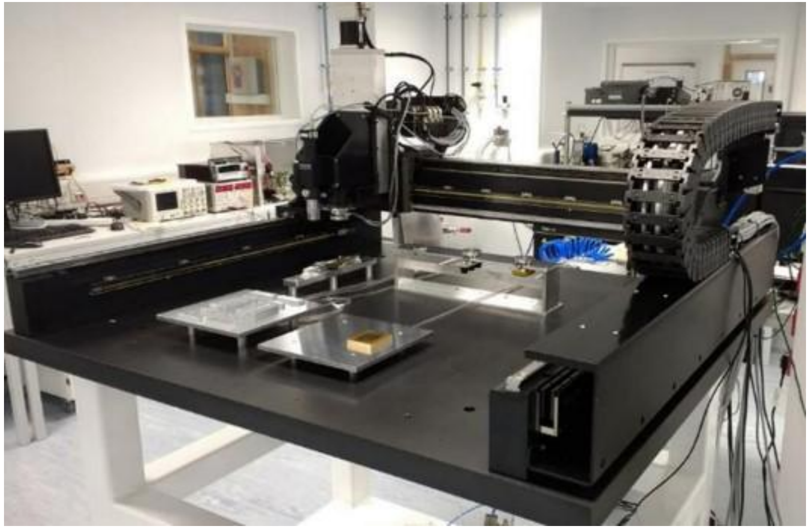
Production of inner layers



Heidelberg/PSI

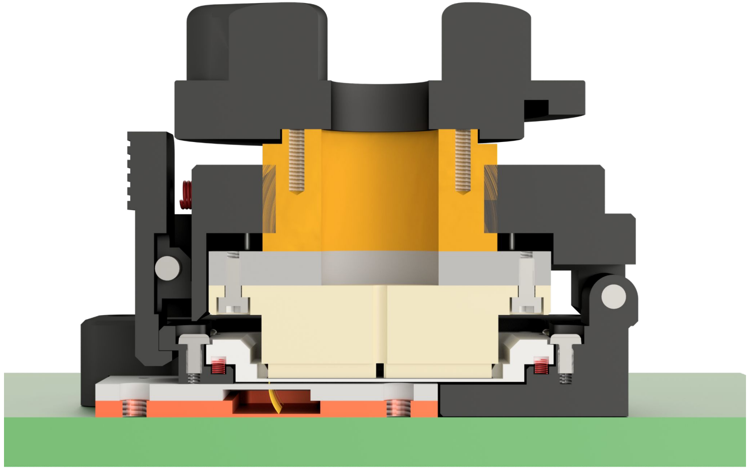
Quick demo: https://youtu.be/0SYqHSbH3U4

Production of outer layers



Oxford/Bristol/Liverpool

Single chip testing



Probe card for single chip: one Mupix layed inside the socket, the knob presses it against the needled. The same card can be used in probe stations with different needles.