Towards the Mu3e Pixel Tracker with MuPix11: Construction & Performance Studies

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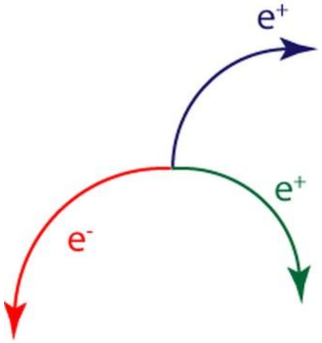
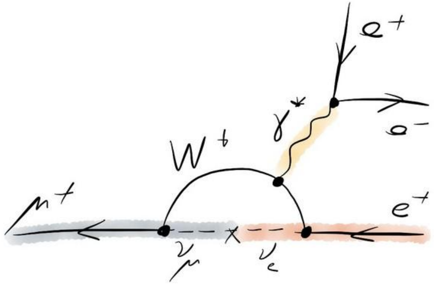
Physikalisches Institut Heidelberg

32nd International Workshop on Vertex Detectors 2023

18.10.2023

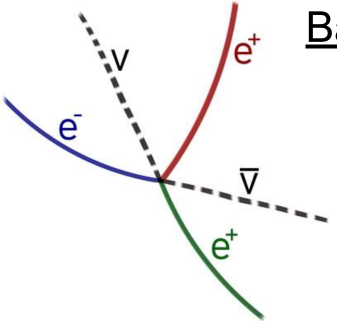
Mu3e: Physics Motivation



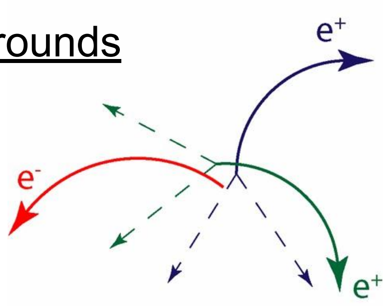


- Search for the cLFV decay **$\mu^+ \rightarrow e^+e^-e^+$** ($\nu$SM: BR < 10^{-54})
- Current limit (SINDRUM) BR < 10^{-12} @ 90% CL
- Sensitivity goal (Phase1): 1 in 10^{15} decays
- Up to 10^8 decays per second
- Suppress background below sensitivity level

<u>Backgrounds</u>

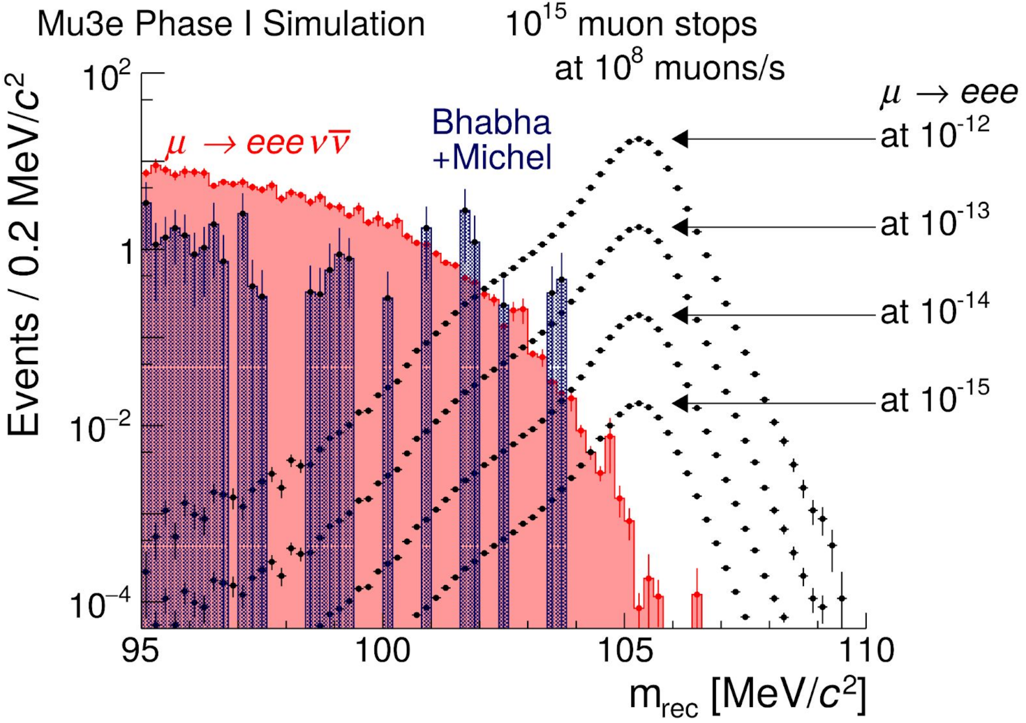


Internal Conversion



Accidental

Experimental sensitivity



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

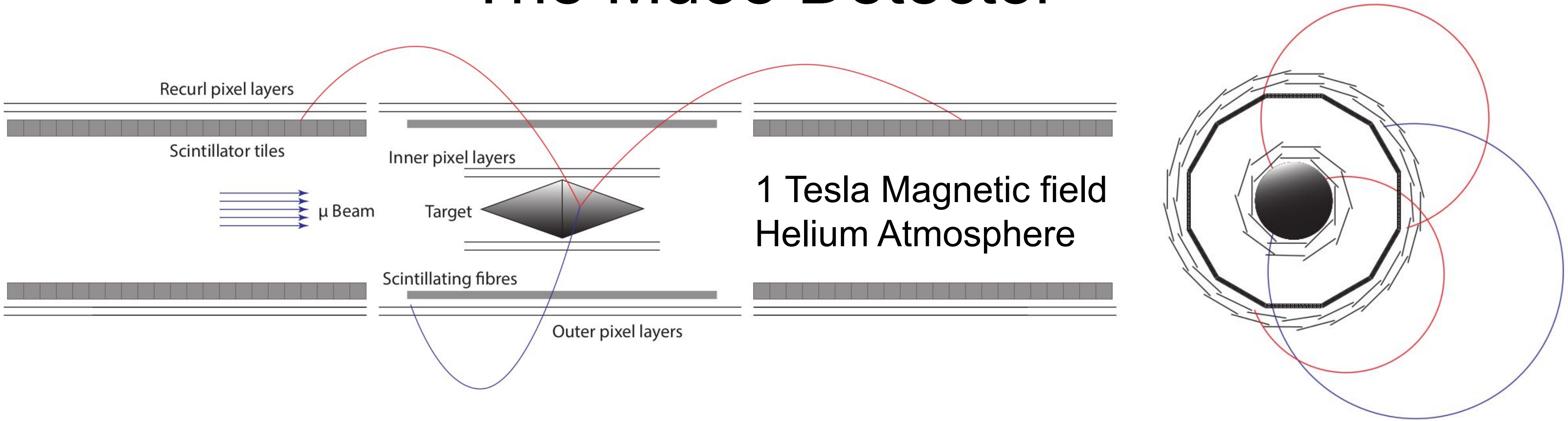
Momentum resolution crucial for detecting the peak at muon mass…

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

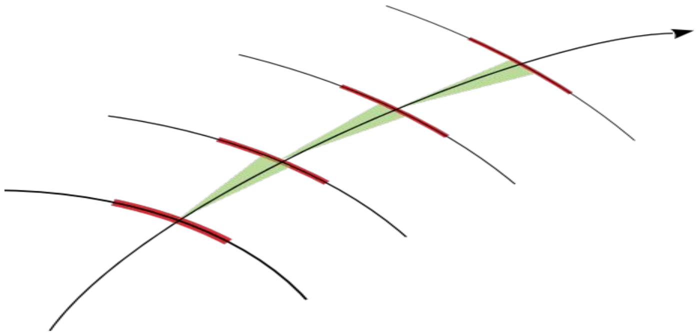
The Mu3e Detector



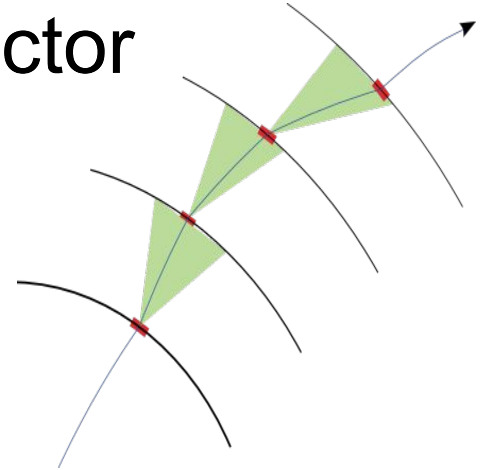
- 10^8 decays per second
- $p_{max} = m_\mu/2 = 53$ MeV
  - ➡ Multiple Coulomb Scattering
  - ➡ Triplet Fit **[arXiv:1606.04990v2]**
- Good vertex and time resolution (100 μm & 500 ps)
- Excellent momentum resolution (0.5 MeV)
- Continuous Beam! No trigger!
  - ➡ Online reconstruction and selection

Helium Gas Cooling
arXiv:2301.13813, **arXiv:2307.14803**

The Mu3e Detector



Spatial resolution dominates



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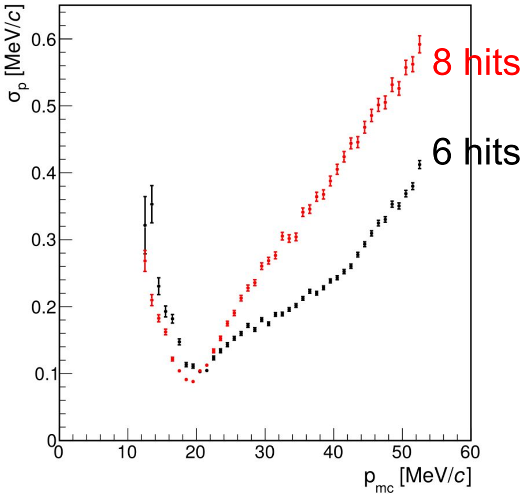

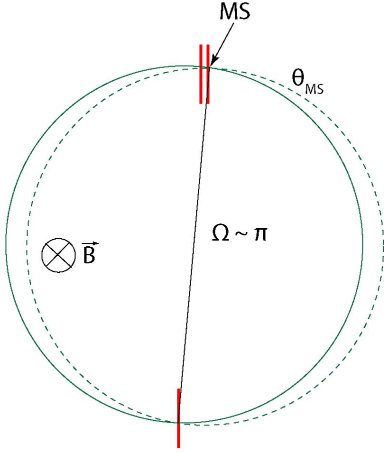

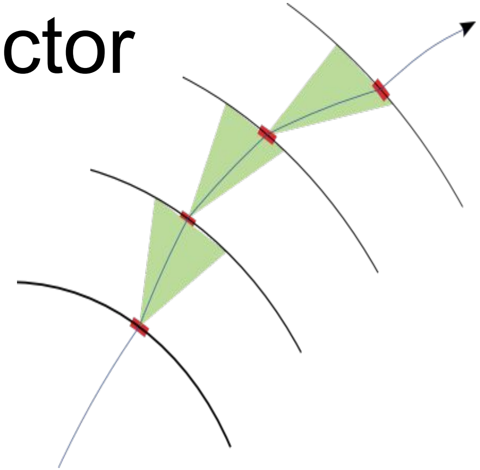

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The Mu3e Detector

Pixel detector requirements:

Pixel Size	Time Resolution	Material Budget	Efficiency
80 x 80 μm^2	< 20 ns	0.1% X_0/layer	> 99 %

Mu3e TDR [arXiv:2009.11690]

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- $p_{max} = m_\mu/2 = 53$ MeV
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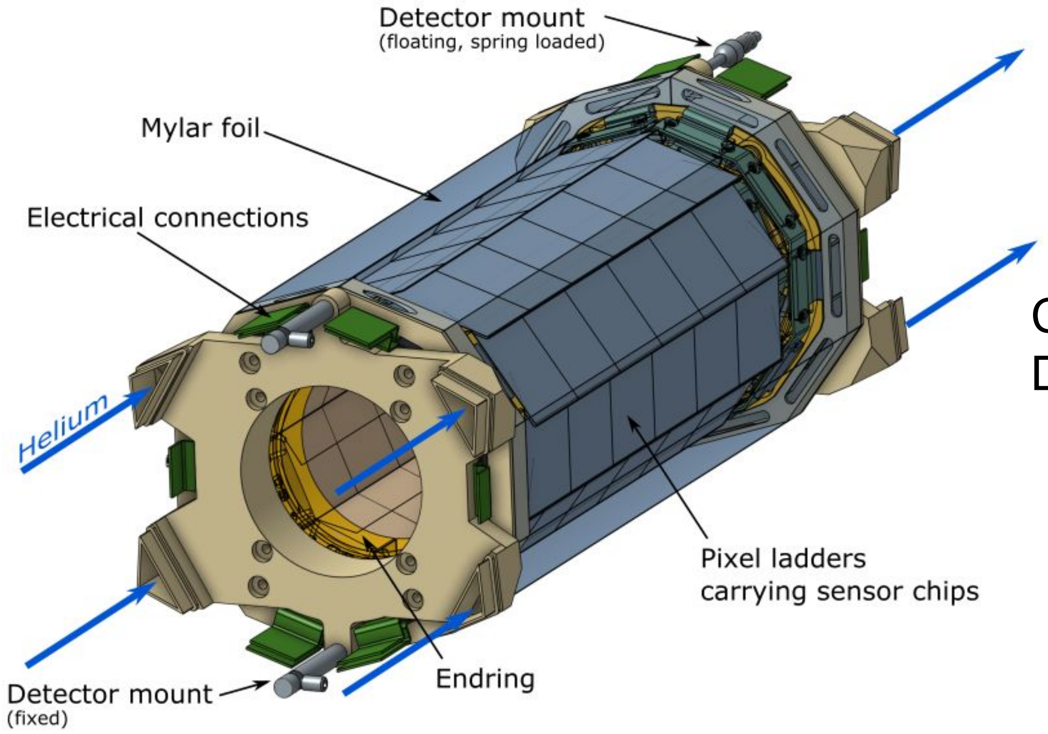
Tracking System - Vertex Detector

Layer 0+1



Chips glued and bonded 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)

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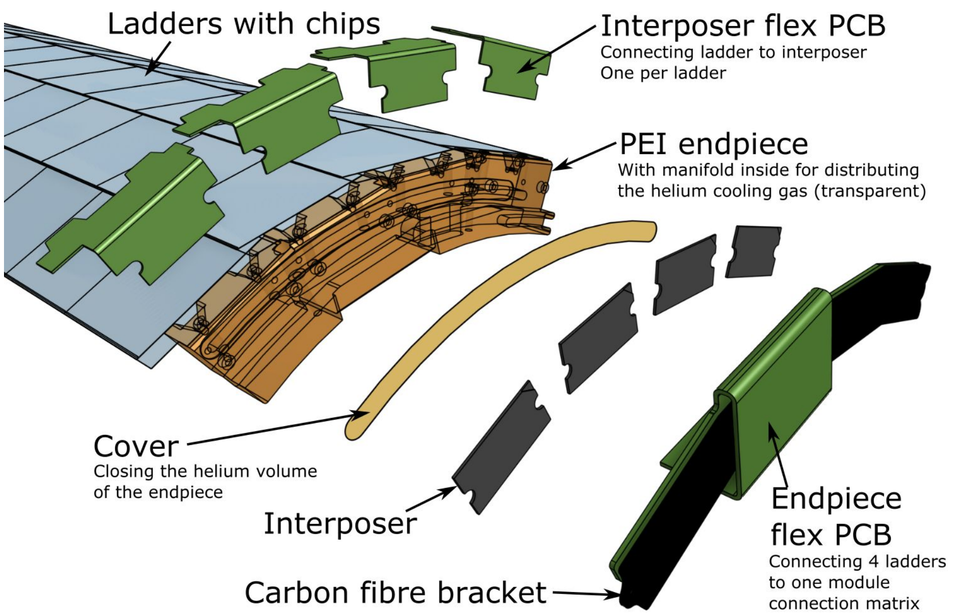

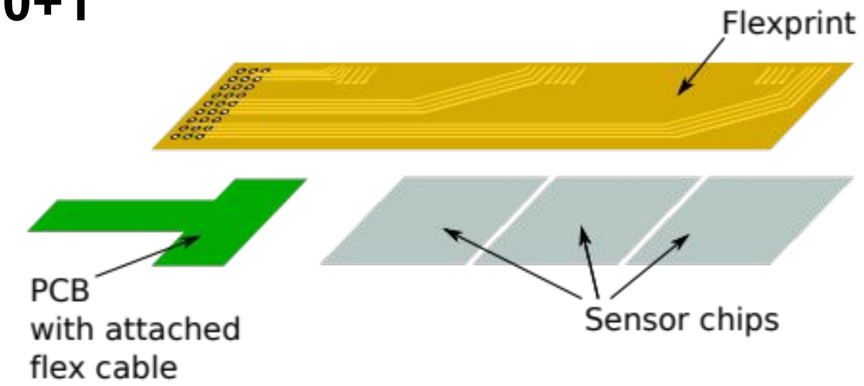

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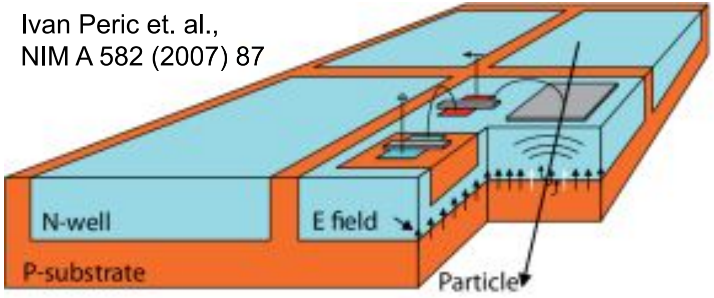
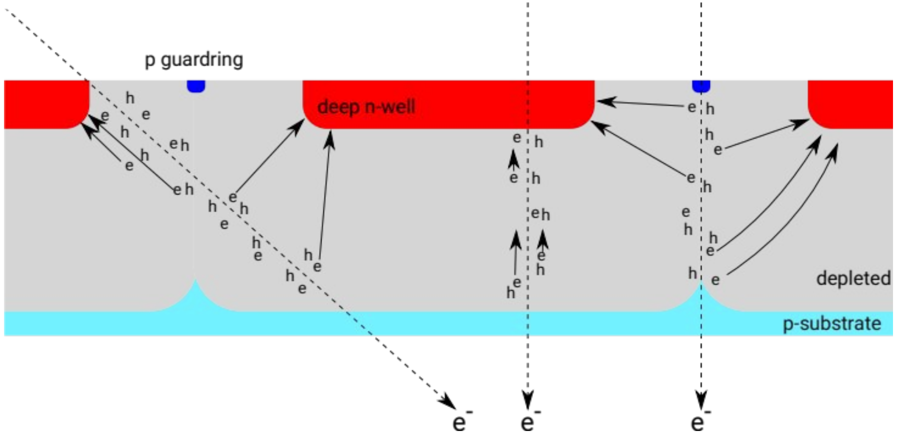
High Voltage - Monolithic Active Pixel Sensors

Ivan Peric et. al.,
NIM A 582 (2007) 87

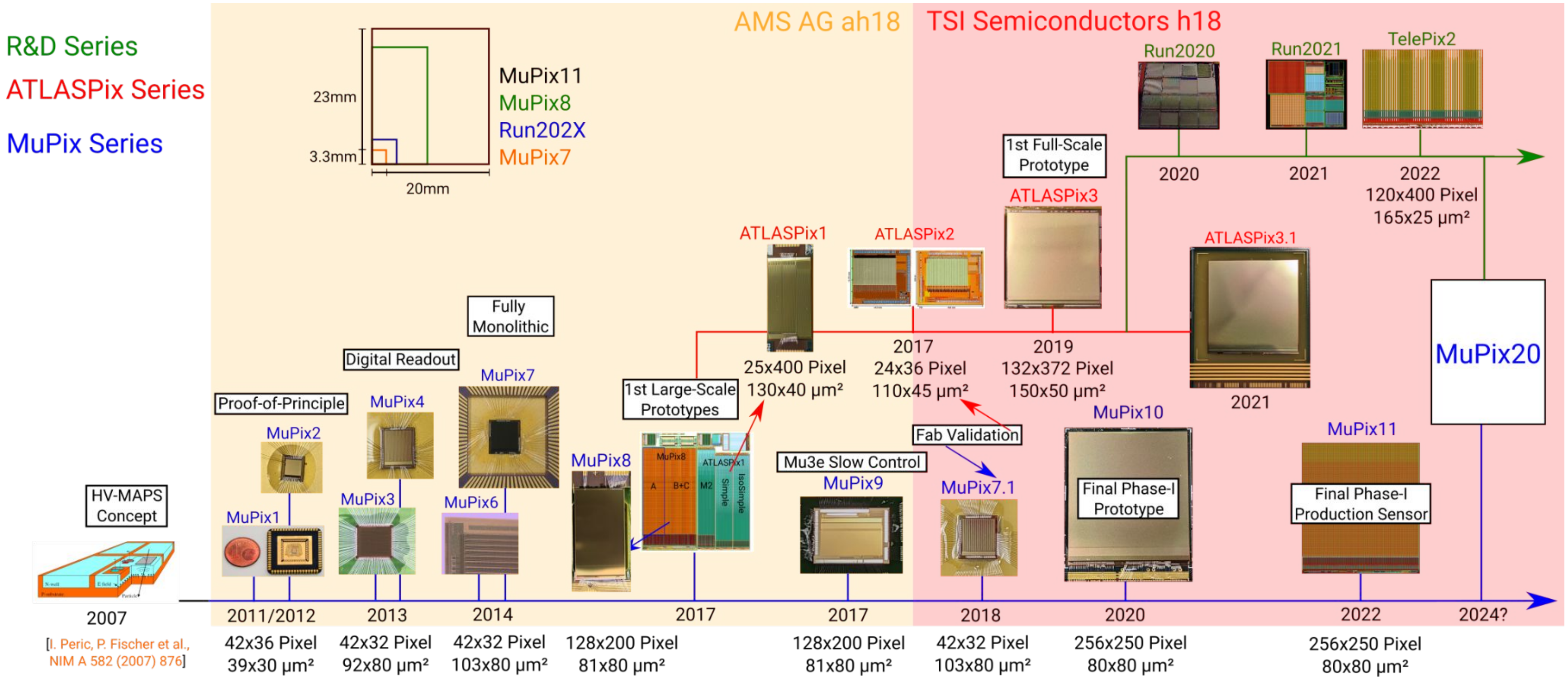


- In-pixel electronics
- Monolithic design:
  Detection and Readout
  combined in one chip
- Chips are thinned to 50 μm

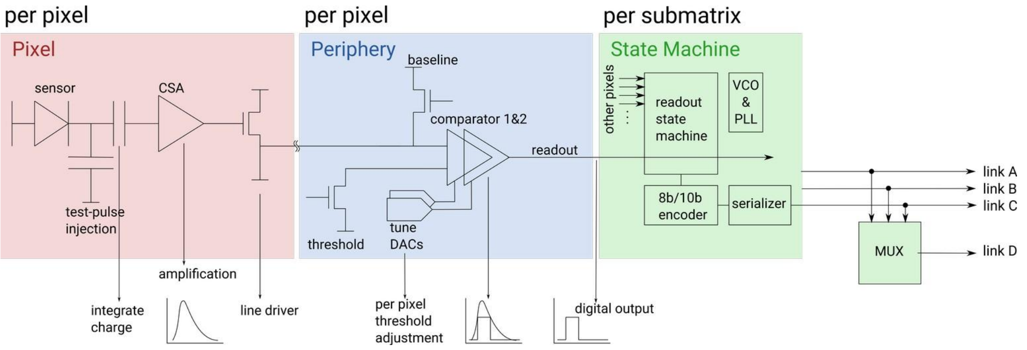
- Commercial HV-CMOS processes:
  TSI 180nm (h18)
- Deep N-well diode
- Low Ohmic substrates (10-400 Ωcm)
- High voltages up to 100V
- Charge collection via drift

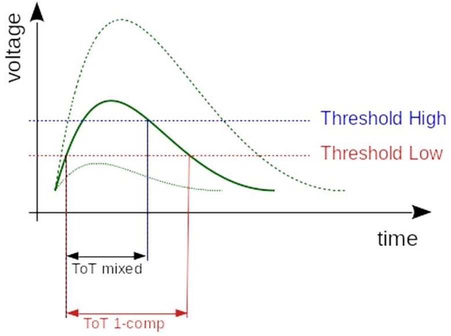


MuPix/HV-MAPS R&D process



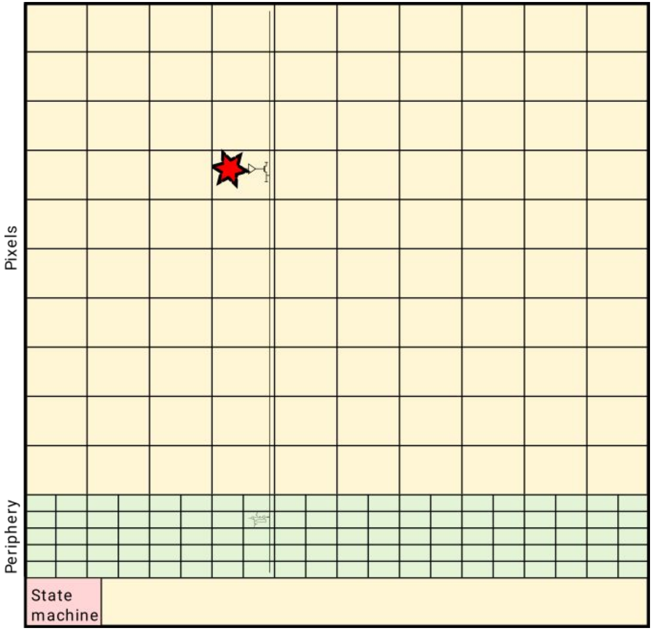
MuPix Architecture





- Clear separation of analog and digital electronics
- 2 comparator design
- Tuning/Trimming and masking available
- Priority encoder / column-drain readout
- Chip sub-divided into 3 matrices → 1 Data link each + 1 multiplexed link

The MuPix Principle



Courtesy: Frank Meier

- Deposited charge amplified by in-pixel amplifier
- Source follower drives the signal to the periphery
- Digitisation in periphery
- Timestamp sampling
- Readout statemachine manages column-drain readout
- Data is send out via a 1.25 Gbit/s differential link

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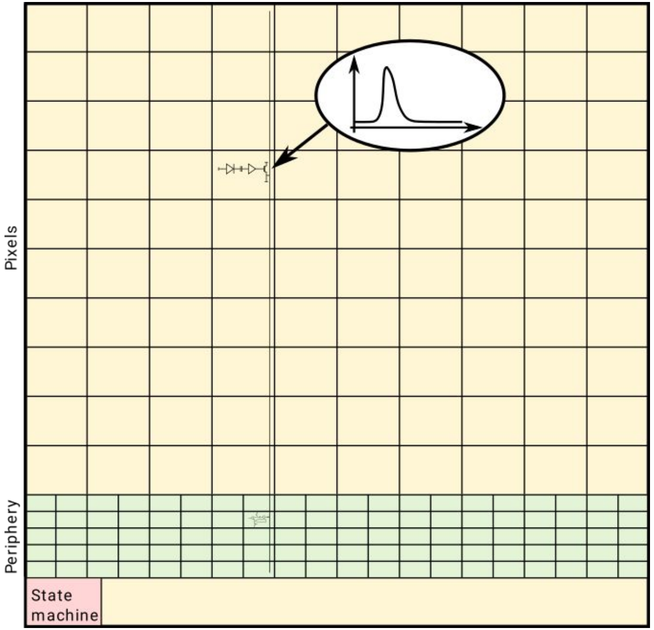

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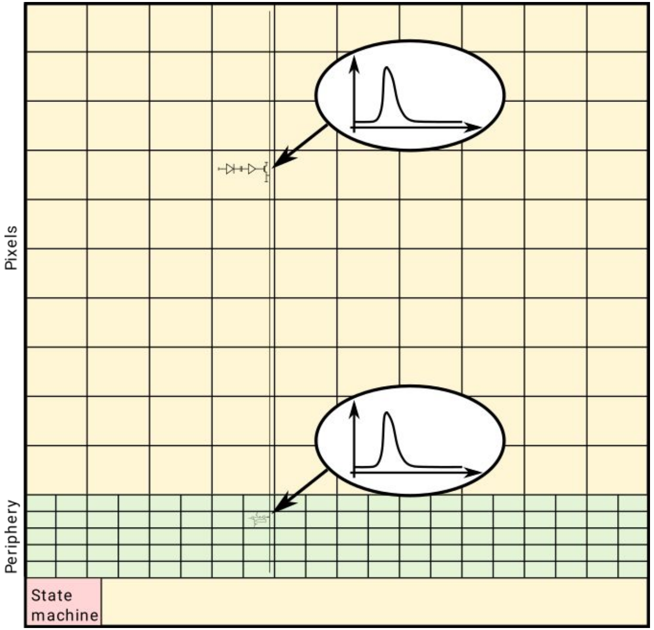

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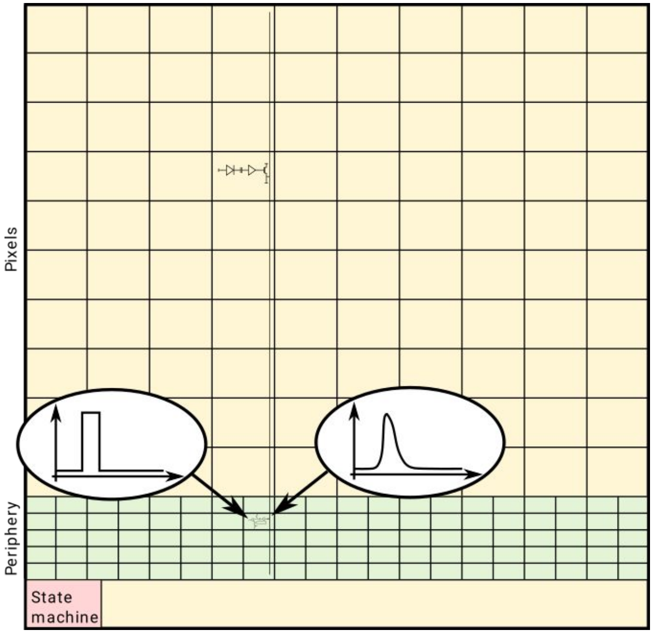

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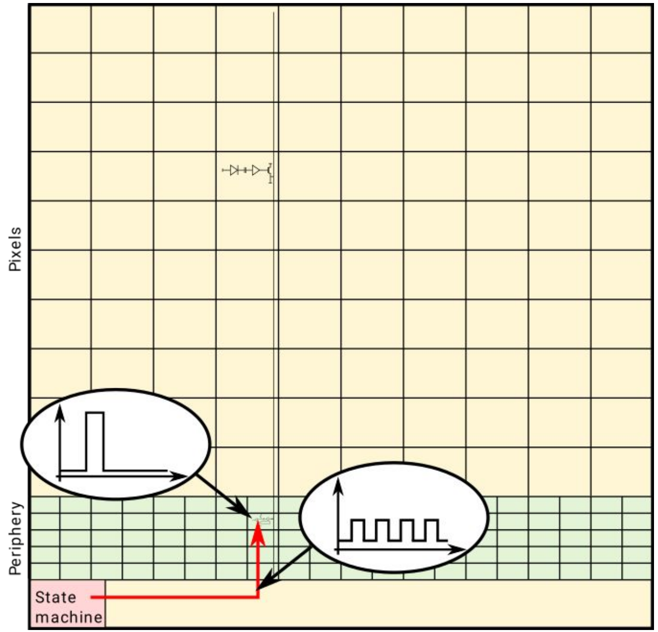

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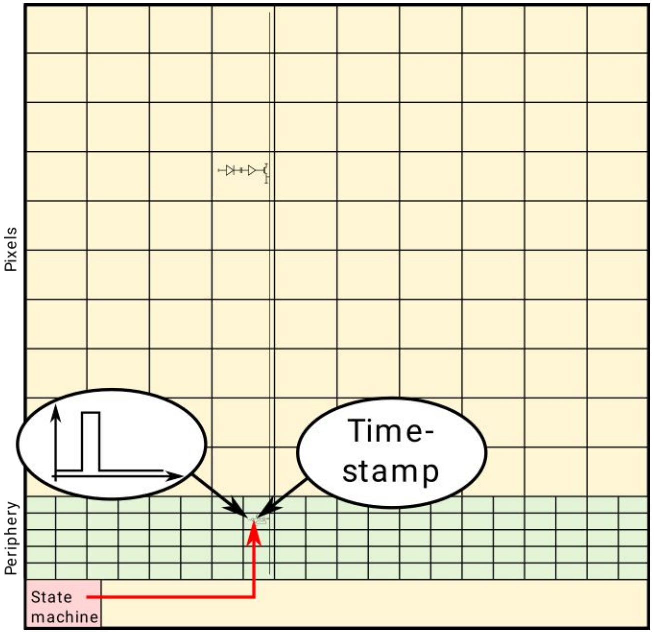

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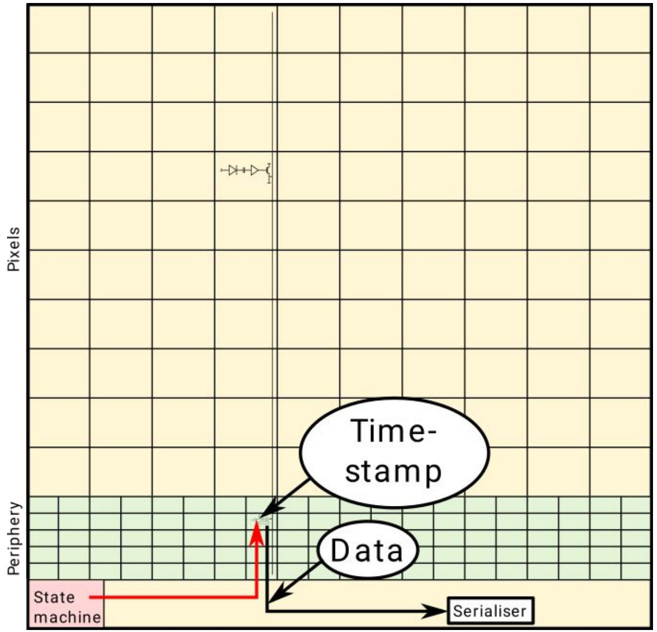

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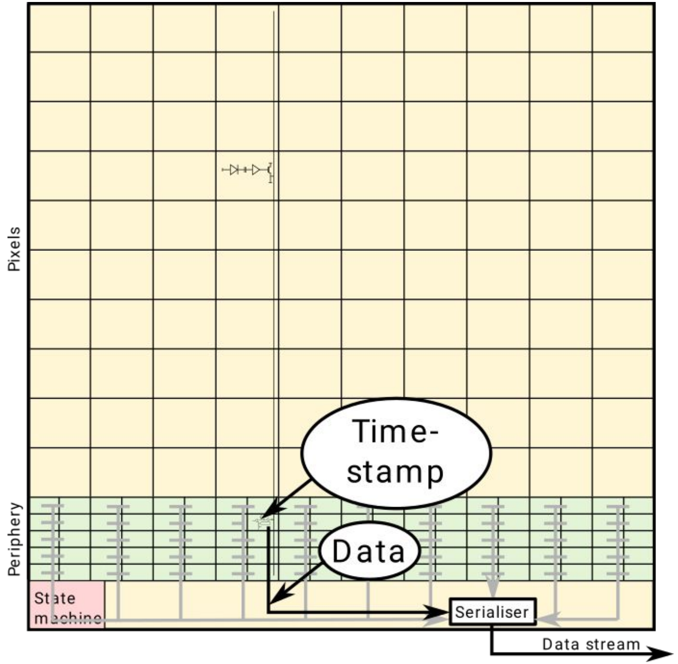

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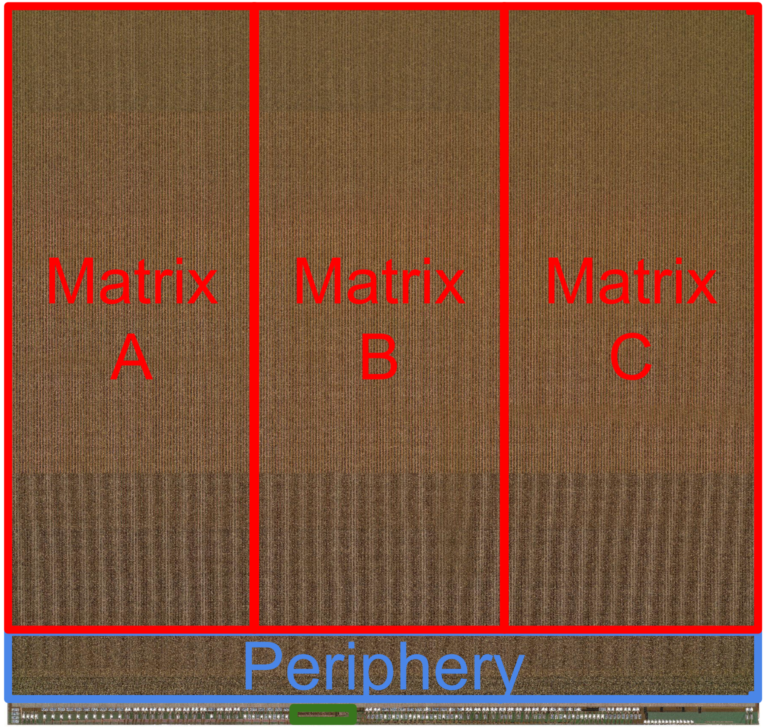
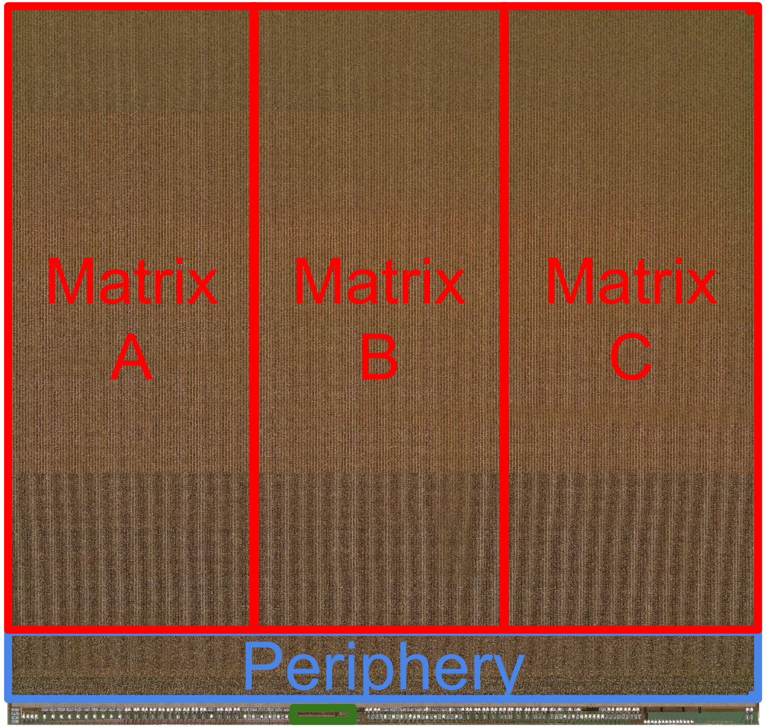
MuPix10 & MuPix11



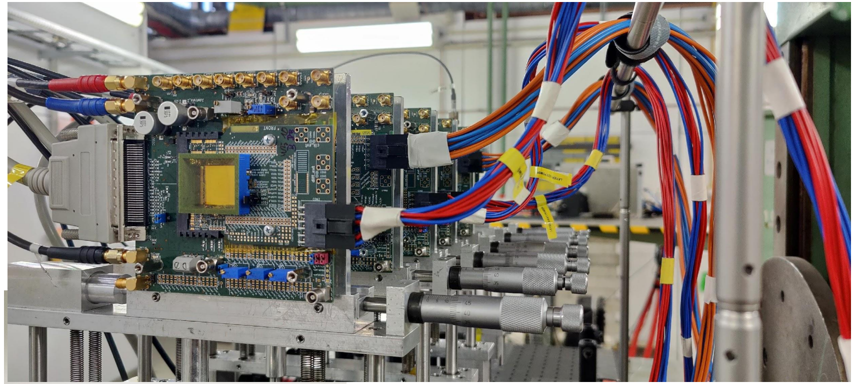
Pixel size [μm²]	80 x 80
Sensor size [mm²]	20.66 x 23.18
Active size [mm²]	20.48 x 20.0
Pixel matrix	256 x 250
Thickness [μm]	**50, 70**
Substrate [Ωcm]	80, 370
Data links	**3+1**
Data speed [Gbit/s]	1.25
Time-of-arrival [bits]	11
ToT [bits]	5
TS binning [ns]	8 (option for 1.6)

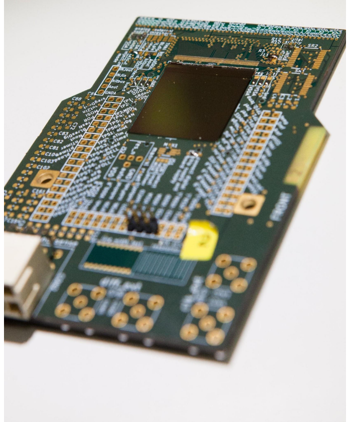
From MuPix10 to MuPix11



- Removal of R&D features
  - ➡ More pads for powering
- Improvement of powering grid
  - ➡ Less on-chip voltage drop
- Buffering of data lines
  - ➡ Full speed readout
    30 MHits/s per sub-matrix
- Re-synthesis of State machine
  - ➡ Fast configuration interface available
- Re-done pixel point-to-point connection
  - ➡ Reduced delays and parasitic couplings

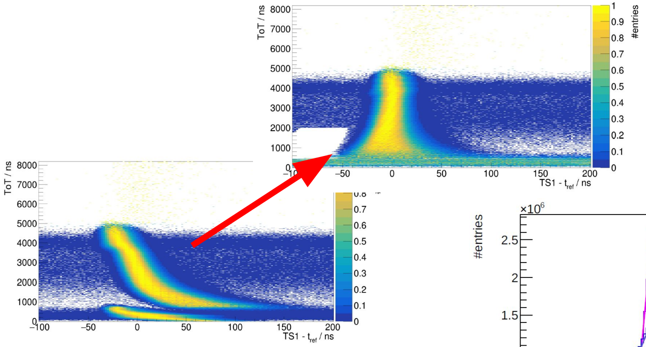
Sensor Characterisation

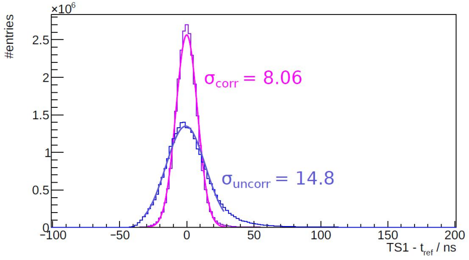




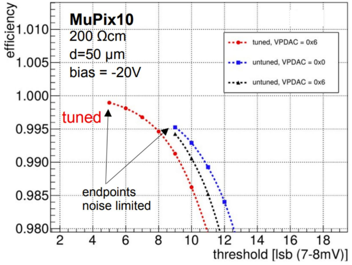
- Lab commissioning
- Lab optimisation:
  Radioactive sources: ^{55}Fe, ^{90}Sr
  Time coincidence
- Testbeam Campaigns:
  DESYII (Hamburg, GER)
  MAMI (Mainz, GER)
  PSI piM1 (Villigen, CH)
- MuPix-Telescope
- Mimosa/Alpide-Telescopes

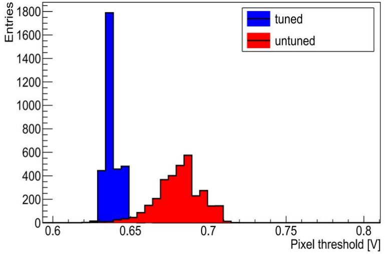
Summary - Results MuPix10



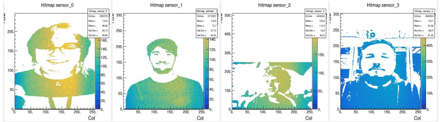


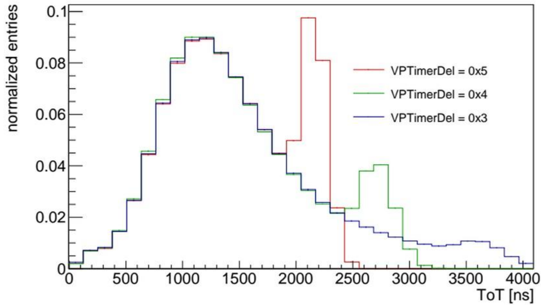
Timing Correction





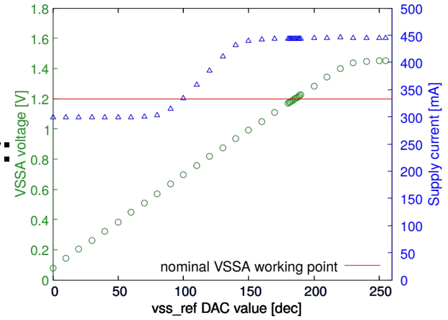
Tuning/Trimming
Masking





Hit readout delay:
Hit Chronology

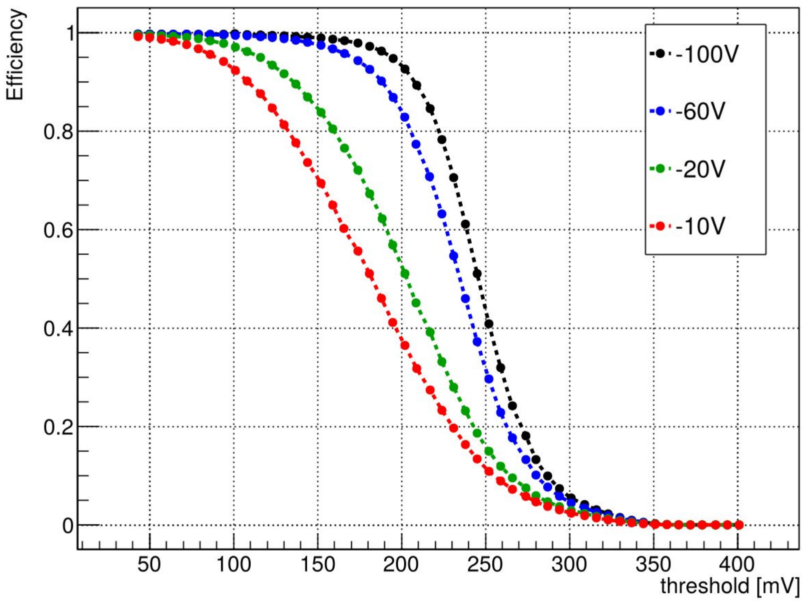
Voltage Regulator:
Single Supply



[arXiv:2012.05868] & VERTEX2022

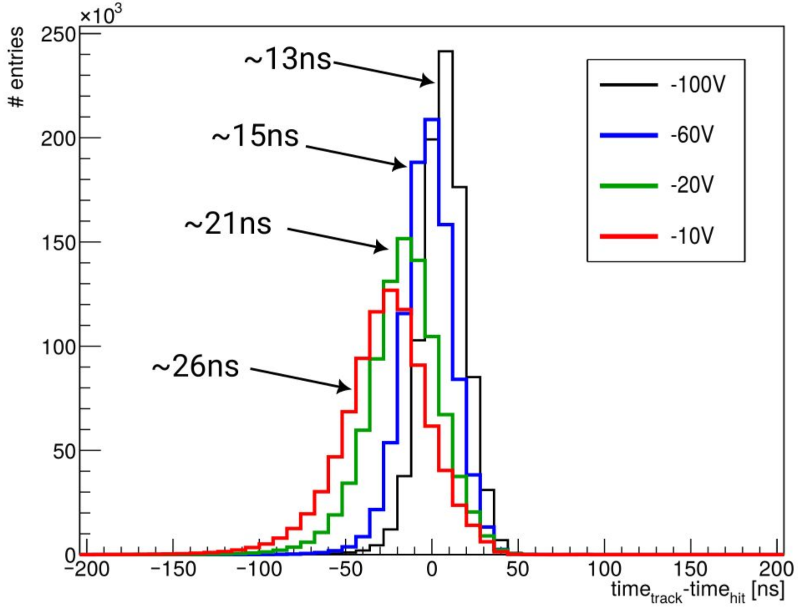
MuPix11 - First Light

Efficiency - 100µm thick sensor



Depletion depth proportional to **sqrt(HV)**

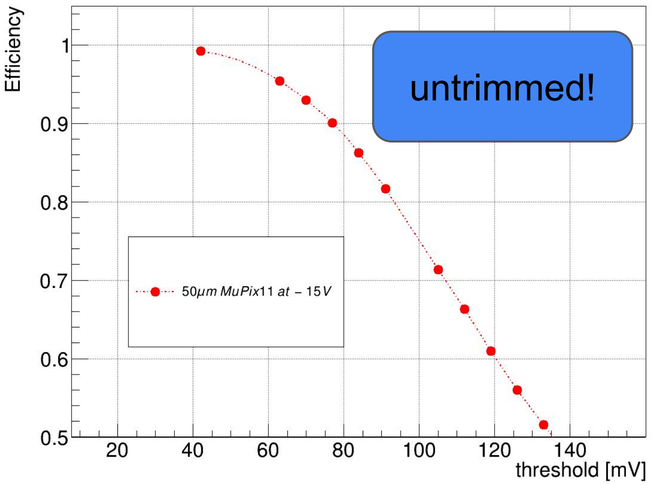
Time resolution (Gaussian estimate)



Raw time resolution,
no corrections of any kind

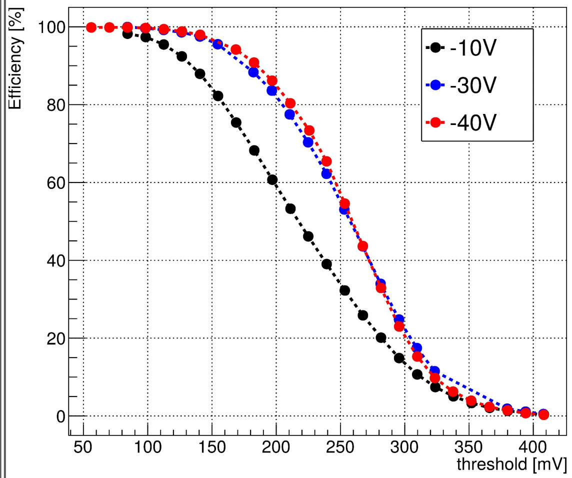
MuPix11 - Efficiency for 50 and 70 µm

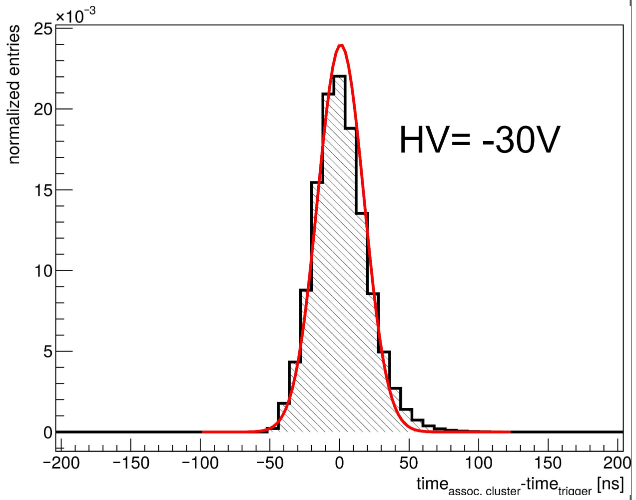
50µm thickness



➡ Needs calibration/trimming!

70µm thickness





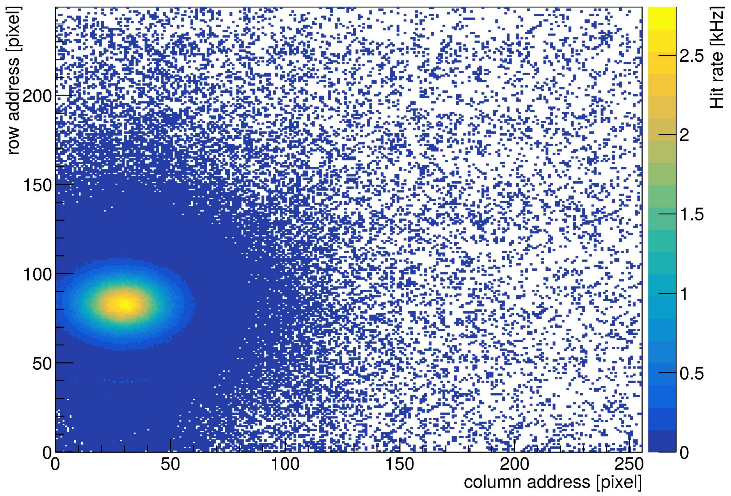
➡ Works out of the box!

$\sigma_{\text{uncorrected}} \sim 16.6\,\text{ns}$

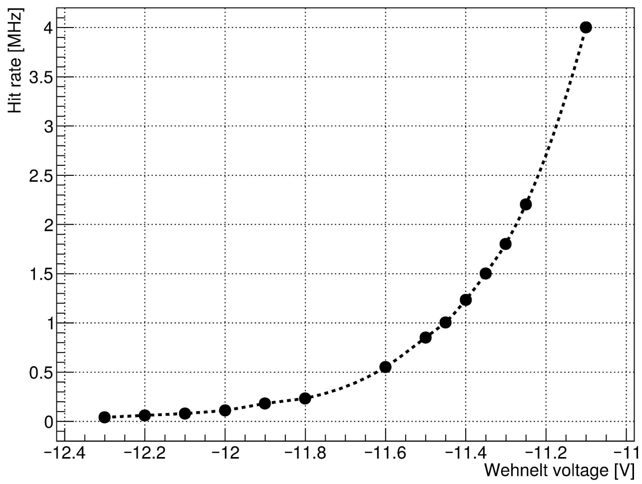
Mu3e: 50µm sensors for the vertex detector (~100 Sensors)
70µm sensors for the outer layers (~3000 Sensors)

MuPix11 - High Rate capability

MAMI - Beam spot on sub-matrix A



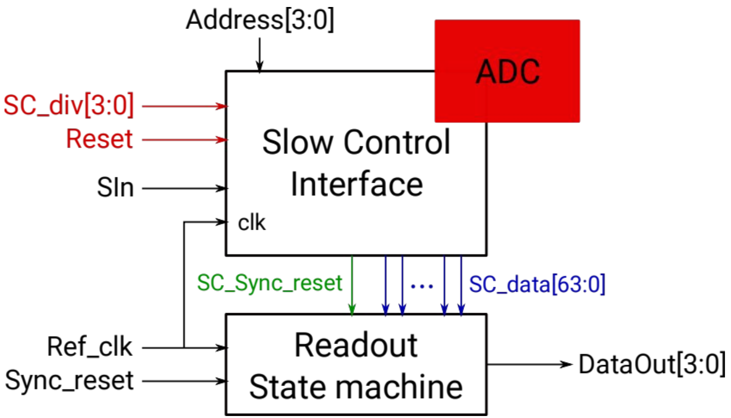
Beam rate measured with MuPix11



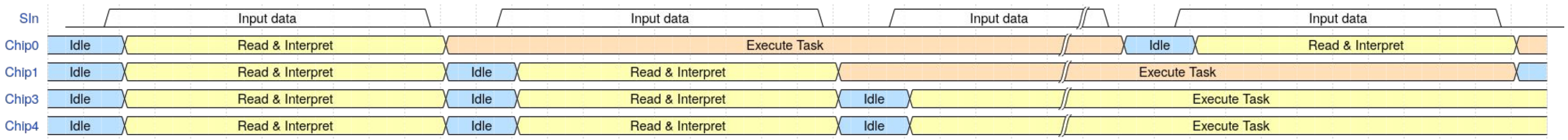
No Readout saturation visible @ 4 MHz Hitrate

➡ Average Rate on “Hottest” Sensor 6 MHz

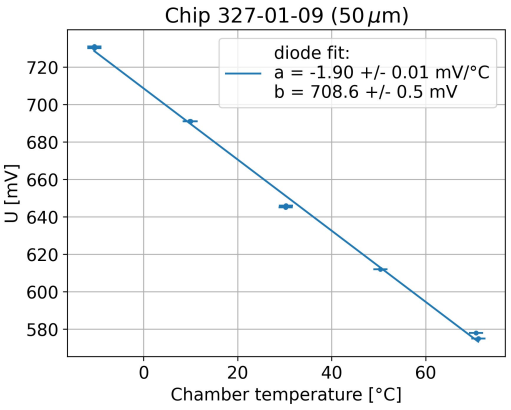
MuPix Fast Configuration Interface

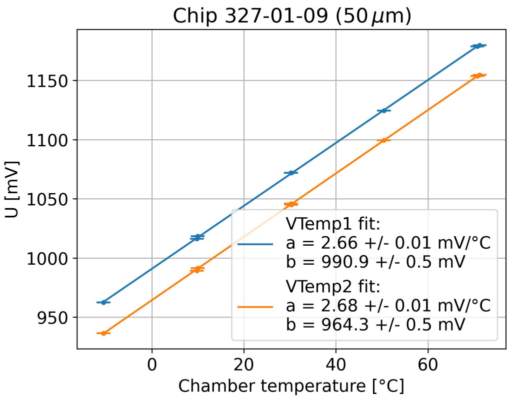


- Chips of a ladder share a bus of clock, synchronous reset and configuration input
- Custom configuration protocol
- Commands interleavable
- **~400ms configuration time** for 9 chip ladder
- **Detector** currently configurable **< 4s**
- ADC data sent out via regular data links



On-Chip Temperature Measurement

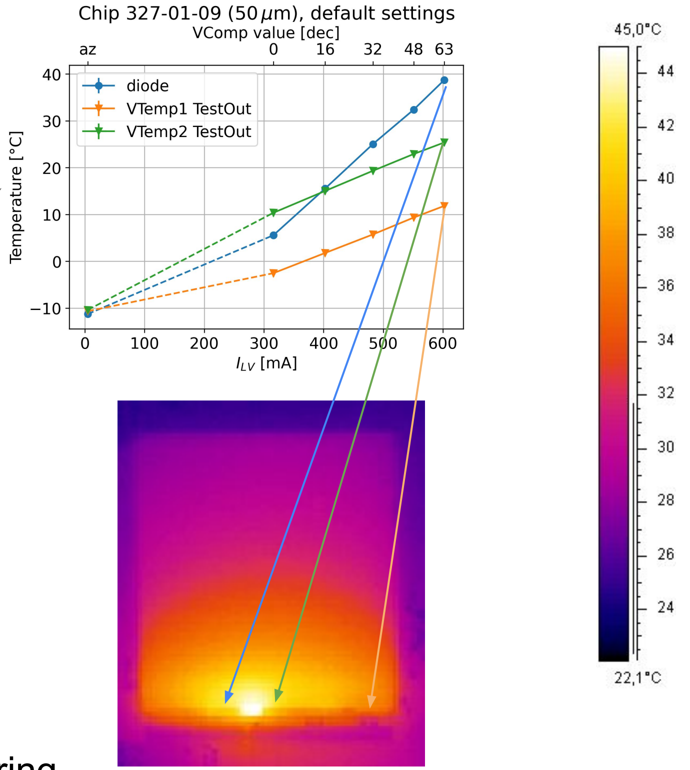




Simple PN-**Diode**
(Shockley)

Gauging

Temperature sensitive circuit
(Read out via ADC)

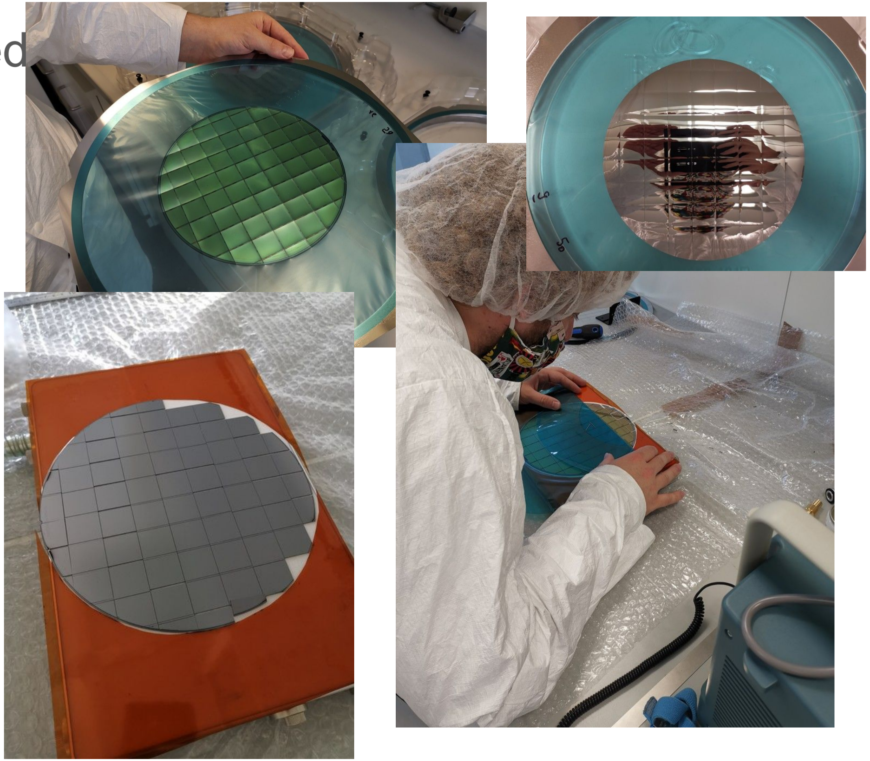


➡ Full detector temperature monitoring

(Pre-)Production Status

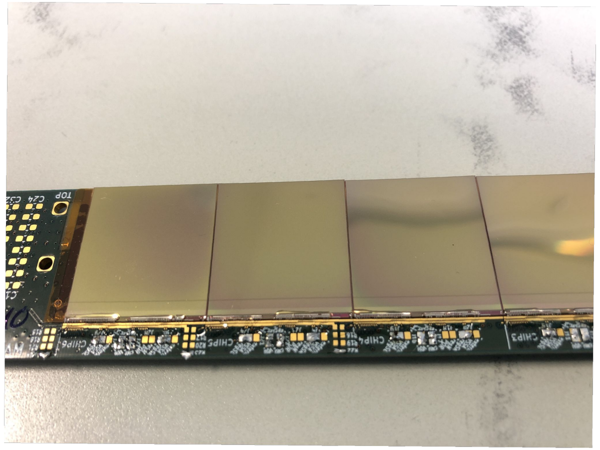
In-House Wafer Handling

- Diced and thinned wafers delivered on tape
- Equipement:
  - Vacuum chuck
  - Pick-up tools (tweezer & suction pen)
  - A lot of patience & time
- Pending on use case thickness vary between 50µm to 100µm + 750µm

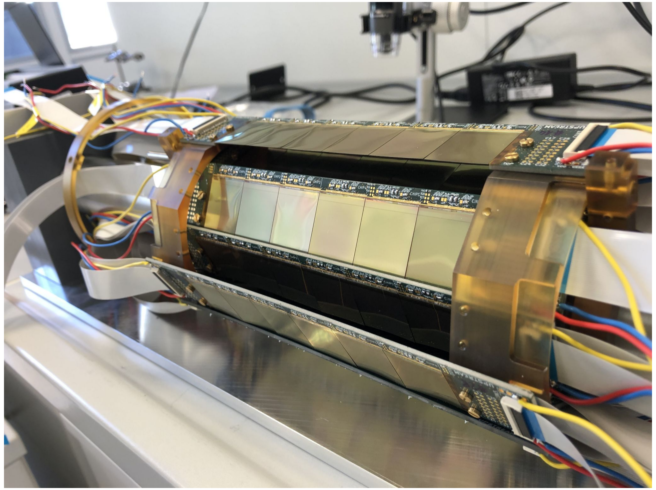


Mu3e ~ 150 Wafers

Proto Vertex Detector



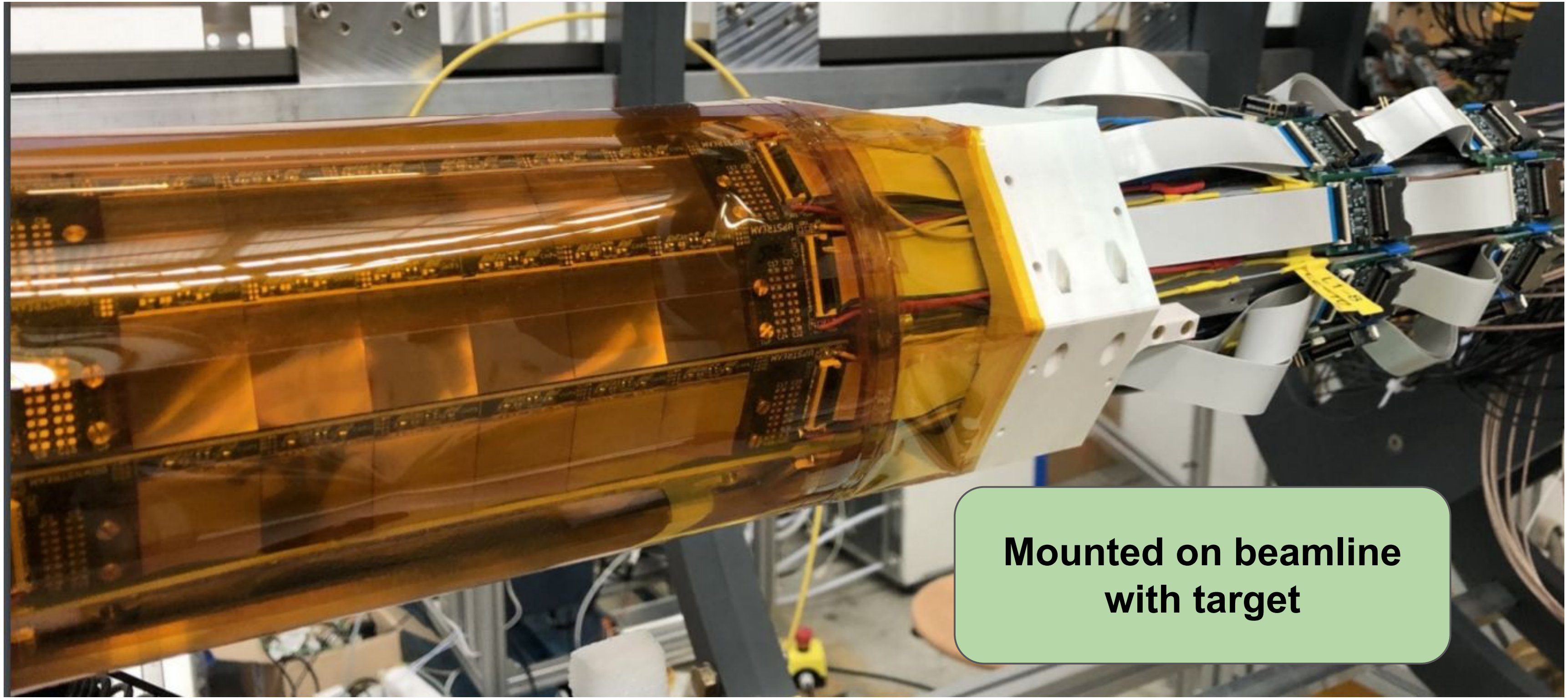
- First proto-detector with 6 chips modules
  - Still PCB based!!!



- Two layer vertex detector (MuPix10)
  - Gain operational experience
  - Test Mu3e readout chain

Operation in experimental conditions

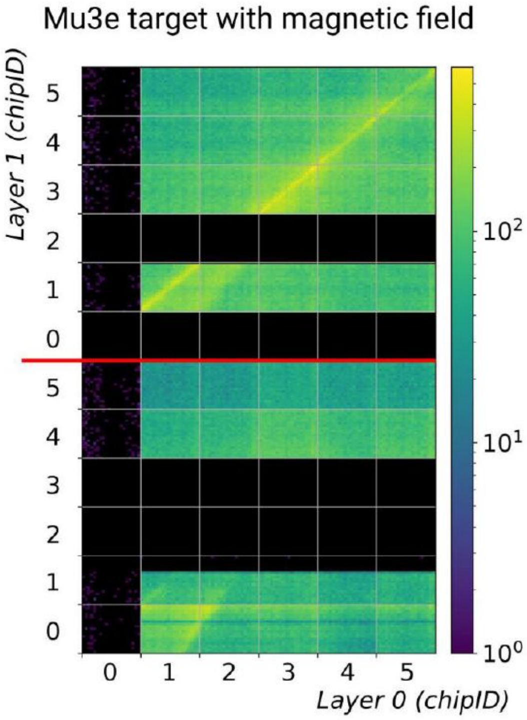
DAQ and experimental concept



Mounted on beamline with target

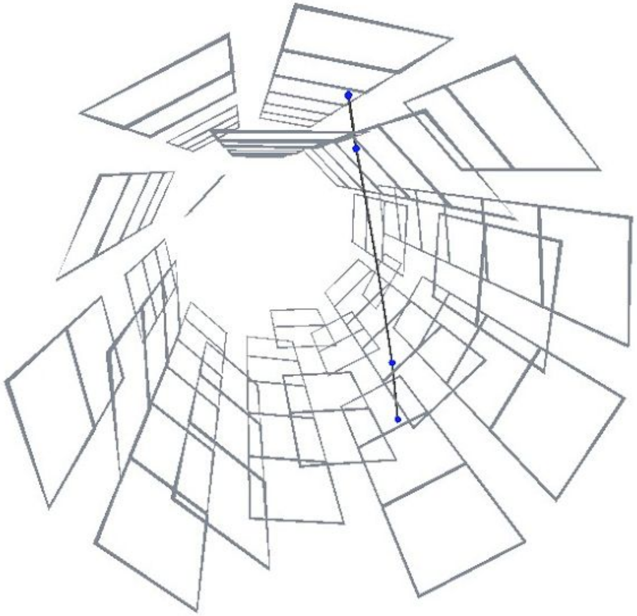
Operation in experimental conditions

With beam (2021)



Layer 0-1 correlation!

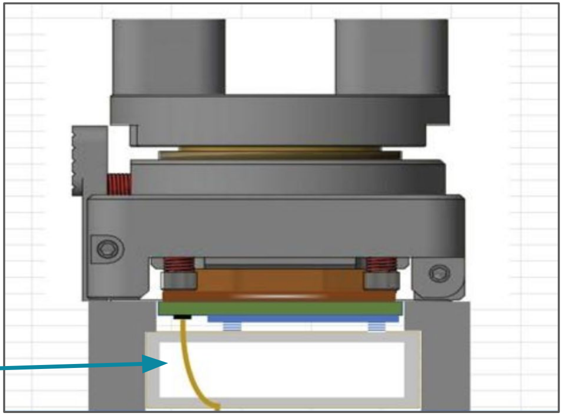
With cosmics (2022)

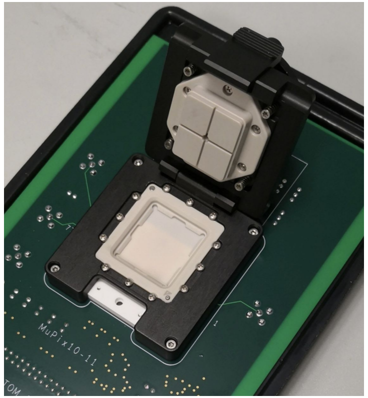


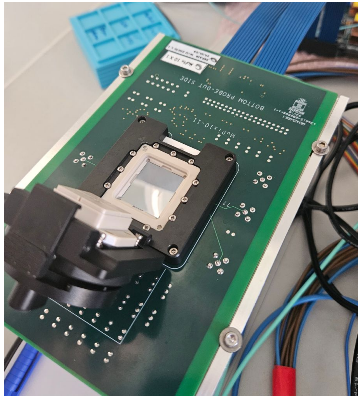
More analysis ongoing

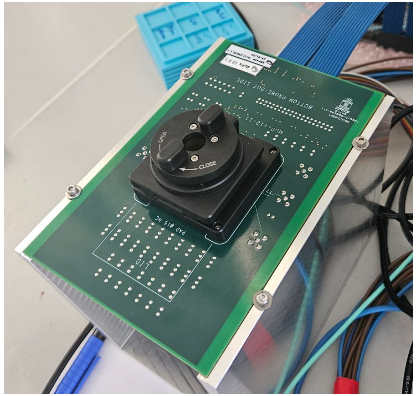
Quality Control (QC)

- Quality assurance is key before a large scale detector assembly
- Testing after assembly is too risky and costly, since dismantling is impossible
- Press down mechanism with contact needles for prior testing

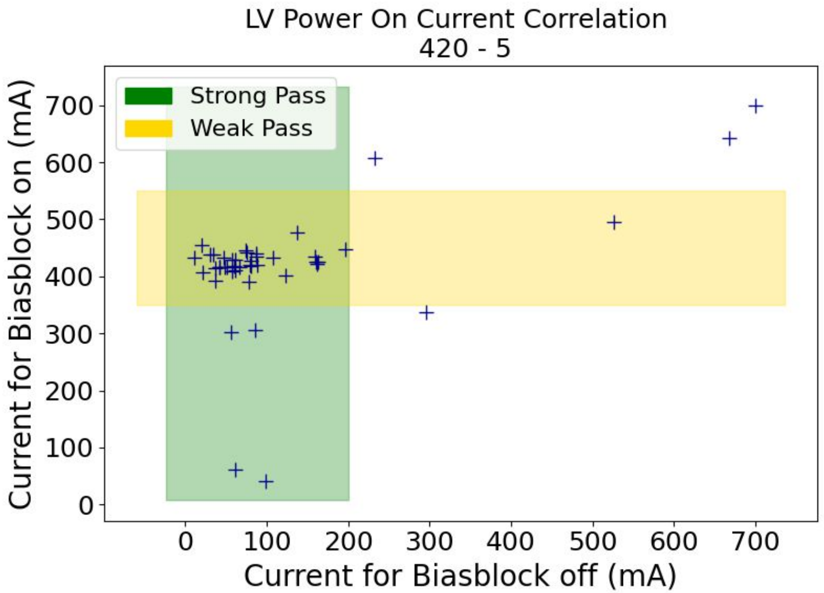


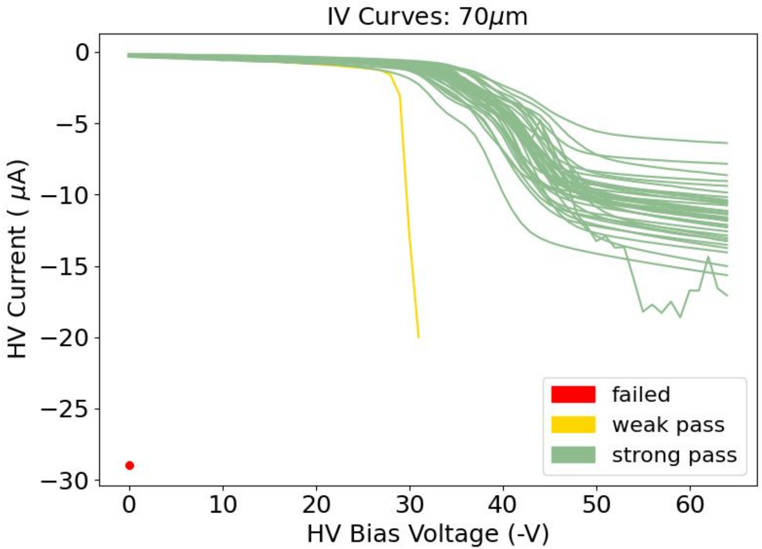






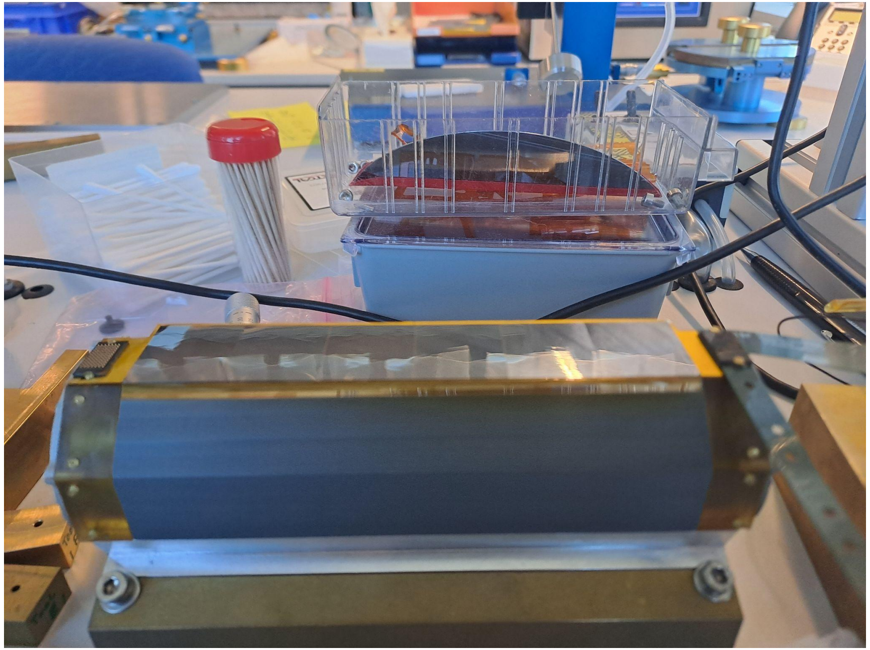
QC - Test procedures



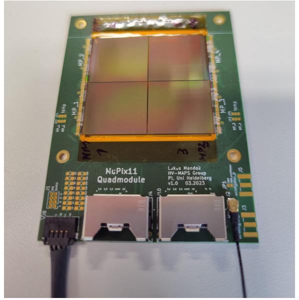


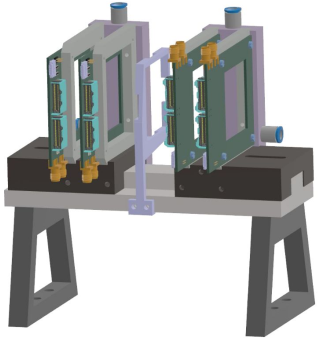
- 2 Single Chip test sites
- First needle card test station being setup in Oxford
- QC procedure still being refined, but almost final
- Grading scheme still adjusting (pre-production)

The Vertex Detector



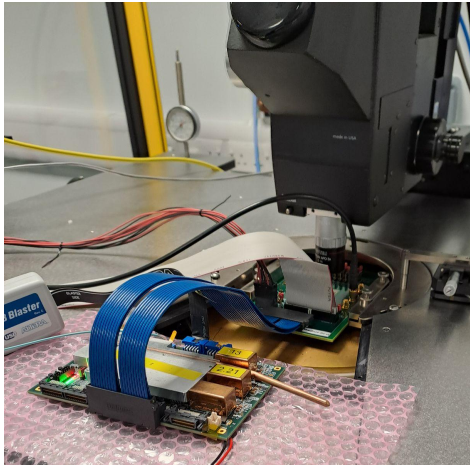
- First Vertex ladders have been produced
- Ladder QC under development in parallel to single chip QC
- Fully functional 50µm ladder in Hand
- Currently running beam time at PSI:
  First time in-beam commissioning of final ladder





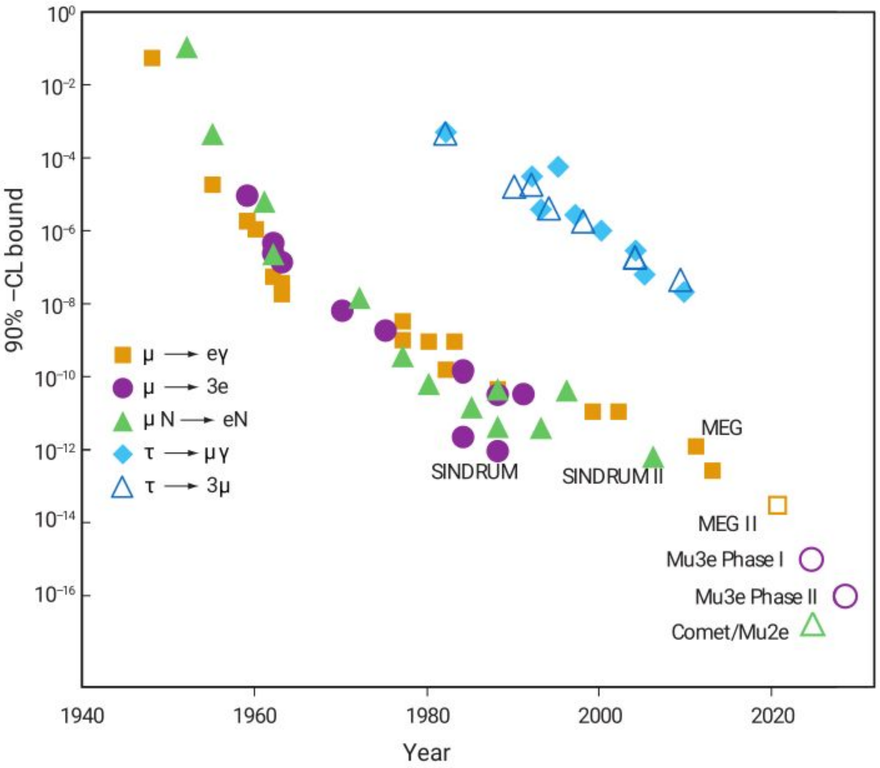
Summary & Outlook

- Successful transition from MuPix10 to MuPix11
  - Everything functional, expected to fulfill Mu3e requirements
- QC procedures have been developed and implemented
  - First successful test of needle card for large volume testing
- Production of Vertex ladders started
  - First in-beam test still this week
  - Full vertex detector expected in Spring
- First ladders of outer pixel layers expected in Spring
- Start with detector commissioning next year

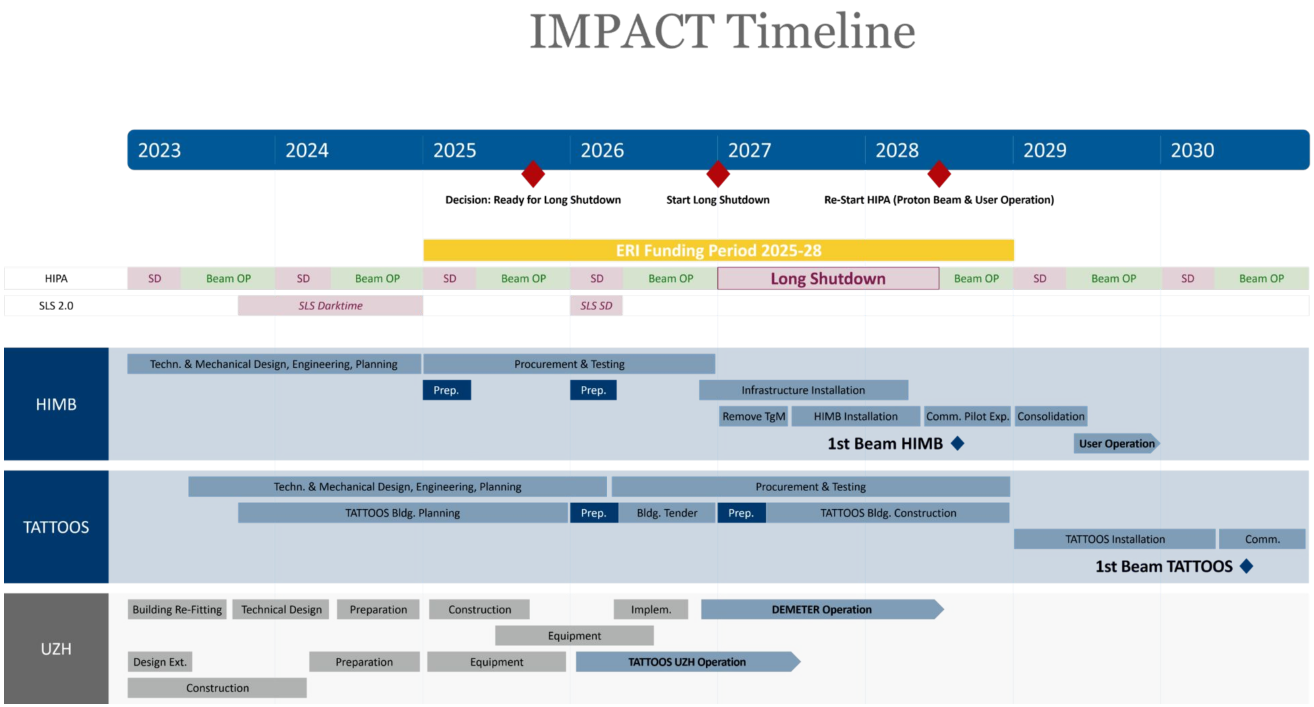


Backup

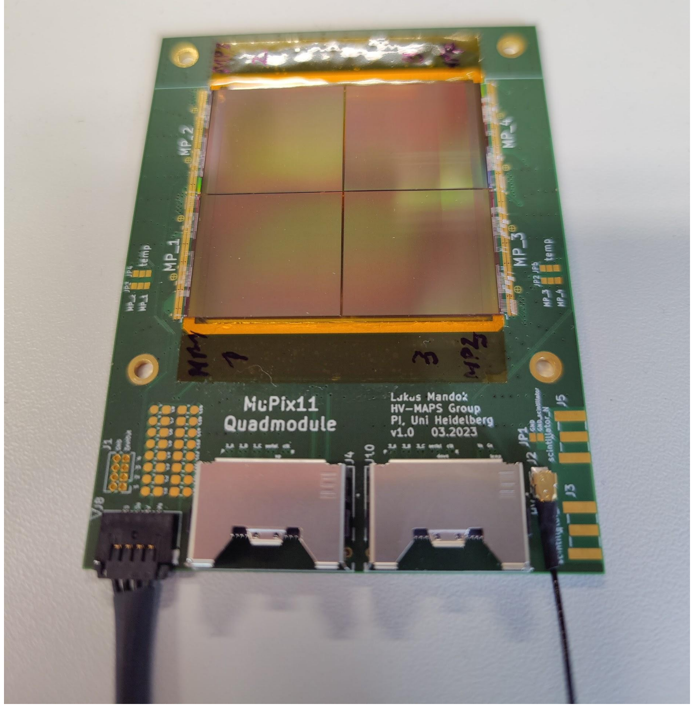
cLFV - Landscape

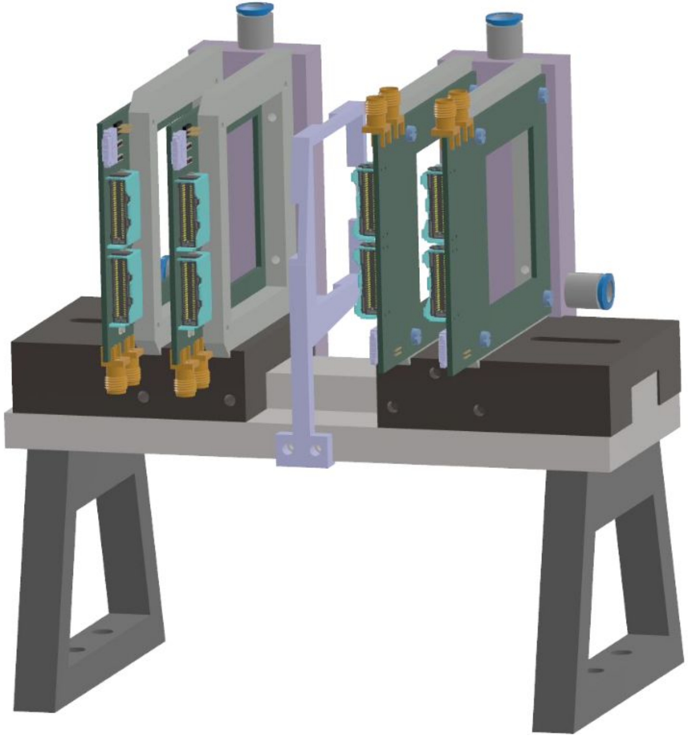


PSI - Beamline Upgrades



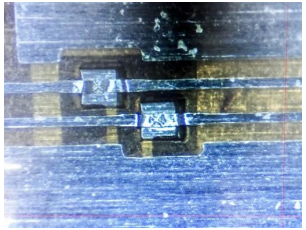
Quad - Module Telescope

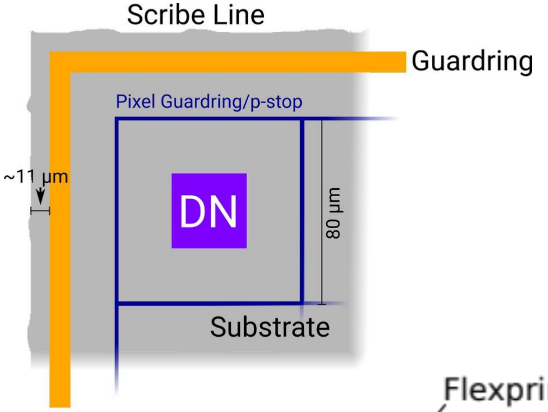


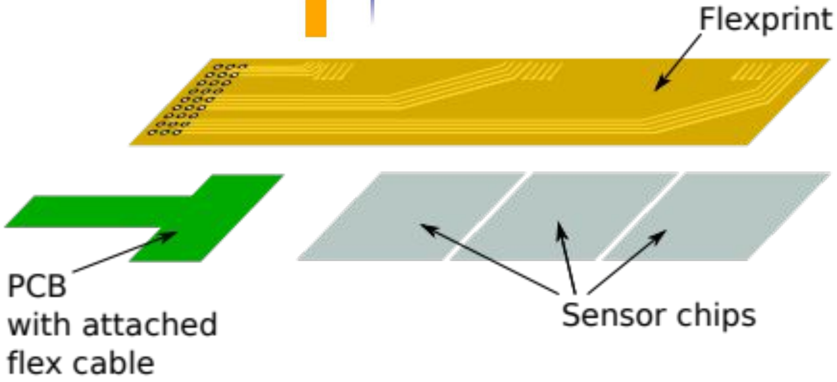


A MuPix Module

- Chips glued and SpTAB-bonded to flexprint
- No additional components!
- 1.15‰ X_0 per layer
- Minimize dead space between the chips
- Only 11 µm dead silicon outside the guardring
- Power consumption limited to 400 mW/cm² (Sensors+Flex)

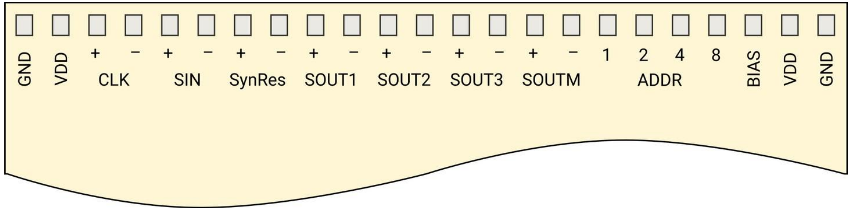




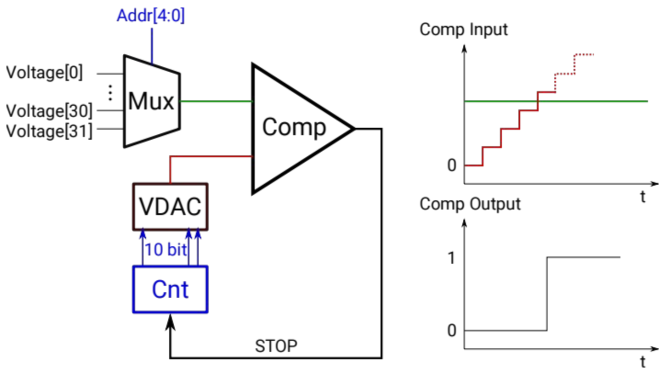


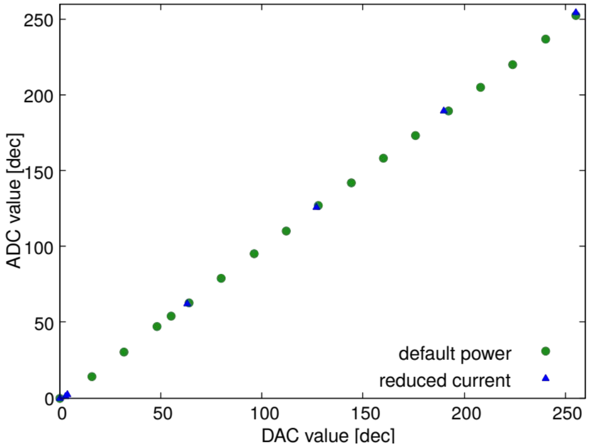
The Flexprint Environment

- 2 layer aluminum polyimide flexprint (LTU)
- Provides:
  Power & HV (parallel)
  Differential Signal I/O
- Only 1 supply voltage, but no LDO-regulators!
- Minimise I/O
- Flex design rules define PadOut



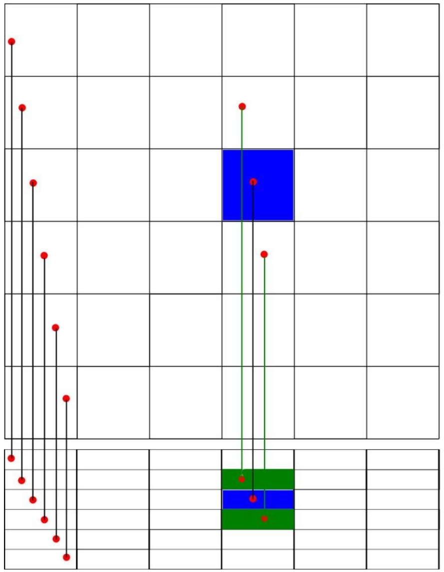
On-chip ADC

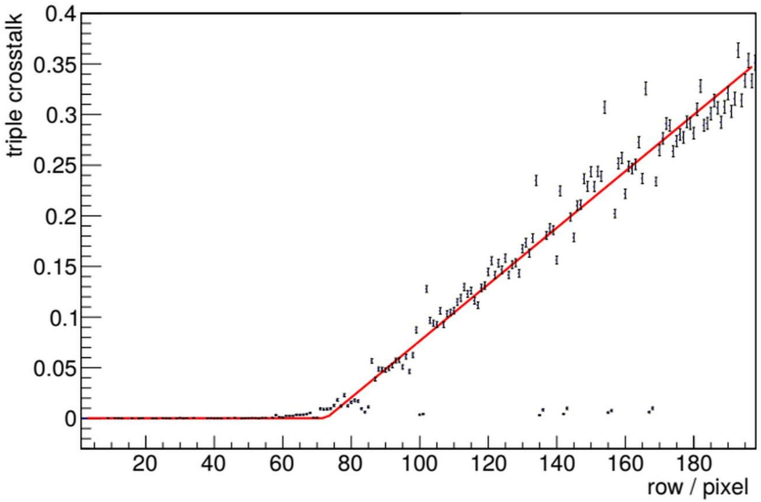




- ADC programmable through Mu3e configuration interface
- Allows measurement of on-chip voltages
- Data send out via 1.25 Gbit/s data links
- ADC shows a nice linearity

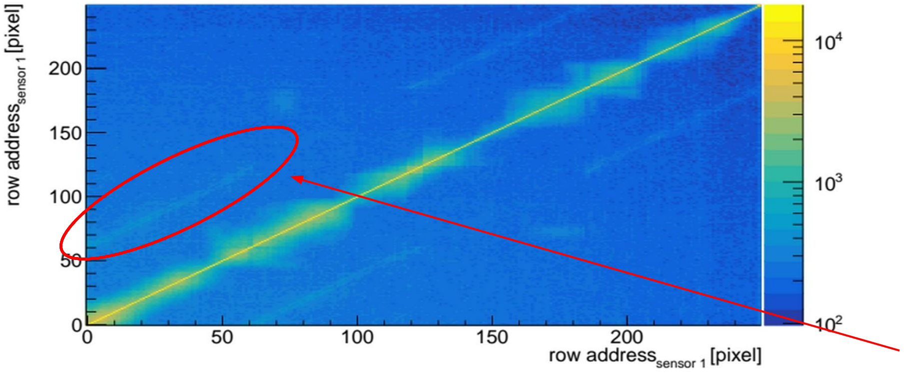
Signal Line Crosstalk - MuPix8





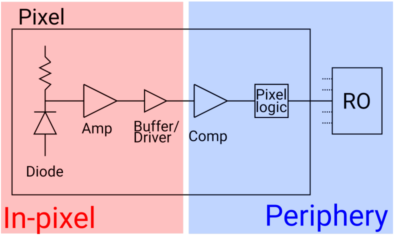
Triple Crosstalk:
hit induced in both neighbouring lines

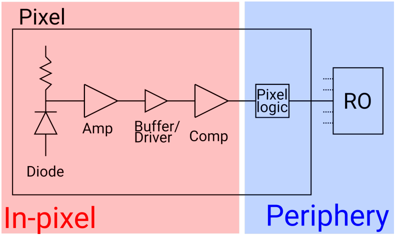
Routing Optimisation - MuPix10

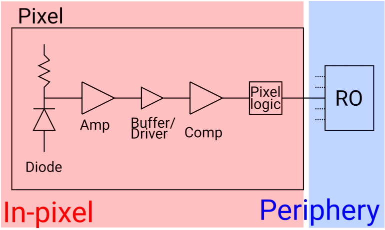


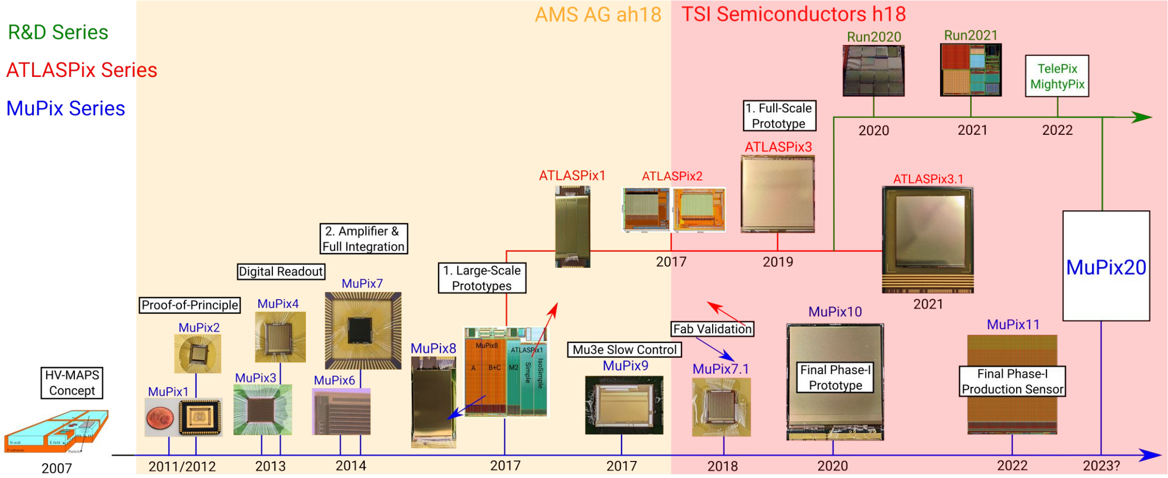
- Equalize but reduce crosstalk
→miminise the length that two line are neighbouring
(¼ of total length, 2cm)
- ~12% triple crosstalk expected
- Make Crosstalk easily detectable
→ neigbouring signal lines are not neigbouring pixels
- Crosstalk can be removed, possibly already during the data taking
- Even more improvement expected for MuPix11

Beyond MuPix11 – Roadmap -- Architectures



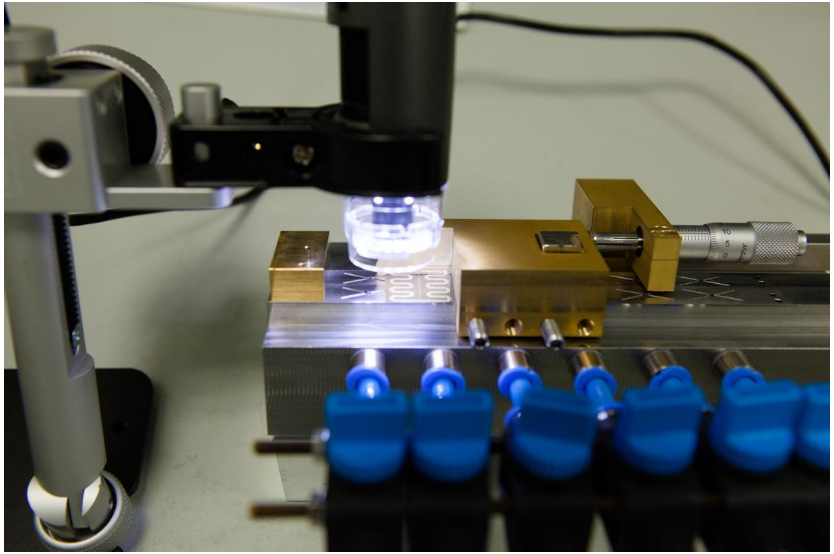






[I. Peric, P. Fischer et al., NIM A 582 (2007) 876]

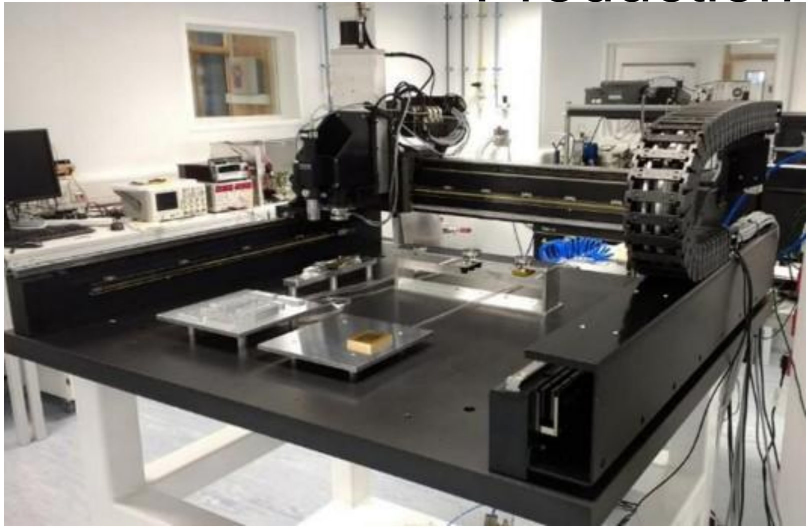
Production of inner layers



Heidelberg/PSI

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

Production of outer layers



Oxford/Bristol/Liverpool