MuPix – A Sensor for Low-material Trackers

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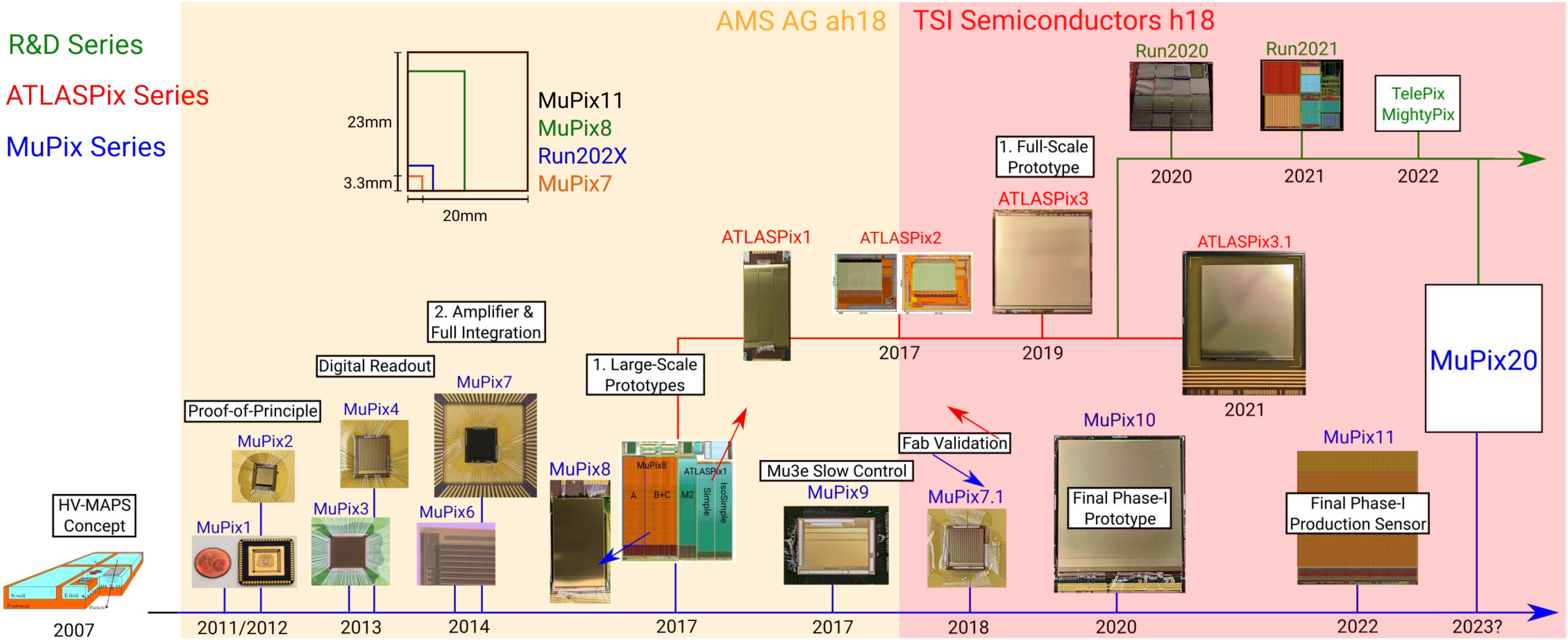
15th Terascale Detector Workshop 2023

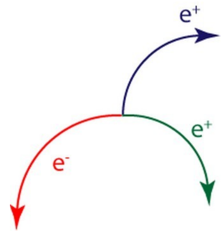
01.03.2023

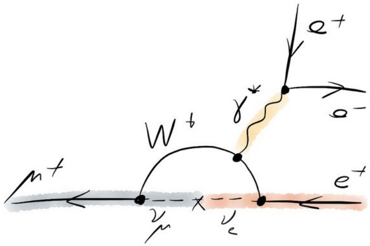
An 11 year journey

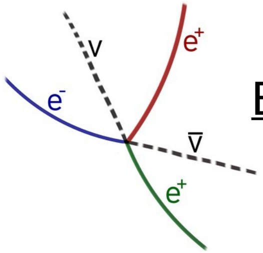


[I. Peric, P. Fischer et al., NIM A 582 (2007) 876]

Mu3e

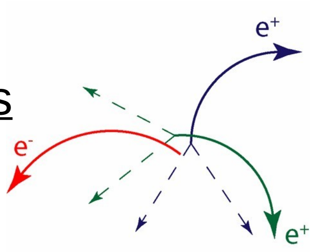






Internal Conversion

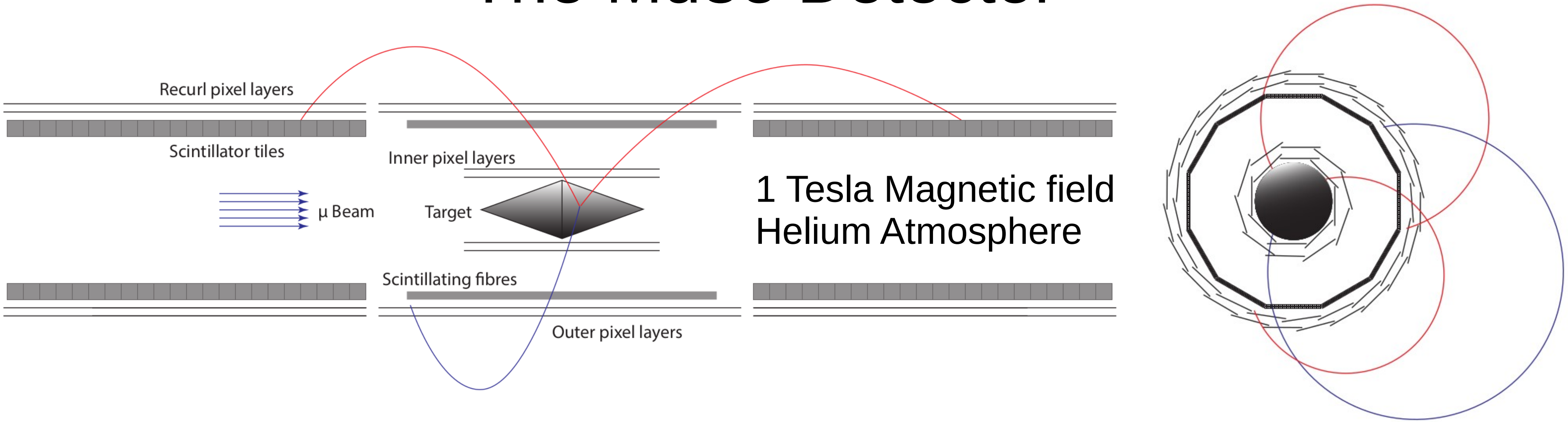
<u>Backgrounds</u>



Accidental

- Search for the cLFV decay
  $\boldsymbol{\mu^+ \rightarrow e^+e^-e^+}$
  (νSM: 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

The Mu3e Detector

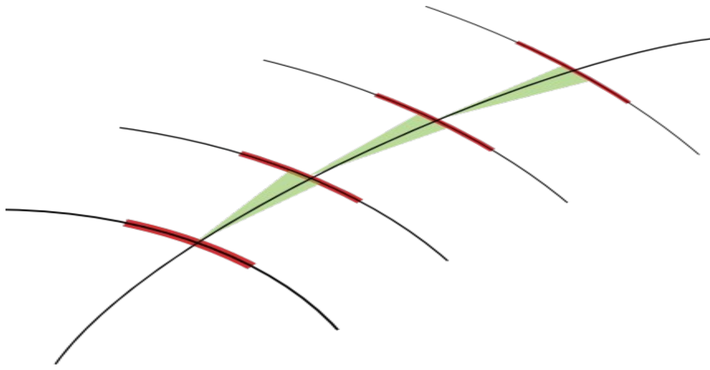


1 Tesla Magnetic field
Helium Atmosphere

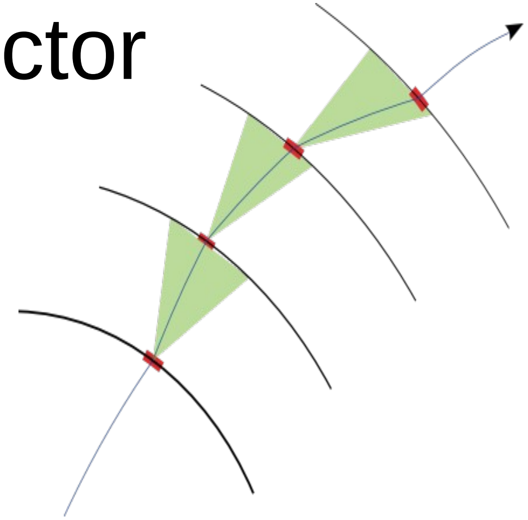
- 10^8 decays per second
- $p_{max} = m_\mu/2 = 53$ MeV
- ➔ Multiple Coulomb Scattering
- ➔ Triplet Fit [arXiv:1606.04990v2]

- Good vertex and time resolution (100 µm & 500 ps)
- Good momentum resolution (0.5 MeV)
- Continuous Beam! No trigger!
- ➔ Online reconstruction and selection
- ➔ Talk by **Nik Berger tomorrow**

The Mu3e Detector



Spatial resolution dominates



Scattering dominates

- 10^8-10^9 decays per second
- $p_{max} = m_\mu/2 = 53$ MeV
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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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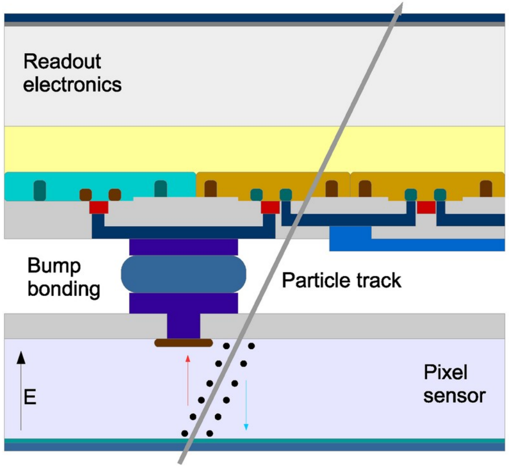
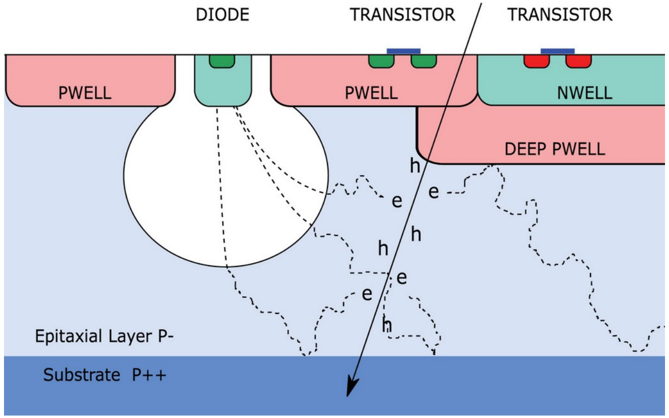
Pixel detector technologies 2011



[https://doi.org/10.3390/instruments4040036]



[https://doi.org/https://doi.org/10.1016/j.nima.2015.09.057]

- Fast charge collection
- High material budget

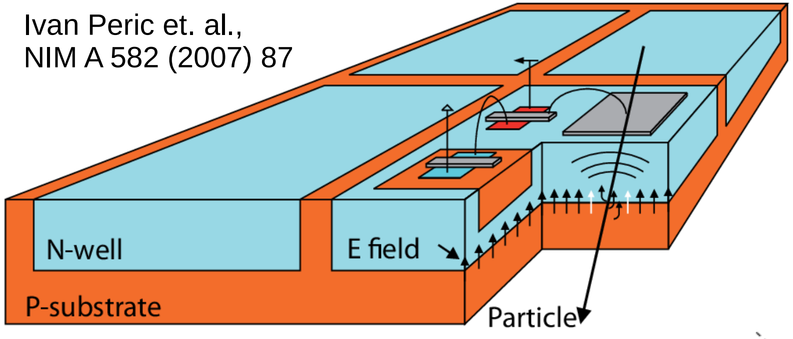
ATLAS, CMS ...

- Charge collection via diffusion
- Lowest material budget possible

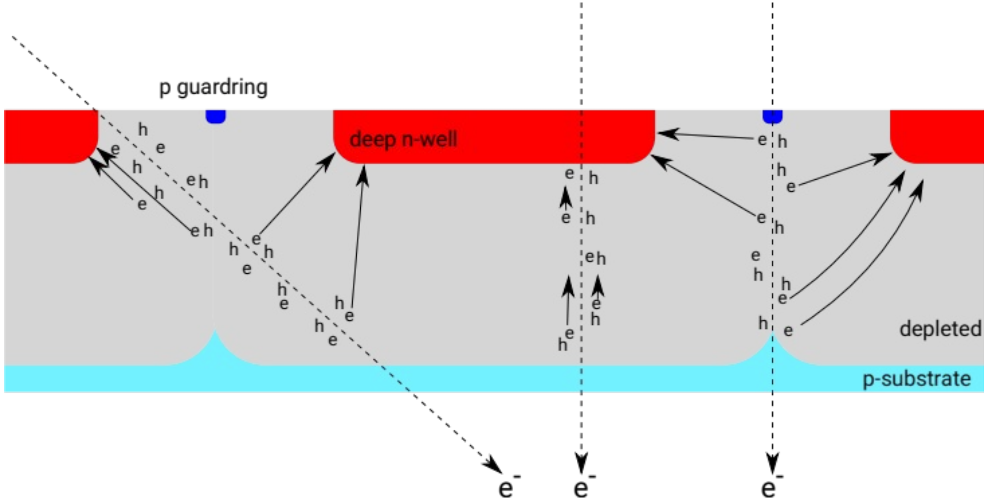
STAR, EUDET-Telescopes ...

High Voltage - Monolithic Active Pixel Sensors

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

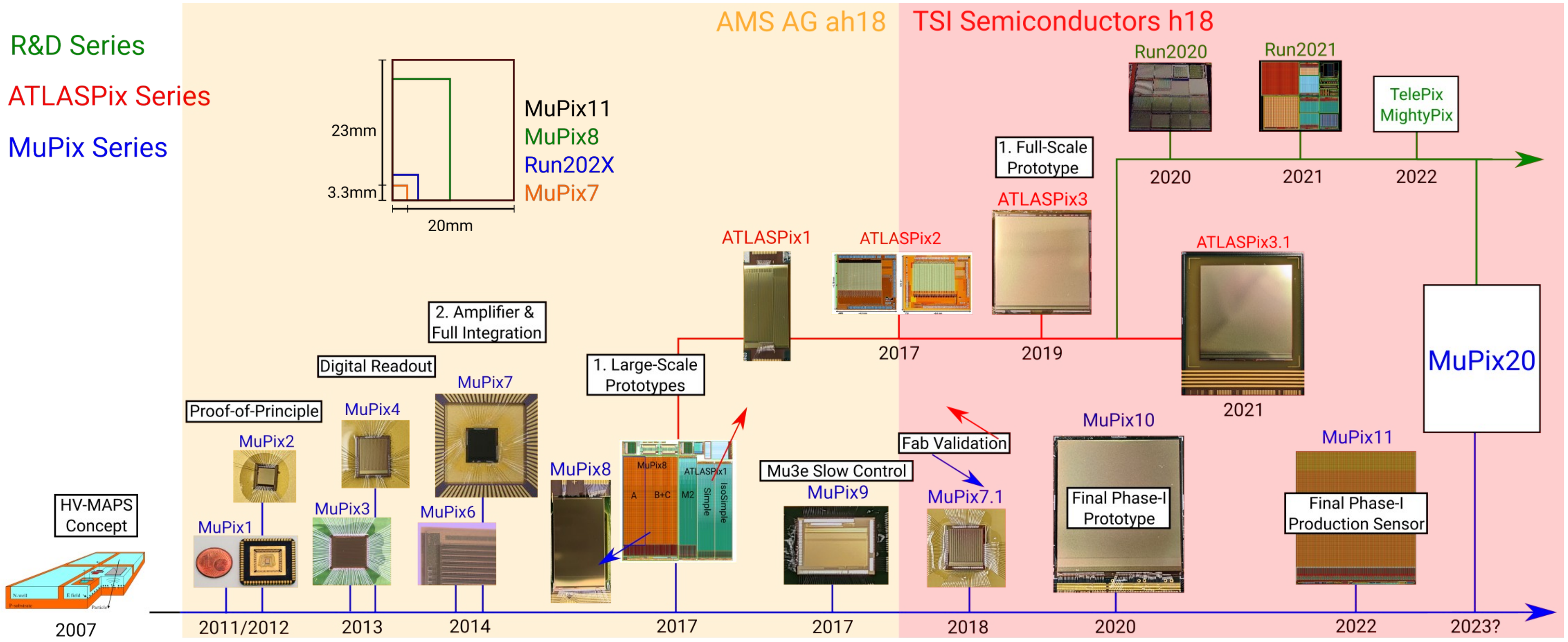


- In-pixel electronics
- Monolithic design: Detection and Readout combined in one chip
- Chips are thinned to 50 µm



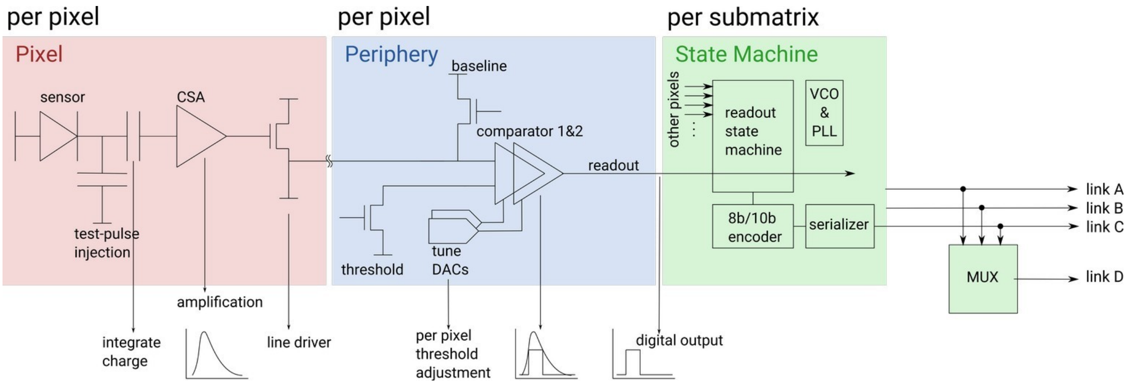
- Commercial HV-CMOS processes: TSI 180nm (h18)
- Deep N-well diode
- Low ohmic substrates (10-400 Ωcm)
- High voltages up to 100V
- Charge collection via drift

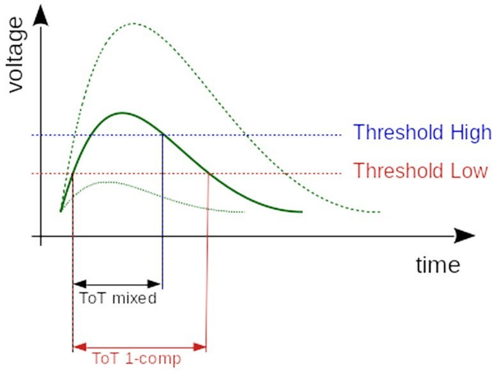
MuPix/HV-MAPS R&D process



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

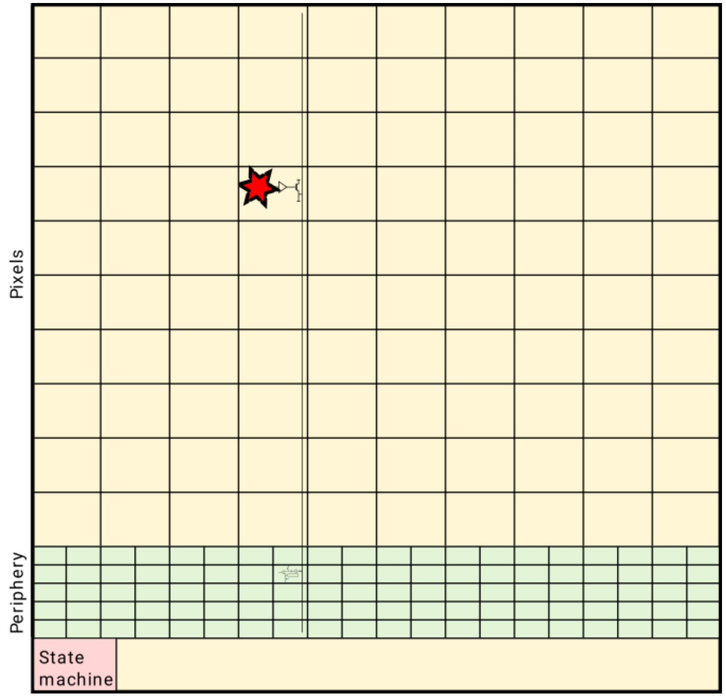
MuPix Architecture





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

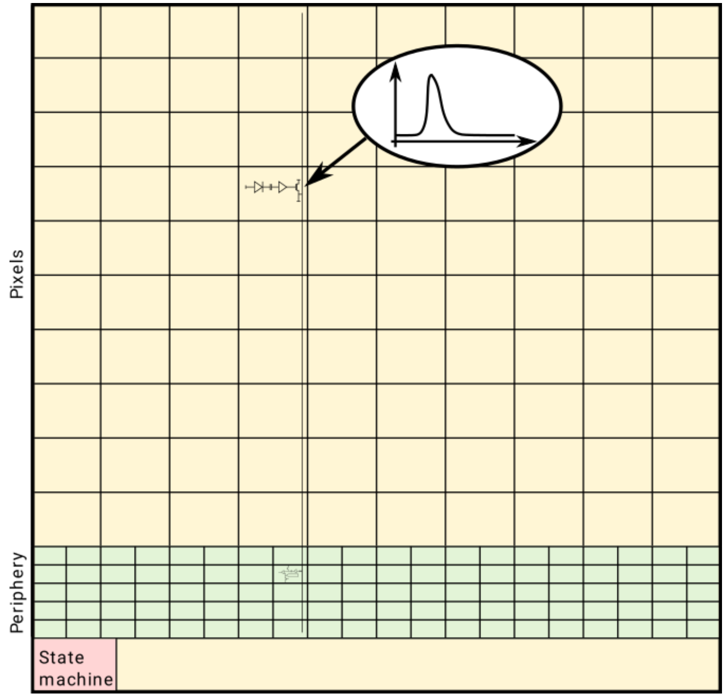
The MuPix Principle



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

The MuPix Principle



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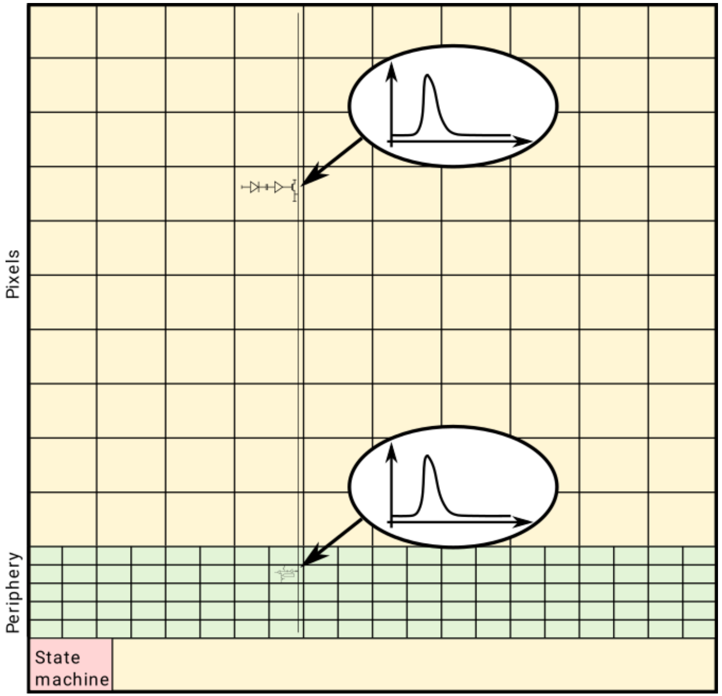

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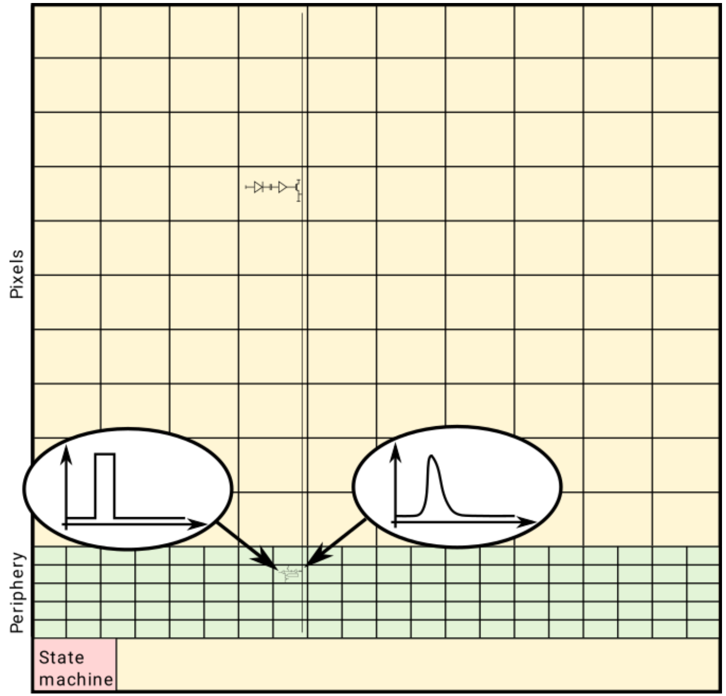

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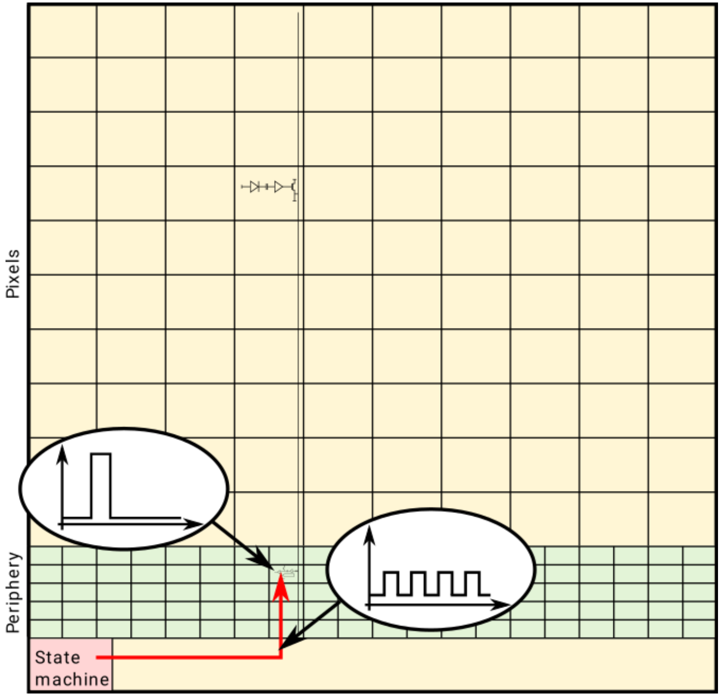

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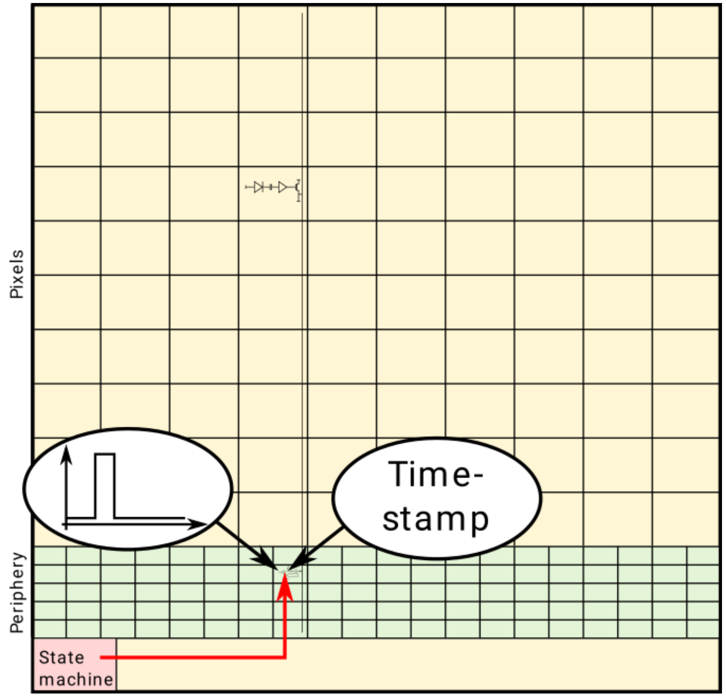

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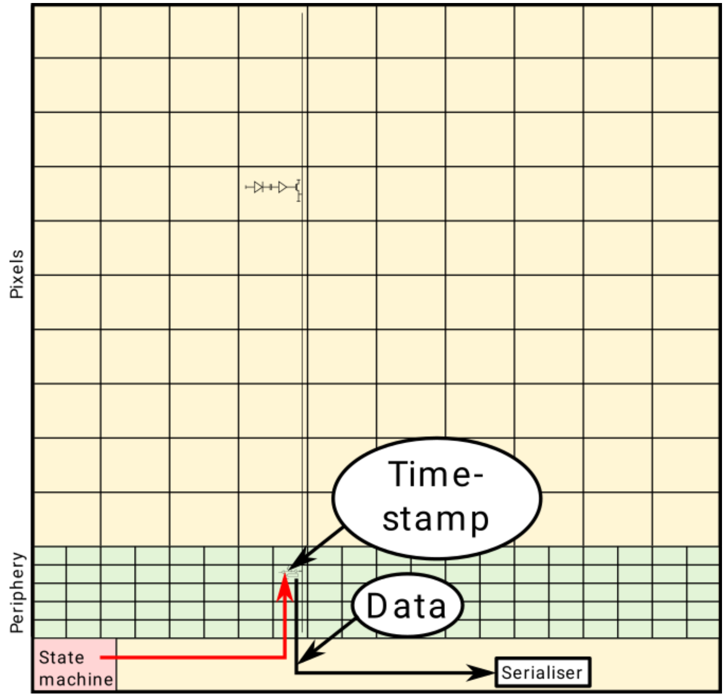

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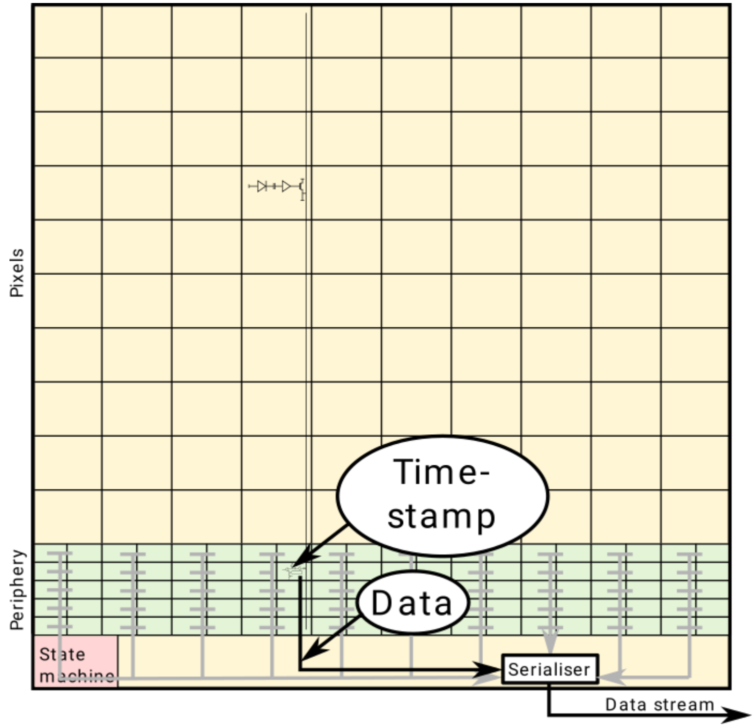

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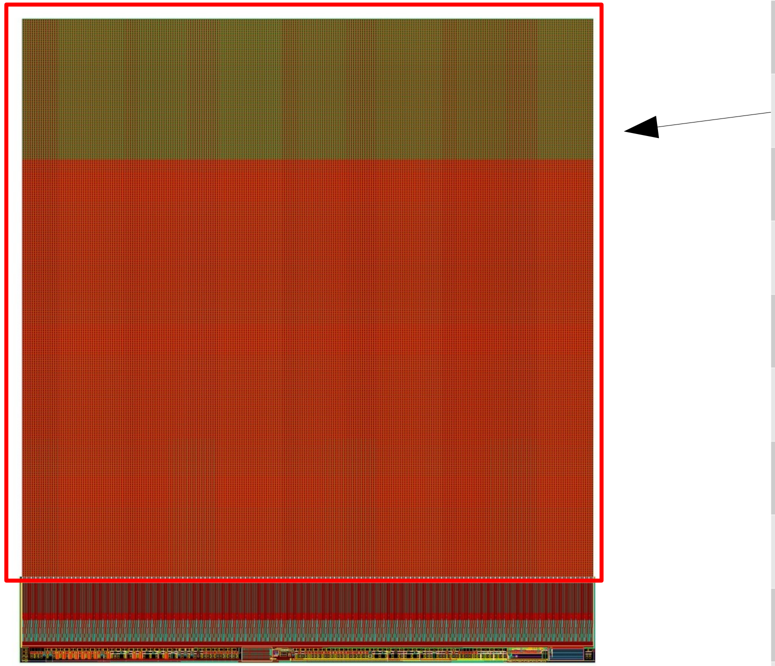
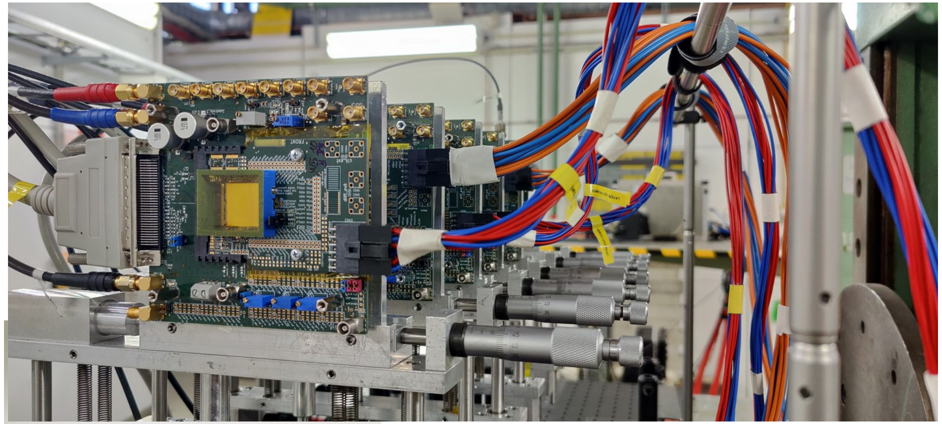
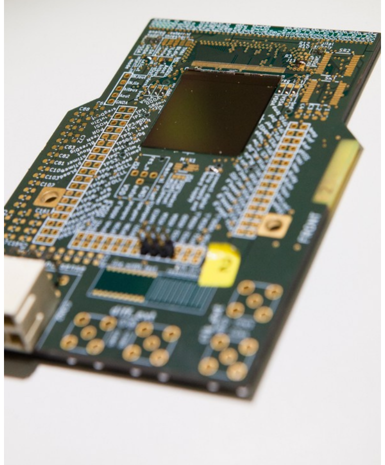
MuPix10 & MuPix11

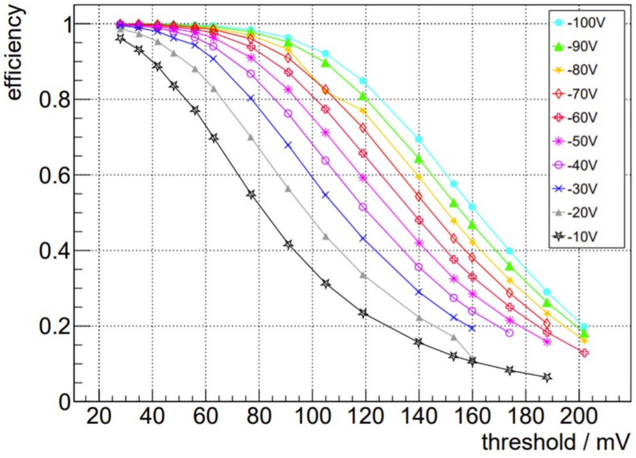


Pixel size [µm²]	80 x 80
Sensor size [mm²]	20.66 x 23.18
Active size [mm²]	20.48 x 20.0
Pixel matrix	256 x 250
Thickness [µm]	50
Substrate [Ωcm]	80, 370
Data links	3+1
Data speed [Gbit/s]	1.25
Time-of-arrival [bits]	11
ToT [bits]	5
TS binning [ns]	8 (option for 1.6)

Sensor Characterisation

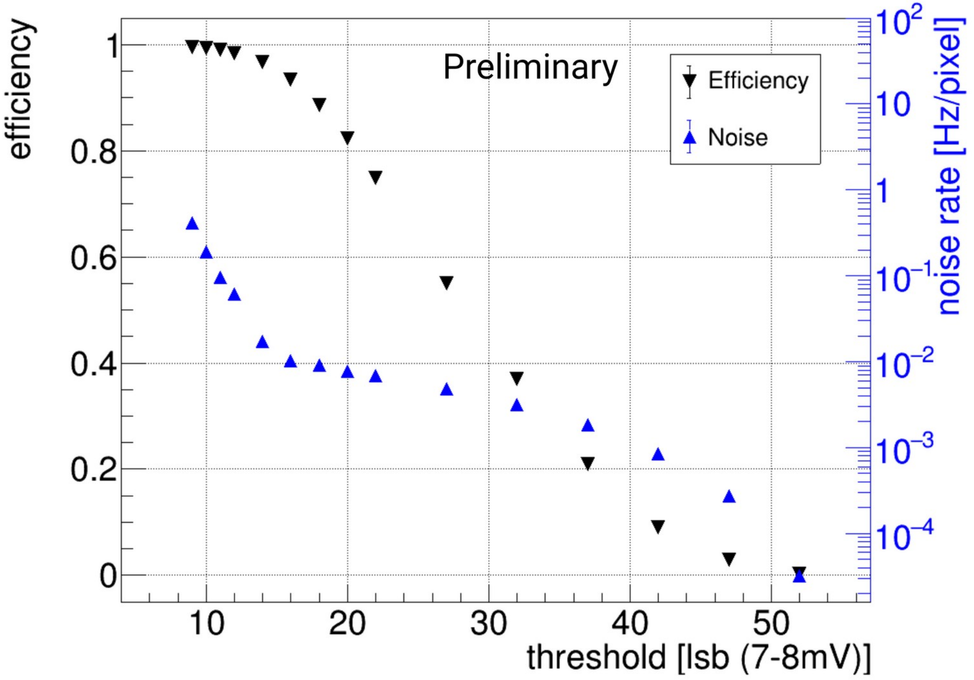


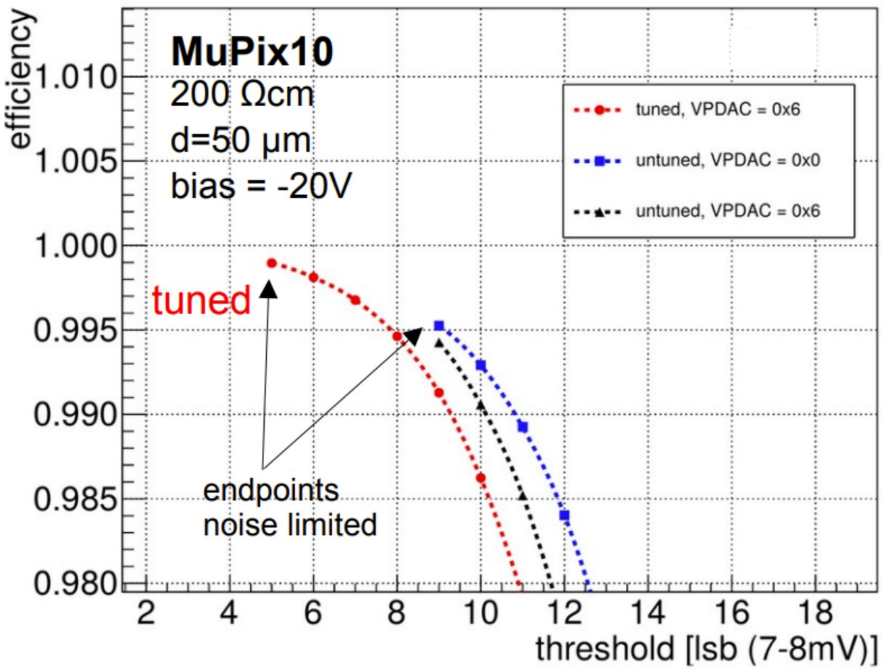




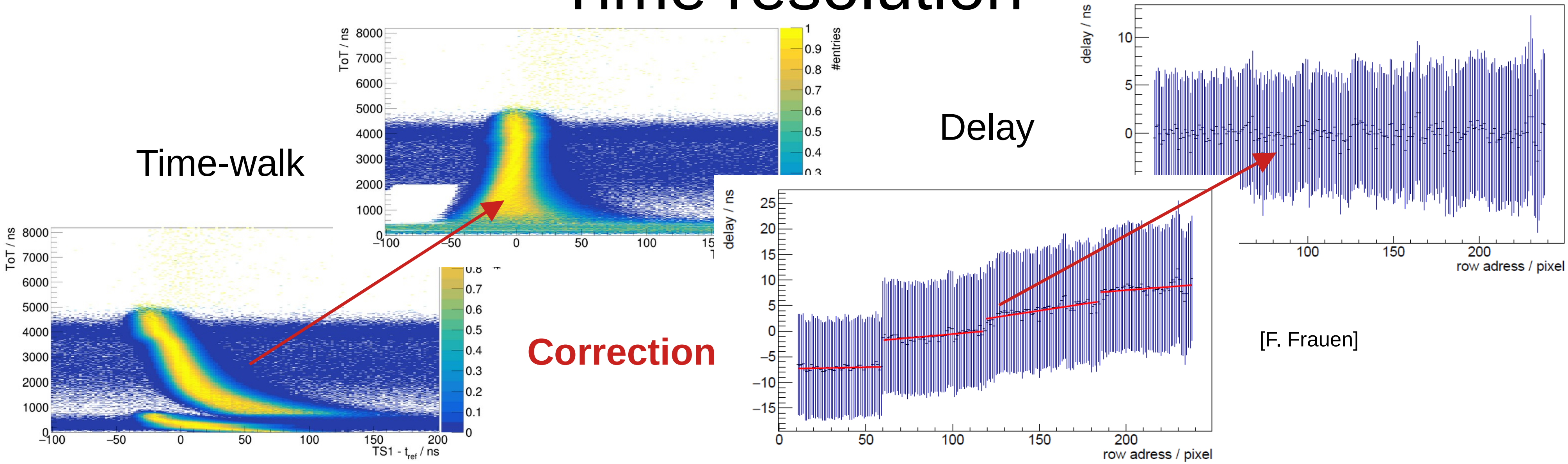
- Lab commissioning
- Lab optimisation:
  Radioactive sources: ^{55}Fe, ^{90}Sr
  Time coincidence
- Testbeam Campaigns:
  DESYII
  PSI piM1
- MuPix-Telescope
- Mimosa/Alpide-Telescopes

Efficiency of a 50µm MuPix

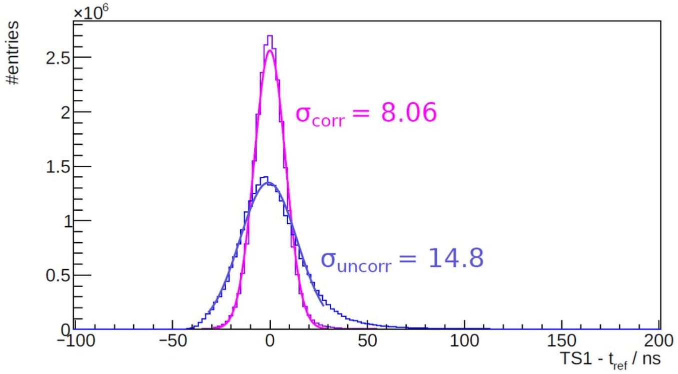




Time resolution

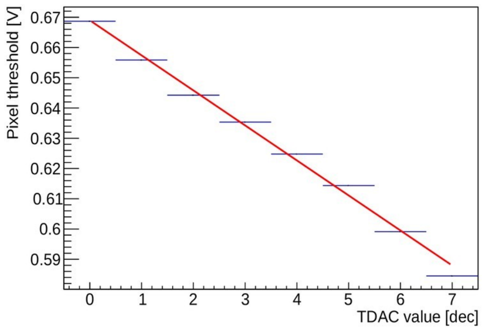


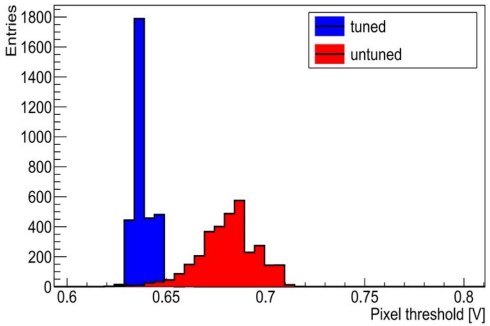
[F. Frauen]



Significant improvement through offline time correction!

Tuning & Masking

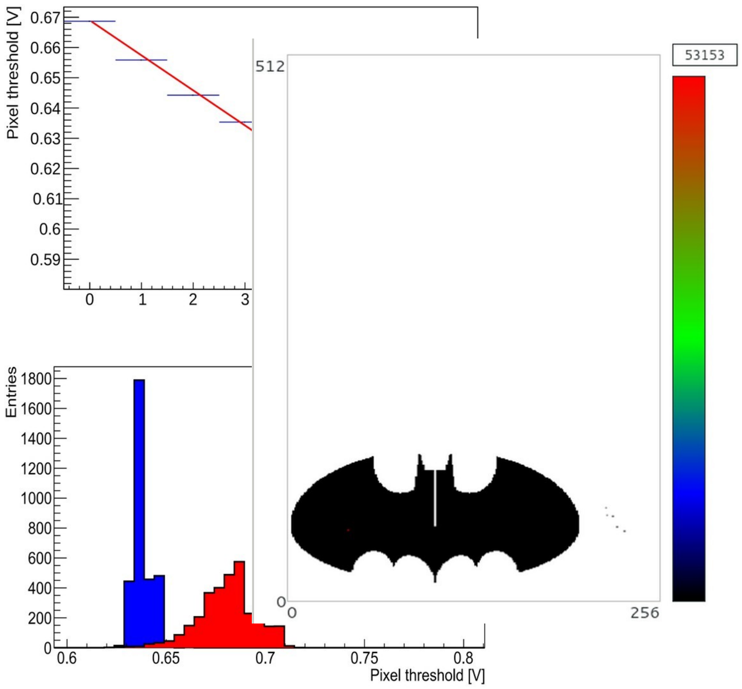




[M. Menzel]

- Usage of the individual tuning and masking bits
- S-curve based tuning approach
- Data:
  Injection of ~3000 e^- (fixed)
  Threshold scanned
- Threshold dispersion:
  Untuned RMS ~240 e^-
  Tuned RMS ~ 75 e^-

Tuning & Masking



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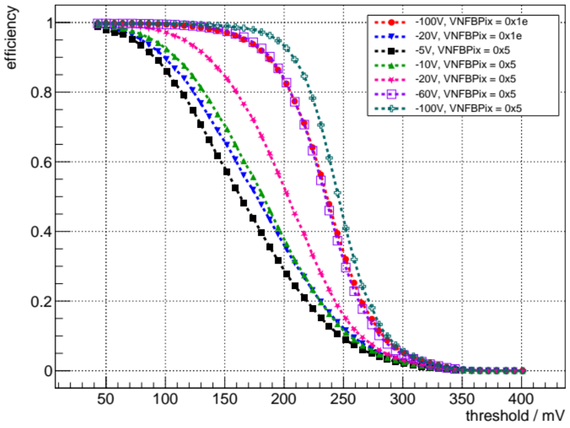
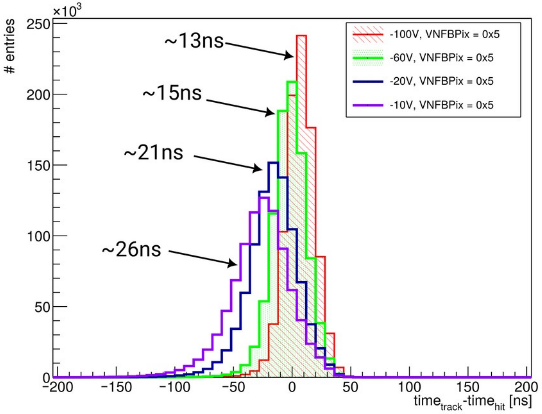
- Data:
  Injection of ~3000 e^- (fixed)
  Threshold scanned
- Threshold dispersion:
  Untuned RMS ~240 e^-
  Tuned RMS ~ 75 e^-
- Masking works nicely too

MuPix11-First look



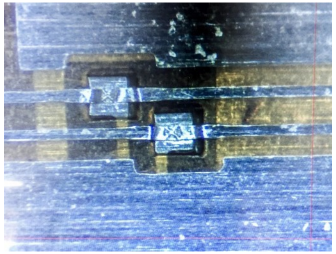
MuPix11
100µm

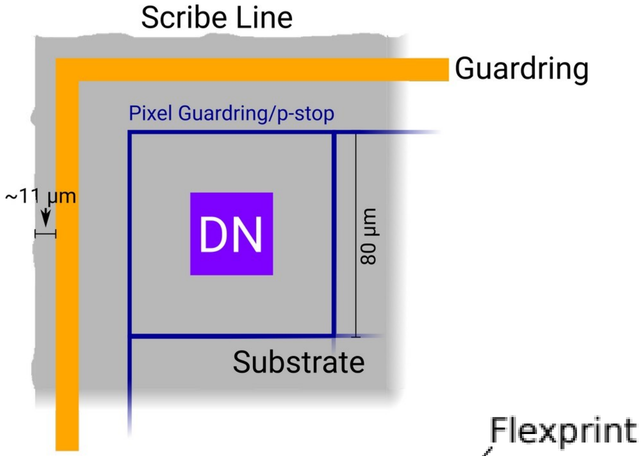


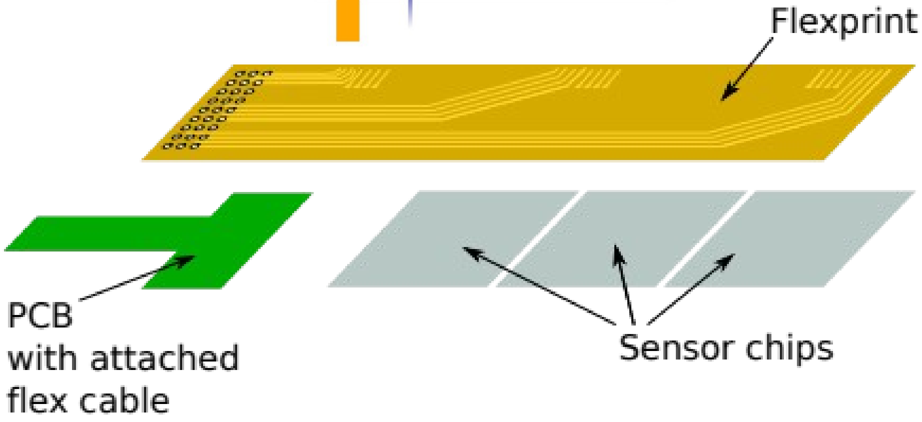
- Chips received end of August 22
- Commissioned and first beam within a week
- MuPix11 fully functioning
- All changes from MuPix10 successful
- Re-do the full characterisation cycle
- Optimize setting for 50µm samples

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)





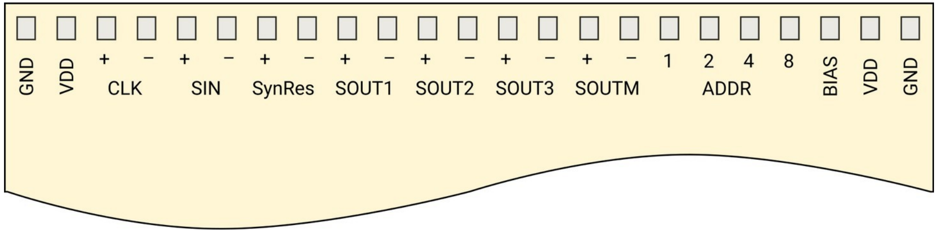


The Flexprint Environment

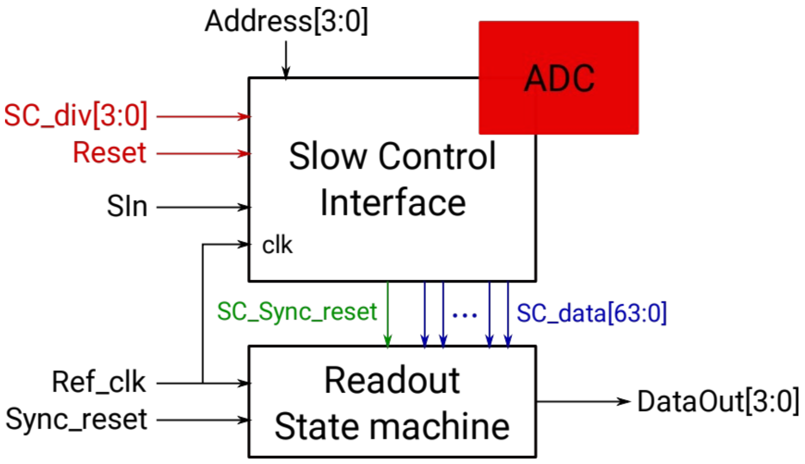
- 2 layer aluminum polyimide flexprint (LTU)
- Provides:
  Power & HV (parallel)
  Differential Signal I/O
- Only 1 supply voltage, but no LDO-regulators!

➔ Minimise I/O

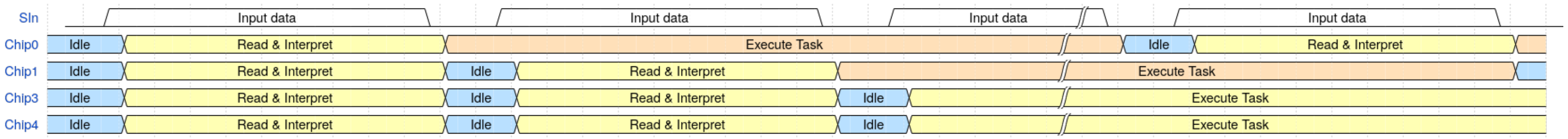
- Flex design rules define PadOut



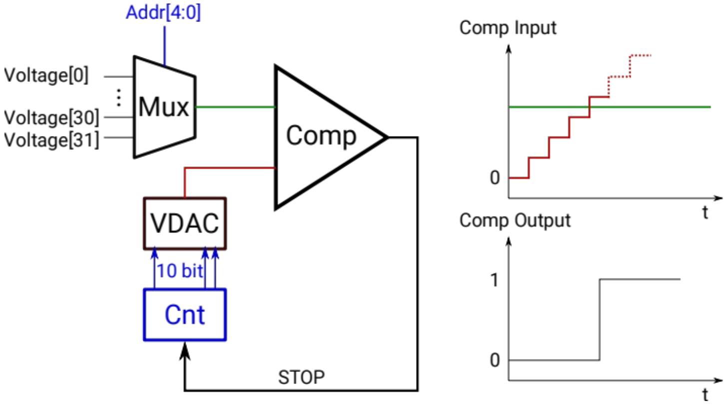
Mu3e Configuration Interface

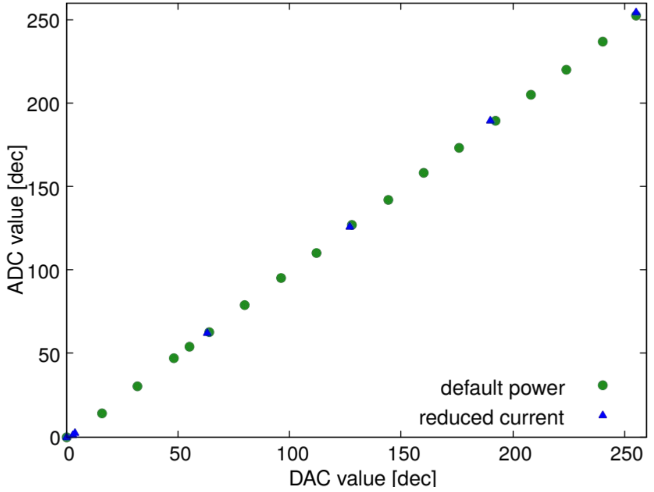


- Chips of a module share a bus of clock, synchronous reset and configuration input
- Chips are addressable individually
- Custom configuration protocol
- Commands interleavable
- ~400ms configuration time for 9 chip module
- Detector currently configurable <4s



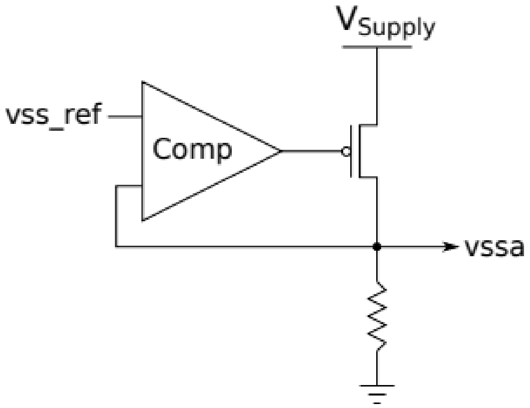
On-chip ADC

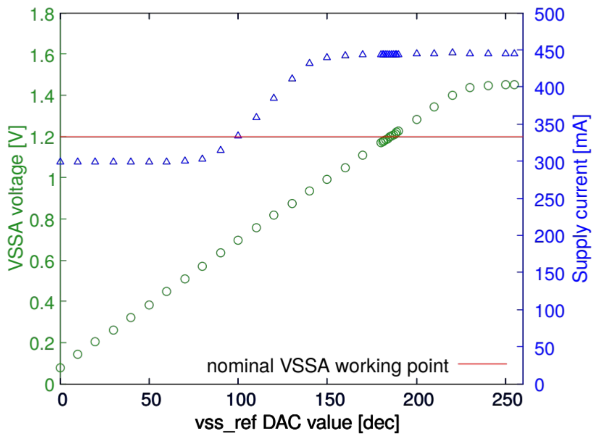




- ADC programmable through Mu3e configuration interface
- Allows measurement of on-chip voltages
- Data send out via 1.25 Gbit/s data links
- ADC shows a nice linearity
- First measurements and calibration is on the way

On-chip Regulator





- Additional lower supply voltage required by amplifier
- No space on flexprint
- Voltage level adjustable through a DAC

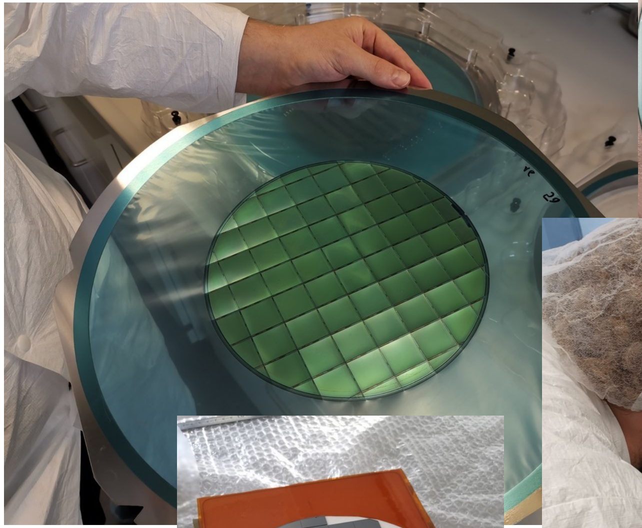
→ Sensor operable with a single supply voltage

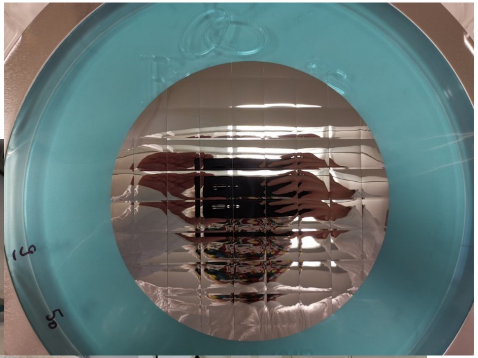
→ Power consumption: 200-250mW/cm²

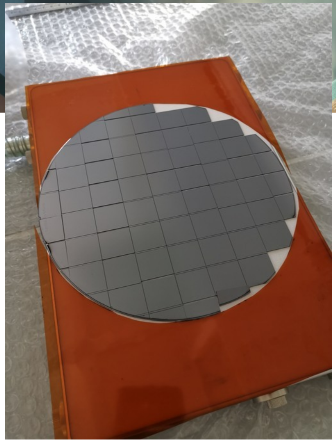
In-house Picking

- Diced Wafers delivered on tape (Company OPTIM)
- Equipment:
  Vaccum chuck
  Vaccum pick-up tool
  Patience
- 3 thicknesses:
  625, 100 and 50 um
- Picking yield very high: >98%
- Effect on “electrical yield”?

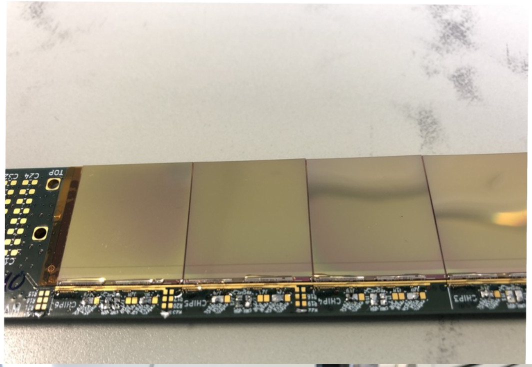
➔ detailed study with mass test is currently ramping up

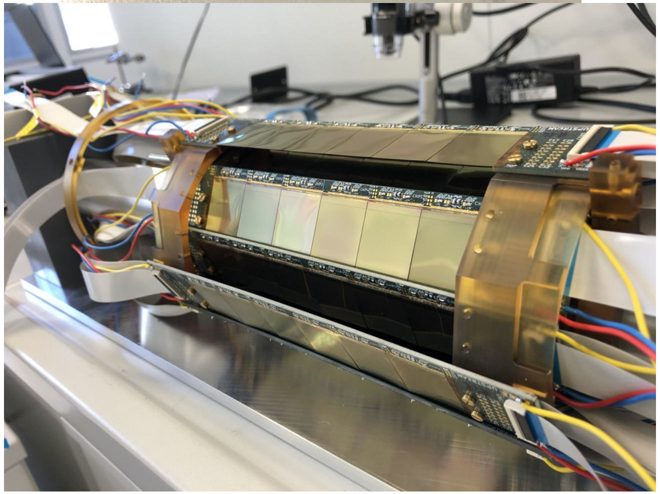






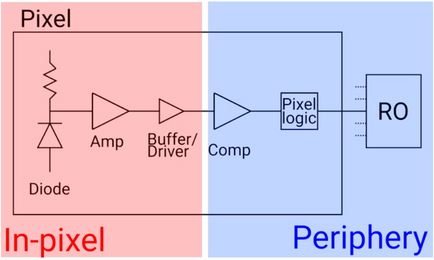
MuPix in Mu3e

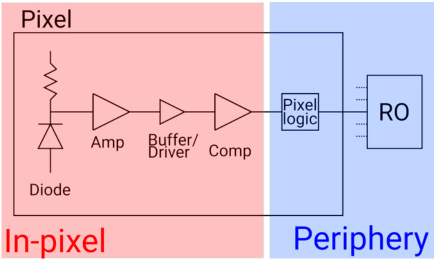


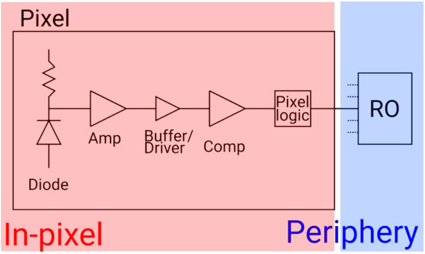


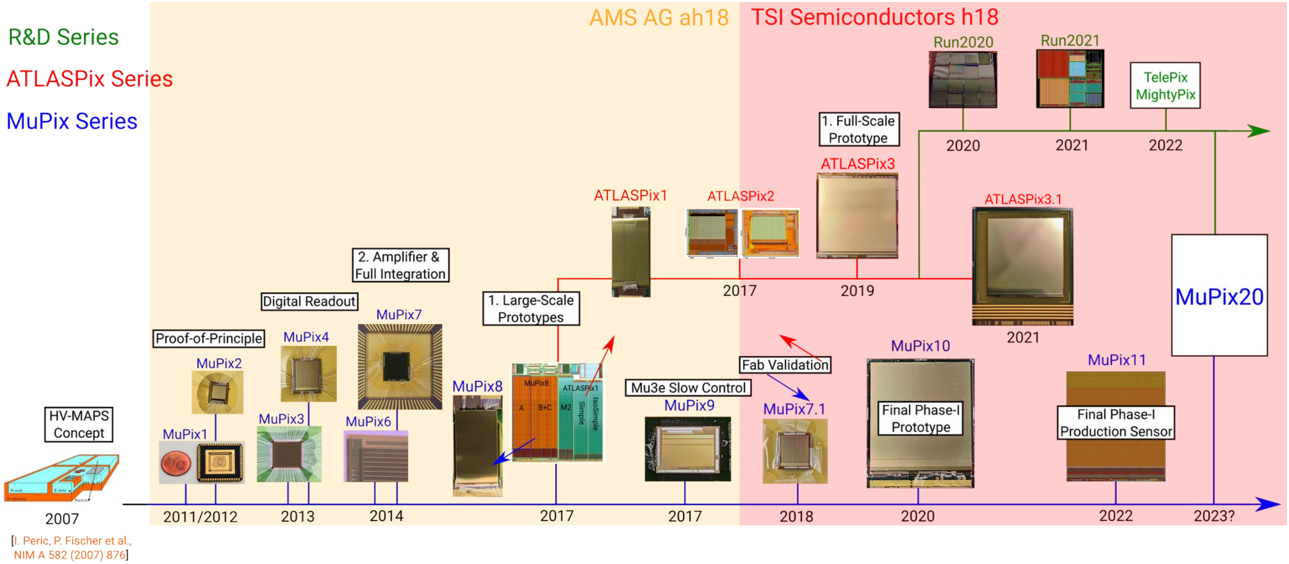
- MuPix10 was used to build a proto-detector:
  PCB based 6 chip modules
- → Detector successfully operated with muon beam
- Final Module production about to start
- Mass testing of chips
- Goal:
  Functioning pixel tracker end of the year

Beyond MuPix11 – Roadmap -- Architectures



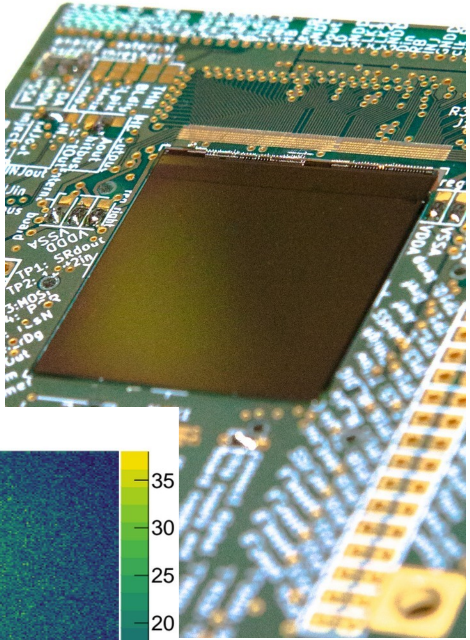


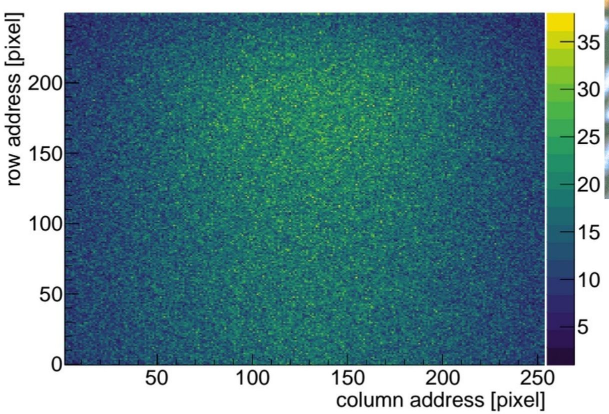




Summary

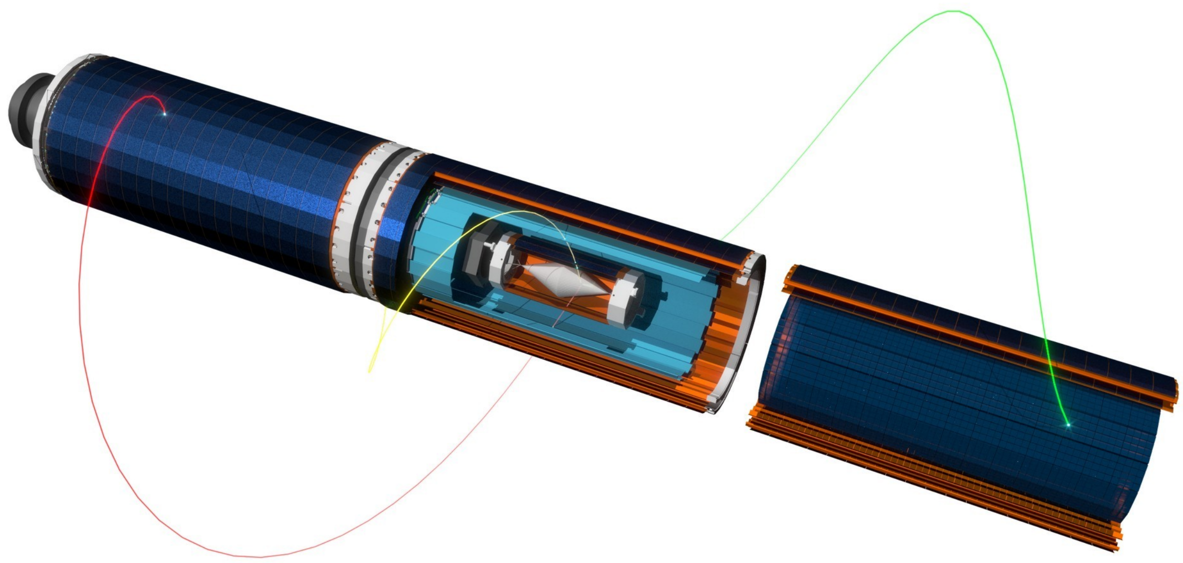
- The final MuPix chip is available
- ➔ All features functioning,
  all updates from MuPix10 successful
- Currently all characterisation measurements are beeing repeated with MuPix11
- Mu3e Module production about to start
- ➔ First HV-MAPS based low material tracker by end of the year



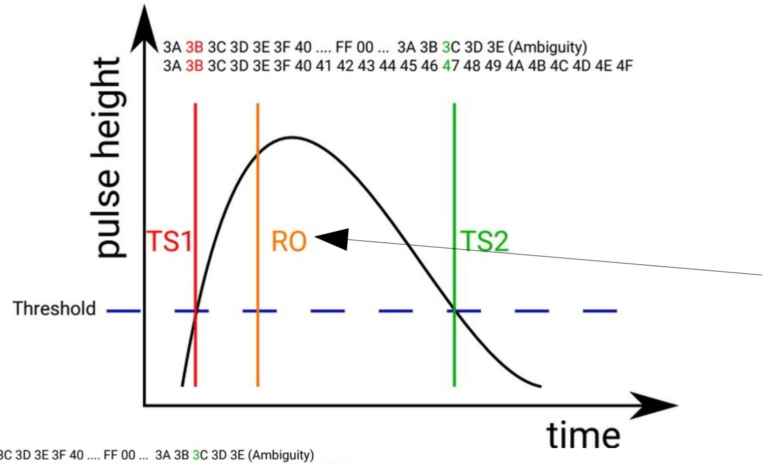


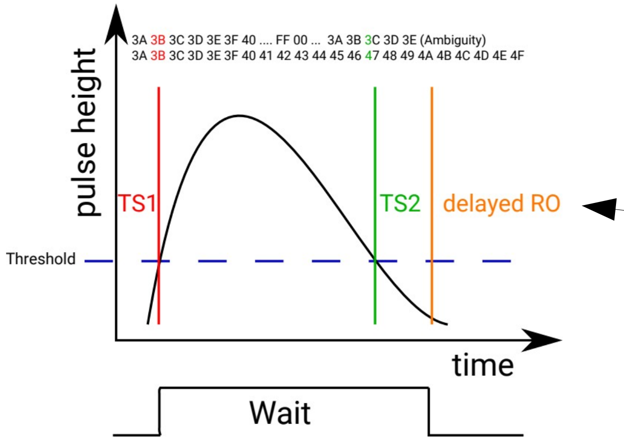
BACKUP

Mu3e Detector



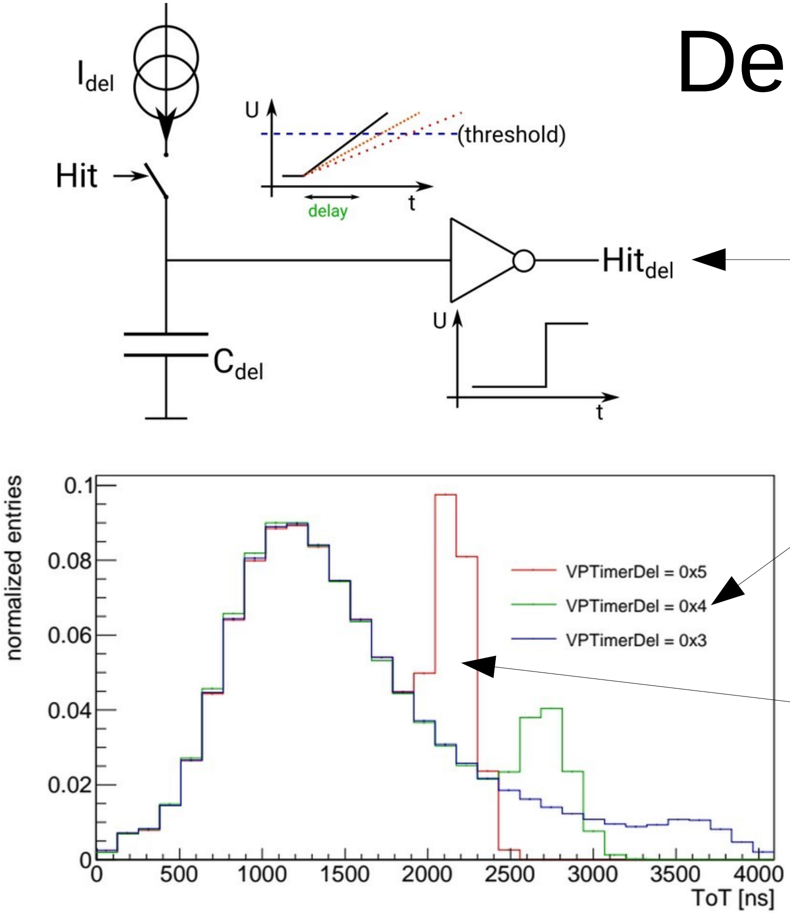
ToT sampling





- ToT correction desired for offline data analysis
- Not foreseen on MuPix8
  → possible readout problem
  → ToT not fully sampled
- Easy Solution:
  Wait for the pulse to end
  → scrambles the chronology of the data
- ➔ Additional complexity for the online sorting
- Better:
  delay every hit by a constant time
  → Chronology conserved

Delay Circuit



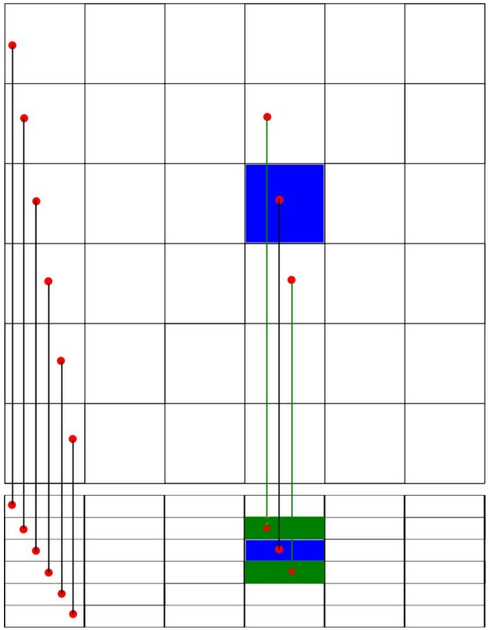
- Analogue Delay
  Designed by Alena Weber(KIT)
- Contained in each digital pixel cell
- Delay programmable
- Delay measurable as maximum ToT
- Further idea: Hits with large ToTs do not gain from ToT correction

➔ Limit the maximum ToT

➔ More precision for low energy depositions

➔ Works nicely!!

Signal Line Crosstalk - MuPix8

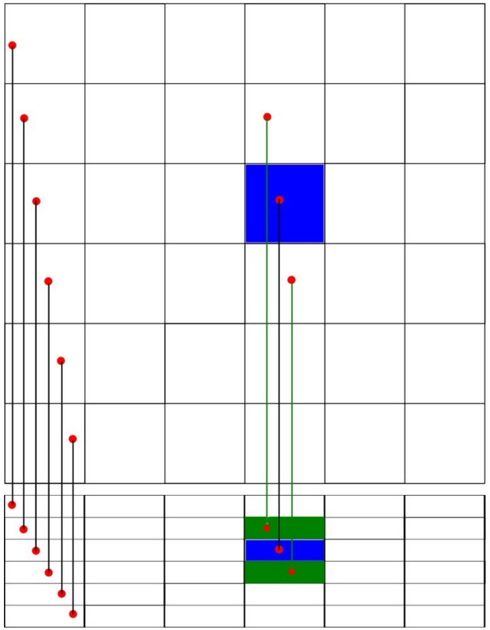


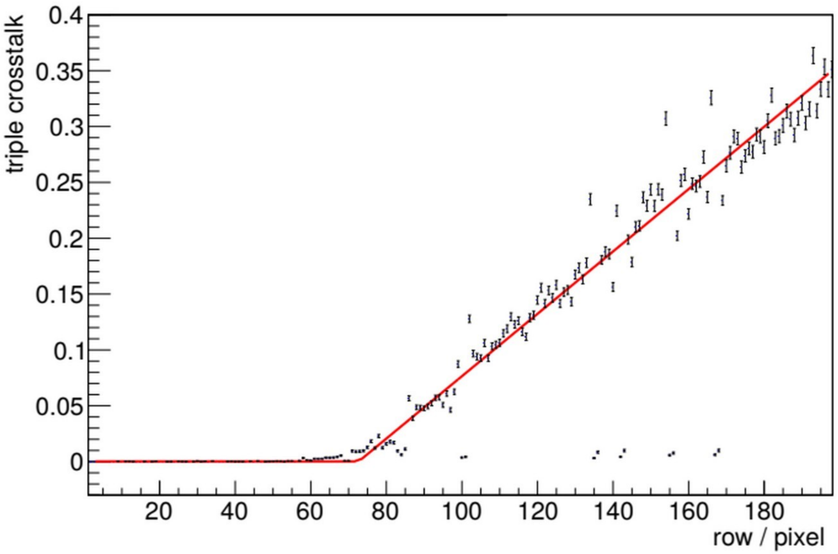
- Point-to-point connection
- Capacitive coupling to neighbouring lines (increases with lenght)
- Crosstalk can induce additional hits

➔ Not easily distinguishable from charge sharing

➔ Additional Readout load

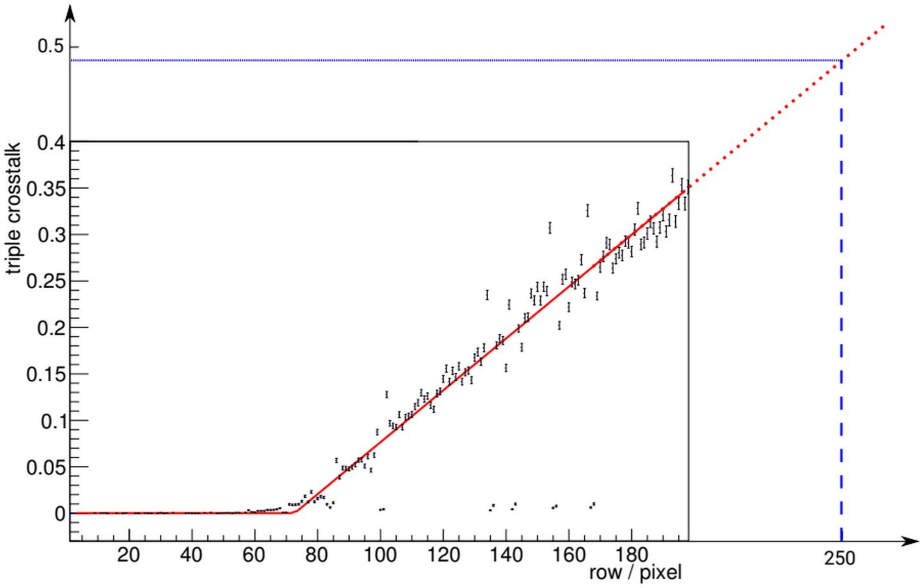
Signal Line Crosstalk - MuPix8





Triple Crosstalk:
hit induced in both neighbouring lines

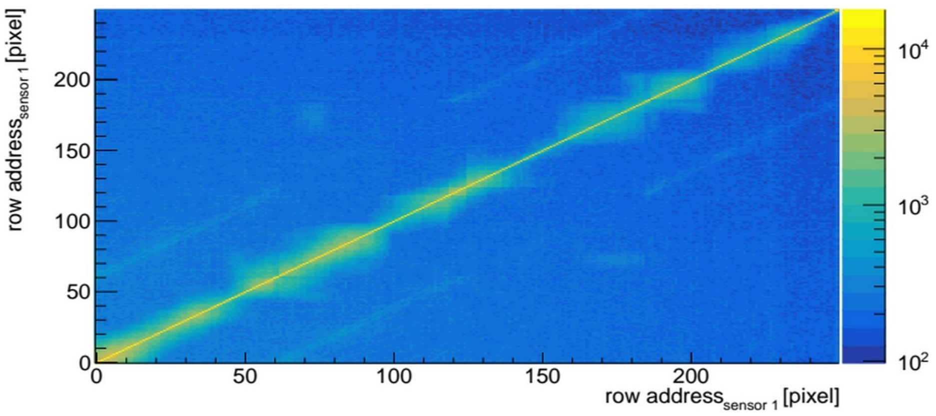
Crosstalk Extrapolation for MuPix10



Triple Crosstalk probability

- Using the same routing density and scheme
- ➔ Almost 48% crosstalk probablility for the longest line
- ➔ Penalty for high row addresses
- ➔ Routing needs to adapt

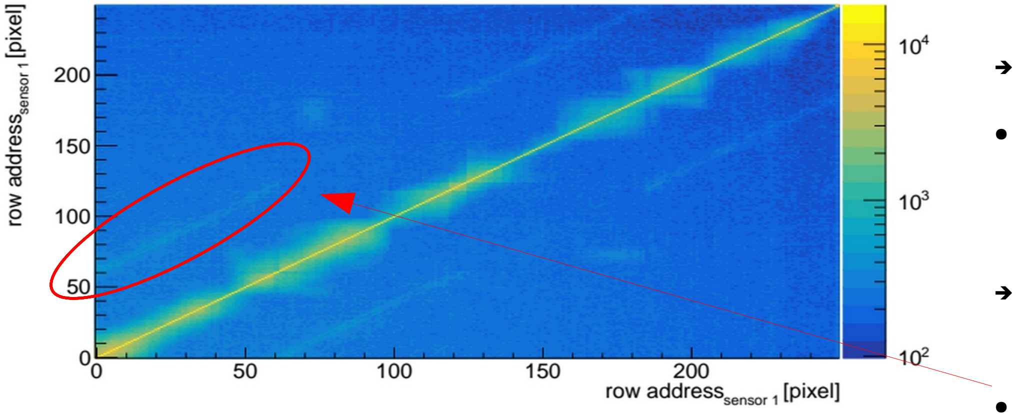
Routing Optimisation - MuPix10



Better plot from David?

- Equalize but reduce crosstalk
  →miminise the length that two lines are neighbouring
  (¼ of total length possible)
- ➔ ~12% triple crosstalk expected
- Make Crosstalk easily detectable
  → neigbouring signal lines are not neigbouring pixels

Routing Optimisation - MuPix10



Better plot from David?

- 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