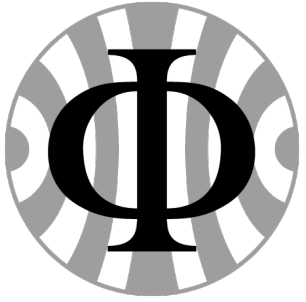
MuPix10: First Results from the Final Design

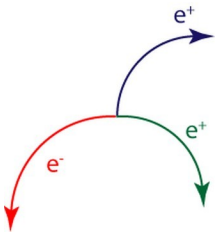


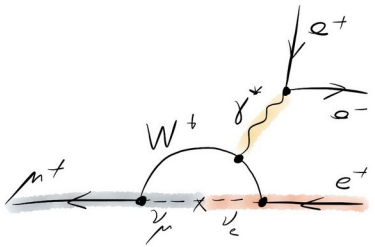
Heiko Augustin on behalf of the Mu3e pixel team
Physikalisches Institut Heidelberg

Vertex2020

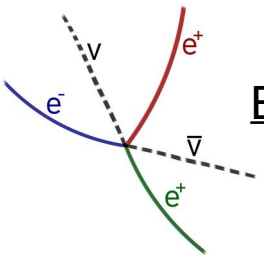
07.10.2020

Mu3e

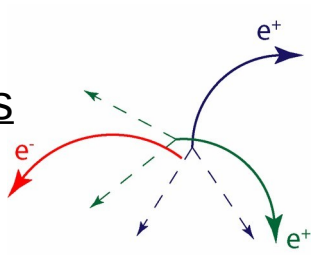




Internal Conversion



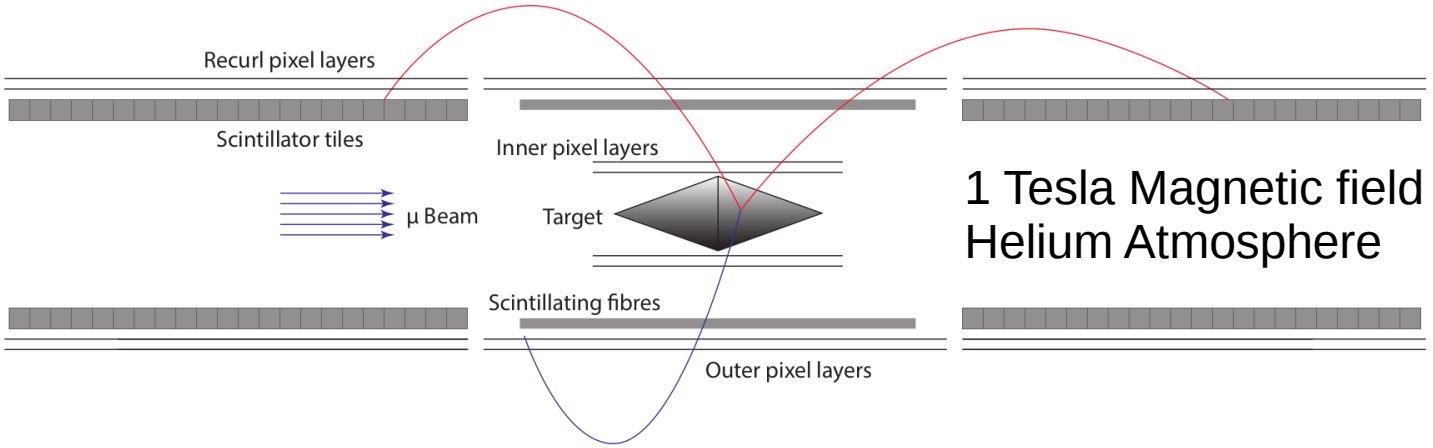
Backgrounds



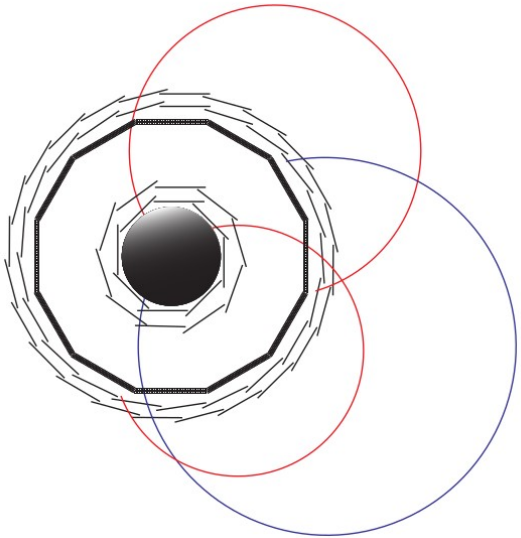
Accidental

- Search for the cLFV decay
  $\mu^+ \rightarrow e^+e^-e^+$
  (νSM: BR < 10^{-54})
- Current limit (SINDRUM)
  BR < 10^{-12} @ 90% CL
- Sensitivity goal:
  1 in 10^{16} decays
- Up to 10^9 decays per second
- Suppress background below sensitivity level

The Mu3e Detector



1 Tesla Magnetic field
Helium Atmosphere



- 10^8-10^9 decays per second
- $p_{max} = m_\mu/2 = 53$ MeV
- ➔ Multiple Coulomb Scattering

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

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]

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

➔ Multiple Coulomb Scattering

- Good vertex and time resolution (100 µm & 500 ps)
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- Continuous Beam! No trigger!

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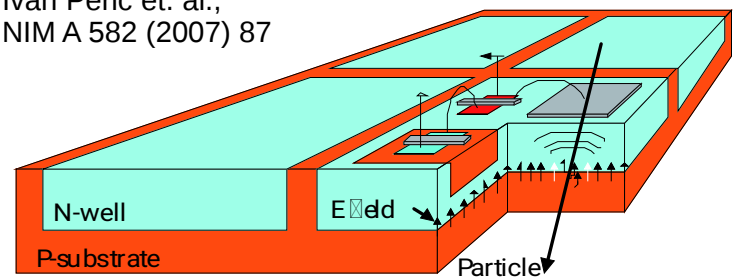
High Voltage - Monolitic Active Pixel Sensors

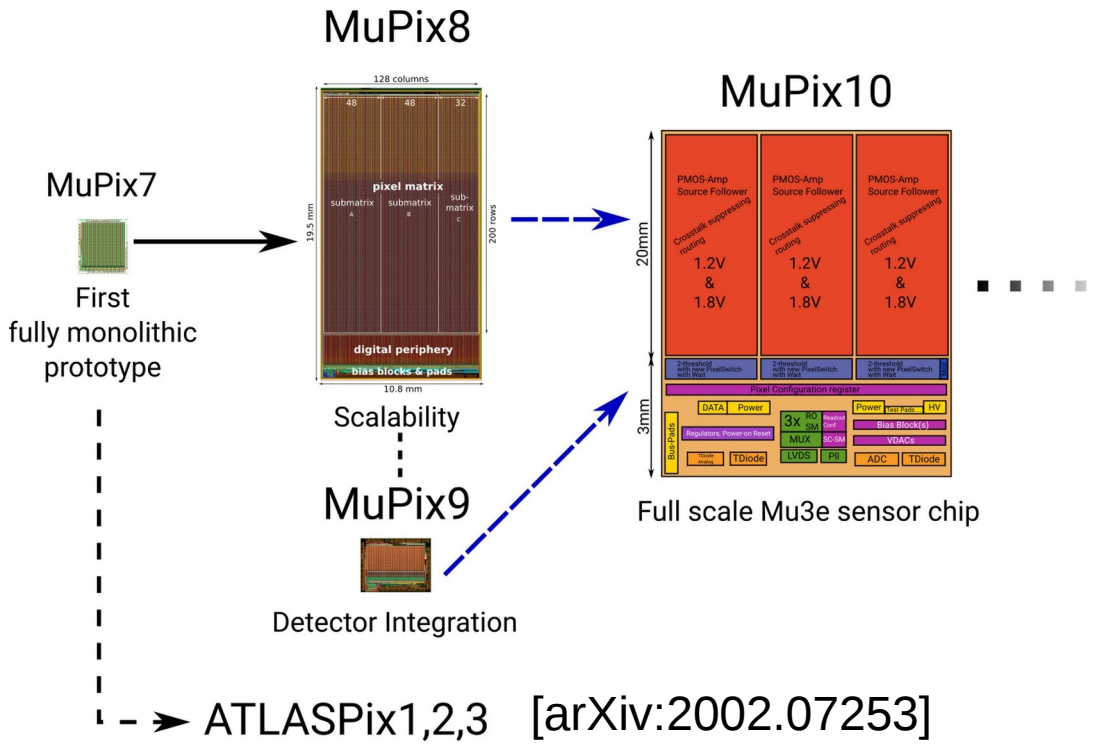
Ivan Peric et. al.,
NIM A 582 (2007) 87



- Low ohmic substrates (10-200 Ωcm)
- High voltage > 100V
- Deep N-well diode
- ~ 30 µm depletion
- Charge collection via drift

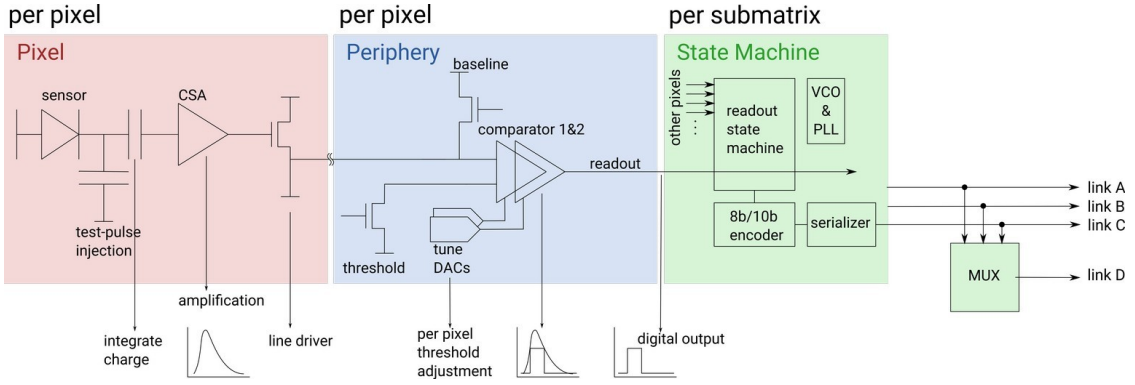
- In-pixel electronics
- Monolithic design:
  Detection and Readout
  combined in one chip
- Commercially available processes:
  AMS 180nm (6M)
  TSI 180nm (7M)
- Chips are thinned to 50 µm

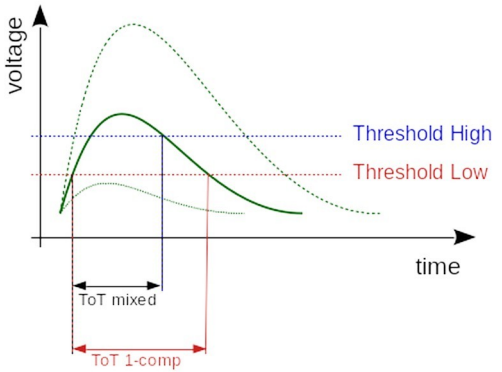
MuPix History



- Small prototype development culminates in MuPix7
- Scaling successful with MuPix8
- Foundry change necessary after MuPix9
- New foundry TSI with same base process (IBM 180nm)
- Large scale prototype MuPix10 and ATLASPix3 successfully produced with TSI

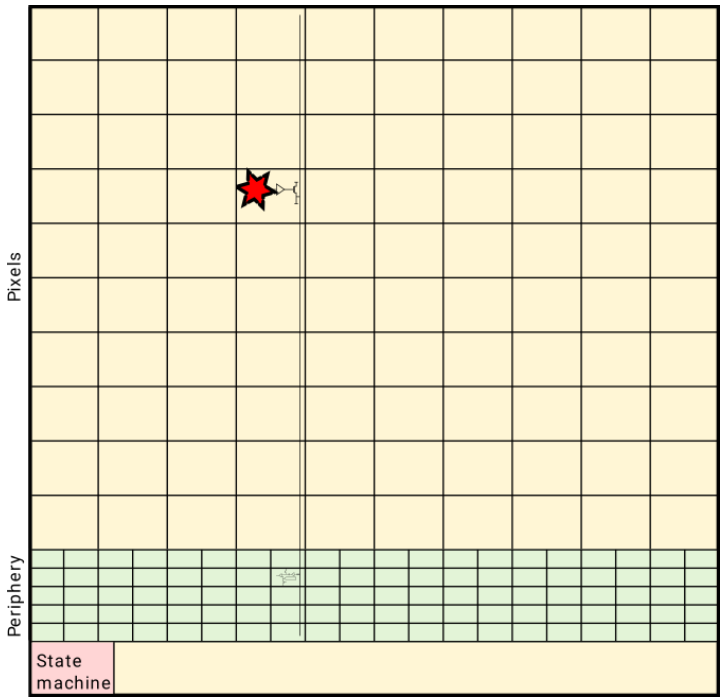
MuPix Architecture





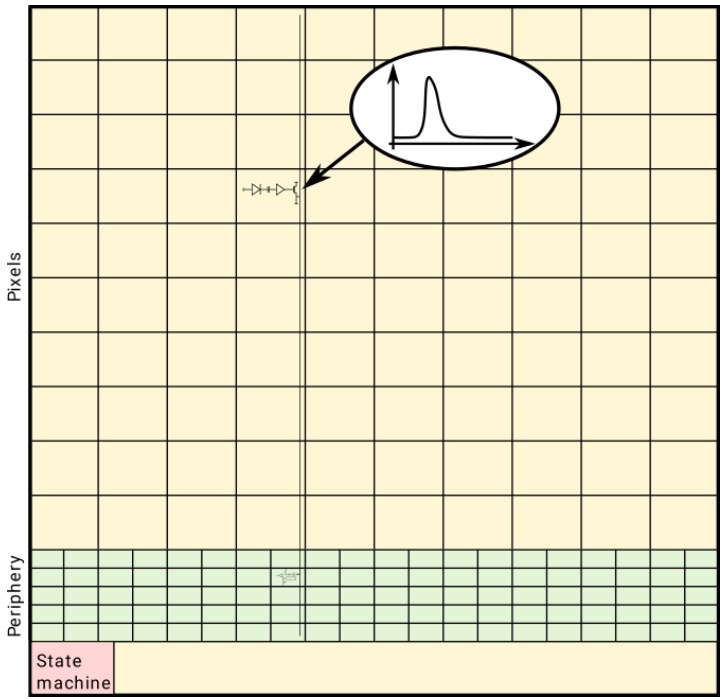
- Clear separation of analog and digital electronics
- 2 comparator design
- Tuning and masking available
- Priority encoder / column-drain readout
- Chip sub-dived into 3 matrices → 1 Data link each + 1 multiplexed link

The MuPix Principle



- 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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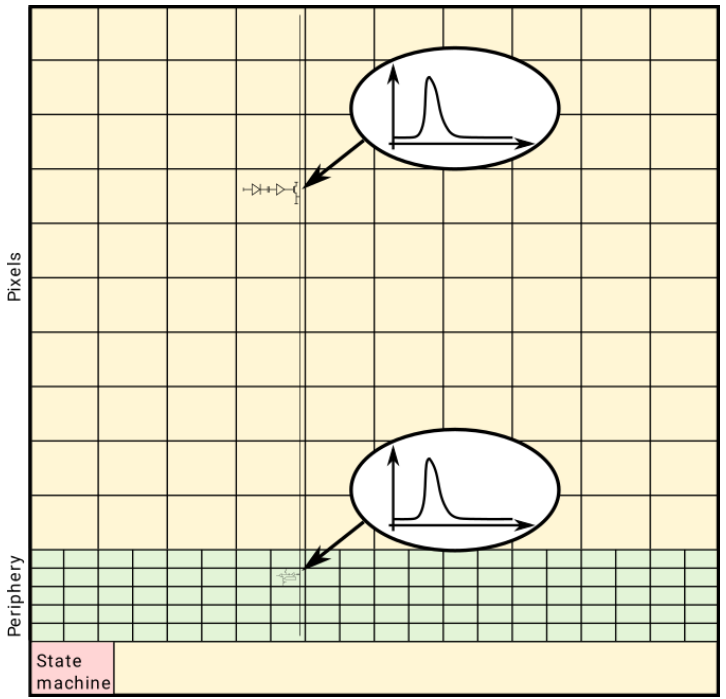

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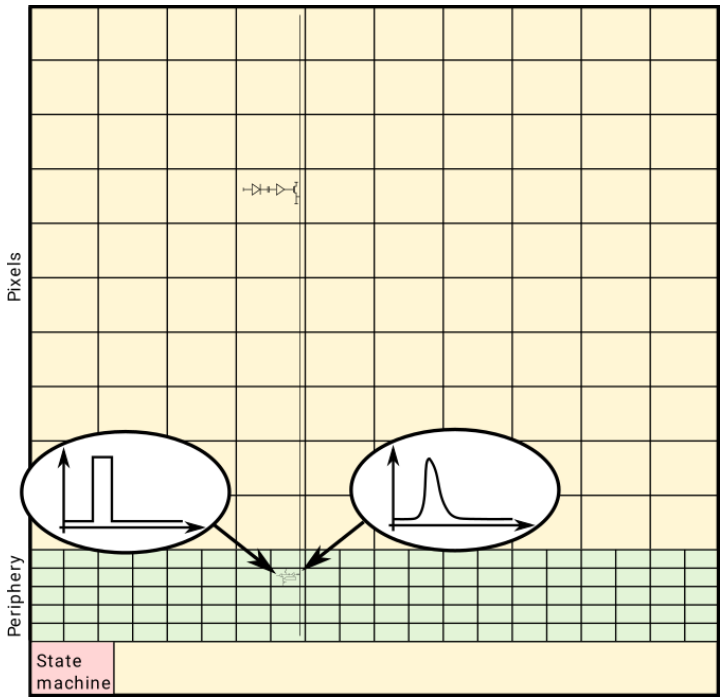

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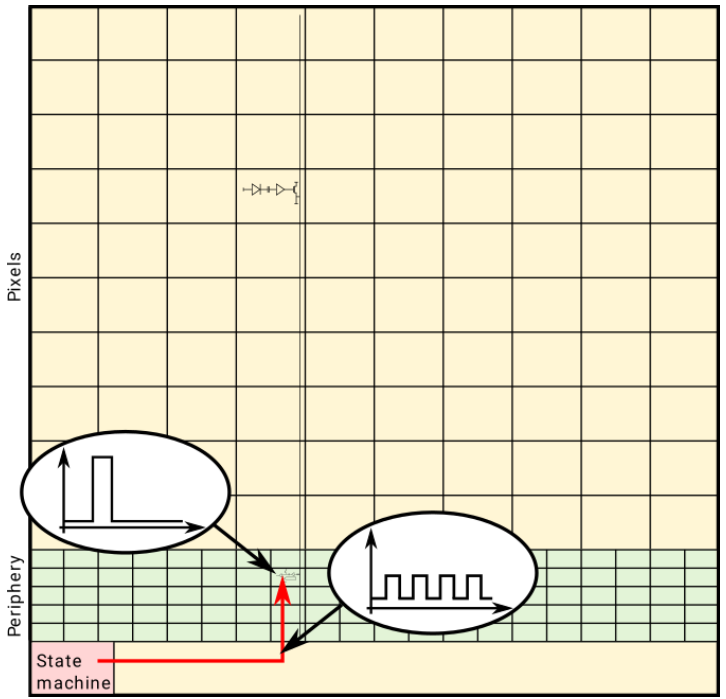

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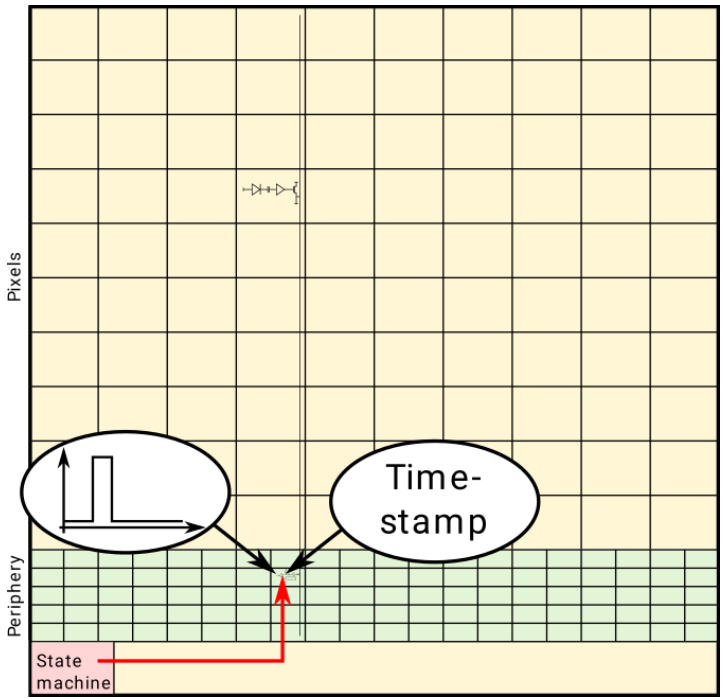

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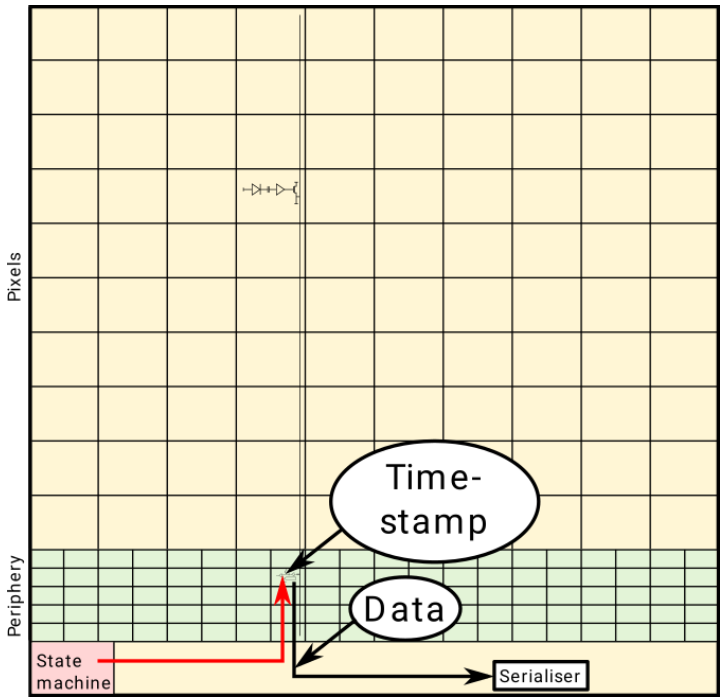

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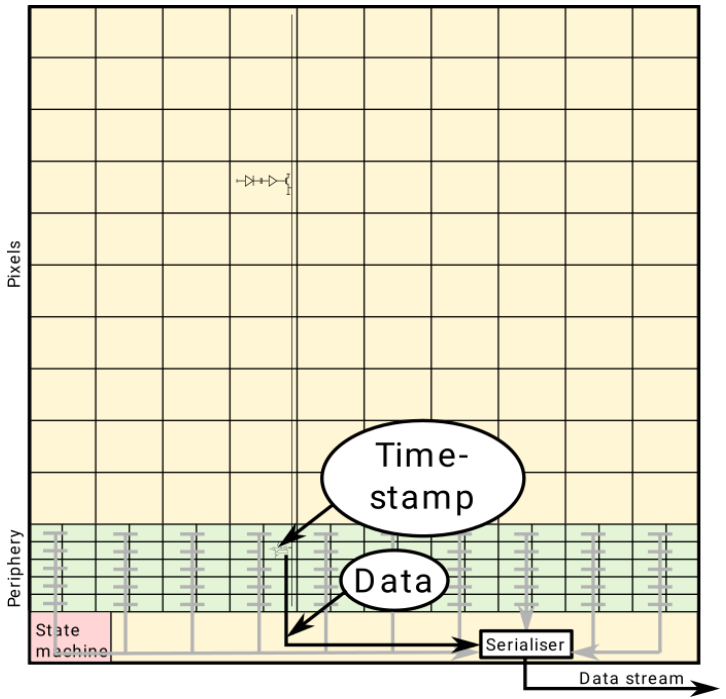
The MuPix Principle



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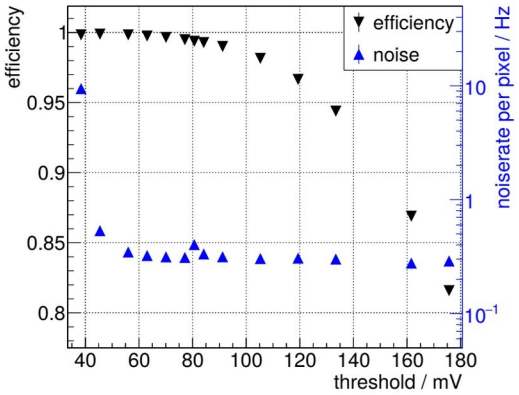
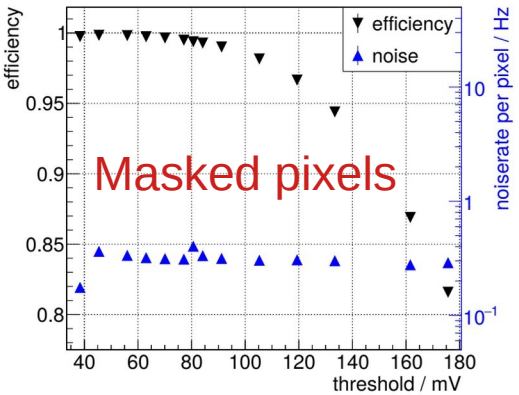
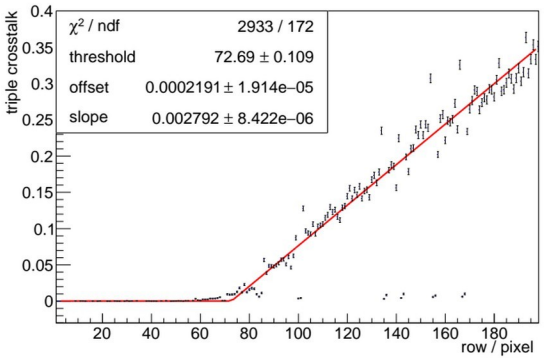
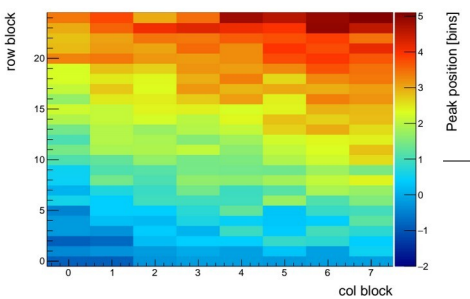
Latest Results - MuPix8



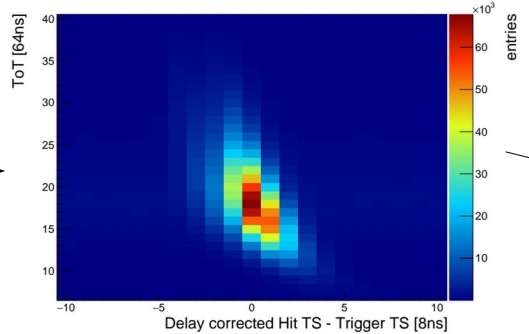


Signal Line Crosstalk





Pixel delay



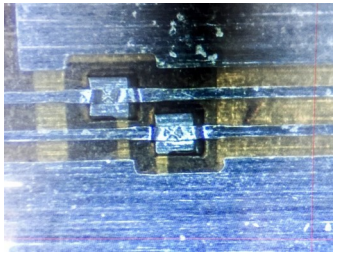
Timewalk

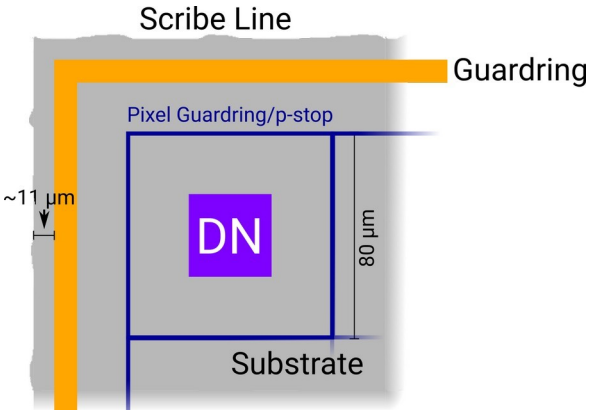
Raw time resolution	14 ns
+ Delay correction + Timewalk correction	6.5 ns

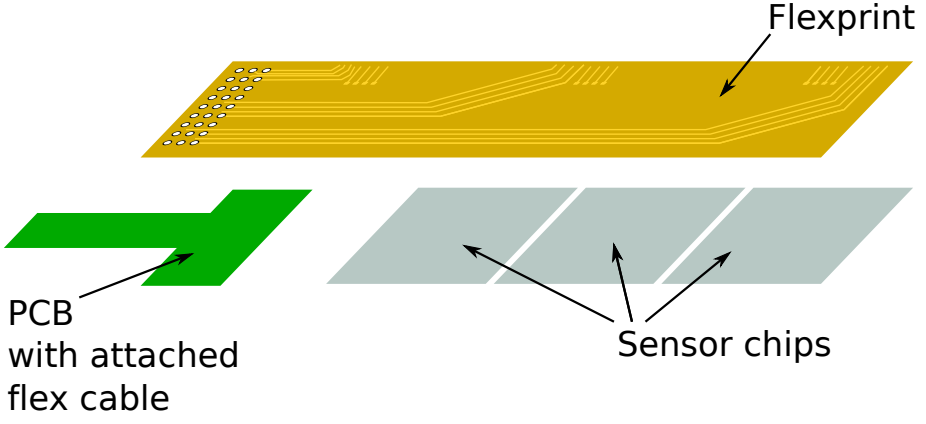
[arXiv:1905.09309]

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)

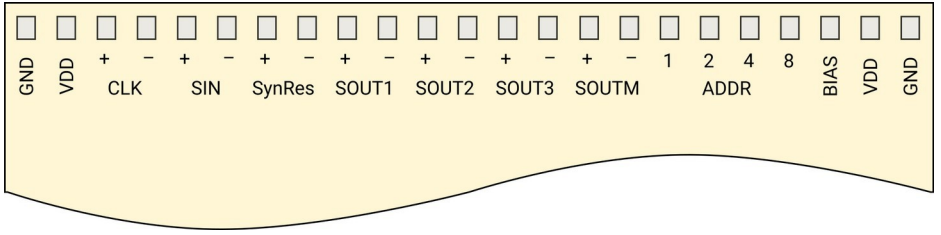




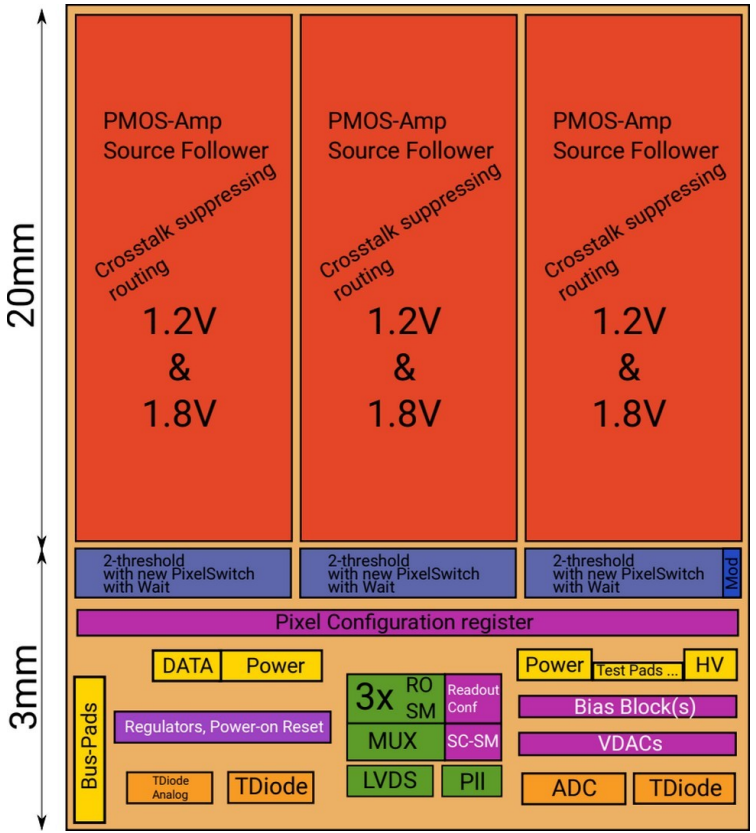


The Flexprint Environment

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

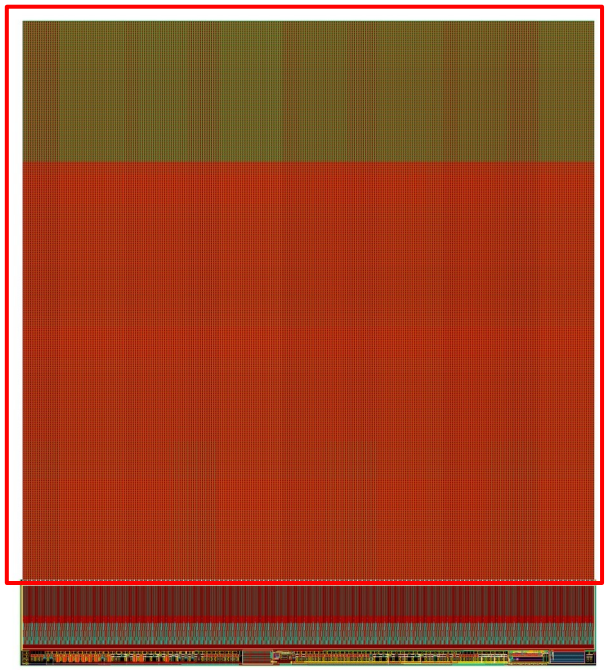


MuPix10 Design



- Module ready!
- ➔ Pad Out compatible with flex
- ➔ Chip size defined by mechanics
- Complete on-chip biasing:
- ➔ triple redundant memory
- ➔ bias and voltage DACs
- 1.2V voltage regulator
- ➔ MuPix10 can be used for Module production

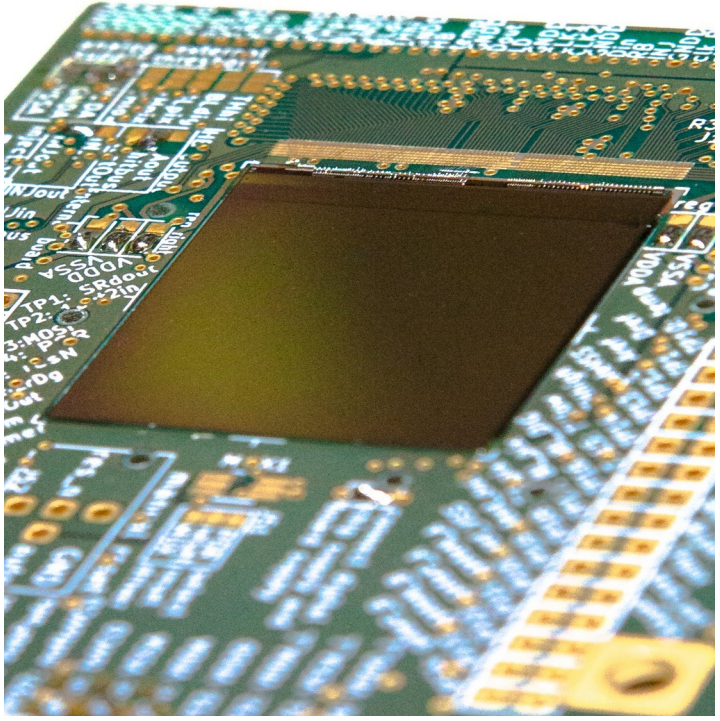
The MuPix10



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]	200-400
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)

MuPix10 timeline

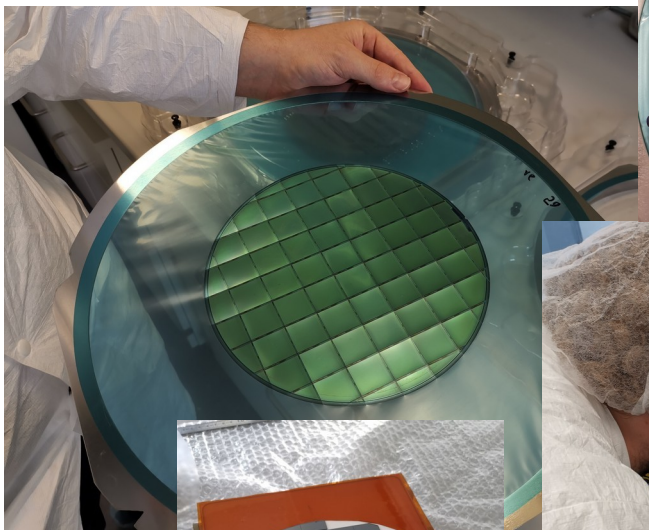
- December 2019:
  Submission to TSI
- March 2020:
  Wafer delivery
  Send for post-processing
- March → May 2020:
  Lock down in France and Germany
- Mid of May 2020:
  Receive first chips

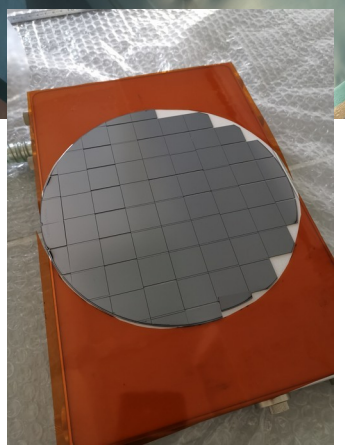


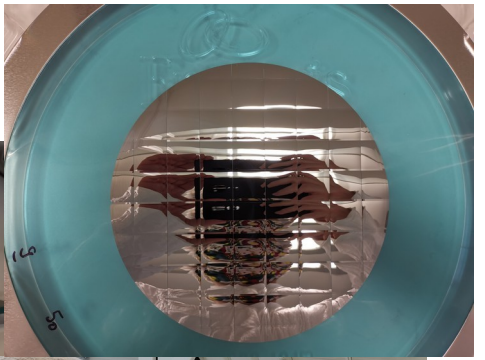
In-house Picking

- 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 probe card is pending

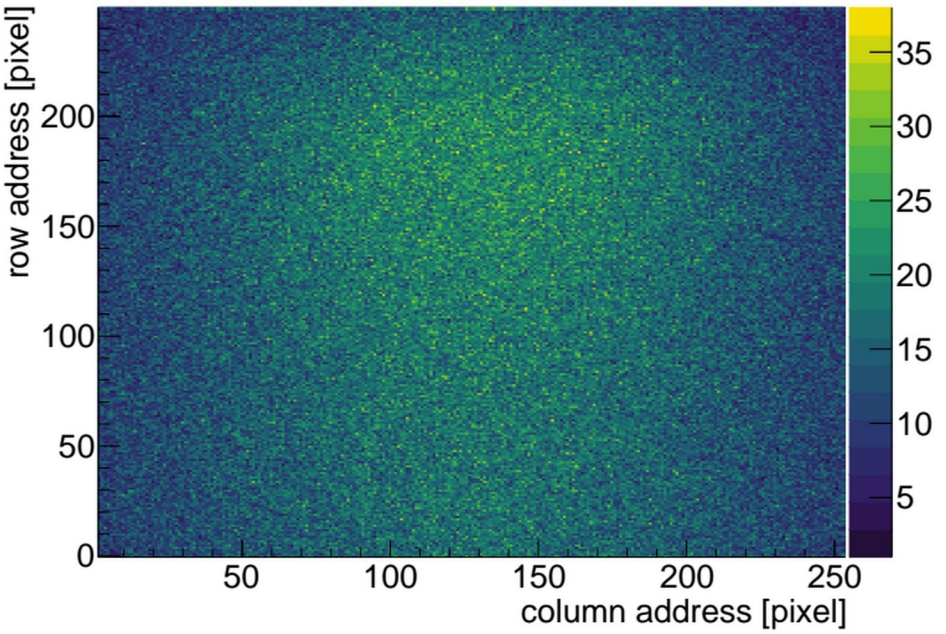






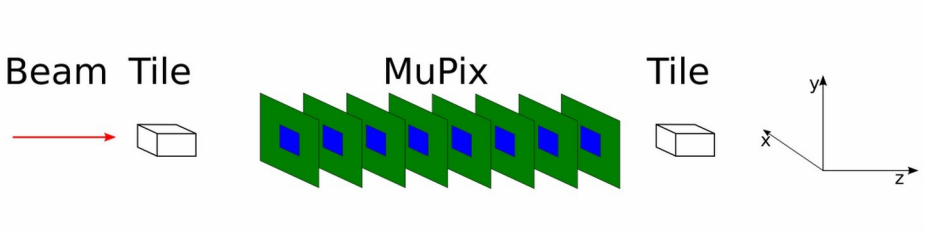
Commissioning & First results

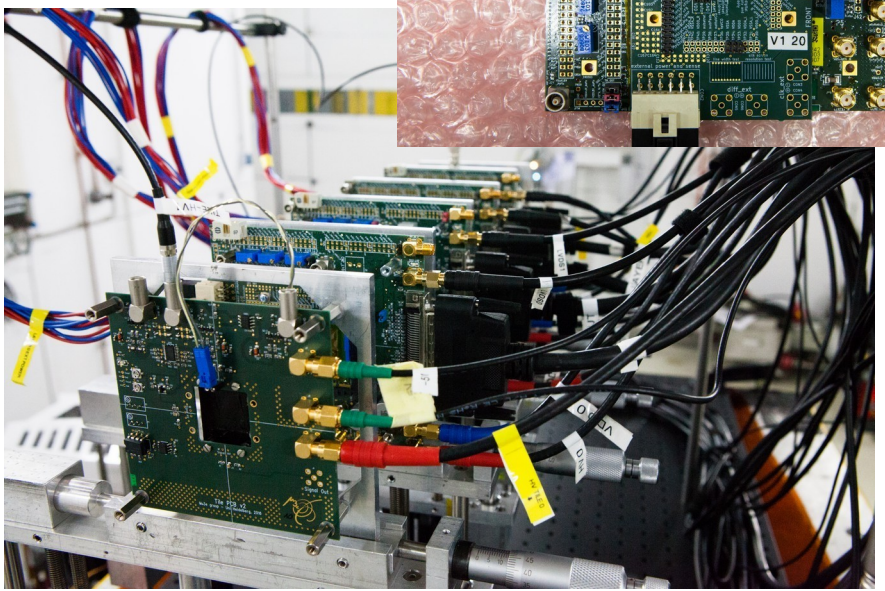
- In the Lab:
  Commissioning and Optimisation with Injection or Sr90 and Fe55
- ➔ Breakdown @ -100V
  → 30-40um depletion
- Testbeam:
  DESY 3 GeV e^-
  PSI 350 MeV π+,μ+,e+(,p+)
- ➔ MuPix10 works nicely



Hitmap DESY testbeam

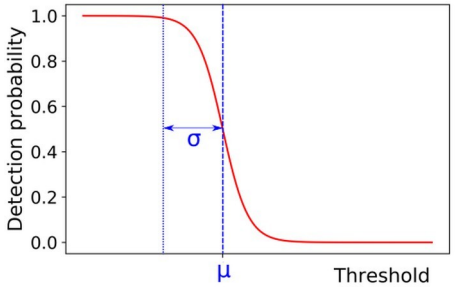
MuPix Telescope

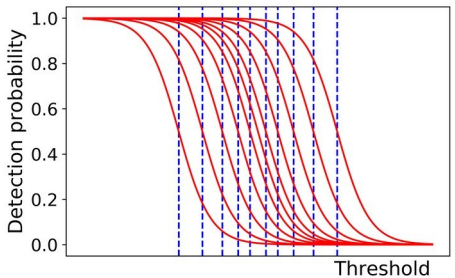




- Co-Development of the DAQ
- Most common setup:
  4 sensor layer (1 DUT)
  coincidence of scintillating tiles
- Evolution of reference plains:
  Mupix6, MuPix7, MuPix8, ATLASPix1, ATLASPix3 and now MuPix10
- MuPix10 telescope used!

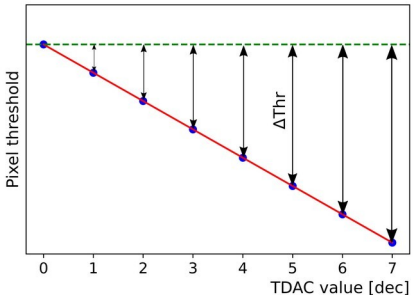
Tuning & Masking

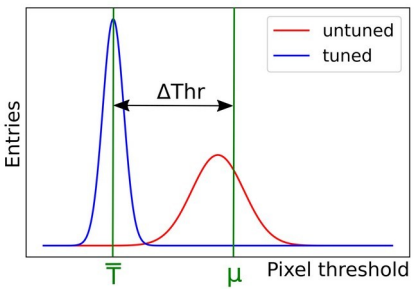




- Usage of the individual tuning and masking bits
- S-curve based tuning approach
- Data:
  Injection of ~3000 e^- (fixed)
  Threshold scanned
- Threshold dispersion:
  Untuned RMS ~240 e^-
  Tuned RMS ~ 75 e^-

Tuning & Masking





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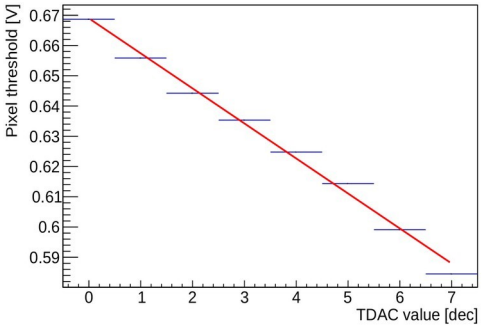

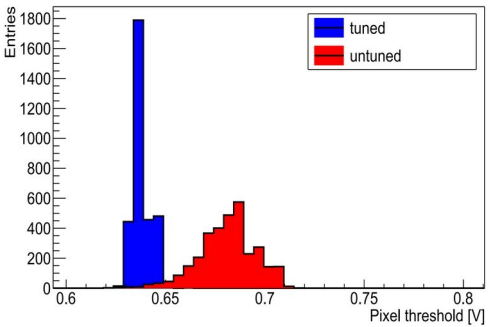

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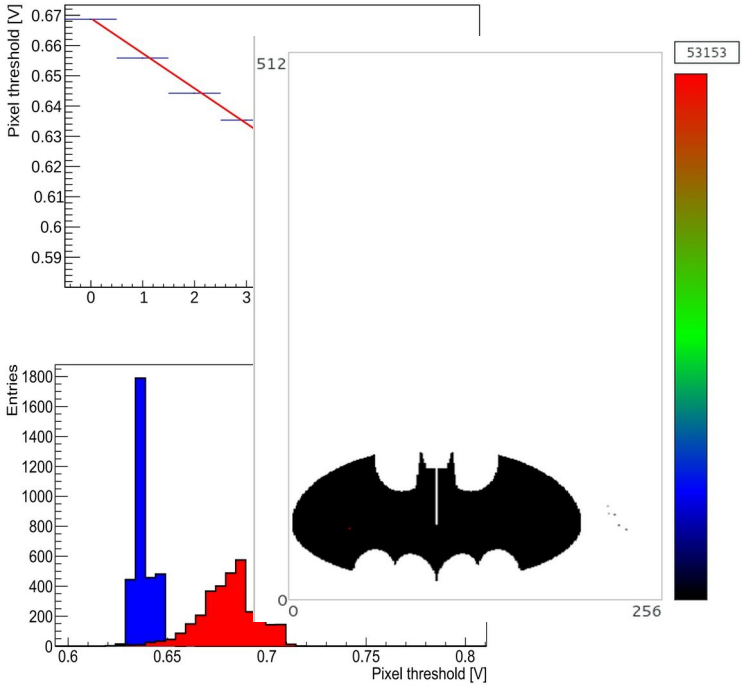

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- S-curve based tuning approach
- Data:
  Injection of ~3000 e^- (fixed)
  Threshold scanned
- Threshold dispersion:
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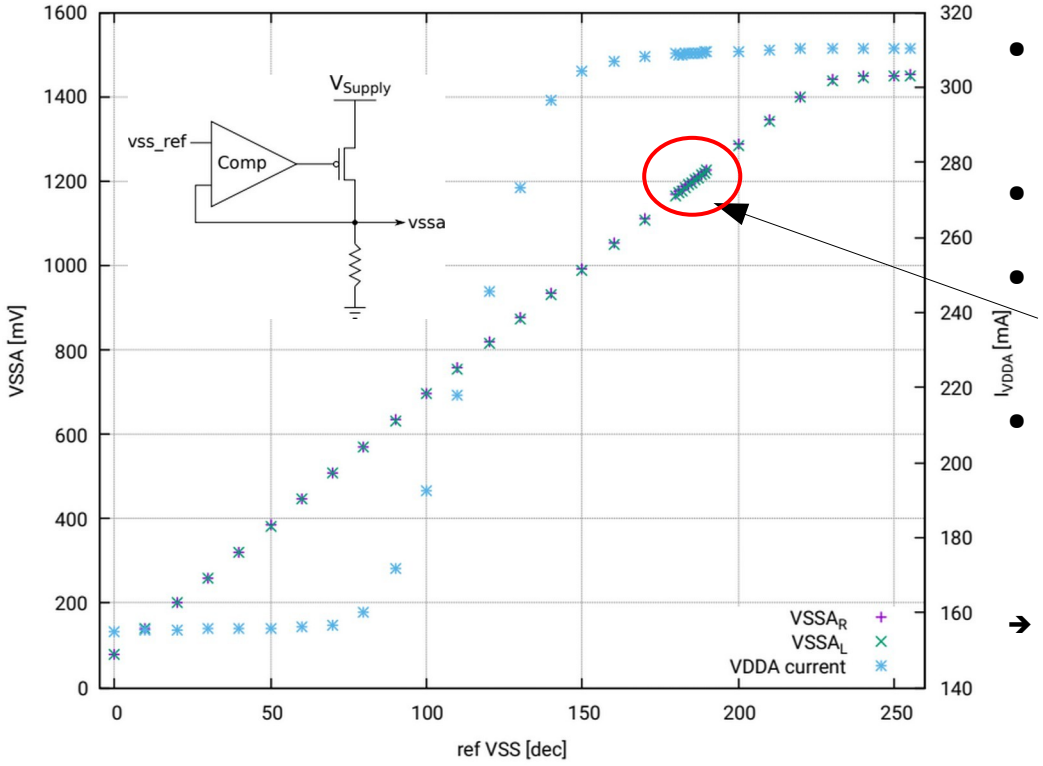
  Tuned RMS ~ 75 e^-
- Masking works nicely too

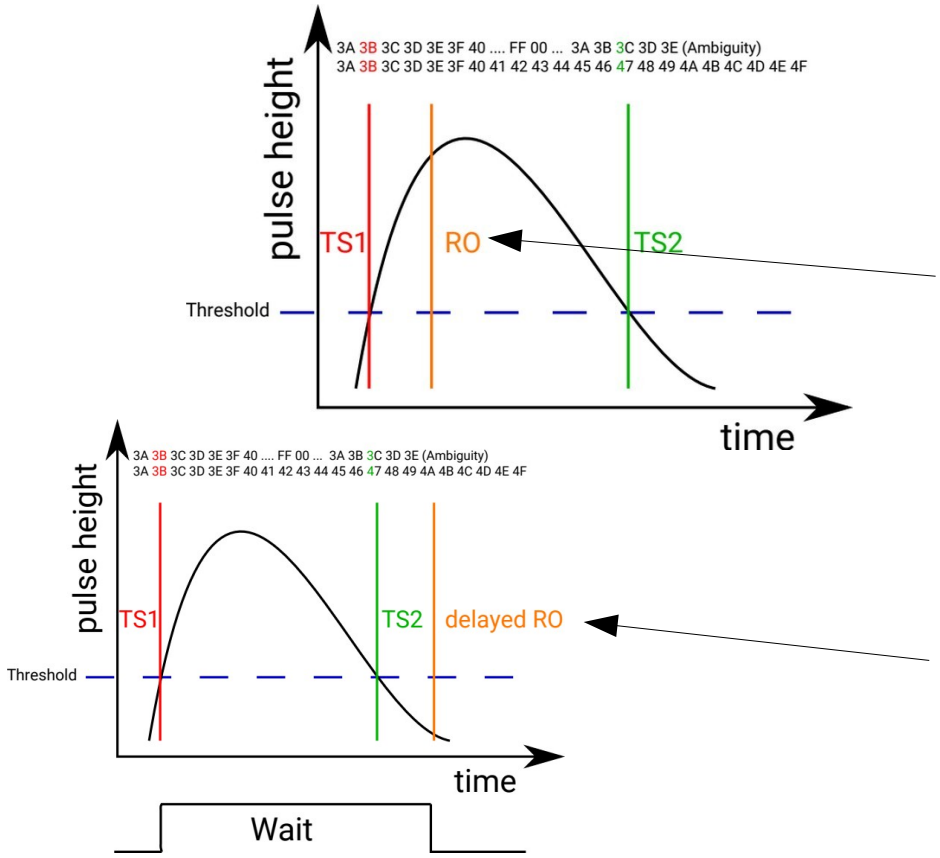
Vssa-Regulator



- Integral for module functionality with a single supply voltage
- No detailed study yet
- Dive into the cold water: the regulator works nicely
- Even colder water: MuPix10 was operated successfully with a single supply voltage

➔ Power consumption: ~ 220mW/cm²

ToT sampling

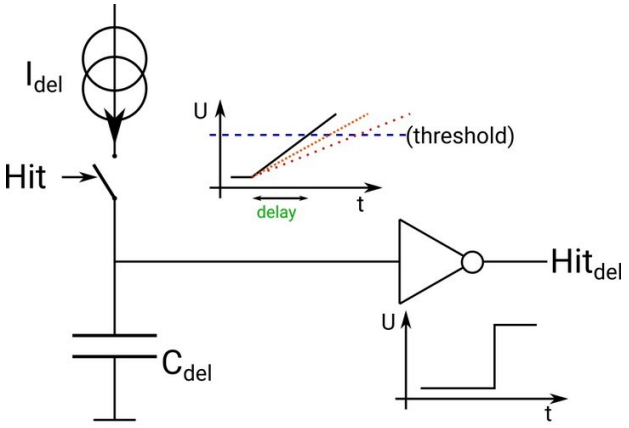


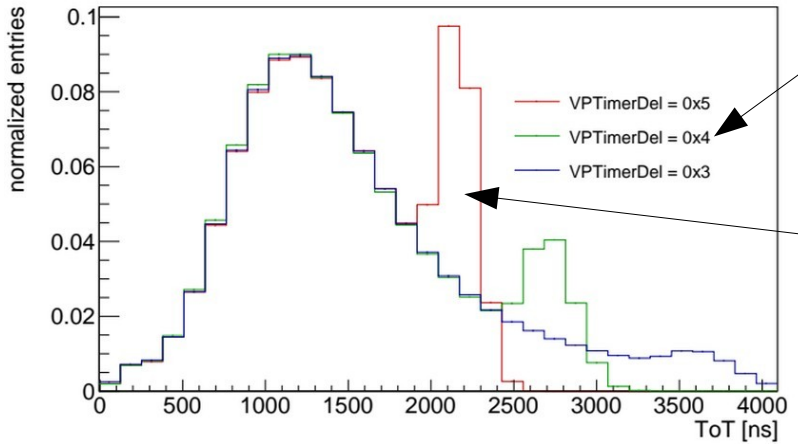
- ToT correction desired for offline data analysis
- Not foreseen on MuPix8
  → possible readout problem
  → ToT not fully sampled
- Easy Solution:
  Wait for the pulse to end
  → scrambles the chronology of the data

➔ Additional complexity for the online sorting

- Better:
  delay every hit by a constant time
  → Chronology conserved

Delay Circuit





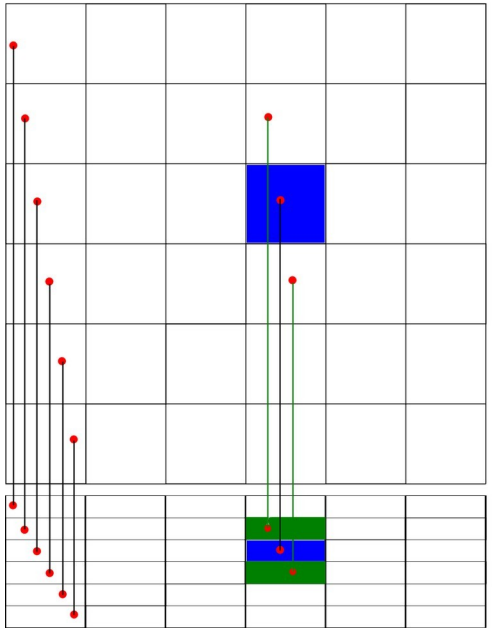
- Analogue Delay
  Designed by Alena Weber(KIT)
- Contained in each digital pixel cell
- Delay programmable
- Delay measurable as maximum ToT
- Further idea: Hits with large ToTs do not gain from ToT correction

➔ Limit the maximum ToT

➔ More precision for low energy depositions

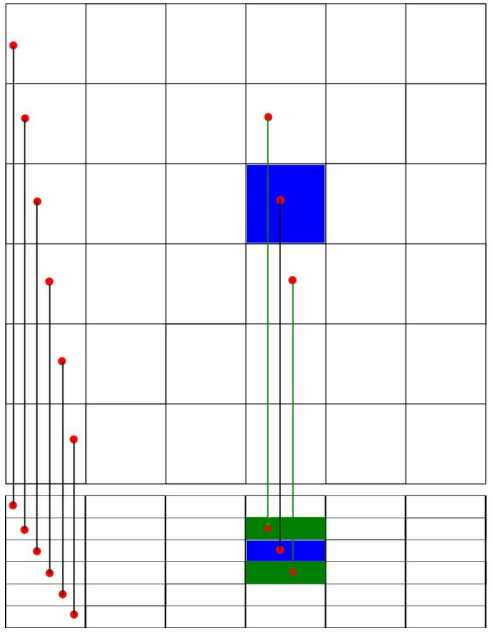
➔ Works nicely!!

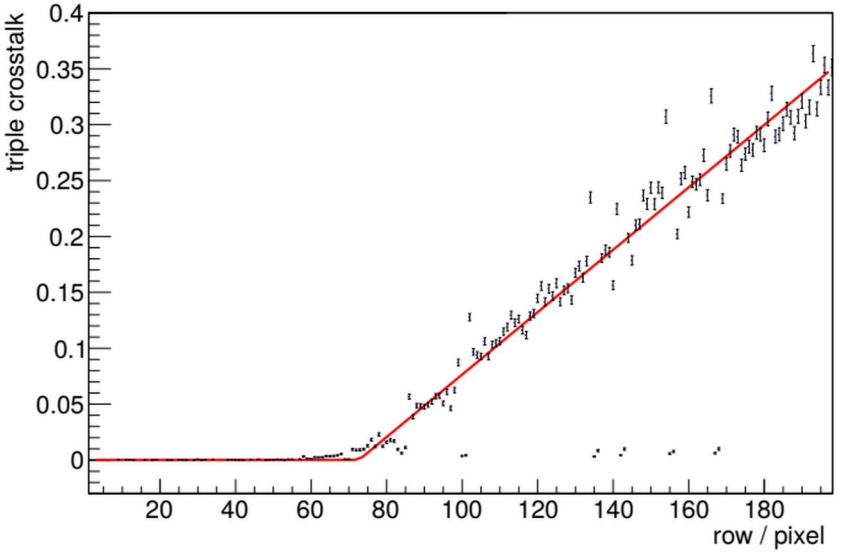
Signal Line Crosstalk - MuPix8



- 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

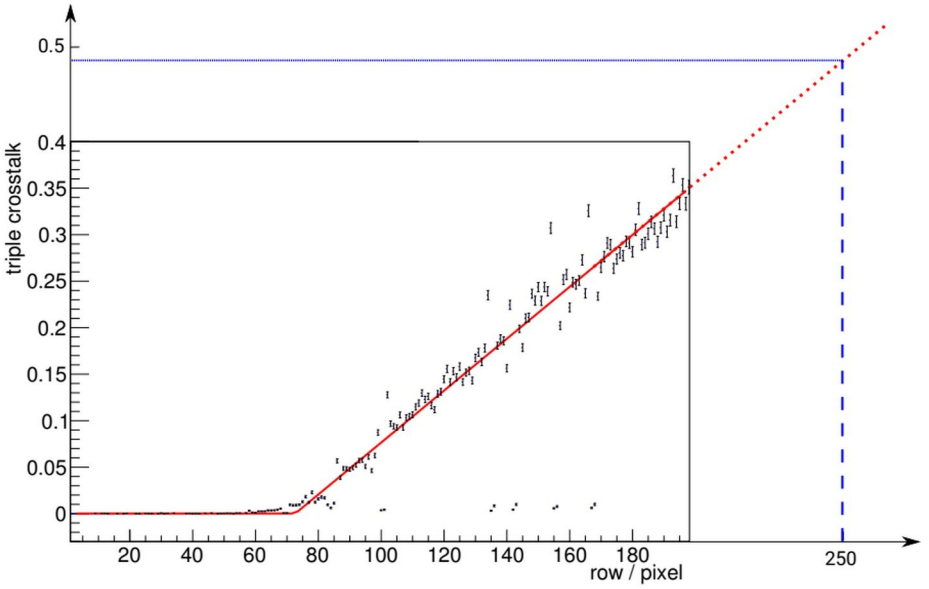
Signal Line Crosstalk - MuPix8





Triple Crosstalk:
hit induced in both neighbouring lines

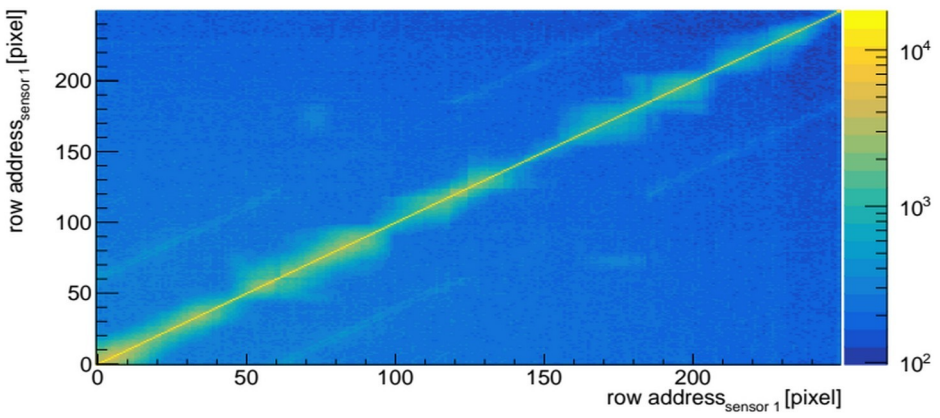
Crosstalk Extrapolation for MuPix10



Triple Crosstalk probability

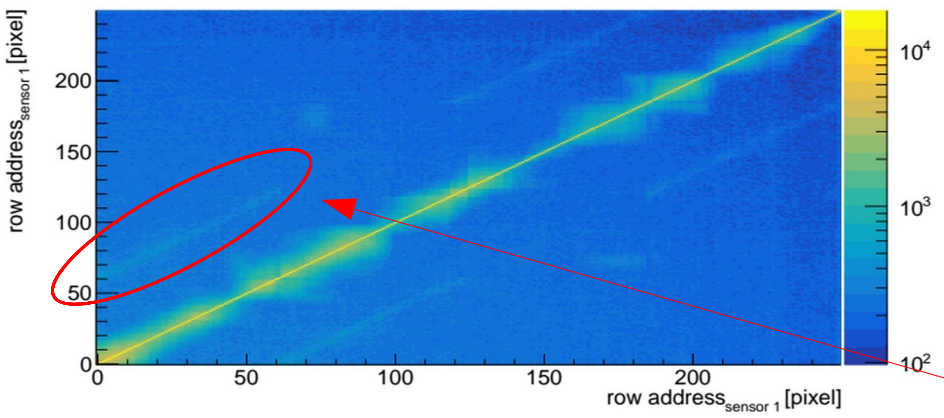
- Using the same routing density and scheme
- ➔ Almost 48% crosstalk probablility for the longest line
- ➔ Penalty for high row addresses
- ➔ Routing needs to adapt

Routing Optimisation - MuPix10



- 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

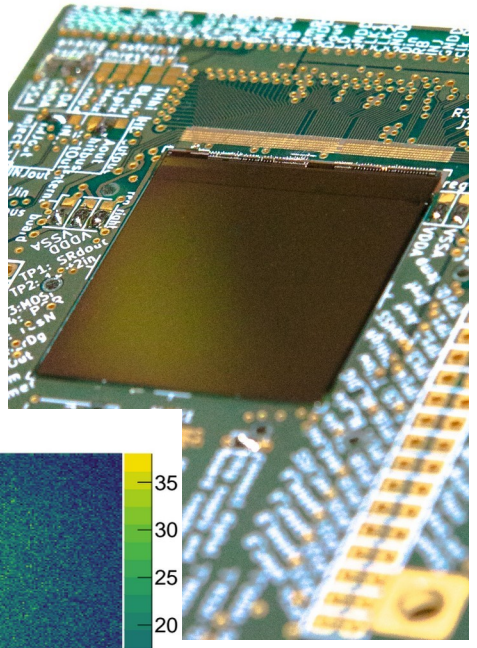
Routing Optimisation - MuPix10

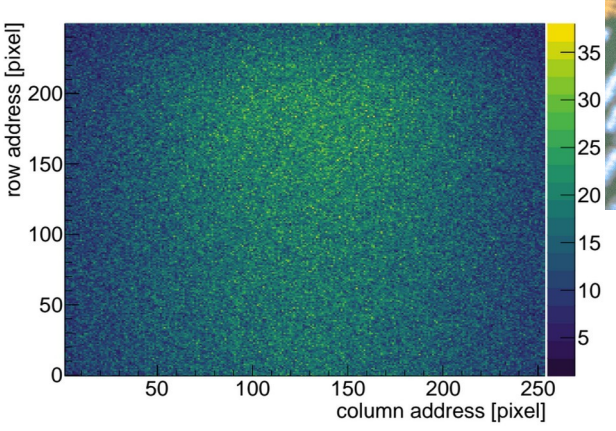


- Equalize but reduce crosstalk
  → miminise the length that two line are neighbouring
  (¼ of total length, 2cm)
- ➔ ~12% triple crosstalk expected
- Make Crosstalk easily detectable
  → neigbouring signal lines are not neigbouring pixels
- ➔ Crosstalk can be removed, possibly already during the data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

Summary

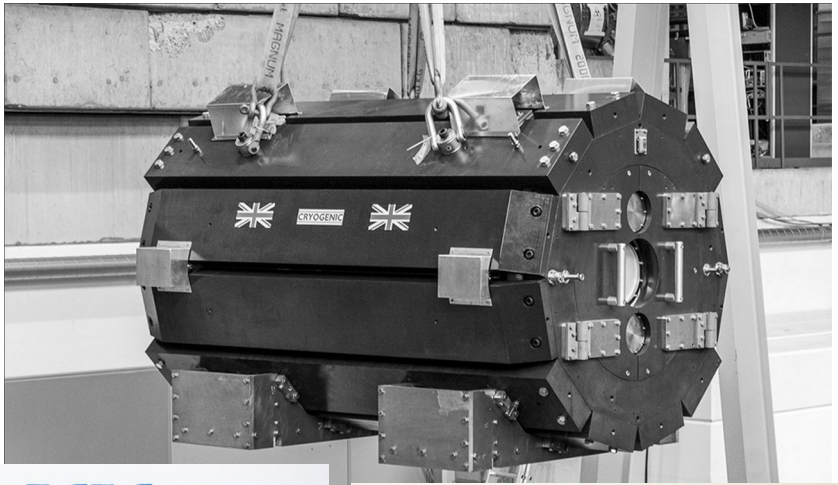
- MuPix10 is working nicely!
- ➔ Full-scale
- ➔ Module ready
- New features implemented successfully
- ➔ Delay circuit, routing
- Final Submission: MuPix11 Summer 2021

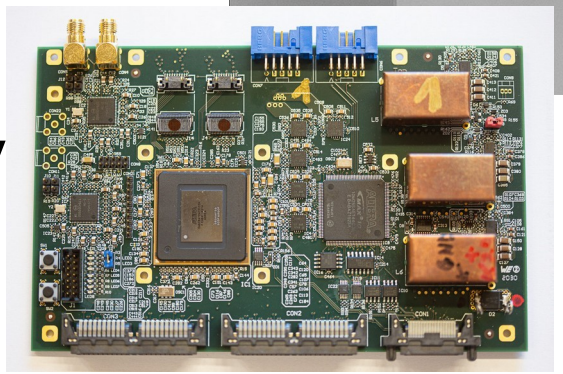


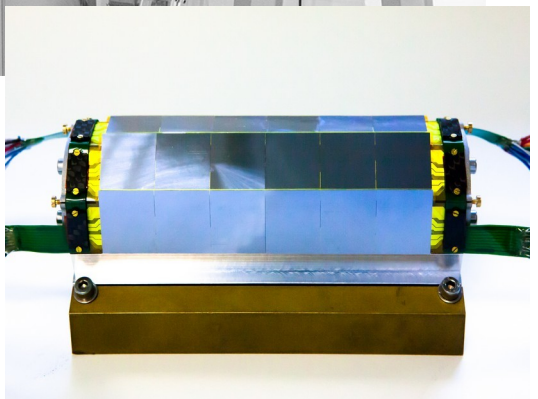


Mu3e Status

- Mu3e Magnet arrived at PSI and is currently cooling down
- Helium cooling system and tests are nicely progressing (Silicon Heater mock-up)
- Hardware of the readout chain available and heavily tested







End of the year plans

- Long beam time @PSI
- Tests within the magnet
- All sub-systems:
  Pixel, Tile and Fibre
- Check of important paths of the readout chain
- First 6 chip module
  (not on flexprint)