Performance of MuPix8
a large scale HV-CMOS pixel sensor

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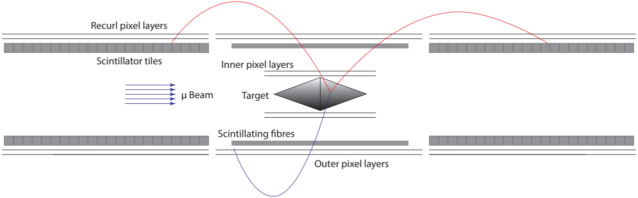
Motivation - The Mu3e Experiment

Searching for the charged Lepton Flavor Violating decay $\mu^+ \rightarrow e^+ e^- e^+$



- sensitivity goal of one in 10^{16} decays, requires high muon rates of $10^9\,s^{-1}$
- reconstruction of electron trajectories in a 1 T solenoidal magnetic field
- multiple coulomb scattering dominated ($p_e < 53\,\mathrm{MeV/c}$)

Motivation - The Mu3e Experiment

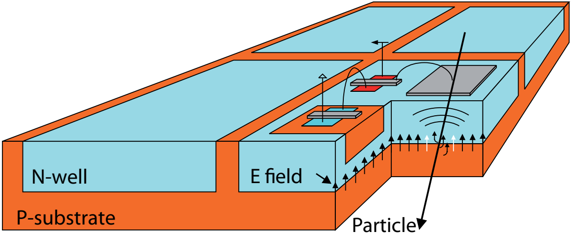
Searching for the charged Lepton Flavor Violating decay $\mu^+ \rightarrow e^+ e^- e^+$

Pixel Sensor Requirements

Pixel Size	Time Resolution	Material Budget	Efficiency
$80 \times 80 \mu m^2$	$< 20 ns$	$< 1‰ X_0$ / layer	$\sim 100\%$

- sensitivity goal of one in 10^{16} decays, requires high muon rates of $10^9\,s^{-1}$
- reconstruction of electron trajectories in a 1 T solenoidal magnetic field
- multiple coulomb scattering dominated ($p_e < 53\,MeV/c$)

High Voltage - Monolithic Active Pixel Sensor (HV-MAPS)

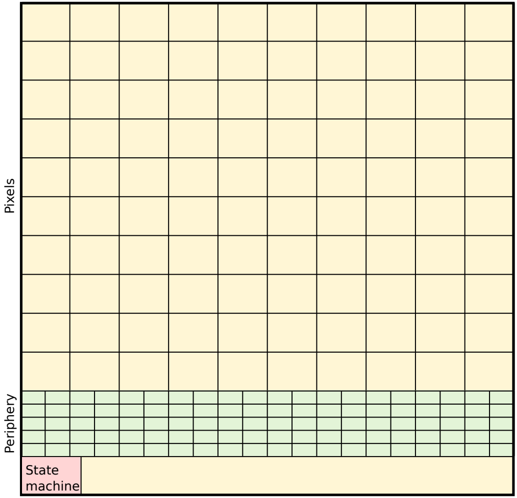


I.Peric, P. Fischer et al., NIM A 582 (2007) 87

- low ohmic substrate ($20\,\Omega$ cm - $200\,\Omega$ cm)
- high voltage ($-120\,$V)
- 180nm HV-CMOS process

- large depleted n-well diode
- charge collection via drift
- no additional readout chip
- thinned to 50 μm

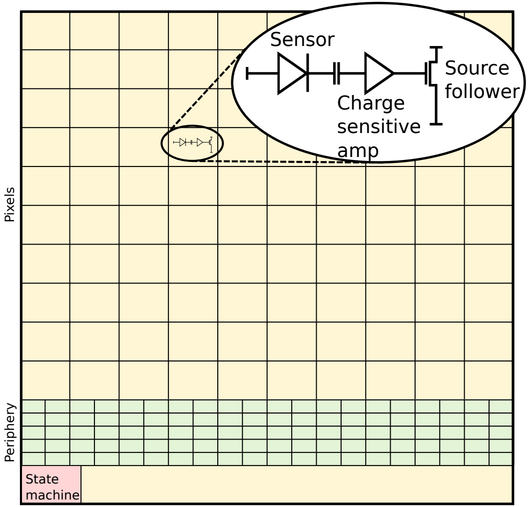
The MuPix Concept



MuPix7 as an example

- active pixel matrix
- digital pixel cell in periphery
- state machine (VCO, PLL, etc., not shown)

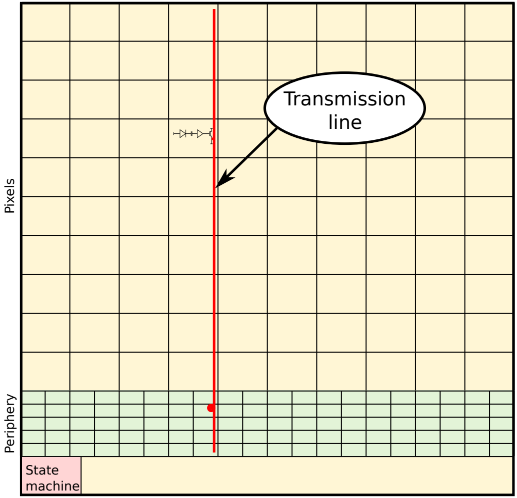
The MuPix Concept



The **pixel** has

- reverse biased diode
- charge sensitive amplifier
- signal transmitter

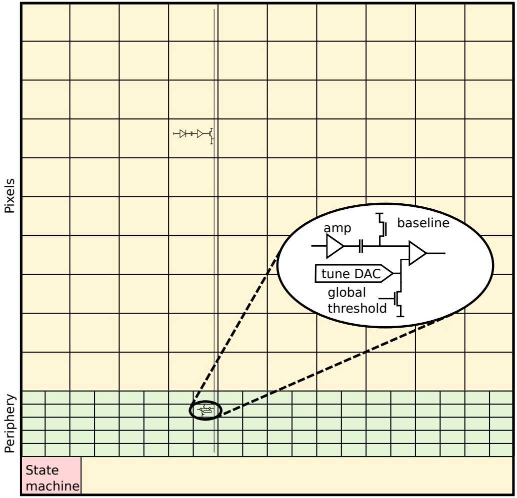
The MuPix Concept



signal transmission:

- point to point connection
- pixel to periphery

The MuPix Concept

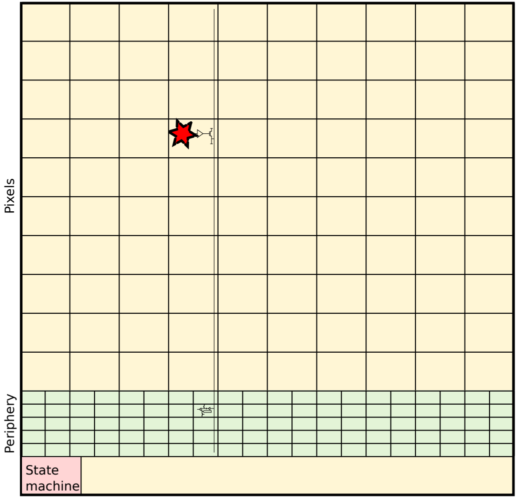


peripheral cell:

- digitisation
- individual pixel tuning (thr)

This separation protects the analog cell from digital crosstalk.

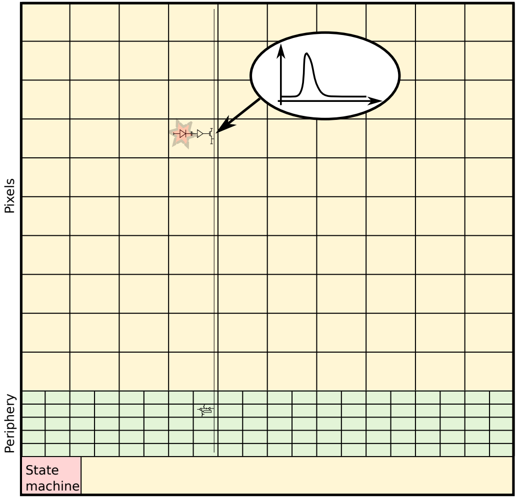
The MuPix Concept



detecting a signal

- signal generation

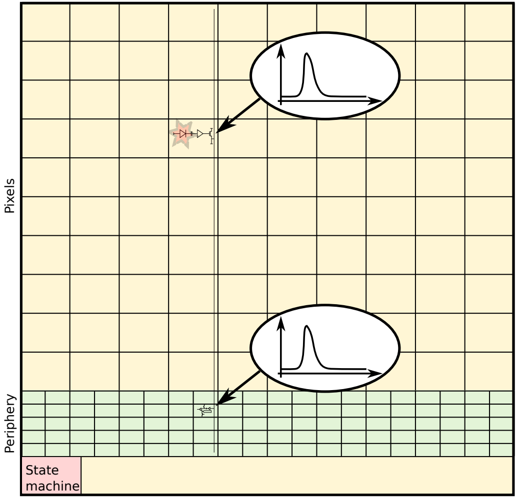
The MuPix Concept



detecting a signal

- signal generation
- amplification

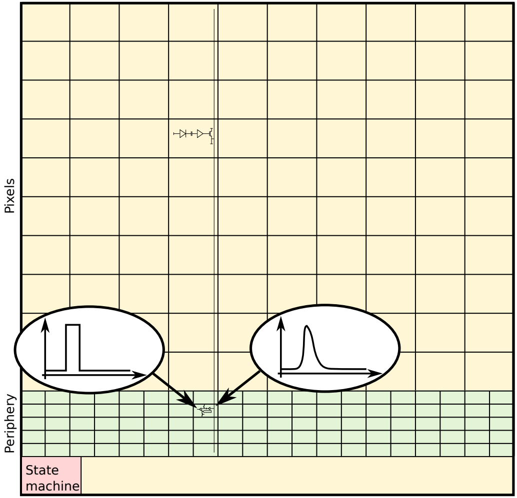
The MuPix Concept



detecting a signal

- signal generation
- amplification
- transmission

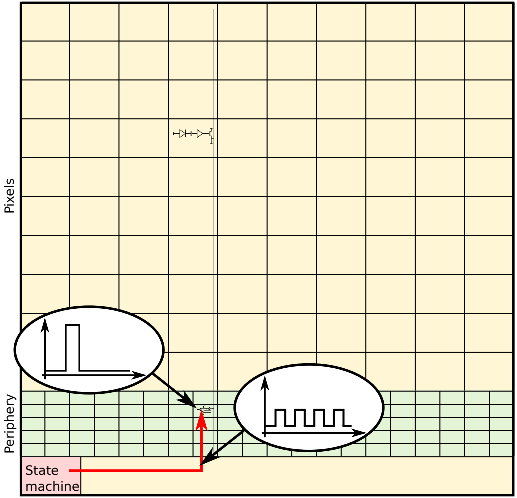
The MuPix Concept



detecting a signal

- signal generation
- amplification
- transmission
- digitisation

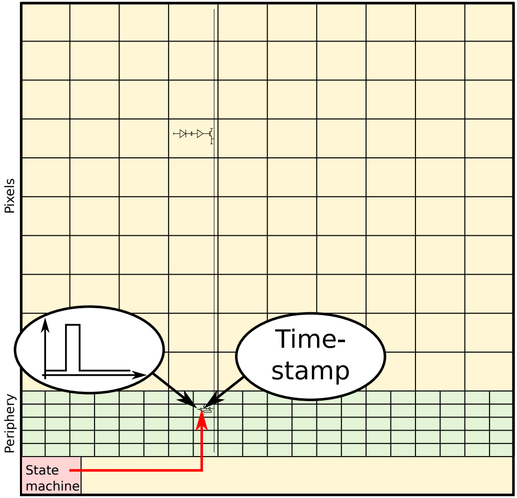
The MuPix Concept



detecting a signal

- signal generation
- amplification
- transmission
- digitisation
- timestamp sampling

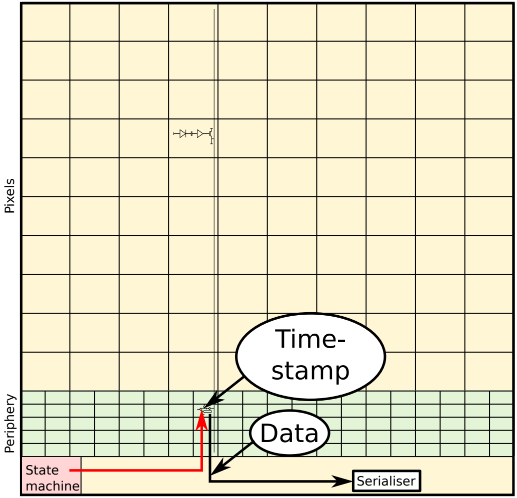
The MuPix Concept



detecting a signal

- signal generation
- amplification
- transmission
- digitisation
- timestamp sampling

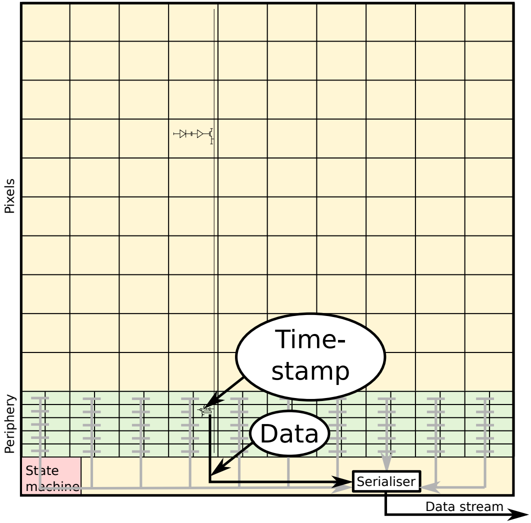
The MuPix Concept



detecting a signal

- signal generation
- amplification
- transmission
- digitisation
- timestamp sampling
- column-drain
- readout of time and address

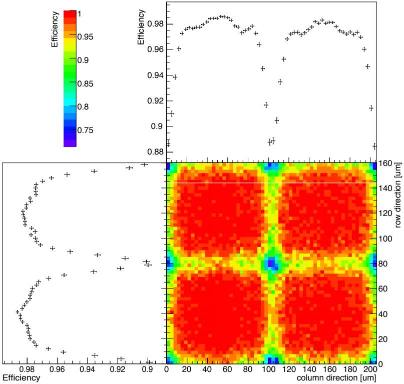
The MuPix Concept



detecting a signal

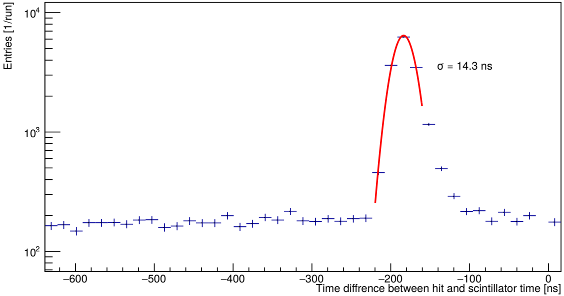
- signal generation
- amplification
- transmission
- digitisation
- timestamp sampling
- column-drain
- readout of time and address
- serialisation and stream out at $1.25\,\text{Gbit}\,\text{s}^{-1}$

The MuPix7 prototype - Results



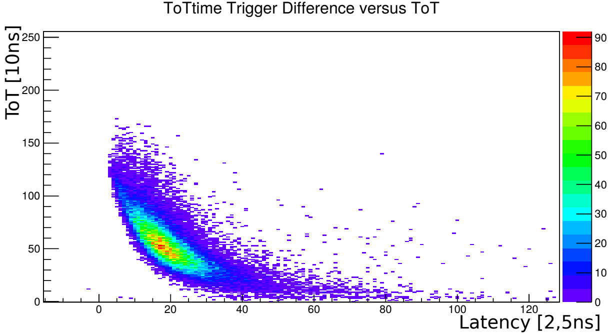
- $80 \times 103\,\mu m^2$ pixel size
- $3.3 \times 3.3\,mm^2$
- $20\,\Omega\,cm$ substrate
- full system on-chip
- very well understood

The MuPix7 prototype - Results



- 99.5% efficiency
  with 14.3 ns time resolution
  @ 300 mW cm^{-2}
- time walk observed & signal line crosstalk

The MuPix7 prototype - Results



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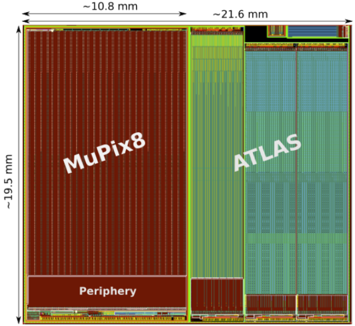
Scale it up!

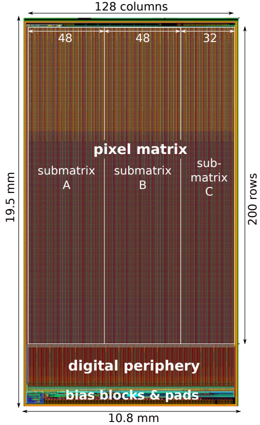
The first large scale prototype - MuPix8



Group Ivan Peric @KIT

- AMS aH18 process (180 nm)
- 80 × 81 μm^2 pixel size
- 16 × 10 mm^2 active area
- 128 × 200 pixels

MuPix8 Design Features

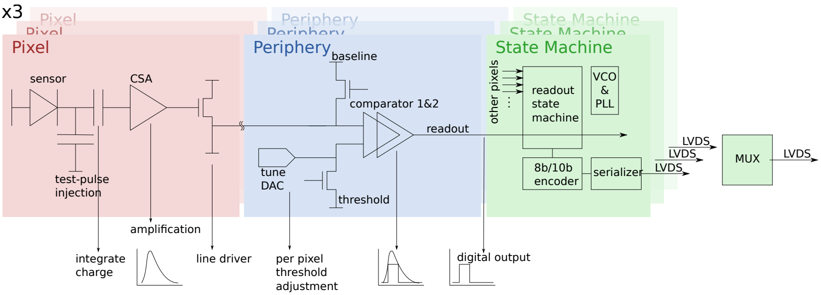


- $2 \times 1\,\text{cm}^2$ chip size

→ full column length

- radiation hard design
- time walk correction possible
- increased signal charge
  ($20 \rightarrow 80 - 200\,\Omega\,\text{cm}$ substrate)
- thinned to $62.5\,\mu\text{m} + 100\,\mu\text{m}$
- bandgap reference, voltage DACs, ...

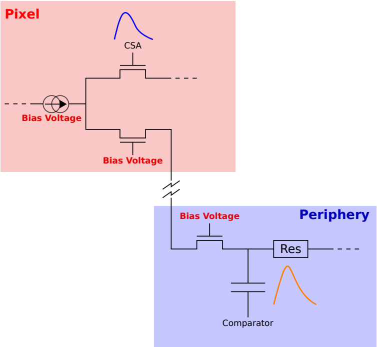
MuPix8 Architecture



- 3 sub-matrices with individual data output
- additional merged/mirrored data output

→ 4 differential links @ 1.25 Gbit/s

MuPix8 - Signal Transmission



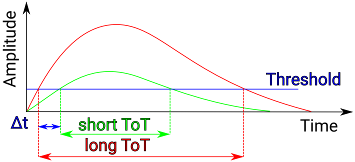
- very dense routing:
  2 metal layers,
  200 signal lines per column
- sub-matrix A: source follower

→ prone to crosstalk

- sub-matrix B&C: current driven

→ aiming for crosstalk reduction

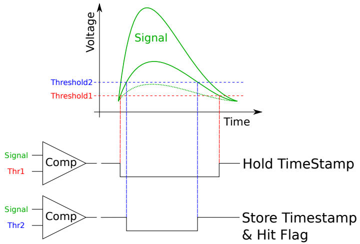
MuPix8 - Pixel Peripheral Cell



Time walk

- 2 comparators
- 3 time walk correction approaches
- 5 tune bits + pixel switch
- 10 timestamp bits
- 6 bit ToT

MuPix8 - Pixel Peripheral Cell



2-threshold
On-Chip suppression

- 2 comparators
- 3 time walk correction approaches
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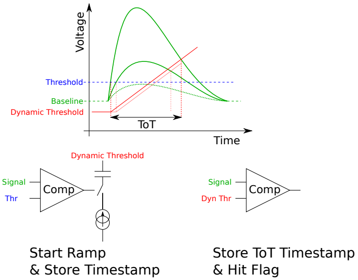
MuPix8 - Pixel Peripheral Cell



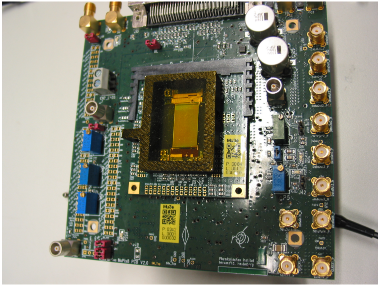
voltage ramp

Off-Chip correction

- 2 comparators
- 3 time walk correction approaches
- 5 tune bits + pixel switch
- 10 timestamp bits
- 6 bit ToT

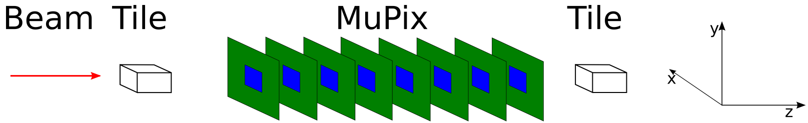
Setup

Characterisation Setup



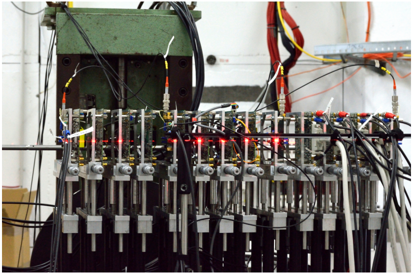
- motherboard with insertable PCB
- versatile tool
- integration for MuPix-like sensors: MuPix8, AtlasPix, MuPix9, MuPix7
- lab characterisation

MuPix Telescope



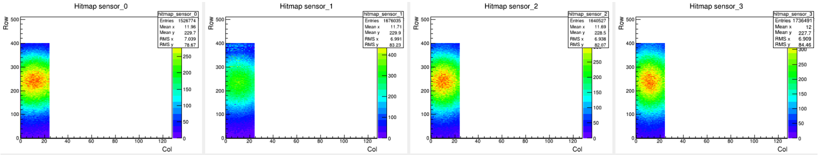
- 4-8 layers of sensors
- one sensor as DUT
- integration test for the Mu3e readout system

MuPix Telescope



- extensive testbeam campaigns: DESY, PSI and MAMI
- online efficiency
- fast analysis framework

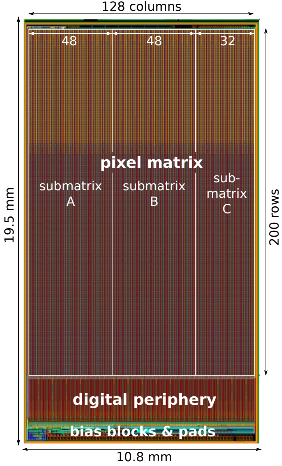
MuPix Telescope



- All-AtlasPix telescope
- proof of principle
- performed exemplary threshold scans

Results

Commissioning



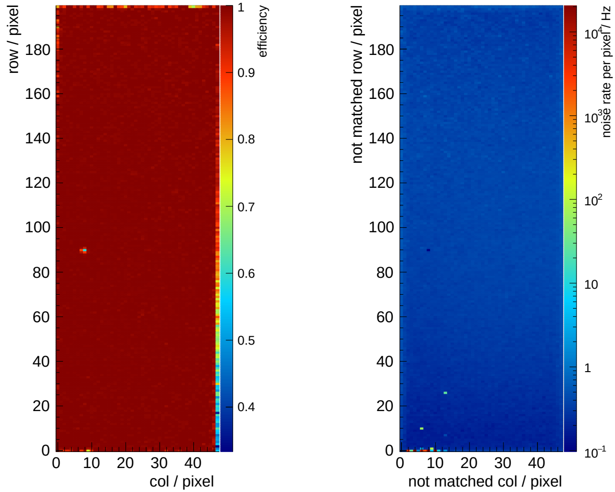
- early breakdown @ $-60\,\mathrm{V}$ (120V design)
- powering issue in the digital part

→ tuning possible but not effective

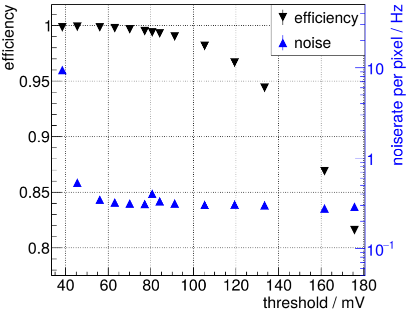
- pixel switch is working
- configuring with $6\,\mathrm{Mbit\,s^{-1}}$ (100 ms per chip)
- more than 10 MHits/s per matrix

Efficiency

Matrix A - Efficiency & Noise



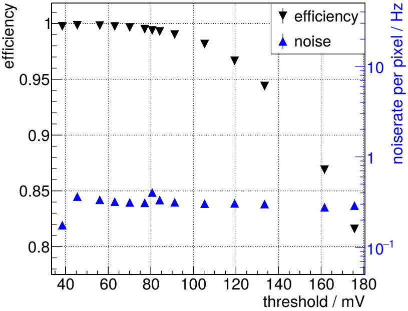
Matrix A - Efficiency & Noise



50 mV threshold $= 650e^-$

- highly efficient($> 99.9\%$), low noise plateau
- further increase by masking hot pixels
- increase with higher HV and resistivity

Matrix A - Efficiency & Noise



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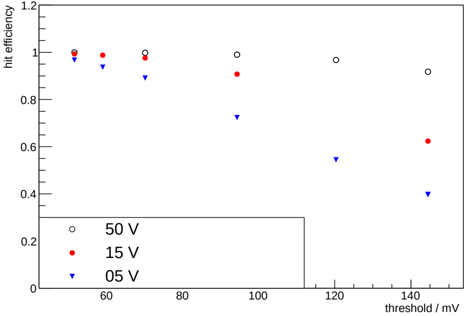

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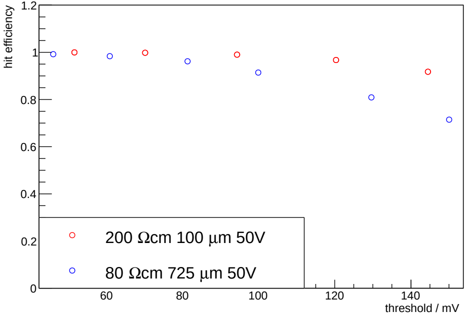

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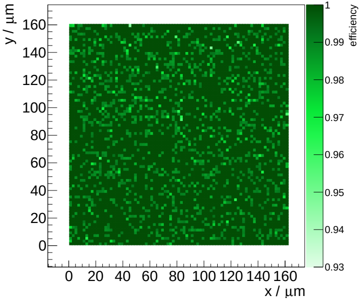
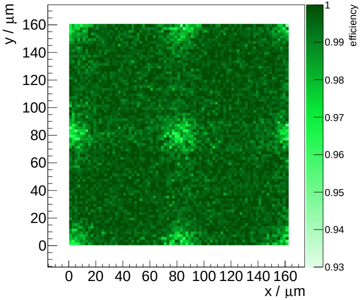
Matrix A - Sub-Pixel Studies



HV = -50V, optimal settings

- utilising the EUDET-telescope at DESY
- position resolution $\approx 6\,\mu m$
- folded map to 2×2 pixel

Matrix A - Sub-Pixel Studies

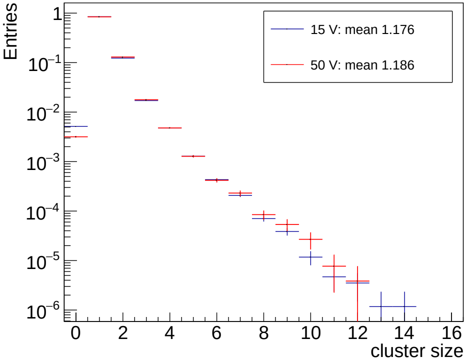


HV = -15V, high threshold

- utilising the EUDET-telescope at DESY
- position resolution $\approx 6\,\mu m$
- folded map to 2×2 pixel

$\rightarrow$ inefficiency at the pixel edges

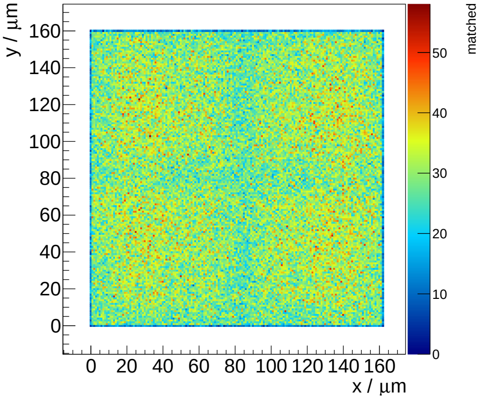
Matrix A - Sub-Pixel Studies - Clustering



Cluster sizes

- very low average cluster size

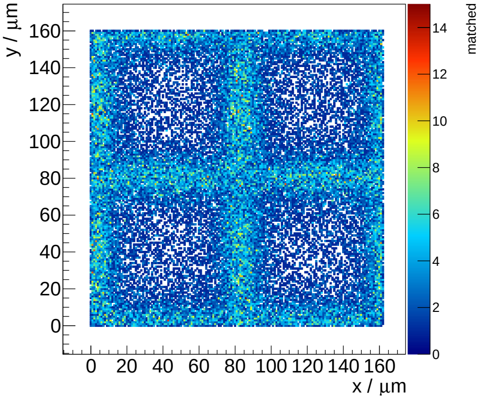
Matrix A - Sub-Pixel Studies - Clustering



Single Hits

- very low average cluster size

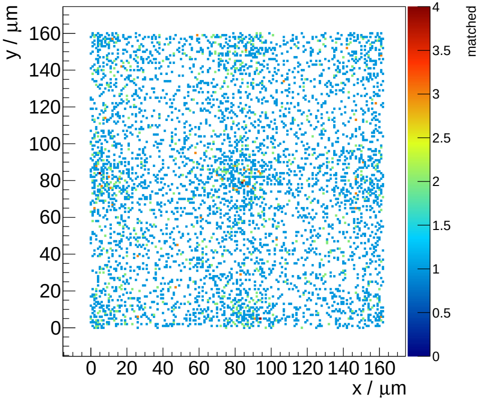
Matrix A - Sub-Pixel Studies - Clustering



Double Cluster

- very low average cluster size
- charge sharing at edges and corners

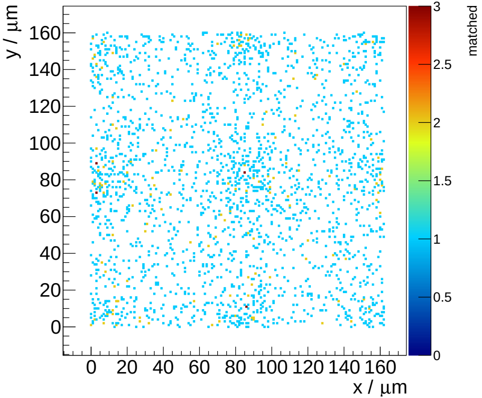
Matrix A - Sub-Pixel Studies - Clustering



Triple Cluster

- very low average cluster size
- charge sharing at edges and corners

Matrix A - Sub-Pixel Studies - Clustering

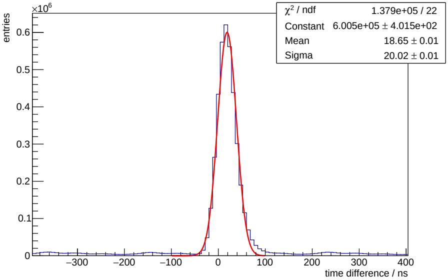


Quadrupel Cluster

- very low average cluster size
- charge sharing at edges and corners

Time Resolution

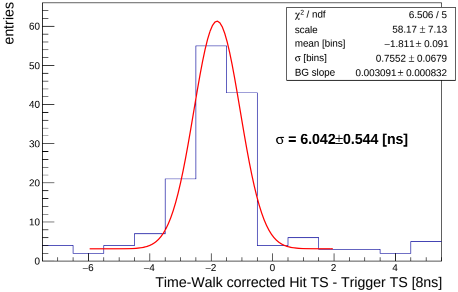
Matrix A - Timing Studies



- lab measurement with Sr90 and scintillating tile
- time walk observed
- pixel position delay (routing and power distribution)

Sensor time resolution: $\approx 20\,\mathrm{ns}$

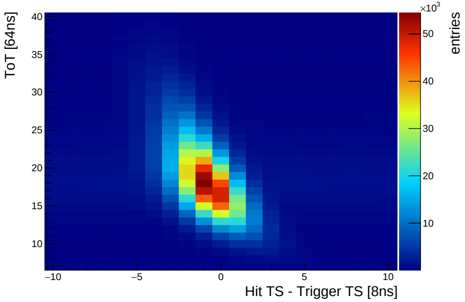
Matrix A - Timing Studies



Single pixel(0/1) time resolution

- lab measurement with Sr90 and scintillating tile
- time walk observed
- pixel position delay (routing and power distribution)

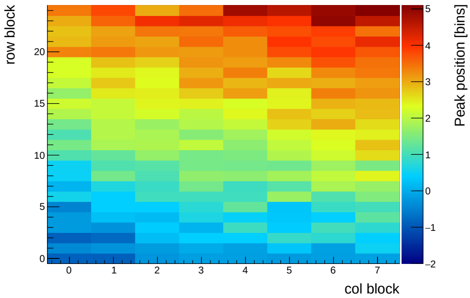
Matrix A - Timing Studies



Time walk: raw data

- lab measurement with Sr90 and scintillating tile
- time walk observed
- pixel position delay (routing and power distribution)

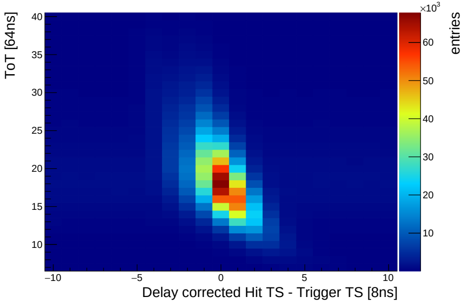
Matrix A - Timing Studies



Pixel position delay

- lab measurement with Sr90 and scintillating tile
- time walk observed
- pixel position delay (routing and power distribution)

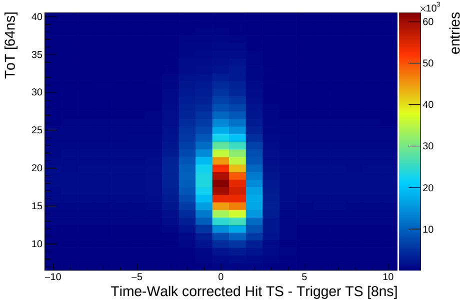
Matrix A - Timing Studies



Time walk: delay corrected

- lab measurement with Sr90 and scintillating tile
- time walk observed
- pixel position delay (routing and power distribution)

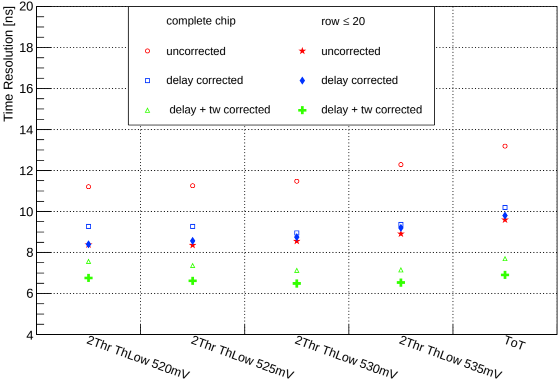
Matrix A - Timing Studies



Delay + Time walk correction

- lab measurement with Sr90 and scintillating tile
- time walk observed
- pixel position delay (routing and power distribution)

Matrix A - Timing Studies

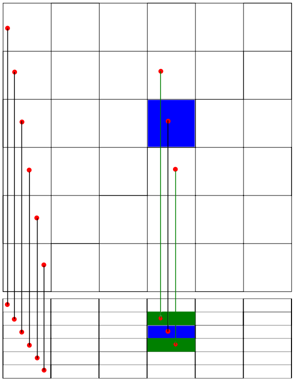


Time resolution: $\sigma = 6.5\,\mathrm{ns}$

($200\,\Omega\,\mathrm{cm}$, HV$=-55\,\mathrm{V}$)

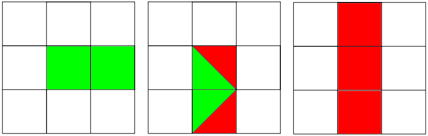
Crosstalk

Matrix A - Signal Line Crosstalk



- capacitive coupling
- row dependence

Matrix A - Signal Line Crosstalk



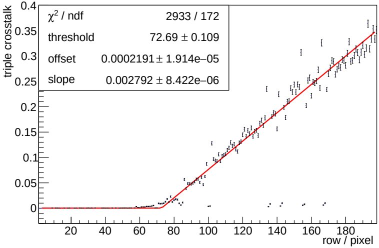
charge sharing

charge sharing / crosstalk

crosstalk

- capacitive coupling
- row dependence

Matrix A - Signal Line Crosstalk



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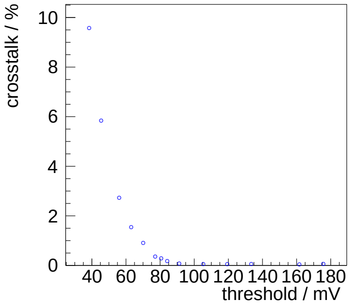
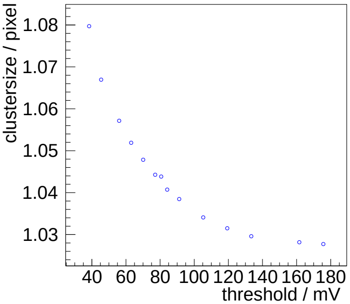


Threshold dependence

- capacitive coupling
- row dependence

→ increased readout load

Matrix A - Signal Line Crosstalk

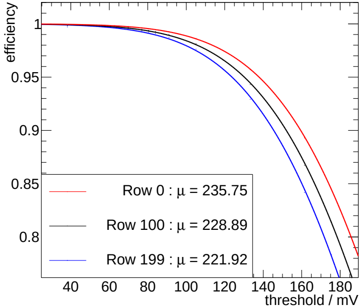


Crosstalk removed
→true cluster size

- capacitive coupling
- row dependence

→ increased readout load

Matrix A - Signal Line Crosstalk



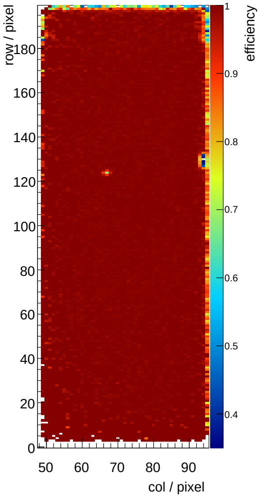
Signal reduction

- capacitive coupling
- row dependence

→ increased readout load
→ signal reduction
→ degrade rising edge

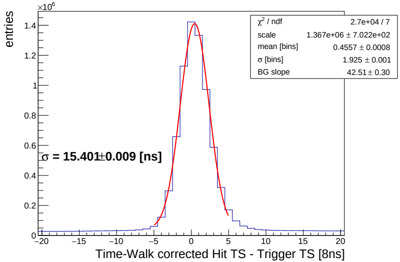
Matrix B - current driver

Matrix B - Efficiency



- recent testbeam measurement
- preliminary result
- highly efficient $> 99\%$
- further analysis ongoing

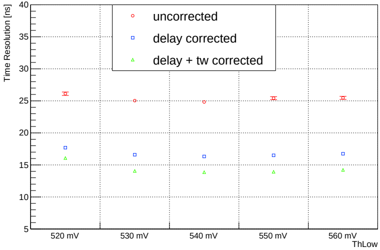
Matrix B - Time Resolution



- investigation with coincidence setup
- delay compensation + time walk correction

→ time resolution: $\sigma < 15\,\text{ns}$

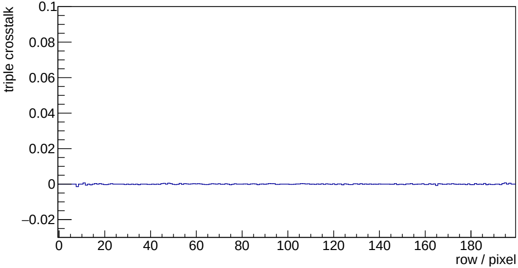
Matrix B - Time Resolution



- investigation with coincidence setup
- delay compensation + time walk correction

→ time resolution: $\sigma < 15\,\text{ns}$

Matrix B - Crosstalk



- no crosstalk observed!
- current driver allows for dense rounting

Summary & Outlook

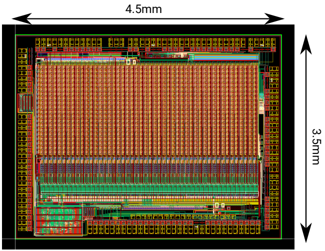
Summary

Pixel Sensor Performance

	Matrix A	Matrix B	AtlasPix
Efficiency	$> 99.9\%$	$> 99\%$	$> 99.9\%$
Time res	6.5 ns	15 ns	10 ns
Crosstalk	yes	no	no
Power	$200\,\mathrm{mW\,cm^{-2}}$	$210\,\mathrm{mW\,cm^{-2}}$	$300\,\mathrm{mW\,cm^{-2}}$

- exceptional performance $\rightarrow$ scaling successful
- obvious improvements at hand: breakdown, powering, ...
- current driver scheme can be further improved

Outlook



MuPix9

- MuPix9: shunt, serial powering, mu3e slowcontrol interface ...
- AMS aH18: long delivery times
- qualification of new foundry: TSI Semiconductors (H18)
- resubmitted MuPix7 to TSI
- testbeam analysis ongoing
- submission of fullscale sensor in 2019

Acknowledgments

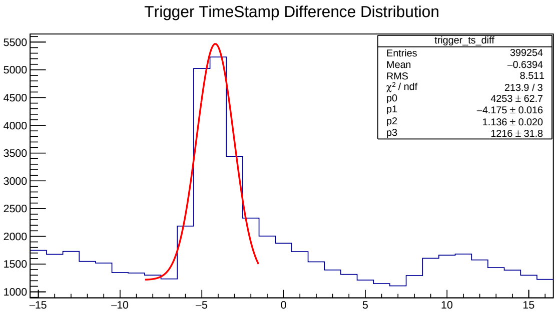
Many important test beam campaigns have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

We would like to thank the PSI for providing high rate test beams under excellent conditions.

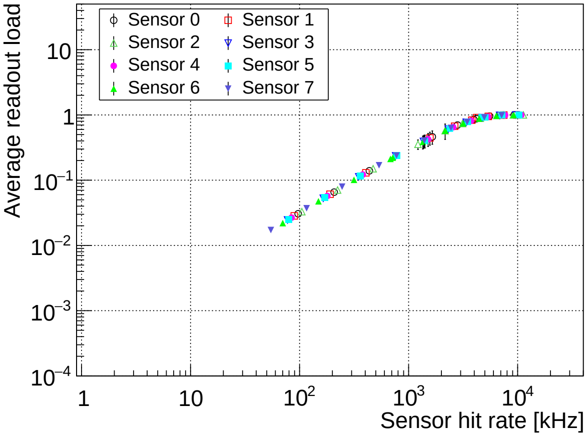
We thank the Institut für Kernphysik at the JGU Mainz for giving us the opportunity to take data at MAMI.

Thank you

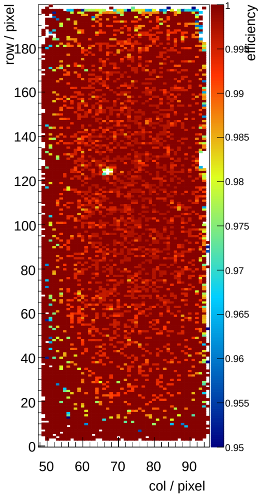
Back-up



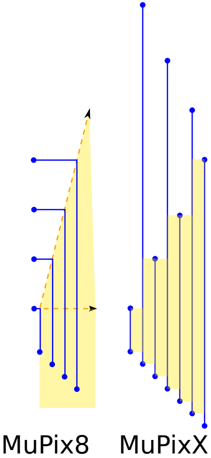
Time resolution:
MuPix7_TSI

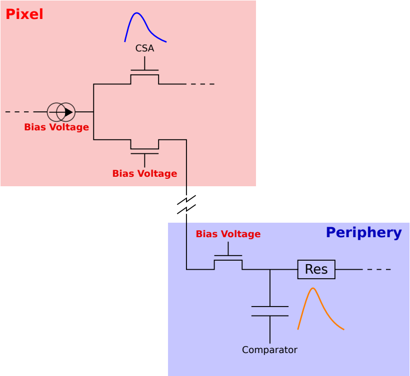

Sensor 0
Sensor 1
Sensor 2
Sensor 3
Sensor 4
Sensor 5
Sensor 6
Sensor 7
Average readout load
10
1
10^-1
10^-2
10^-3
10^-4
1
10
10^2
10^3
10^4
Sensor hit rate [kHz]

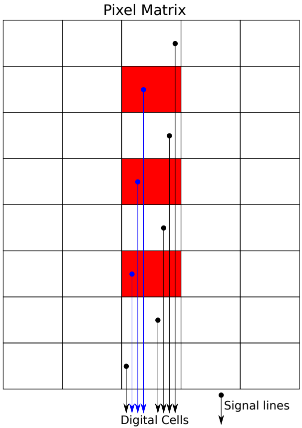
Rate test

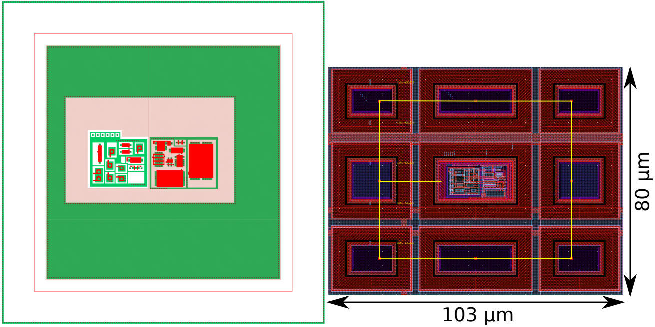


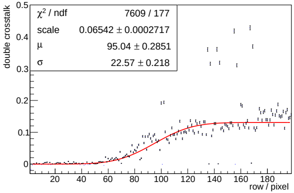
Matrix B: zoom


MuPix8
MuPixX

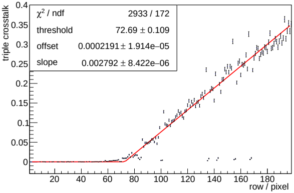

Pixel
CSA
Bias Voltage
Bias Voltage
Bias Voltage
Periphery
Res
Comparator


Pixel Matrix
Digital Cells
Signal lines

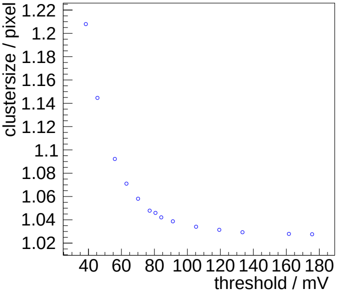

80 µm
103 µm



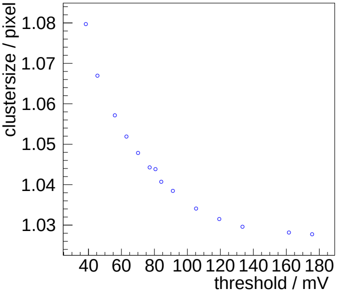
χ2 / ndf 7609 / 177
scale 0.06542 ± 0.0002717
μ 95.04 ± 0.2851
σ 22.57 ± 0.218
double crosstalk
row / pixel



χ2 / ndf 2933 / 172
threshold 72.69 ± 0.109
offset 0.0002191 ± 1.914e−05
slope 0.002792 ± 8.422e−06
triple crosstalk
row / pixel


clustersize / pixel
1.22
1.2
1.18
1.16
1.14
1.12
1.1
1.08
1.06
1.04
1.02
40 60 80 100 120 140 160 180
threshold / mV

w/ crosstalk



w/o crosstalk