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 $10^9 \text{s}^{-1}$
- reconstruction of electron trajectories in a 1 T solenoidal magnetic field
- multiple coulomb scattering dominated ($p_e < 53 \text{ MeV/c}$)
Motivation - The Mu3e Experiment

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

Pixel Sensor Requirements

<table>
<thead>
<tr>
<th>Pixel Size</th>
<th>Time Resolution</th>
<th>Material Budget</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$80 \times 80 \mu m^2$</td>
<td>$&lt; 20 ns$</td>
<td>$&lt; 1% X_0$ / layer</td>
<td>$\sim 100%$</td>
</tr>
</tbody>
</table>

- sensitivity goal of one in $10^{16}$ decays, requires high muon rates of $10^9 \text{s}^{-1}$
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High Voltage - Monolithic Active Pixel Sensor (HV-MAPS)

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

- Low ohmic substrate (20 Ω cm - 200 Ω 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

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- digitisation
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detecting a signal

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- amplification
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- digitisation
- timestamp sampling
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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 Gbit s⁻¹
The MuPix7 prototype - Results

- 80 × 103 µm² pixel size
- 3.3 × 3.3 mm²
- 20 Ω 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

- 99.5% efficiency
- with 14.3 ns time resolution
- @ 300 mW cm$^{-2}$
- time walk observed & signal line crosstalk
Scale it up!
The first large scale prototype - MuPix8

- AMS aH18 process (180 nm)
- 80 × 81 μm² pixel size
- 16 × 10 mm² active area
- 128 × 200 pixels

Group Ivan Peric @KIT
MuPix8 Design Features

- 2 × 1 cm² chip size
- full column length
- radiation hard design
- time walk correction possible
- increased signal charge
  (20 → 80 – 200 Ω cm substrate)
- thinned to 62.5 μm + 100 μm
- bandgap reference, voltage DACs, ...

200 rows

10.8 mm

128 columns

48 48 32

2 chip size

→ full column length

radiation hard design

time walk correction possible

increased signal charge

(20 → 80 – 200 Ω cm substrate)

thinned to 62.5 μm + 100 μm

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

- 2 comparators
- 3 time walk correction approaches
- 5 tune bits + pixel switch
- 10 timestamp bits
- 6 bit ToT
MuPix8 - Pixel Peripheral Cell

- 2 thresholds
- On-Chip suppression

- 2 comparators
- 3 time walk correction approaches
- 5 tune bits + pixel switch
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MuPix8 - Pixel Peripheral Cell

- 2 comparators
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voltage ramp

Off-Chip correction
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 @ $-60\,\text{V}$ (120V design)
- powering issue in the digital part → tuning possible but not effective
- pixel switch is working
- configuring with 6 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
50 mV threshold = 650e⁻

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Matrix A - Efficiency & Noise

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50 mV threshold = 650e−
Matrix A - Sub-Pixel Studies

HV = -50V, optimal settings

- utilising the EUDET-telescope at DESY
- position resolution ≈ 6 µm
- folded map to 2 × 2 pixel
Matrix A - Sub-Pixel Studies

HV = -15V, high threshold

- utilising the EUDET-telescope at DESY
- position resolution ≈ 6 μm
- folded map to 2 × 2 pixel
- 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

- 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

Sensor time resolution: $\approx 20$ ns

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

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

Single pixel(0/1) time resolution
Matrix A - Timing Studies

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

Time walk: raw data
Matrix A - Timing Studies

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

Pixel position delay
Matrix A - Timing Studies

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

Time walk: delay corrected
Matrix A - Timing Studies

- Lab measurement with Sr90 and scintillating tile
- Time walk observed
- Pixel position delay (routing and power distribution)

Delay + Time walk correction
Matrix A - Timing Studies

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

$(200\, \Omega\, \text{cm}, \text{HV}=\text{−55 V})$
Crosstalk
Matrix A - Signal Line Crosstalk

- capacitive coupling
- row dependence
Matrix A - Signal Line Crosstalk

- capacitive coupling
- row dependence
Matrix A - Signal Line Crosstalk

![Graph showing triple crosstalk vs row/pixel]

- capacitive coupling
- row dependence

*Chi-squared / ndf*: 2933 / 172
*Threshold*: 72.69 ± 0.109
*Offset*: 0.0002191 ± 0.0002191
*Slope*: 0.002792 ± 0.002792

*Capacitive coupling*:  
*Row dependence*:

→ increased readout load
→ signal reduction
→ degrade rising edge
Matrix A - Signal Line Crosstalk

Threshold dependence

- capacitive coupling
- row dependence

→ increased readout load
Matrix A - Signal Line Crosstalk

- Capacitive coupling
- Row dependence

→ Increased readout load

Crosstalk removed
→ True cluster size
Matrix A - Signal Line Crosstalk

- capacitive coupling
- row dependence
  - increased readout load
  - signal reduction
  - degrade rising edge

Signal reduction
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: $\sigma < 15$ ns
Matrix B - Time Resolution

- investigation with coincidence setup
- delay compensation + time walk correction
→ time resolution: $\sigma < 15$ ns
Matrix B - Crosstalk

- no crosstalk observed!
- current driver allows for dense rounting
Summary & Outlook
# Summary

<table>
<thead>
<tr>
<th></th>
<th>Matrix A</th>
<th>Matrix B</th>
<th>AtlasPix</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Efficiency</strong></td>
<td>&gt; 99.9%</td>
<td>&gt; 99%</td>
<td>&gt; 99.9%</td>
</tr>
<tr>
<td><strong>Time res</strong></td>
<td>6.5 ns</td>
<td>15 ns</td>
<td>10 ns</td>
</tr>
<tr>
<td><strong>Crosstalk</strong></td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>200 mW cm$^{-2}$</td>
<td>210 mW cm$^{-2}$</td>
<td>300 mW cm$^{-2}$</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>trigger_ts_diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
<tr>
<td>$\chi^2 / \text{ndf}$</td>
</tr>
<tr>
<td>$p_0$</td>
</tr>
<tr>
<td>$p_1$</td>
</tr>
<tr>
<td>$p_2$</td>
</tr>
<tr>
<td>$p_3$</td>
</tr>
</tbody>
</table>

Time resolution:
MuPix7_TSI
<table>
<thead>
<tr>
<th>Sensor</th>
<th>Hit Rate [kHz]</th>
<th>Average Readout Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>10^{-1}</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>10^{-5}</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>10^{-6}</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>10^{-7}</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>10^{-8}</td>
</tr>
</tbody>
</table>

The graph shows the relationship between the sensor hit rate [kHz] and the average readout load on a logarithmic scale. The data points for each sensor are color-coded and clearly visible on the graph.
Matrix B: zoom
**Introduction**

**MuPix8**

**Results**

**Summary & Outlook**

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**Double Crosstalk**

- \( \chi^2 / \text{ndf} \): 7609 / 177
- Scale: 0.06542 ± 0.0002717
- \( \mu \): 95.04 ± 0.2851
- \( \sigma \): 22.57 ± 0.218

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**Triple Crosstalk**

- \( \chi^2 / \text{ndf} \): 2933 / 172
- Threshold: 72.69 ± 0.109
- Offset: -1.914e± 0.0002191
- Slope: -8.422e± 0.002792
w/ crosstalk
w/o crosstalk