Performance and integration studies of a first large scale HV-CMOS prototype

Lennart Huth
Physikalisches Institut Heidelberg

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Motivation

- Mu3e searches cLFV
- Final SES target: 1 in $10^{16}$
- High rate ($10^9$ muons/s)
- Low momentum → Scattering dominates resolution
- Almost everything will be background → Need novel pixel tracker HV-MAPS
HV-MAPS

- Monolithic sensor
- p-n-junction
- HV between p-n
- Drift based charge collection
- In-pixel amplification
- Digital partner cell with
  → Digitization
  → Time stamping
  → ToT/charge measure
- RO statemachine and serializer

(I. Peric, P. Fischer et al., NIM A 582 (2007) 876)
MuPix8 in numbers

- 128 x 200 pixel
- 80 x 81 µm² pixel size
- 4 LVDS links at 1.25 GBit/s
- 2 comparators
- 2/3 bit tuneDACs
- All crucial pads on bottom side
- Pixel masking
- Temperature stable voltage references
- On-chip thresholds
- Temperature diode
MuPix Telescope
MuPix Telescope

- 4 MuPix8 layers
- 2 tiles for time reference
- On-FPGA time sorting and data buffering optional
- FPGA to steer sensors and receive data
- Data transfer to PC via polling or DMA
- Multi-threaded software DAQ
- Results within 5 mins after data taking
- MuPix/AtlasPix used as DUT
  → Only MuPix in this talk

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Test beam measurements
- all results are preliminary!
setup and runs

- 2 campaigns at desy
- Telescope setup and mimosa setup in use
- Tested various settings and sensors
- Time resolution, efficiency, noise, clustering and crosstalk
- Data analysis still ongoing
Time resolution

- Matrix A uses the transmission scheme from MuPix7
- Matrix B+C use a new transmission scheme and is not optimized
- Matrix A has significantly better time resolution
- We will focus on Matrix A for the rest of the talk
- Low threshold
• Matrix A uses the transmission scheme from MuPix7
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- After reverting a feature on the PCB, which doubled the available current, resolution of 24 ns are observed
ToT and Timewalk
ToT and timewalk measurements

ckdivend1=0x1, ckdivend2=0xf

ToT-time Trigger Difference versus ToT

ToTDistribution

<table>
<thead>
<tr>
<th>tots2</th>
<th>Entries</th>
<th>Mean</th>
<th>Std Dev</th>
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<tr>
<td></td>
<td>281413</td>
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Entries [1/Run]

<table>
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<th>ToT [128ns]</th>
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<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>40</td>
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<tr>
<td>60</td>
</tr>
<tr>
<td>80</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>120</td>
</tr>
<tr>
<td>140</td>
</tr>
<tr>
<td>160</td>
</tr>
</tbody>
</table>

Entries [1/Run]
Pixel masking
Pixel masking

- 25k pixels
- Some will be really noisy/broken → pixel masking
- Tested by drawing a nice logo
- Routine can be used in telescope and single setup
- Voltage level to store masking slightly too high - some pixels are not masked correctly.
Efficiency and noise
Threshold 45 mV

![Image of Efficiency and Noise Rate](image)

- **Efficiency**
  - Values range from 0 to 1
  - Colored scale indicates efficiency levels

- **Noise Rate [Hz]**
  - Values range from 1 to 10
  - Logarithmic scale

- **Column and Row Values**
  - Columns range from 10 to 40
  - Rows range from 50 to 150

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Threshold scan at -30V

- Essentially noise free (mu3e allows up to 10 Hz/pixel)
- Chip untuned
- Up to 25 pixels ignored in analysis
- 98.5 % efficiency seen
- HV is only -30 V → HV can be increased
Increasing Bias Voltages

- $V_{DD}/V_{DDA} = 1.9$ V
- $V_{SSA} = 1.1$ V
- Efficiency of 99.1%
- Time resolution improves by 15%
- Noise stays unchanged
- Substantial voltage drop over the MuPix8
Crosstalk and clustering
Crosstalk

- Connection lines between active pixel and digital periphery are crosstalk effected
- Crosstalk can be calculated by looking at differences in vertical and horizontal cluster sizes (pixels are squared)
- Double and triple cluster in 1d indicate crosstalk
- Line crosstalk only in vertical direction → 11.8 % for a threshold of 45 mV
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Clustering

- First studies → very preliminary
- Only clusters with matched hits are counted
- Cluster size 180 mV threshold: 1.053
- Cluster size 45 mV threshold: 1.384
- Cluster sizes are affected by crosstalk
Summary and Outlook

- MuPix8 telescope in operation and functional
- Time resolution of 12.8 ns (20 ns low power settings)
- Efficiencies above 98% at low noise (99.1% for increased supply voltages)
- No timewalk observed at operational thresholds
- Crosstalk and clustering seen, but seems to be smaller than expected - average cluster size < 1.4
- Increasing VDDA, VDD and VSSA by 100mV each improves performance
- Injection tests and lab studies in preparation/ongoing
Masked pixels

Pixels with a factor 10 more rate above the average and at least 2 Hz rate are masked
Temperature diode

- $T_{IR} \approx 30 ^\circ C$ - min. power consumption
- $T_{IR} \approx 34 ^\circ C$
- $T_{IR} \approx 35 ^\circ C$
- $T_{IR} \approx 40 ^\circ C$ - default settings
- $T_{IR} \approx 54 ^\circ C$
- $T_{IR} \approx 56 ^\circ C$
- $T_{IR} \approx 59 ^\circ C$
- $T_{IR} \approx 64 ^\circ C$ - max. power consumption
Temperature diode

\[ T_{\text{MuPix8}} \, [^\circ \text{C}] \]

\[ \chi^2 / \text{ndf} \quad 23.71 / 6 \]
\[ p0 \quad 228 \pm 3.177 \]
\[ p1 \quad -0.3318 \pm 0.005858 \]

default setting

\[ V_{\text{diode}} \, [\text{mV}] \]
MuPix8 readout

Pixel

- sensor
- test-pulse injection
- integrate charge

Periphery

- CSA
- amplification
- line driver

State Machine

- baseline
- comparator 1&2
- threshold
- digital output
- readout
- tune DAC

VCO & PLL

8b/10b encoder

Serializer

MUX

LVDS connections

Other pixels

Test-pulse injection

Integrate charge

Amplification

Line driver

Threshold

Digital output

LVDS connections

MUX
auxiliary
Frequency tests

- Setup allows to use a reference frequency (w PLL) or external clock (w/o PLL)
- Tested with 10 MHz external clock: looks as if threshold can be lowered further than running at full speed (125 MHz reference → factor 62.5 faster!)
- Will be investigated using telescope
- Side note: Checked data quality of MuPix telescope @ 1.25 Gb/s: no bit errors observed for all channels: BER < $10^{-14}$
Frequency tests - 10 MHz external clock commissioning

- Bin size 500 ns
- Commissioning of single MuPix setup with slow external clock (10 MHz)
- Top: tile-MuPix correlation
- Bottom: time stamp difference between two consecutive MuPix hits
DAC Scans at VDD/A = 1.9 V & VSSA = 1.1 V

<table>
<thead>
<tr>
<th>efficiency [%]</th>
<th>noise [kHz/chip]</th>
<th>VNPix</th>
<th>VnFbPix</th>
<th>VNOutPix</th>
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<td>0x10</td>
<td>0x12</td>
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<tr>
<td>98.9</td>
<td>4.1 kHz</td>
<td>0x15</td>
<td>0x10</td>
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<td>98.4</td>
<td>2.1 kHz</td>
<td>0x1B</td>
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<td>96.8</td>
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Default DACs

- **VNRegCasc**: 20
- **VDel**: 16
- **VPComp**: 5
- **VPDAC**: 0
- **BLResDig**: 10
- **VPDelDclMux**: 6
- **VNDelDclMux**: 12
- **VPDelDcl**: 6
- **VNDelDcl**: 12
- **VPDelPreEmp**: 6
- **VNDelPreEmp**: 12
- **VPDcl**: 24
- **VNDcl**: 12
- **VNLVDS**: 63
- **VNLVDSDel**: 0
- **Bandgap1/2_on**: 0
- **Biasblock1/2_on**: 5
- **VPVCO**: 10
- **VNVCO**: 10
- **slowdownend**: 0
- **timerend**: 3
- **BLResPix**: 5
- **VNPix**: 20
- **VNFBPix**: 10
- **VNFollPix**: 10
- **VNPix2**: 0
- **VNBiasPix**: 0
- **VPLoadPix**: 5
- **VNOOutPix**: 16
- **VPFoll**: 10
- **VNFollPix**: 10
- **maxcycend**: 63
- **VPVPO**: 20
- **resetckdivend**: 3
- **SelectTest**: 0
- **SelectTestOut**: 0
- **DisableHitbus**: 0
- **sendcounter**: 0
- **Linkselect**: 0
- **Termination**: 0
- **AlwaysEnable**: 1
- **ThHigh**: 336
- **ThLow**: 293
- **ThPix**: 463
- **BLPix**: 463 (800mV)
- **BLDigi**: 256 (500mV)
- **tsphase**: 0
- **ckdivend2**: 7
- **ckdivend**: 0
- **VPRegCasc**: 20
- **VPRamp**: 0
- **VPBiasReg**: 30
- **VNBiasReg**: 30
- **enable2threshold**: 0
- **enableADC**: 0
- **Invert**: 0
- **SelEx**: 0
- **SelSlow**: 0
- **EnablePLL**: 1
- **Readout_reset_n**: 1
- **Serializer_reset_n**: 1
- **Aurora_reset_n**: 1
Lazy bits

VDD/A 1.9 V & VSSA 1 V

VDD/A 1.8 V & VSSA 1.1 V

Timestamp Bits

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<tr>
<th>tsbits</th>
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<td>RMS</td>
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gray encoded ts bits

probability to be 1

0 1 2 3 4 5 6 7 8 9

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Lazy bits

VDD/A 1.9 V & VSSA 1 V

VDD/A 1.8 V & VSSA 1.1 V
Correlation of 5 LSBs in Sensor 0 and Trigger 0

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Column and row dependence of the time resolution

![Graph showing time resolution versus row/col address](image)

- **Time resolution (σ)**: The time resolution varies from 2.8 ns to 4.8 ns with increasing row/col address.
- **Peak position (peakpos)**: The peak position increases from 2 to 6 ns as the row/col address increases.

The graphs illustrate the dependence of time resolution and peak position on the row/col address, highlighting the systematic increase with addressing.