The MuPix Telescope - Working Principle, Performance and MuPix Test Beam Results

Lennart Huth for the Mu3e collaboration
Physikalisches Institut Heidelberg
BTTB Workshop
Jan 2017
Motivation
Motivation

- new physics searches at low momenta require thin and fast pixel sensors e.g. **Mu3e**: search for $\mu^+ \rightarrow e^+ e^- e^+$
- Mu3e pushes **HV-MAPS** development $\rightarrow$ requires a lot of test beams and integration studies
- we need a test setup, that combines multiple aspects of the Mu3e detector
The MuPix Telescope
Idea: Build a tracking telescope from Mu3e detector components to test read out, synchronization and carry out test beams.

Use one pixel layer as device under test (dut).
High Voltage - Monolithic Active Pixel Sensors (HV-MAPS)

- digital position and time read out
- $80 \times 80 \mu m^2$ pixel size
- $256 \times 256$ pixel
- $2 \times 2 cm^2$ total size
- $\sigma_t < 11$ ns measured
- efficiency $> 99.5\%$ measured
- $50 \mu m$ thin $\approx 0.05\%$ radiation length
MuPix 7

- full self-triggered zero-suppressed readout running in on-chip state machine
- 1.25 GBit/s serial data output
- 125 MHz external reference clock
- $32 \times 40$ pixel with size of $103 \times 80 \, \mu\text{m}^2$
- active area: $3.3 \, \text{mm} \times 3.2 \, \text{mm}$
MuPix7 II

Pixel
- sensor
- CSA
- source follower
- test-pulse injection
- amplification
- integrate charge

Periphery
- 2\textsuperscript{nd} amplifier
- DAC
- threshold
- baseline
- AC coupling via CR filter
- line driver
- per pixel threshold adjustment

State Machine
- readout state machine
- VCO & PLL
- 8b/10b encoder
- serializer
- digital output
- LVDS
- other pixels
- readout
- per pixel threshold adjustment

AC coupling via CR filter
- digital output
Readout and Control Scheme

MuPix

FPGA 0

readout computer

PCIe bus

Lenna Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Readout and Control Scheme

MuPix

0 1 2 3

FPGA 0

PCIe bus

GUI C P U

readout computer

Lennart Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Readout and Control Scheme

MuPix

0 1 2 3

config

control register

FPGA 0

readout computer

GUI

CPU

PCIe bus

Lennart Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Readout and Control Scheme

MuPix

FPGA 0

control register

readout computer

PCIe bus

GUI

CPU

Lennart Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Readout and Control Scheme

MuPix

FPGA 0

time sorting

control register

readout computer

PCIe bus

GUI

CPU

Lennart Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Readout and Control Scheme

MuPix

0 1 2 3

FPGA 0

time sorting

control

register

DMA

polling

FPGA 0

PCIe bus

readout computer

GUI

CPU

Lennart Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Readout and Control Scheme

MuPix

FPGA 0

time sorting

control register

DMA

polling

readout computer

DDR3

GUI

CPU

PCIe bus

Lennart Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Readout and Control Scheme

MuPix

0 1 2 3

FPGA 0

control register

DMA

polling

time sorting

readout computer

DDR3

PCIe bus

GUI

data merger

CPU
Readout and Control Scheme

MuPix

FPGA 0

time sorting

control register

DMA

polling

readout computer

DDR3

GUI

monitoring & tracking

data merger

CPU

PCie bus

Lennart Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Readout and Control Scheme

MuPix

0 1 2 3

FPGA 0
time sorting
control register
DMA
polling

readout computer

DDR3
GUI
monitoring & tracking
data merger

CPU
GPU
HDD

Lennart Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
FPGA 0

MuPix

readout computer

DDR3

GUI

data merger

monitoring & tracking

CPU

GPU

H

D

C

P

D

H

Lenna rt Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Readout and Control Scheme

FPGA 0
- Time sorting
- Control register
- DMA
- Polling

125 MHz oscillator

MuPix
- Clock
- Reset

readout computer
- DDR3
- GUI
- Monitoring & tracking
- Data merger
- CPU

PCIe bus

Lenna
Telescope Design Goals

<table>
<thead>
<tr>
<th></th>
<th>target</th>
<th>current status</th>
</tr>
</thead>
<tbody>
<tr>
<td>pixel size [µm]</td>
<td>80x80</td>
<td>103x80</td>
</tr>
<tr>
<td># layers</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>track rate [MHz]</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>material budget per layer</td>
<td>50 µm sensor</td>
<td>50 µm sensor</td>
</tr>
<tr>
<td></td>
<td>25 µm support</td>
<td>100 µm support</td>
</tr>
<tr>
<td>radiation length %</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>time resolution σ [ns]</td>
<td>17</td>
<td>1 (tiles)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14 (mupix)</td>
</tr>
</tbody>
</table>
Test Beam Results
Alignment & Resolution

- Residuals in y for plane 0
- Residuals in y for plane 1
- Residuals in y for plane 2
- Residuals in y for plane 3
- Residuals in y for plane 4

Graphs showing residual plots for different planes with run numbers ranging from 260 to 400.

Run number

260
280
300
320
340
360
380
400

Residuals y mean [um]

-8 -6 -4 -2 0 2 4 6 8

Residual of matched hit [um]

Entries [1/run]

x10^3

Lennart Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Alignment & Resolution

RMS of residuals y mean [µm]

RMS of residuals in y for plane 0
RMS of residuals in y for plane 1
RMS of residuals in y for plane 2
RMS of residuals in y for plane 3
RMS of residuals in y for plane 4

Run number
260
280
300
320
340
360
380
400

Run 68

y Residual σ 30.6±0.1 µm
X Residual σ 38.1±0.1 µm

Residual of matched hit [µm]

Entries [1/run]
Alignment & Resolution

![Graph of residuals x and y for different planes with run numbers and RMS values for both x and y directions.](image)

Lennart Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Efficiency Studies using the MuPix Telescope

define ROI to eliminate sensor edge effects
Efficiency Studies using the MuPix Telescope II

- dut rotated
- thicker effective depletion zone - higher signal - more efficient
- similar effect with higher substrate resistivity
- new prototype!

---

Search Window 800 µm and time cut 48 ns

Threshold [V]

0.68 0.7 0.72 0.74 0.76

Efficiency

0.94
0.95
0.96
0.97
0.98
0.99
1

Rotation [deg]

0
15
30
45
60

m and time cut 48 ns µSearch Window 800 µ

d and time cut 48 ns µSearch Window 800 µ

Lennart Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Time Resolution

σ = 14.3 ns

σ = 14.3 ns

σ = 14.3 ns

σ = 14.3 ns
Studies using the Duranta Telescope

Mupix7, 720 mV threshold, HV = -85 V

Mupix7, 735 mV threshold, HV = -85 V

Lennart Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Conclusion & Outlook

Conclusion

• MuPix Telescope is a crucial tool for system integration and test beam studies
• thin and fast telescope: 0.9% $X/X_0$ per layer and 1 MHz track rate
• intensively used to study MuPix7:
  99.5% efficiency
  14 ns time resolution
• will also be used with next prototype generation

Outlook

• integrate the MuPix8
• improve user friendliness
Time Resolution with DURANTA

Mupix7, 730 mV threshold, HV = -40 V

Mupix7, 730 mV threshold, HV = -40 V

Lennart Huth - huth@physi.uni-heidelberg.de (PI HD) Jan 2017
Momentum measurement

- Apply magnetic field (e.g. 1 Tesla)
- Measure curvature of particles in field
- Limited by detector resolution and scattering in detector
Track Model

Trackmodel: Straight track without scattering

\[ \vec{x}(z) = \vec{x}_0 + \vec{a} \cdot z \]

\[ \chi^2 \] can be analytically minimized

\[ \chi^2 = \sum_{i=1}^{n} \left( \frac{(x_i - (x_0 + a_x \cdot z_i))^2}{\sigma_{x,m_i}^2} + \frac{(y_i - (y_0 + a_y \cdot z_i))^2}{\sigma_{y,m_i}^2} \right) \]

assuming \( \sigma_{x/y,m_i} = \text{pixel resolution} = \frac{\text{pixel size}}{\sqrt{12}} \)

\[ \rightarrow \] Fast and robust track model!
Crosstalk

Column/Row Address
0 5 10 15 20 25 30 35
Crosstalk Prob
4−10
3−10
2−10
triple_hit_row
row
col

title: triple_hit_row

Crosstalk Prob
10^{-3}
10^{-2}
10^{-1}
10^{0}

Column/Row Address
0 5 10 15 20 25 30 35
Mass Scale Sensitivity