HV-MAPS Tracking Telescope
For High Rates and Low Momentum Particles

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on Behalf of the Mu3e Collaboration

DESY Telescope Workshop

30.06.2014 - 02.07.2014
Outline

1. Motivation
2. Sensors
3. Mechanics
4. Electronics
5. Software
6. Test Beams
7. Conclusion
The MuPix Telescope

Idea: Build a tracking telescope out of Mu3e parts:
Comparison

Table 1: Comparison of existing beam telescopes and the proposed project.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>55 μm</td>
<td>18.4 μm</td>
<td>80 μm</td>
</tr>
<tr>
<td>Pointing resolution</td>
<td>2 μm</td>
<td>1.8 μm</td>
<td>≈ 12 μm</td>
</tr>
<tr>
<td>(180 GeV π) 50 MeV e⁻</td>
<td>400 μm</td>
<td>180 μm</td>
<td>150 μm</td>
</tr>
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<td>2 μm</td>
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<tr>
<td>(50 MeV e⁻)</td>
<td>400 μm</td>
<td>180 μm</td>
<td>150 μm</td>
</tr>
<tr>
<td>Material in radiation</td>
<td>300 μm sensor</td>
<td>50 μm sensor</td>
<td>50 μm sensor</td>
</tr>
<tr>
<td>lengths</td>
<td>700 μm readout</td>
<td>50 μm protective foil</td>
<td>25 μm Kapton foil</td>
</tr>
<tr>
<td>Time resolution</td>
<td>1 ns (in special plane)</td>
<td>115.2 μs</td>
<td>17 ns</td>
</tr>
<tr>
<td></td>
<td>16 ms otherwise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame rate</td>
<td>60 Hz</td>
<td>9 KHz</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Maximum track rate</td>
<td>15.5 KHz</td>
<td>≈ 100 KHz</td>
<td>≈ 20 MHz</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>mostly offline</td>
<td>offline</td>
<td>online</td>
</tr>
</tbody>
</table>

(1) Assuming 1 cm flight distance and dominating multiple scattering effects.

Test beams

<table>
<thead>
<tr>
<th>Test beams</th>
<th>T4-H8A @ CERN</th>
<th>T22 @ DESY</th>
<th>πM1 @ PSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>180</td>
<td>1-6</td>
<td>≈0.25</td>
</tr>
<tr>
<td>Particles</td>
<td>π⁺</td>
<td>e⁻</td>
<td>e, π, μ</td>
</tr>
<tr>
<td>Rate</td>
<td>1 kHz</td>
<td>&gt;GHz</td>
<td></td>
</tr>
</tbody>
</table>
New Physics and Mu3e

Search for LFV decay: $\mu^+ \rightarrow e^+ e^+ e^-$ with sensitivity of 1 in $10^{16}$

Signal Decay
- $10^9 \, \mu/s$
- precise timing
- $E_{max} = 53$ MeV

Random Combinations
- high momentum resolution
- high vertex resolution
- high time resolution

→ Use new detector technologies for high rates, good vertex and momentum resolution
→ Low momentum particles → avoid multiple scattering
**Concept:** Stop muons at target and measure decay particles

\[ \rightarrow E_{\text{max}} = 53 \text{ MeV} \]

1 m² pixel detector
High Voltage - Monolithic Active Pixel Sensors (HV-MAPS)

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

- Zero suppressed
- 8 bit Time stamp
- $80 \times 80 \, \mu m^2$
- Time resolution $< 17$ ns
- Efficiency $> 99\%$
- 50 $\mu m$ thin

more details: M. Kiehn 17:05 today
## MuPix Prototypes

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Active Area</th>
<th>Functionality</th>
<th>Bugs</th>
<th>Improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>MuPix1</td>
<td>1.77 mm²</td>
<td>Sensor + analog</td>
<td>Comparator “ringing”</td>
<td>First MuPix prototype</td>
</tr>
<tr>
<td>MuPix2</td>
<td>1.77 mm²</td>
<td>Sensor + analog</td>
<td>Temperature dependence</td>
<td>No ringing</td>
</tr>
<tr>
<td>MuPix3</td>
<td>9.42 mm²</td>
<td>Sensor, analog, dig.</td>
<td>bad pixel on/off,</td>
<td>First part of dig. readout</td>
</tr>
<tr>
<td>MuPix4</td>
<td>9.42 mm²</td>
<td>Sensor, analog, dig.</td>
<td>Zero timestamp and row address for 50% of pixels</td>
<td>First working digital readout, first timestamp, temperature stable</td>
</tr>
<tr>
<td>MuPix6</td>
<td>10.55 mm²</td>
<td>Sensor, analog, dig.</td>
<td>?</td>
<td>Removed zero time-stamp and address bug</td>
</tr>
</tbody>
</table>
Sensor Development

On Carrier
- 2.2 mm ceramic
- 1.7 mm PCB board
- 250 µm chip
- \( x/X_0 = 23\% \)

On Board
- No ceramic
- 100 µm PCB board
- 250 µm chip
- \( x/X_0 = 2.5\% \)

On Kapton
- No ceramic + PCB
- 25 µm Kapton
- 250 µm chip
- \( x/X_0 = 2.1\% \)

Final Goal: 50 µm Si + 25 µm Kapton \( \rightarrow X_0 = 0.6\% \)
Mechanical Structure

- Mounted on optical rail
- Layers move independently
- Compact system
- Most components: Thorlabs
Signal Transmission

Plain ribbon cable

AL shielded ribbon cable
Readout Chain
Readout Chain

1

2

8x40 wire ribbon cables

3

4
Readout Chain

1 TOP
2 BOT
2 FPGAs
Readout Chain
Concept

- Telescope is operating in streaming mode at high particle rates
  → Continuous data readout, no trigger and a lot of data
  → Need a lot computing power
  → Share the work
- Several Threads
  → Readout, monitoring, time sorting, storing, tracking → Synchronization, coordination, communication
- Data handling via lock-free spsc fifo queues
- Reconstruct the tracks online
Readout Software

- Top Trigger Queue
- Top Hit Queue
- Bottom Trigger Queue
- Bottom Hit Queue

- RO TOP
- RO BOTTOM

Readout threads
Copy data from FPGA
Fill hit and trigger queues
Readout Software

Data sorting
Frame creation
data storing
Readout Software

**Motivation**

**Sensors**

**Mechanics**

**Electronics**

**Software**

**Test beam**

**Conclusion**

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**Readout Software**

- **RO TOP**
  - Top Hit Queue
  - Dataprocess. Top
  - FileWriter
  - HDD
  - Data Frames
  - Root Trees
  - Monitoring

- **RO BOTTOM**
  - Bottom Hit Q.
  - Bottom Trigger Queue
  - Dataprocess. Bottom
  - FileWriter
  - HDD
  - Data Frames
  - Root Trees
  - Monitoring
Readout Software

**Motivation**

- Sensors
- Mechanics
- Electronics

**Software**

- Test beam
- Conclusion

**RO**

- TOP
  - Top Hit Queue
  - Top Trigger Queue
  - Control
  - Data Frames
  - HDD
  - DataFrames
  - Root Trees

- Bottom
  - Bottom Hit Queue
  - Bottom Trigger Queue

**FileWriter**

- Not Implemented!!

**MainWindow**

- Tracking

**Dataprocess.**

- Top
- Bottom

**Monitoring**
Performance

Data Taking

- 2.5 days data taking w/o crash at 5 GeV electron energy
- highest rate with noise: 755 k hits/s per plane

Online Monitoring
Correlations & Alignment & Resolution

MuPix 4: Pixel size 92x80 $\mu m^2$

Intrinsic resolution $= 0.28$ Pixel $< 0.79$ Pixel $= \text{distribution width}$
PCB Holder - Development
Lessons Learned

- First HV-MAPS telescope in operation
- Chip DAC settings must be improved
- Software is stable and working
- Improve mechanics
- Data format can be improved
- Ribbon cables introduce a lot of digital crosstalk
PSI test beam June 14
PSI Test Beam

Goals

- Test new Software and LVDS links
- Take high statistics to test track reconstruction
- Test time stamp influence
- Use the new sensor prototype MuPix 6

PSI accelerator cavity

- No beam due to accelerator maintenance complications
- Only source tests performed
Timing with 3.7 MBq $^{90}\text{Sr}$-source

MuPix 6 prototype
Summary

- First HV-MAPS telescope tested successfully
- Track reconstruction under test
- High rates ($\approx 1$ MHz) can be handled
- New MuPix sensor is under test
- Time stamps are working and system is synchronized
Outlook

- Next Testbeam: July @ PSI
- Online track reconstruction
- Thin sensors
- Final chip $\mathcal{O}$ (cm$^2$)
- Increase time resolution up 5 ns

- Thanks to the DESY testbeam group
- Looking forward to autumn beam
Thank you!