A HV-MAPS Pixel Tracker for the Mu3e Experiment

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DPG Spring Meeting
T72.1
02. March 2016
Mu3e
The Physics Goal

- $\mu^+ \rightarrow e^+e^-e^+$ suppressed to a BR below $10^{-54}$ in the Standard Model
- Any observed signal is a sign for new physics
- Current limit BR < $10^{-12}$ (SINDRUM)
- Aiming for sensitivity of 1 in $10^{16}$ decays

SINDRUM: "Search for the decay muto3e" Nucl. Phys.,B299 1, 1988
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The Signal Decay

- Muons decay at rest: $\sum \vec{p} = 0$
- Common vertex and coincident in time
- Maximal momentum 53 MeV/c
- Reconstruct invariant mass from charged particle tracks ($E_{tot} = m_\mu$)
The Background

Accidental & Combinatorial

- $10^9$ decays per second
- Gives rise to accidental & combinatorial background
- Good time and vertex resolution needed
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The Background

Irreducible background from radiative decays with internal conversion:

\[ \mu^+ \rightarrow e^+ e^- e^+ \bar{\nu}_\mu \nu_e \]

- Good momentum resolution needed to suppress SM background
- Momentum resolution is dominated by multiple scattering \( \propto \sqrt{x/p} \)

The Detector

1T magnetic field
The Detector

1T magnetic field
The Detector

1T magnetic field
The Detector

1T magnetic field
The Detector

1T magnetic field
The Detector

1T magnetic field

- Recurl pixel layers
- Scintillator tiles
- Inner pixel layers
- Target
- Scintillating fibres
- Outer pixel layers
- μ Beam
- Target
- Inner pixel layers
- Recurl pixel layers
- Scintillator tiles
- μ Beam

02/03/16
HV-MAPS
Heiko Augustin
The Requirements for the Silicon Pixel Tracker

- Good vertex resolution
- Good time resolution & low dead time → fast signal generation & shaping
- Good momentum resolution → low material budget
The Requirements for the Silicon Pixel Tracker

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>$&lt; 1%_0 X_0/layer$</td>
<td>$&gt; 99%$</td>
</tr>
</tbody>
</table>

- Good vertex resolution
- Good time resolution & low dead time
  - fast signal generation & shaping
- Good momentum resolution $\rightarrow$ low material budget
The Pixel Tracker

- Readout & Powering via Flexprints: T42.7
- Cooling in Helium atmosphere: T75.2
The Pixel Tracker

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The Pixel Tracker

Readout

- 1056 Pixel Sensors
  - up to 36 1.25 Gbit/s links
- 34 FPGAs
- Switching Boards
  - 1 6 Gbit/s link each
- 12 PCs
- Mass Storage
  - Gbit Ethernet
- Data Collection Server
- Front-end (inside magnet)

- Untriggered readout
- 1 Tbit/s raw data rate
- GPU based online reconstruction
- Sessions: T42.5, T42.6, T22.5, T22.4, T98.1, T98.5
High Voltage Monolithic Active Pixel Sensors

- Deep n-well in p-doped substrate
- Depleted area is the active detector volume $\approx 15 \, \mu m$
- Fast charge collection via drift
- Sensor can be thinned to $< 50 \, \mu m$

I. Peric, P. Fischer et al., NIM A 582 (2007) 87
The MuPix7 Prototype

- Commercial 180 nm HV-CMOS process
- Thinned to 50 µm
The MuPix7 Prototype
The MuPix7 Prototype

**Pixel**
- Sensor
- CSA
- Source follower
- Test-pulse injection
- Amplification
- Integrate charge

**Periphery**
- 2nd amplifier
- Comparator
- AC coupling via CR filter
- Line driver
- Per pixel threshold adjustment

**State Machine**
- Baseline
- Comparator
- Readout state machine
- 8b/10b encoder
- VCO & PLL
- Serializer
- LVDS
- Digital output

**Acronyms**
- DAC: Digital-to-Analog Converter
- PLL: Phase-Locked Loop
- LVDS: Low-Voltage Differential Signaling
- AC coupling: Alternating Current coupling

**Date**
- 02/03/16

**Authors**
- HV-MAPS
- Heiko Augustin
The Pixel

- 3.2 × 3.2 mm² active area
- 32 × 40 pixels
- 3 × 3 diode structure
- In-pixel amplifier
The Pixel

- **In-pixel amplifier**
- **Point-to-point connection to periphery**
The Periphery

- Additional amplification stage
- Signal digitisation
- 8-bit time stamps
- Zero-suppressed readout

7 µm
51 µm
The Periphery

- Individual pixel tuning
- Characterise analogue behaviour

T72.2 & 3
The Analogue Behaviour

- Test of general functionality
- HV-dependence
- Analogue performance
- Pulse shape reconstruction
- SNR determination

More Details: T72.2, T72.3
The Analogue Behaviour

- Test of general functionality
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More Details: T72.2, T72.3
The MuPix State Machine
The MuPix State Machine

- On-chip readout state machine
- VCO & PLL
- LVDS Gbit data link
Voltage Controlled Oscillator & Phase Locked Loop

- Stable working point
- Chip as line driver
- Jitter <100 ps (→ T72.2)
- 1.25 Gbit/s 8b10b encoded data
- Up to 30 MHits/s possible
Power Consumption

- Upper limit of 400 mW cm$^{-2}$
- Temperature gradient of 50 K ($\rightarrow$ T75.7)
- Investigation of temperature dependence ($\rightarrow$ T72.2)
Testbeam Measurements
Time Resolution

Time resolution measured to <11ns

Time walk observed for pixel analogue behaviour
Time Resolution

MuPix7 Pulse

Threshold

small
medium
large
Energy-deposition

MuPix7 Pulse

Threshold

input pulse

Comparator Response

Latency

ToT
Time Resolution

- Sandwich scintillator setup
- Time resolution measured to <11 ns

\[ \sigma < 11 \text{ ns} \]
Time Resolution

- Sandwich scintillator setup
- Time resolution measured to <11 ns
- Time walk observed for pixel analogue behaviour
The MuPix Telescope (T99.5)

- 4 layers MuPix7
- Use one as DUT
- Time sorted data (T22.4)
- Resolution <30 μm
- Position resolved analysis
Efficiency Measurements

- Use telescope setup
- 220 MeV mixed pion beam provided by PSI
Efficiencies above 99 % observed
Tuning results in sharp noise edge
Power consumption: \( \approx 300 \text{ mW cm}^{-2} \)
Crosstalk

Pixel Matrix

Digital Cells

Signal lines
Crosstalk

![Graph showing crosstalk probability vs row address](image)
Crosstalk

![Graph showing crosstalk probability against row address. The x-axis represents row address from 0 to 35, while the y-axis shows crosstalk probability on a logarithmic scale from $10^{-4}$ to $10^{-2}$. The graph indicates a general decrease in crosstalk probability as the row address increases.]
Crosstalk observed
Matches signal routing
MuPix8 Prototype

- Submission planned for June 2016
- First big chip $2.3 \times 1.3 \text{ cm}^2$
- Pixel size $80 \times 80 \text{ µm}^2$
- Higher resistivity substrate
- First module prototypes
Summary

- Reliable characterisation setup & frame work
- Very well performing chip technology
- First HV-MAPS prototype with integrated readout
- Many design goals already satisfied
Acknowledgments

The efficiency measurements for several power settings 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.

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We thank the Institut für Kernphysik at the JGU Mainz for giving us the opportunity to take data at MAMI.
Mu3e Talks

- Front-End Board: T22.4
- Switching Board: T22.5
- GPU-Online Reconstruction: T42.5
- GPU-Telescope Reconstruction: T42.6
- Flexprints: T42.7
- MuPix T-Dependence: T72.2
- MuPix Tuning: T72.3
- Mechanic & Cooling: T75.7
- Track reconstruction: T98.1
- Detector alignment: T98.5
- MuPix7 Telescope: T99.5