Mupix: Monolithic sensors for the Mu3e experiment

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Vertex 2022
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Mu3e: Physics Motivation

- Search for $\mu \to eee$
  - Standard Model: $\text{BR} (\mu \to eee) < 10^{-54}$
- New physics might enhance BR
- Current limit:
  - $\text{BR} (\mu \to eee) < 10^{-12}$ (SINDRUM, 1988)
- Aimed single-event sensitivity:
  - $\text{BR} (\mu \to eee) < 2 \cdot 10^{-15}$ (Phase 1)
  - $\text{BR} (\mu \to eee) < 10^{-16}$ (Phase 2)
- Phase 2: PSI High Intensity Muon Beamline
- Phase 1 pre-production starting by end of the year
Experimental concept

- Tracking electrons coming from muon decays at rest (~10^8 Hz in Phase I)
- Magnetic field (1 T)

3 electrons
- Same vertex
- Same time
- Total invariant mass = muon mass

3 stations
Experimental concept

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Experimental concept

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Gaseous Helium as coolant
Experimental concept

- Tracking electrons coming from muon decays (~$10^8$ Hz in Phase I)
- Magnetic field (1 T)

Complex cooling system
Experimental sensitivity

Momentum resolution crucial for detecting the peak at muon mass…

Material budget is key factor!

1 MeV resolution with 0.1% * $X/X_0$ per layer

Mu3e TDR at

*Nucl.Instrum.Meth.A* 1014, 165679
Experimental sensitivity

Mu3e Phase I

Events / 0.2 MeV/c^2

10^2

10^1

10^0

10^-1

10^-2

10^-3

95

Invariant mass background (Bl)

Mu3e TDR

Momentum resolution

All done by a collaboration of 12 institutes in 3 countries

Mu3e Collaboration Meeting
PSI 2022
Layer 0/1

- 6 chips glued on layer 0 and 1
- 17/18 chips on layer 2 and 3
- 50 μm thin
- Connection via interposers (pressed against RO flexes)

Chips glued on High Density Interconnects (HDIs)
Layer 0/1

**HDIs:**
- Kapton/Aluminum foils
- Serve as mechanical support
- Electrical traces
- Produced by LTU (Ukraine)
- No extra components

Reduce material budget for electronics as well!
Layer 1/2

Detector mount (floating, spring loaded)

Mylar foil

Electrical connections

Helium

Detector mount (fixed)

Endring

Pixel ladders carrying sensor arrays

HDIs

Very limited amount of lines for each ladder
All going to the service area (~2 m away)

Reduce material budget for electronics as well!

No extra components
Electrical connections with Single Point Tape Automated Bonding (SpTAB)
MuPix sensors

- Monolithic HV-CMOS
  - Readout electronics embedded inside silicon bulk
    - In deep n-well
  - No need for hybridization
  - Can be thinned while maintaining high performance
MuPix sensors

- Monolithic HV-CMOS
  - Can be thinned while maintaining high performance
- 180 nm H18 technology derived from IBM
  - AMS until 2018
  - TSI afterwards
- Long R&D campaign
  - Mupix7 first fully monolithic
  - Mupix8 first large area
  - Mupix9 implemented slow control
  - Mupix10 with final size
    - Used for prototyping
  - Mupix11 final chip
    - Characterization ongoing
MuPix sensors: MuPix10/11

- ~2x2 cm$^2$ active area
- Chip periphery on bottom
- 250 mW/cm$^2$ power consumption
MuPix sensors: MuPix10/11

- ~2x2 cm$^2$ active area
- Chip periphery on bottom
- 250 mW/cm$^2$ power consumption
- Signal collected and amplified by pixels
- Analogue signal driven to periphery
- Each pixel mirrored in periphery
  - Analogue signal digitized
- State machine collects hits from double columns
- Continuous read-out!
- 4 LVDS link
  - 3 per matrix (inner trackers)
  - 1 multiplexed (outer layers)
MuPix sensors: design challenges

- 2 LVDS input lines as bus lines (common to 3/9 chips)
  - Clock and Serial input
  - 125 MHz clock
- 9 Data lines
  - 3x3 inner layers or 1x9 outer layers (multiplexed)
  - 1.25 Gbit/s
- 3 DC lines per ladder
  - VDD+GND sense \(\rightarrow\) Recover voltage drops
  - Temperature sense \(\rightarrow\) Hardware interlock
- Slow control
  - ADC to read internal voltages and temperature
  - Readings sent out via data links
  - Extra temperature diode (analogue output)
MuPix sensors: design challenges

- Hit-delay circuit
  - Hit recorded after a fixed delay from ToA
  - Easier time sorting procedure
  - Incidental effect: max value on ToT
- No active or passive components to “help” on flexes
- Proved to work until 1 MHz particle rate
  - Within specs
Experiment’s validation

● Prove performance requirements
  ○ Lab tests
  ○ Testbeams
● Operate with HDIs
● Operate in experimental conditions
  ○ Prototyping
  ○ Beam, target, magnet
  ○ Cosmic only
● Thermo-mechanical mockup
  ○ See backup
# MuPix sensors: requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size $[\mu m^2]$</td>
<td>$80 \times 80$</td>
</tr>
<tr>
<td>Sensor size $[mm^2]$</td>
<td>$20 \times 23$</td>
</tr>
<tr>
<td>Active area $[mm^2]$</td>
<td>$20 \times 20$</td>
</tr>
<tr>
<td>Active area $[mm^2]$</td>
<td>400</td>
</tr>
<tr>
<td>Sensor thinned to thickness $[\mu m]$</td>
<td>50</td>
</tr>
<tr>
<td>LVDS links</td>
<td>$3 + 1$</td>
</tr>
<tr>
<td>Maximum bandwidth $^\S [Gbit/s]$</td>
<td>$3 \times 1.6$</td>
</tr>
<tr>
<td>Timestamp clock $[MHz]$</td>
<td>$\geq 50$</td>
</tr>
<tr>
<td>RMS of spatial resolution $[\mu m]$</td>
<td>$\leq 30$</td>
</tr>
<tr>
<td>Power consumption $[mW/cm^2]$</td>
<td>$\leq 350$</td>
</tr>
<tr>
<td>Time resolution per pixel $[ns]$</td>
<td>$\leq 20$</td>
</tr>
<tr>
<td>Efficiency at 20 Hz/pix noise $[%]$</td>
<td>$\geq 99$</td>
</tr>
<tr>
<td>Noise rate at 99% efficiency $[Hz/pix]$</td>
<td>$\leq 20$</td>
</tr>
</tbody>
</table>
MuPix10: results

100 µm thickness
110 V breakdown
Efficiency plateau well defined above 20 V
MuPix10: results

- 50 μm thickness
- 20 V (see later why)
- Efficiency and noise requirements met
Mupix10 detailed studies

Testbeam at DESY

Alpide telescope

6 layers

5 μm resolution

EuDAQ + Corryvreckan
Mupix10 detailed studies

In-pixel efficiency

100 μm thick

43 mV threshold

A.M. Gonzales
MuPix10: results

Time resolution well within specifications
~15 ns without corrections
6 ns after row and time-walk corrections
MuPix10: results

Tunable threshold for each pixel

Tuning with threshold scans:

Low threshold dispersion
MuPix10: results

Tuning by lowering threshold while keeping noise constant: maximize efficiency!

MuPix10
200 Ωcm
d=50 μm
bias = -20V

DESY testbeam Dec. 2021
Preliminary
MuPix10: thinning

MuPix10 devices thinned at different thicknesses (by mechanical grinding only).

IV curves affected

$d \propto \sqrt{U \rho}$

Early increase due to depletion region reaching the backside

Full depletion compatible with 400 Ωcm resistivity (nominal: 200 Ωcm, Measured: 370 Ωcm)
Thinning

Investigated thinning with AtlasPix3.1: with and without plasma etching

50 μm thin

Plasma etching shows significant improvement both mechanically and electrically (IV curves)

80-100 Ωcm wafers will reach 50 μm full depletion at ~100 V
Mupix10 with HDIs

Aluminum HDIs tested with Mupix10

Differential impedance matching (100 Ohms)

Tested with long single chip HDI

Length: 24 cm. Max length in experiment: 18 cm
Operation in experimental conditions

DAQ and experimental concept

Prototype of vertex detector

Jun/Jul 2021 and 2022

50 μm-thin chips mounted on katpon foils

Connected to ladder-boards

Same shape as inner tracker, slightly larger radii

External connection with ribbon cables
Operation in experimental conditions

DAQ and experimental concept

Mounted on beamline with target
Operation in experimental conditions

DAQ and experimental concept

In experimental cage
Operation in experimental conditions

DAQ and experimental concept

Helium flow
Operation in experimental conditions

DAQ and experimental concept

More pics at
https://www.flickr.com/photos/nberger/albums/72157719305216074/page1/
Operation in experimental conditions

Results

With beam (2021)

Mu3e target with magnetic field

Layer 0-1 correlation!

With cosmics (2022)

More analysis ongoing
Conclusions

- Mu3e is a CLFV experiment which uses HV-MAPS to track electrons and positrons from muon decays
  - High rates
  - Low energy
- Tight experimental constraints on pixels → HV-CMOS!
- MuPix development at the forefront of HV-CMOS R&D
- MuPix10 satisfies most of experimental requirements
- Prototype of vertex detector successful
- MuPix11 testing ongoing
- Pre-production of Mu3e starting by end of the year
Backup
Mupix11 results (preliminary)
MuPix sensors: MuPix10

Single pixel read-out: in-cell
MuPix sensors: MuPix10

Single pixel read-out: periphery

Comparator in digital cell
Records Time-of-Arrival (ToA)
Records time of falling edge
Time-over-Threshold (ToT) computed

2 threshold mode:
- hit flag raised with high threshold
- ToA recorded with low threshold
- Falling edge on high threshold
Decreases time-walk
Backup: crosstalk
MuPix10: results

Cross-talk

Multiple metal layers (TSI specific) used to minimize inter-line capacitances. Cross-talk probability < 1.5%

Neighbouring pixels are routed on different lines: cross talk distinguishable from charge sharing
Cluster size vs threshold
Large threshold -> bias towards delta rays
Operation in experimental conditions

Results

Distribution of $z_0$: closest point of approach along $z$ axis

With cosmics

B. Gayther
Backup: chip picking
Backup: thinning issue

Atomic force microscopy on backside
Backup: Prototyping

Thermo-mechanical stability

Silicon heater prototype

Reproduction of inner tracker with same materials and connections

Chips are just passive silicon heaters
Backup: Prototyping

Thermo-mechanical stability

Silicon heater prototype

Test stand with Helium cooling system
Backup: Prototyping

Thermo-mechanical stability

- Measurement of temperature-to-power relation
- Temperature difference linearly depending on heat dissipation
- Expected $\Delta T < 70$ K for 350 mW/cm² (conservative limit)
- Cooling concept works ✓
- More detailed studies to come
Backup: Prototyping

Thermo-mechanical stability

Silicon heater prototype
Production of inner layers

Heidelberg/PSI

Quick demo: https://youtu.be/0SYqHSbH3U4
Production of outer layers

Oxford/Bristol/Liverpool
Probe card for single chip: one Mupix layed inside the socket, the knob presses it against the needed. The same card can be used in probe stations with different needles.