The MuPix Pixel Sensors, the Mu3e DAQ and tracking in multiple scattering dominated environments

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Overview

• Tracking in multiple scattering dominated environments

• The MuPix High-Voltage Monolithic Active Pixel Sensors

• Some Ideas from the Mu3e Data Acquisition

• Many Questions
Momentum measurement

- Apply magnetic field
- Measure curvature of particles in field
- Limited by detector resolution and scattering in detector

\[ \theta_0 = \frac{13.6 \text{ MeV}}{\beta cp} z \sqrt{\frac{x}{X_0}} \left[ 1 + 0.088 \log_{10}(\frac{x z^2}{X_0 \beta^2}) \right] \]
Momentum measurement

- Apply magnetic field
- Measure curvature of particles in field
- Limited by detector resolution and scattering in detector

- Below few 100 MeV/c momentum: Scattering completely dominates
- Large pixels (Mu3e: 80 μm)
- Very little material (0.1% $X_0$ per layer)
Momentum measurement

- Resolution dominated by multiple scattering
- Measure a direction (double plane) and then curvature over large drift distance
Momentum measurement

- Resolution dominated by multiple scattering

- Measure a direction (double plane) and then curvature over large drift distance (also works in the other direction)
Momentum measurement

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- Momentum resolution to first order:

\[ \frac{\sigma_p}{p} \sim \frac{\theta_{MS}}{\Omega} \]
Momentum measurement

- Resolution dominated by multiple scattering

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- Momentum resolution to first order:
  \[ \frac{\sigma_P}{P} \sim \frac{\theta_{\text{MS}}}{\Omega} \]

- Precision requires large lever arm (large bending angle \(\Omega\)) and low multiple scattering \(\theta_{\text{MS}}\)
Precision vs. Acceptance

- Best resolution for semi-circles: Multiple scattering cancels to first order
- In Mu3e: Get to 100 keV/c resolution for ~20 MeV/c tracks
- Treat hit measurements as arbitrarily precise
- Consider scattering in each detector plane
- Two hits, two helices: Underconstrained problem
- Minimize scattering angles
- Use multiple scattering theory to define $\chi^2$

Measuring multiple scattering

- Study multiple Coulomb scattering in thin silicon wafers
- 1 day measurement at the DESY electron test beam
- Using the EUDET telescope
Measuring multiple scattering

- Measure with and without silicon
- Fit distributions, difference is scattering in silicon
Measuring multiple scattering

- Measure with and without silicon
- Fit distributions, difference is scattering in silicon
- Shape well described by Student’s t distribution
Measuring/simulating multiple scattering

- RMS of the central 98% of the distribution well described by Highland formula and Geant4 models
Measuring/simulating multiple scattering

- RMS of the central 98% of the distribution well described by Highland formula and Geant4 models


- Models do not have enough tails ($\nu \to \infty$ : Gaussian)
- Would like to extend this to lower momenta
Mu3e Detector Design
EDM Momentum Resolution Detector

- A double plane of detectors
- Optimum momentum resolution for circling positrons
- Likely loose some positrons
Questions:

- What momentum resolution do we need? Few MeV/c?
- Acceptance should be close to 100%?
- What will dominate the systematic uncertainty? Tracking efficiency? Up-/down differences in tracking efficiency?
Efficiency:
- Use highly efficient sensors
- Be highly redundant

More redundancy means more material means less momentum resolution - one of the trade-offs for this experiment
EDM Tracking Detector?

- How many blades?
- Inside orbit?
- Vertical dimension?
- Trigger?
- Services?
- Cooling?
- What sensors?
Misalignment systematic

- Tilt of any sensors relative to the horizontal will lead to different path-lengths for up- and down-going positrons
- Different efficiency
- Different scattering
High-Voltage
Monolithic Active Pixel Sensors
Hybrid vs. monolithic detectors

Sensor 250μm

Readout chip 180μm

Connection via solder bump

Pixel electronics

Global logic and data driver

Monolithic Sensor 50μm

Pixel

Pixel electronics

On-chip interconnect

Global logic and data driver
Use commercial CMOS processes

- Charge collection from epitaxial layer
- No electrical field
- Diffusion: Slow
- Substrate does not contribute: Can be made thin: 50 μm
- PMOS transistors act as parasitic charge collection diodes: Need to be shielded: More complex manufacturing
MAPS: Monolithic Active Pixel Sensors

- Current state: ALPIDE sensor for ALICE pixel detector
- 180 nm TowerJazz imaging process
- Partial depletion (white)
- Low power (< 40 mW/cm²)
- Still slow: ~2 μs peaking time

Faster sensors: Depleted MAPS

- Fully deplete the active volume
- Either via high voltage (high voltage processes, MuPix)
  Large collection electrodes
- High resistivity substrate and modified imaging processes (afternoon)
  Small collection electrodes
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

• Use a high voltage commercial process (automotive industry)
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
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• Implement logic directly in N-well in the pixel - smart diode array
• Can be thinned down to < 50 μm

(I. Perić, P. Fischer et al., NIM A 582 (2007) 876)
**HV-MAPS Prototypes - History**

Mupix7 was the first small scale prototype integrating all relevant features of a fully monolithic chip (VCO, PLL, state machine, ...)

Slide by A. Schöning
**MuPix8 & ATLASpix1**

**MuPix8**
- pixel: 80 x 81 $\mu$m²
- 200 rows x 48 cols
- amplifier in pixel cell
- discriminators in periphery
- 6 bit ToT
- state machine
- serial link up to 1.6 Gbit/s

**ATLASpix**
- pixel: 40 x 130 $\mu$m²
- 400 rows x 25 cols
- amplifier in pixel cell
- discriminators in active pixel cell
- 6 bit ToT
- state machine
- serial link up to 1.6 Gbit/s

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Source current
Follower drivers
Continuous RO

Trigger continuous
Buffers readout

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*Slide by A. Schöning*
**Mupix8**
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Example: Mupix8 Architecture

MuPix8

Pixel
- sensor
- test-pulse injection
- integrate charge
- amplification
- line driver
- per pixel threshold adjustment
- digital output

Periphery
- baseline
- comparator 1&2
- tune DACs

State Machine
- readout state machine
- VCO & PLL
- 8b/10b encoder
- serializer

MUX
- link A
- link B
- link C
- link D

MuPix8
- active
- periphery & SM

André Schöning, Heidelberg (PI)

Vertex2019, 15. October, 2019
Mupix8 Performance Plots

efficiency
~99.9%

noise
~1Hz/pixel

80 Ω cm

100mV ~ 1300 e^-
MuPix8 Performance

- Charge sharing only at pixel edges
Mupix/ATLASpix Readout Architecture

Problem:
→ capacitive coupling between RO lines

ATLASpix (discriminator in cell)
✓ binary(discriminated) RO

MuPix (analog amplified signal)
✗ source follower (A) → cross talk
✗ current driver (B+C) → in principle ok, but design issues with Mupix8
Mupix8 Cross Talk (Source Follower)

Time over Threshold (dE/dx)

"Triplet" Probability

χ² / ndf: 2933 / 172
threshold: 72.69 ± 0.109
offset: 0.0002191 ± 1.914e-05
slope: 0.002792 ± 8.422e-06

row number is proportional to length of trace!

André Schöning, Heidelberg (PI)
Time Resolution with and w/o TWC

MuPix8

ATLASpix_simple
(NMOS comparator)

ATLASpix_simple_iso
(CMOS comparator)

[sampling 8 ns]

w/o TWC: 8.8 ns

with TWC: 6.5 ns (6.2 ns)

internal res.: 6.1 ns (5.8 ns)
(short traces)

[sampling 16 ns]

8.1 ns

5.9 ns

3.7 ns

[sampling 16 ns]

6.8 ns

5.8 ns

3.6 ns

André Schöning, Heidelberg (PI)
Substrate Resistivity Dependence ATLASpix1

significant larger depletion with higher resistivity!

André Schöning, Heidelberg (PI)
Neutron Irradiated 80 Ωcm ATLASpix1 @ 60V

- Efficiency:
  - no tuning
  - fluence-dependence

- Data Points:
  - $5 \times 10^{14}$ neq/cm² (19 pixels masked)
  - $10^{15}$ neq/cm² (38 pixels masked)
  - $2 \times 10^{16}$ neq/cm² (81 pixels masked)

- Specifications:
  - 80 Ω cm
  - d=62 μm
  - bias=60V
  - $T \sim 5^\circ$C

André Schöning, Heidelberg (PI)
Pixel Sensor Integration Highlight I

MuPix8 successfully operated on LTU flexprint!

- no decoupling capacitors
- common VDD and VDDA supply
  → low noise
  → no LVDS bit errors
Pixel Sensor Integration Highlight II

Mupix8 operated with DC/DC converters developed for Mu3e w/o decoupling capacitors (common VDD and VDDA) → milestone!

Expected for MuPix10: ~200 mW/cm²

With filtering: 20 mV Pk-Pk

MuPix8 at DESY testbeam

Efficiency Map

thr = 45 mV
VSSA=1.0V

Slide by A. Schöning
• Hits are streamed out on a 1.25 Gbit/s LVDS link

• Up to 30 MHz hits

• Tested up to 2.5 MHz - no loss of efficiency beyond single pixel dead-time (~ 1 μs)
How to get to $\sim 0.1 X_0$ per layer

50 µm silicon is not self-supporting
- Need “no-mass” mechanics
- Also: “no-mass” connection to the outside world

Chips are active: $\sim 200 \text{ mW/cm}^2$
- Need “no-mass” cooling
- Gaseous helium at very high flow speeds for Mu3e - challenging project
- Prototype tests so far successful, full mock-up under construction

- Note: The PANDA luminosity detector will operate MuPix in vacuum: Cooling via diamond wafers
Questions:

- How much sensor area is needed?
- Can we operate the sensors in a cooling gas?
- How much access do we have for services?
- FPGAs in magnet? DC/DC in magnet?
- Do the pixels have to generate an injection trigger? (short latency?)
More questions:

- How to control for up/down differences in efficiency?
- How to align the sensors without calibrating away an EDM? Track-based alignment? Optical system? What are possible weak modes?
Data Acquisition
(the Mu3e Example)
MuPix output

• 1.25 Gbit/s 8b10b encoded LVDS links
• Either three submatrices with a link each or one link multiplexing the sub-matrices
• Roughly 30 MHits/s per link maximum
• Hits are 32 bit: column, row, time, charge
• Hits are not strictly time sorted on link
Timing detectors

- Mu3e also has scintillating fibres and tiles for improved timing
- SiPMs read out via a custom ASIC, the MuTrig (KIP Heidelberg)
- Output also 1.25 GBit/s LVDS link
- Allows for very uniform DAQ
Data Acquisition

Phase I:
- 280 Million pixels (+ fibres and tiles)
- No trigger
- ~ 100 Gbit/s
- FPGA-based switching network
- 12 PCs with GPUs
Data Acquisition

Front end (Altera Arria V FPGAs):
- Receive and decode data
- Correct for time-walk
- Time sorting (most resources)
- Slow control and configuration
- Send data out via 6 Gbit/s optical link
Switching (Altera Arria 10 FPGAs):
- PCIe40 board (Marseille, LHCb and ALICE)
- Merge datastreams
- Inject pixel configuration data
- Perform monitoring tasks
Data Acquisition

PCs (Altera Arria 10 FPGAs):
- DE5a-NET board (Terasic Inc.)
- Receive data, preprocess
- DMA to GPU
- Buffering
Online reconstruction

- 280 Million pixels (+ fibres and tiles)
- No trigger
- ~ 1 Tbit/s
- Need to find and fit billions of tracks/s
Online filter farm

- PCs with Graphics Processing Units (GPUs)
- Online track and event reconstruction
- $10^9$ 3D track fits/s achieved
- Data reduction by factor $\sim 1000$
- Data to tape $< 100$ Mbyte/s
- MIDAS software (S. Ritt & Co.) for data and slow control handling
Some things we like

- LVDS links to FPGAs on detector, everything else optical (galvanic decoupling, no cross-talk, space-efficient, commercial components)
- PCIe as the interface between custom and PC logic (fast, operating system support, have our own well-debugged firmware and drivers)
- Using commercial FPGA evaluation boards wherever possible (cheap, well debugged)
- GPUs allow for handling very large reconstruction loads on a budget
Final Questions

• Momentum resolution/redundancy trade-off?

• Can we cool sensors in the active volume? (how much? vacuum or gas?)

• What is limiting the result? Momentum? Timing? Efficiency? What does this mean for the sensor?

• What are the challenges for the DAQ?

• Are there ideas on how to go beyond single muons at a time?