The trigger-less TBit/s readout for the Mu3e experiment

Dirk Wiedner
On behalf of the Mu3e collaboration
The Mu3e Signal

• $\mu \rightarrow eee$ rare in SM
• Enhanced in:
  o Super-symmetry
  o Grand unified models
  o Left-right symmetric models
  o Extended Higgs sector
  o Large extra dimensions

- Rare decay (BR<10^{-12}, SINDRUM)
- For BR $O(10^{-16})$
  - $>10^{16}$ muon decays
  - High decay rates
    $O(10^9$ muon/s)
The Mu3e Experiment

- Muon beam $O(10^9/s)$
- Helium atmosphere
- 1 T B-field

- Target double hollow cone
- Silicon pixel tracker
- Scintillating fiber tracker
- Recurl station
- Tile hodoscope
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Readout Requirements

- 2.5 GHz muon decays
- 50 ns readout frames (pixel)
- $O(5000)$ pixel chips
- $O(7000)$ scintillating fibers
- $O(7000)$ timing tiles
- Online filtering
Timing Detectors

- Scintillating fiber hodoscope
- Timing tiles
- On detector zero-suppression

Poster Session:
- STiC - A Mixed Mode Silicon-Photomultiplier Readout ASIC for Time-of-Flight Applications (Tobias Harion)

O(7000) fibers
O(7000) tiles
Silicon Pixel Detector

- Inner double layer
- Outer double layer
- Re-curl layers
  - Both sides (x2)
- Sensor size
  - 1x2 cm$^2$ inner layers
  - 2x2 cm$^2$ outer layers

180 inner sensors
4680 outer sensors
HV-MAPS

- **High Voltage Monolithic Active Pixel Sensors**
- HV-CMOS technology
- Reversely biased ~60V
  - Charge collection via drift
    - Fast O(100 ns)
  - Thinning to < 50 μm possible

by Ivan Peric

I. Peric, A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology
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  o Zero suppression
  o 800Mbit/s serial LVDS outputs

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Pixel Readout Scheme
**Pixel Readout Scheme**

- **Pixel logic**
  - Pixel address (8 bit)
  - Frame number (4 bit)
  - 50 ns frames

- **Column logic**
  - Pixel data
  - Column address
  - Coarse time

- **Frame logic**
  - Super Frame
  - Contains 16 x 50 ns readout frames
  - + Sensor header

- **Readout buffer**
- **Serializer and fast link(s)**

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● Dirk Wiedner TWEPP2013
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```
Pixel address

Pixel Logic

Column Logic

Frame logic
Readout buffer
Serializer

4 x serial @ 800 Mb/s
```
Data Link Scheme

From detector slices to time slices
Link Overview

- Front end links
  - Pixel sensor to on-detector FPGA
    - 400 – 800 Mbit/s
    - LVDS
  - Timing detector readout
- Optical links from detector
  - Front end FPGAs
  - ... to readout boards
  - 5 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - ...to PC Farm
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O(8Tbit/s)
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  - Off-detector read out boards
  - ... to PC Farm

\[O(4Tbit/s)\]
Front End FPGAs

- FPGAs on detector
  - 86 (+96) pieces
- Receive sensor data
  - 108 LVDS inputs
- 5 Gbit/s outputs
  - 8 optical links
  - ... to counting house
- Switching data between readout boards farms A-D
Front End FPGAs

- FPGAs on detector
  - 86 (+96) pieces

- Receive sensor data
  - 108 LVDS inputs

- 5 Gbit/s outputs
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Diagram:

- Pixel Sensor
  - 800 Mbit/s LVDS in
    x 108
- Front end FPGA
  - 5 Gbit/s optical
- Readout board A
- Readout board B
- Readout board C
- Readout board D
• FPGA readout boards
  o 4 per sub-detector
• 5 Gbit/s optical inputs
  o 16-28 inputs
• 10 Gbit/s optical output
  o 12 outputs to PCs
• Switching network
  o A-D sub-farms
  o One output per PC
Readout Board

- FPGA readout boards
  - 4 per sub-detector
- 5 Gbit/s optical inputs
  - 16-28 inputs
- 10 Gbit/s optical output
  - 12 outputs to PCs
- Switching network
  - A-D sub-farms
  - One output per PC
GPU-PC

- PC with GPU
- 10 Gbit/s Fiber input
  - 8 inputs from sub-detectors
- Data filtering
  - Timing Filter on FPGA
  - Track filter on GPU
  - Data to tape < 100 MB/s
GPU-PC

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Timming Filter

- Entire event on PCIe FPGA
- Tile and Fiber data
  - Easy to match
  - Look for three tracks
- Reject data without three hits
  - ... inside time interval
Timing Filter

• Entire event on PCIe FPGA
• Tile and Fiber data
  o Easy to match
  o Look for three tracks
• Reject data without three hits
  o ... inside time interval
Vertex Filter

- Entire event on GPU
- Large target
  - Large spread of muons
  - Easy vertex separation
- Reject data without three tracks
  - ... inside area interval on target
Vertex Filter

- Entire event on GPU
- Large target
  - Large spread of muons
  - Easy vertex separation
- Reject data without three tracks
  - ... inside area interval on target
Summary

- Mu3e has 280M pixels @ >10⁹ muons/s
- >1 Tbit/s data
- 0-suppressed serial data from active pixel sensors
- Switched optical network
- GPU filter farm with optical inputs
Physics Motivation

Lepton flavor violation?

Standard model:
• No lepton flavor violation
Physics Motivation

Lepton flavor violation: $\mu^+ \rightarrow e^+ e^- e^+$

Standard model:
- No lepton flavor violation, but:
  - Neutrino mixing
  - Branching ratio $<10^{-50} \rightarrow$ unobservable
The Mu3e Signal

- $\mu \rightarrow eee$ rare in SM
- Enhanced in:
  - Super-symmetry
  - Grand unified models
  - Left-right symmetric models
  - Extended Higgs sector
  - Large extra dimensions
The Mu3e Background

• Combinatorial background
  o $\mu^+ \rightarrow e^+\nu\nu$ & $\mu^+ \rightarrow e^+\nu\nu$ & $e^+e^-$
  o many possible combinations

➢ Good time and
➢ Good vertex resolution required
The Mu3e Background

- $\mu^+ \rightarrow e^+ e^- e^+ \nu\nu$
  - Missing energy ($\nu$)
  - Good momentum resolution

Pixel Sensor Links

• Vertex Sensor chips
  o 180 chips
  o 4 LVDS links
  o 800 Mbit/s per link

• Central Silicon Tracker
  o 936 chips
  o 2 LVDS links
  o 800 Mbit/s

• Recurl stations
  o 3744 chips
  o 1 LVDS link
  o 400 Mbit/s
Pixel Sensor Links

- **Vertex Sensor chips**
  - 180 chips
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Optical transceiver FE board
Average Occupancies

- All numbers per frame of 50 ns
- Vertex detector
  - 2 hits per sensor
- Central silicon tracker
  - 0.6 hits per sensor
- Recurl stations
  - 0.13 hit per sensor
- Fiber hodoscope
  - 0.16 hits per fiber
- Timing tiles
  - 0.09 hits per tile
Maximum Occupancies

- All numbers per frame of 50 ns
- Vertex detector
  - 5 hits per sensor
- Central silicon tracker
  - 2 hits per sensor
- Recurl stations
  - 1 hit per sensor
- Fiber hodoscope
  - 0.24 hits per fiber
- Timing tiles
  - 0.14 hits per tile