The Ultra Lightweight Support Structure and Gaseous Helium Cooling for the Mu3e Silicon Pixel Tracker

Dirk Wiedner on behalf of Mu3e
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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 ($\text{BR}<10^{-12}$, SINDRUM)
- For BR $\mathcal{O}(10^{-16})$
  - $>10^{16}$ muon decays
  - High decay rates $\mathcal{O}(10^9 \text{ muon/s})$
The Mu3e Background

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

- Good time and
- Good vertex resolution required
Combinatorics
The Mu3e Background

- $\mu^+ \rightarrow e^+ e^- e^+ \nu

  - Missing energy ($\nu$)
  - Good momentum resolution

Challenges

- High rates
- Good timing resolution
- Good vertex resolution
- Excellent momentum resolution
- Extremely low material budget
Challenges

• High rates: $10^9 \mu s$
• Good timing resolution: 100 ps
• Good vertex resolution: $\sim 100 \mu m$
• Excellent momentum resolution: $\sim 0.5 \text{ MeV}/c^2$

➢ Extremely low material budget:
  ➢ $1 \times 10^{-3} X_0$ (Si-Tracker Layer)
  ➢ HV-MAPS spectrometer
    ➢ 50 $\mu m$ thin sensors
    ➢ $B \sim 1 \text{ T}$ field
  ➢ + Timing detectors
Phased Experiment

- Target double hollow cone
- Silicon pixel tracker
- Scintillating fiber tracker
- Recurl station
- Tile detector

• Muon beam $O(10^7/s)$
• Helium atmosphere
• 1 T B-field

Phase Ia
• Muon beam $O(10^8/s)$
• Helium atmosphere
• 1 T B-field

• Target double hollow cone
• Silicon pixel tracker
• Scintillating fiber tracker
• Recurl station
• Tile detector
Phased Experiment

- Target double hollow cone
- Silicon pixel tracker
- Scintillating fiber tracker
- Recurl station x 2
- Tile detector x 2
- Muon beam $O(10^9/s)$
- Helium atmosphere
- 1 T B-field
- Target double hollow cone
- Silicon pixel tracker
- Scintillating fiber tracker
- Recurl station x 2
- Tile detector x 2

Ca. 2 m total length
Ultra Light Support Structure for the Pixel Tracker
Sandwich Design

• HV-MAPS
  o Thinned to 50 μm
  o Sensors 1 x 2 cm² or 2 x 2 cm²

• Kapton™ flex print
  o 25 μm Kapton™
  o 12.5 μm Alu traces

• Kapton™ Frame Modules
  o 25 μm foil
  o Self supporting

• Alu end wheels
  o Support for all detectors

<0.1% of X₀
Thinned Pixel Sensors

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  o Sensors 1 x 2 cm² or 2 x 2 cm²
• Kapton™ flex print
  o 25 μm Kapton™
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*Previous talk: Tobias Weber
“High Voltage Monolithic Active Pixel Sensors for the PANDA Luminosity Detector”
Kapton™ Flex Print

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Laser-cut flex print prototype
Pixel Modules

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CAD of Kapton™ frames
Overall Design

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• Two halves for layers 1+2
• 6 modules in layer 3
• 7 modules in layer 4

CAD of Kapton™ frames
Inner Layers

• **HV-MAPS**
  - Thinned to 50 μm
  - Sensors 1 x 2 cm² or 2 x 2 cm²

• **Kapton™ flex print**
  - 25 μm Kapton™
  - 12.5 μm Alu traces

• **Kapton™ Frame Modules**
  - 25 μm foil
  - **Self supporting**

• **Alu end wheels**
  - Support for all detectors

Vertex Prototype with 100 μm Glass
Outer Module

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Layer 3 Prototype in Assembling Frame with 50 μm Glass
Detector Frame

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Layer 3 Prototype in Assembling Frame with 50 μm Glass
Cooling
Cooling Concept

- Liquid cooling
  - For readout-electronics
- Gaseous He cooling
  - For Silicon tracker
Liquid Cooling

- Beam pipe cooling
  - With cooling liquid
  - 5°C temperature
  - Significant flow possible
  - ... using grooves in pipe
- For electronics
  - FPGAs and
  - Power regulators
  - Mounted to cooling plates
- Total power several kW
He Cooling

• Gaseous He cooling
  o Low multiple Coulomb scattering
  o He more effective than air

• Global flow inside Magnet volume

• Local flow for Tracker
  o Distribution to Frame
    • V-shapes
    • Outer surface

\[ 150 \text{mW/cm}^2 \times 19080 \text{cm}^2 = 2.86 \text{KW} \]
He Cooling

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- Global flow inside Magnet volume
- Local flow for Tracker
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Temperatures between 20°C to 70°C ok.
He Cooling

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Comparison Simulation He and Air

\[ v = 4.0 \text{ m/s} \]
Tests

- **Full scale prototype**
  - Layer 3+4 of silicon tracker
  - Ohmic heating (150mW/cm$^2$)
  - 561.6 W for layer 3 +4
  - ... of Aluminum-Kapton™
- **Cooling with external fan**
  - **Air** at several m/s
- Temperature sensors attached to foil
  - LabView readout
- First results promising
  - $\Delta T < 60^\circ K$

○ Dirk Wiedner INSTR14

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  - Air at several m/s
- Temperature sensors attached to foil
  - LabView readout
- First results promising
  - $\Delta T < 60^\circ$K
  - No sign of vibration in air
Comparison Simulation and Tests

Air Flow $T_{in} = 20 \, ^\circ C$  
4th Layer TOP
- Simulation Air
- Simulation Helium
- Measurement

$\Delta T_{\text{max}} \, [^\circ C]$ vs $v \, [\text{m/s}]$
Simulation with V-shape cooling

• Configuration:
  - Main helium flux: \( v = 0.5 \text{ m/s} \)
  - Flux in Nozzle: \( v = 5 \text{ m/s} \)
    - In V-shape against main flux
    - Next to V-shape against main flux
      - 31.42 mL/s per nozzle
      - 6.786 L/s for 3. Layer

• Results:
  - \( T_{\text{max}} \approx 42^\circ\text{C} \)
  - \( T_{\text{max}} \) close to end of tube
  - \( T \) raises at last third of tube

→ Extra Improvement using V-shapes as cooling channels
Simulation with V-shape cooling

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Summary

• Mechanics
  o Ultralight Sandwich Structure <0.1%\(X_0\)
  o Self Supporting
  o Assembly tests have started

• Cooling
  o Liquid cooling of beam pipe
  o Gaseous He cooling of Tracker
  o Ongoing studies encouraging
Backup slides
He Properties

- Molecular weight: 4.0026 g/mol
- Gaseous phase
- Gas density (1.013 bar at boiling point): 16.752 kg/m³
- Gas density (1.013 bar and 15 °C (59 °F)): 0.1692 kg/m³
- Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)): 1.0005
- Specific gravity: 0.138
- Specific volume (1.013 bar and 25 °C (77 °F)): 6.1166 m³/kg
- Heat capacity at constant pressure (Cp) (1.013 bar and 25 °C (77 °F)): 0.0208 kJ/(mol.K)
- Heat capacity at constant volume (Cv) (1.013 bar and 25 °C (77 °F)): 0.0125 kJ/(mol.K)
- Ratio of specific heats (Gamma:Cp/Cv) (1.013 bar and 25 °C (77 °F)): 1.6665
- Viscosity (1.013 bar and 0 °C (32 °F)): 1.8695E-04 Poise
- Thermal conductivity (1.013 bar and 0 °C (32 °F)): 146.2 mW/(m.K)
Air Properties

- Molecular weight: 28.96 g/mol
- Gaseous phase
- Gas density (1.013 bar at boiling point): 3.2 kg/m³
- Gas density (1.013 bar and 15 °C (59 °F)): 1.225 kg/m³
- Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)): 0.9996
- Specific gravity: 1
- Specific volume (1.013 bar and 25 °C (77 °F)): 0.8448 m³/kg
- Heat capacity at constant pressure (Cp) (1.013 bar and 25 °C (77 °F)): 0.0291 kJ/(mol.K)
- Heat capacity at constant volume (Cv) (1.013 bar and 25 °C (77 °F)): 0.0208 kJ/(mol.K)
- Ratio of specific heats (Gamma:Cp/Cv) (1.013 bar and 25 °C (77 °F)): 1.4018
- Viscosity (1 bar and 0 °C (32 °F)): 1.721E-04 Poise
- Thermal conductivity (1.013 bar and 0 °C (32 °F)): 24.36 mW/(m.K)
Radiation Length

- Radiation length per layer
  - 2x 25 μm Kapton
    - $X_0 = 1.75 \cdot 10^{-4}$
  - 15 μm aluminum traces
    - (50% coverage)
    - $X_0 = 8.42 \cdot 10^{-5}$
    - 50 μm Si MAPS
      - $X_0 = 5.34 \cdot 10^{-4}$
    - 10 μm adhesive
      - $X_0 = 2.86 \cdot 10^{-5}$
- Sum: $8.22 \cdot 10^{-4}$ (x4 layers)
  - For $\Theta_{\text{min}} = 22.9^\circ$
    - $X_0 = 21.1 \cdot 10^{-4}$
Thinning

- 50 μm Si-wafers
  - Commercially available
  - HV-CMOS 75 μm (AMS)
- Single die thinning
  - For chip sensitivity studies
  - < 50 μm desirable
  - 90 μm achieved and tested
  - In house grinding?
Thinned Sensors

• Single dies thinned:
  o MuPix2 thinned to < 80μm
  o MuPix3 thinned to < 90μm

• Good performance of thin chips
  o In lab
  o In particle beam

• Similar Time over Threshold (ToT)
  o PSI test-beam
  o PiM1 beam-line
  o 193 MeV π⁺
Combinatorics using Timing System
Muon Stopping Target

- Requirements:
  - Sufficient material in beam direction to stop 29 MeV/c surface muons
  - Thin for decay electrons in detector acceptance

- Baseline solution:
  - Hollow double cone
  - Aluminum
  - Thickness: 30 μm (us cone), 80 μm (ds cone)

- Manufacturing (brainstorming):
  - Rolled up Al-foil
  - Additive manufacturing / 3D printing
  - Casting (D: Giessen)
  - Impact extrusion (D: Fliesspressen) → first trial
Target Prototyping

- Components of mold
  - Casting mold
  - Spike
  - Additional spacer

- Achievable properties:
  - Density ~1.8 g/cm³
  - Minimal wall thickness ~50 μm

- Next steps:
  - New mold
    - (first one "deformed" due to frequent pressure cycles)
  - Proof listed properties by manufacturing of cone
Target Prototyping

- Components of mold
  - Casting mold
  - Spike
  - Additional spacer

- Achievable properties:
  - Density $\sim 1.8 \text{ g/cm}^3$
  - Minimal wall thickness $\sim 50 \mu\text{m}$

- Next steps:
  - New mold
    - (first one „deformed“ due to frequent pressure cycles)
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  o Proof listed properties by manufacturing of cone
Fiber Tracker

- Fiber ribbon modules
  - 16 mm wide
  - 360 mm long
  - 3 layers fibers of 250 μm dia.
  - 3 STiC readout chips
- Total fiber Tracker:
  - 24 ribbon-modules
  - 72 read-out chips
  - 4536 fibers
- Prototype ribbons built:
  - 3 layers
  - 16 mm wide
  - 360 mm long
- CAD in progress

See:
- Fibres
- Alessandro Bravar
  (Geneva University)
Tile Detector

- Scintillating tiles
  - 8.5 x 7.5 x 5 mm³
- 12 Tile Modules per station
  - 192 tiles/module
  - Attached to end rings
- SiPMs attached to tiles
  - Front end PCBs below
  - Readout through STiC

See:
Tiles
Patrick Eckert
(KIP Uni Heidelberg)

Sketch of Tile detector station
Tile Detector

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See: Tiles
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CAD of Tile Detector integration
Beam Pipe

- Stainless steel pipe
  - Shields against background
- Mechanical support
  - Detectors attached to beam pipe
  - Via end rings
- Read-out PCBs attached
  - FPGAs mounted directly
  - Integrated cooling

Beam pipe design
Beam Pipe

• Stainless steel pipe
  o Shields against background

• Mechanical support
  o Detectors attached to beam pipe
  o Via end rings

• Read-out PCBs attached
  o FPGAs mounted directly
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- Stainless steel pipe
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PCBs mounted on beam pipe
Overall Assembly

• CAD of:
  o Silicon Tracker +
  o Tile detector +
  o Target +
  o PCBs +
  o Beam pipe +
  o Cooling

• To be added:
  o Scintillating fiber detector
  o Cabling
  o Cage and rails in Magnet

CAD of Phase I detector
Tile Detector

- Scintillating tiles
  - 8.5 x 7.5 x 5 mm³
- 12 Tile Modules per station
  - 192 tiles/module
  - Attached to end rings
- SiPMs attached to tiles
  - Front end PCBs below
  - Readout through STiC

See: Tiles
Patrick Eckert
(KIP Uni Heidelberg)

Tile detector 4 x 4 prototype
Magnet
Magnet Specification

- 0.8 – 2 T field
- 1 m warm bore
- 2 m homogenous in z
- 2.5 m coil + shielding
- Compensation coils
- $10^{-3}$ homogeneity
- $10^{-4}$ stability

D0 magnet similar
Magnet Specification

- 0.8 – 2 T field
- 1 m warm bore
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Magnet Dimensions
Magnet Specification

- 0.8 – 2 T field
- 1 m warm bore
- 2 m homogenous in z
- 2.5 m coil + shielding
- Compensation coils
- $10^{-3}$ homogeneity
- $10^{-4}$ stability

Compensation coil effect
2 m plus Compensation Coils vs 3 m Coil

2 m plus compensation coils

z field

Radial field

3 m

z field

Radial field
Momentum Resolution

2 m coil

3 m coil

RMS: 1.14 MeV
\[ \sigma_1: 0.38 \text{ MeV} \]
\[ \sigma_2: 1.31 \text{ MeV} \]
\[ \sigma_{av}: 0.53 \text{ MeV} \]

RMS: 0.99 MeV
\[ \sigma_1: 0.25 \text{ MeV} \]
\[ \sigma_2: 1.10 \text{ MeV} \]
\[ \sigma_{av}: 0.31 \text{ MeV} \]
Efficiency

Compensation

Efficiency vs. length Magnet
Space Restrictions

- Phase I:
  - Beam line at πE5
  - Surface muons from target E
  - Up to a $10^8 \mu/s$
- Space shared with MEG experiment
Mu3e Compact Beam Line

Quadrupole Triplet
Separator
Dipole Magnets
Mu3e Spectrometer Solenoid

MEG 2 working site
Space Restrictions

- Phase I:
  - Beam line at πE5
  - Surface muons from target E
  - Up to $10^8 \mu/s$
- Space shared with MEG experiment
- Maximum magnet size:
  - 3.1 m long
  - 2 m diameter
- Air-cushions underneath
- Limited roof height 3.5 m
Outlook

• Mechanics
  o Functional tests of prototypes
  o Integration of prototypes in global design

• Cooling
  o Test local cooling with module prototypes
  o He tests

• Magnet
  o DFG application