

The Ultra Lightweight Support Structure and Gaseous Helium Cooling for the Mu3e Silicon Pixel Tracker Dirk Wiedner on behalf of Mu3e February 2014



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





- ➢ Rare decay (BR<10⁻¹², SINDRUM)
- For BR O(10⁻¹⁶)
 - > >10¹⁶ muon decays
 - ➢ High decay rates O(10⁹ muon/s)

The Mu3e Background

Combinatorial background

 µ⁺→e⁺vv & µ⁺→e⁺vv & e⁺e⁻
 o many possible combinations

- Good time and
- Good vertex resolution required





Combinatorics



The Mu3e Background

μ⁺→e⁺e⁻e⁺∨∨

Missing energy (v)

Good momentum resolution





(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)



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: ~100 μm
- Excellent momentum resolution: ~ 0.5 MeV/ c^2
- Extremely low material budget:
 - 1x10⁻³ X₀ (Si-Tracker Layer)
- HV-MAPS spectrometer
 - \succ 50 µm thin sensors
 - ➤ B ~1 T field
- + Timing detectors











- 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



Ultra Light Support Structure for the Pixel Tracker

• • •

25.02.2014 • 11

Met

Sandwich Design

• HV-MAPS

Thinned to 50 µm
Sensors 1 x 2 cm² or 2 x 2 cm²

- Kapton[™] flex print
 25 µm Kapton[™]
 - o 12.5 µm Alu traces

Kapton[™] Frame Modules

- o 25 µm foil
- Self supporting
- Alu end wheels

 Support for all detectors

<0.1% of X₀

Thinned Pixel Sensors

HV-MAPS*

- $_{\odot}$ Thinned to 50 μm
- \circ 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
 - Self supporting
- Alu end wheels

 Support for all detectors

*Previous talk: Tobias Weber

"High Voltage Monolithic Active Pixel Sensors for the PANDA Luminosity Detector"



MuPix3 thinned to < 90μ m

Dirk Wiedner INSTR14



KaptonTM Flex Print

• HV-MAPS

ο Thinned to 50 μm

 \circ 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
- Self supporting
- Alu end wheels

 Support for all detectors



Laser-cut flex print prototype



Pixel Modules

• HV-MAPS

- \circ Thinned to 50 μ m
- \circ 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

- \circ 25 µm foil
- Self supporting
- Alu end wheels

 Support for all detectors



CAD of KaptonTM frames

25.02.2014 • 15



Overall Design

• HV-MAPS

ο Thinned to 50 μm

 \circ 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
- Self supporting
- Alu end wheels
 - Support for all detectors

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



CAD of KaptonTM frames



Inner Layers

• HV-MAPS

- \circ Thinned to 50 μ m
- \circ 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
- Self supporting
- Alu end wheels

 Support for all detectors



Vertex Prototype with 100 µm Glass



Outer Module

HV-MAPS

- \circ Thinned to 50 μ m
- \circ 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
- Self supporting
- Alu end wheels

 Support for all detectors



Layer 3 Prototype in Assembling Frame with 50 µm Glass



Detector Frame

• HV-MAPS

- \circ Thinned to 50 μ m
- \circ 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
- Self supporting
- Alu end wheels
 - Support for all detectors



Layer 3 Prototype in Assembling Frame with 50 µm Glass



Cooling

25.02.2014 • 20



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





- Gaseous He cooling
 - Low multiple Coulomb scattering
 - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker
 Distribution to Frame
 - V-shapes
 - Outer surface



150mW/cm² x 19080cm² = 2.86 KW



- Gaseous He cooling
 - Low multiple Coulomb scattering
 - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker
 Distribution to Frame
 - V-shapes
 - Outer surface



Temperatures between 20°C to 70°C ok.



- Gaseous He cooling
 - Low multiple Coulomb scattering
 - He more effective than air
- Global flow inside Magnet volume

Local flow for Tracker

- Distribution to Frame
 - V-shapes
 - Outer surface





- Gaseous He cooling
 - Low multiple Coulomb scattering
 - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker
 - Distribution to Frame
 - V-shapes
 - Outer surface







- Gaseous He cooling
 - Low multiple Coulomb scattering
 - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker
 Distribution to Frame
 - V-shapes
 - Outer surface





- Gaseous He cooling
 - Low multiple Coulomb scattering
 - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker

 Distribution to Frame
 - V-shapes
 - Outer surface



Comparison Simulation He and Air He Air





$v = 4.0 \ m/_{s}$





Full scale prototype

- Layer 3+4 of silicon tracker
- Ohmic heating (150mW/cm²)
- o 561.6 W for layer 3 +4
- o ... of Aluminum-Kapton™
- Cooling with external fan

 Air at several m/s
- Temperature sensors attached to foil

 LabView readout
- First results promising

 ΔT < 60°K









- Full scale prototype
 - Layer 3+4 of silicon tracker
 - Ohmic heating (150mW/cm²)
 - o 561.6 W for layer 3 +4
 - o ... of Aluminum-Kapton™
- Cooling with external fan

 Air at several m/s
- Temperature sensors attached to foil

 LabView readout
- First results promising $\circ \Delta T < 60^{\circ} K$





Test Results

• Full scale prototype

- Layer 3+4 of silicon tracker
- Ohmic heating (150mW/cm²)
- o 561.6 W for layer 3 +4
 o ... of Aluminum-Kapton[™]
- Cooling with external fan

 Air at several m/s
- Temperature sensors attached to foil

 LabView readout

First results promising

- ΔT < 60°K</p>
- No sign of vibration in air



Comparison K Simulation and Tests



Simulation with V-shape cooling



→ Extra Improvement using V-shapes as cooling channels

• Dirk Wiedner INSTR14

Cooling outlets

25.02.2014 • 35

/-shape

Simulation with V-shape cooling



→ Extra Improvement using V-shapes as cooling channels



25.02.2014 • 36

Dirk Wiedner INSTR14



Summary

- Mechanics
 - \circ Ultralight Sandwich Structure < 0.1%X₀
 - Self Supporting
 - Assembly tests have started
- Cooling
 - Liquid cooling of beam pipe
 - Gaseous He cooling of Tracker
 - Ongoing studies encouraging





Backup slides

25.02.2014 • 38



He Properties

•	Molecular weight:	4.0026 g/mol	
•	Gaseous phase		
•	Gas density (1.013 bar at boiling point) :	16.752 kg/m ³	
•	Gas density (1.013 bar and 15 °C (59 °F)) :	0.1692 kg/m ³	
•	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 m ³ /kg	
•	Heat capacity at constant pressure (Cp) (1.013 bar an	d 25 °C (77 °F)) : 0.0208 kJ/(mol.K))
•	Heat capacity at constant volume (Cv) (1.013 bar and	1 25 °C (77 °F)) : 0.0125 kJ/(mol.K))
•	Ratio of specific heats (Gamma:Cp/Cv) (1.013 bar and	d 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)	
	Dirk Wiedner INSTR14	25.02.2014	• 39



40

Air Properties

•	Molecular weight :	28.96 g/mol
•	Gaseous phase	
•	Gas density (1.013 bar at boiling point) :	3.2 kg/m ³
•	Gas density (1.013 bar and 15 °C (59 °F)) :	1.225 kg/m ³
•	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 m ³ /kg
•	Heat capacity at constant pressure (Cp) (1.013 bar ar	nd 25 °C (77 °F)) : 0.0291 kJ/(mol.K)
•	Heat capacity at constant volume (Cv) (1.013 bar and	d 25 °C (77 °F)) : 0.0208 kJ/(mol.K)
•	Ratio of specific heats (Gamma:Cp/Cv) (1.013 bar an	d 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)
	Dirk Wiedner INSTR14	25.02.2014



Radiation Length

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





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
 - o In house grinding?





Thinned Sensors

- Single dies thinned:

 MuPix2 thinned to < 80µm
 MuPix3 thinned to < 90µm
- Good performance of thin chips
 - o In lab
 - In particle beam
- Similar Time over Threshold (ToT)
 - PSI test-beam
 - PiM1 beam-line
 - 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) \rightarrow first trial
 - Impact extrusion (D: Fliesspressen)

• Dirk Wiedner INSTR14



Target Prototyping

- Components of mold
 - Casting mold
 - o 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
 - o 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
 - o 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











Fiber Tracker

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





Scintillating fiber ribbons

See: Fibres Alessandro Bravar (Geneva University)

 wasanga y		
 Lodge de	- marker of the	
	1 m	
 	attaining theme	
	1 January	



Tile Detector

- Scintillating tiles

 8.5 x 7.5 x 5 mm³
- 12 Tile Modules per station
 - o 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

asses /	
Lodar de	- market
	/ Income



Tile Detector

- Scintillating tiles

 8.5 x 7.5 x 5 mm³
- 12 Tile Modules per station
 - o 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)

CAD of Tile Detector integration

25.02.2014 • 51





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

- 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 supports detectors





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



PCBs mounted on beam pipe

inter the second	and the second s
	 toritor for two stringer
	atter tage
- Consideration	 Internet Laboration internet internet



Overall Assembly

- CAD of:
 - Silicon Tracker +
 - Tile detector +
 - o Target +
 - o PCBs +
 - Beam pipe +
 - o Cooling
- To be added:
 - Scintillating fiber detector
 - o Cabling
 - Cage and rails in Magnet



CAD of Phase I detector

		~	
Lodge de	and the second se		
	Auge -		
	and a second second		
	S. / Concentration		



Tile Detector

- Scintillating tiles

 8.5 x 7.5 x 5 mm³
- 12 Tile Modules per station
 - o 192 tiles/moduleo 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

25.02.2014 • 57



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
- 2 m homogenous in z
- 2.5 m coil + shielding
- Compensation coils
- 10⁻³ homogeneity
- 10⁻⁴ stability



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 3 m

2 m plus compensation coils

z field









Radial field



Momentum Resolution 2 m coil 3 m coil









Space Restrictions

- Phase I:
 - \circ Beam line at π E5
 - Surface muons from target E
 - $_{\odot}$ Up to a 10⁸ μ/s
- Space shared with MEG experiment







Space Restrictions

- Phase I:
 - \circ Beam line at π E5
 - Surface muons from target E
 - \circ Up to 10⁸ µ/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
 - Functional tests of prototypes
 - Integration of prototypes in global design
- Cooling
 - Test local cooling with module prototypes
 - o He tests
- Magnet
 - DFG application

