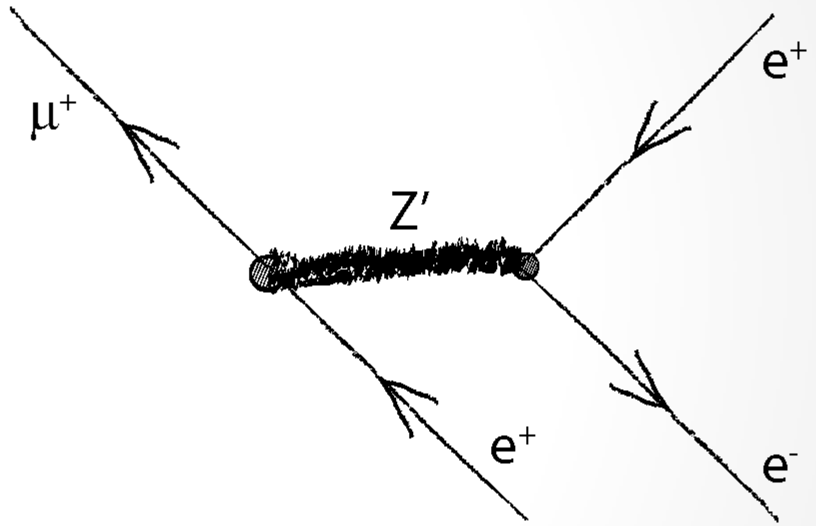
The Ultra Lightweight Support Structure and Gaseous Helium Cooling for the Mu3e Silicon Pixel Tracker

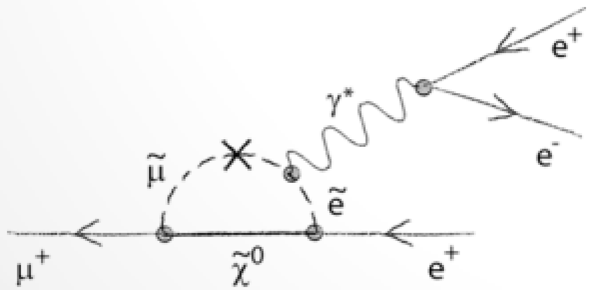
Dirk Wiedner on behalf of Mu3e

February 2014

The Mu3e Signal

- μ→eee rare in SM
- Enhanced in:
  - Super-symmetry
  - Grand unified models
  - Left-right symmetric models
  - Extended Higgs sector
  - Large extra dimensions

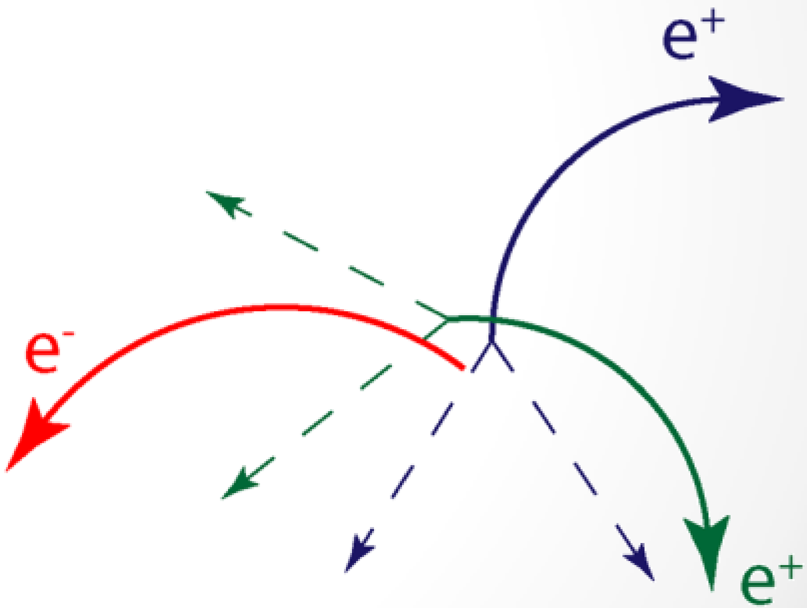




- Rare decay (BR<10^{-12}, SINDRUM)
- For BR O(10^{-16})
  - >10^{16} muon decays
  - High decay rates O(10^{9} muon/s)

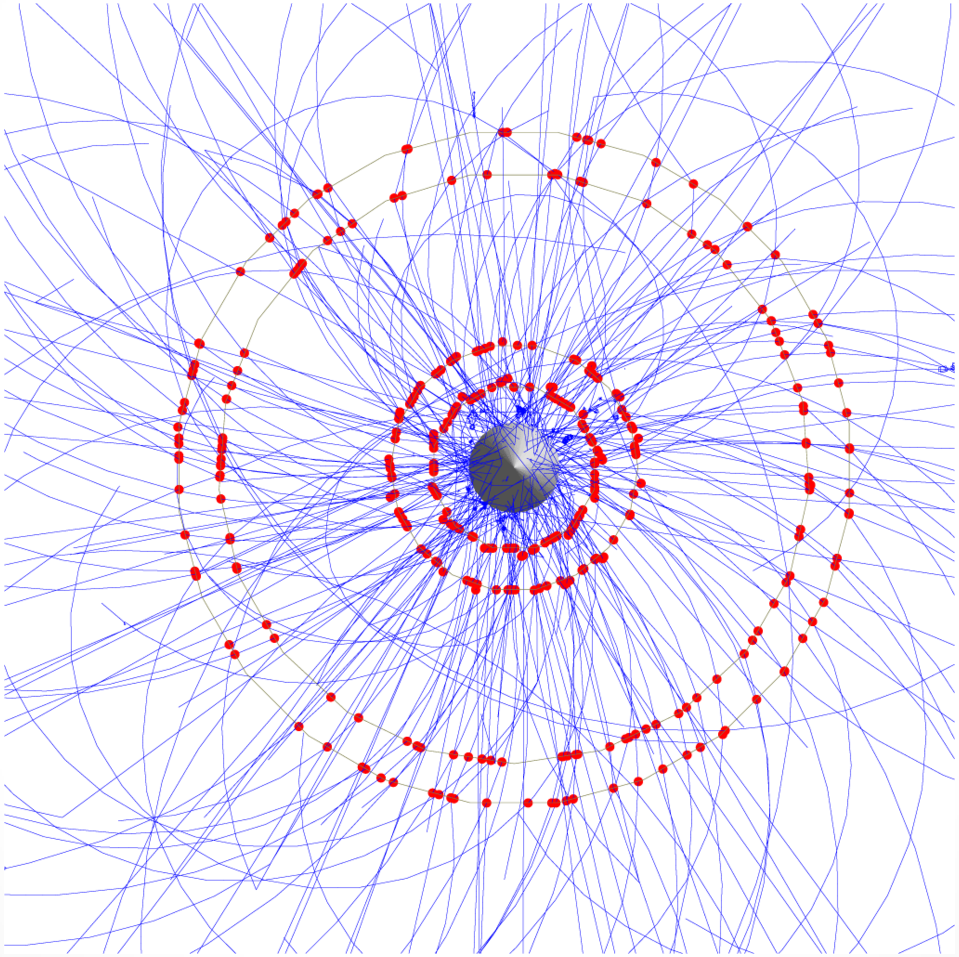
The Mu3e Background

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



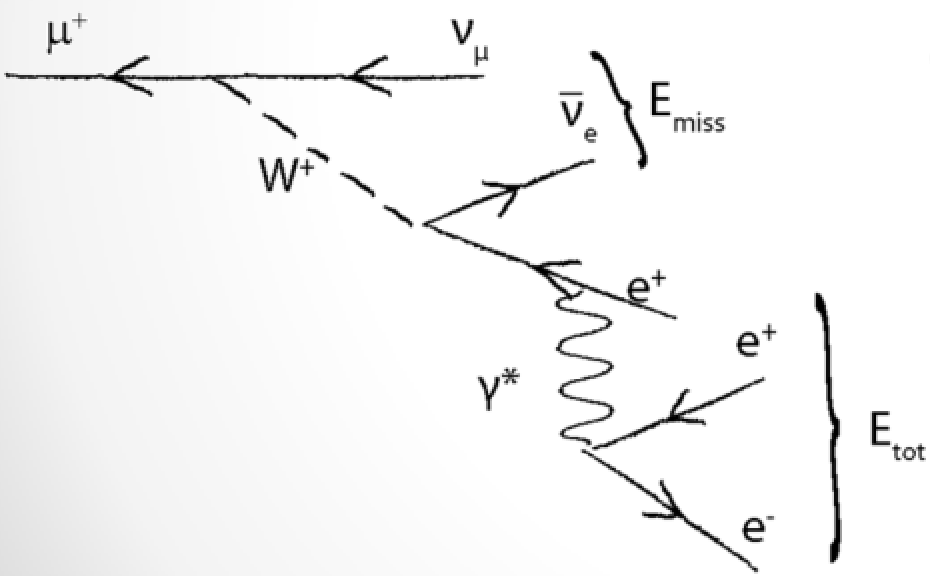
- Good time and
- Good vertex resolution required

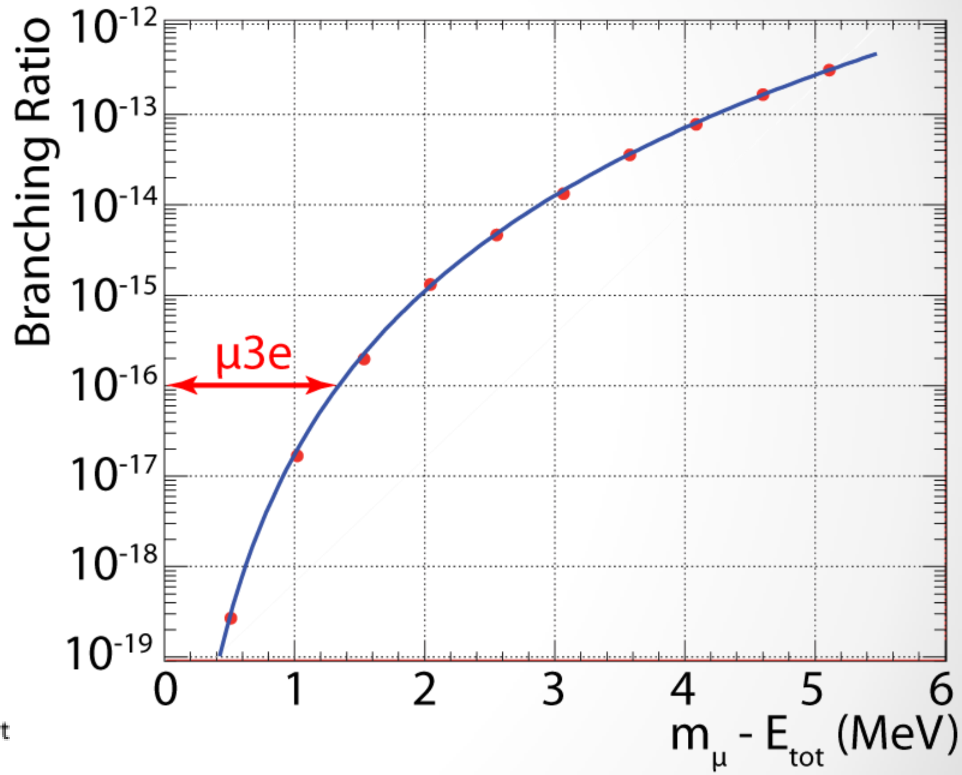
Combinatorics



The Mu3e Background

- $\mu^+ \rightarrow e^+ e^- e^+ \nu\nu$
  - Missing energy (ν)
  - ➢ 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

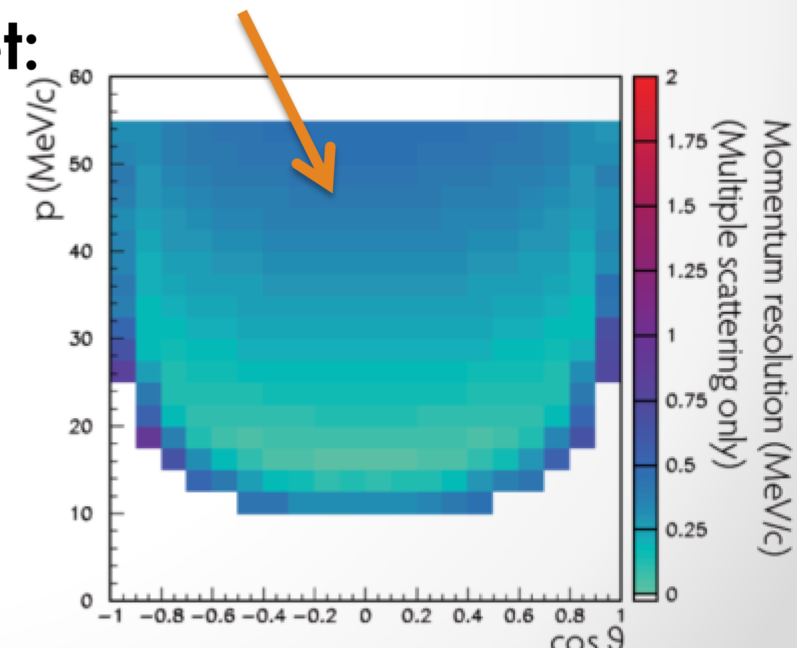
Challenges

- High rates: 10^9 μ/s
- Good timing resolution: 100 ps
- Good vertex resolution: ~100 μm
- Excellent momentum resolution: ~ 0.5 MeV/c^2

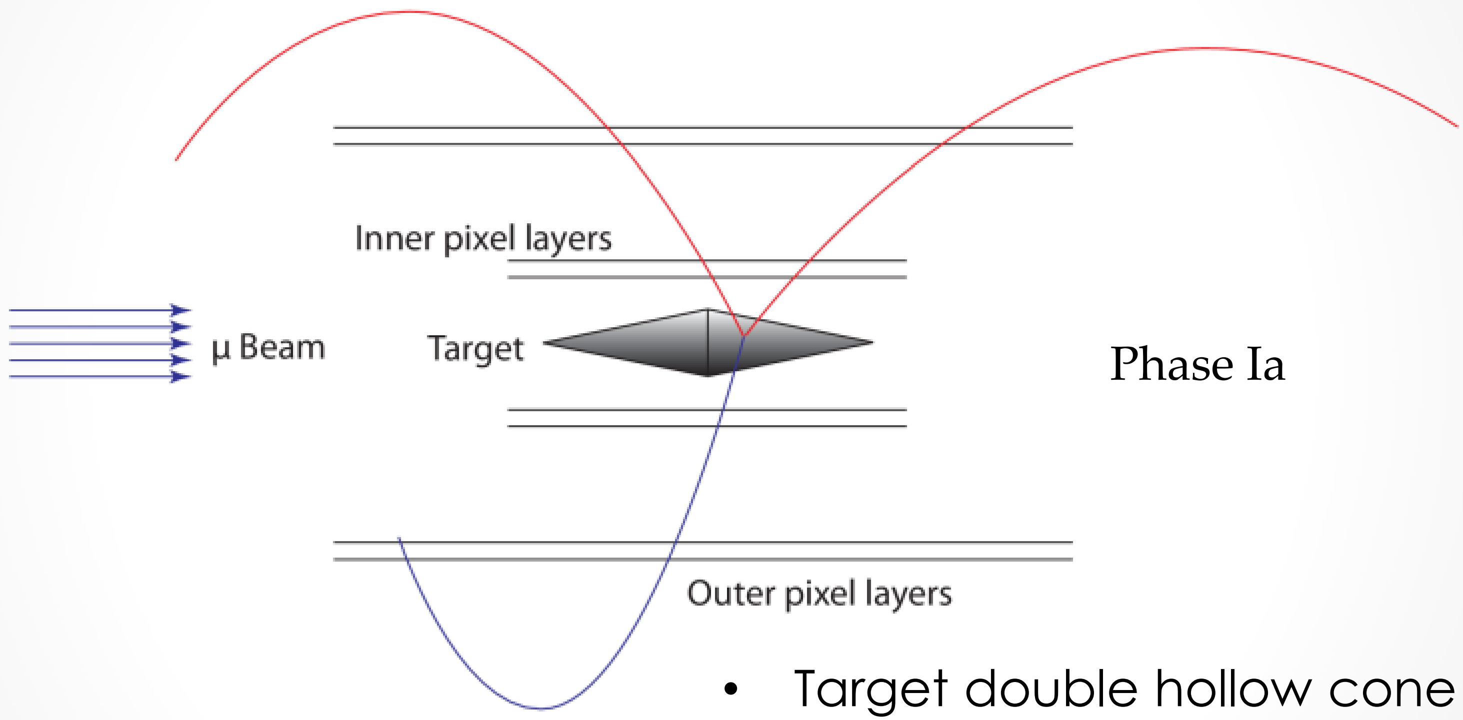
➢ **Extremely low material budget:**
  - ➢ **1×10^{-3} X_0** (Si-Tracker Layer)

➢ HV-MAPS spectrometer
  - ➢ 50 μm thin sensors
  - ➢ B ~1 T field

➢ + Timing detectors



Phased Experiment

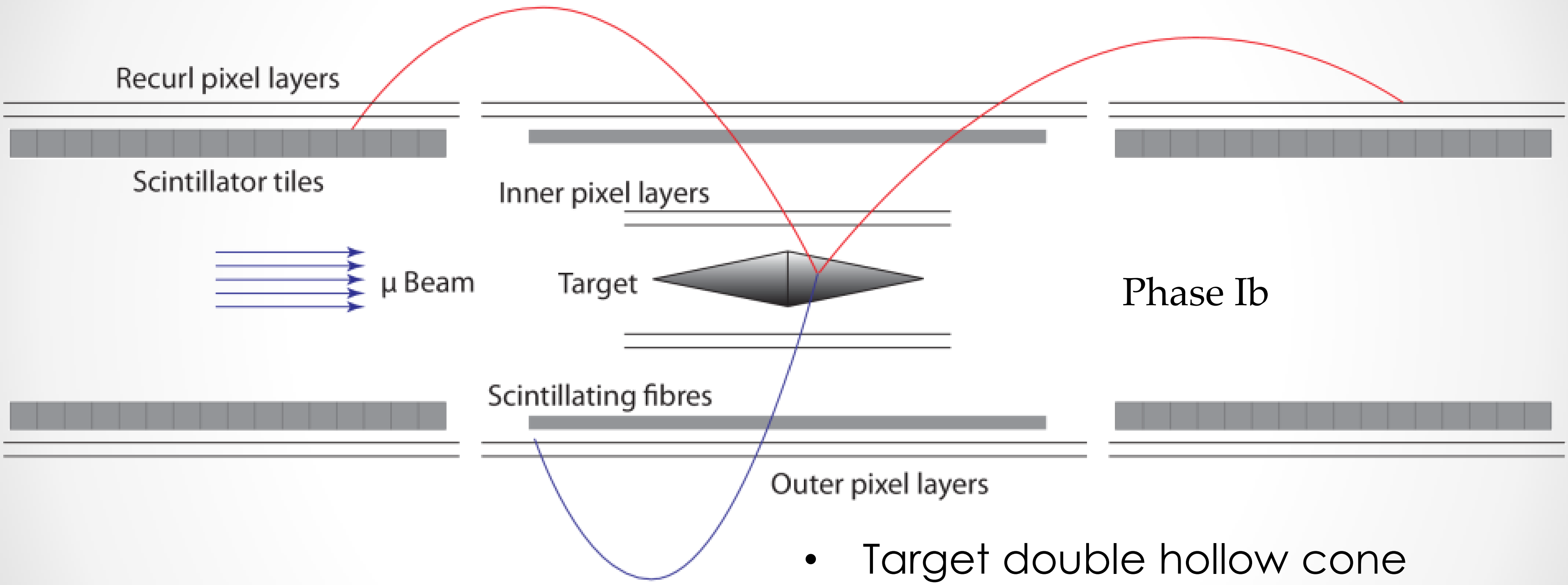


Phase Ia

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

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

Phased Experiment

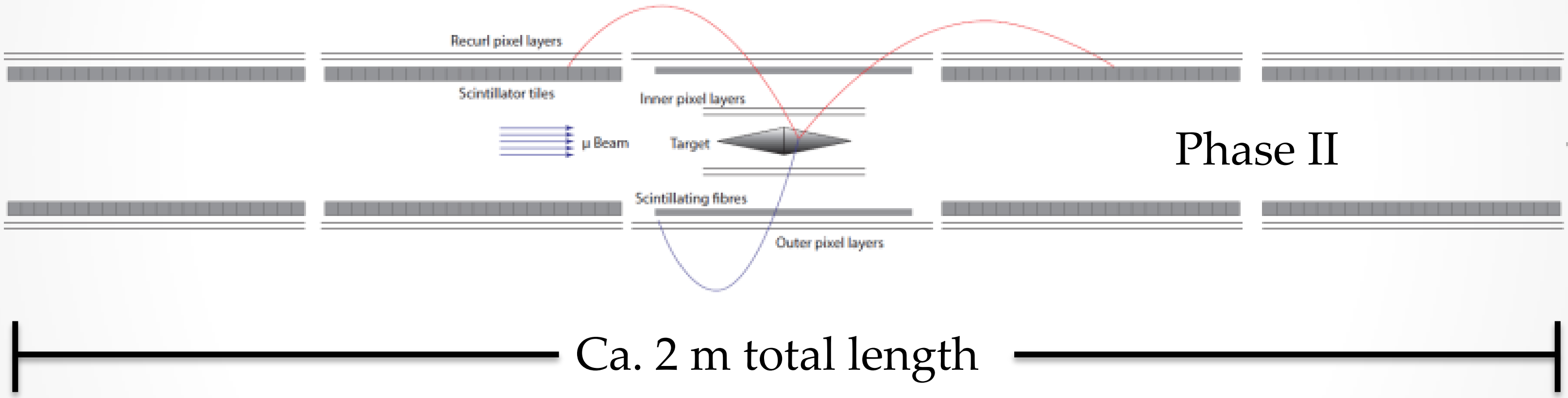


Phase Ib

- 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



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

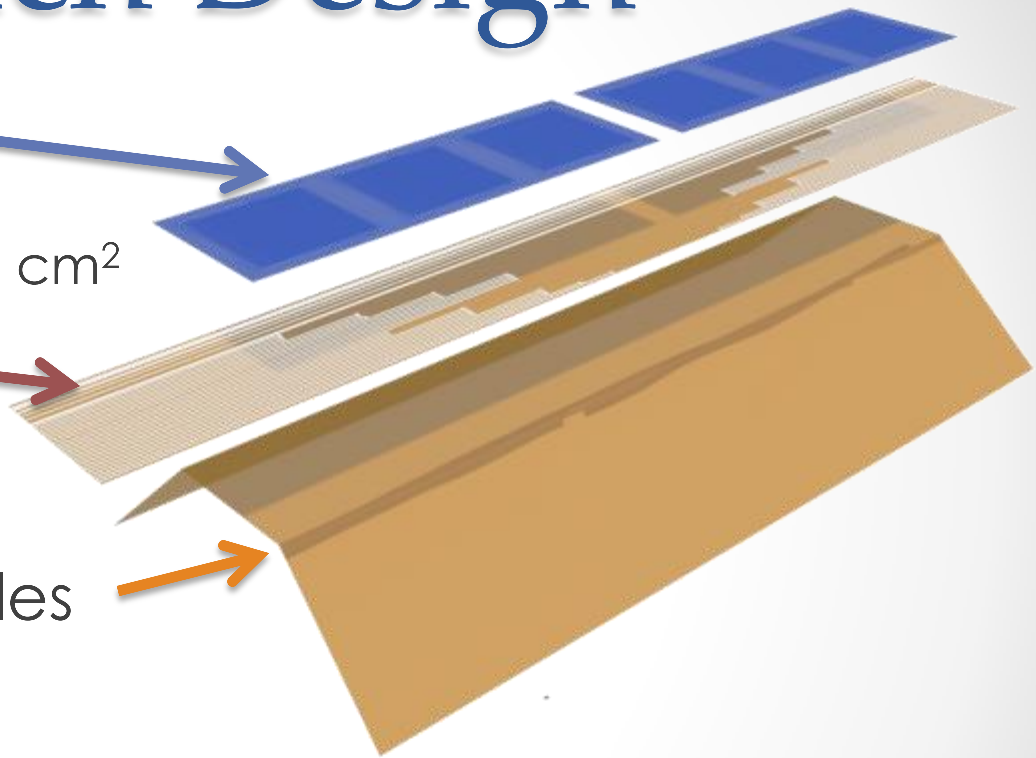
- Target double hollow cone
- Silicon pixel tracker
- Scintillating fiber tracker
- Recurl station x 2
- Tile detector x 2

Ultra Light Support Structure for the Pixel Tracker

…

Sandwich Design

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 1 x 2 cm^2 or 2 x 2 cm^2
- 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



$<0.1\%$ of X_0

Thinned Pixel Sensors

- **HV-MAPS***
  - Thinned to 50 µm
  - Sensors 1 x 2 cm^2 or 2 x 2 cm^2
- Kapton™ flex print
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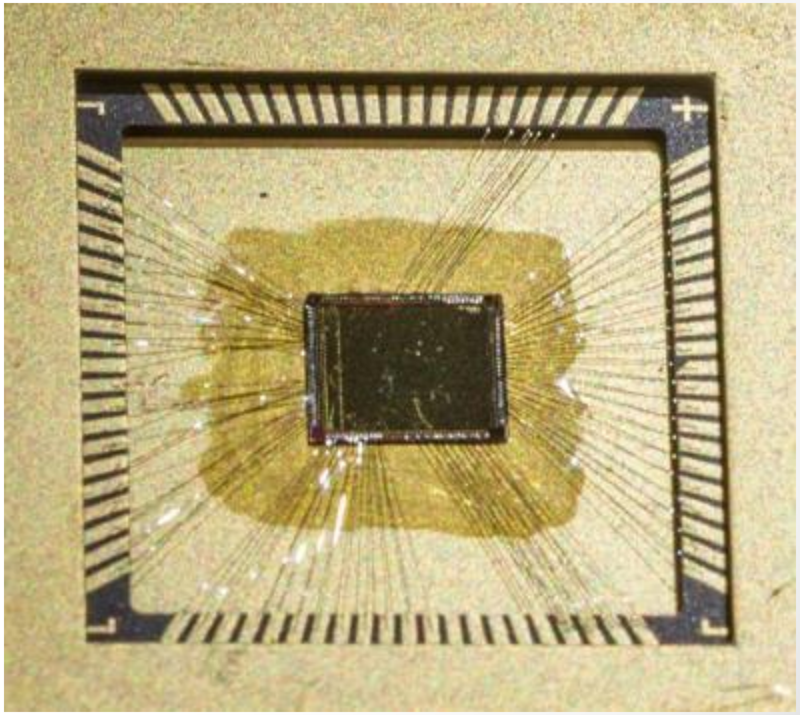

MuPix3 thinned to < 90µm

*Previous talk: Tobias Weber
"High Voltage Monolithic Active Pixel Sensors for the PANDA Luminosity Detector"

Kapton™ Flex Print

- 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
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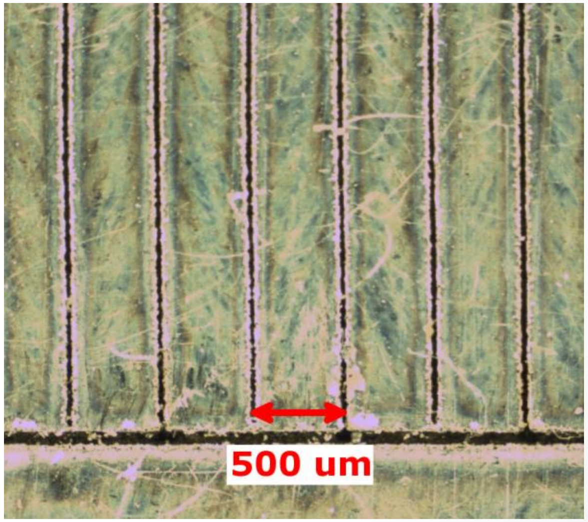

Laser-cut flex print prototype

Pixel Modules

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 1 x 2 cm^2 or 2 x 2 cm^2
- Kapton™ flex print
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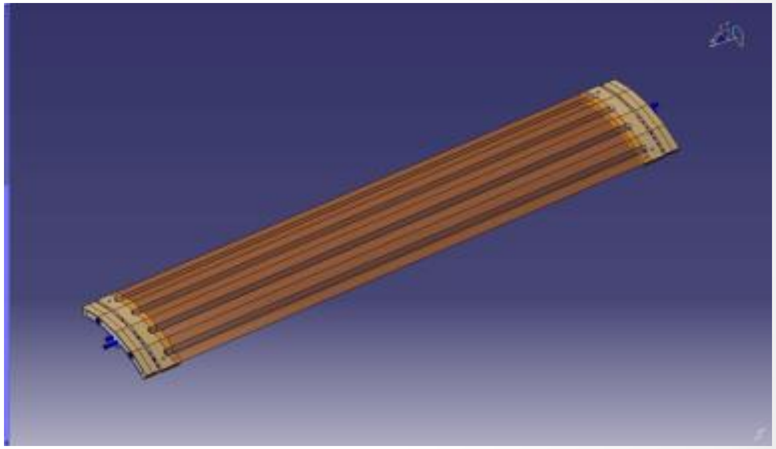

CAD of Kapton™ frames

Overall Design

- 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
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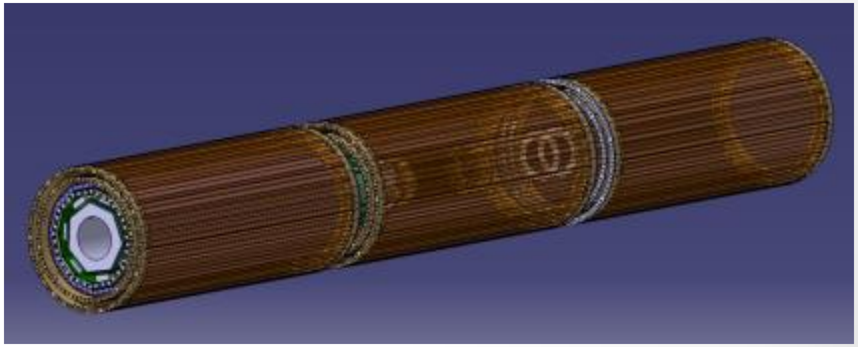
  - Support for all detectors

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



CAD of Kapton™ frames

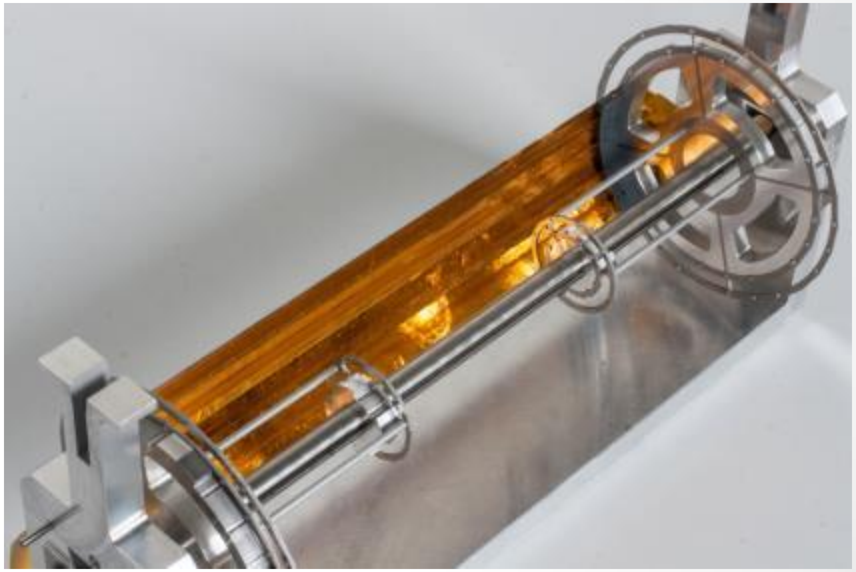
Inner Layers

- 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

- 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



Layer 3 Prototype in Assembling Frame with 50 µm Glass

Detector Frame

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 1 x 2 cm^2 or 2 x 2 cm^2
- Kapton™ flex print
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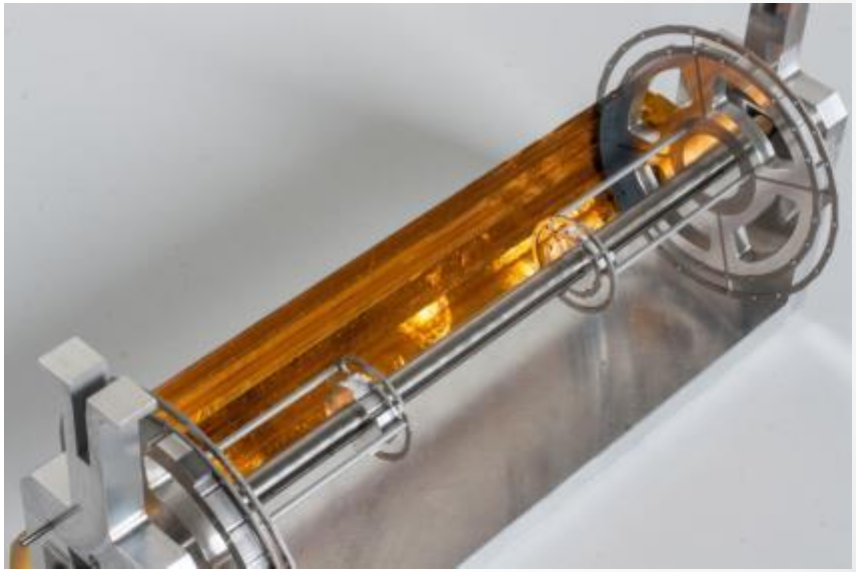
- Kapton™ Frame Modules
  - 25 µm foil
  - Self supporting
- **Alu end wheels**
  - Support for all detectors

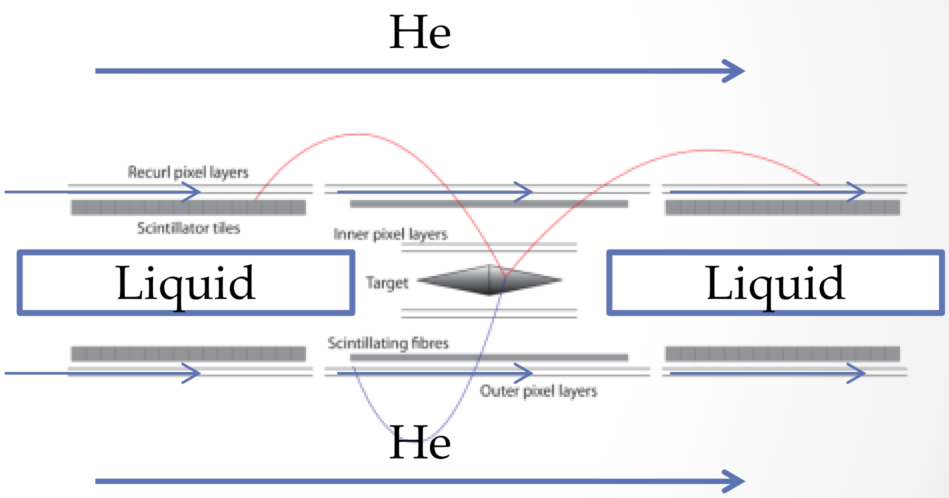


Layer 3 Prototype in Assembling Frame with 50 µm Glass

Cooling

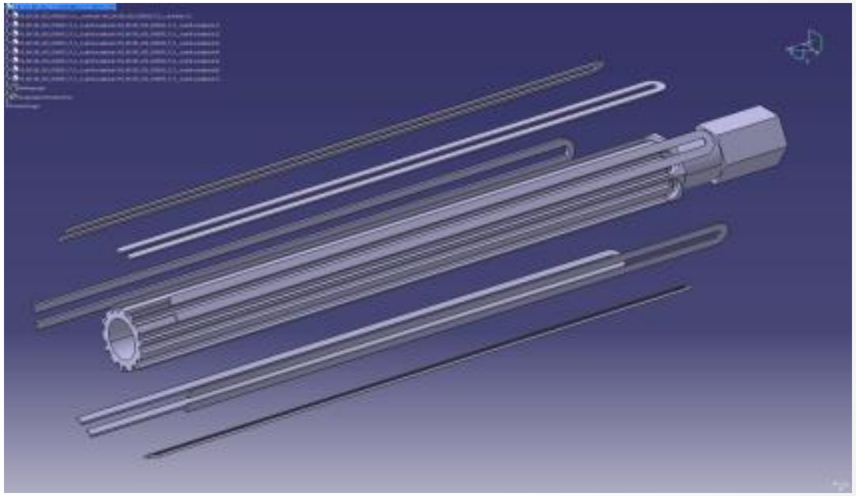
Cooling Concept

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



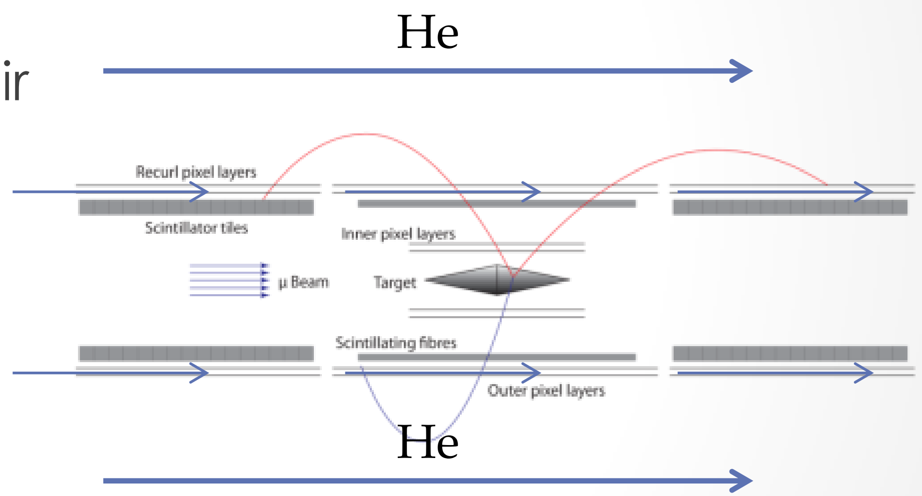
Liquid Cooling

- 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
  - 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



$$150\,\text{mW/cm}^2 \times 19080\,\text{cm}^2 = 2.86\ \text{KW}$$

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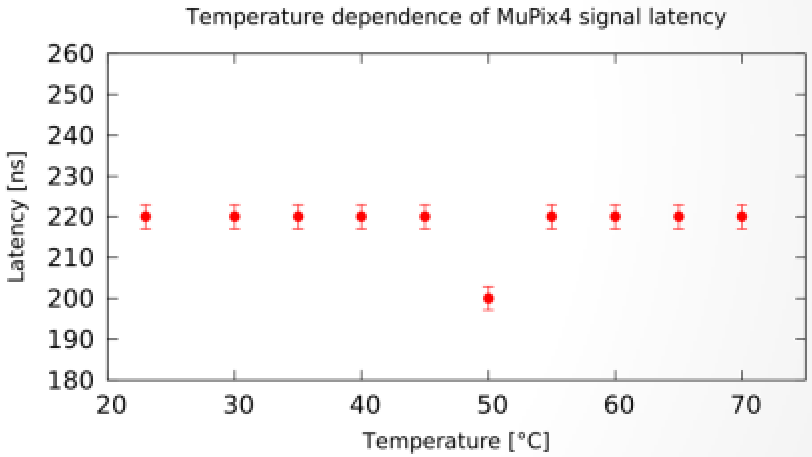

Temperatures between 20°C to 70°C ok.

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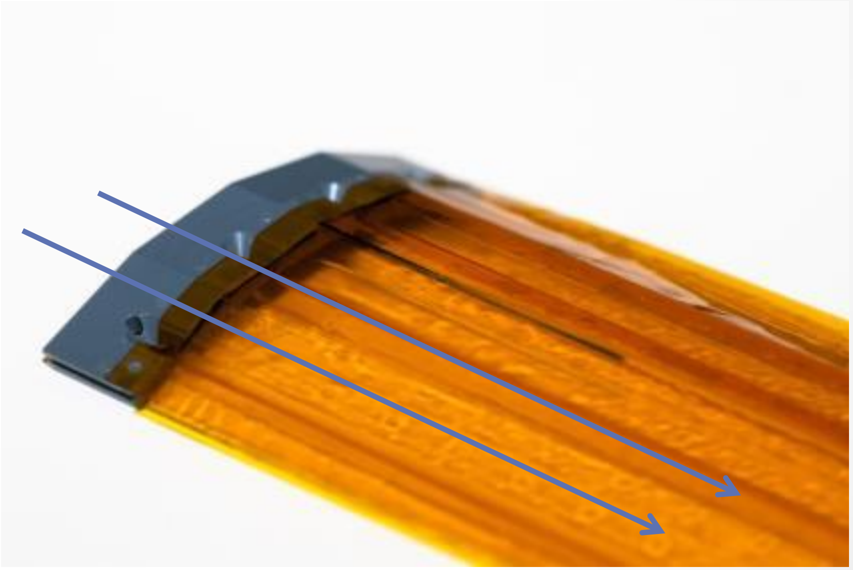

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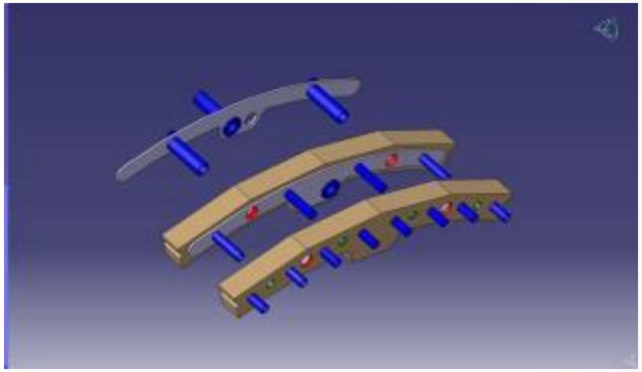

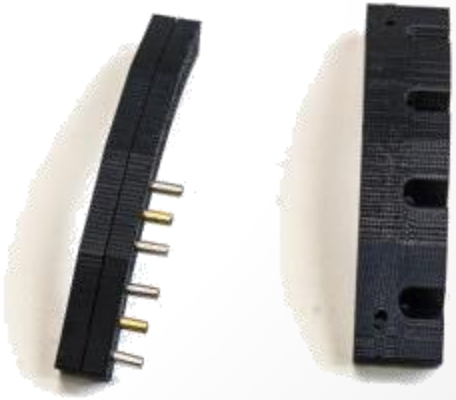

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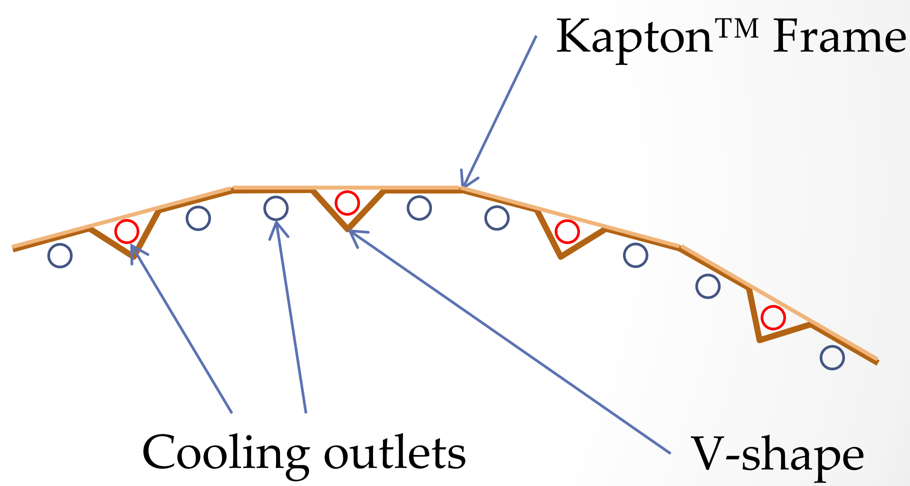

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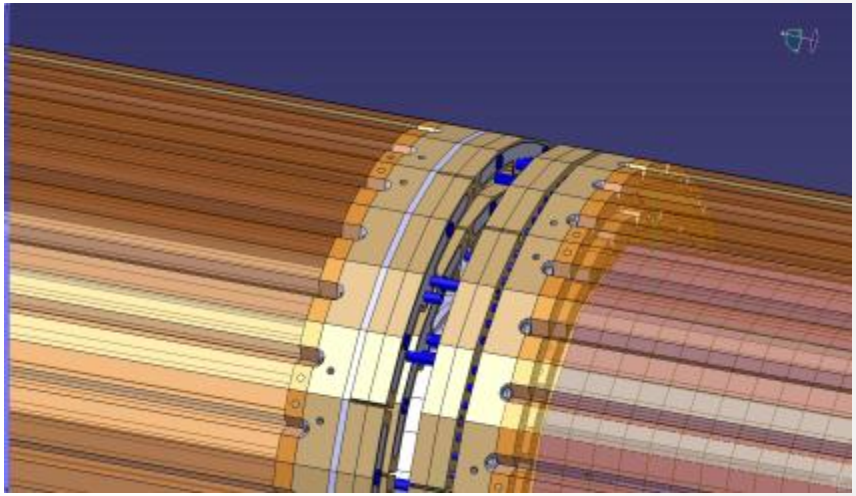
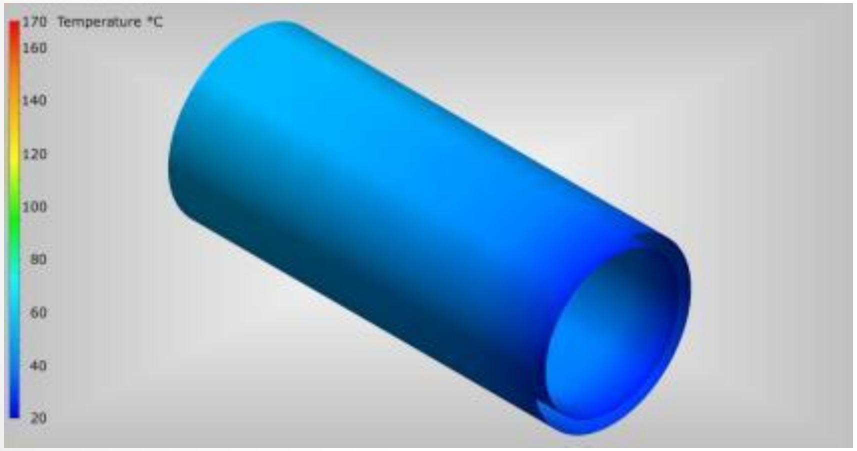
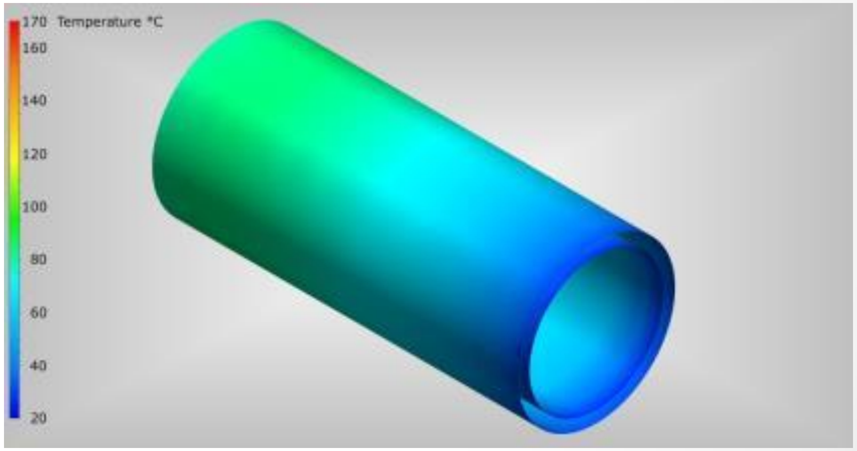


Comparison Simulation He and Air

He | Air

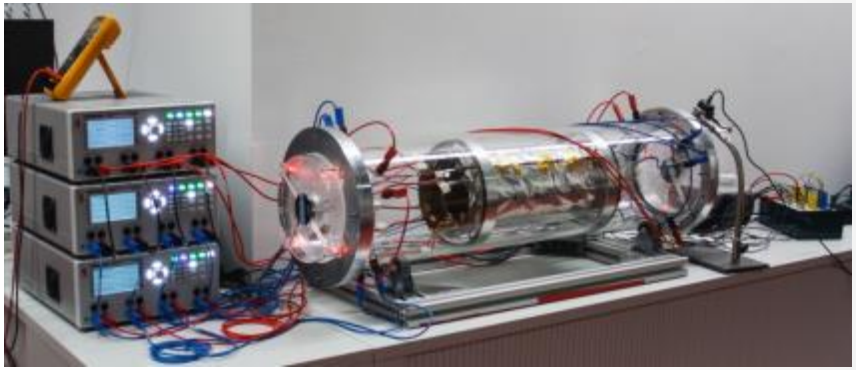


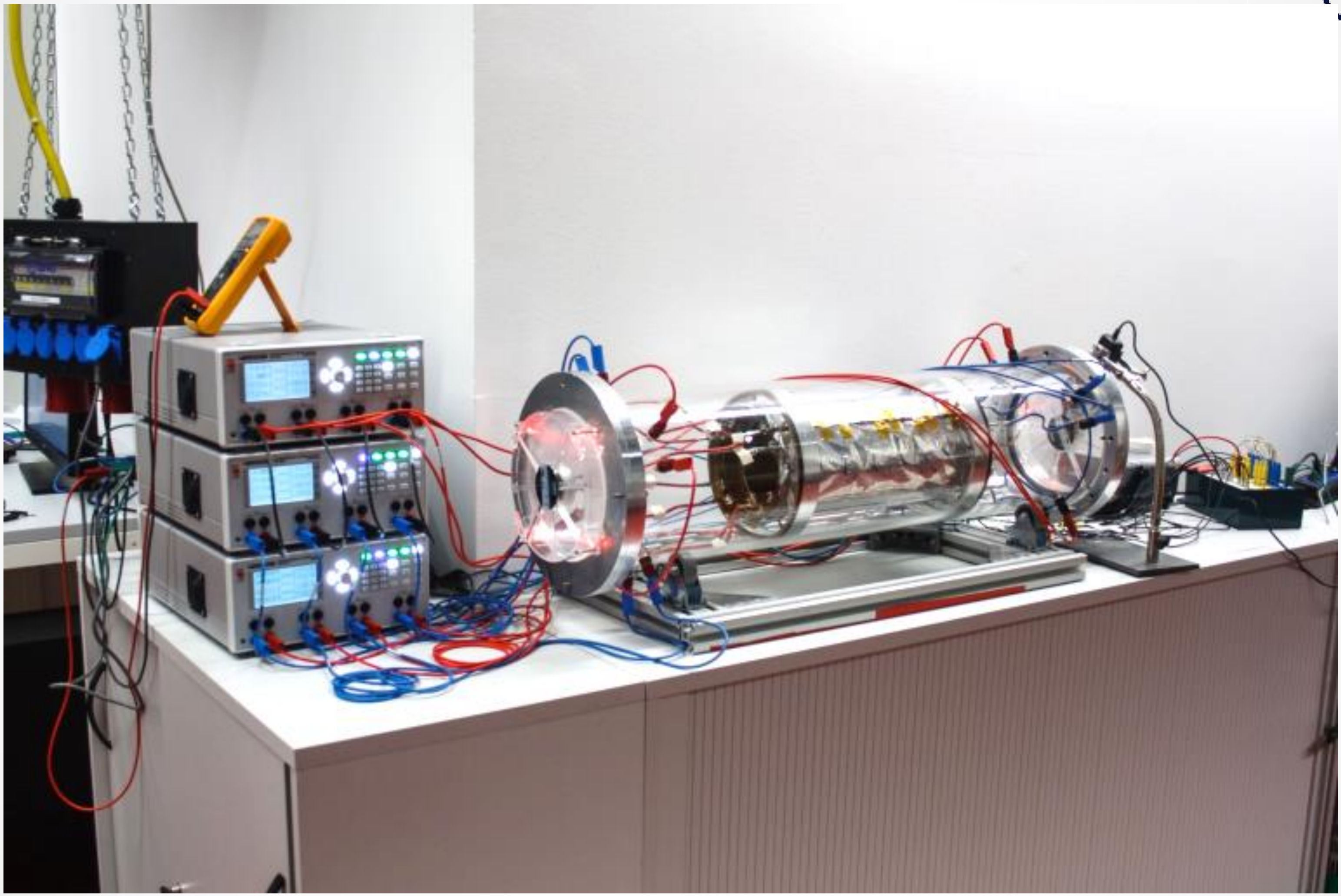


$$v = 4.0\ ^{m}/_{s}$$

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
  - $\Delta T < 60°K$





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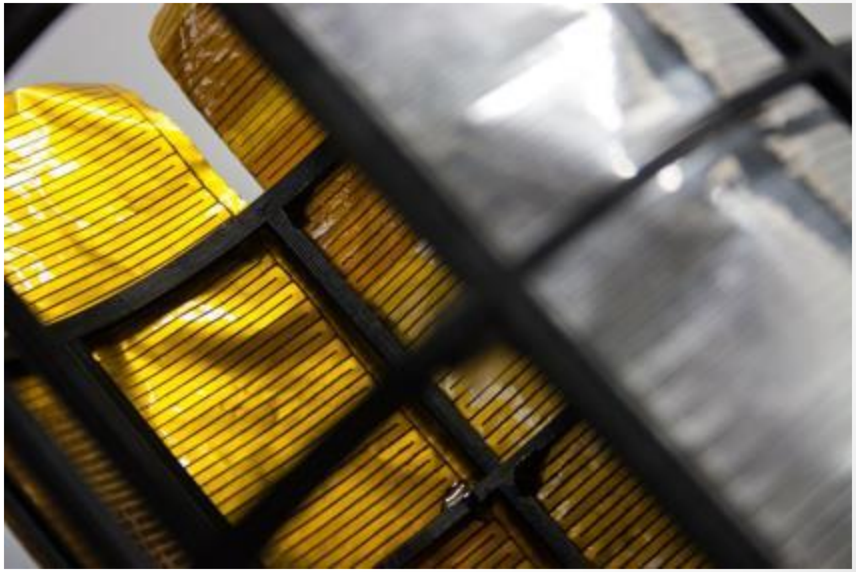

Test Results

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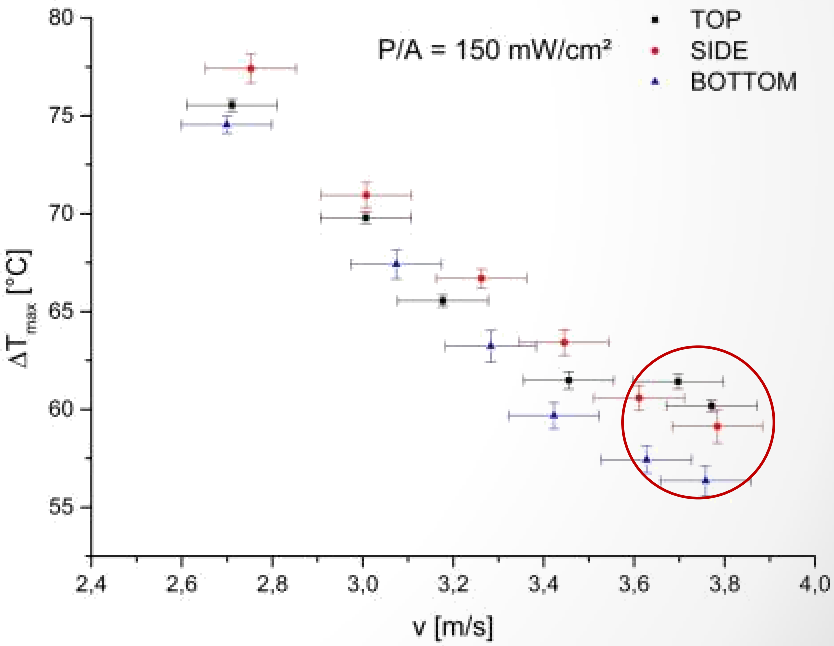
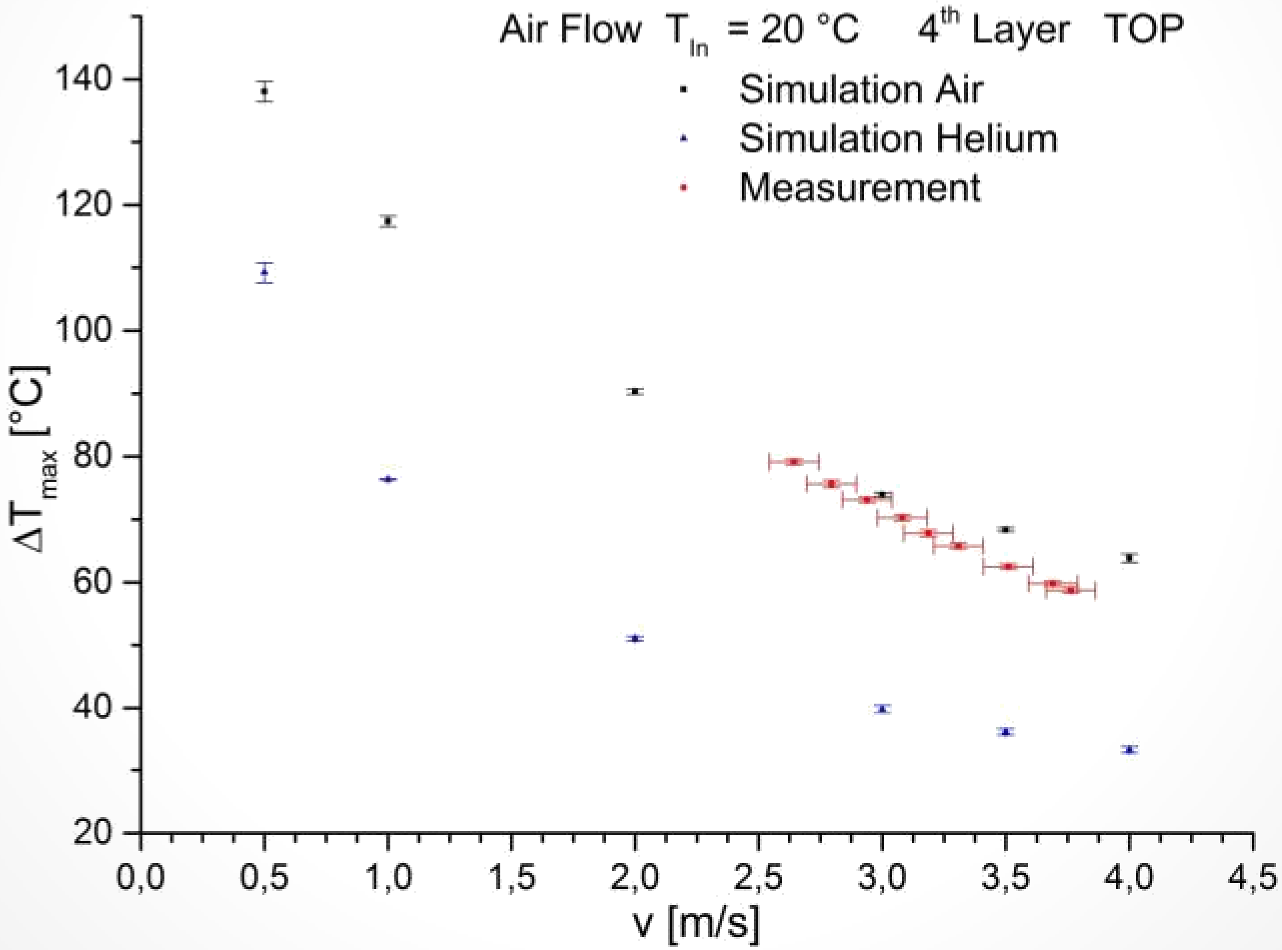
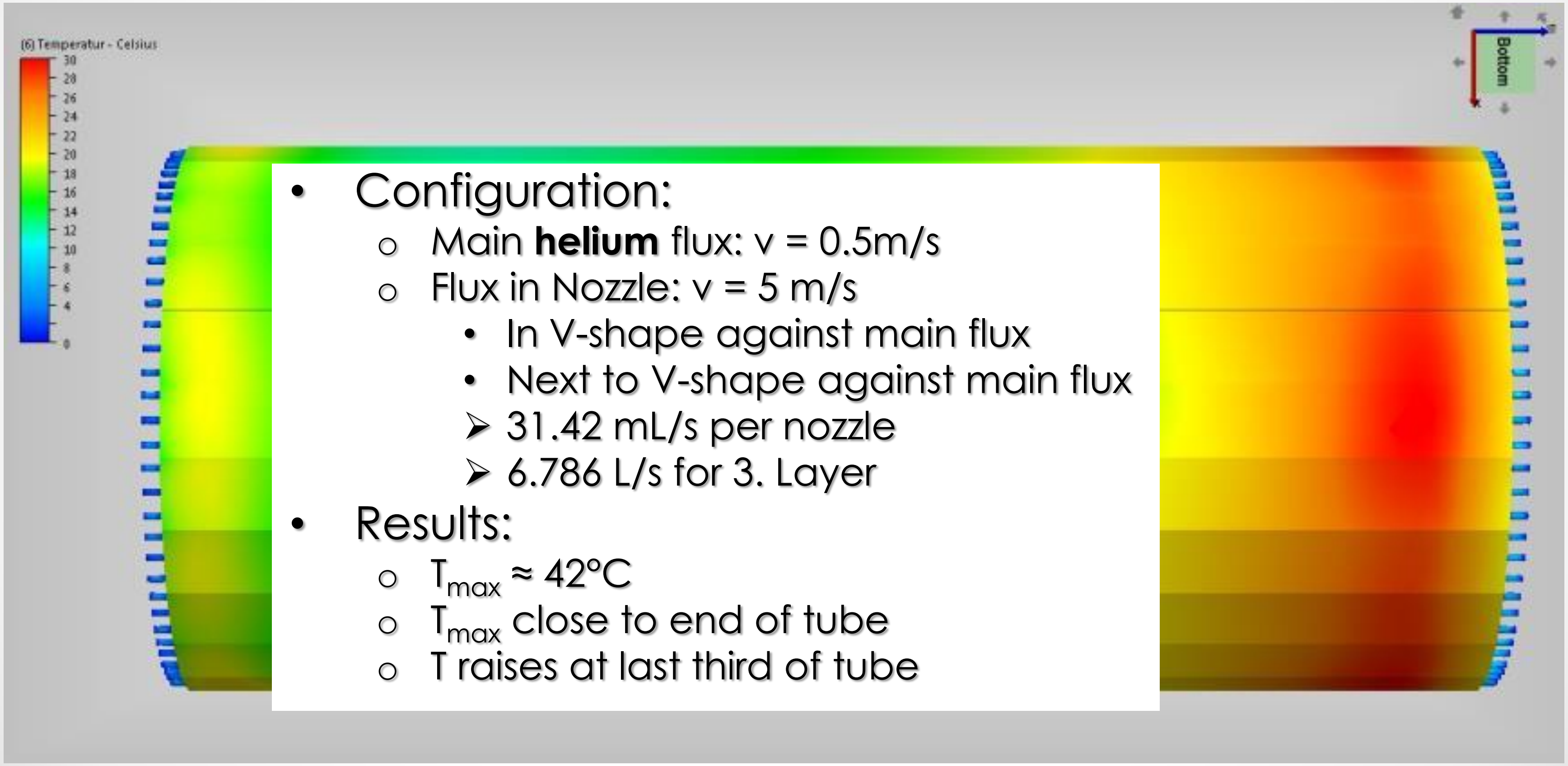
  - 561.6 W for layer 3 +4
  - … of Aluminum-Kapton™
- Cooling with external fan
  - Air at several m/s
- Temperature sensors attached to foil
  - LabView readout
- **First results promising**
  - **ΔT < 60°K**
  - ➢ **No sign of vibration in air**



Comparison Simulation and Tests



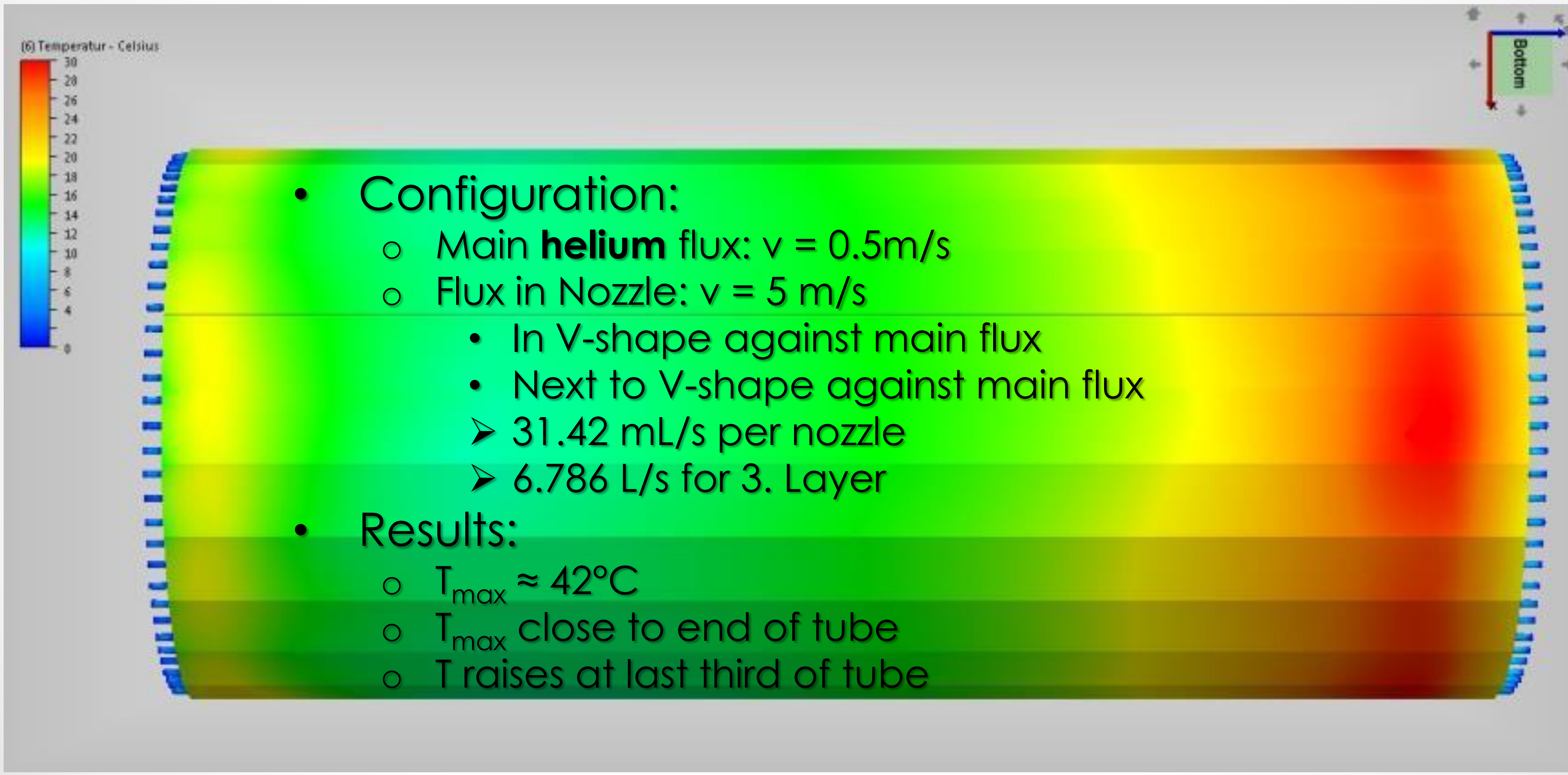
Simulation with V-shape cooling



- Configuration:
  - Main **helium** flux: v = 0.5m/s
  - Flux in Nozzle: v = 5 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:
  - $T_{max} \approx 42°C$
  - T_{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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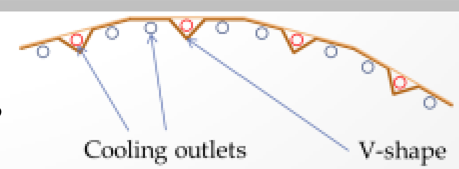
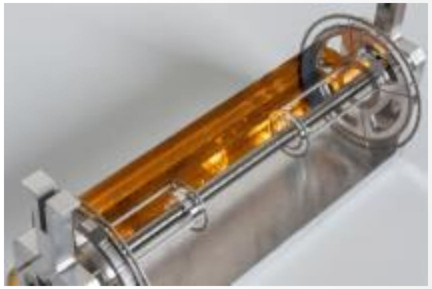


Summary

- Mechanics
  - Ultralight Sandwich Structure <0.1%X_0
  - Self Supporting
  - Assembly tests have started
- Cooling
  - Liquid cooling of beam pipe
  - Gaseous He cooling of Tracker
  - Ongoing studies encouraging



Backup slides

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He Properties

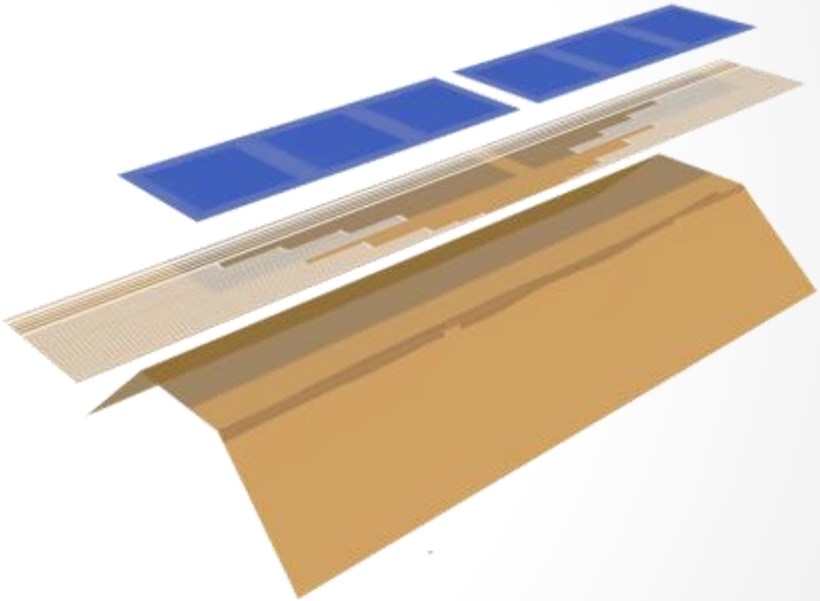
- Molecular weight : 4.0026 g/mol
- Gaseous phase
- Gas density (1.013 bar at boiling point) : 16.752 kg/m^3
- Gas density (1.013 bar and 15 °C (59 °F)) : 0.1692 kg/m^3
- Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)) : 1.0005
- Specific gravity : 0.138
- Specific volume (1.013 bar and 25 °C (77 °F)) : 6.1166 m^3/kg
- Heat capacity at constant pressure (Cp) (1.013 bar 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/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 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)

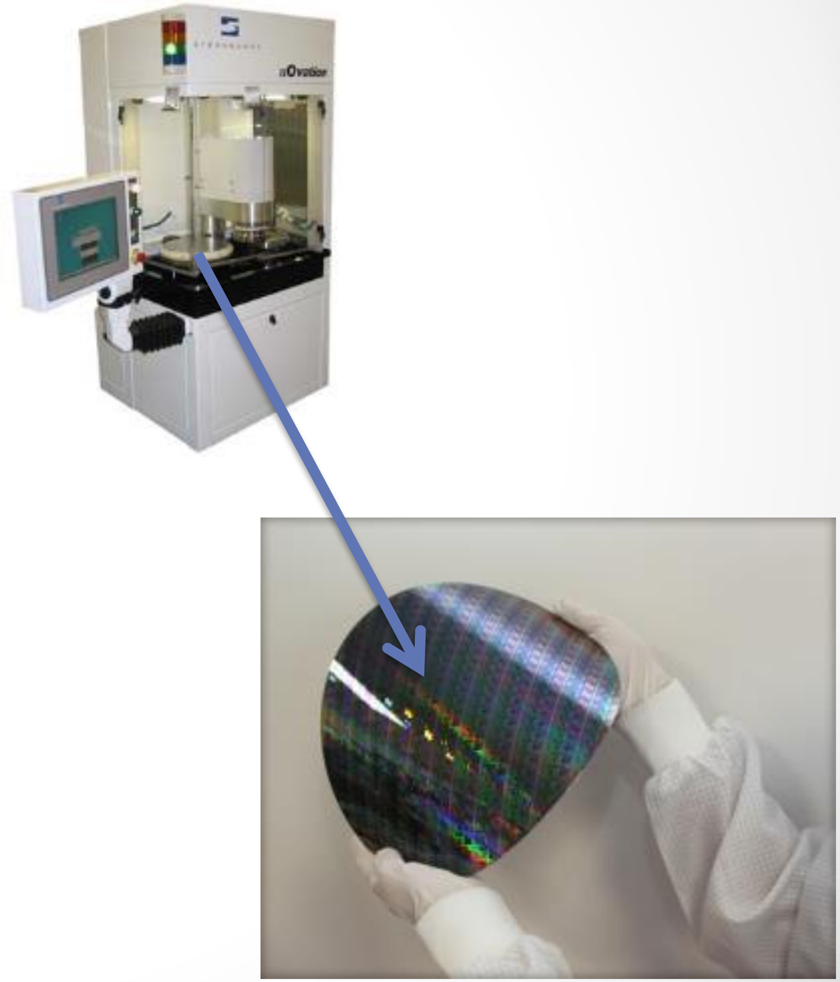
Radiation Length

- 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 $\Theta_{min} = 22.9°$
  - $X_0 = 21.1 \cdot 10^{-4}$



Thinning

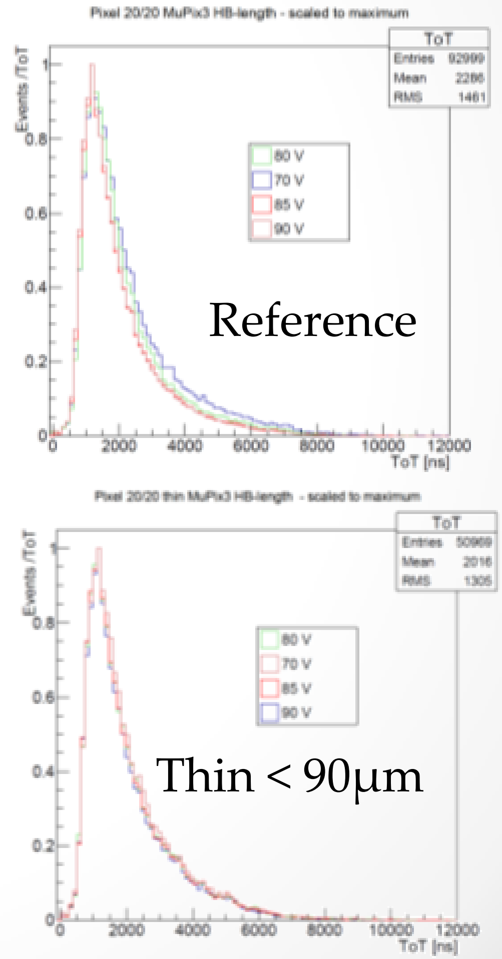
- 50 µm Si-wafers
  - Commercially available
  - HV-CMOS 75 µm (AMS)
- Single die thinning
  - For chip sensitivity studies
  - < 50 µm desirable
  - 90 µm achieved and tested
  - In house grinding?



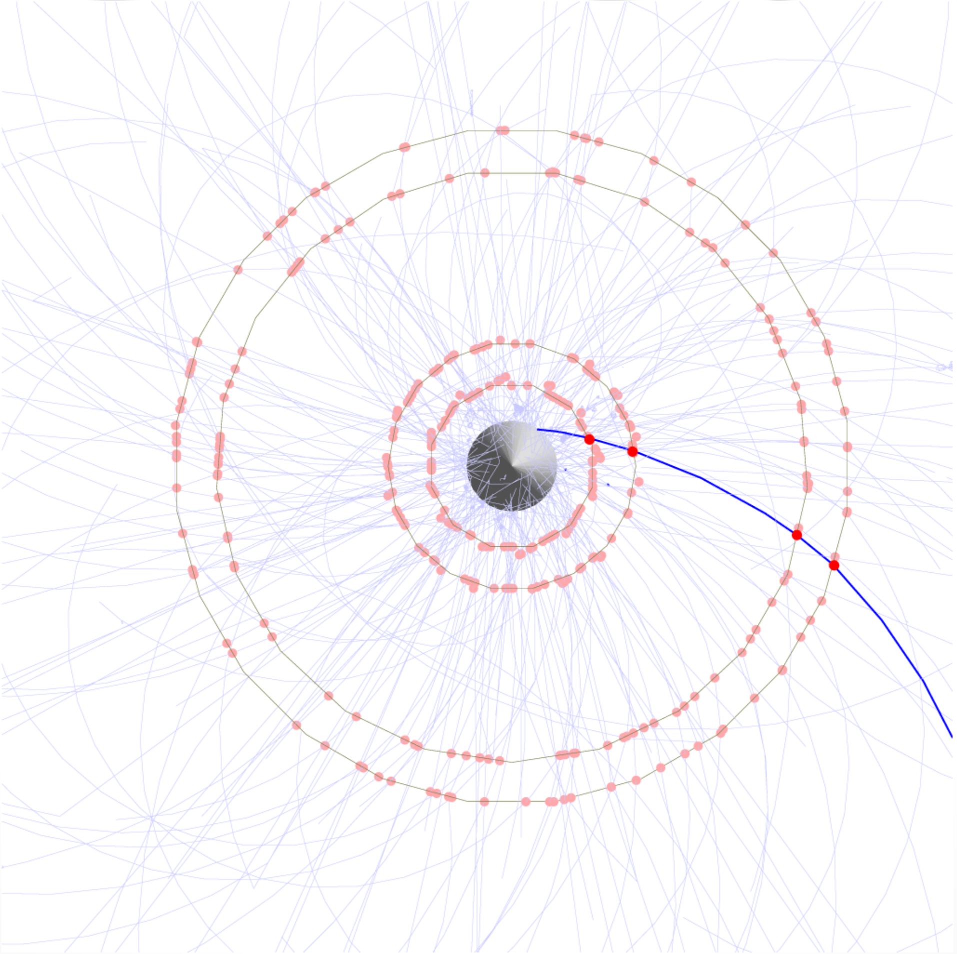
Thinned Sensors

- Single dies thinned:
  - MuPix2 thinned to < 80µm
  - MuPix3 thinned to < 90µm
- Good performance of thin chips
  - In lab
  - In particle beam
- Similar Time over Threshold (ToT)
  - PSI test-beam
  - PiM1 beam-line
  - 193 MeV π^+

Time Over Threshold



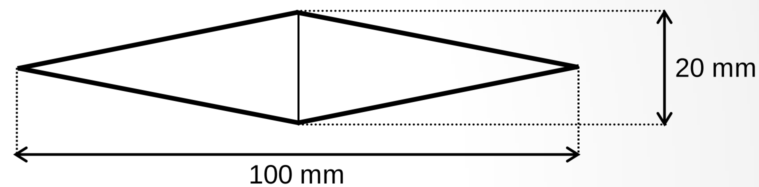
Combinatorics using Timing System



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)

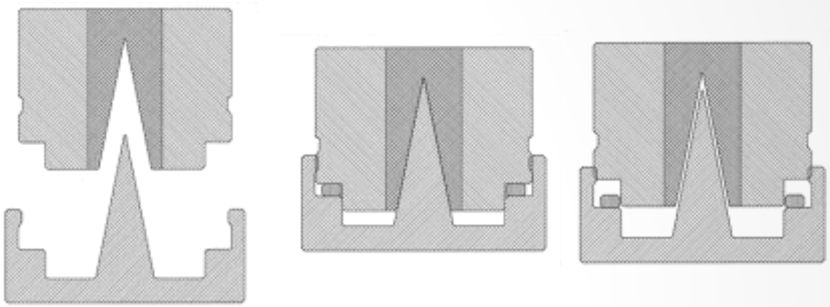


- Manufacturing (brainstorming):
  - Rolled up Al-foil
  - Additive manufacturing / 3D printing
  - Casting (D: Giessen)
  - **Impact extrusion** (D: Fliesspressen)

  } → 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

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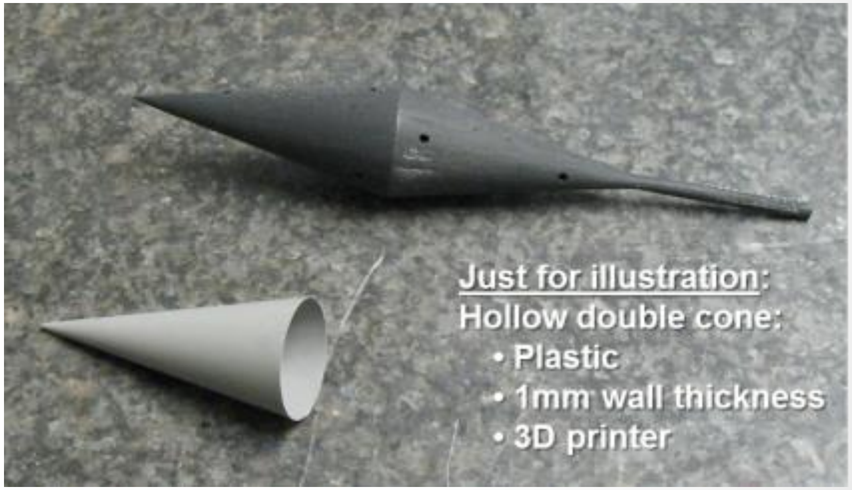


Target Prototyping

- 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

Fiber Tracker

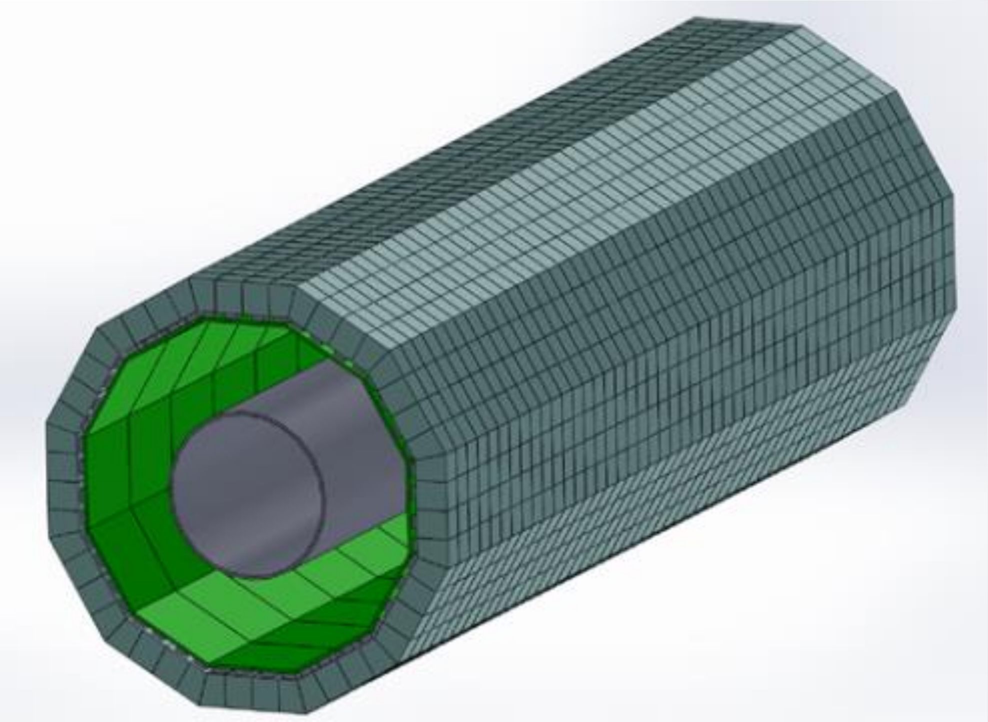
- Fiber ribbon modules
  - 16 mm wide
  - 360 mm long
  - 3 layers fibers of 250 μm dia.
  - 3 STiC readout chips
- Total fiber Tracker:
  - 24 ribbon-modules
  - 72 read-out chips
  - 4536 fibers
- Prototype ribbons built:
  - 3 layers
  - 16 mm wide
  - 360 mm long
- CAD in progress

Scintillating fiber ribbons

See:
Fibres
Alessandro Bravar
(Geneva University)

Tile Detector

- Scintillating tiles
  - 8.5 x 7.5 x 5 mm^3
- 12 Tile Modules per station
  - 192 tiles/module
  - Attached to end rings
- SiPMs attached to tiles
  - Front end PCBs below
  - Readout through STiC



Sketch of Tile detector station

See:
Tiles
Patrick Eckert
(KIP Uni Heidelberg)

Tile Detector

- Scintillating tiles
  - 8.5 x 7.5 x 5 mm^3
- 12 Tile Modules per station
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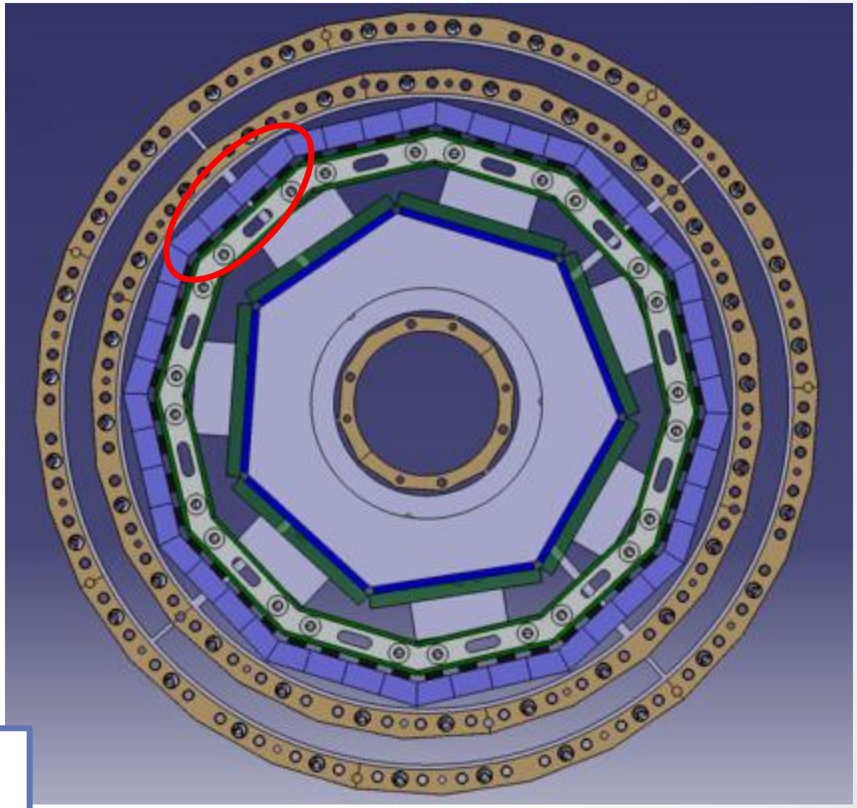
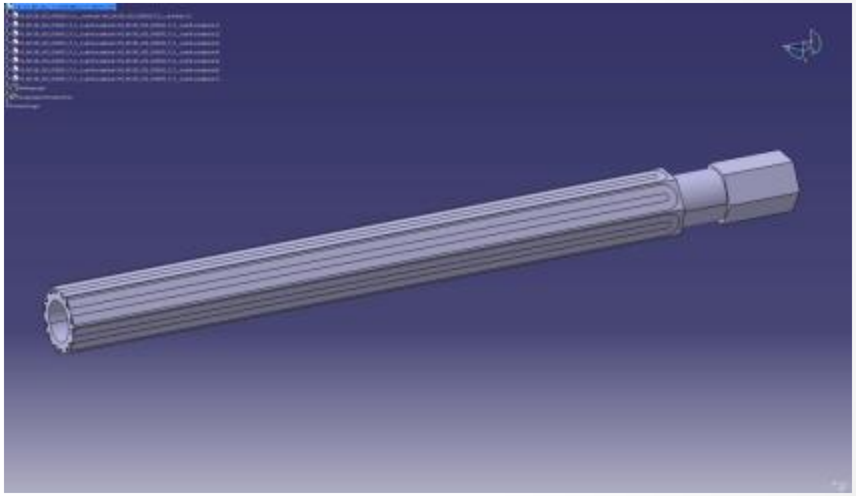


CAD of Tile Detector integration

See:
Tiles
Patrick Eckert
(KIP Uni Heidelberg)

Beam Pipe

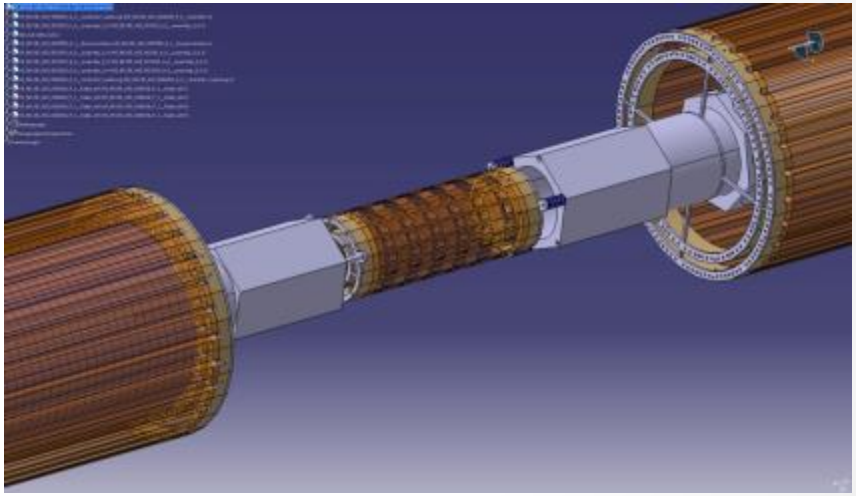
- Stainless steel pipe
  - Shields against background
- Mechanical support
  - Detectors attached to beam pipe
  - Via end rings
- Read-out PCBs attached
  - FPGAs mounted directly
  - Integrated cooling



Beam pipe design

Beam Pipe

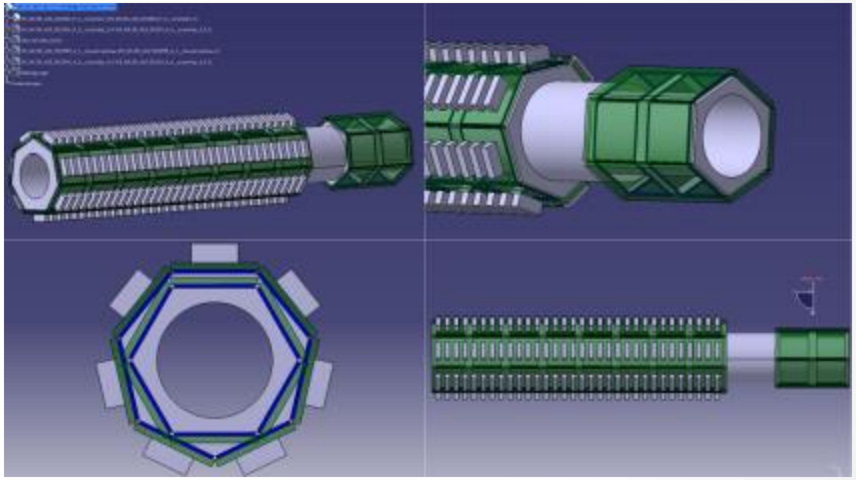
- Stainless steel pipe
  - Shields against background
- Mechanical support
  - Detectors attached to beam pipe
  - Via end rings
- Read-out PCBs attached
  - FPGAs mounted directly
  - Integrated cooling



Beam pipe supports detectors

Beam Pipe

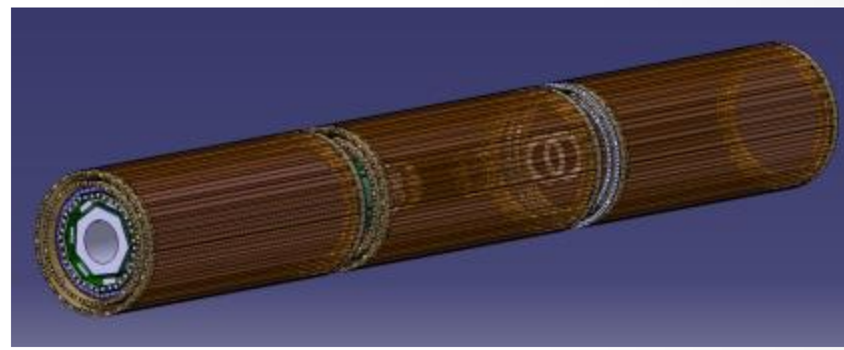
- Stainless steel pipe
  - Shields against background
- Mechanical support
  - Detectors attached to beam pipe
  - Via end rings
- Read-out PCBs attached
  - FPGAs mounted directly
  - Integrated cooling



PCBs mounted on beam pipe

Overall Assembly

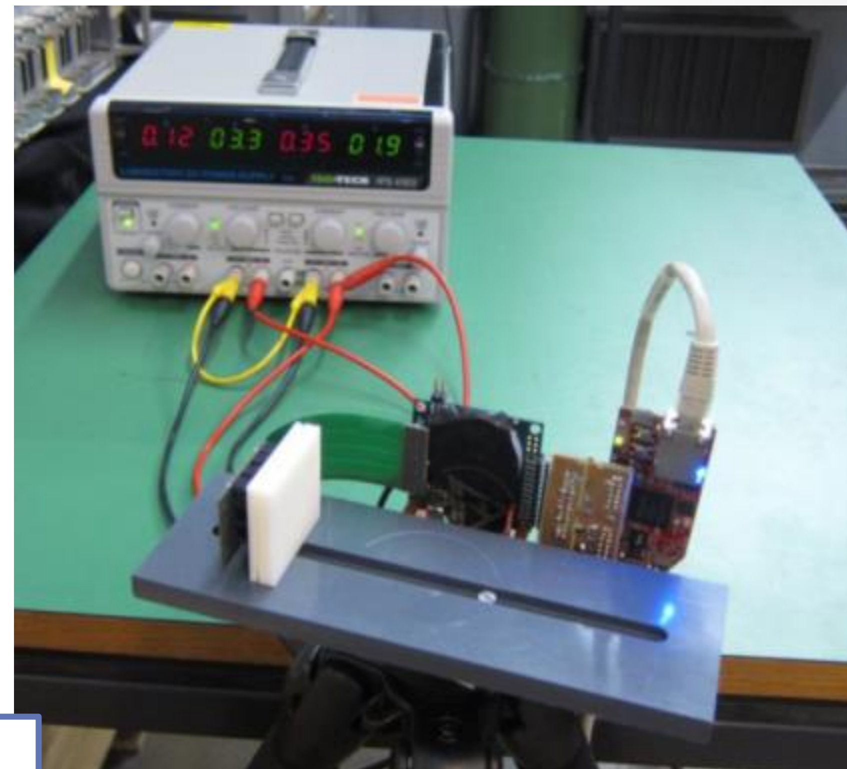
- CAD of:
  - Silicon Tracker +
  - Tile detector +
  - Target +
  - PCBs +
  - Beam pipe +
  - Cooling
- To be added:
  - Scintillating fiber detector
  - Cabling
  - Cage and rails in Magnet



CAD of Phase I detector

Tile Detector

- Scintillating tiles
  - 8.5 x 7.5 x 5 mm^3
- 12 Tile Modules per station
  - 192 tiles/module
  - Attached to end rings
- SiPMs attached to tiles
  - Front end PCBs below
  - Readout through STiC



Tile detector 4 x 4 prototype

See:
Tiles
Patrick Eckert
(KIP Uni Heidelberg)

Magnet

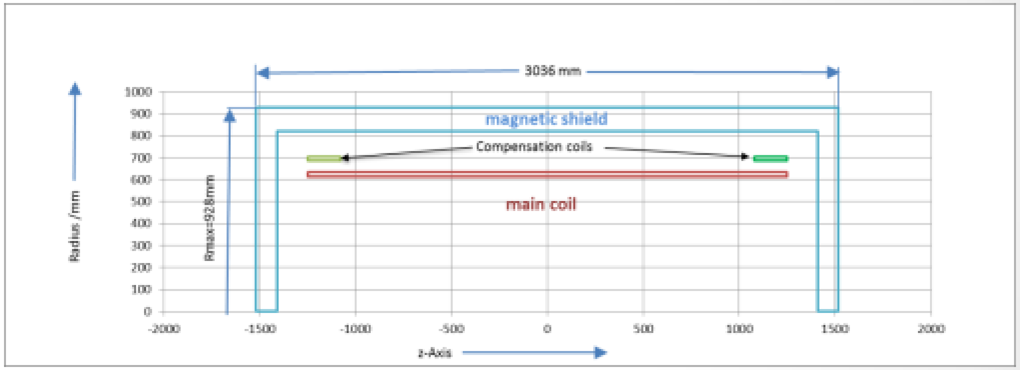
Magnet Specification

- 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

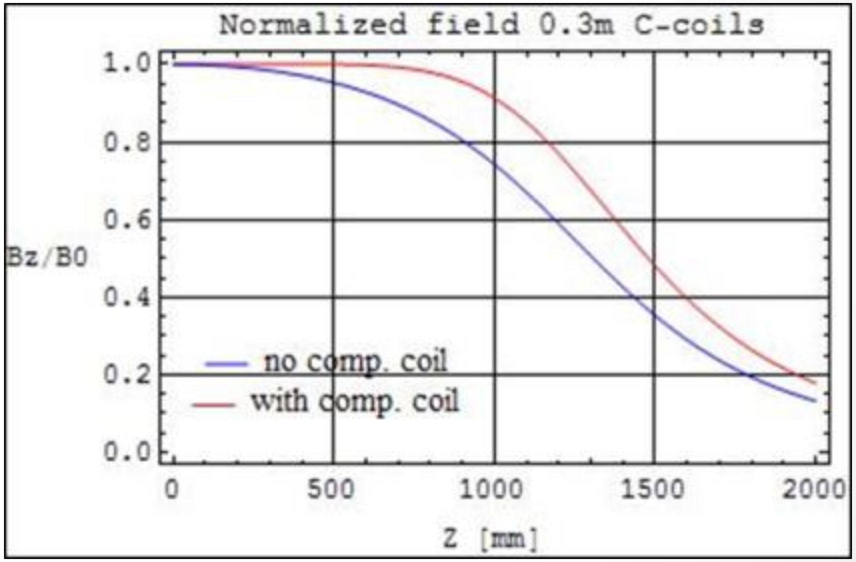
- 0.8 – 2 T field
- 1 m warm bore
- 2 m homogenous in z
- 2.5 m coil + shielding
- Compensation coils
- 10^{-3} homogeneity
- 10^{-4} stability



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

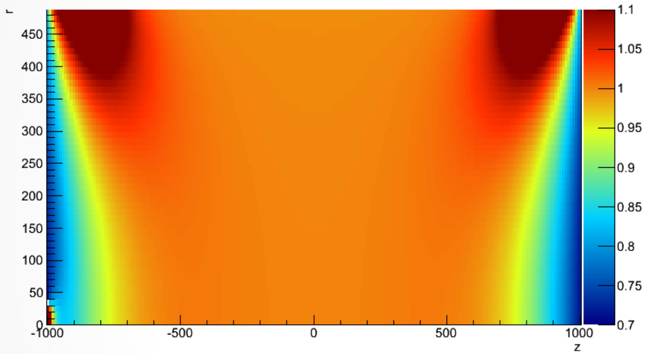


Compensation coil effect

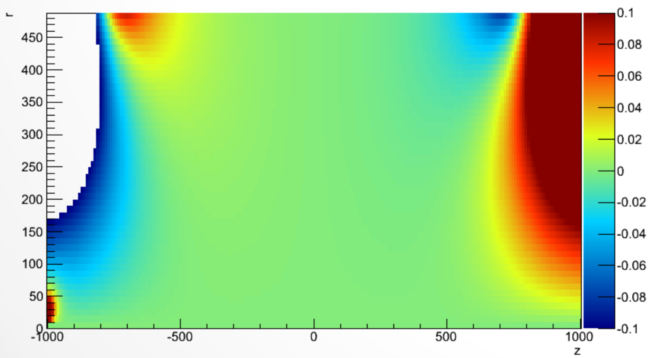
2 m plus Compensation Coils vs 3 m Coil

2 m plus compensation coils

z field

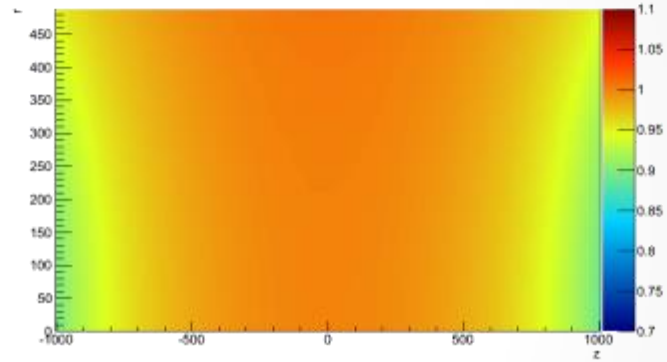


Radial field

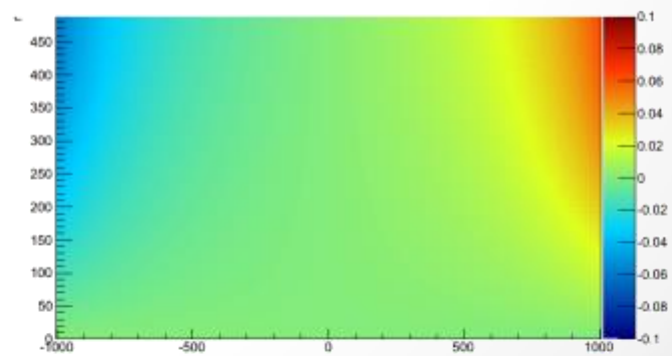


3 m

z field

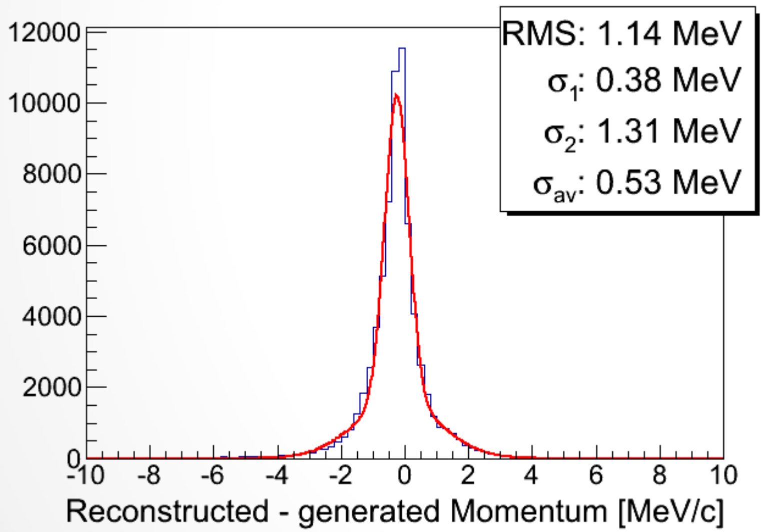


Radial field

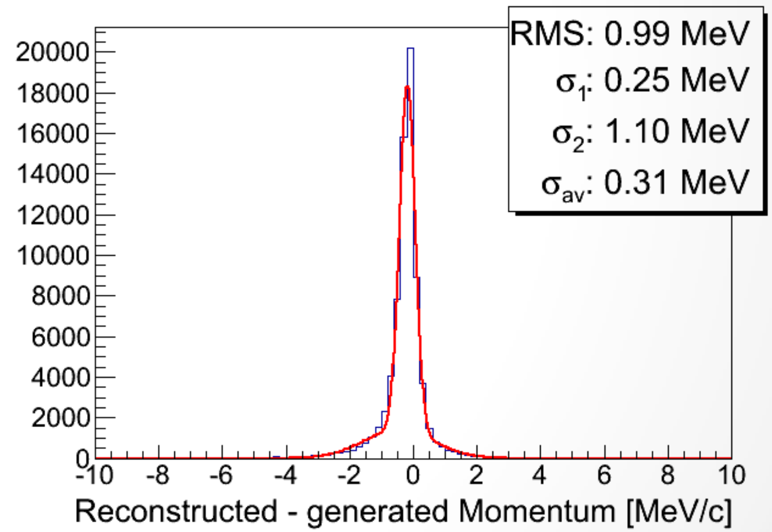


Momentum Resolution

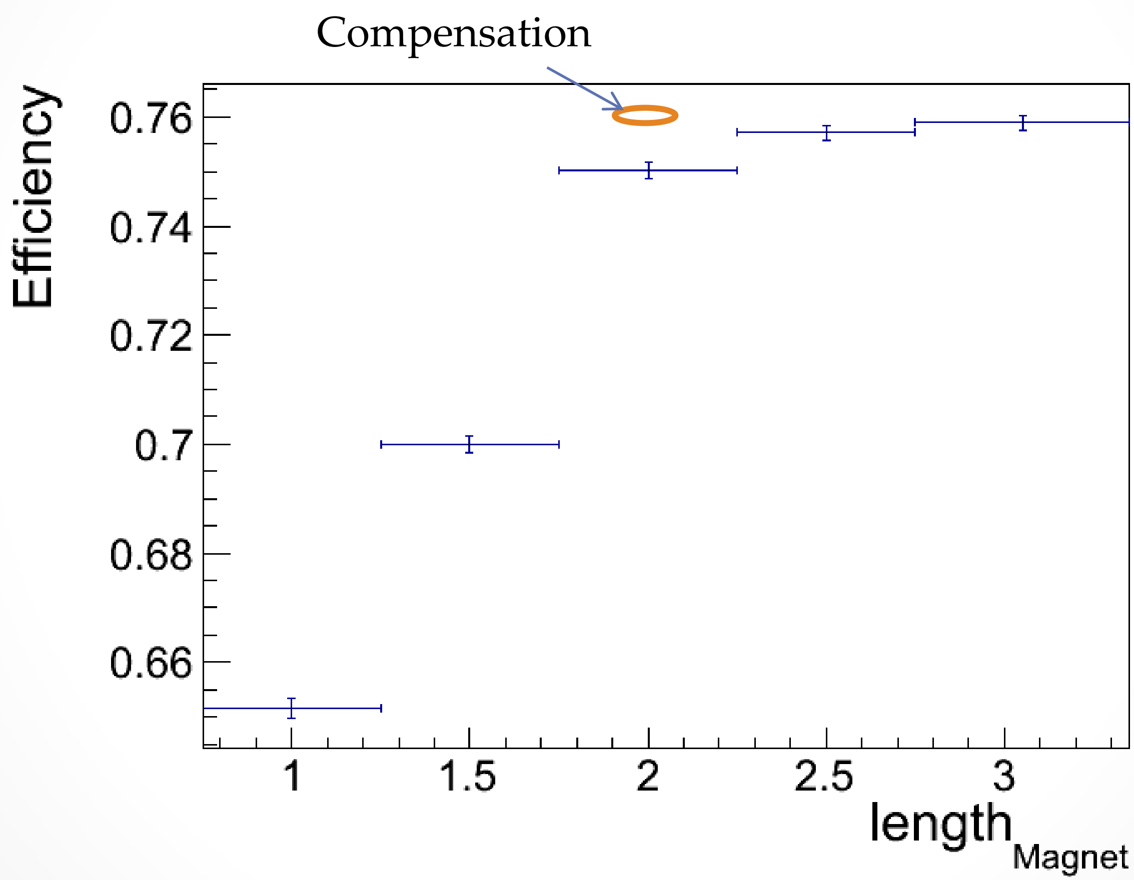
2 m coil



3 m coil

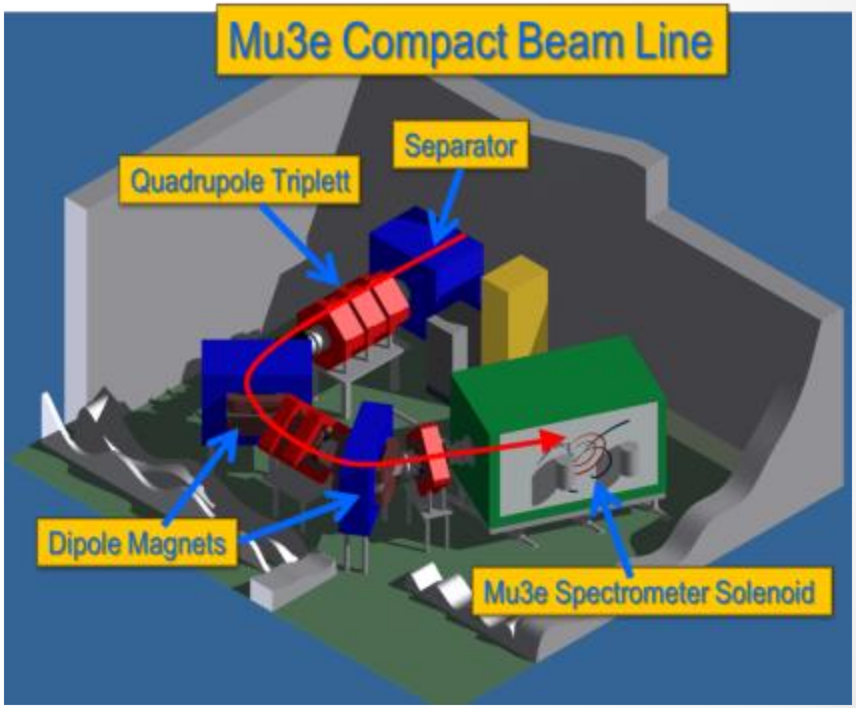


Efficiency

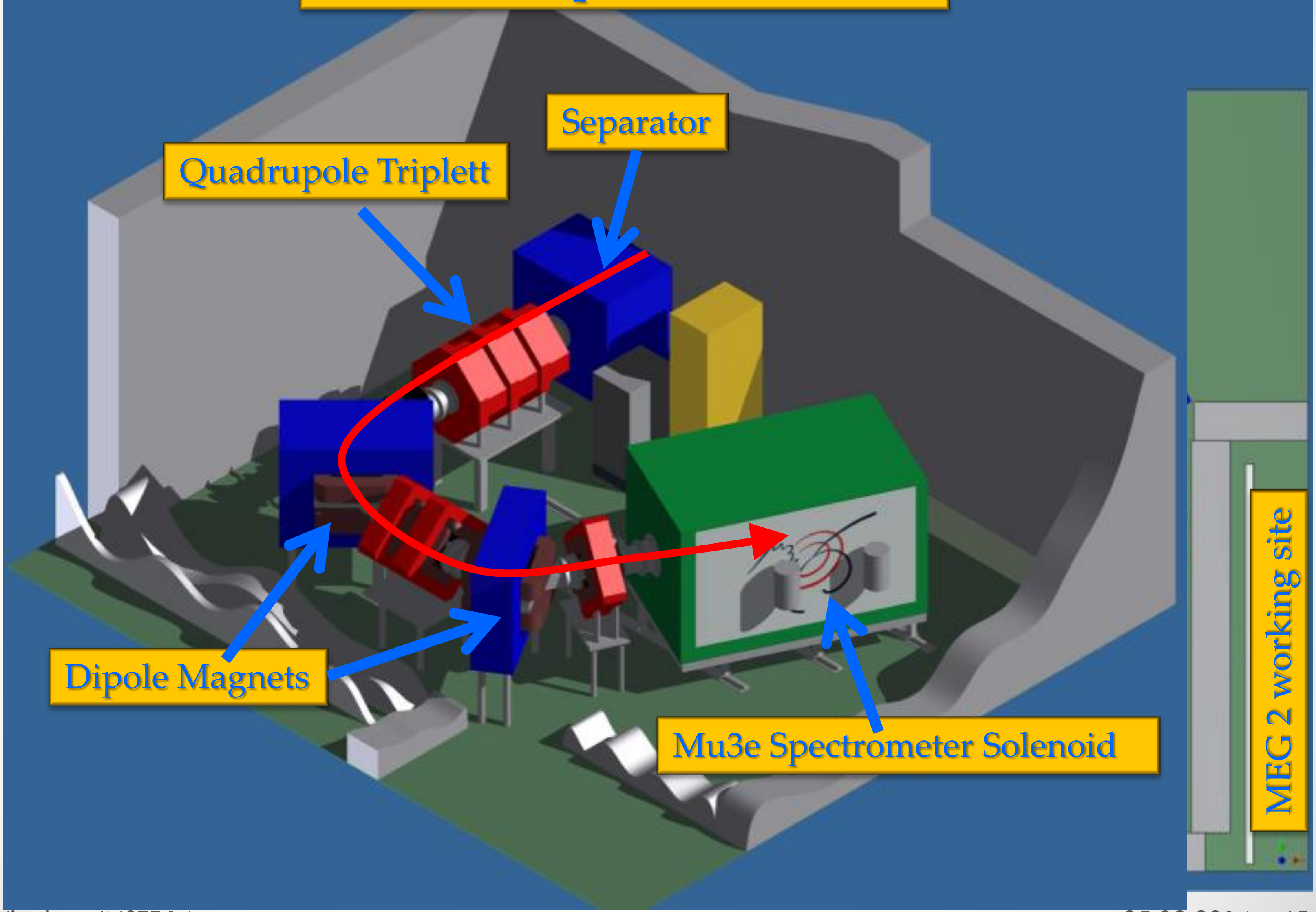

Compensation
Efficiency
0.76
0.74
0.72
0.7
0.68
0.66
1
1.5
2
2.5
3
$length_{Magnet}$

Space Restrictions

- Phase I:
  - Beam line at πE5
  - Surface muons from target E
  - Up to a 10^8 μ/s
- Space shared with MEG experiment

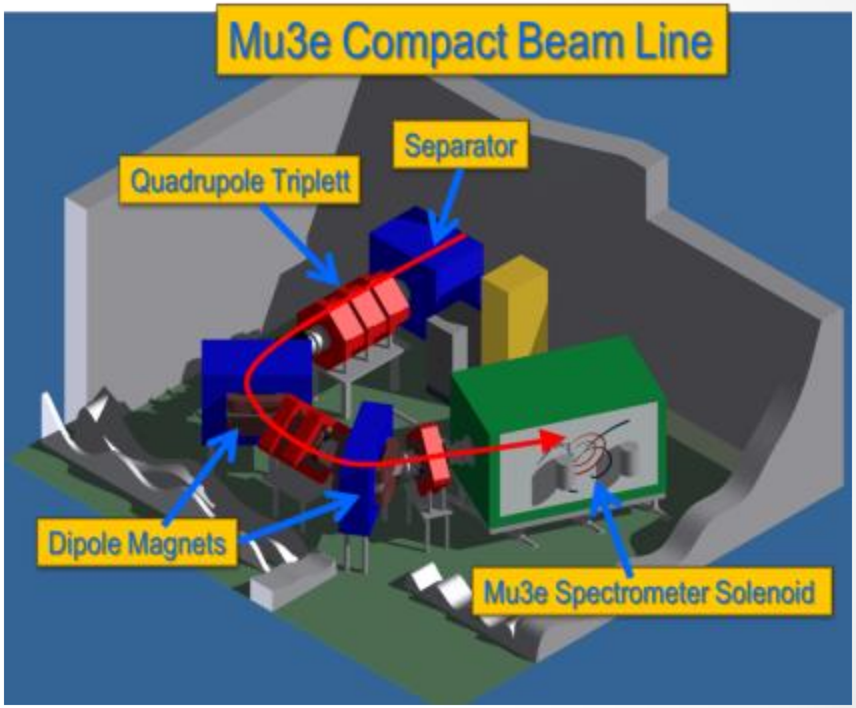


Mu3e Compact Beam Line



Space Restrictions

- Phase I:
  - Beam line at πE5
  - Surface muons from target E
  - Up to 10^8 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
  - He tests
- Magnet
  - DFG application