



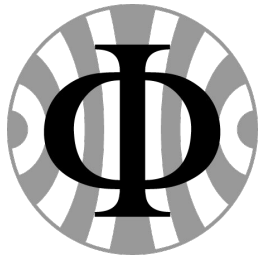
The Mu3e Detector and prototyping and tooling for the Mu3e vertex detector

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University of Heidelberg

Forum on Tracking Detector Mechanics

19/05/2021



Overview

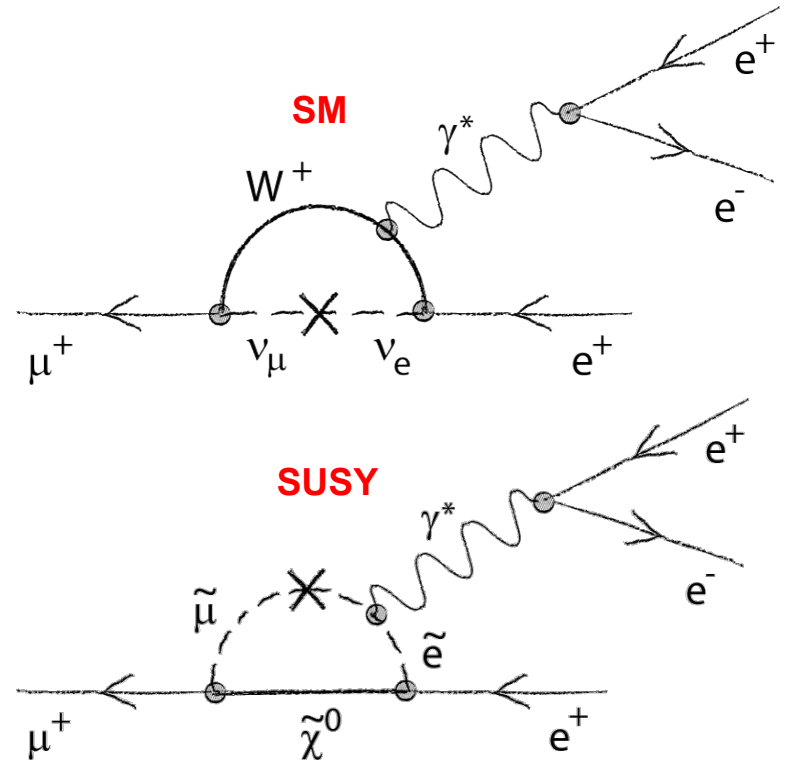


- Physics motivation
- Experimental challenges
- Experiment features
 - Sensor
 - Mechanics
 - Connections
 - Cooling
- Production and tooling
- Mock-up tests
 - Silicon Heater

Mu3e: Physics Motivation



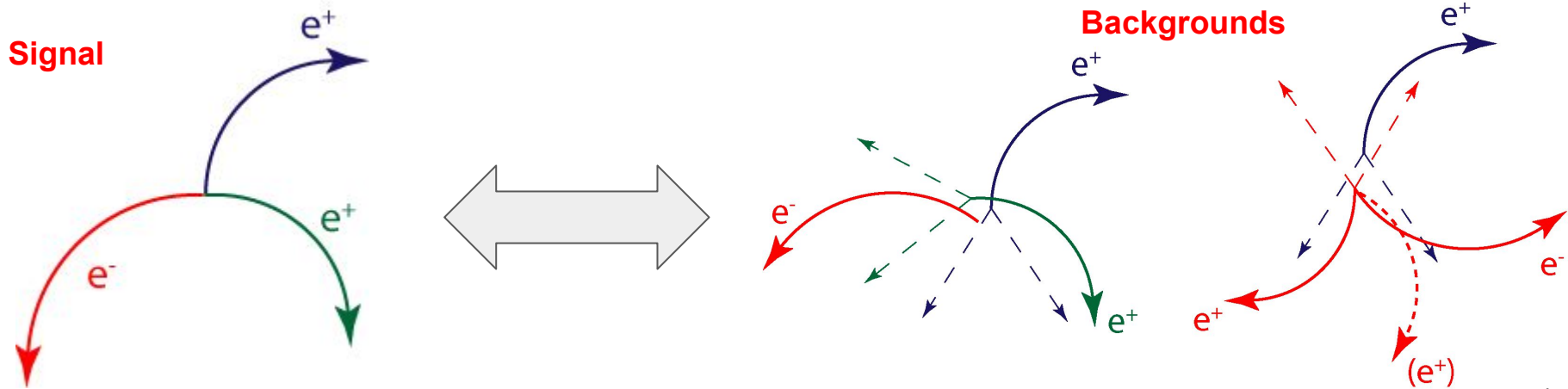
- Search for $\mu \rightarrow eee$
 - Standard Model: $\text{BR}(\mu \rightarrow eee) < 10^{-54}$
- New physics might enhance BR
- Current limit:
 - $\text{BR}(\mu \rightarrow eee) < 10^{-12}$ (SINDRUM, 1988)
- Aimed single-event sensitivity:
 - $\text{BR}(\mu \rightarrow eee) < 2 \cdot 10^{-15}$ (Phase 1)
 - $\text{BR}(\mu \rightarrow eee) < 10^{-16}$ (Phase 2)
- PSI High Intensity Muon Beamline
- Phase 1 construction starting by the end of the year



Experimental challenges



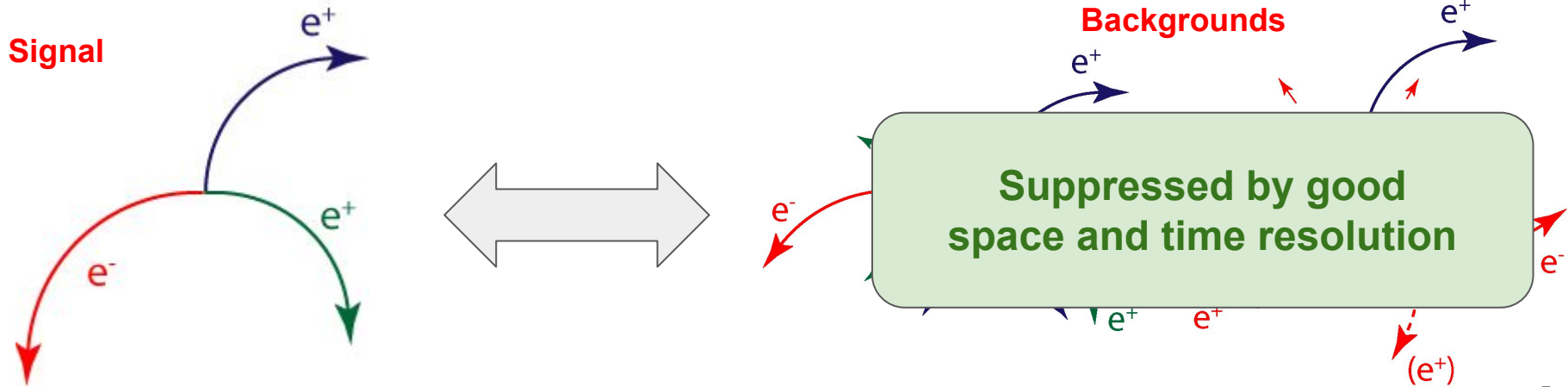
- Tracking electrons coming from muon decays
- High muon rates
 - 10^8 Hz Phase I
 - 10^9 Hz Phase II



Experimental challenges



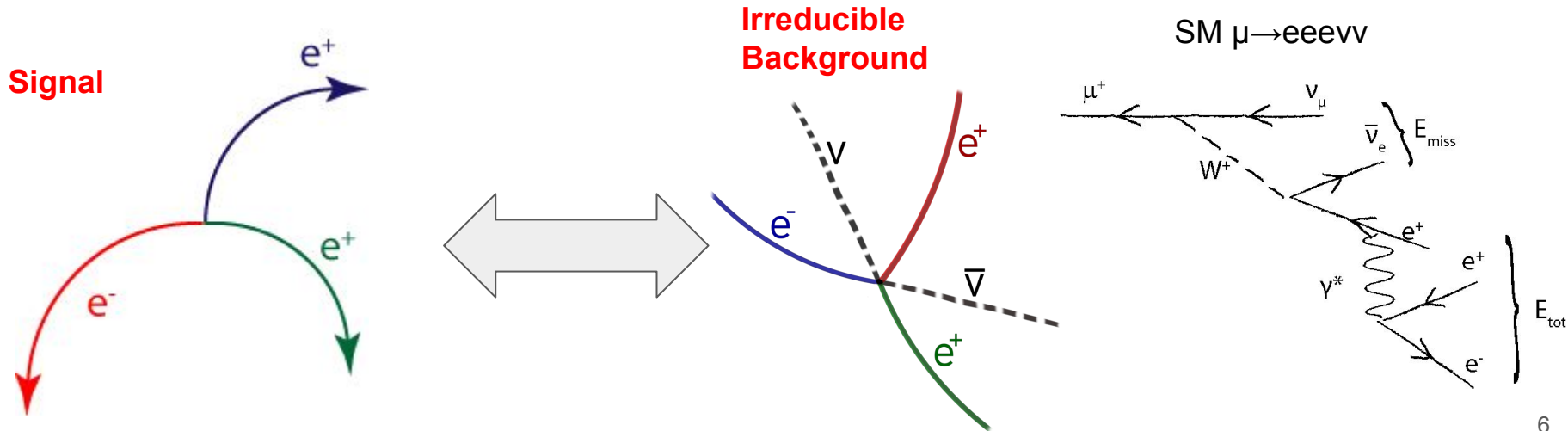
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Experimental challenges



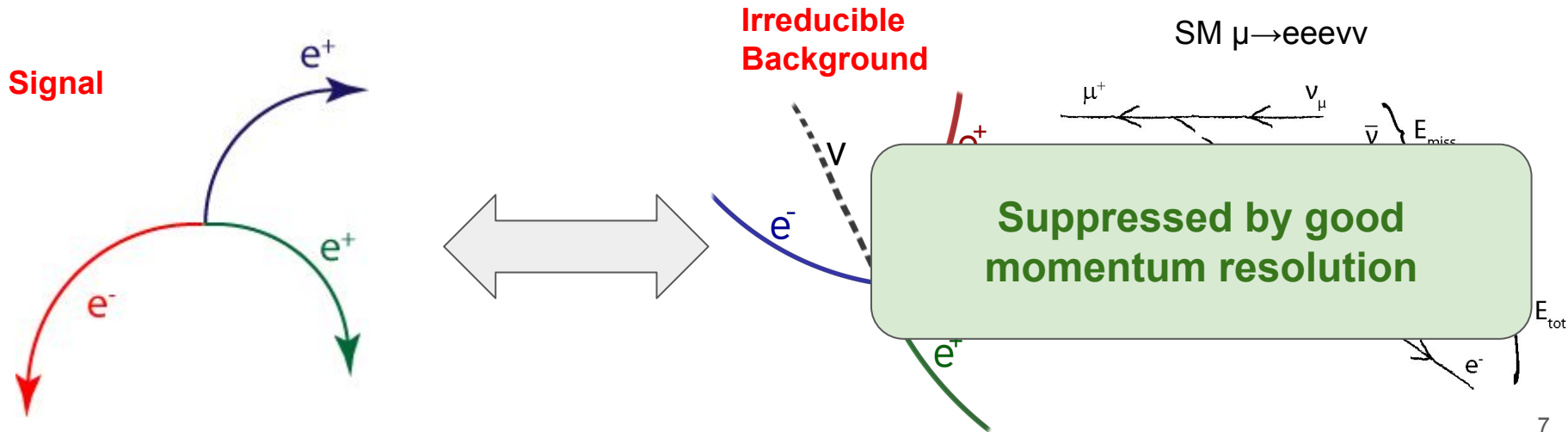
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Experimental challenges



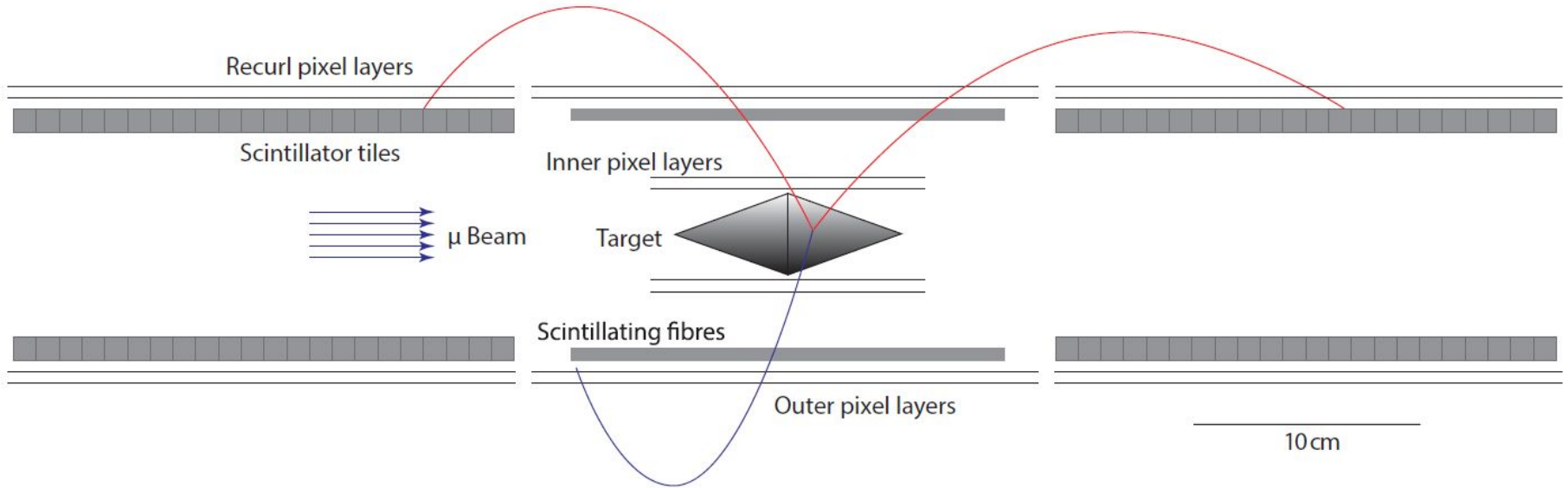
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Experimental challenges



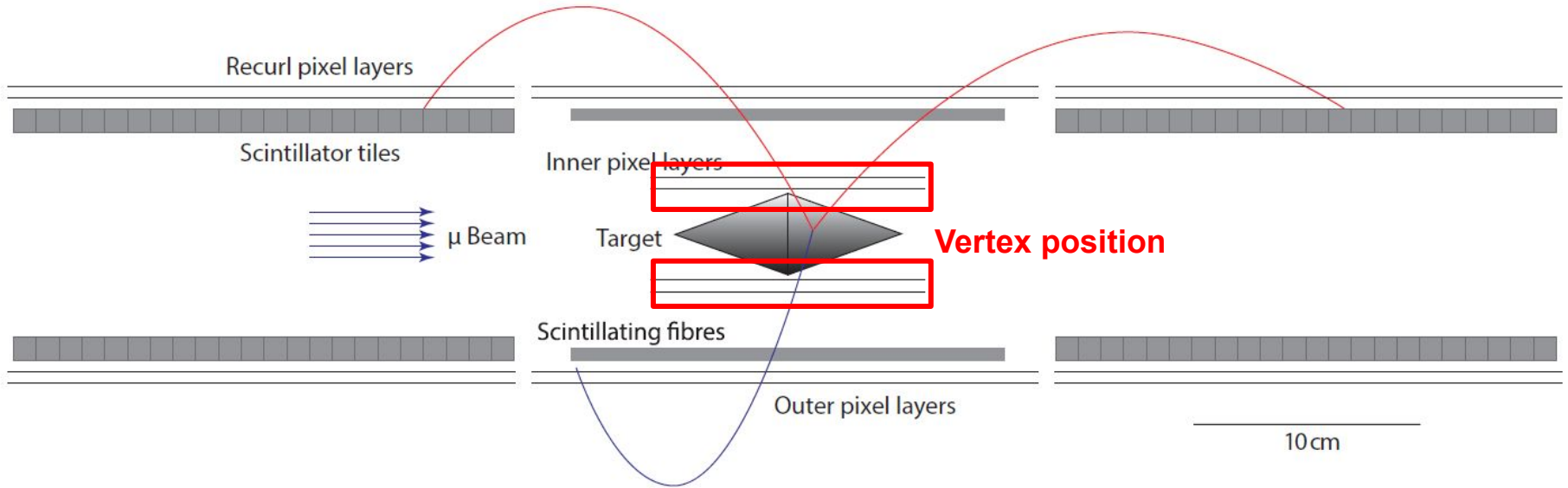
- Tracking electrons coming from muon decays
- Magnetic field (1 T)



Experimental challenges



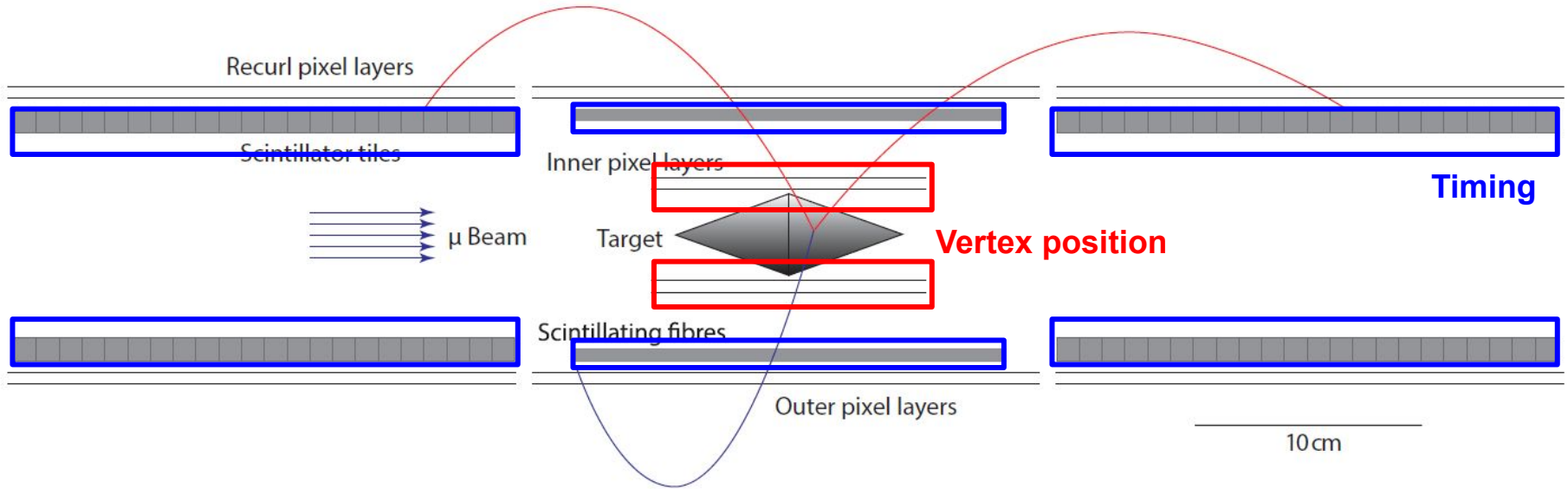
- Tracking electrons coming from muon decays
- Magnetic field (1 T)



Experimental challenges



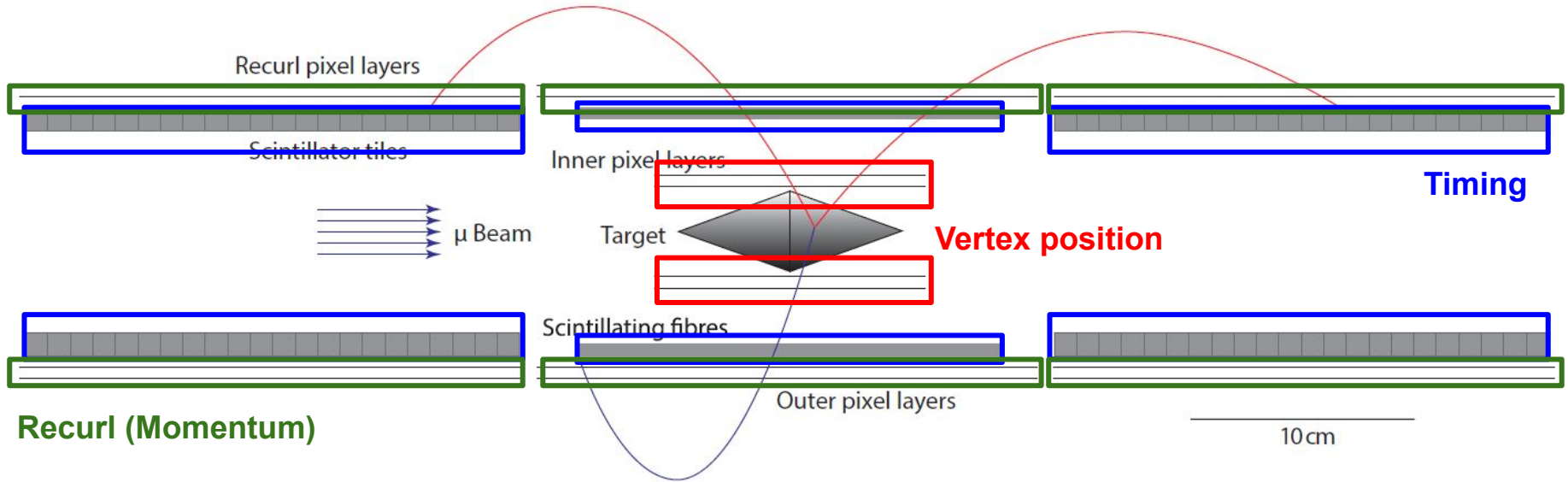
- Tracking electrons coming from muon decays
- Magnetic field (1 T)



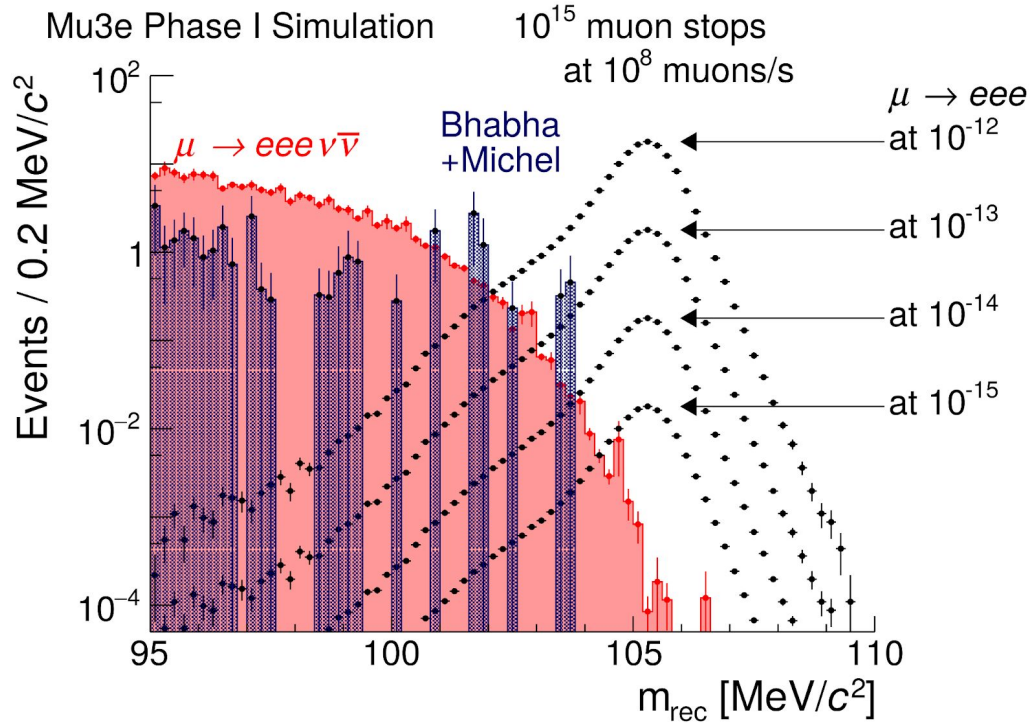
Experimental challenges



- Tracking electrons coming from muon decays
- Magnetic field (1 T)



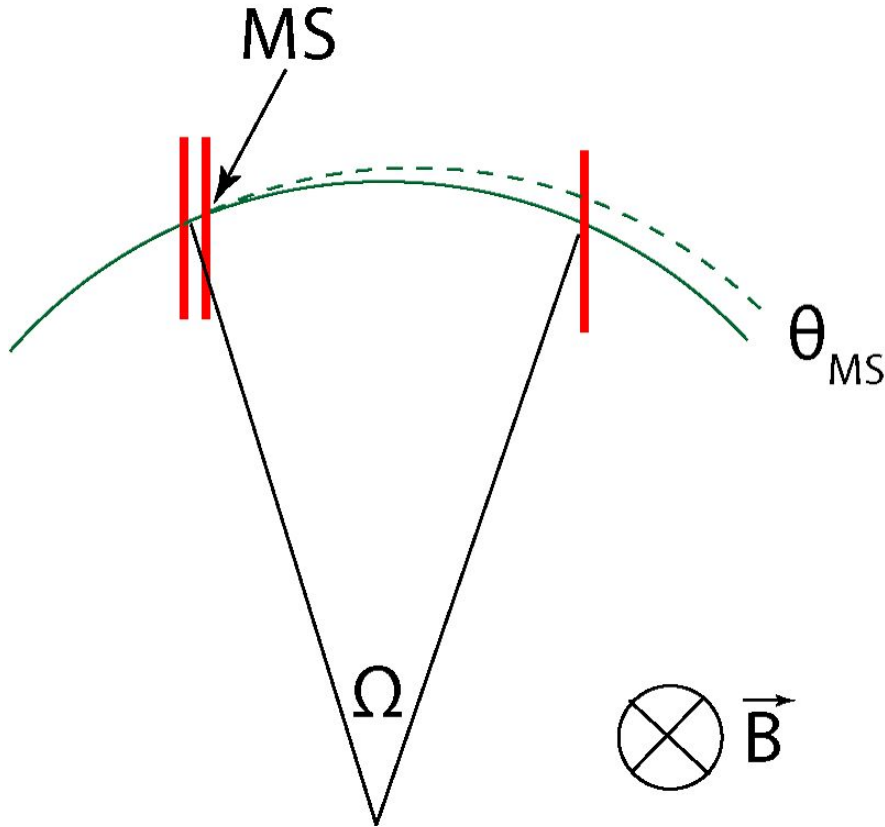
Experimental challenges



Momentum resolution crucial for detecting the peak at muon mass...

Invariant mass of signal decay, radiative decay and accidental background (Bhabha+Michel) [[Mu3e TDR](#)]

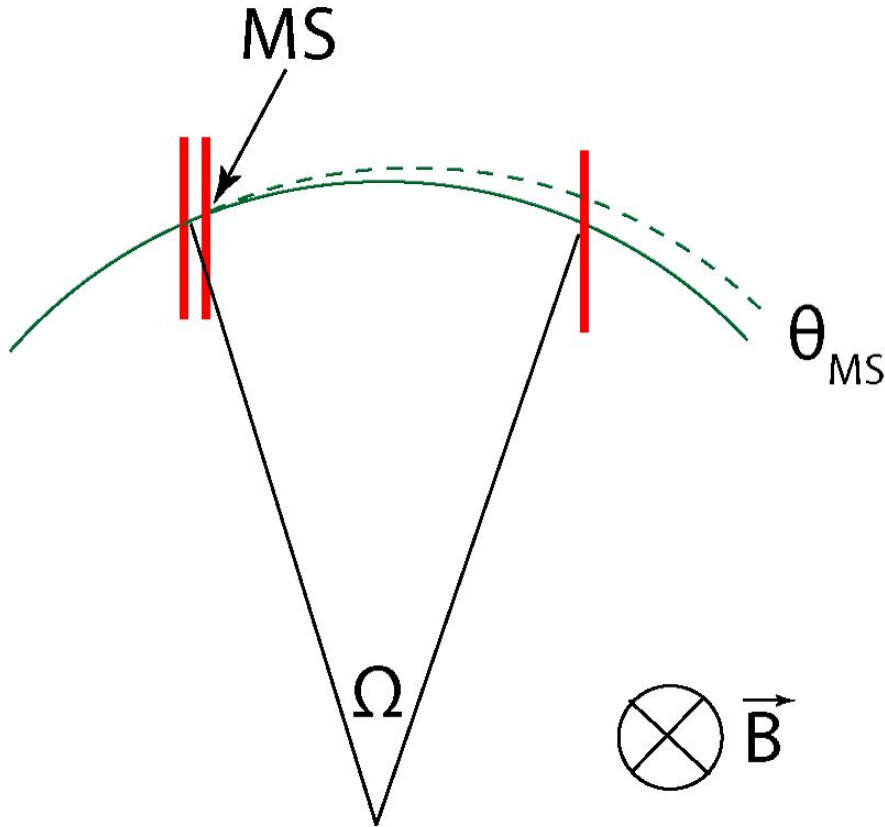
Experimental challenges



Electron energy very low
(< 53 MeV)

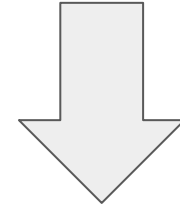
Multiple scattering main factor
to momentum resolution

Experimental challenges



Electron energy very low
(< 53 MeV)

Multiple scattering main factor
to momentum resolution



Material budget
minimization
is the key factor

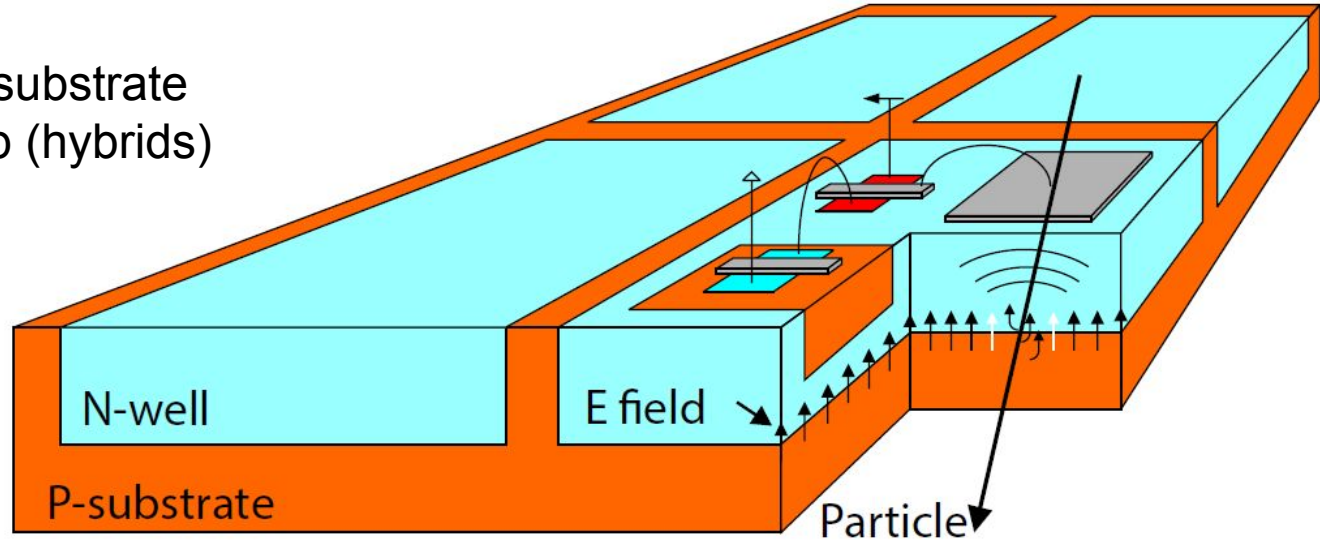
Material budget minimization



Reduce silicon thickness of tracker

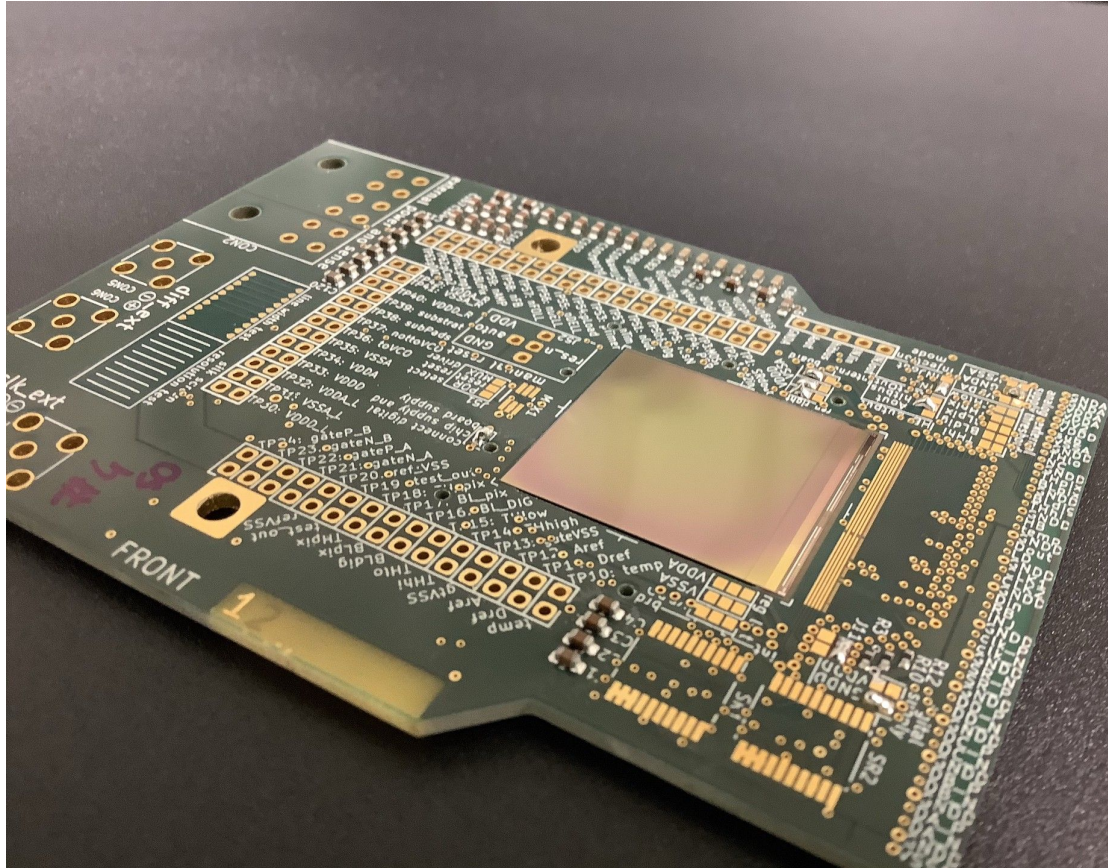
HV-CMOS sensors

Read-out in substrate
No extra chip (hybrids)



HV allows for high speed and efficiency

Mupix10



First full-scale prototype

256x250 pixels, $80 \times 80 \mu\text{m}^2$ size

Final sensor Mupix11 -expected in Autumn

Specifications:

- $\sim 2 \times 2 \text{ cm}^2$ active matrix
- Efficiency $> 99 \%$
- Time resolution $< 20 \text{ ns}$
- Thinned to $50 \mu\text{m}$ ($X/X_0 = 0.054 \%$)

Material budget minimization



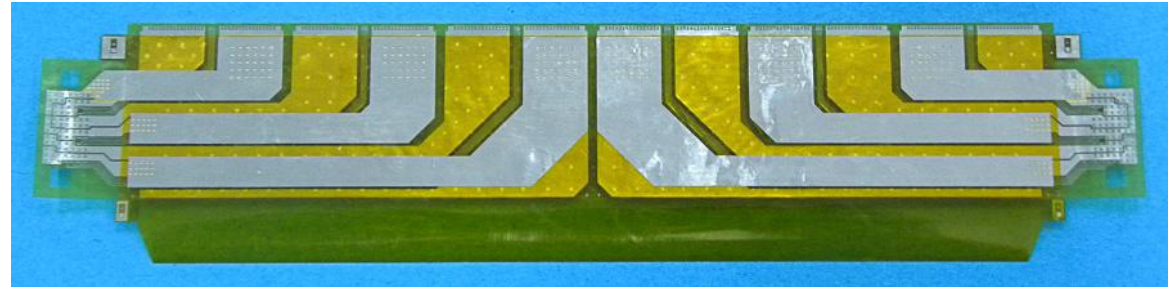
Kapton aluminum flexes for

- Support structure
- Electrical connections



Cross section

High Density Interconnects HDIs



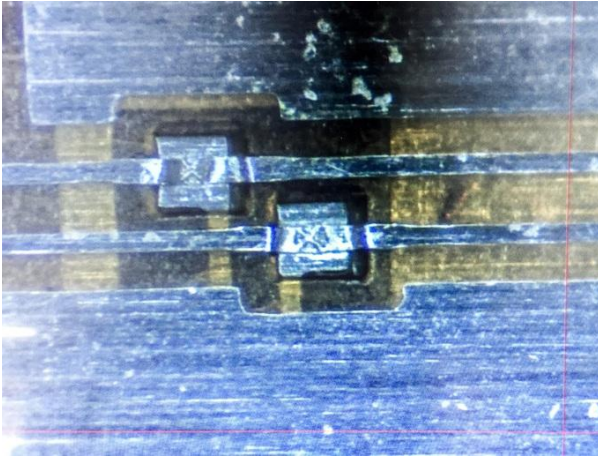
**Example
Produced by LTU (Ukraine)**

Material budget minimization



Connections

Pixels to ladders



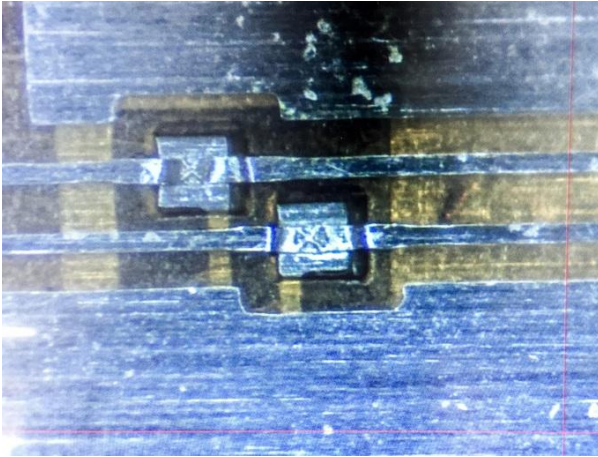
SpTAB bonds
(Single Point Tape Automated Bonding)

Material budget minimization



Connections

Pixels to ladders



No extra material
No wires

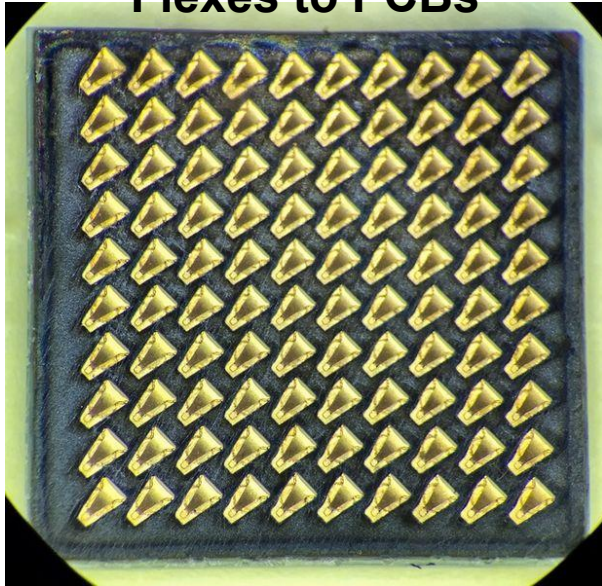
SpTAB bonds
(Single Point Tape Automated Bonding)

Material budget minimization



Connections

Ladders to flexes
Flexes to PCBs



Gold ball interposers

Material budget minimization



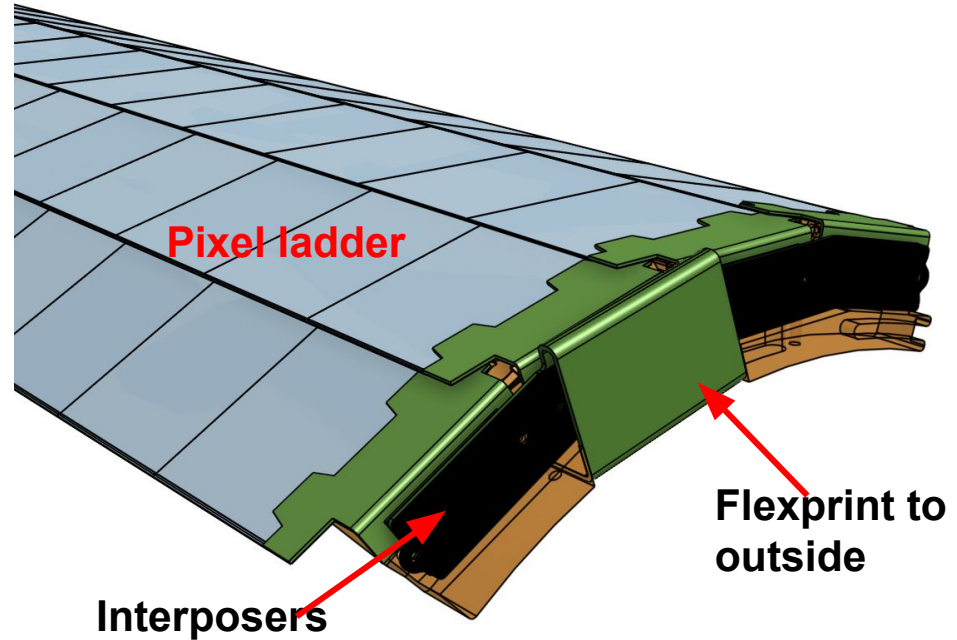
Connections

Ladders to flexes
Flexes to PCBs



Connected via screws
Easy to attach/remove
Modularity
Compactness

Gold ball interposers

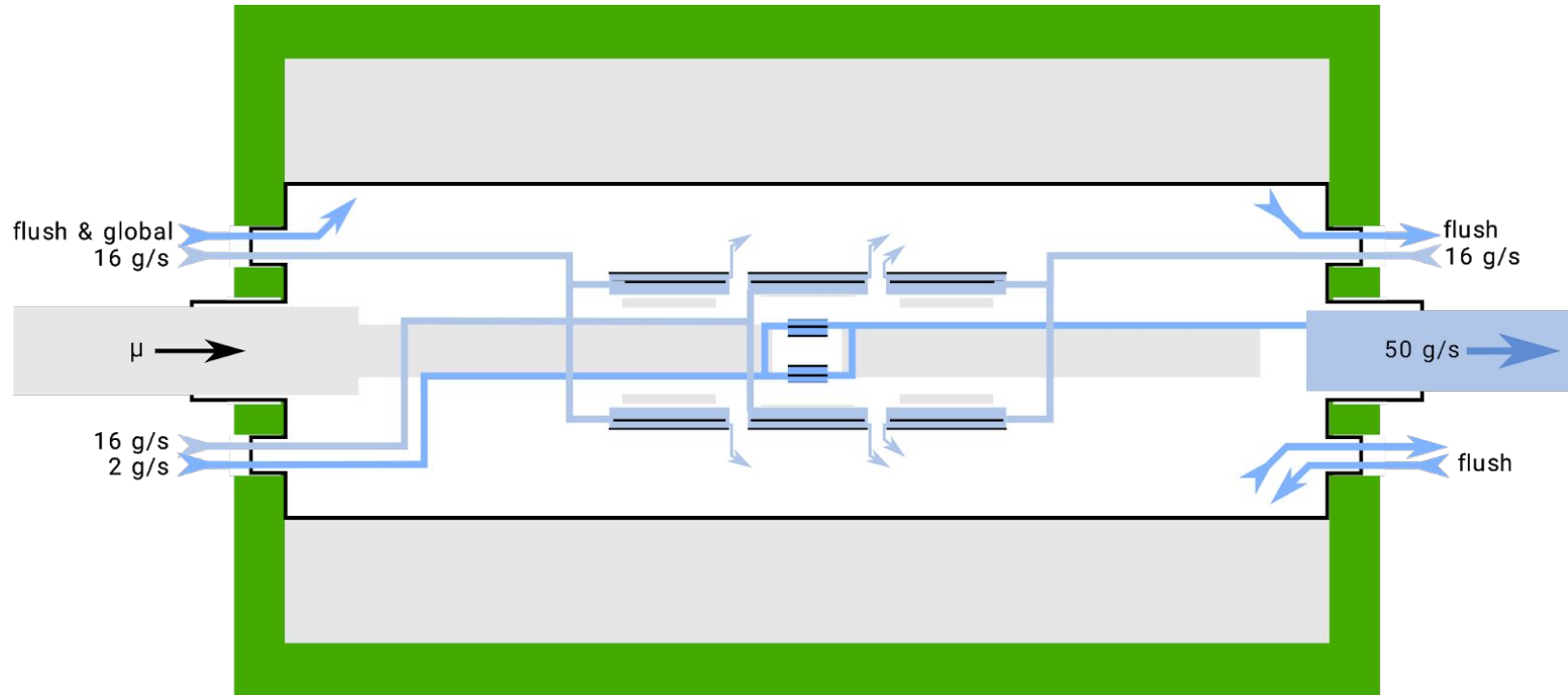


Material budget minimization



Cooling (Global)

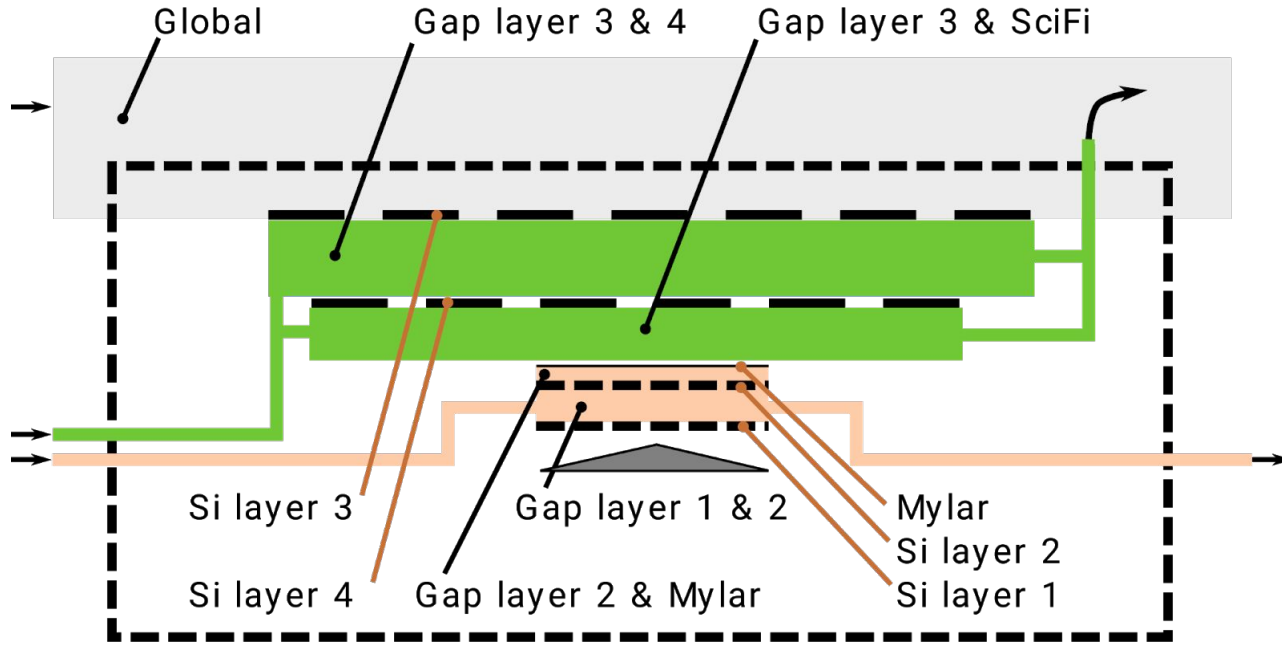
Gaseous Helium used as coolant



Material budget minimization

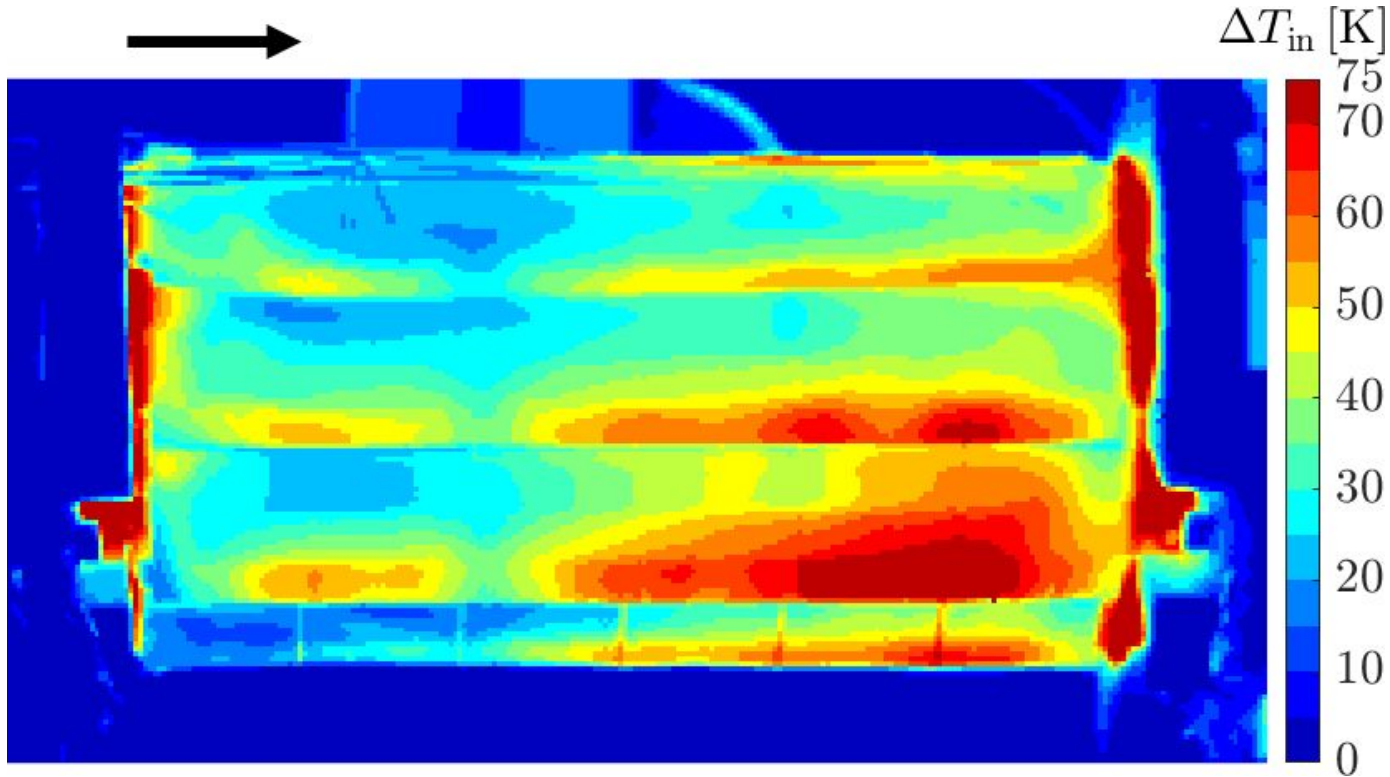


Cooling (Pixels detailed)



Temperature < 70° (glass-transition temperature of the adhesives)

Material budget minimization



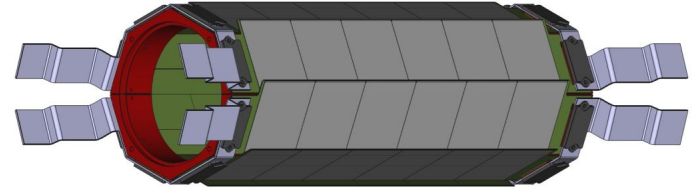
**Simulations:
70 K of ΔT with
400 mW/cm² power
consumption
(double the nominal)**

Tracker overview



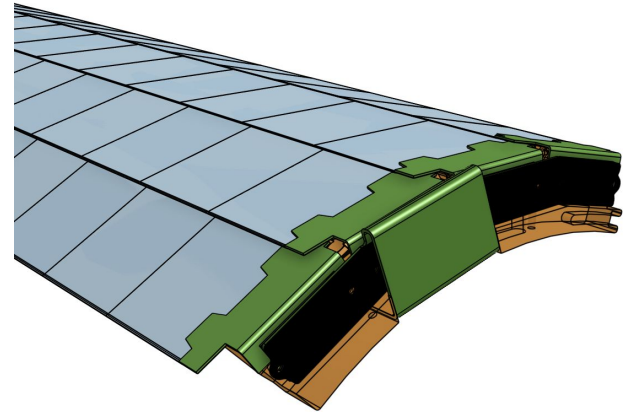
Inner layers:

- In central station around target
- 2 layers with 8/10 ladders
- 6 chips per ladder



Outer layers:

- 3 stations
- 2 layers with 24/28 ladders
- 17/18 chips per ladder

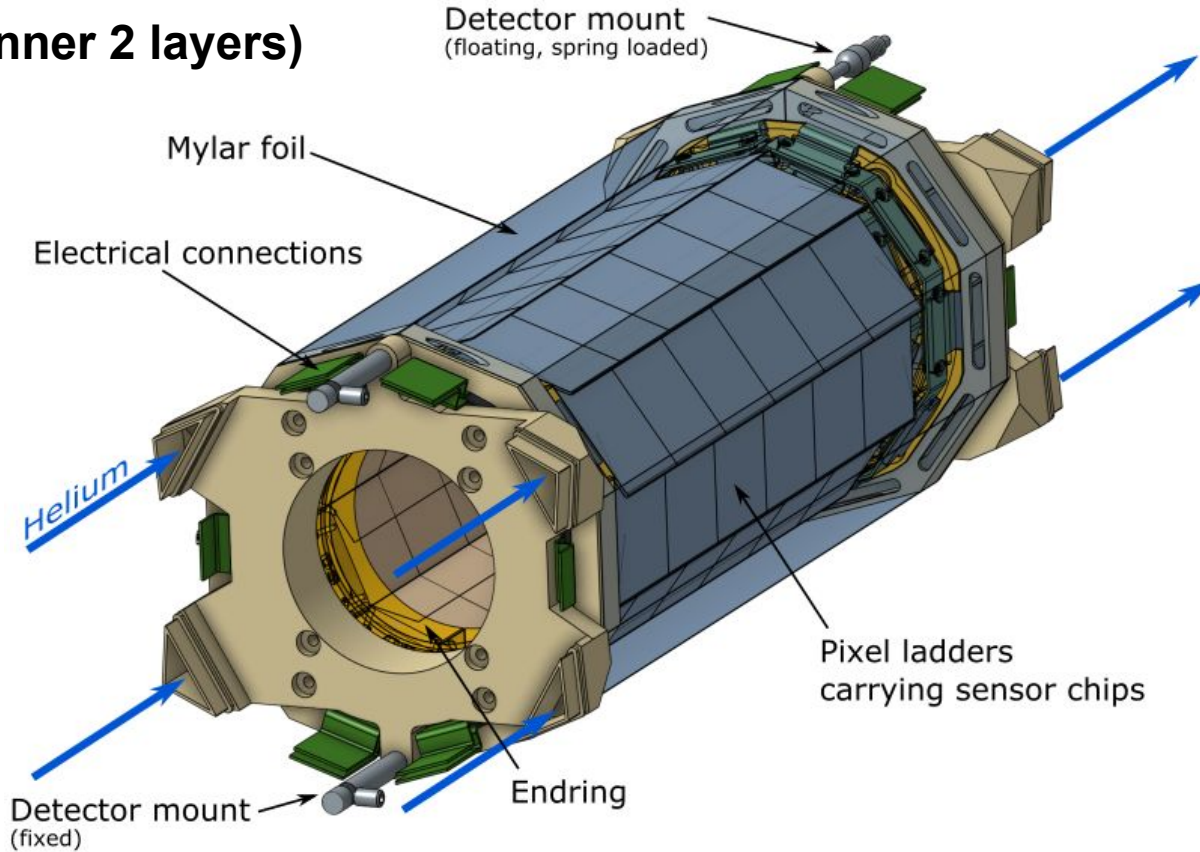


Total material budget per layer: $0.115\% X/X_0$

Tracker overview



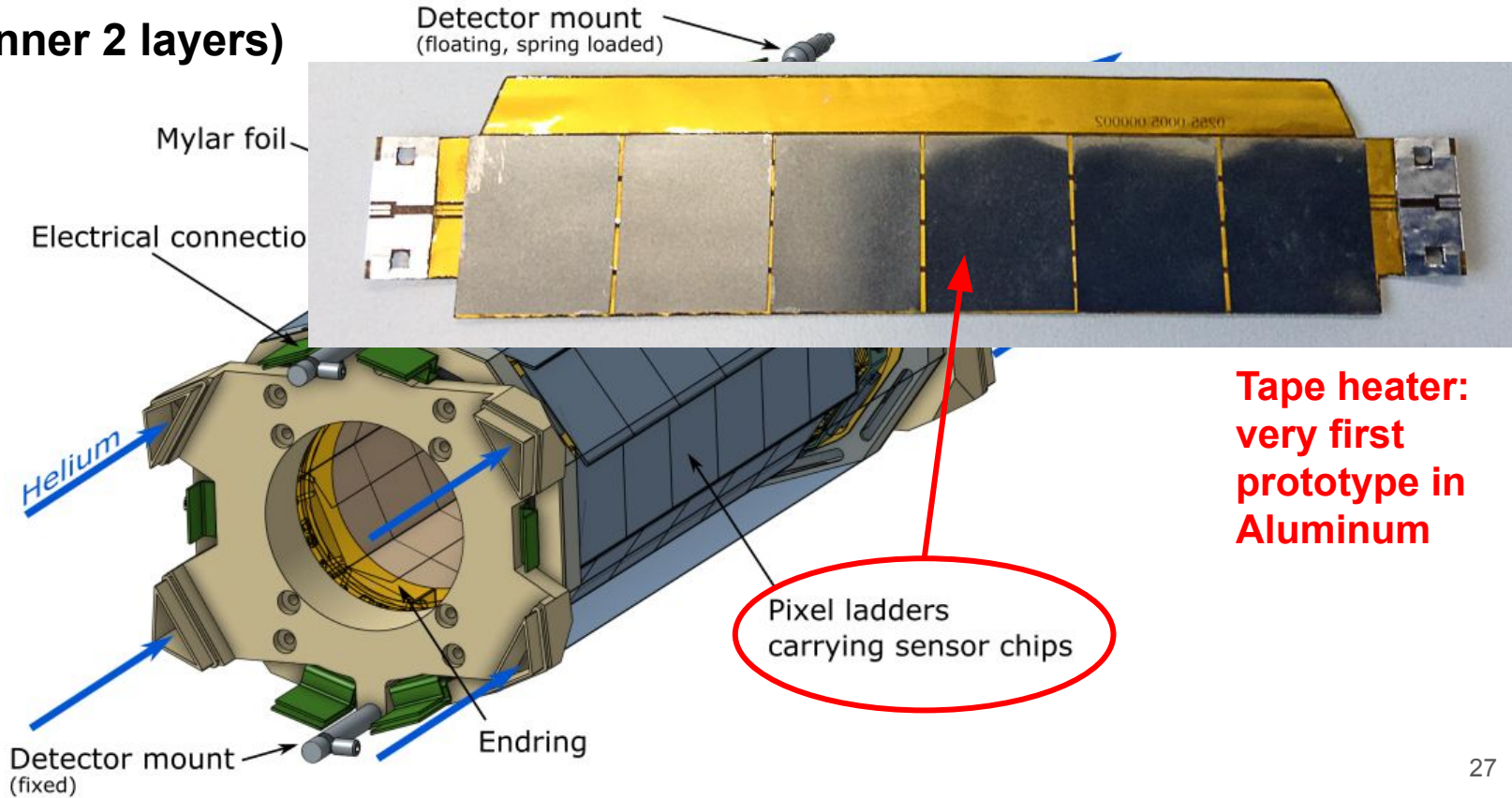
Vertex (inner 2 layers)



Tracker overview



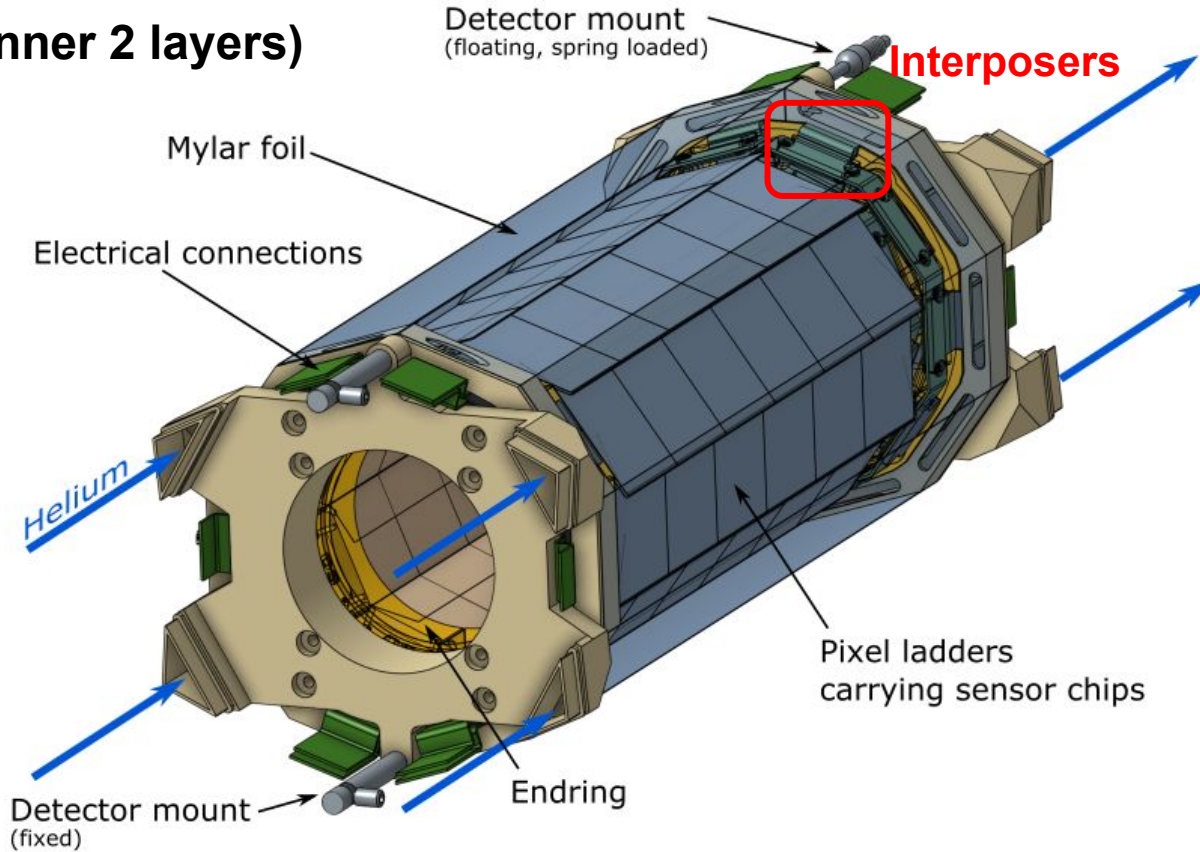
Vertex (inner 2 layers)



Tracker overview



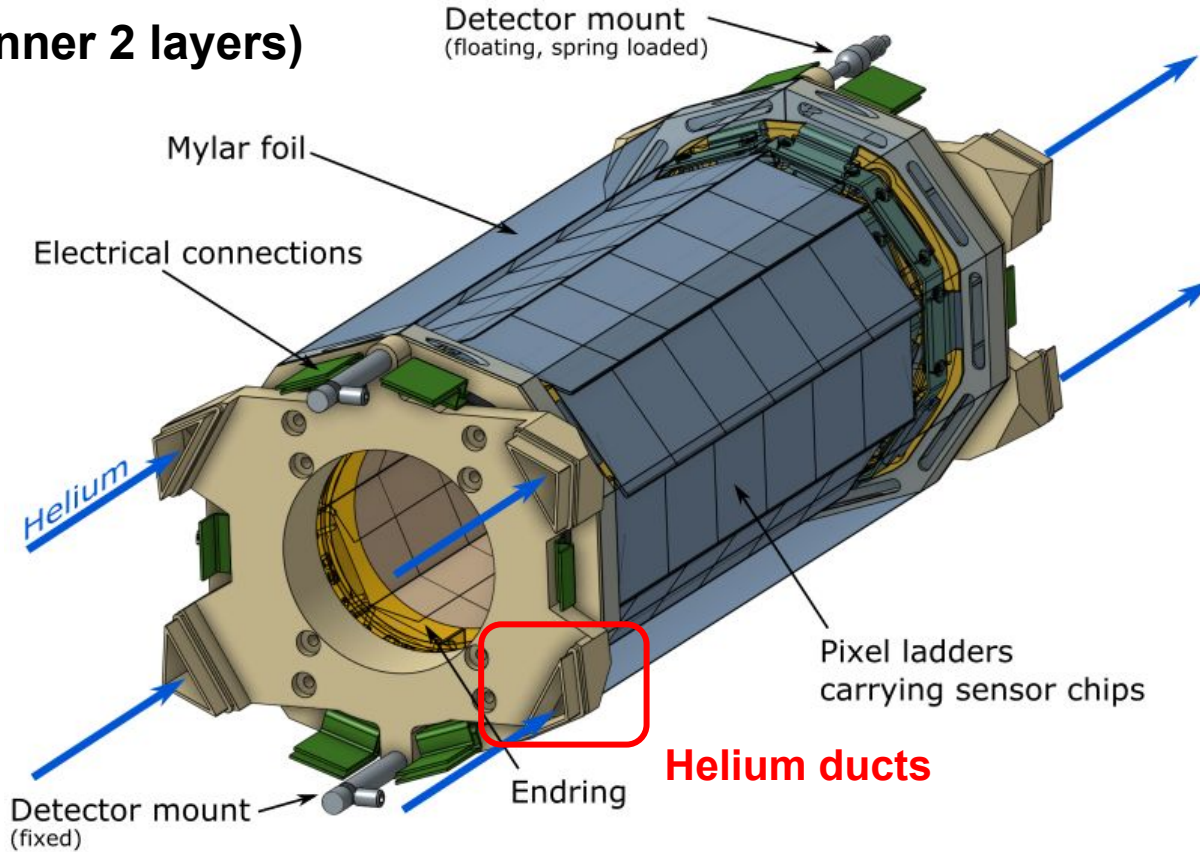
Vertex (inner 2 layers)



Tracker overview



Vertex (inner 2 layers)



Prototype: Silicon heater

- Prototype made of
 - 50 μm thin silicon heaters with a $\sim 1.2 \text{ k}\Omega$ resistive thermometer
 - High-density interconnects from LTU (same technology as final detector)
- Perfect matching of geometry and material
- Construction proved that specification can be met:
 - Final chip placement precision of 5 μm (along beam direction)
 - Glue thickness $\approx 5 \mu\text{m}$
 - Electrical connections via spTAB established



Silicon heater chip

Production

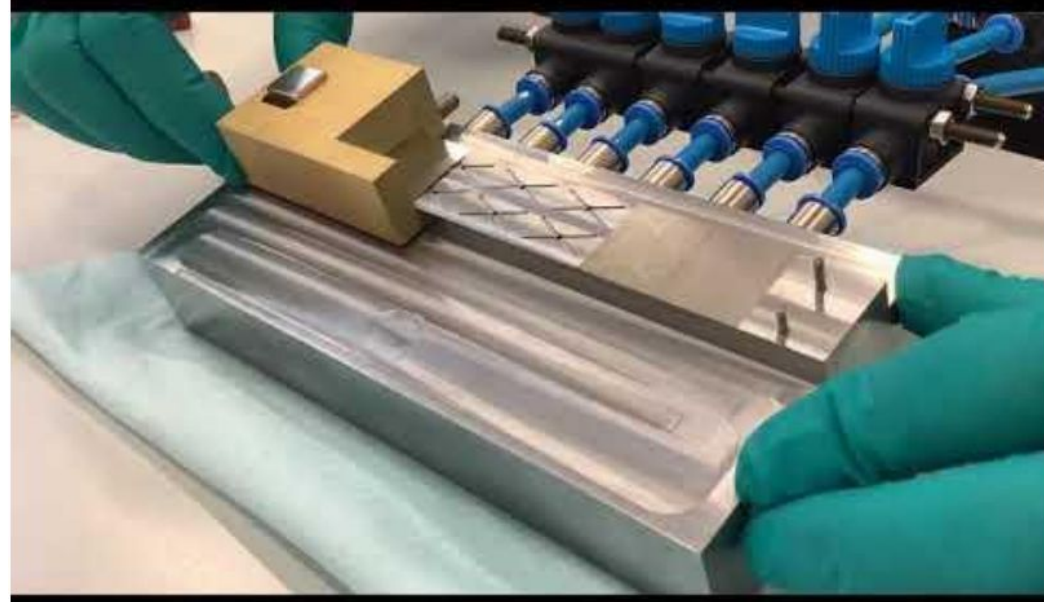


Vertex (inner 2 layers)

Chips placed by hand on vacuum structure

Each chip position has dedicated vacuum channel

[\(67\) Mounting Tool Prototype for Layer 1/2 \(Mu3e\) - YouTube](#)



Production



Vertex (inner 2 layers)



**Accuracy required:
5 μm**

Production



Vertex (inner 2 layers)

Chip relative
position controlled
by microscope
(1.5 μm resolution)

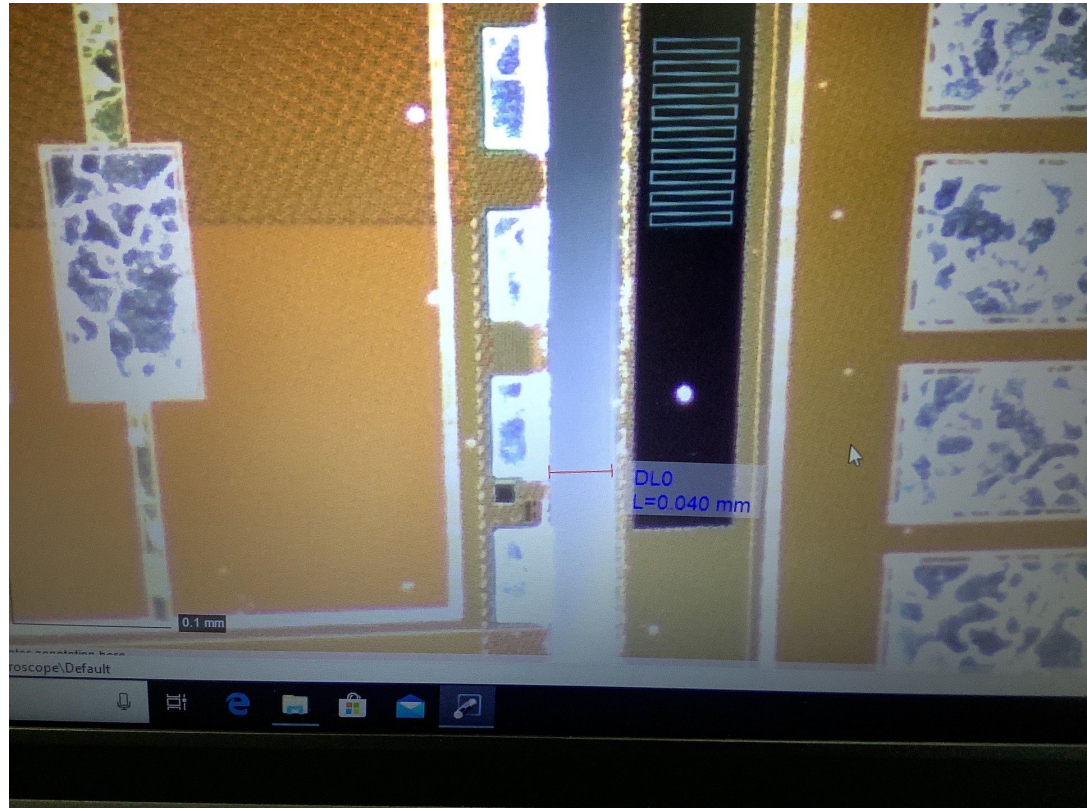


Production



Vertex (inner 2 layers)

Chip relative
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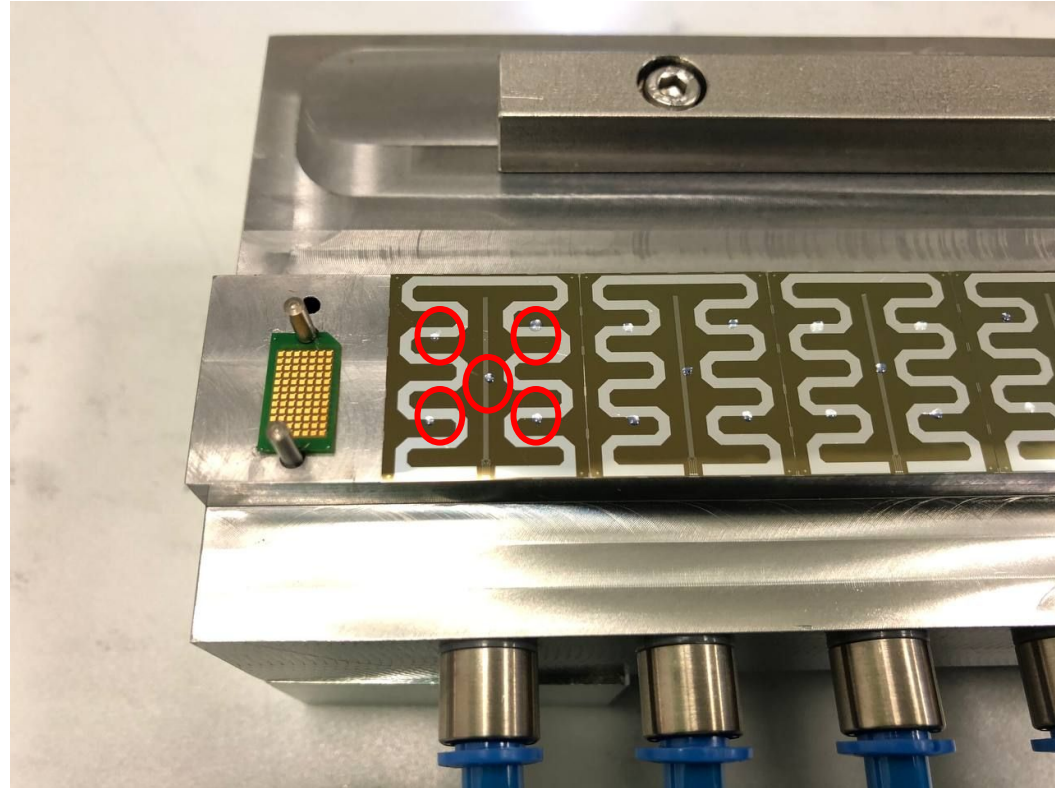


Production



Vertex (inner 2 layers)

Glue deposited



Production

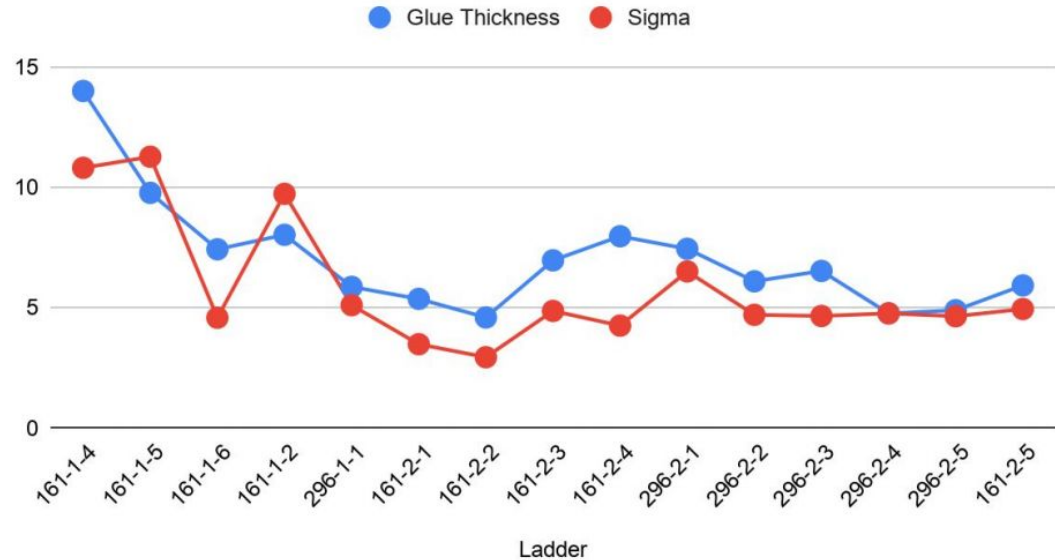


Vertex (inner 2 layers)

Glue deposited

Thickness of 5 μm
achieved after few trials

Glue Thickness and Standard Deviation

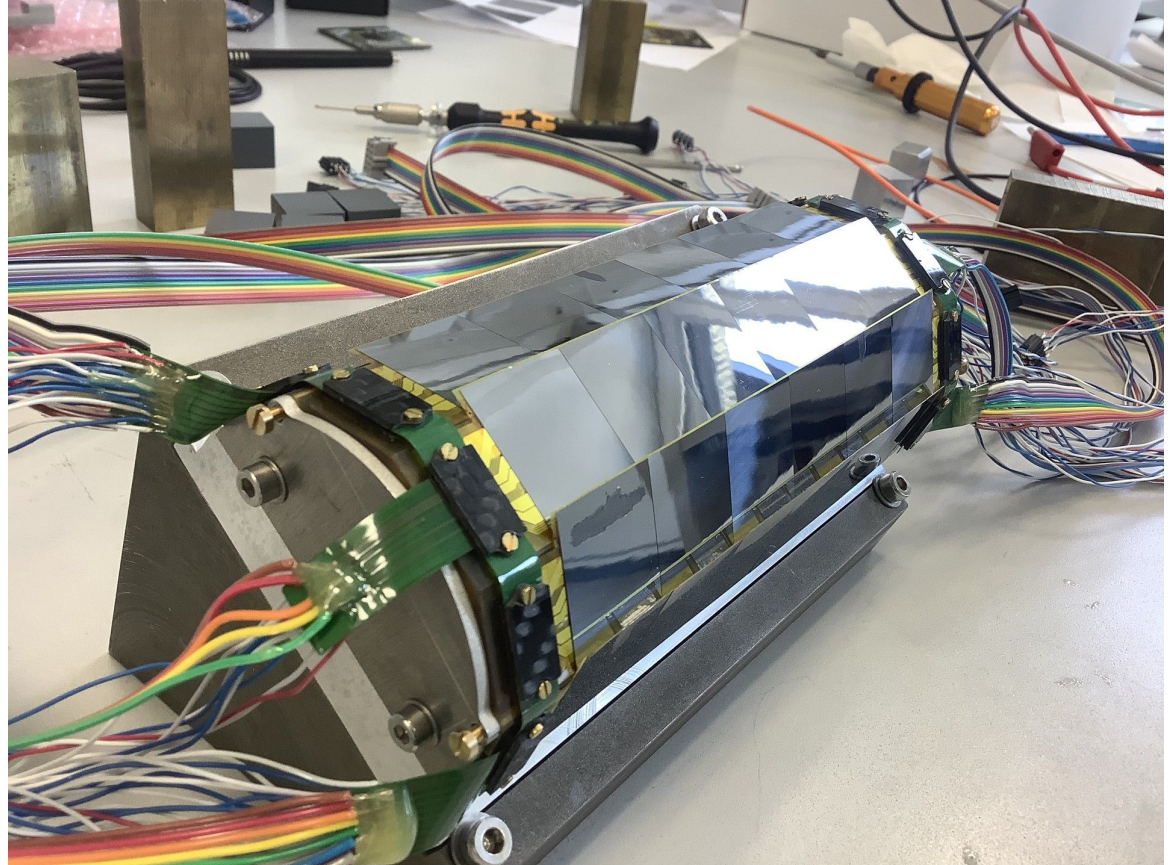


Production



Vertex (inner 2 layers)

Ladders mounted together on the support structures (half-layers)



Production



Vertex (inner 2 layers)

Check of
connections

Quick heating and
thermal camera



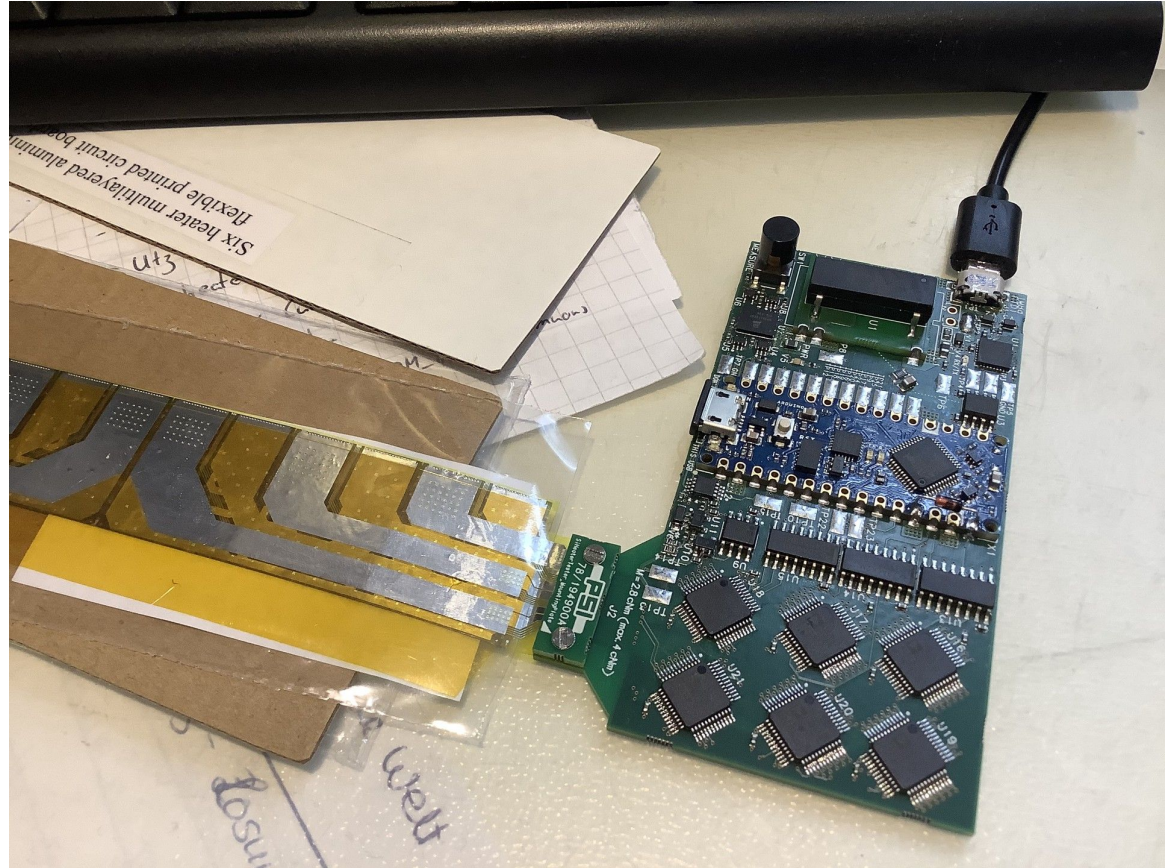
Production



Vertex (inner 2 layers)

Check of
connections

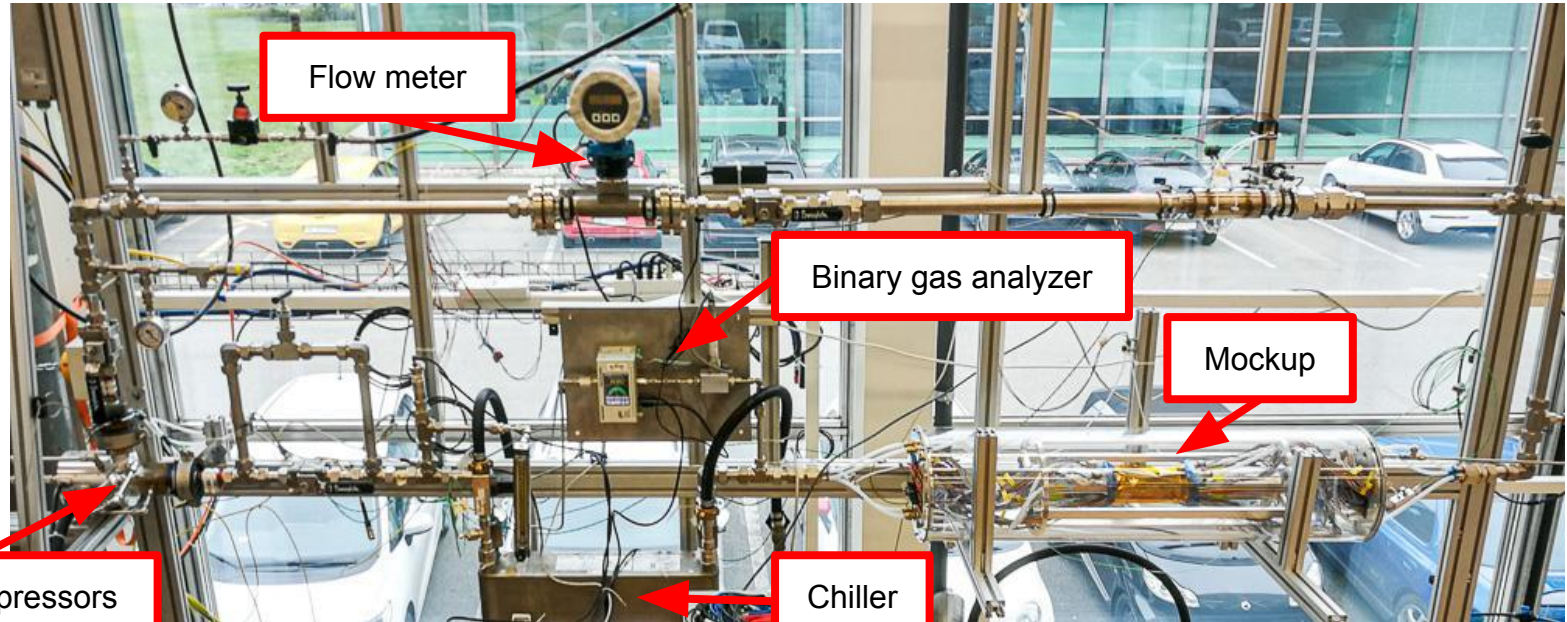
Board to compute
resistivity between
channels



Results of prototype tests



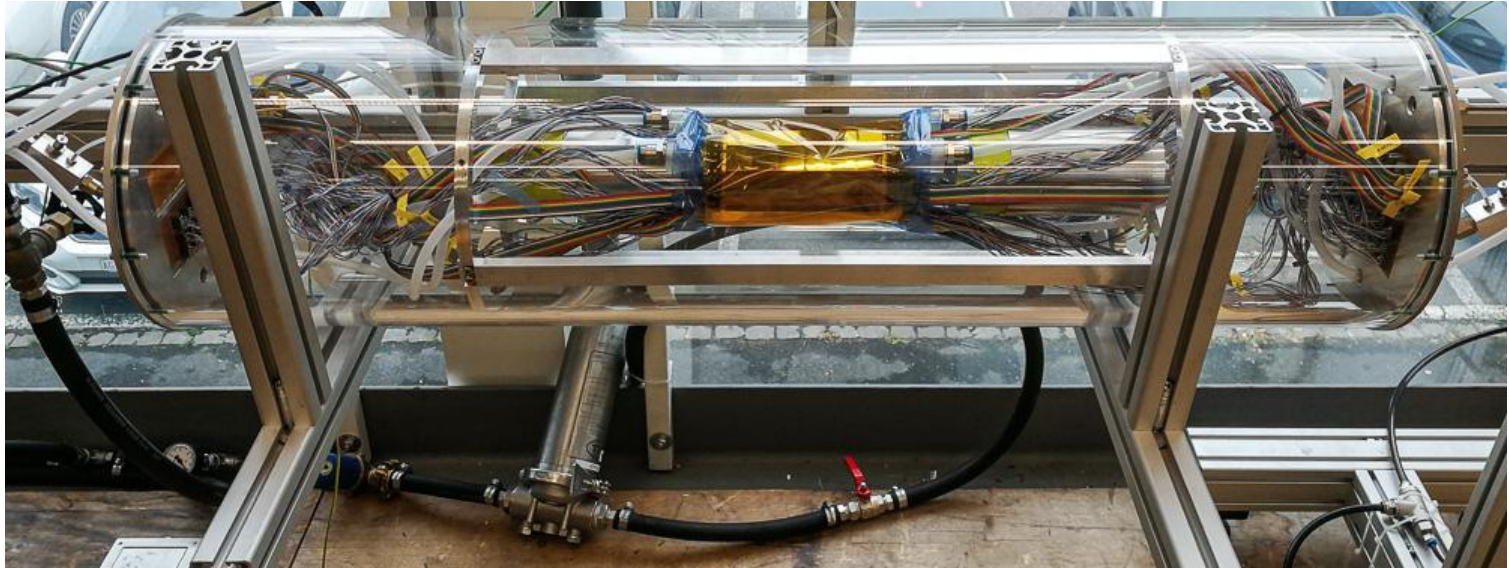
- Test stand for vertex tracker cooling at FHNW Brugg/Windisch



Results of prototype tests



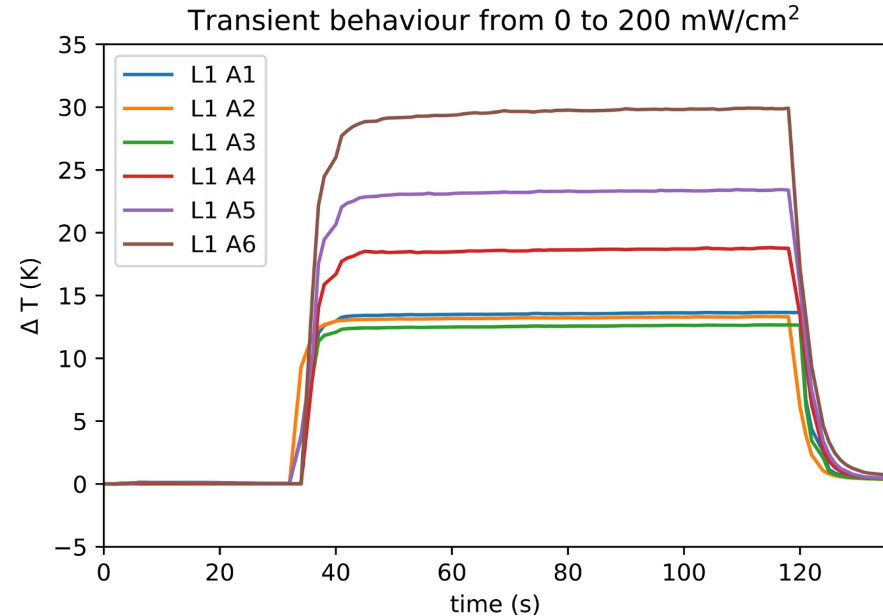
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Results of prototype tests




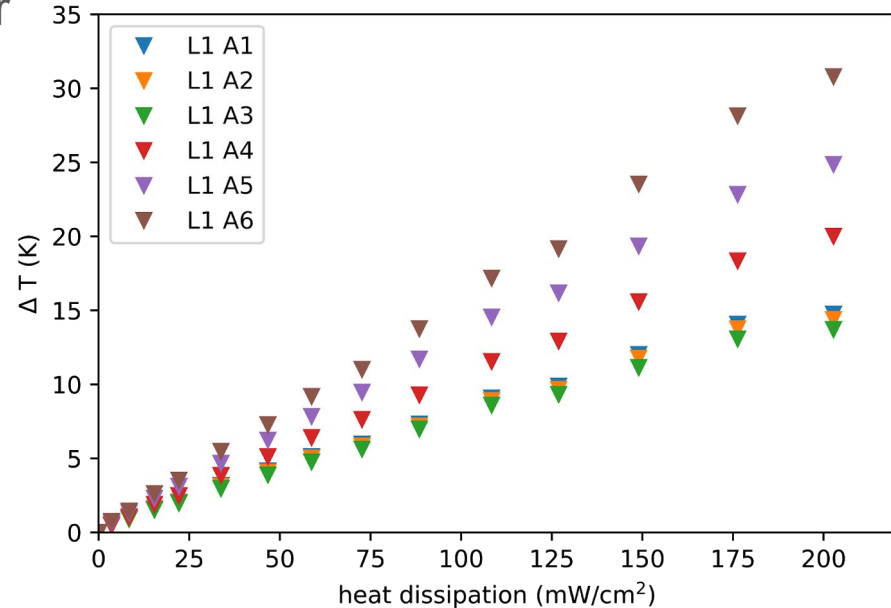
- Temperature measured for 6 sensor on one inner ladder
- Silicon heater prototype operated at nominal heat load of 200 mW/cm²
- Equilibrium reached in seconds
- Maximum allowed temperature is 70°C
- Maximum $\Delta T \sim 30$ K
(foreseen inlet temperature $\sim 5^\circ\text{C}$)



Results of prototype tests



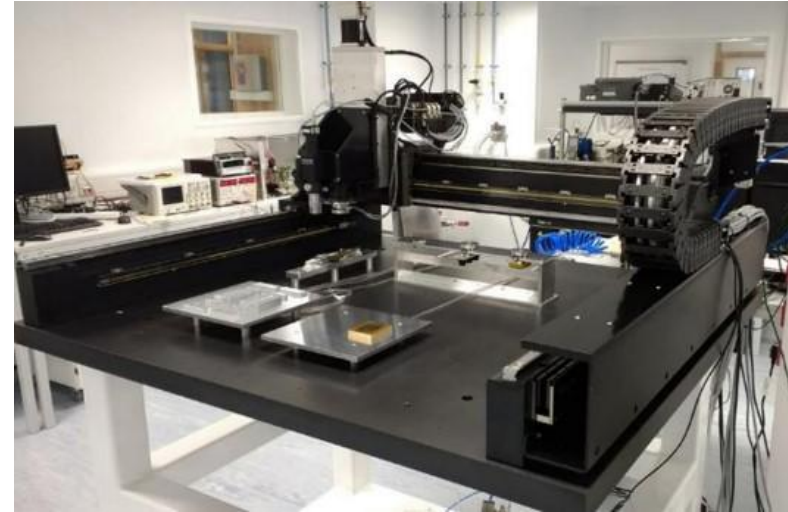
- Measurement of temperature-to-power relation
- Temperature difference linearly depending on heat dissipation
- Expected $\Delta T < 70$ K for 400 mW/cm^2 (conservative limit)
- Cooling concept works 
- More detailed studies to come



Outer pixel layers production



Performed in Oxford.



Automatized process
Gantry: chip absolute position with high precision

Conclusions

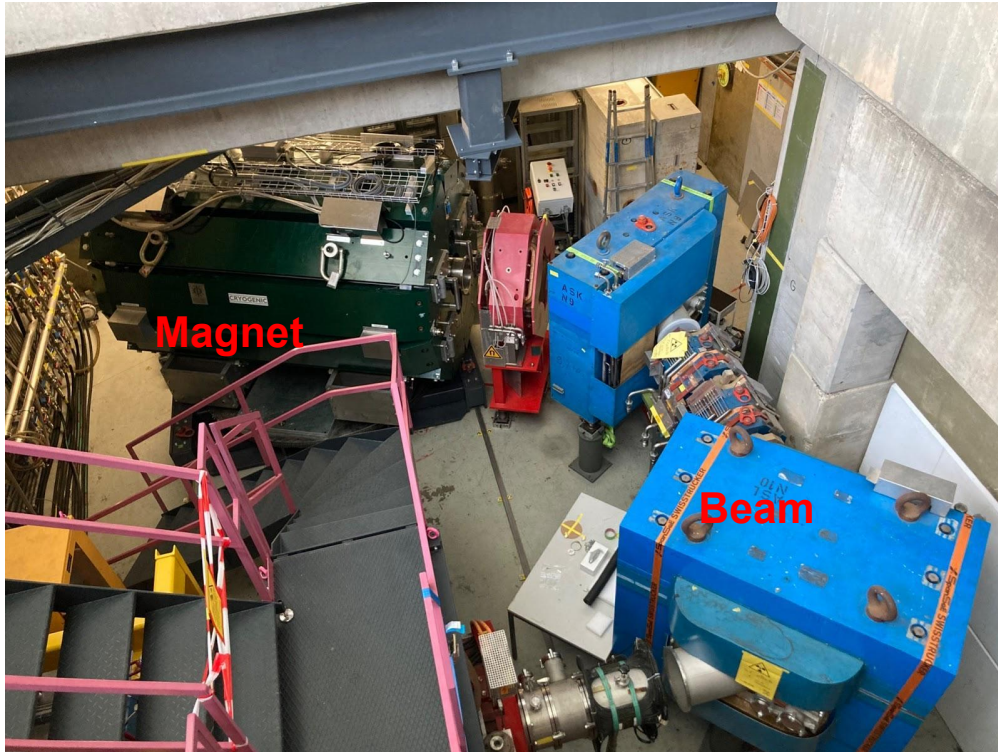


- Mu3e will investigate non-SM decays
- Several challenges in pixel tracker design
 - Material budget minimization
 - Compactness
- Construction will begin at the end of the year
- Production flow for inner layers tested with prototypes
 - Silicon heater: same thermo-mechanical properties as final detector
 - Helium cooling
 - Promising results
- Looking forward to start production!

Bonus



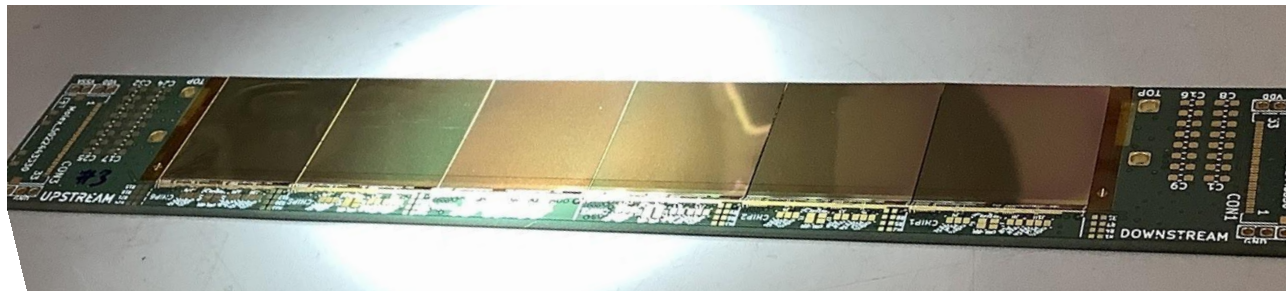
Testbeam at PSI on muon beamline (14/06)



Bonus



Testbeam at PSI on muon beamline (14/06)



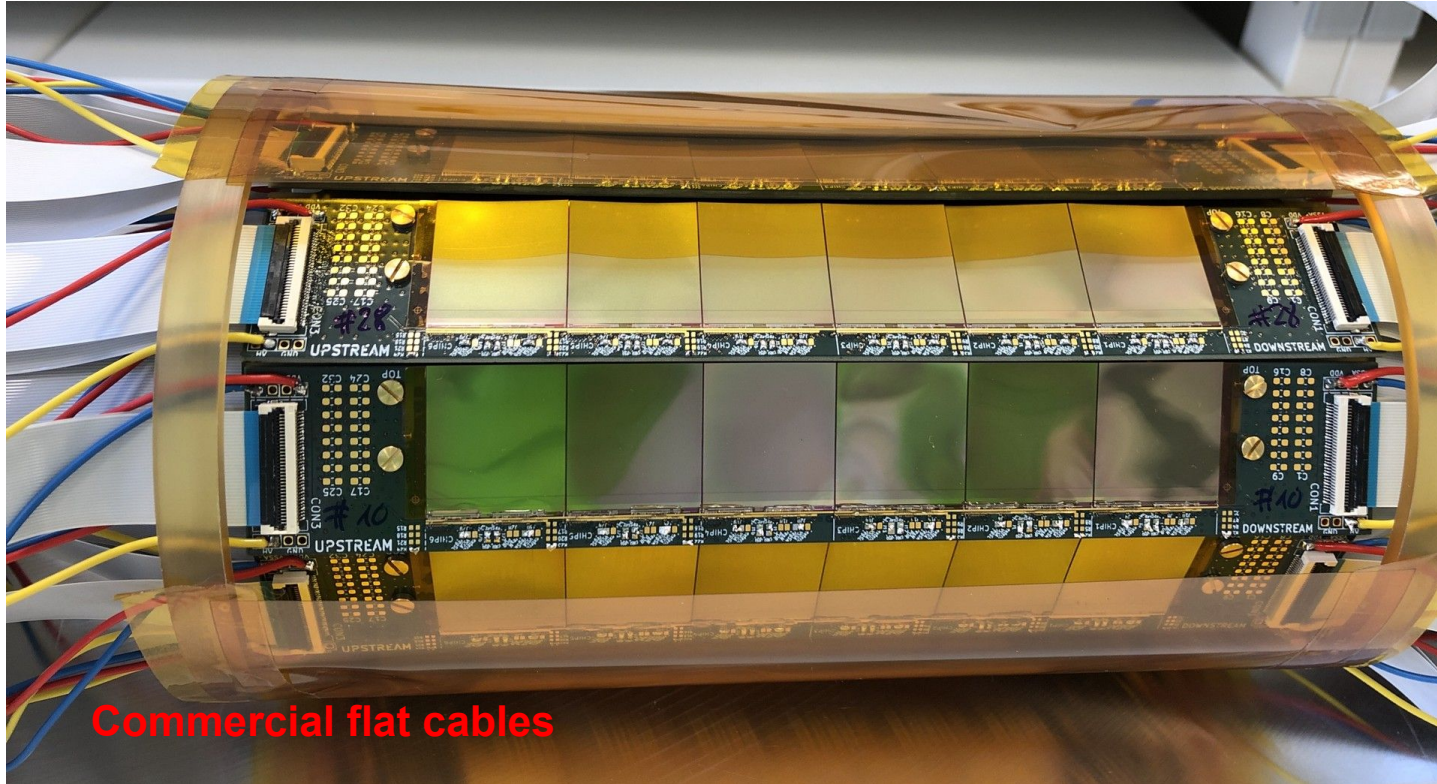
Pixel detector

- Mupix10, 50 μm thin
- Glued on kapton-aluminum flex (same as final detector)
- Mounted on PCB
 - Mupix10 need extra single-ended lines
 - HDIs cannot be used
 - Reduced angular acceptance
- First time operating 6 chips together

Bonus



Testbeam at PSI on muon beamline (14/06)



Pixel detector

Commercial flat cables