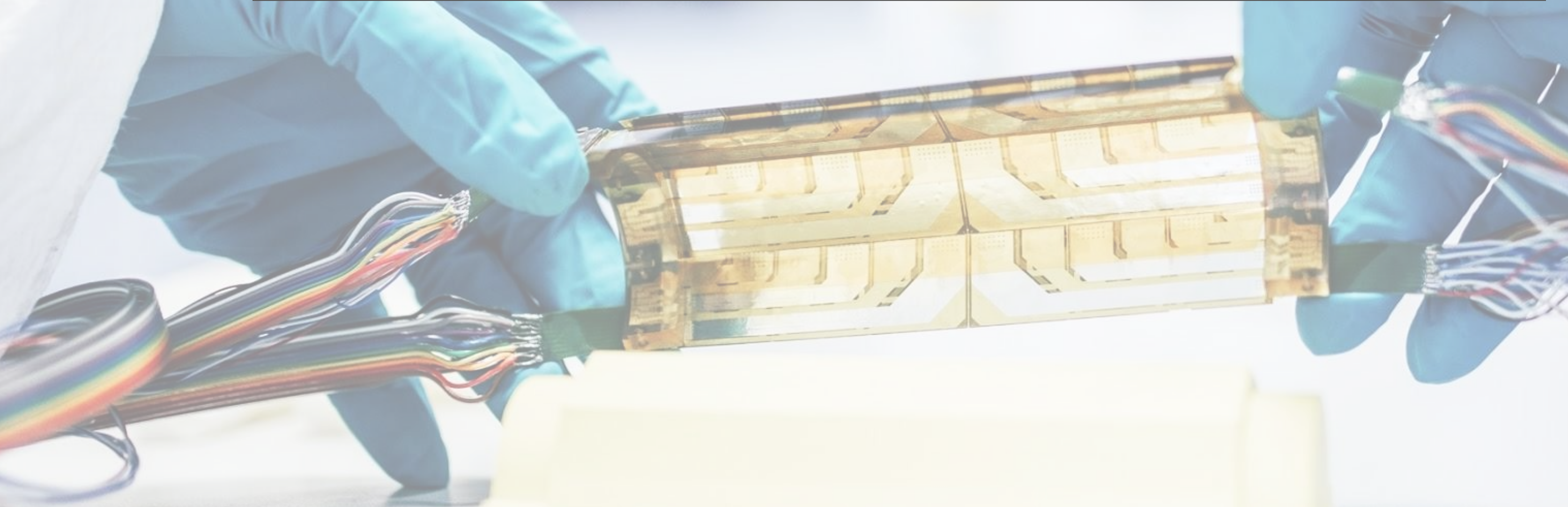
The Mu3e experiment: Toward the construction of an HV-MAPS vertex detector



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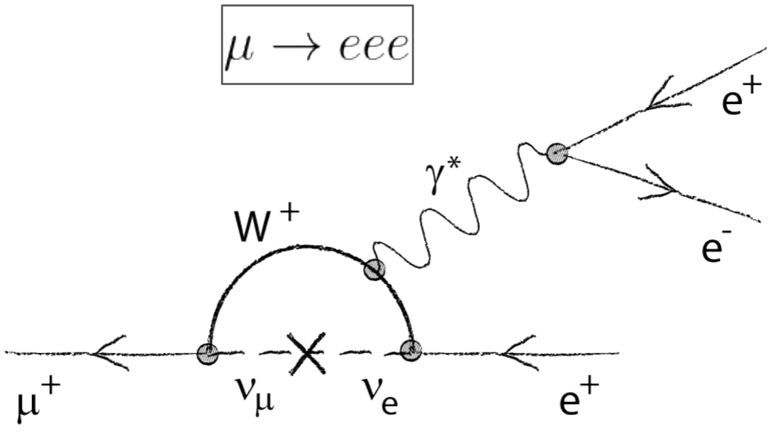
LCWS 2021 - 18.03.2021

Probing the Standard Model with Mu3e

- Mu3e is a high-precision experiment at PSI, Switzerland
- $\mu \rightarrow eee$ in SM including neutrino mixing
  ➡️ BR ($\mu \rightarrow eee$) < 10^{-54}
  ➡️ beyond observable levels
- New physics might enhance BR by several orders
- Current limit:
  BR ($\mu \rightarrow eee$) < 10^{-12} (SINDRUM, 1988)
- Aimed single-event sensitivity:
  BR ($\mu \rightarrow eee$) < $2 \cdot 10^{-15}$ (Phase 1)
  BR ($\mu \rightarrow eee$) < 10^{-16} (Phase 2)

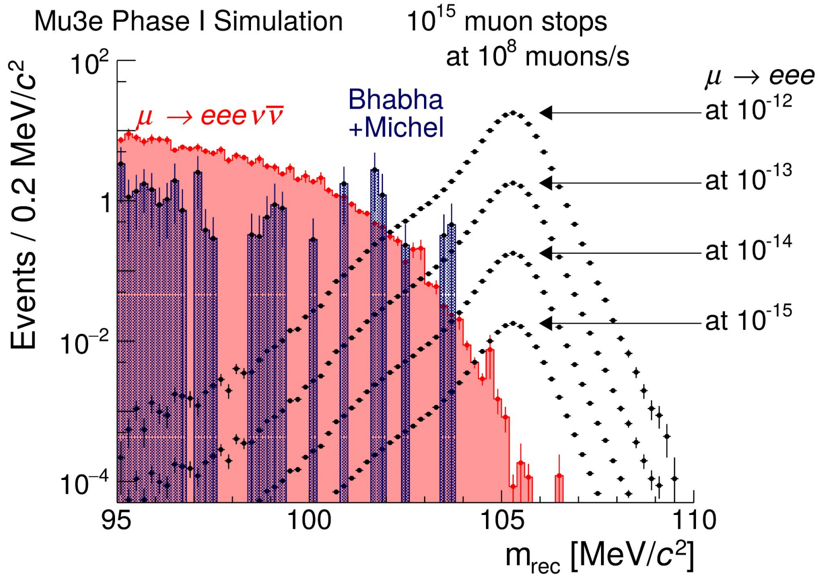


Standard Model decay via neutrino mixing

Experimental challenges

- High rates (≥ 10^8 μ^+ decays per second)
- Low-momentum particles
  - Muons decay at rest
  - Electron/Positron momenta < 53 MeV/c
- Signal-to-background discrimination
  - μ→eeevv (main background channel)
  - Limited by multiple-Coulomb scattering
  - Accidental background

➡️ **low material budget**
➡️ **fast detectors**
➡️ **high granularity**

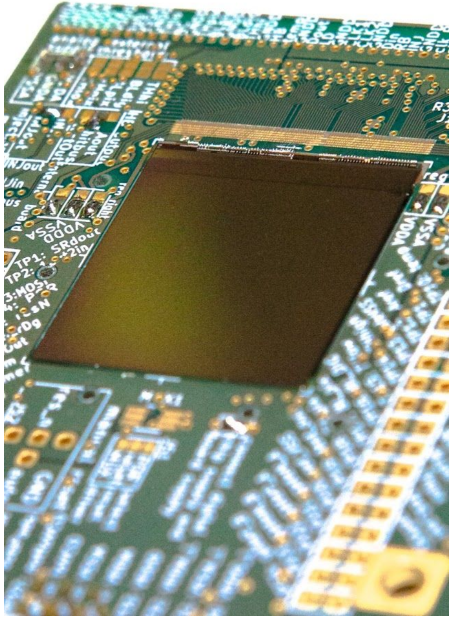


Invariant mass of signal decay, radiative decay and accidental background (Bhaba+Michel) [Mu3e TDR]

The Mu3e pixel sensors

- High-Voltage Monolithic Pixel Sensors (HV-MAPS)
- 180 nm HV-CMOS process
- Collects charge via drift (fast)
- Digital readout fully integrated

- Specifications:
  - ~ 2x2 cm^2 active matrix
  - Efficiency > 99 %
  - Time resolution < 20 ns
  - Thinned to 50 µm (X/X_0= 0.054 %)

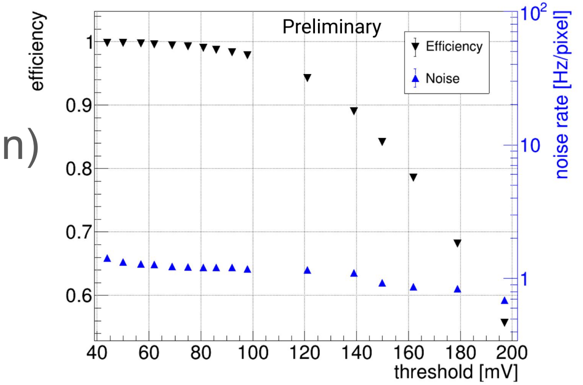


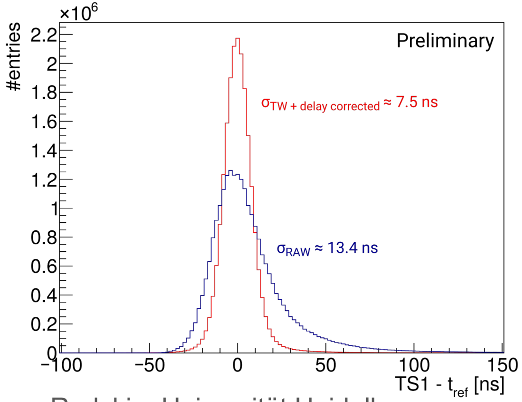
MuPix10 prototype sensor on test PCB

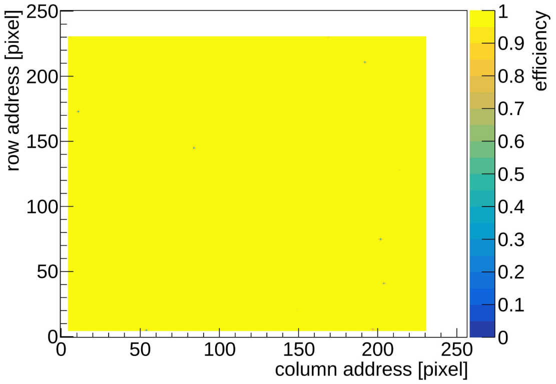
MuPix10 characteristics

- MuPix10 is 1st full-scale prototype
- Operated with single input voltage (important for integration)
  ➡️ Internal voltage regulators successfully tested

- Sensors characterized in testbeam at DESY[1]
- Efficiency > 99 % (w/o tuning or masking)
- Noise rate < 2 Hz/pixel
  (including beam particles)
- Time resolution:
  7.5 ns (after corrections)
- Power consumption
  < 200 mW/cm²

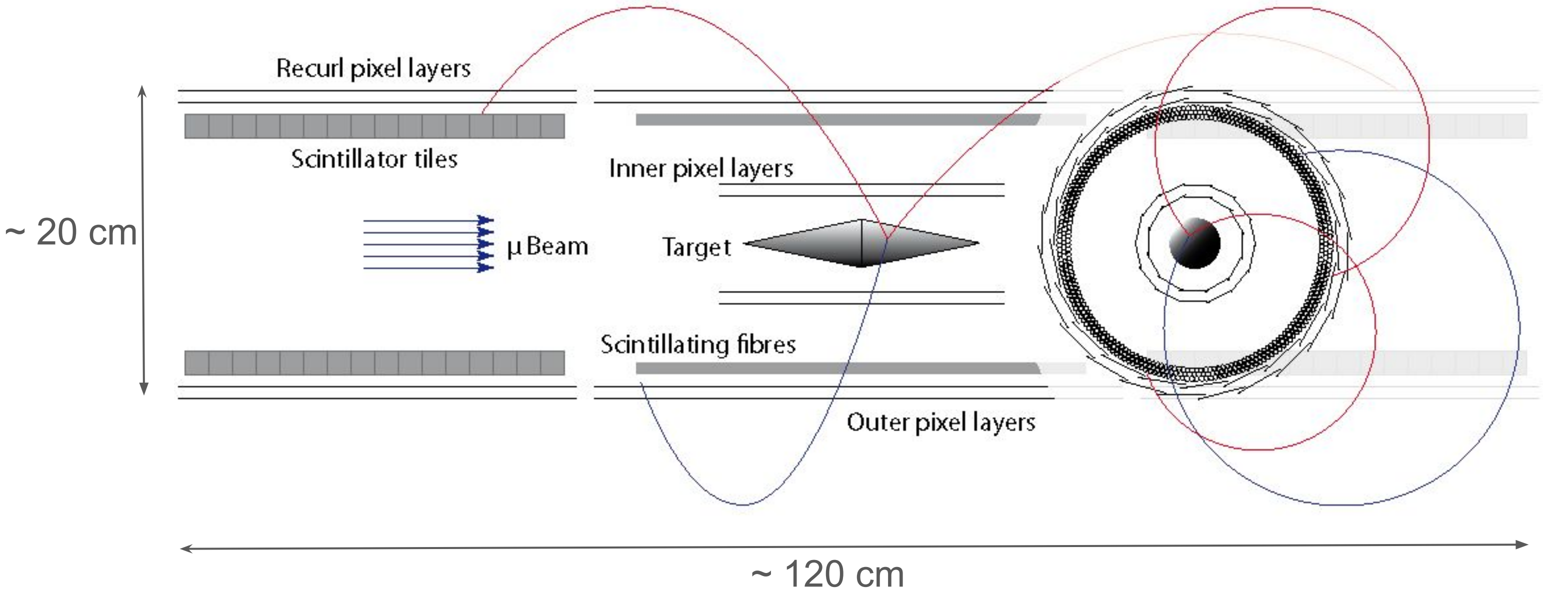


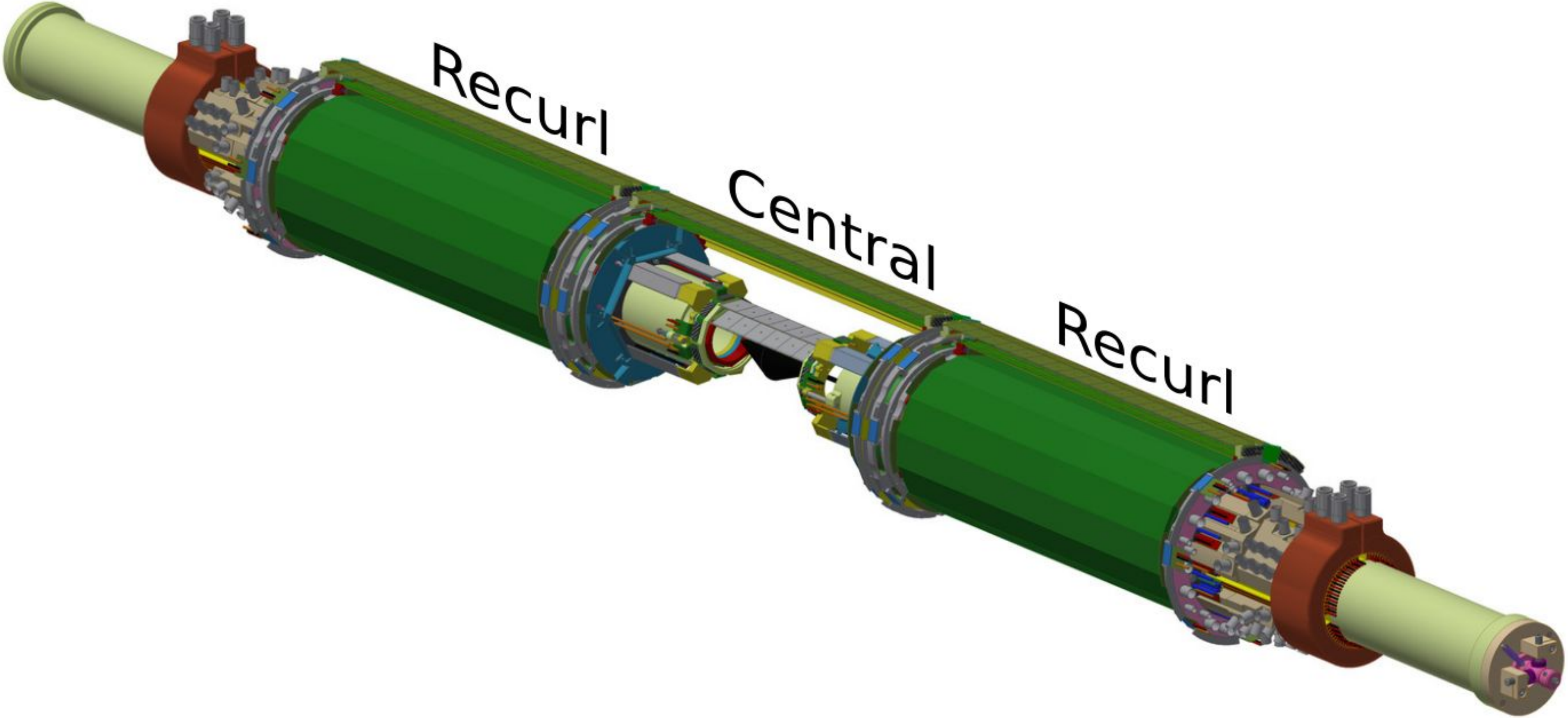




1: The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)

The Mu3e experiment




Recurl
Central
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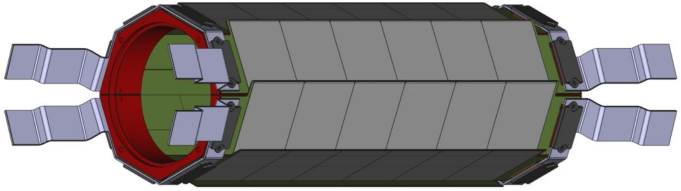
Mu3e HV-MAPS pixel detector

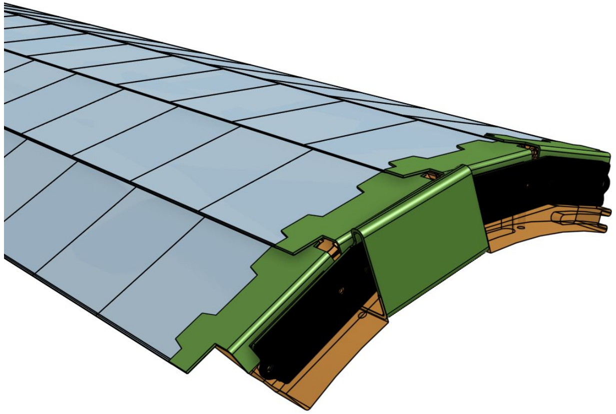
Inner layers:

- 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



Mu3e HV-MAPS pixel detector

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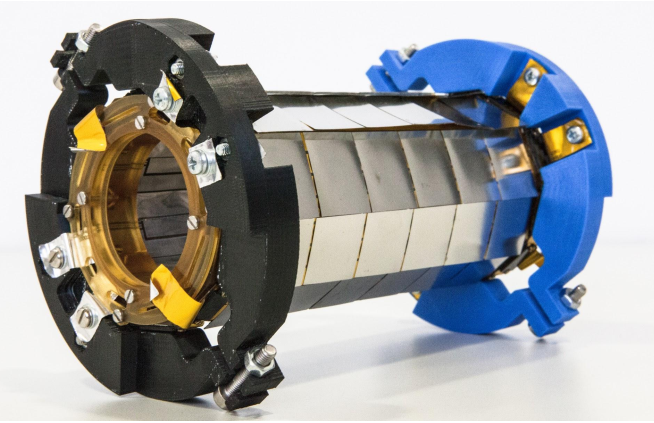
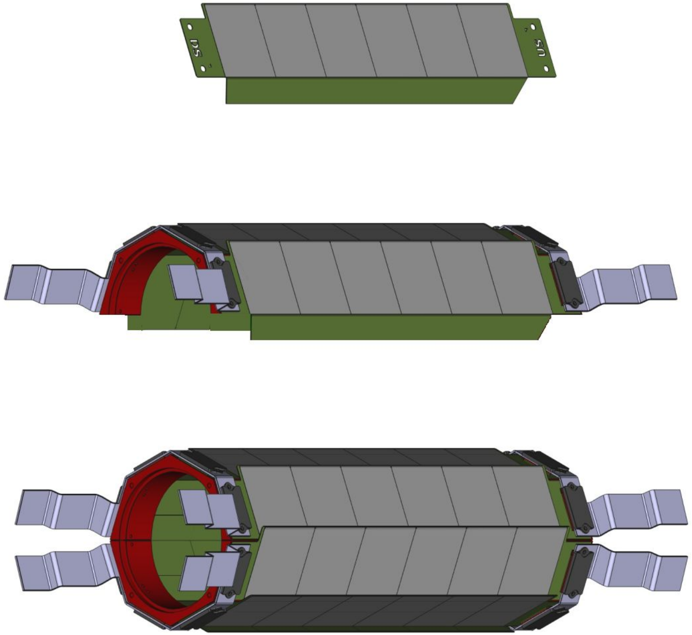




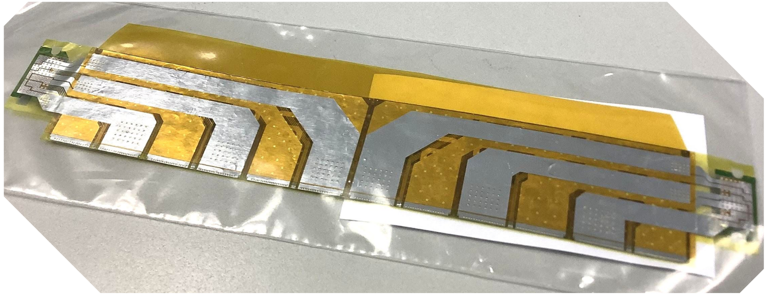
Ladder

Module

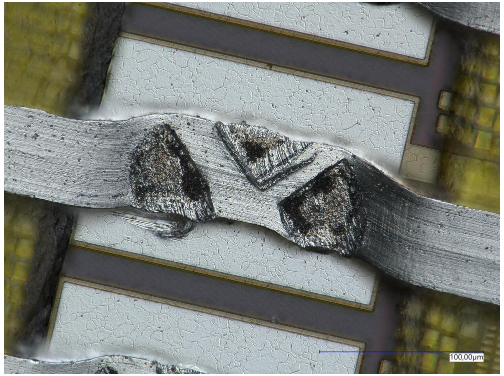
Layer

Mu3e HV-MAPS vertex detector

- Chips are glued to high-density interconnects (HDI, 50 µm thin)
- HDI supplies LV, HV, signals & serves as support structure
- Electrical connection via spTAB



HDI for heater chips



spTAB bond

Mu3e HV-MAPS vertex detector

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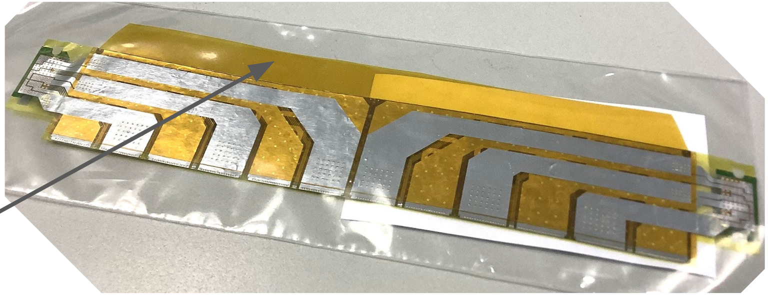
- Glued together with gluing flap



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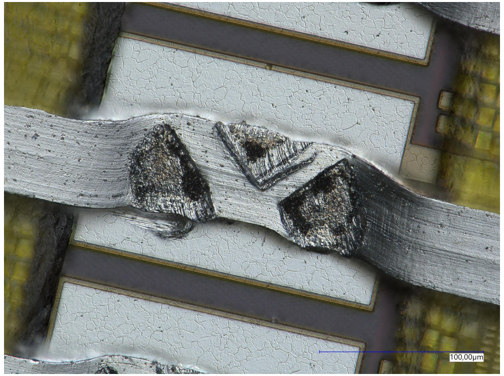
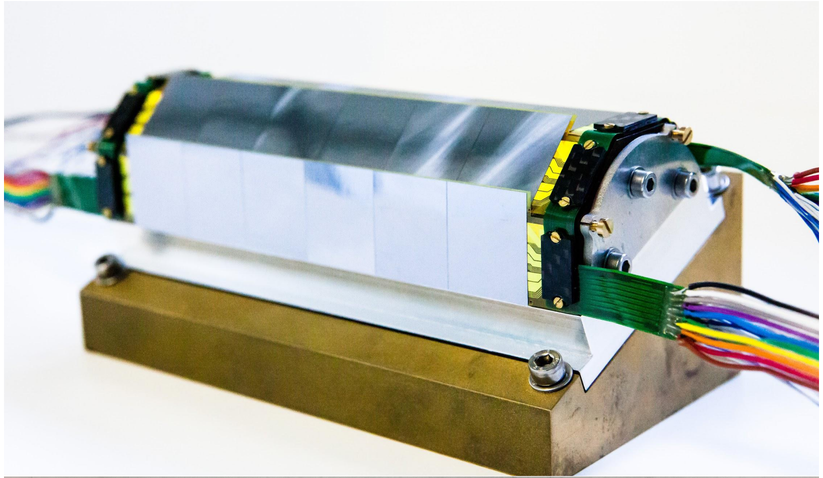


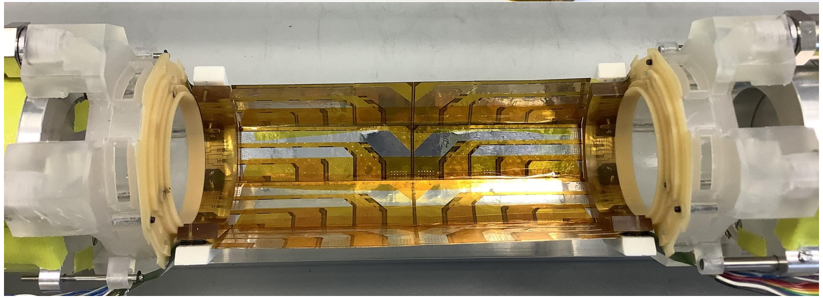
spTAB bond

Mu3e HV-MAPS vertex detector

- Chips are glued to high-density interconnects (HDI, 50 µm thin)
- HDI supplies LV, HV, signals & serves as support structure
- Electrical connection via spTAB

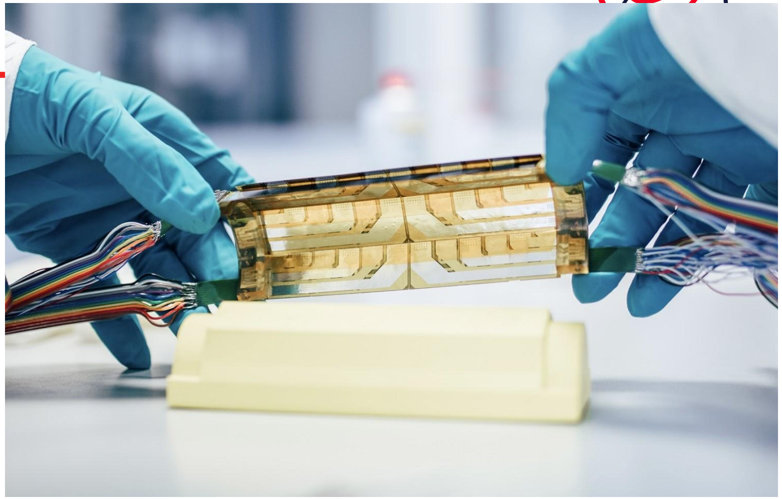
- Glued together with gluing flap
- Modules are self-supporting
- Directly mounted on beam pipes

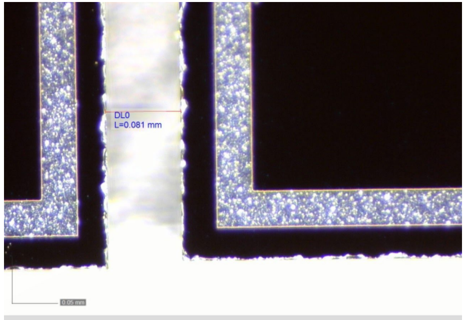




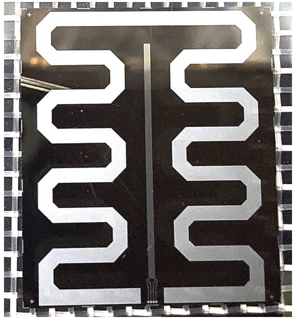
Prototyping

- Prototype made of
  - 50 µm thin silicon heaters with a ~ 1.2 kΩ 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 ≈ 5 µm
  - Electrical connections via spTAB established



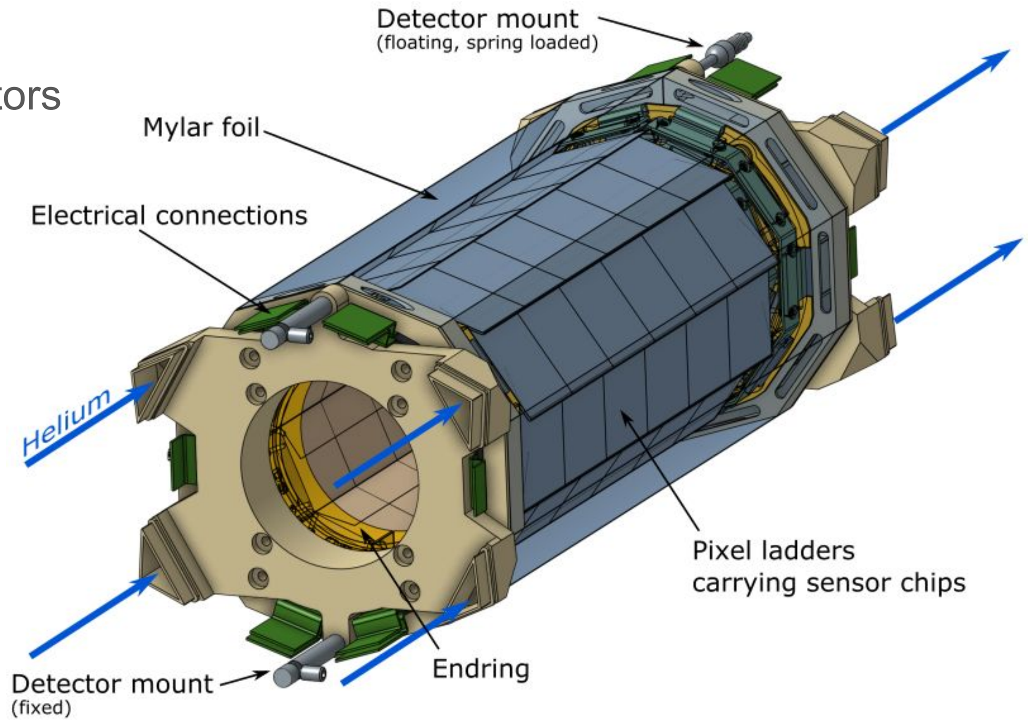


Chip placement

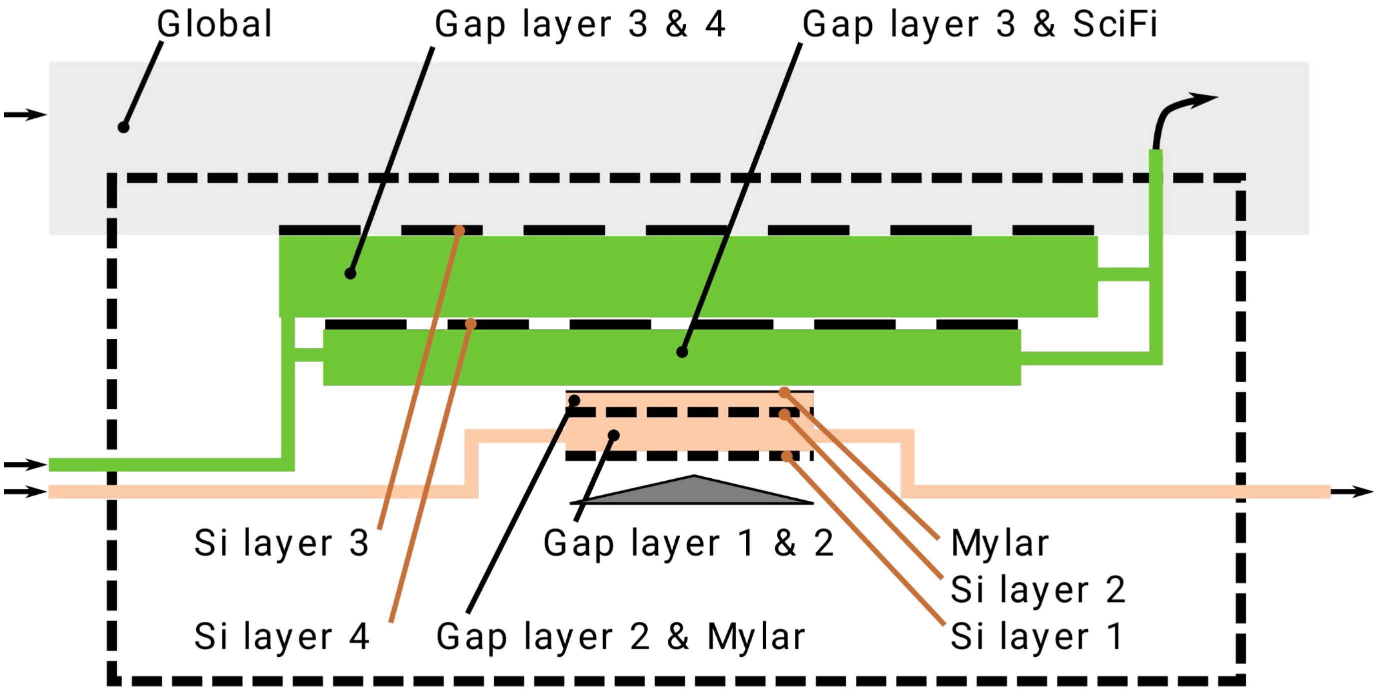

Silicon heater chip

Vertex detector cooling

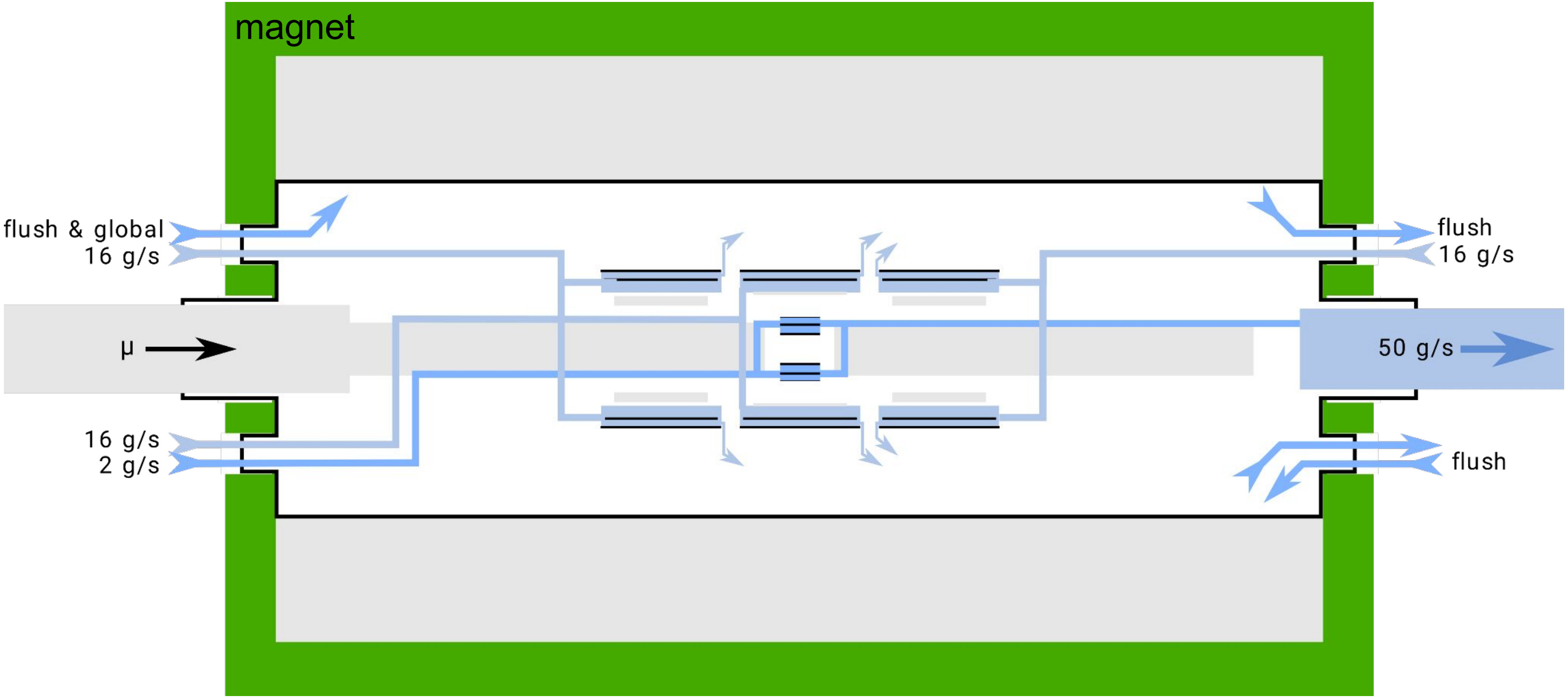
- Gaseous helium as coolant
- Guided along beam pipe to the detectors
- Two helium flows
  - Flow between the 2 layers
  - Flow around 2nd layer
    ➡️ confined volume by mylar foil
- Analogous cooling concept for outer layers



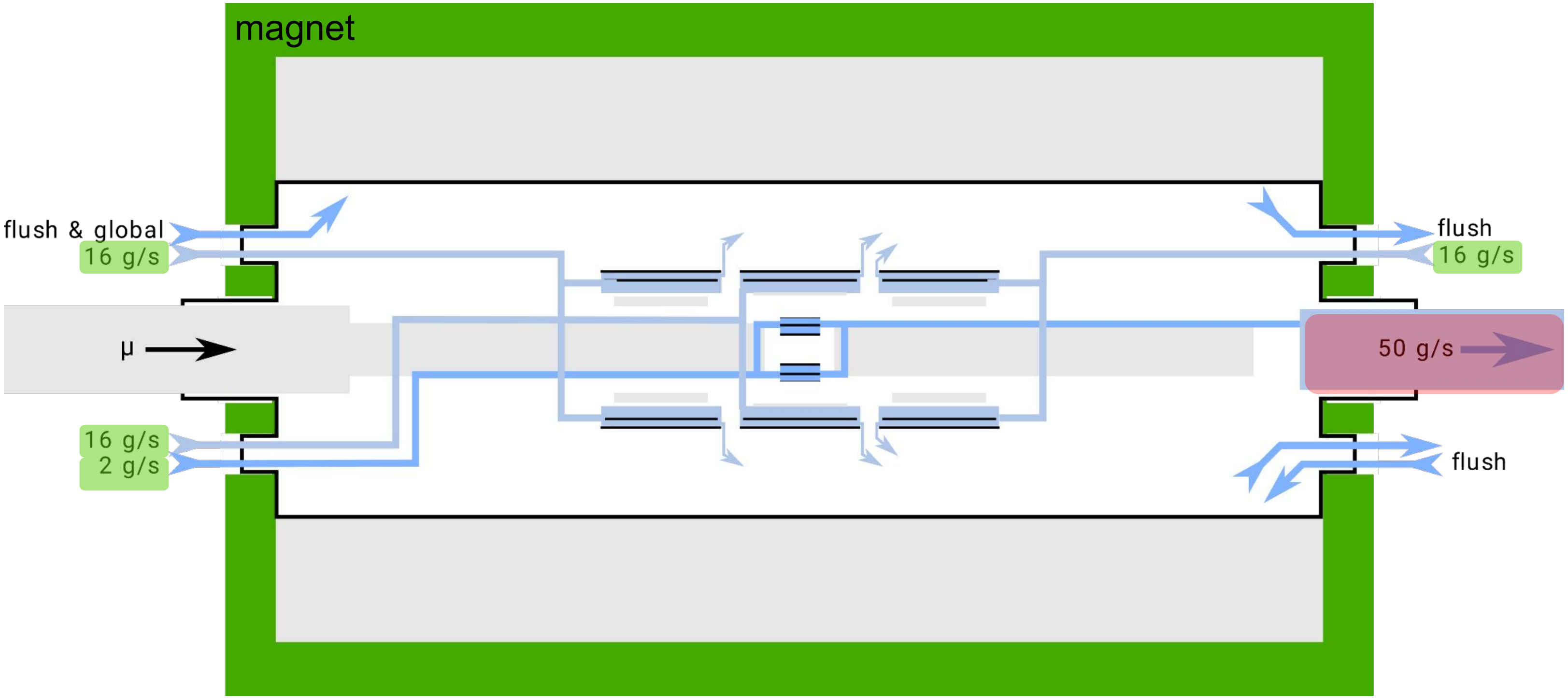
Pixel detector cooling



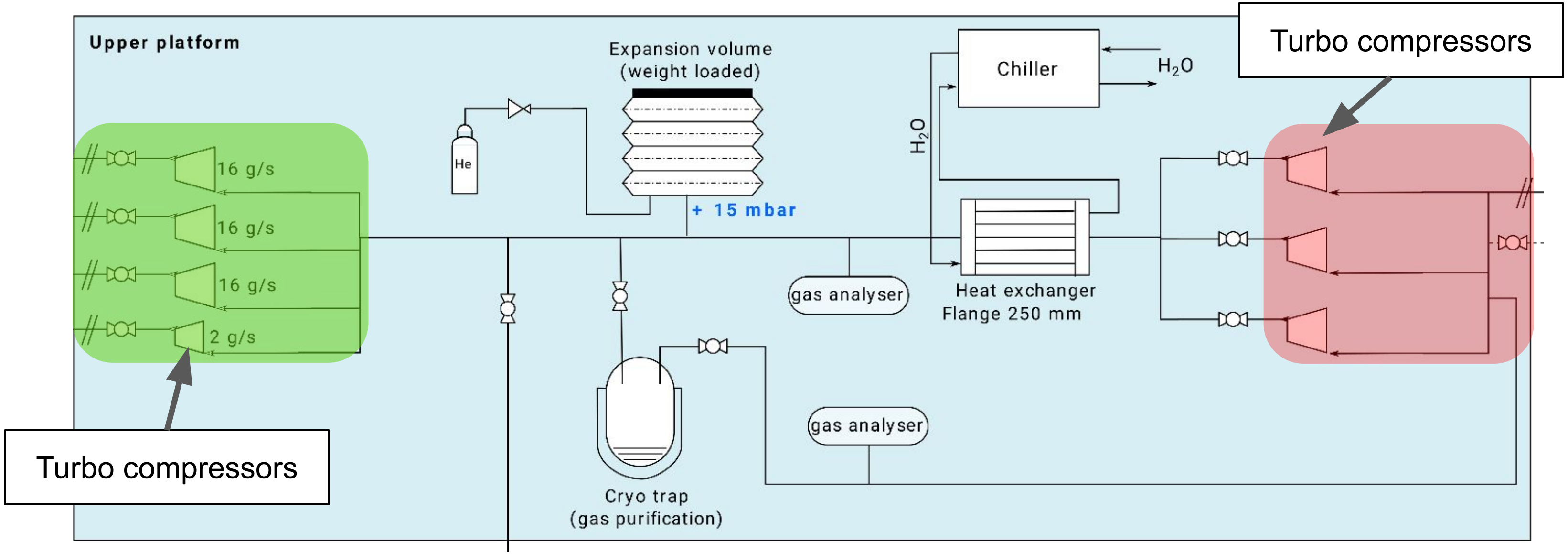
Pixel detector cooling



Pixel detector cooling

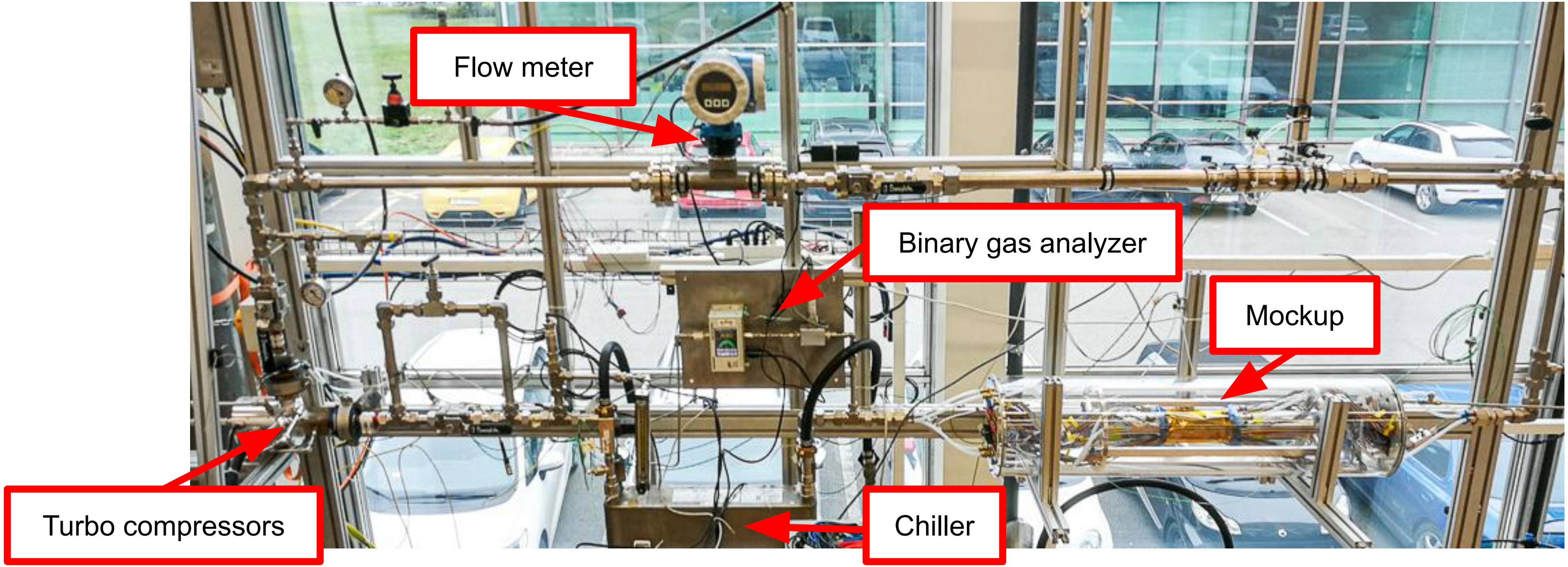


Helium cooling plant



Cooling studies

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



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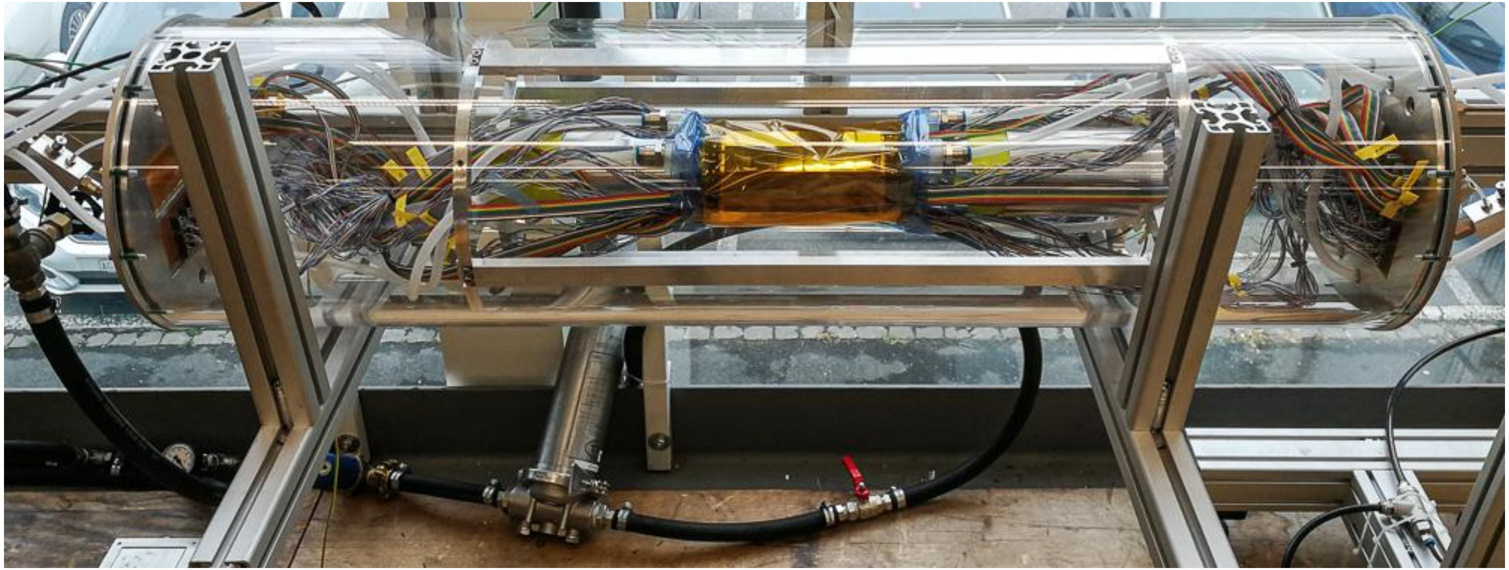
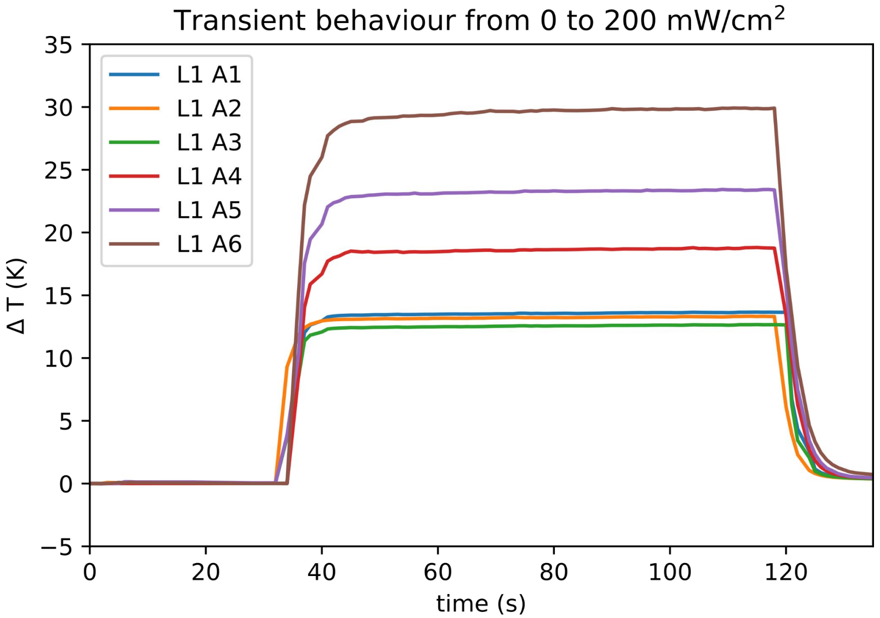


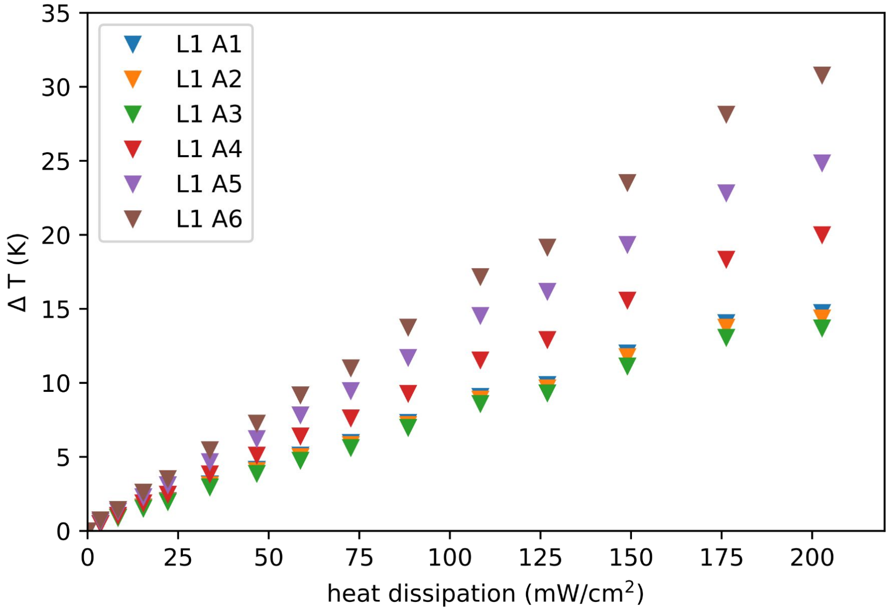
Cooling studies

- 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 ΔT ~ 30 K
  (foreseen inlet temperature ~ 5°C)



Cooling studies

- Measurement of temperature-to-power relation
- Temperature difference linearly depending on heat dissipation
- Expected ΔT < 70 K for 400 mW/cm² (conservative limit)
- Cooling concept works ✔️

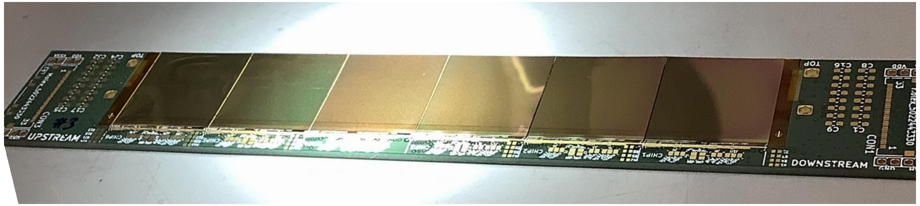


Summary & Outlook

- MuPix10 performance in specs ✔
- Vertex detector tooling & mounting procedure ready ✔
- Cooling concept verified for inner layers ✔

2021:

- 1st time operation of 6 chips on a single PCB ✔
- Demonstrator run using vertex tracker with PCB modules
- HDI with 6x MuPix10
- Submission of MuPix11 (final sensor)
- 1st HDI with 6x MuPix11 (end of the year)
- Start mass production



Backup

ToDos

- TDR
- Overall pressure difference
- MP10 Results slide

Backup

- Mounting tools
- Microscope pictures