The Mu3e vertex detector: prototyping, cooling, and upcoming production

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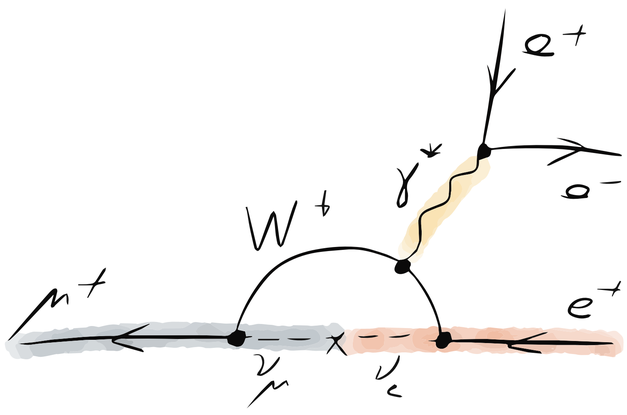
Physics motivation of Mu3e:

- Search for charged lepton flavor violation in the decay:

$$\mu^+ \to e^+ e^- e^+$$

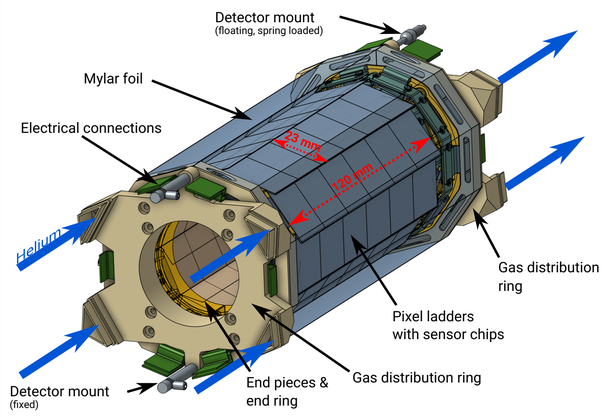
- In the Standard Model including neutrino mixing, this process is highly suppressed with a branching fraction of $\mathcal{B} < 10^{-54}$ (Figure below).



- Thus, an observed signal would indicate the presence of new physics.

The vertex detector:

- Two innermost layers of the HV-MAPS based pixel detector



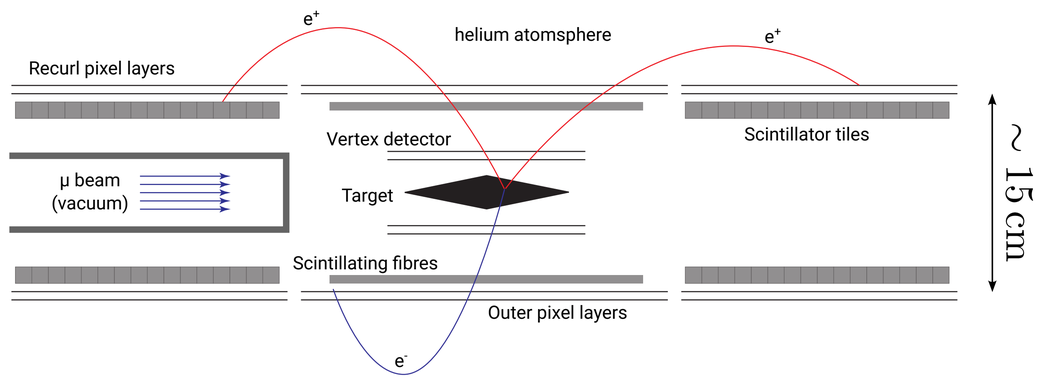
- 2 tracking layers:
  - ◇ radii at 23.3 mm and 29.8 mm
- MuPix11 chips:
  - ◇ Area: 20.66 x 23.18 mm²
  - ◇ Thickness: 50 µm
- Pixel ladders:
  - ◇ Based on ~ 70 µm thin HDIs (aluminium-polyimid)
  - ◇ Provide power, data lines, and only support structure

Why gaseous helium as coolant for the pixel detectors?

- Signal decay has to be distinguished from: $\mu^+ \to e^+ e^- e^+ \nu \bar{\nu}$
- Only possible for sufficient momentum resolution.
- Resolution is multiple-Coulomb scattering dominated

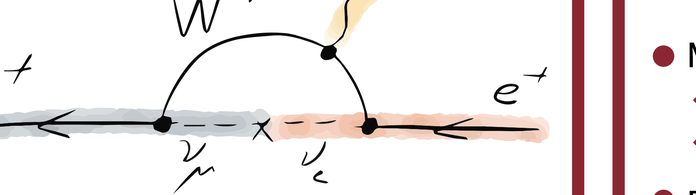
little material budget: $\sim 0.1\,\% X_0$ per tracking layer
negligible scattering in passive part of detector
gaseous cooling adds least material

	Helium	Air
density:	$0.18\,\mathrm{kg/m^3}$	$1.29\,\mathrm{kg/m^3}$
therm. conductivity:	$1.43\,\mathrm{mW/(cm \cdot K)}$	$0.241\,\mathrm{mW/(cm \cdot K)}$
spec. heat capacity:	$5.23\,\mathrm{kJ/(kg \cdot K)}$	$1.01\,\mathrm{kJ/(kg \cdot K)}$
radiation length:	$0.018\,\%\ X_0/m$	$0.33\,\%\ X_0/m$

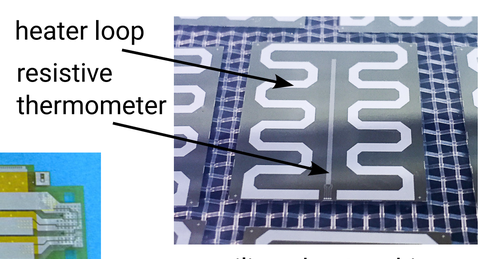


Thermal-mechanical mock-up:

- Mechanical copy of vertex detector
- HDIs equipped with 50 µm thin silicon heater chips.



silicon heater HDI

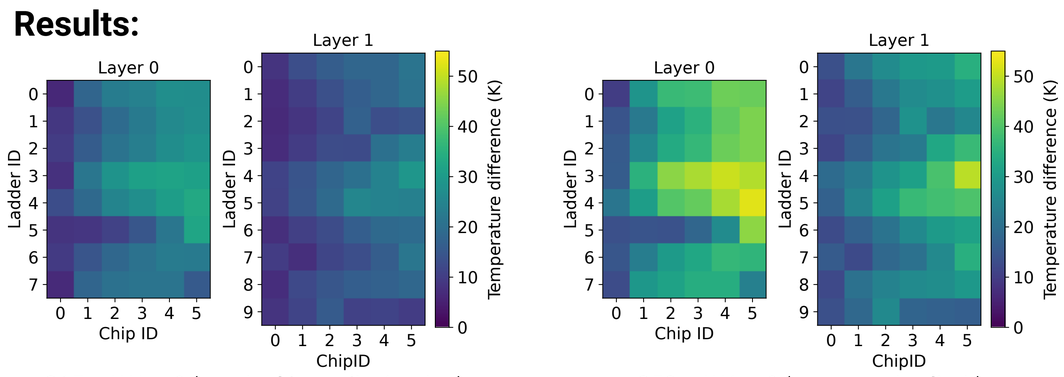


silicon heater chip

Cooling studies:

Heat loads:	215 mW/cm² & 350 mW/cm²
Gas flow:	2 g/s helium, flow from chip 0 to 5
Flow channels:	Between the 2 layers & around the outer layer
Measurement:	Map of all chip temperatures (see below)

Results:



215 mW/cm² (nominal heat dissipation)

$T_{L0,mean} = 20.3(7)\,\mathrm{K}$ $T_{L1,mean} = 14.8(2)\,\mathrm{K}$

$T_{L0,max} = 33.2(12)\,\mathrm{K}$ $T_{L1,max} = 28.9(15)\,\mathrm{K}$

350 mW/cm² (conservative limit)

$T_{L0,mean} = 32.0(7)\,\mathrm{K}$ $T_{L1,mean} = 24.1(3)\,\mathrm{K}$

$T_{L0,max} = 52.5(9)\,\mathrm{K}$ $T_{L1,max} = 49.3(15)\,\mathrm{K}$

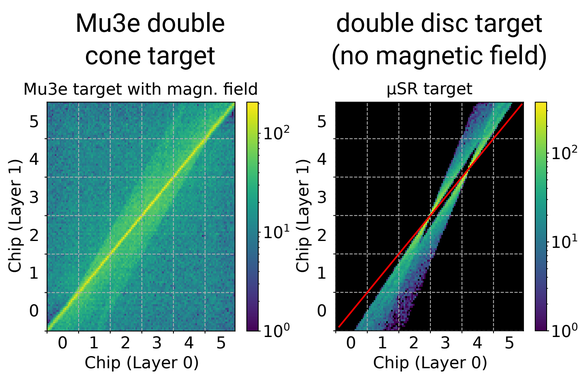
* temperature difference to inlet gas temperature

- Temperatures are well below $T_{crit} = 70\,^\circ\mathrm{C}$ (glass transition temperature of adhesives used) for an inlet temperature of 0°C

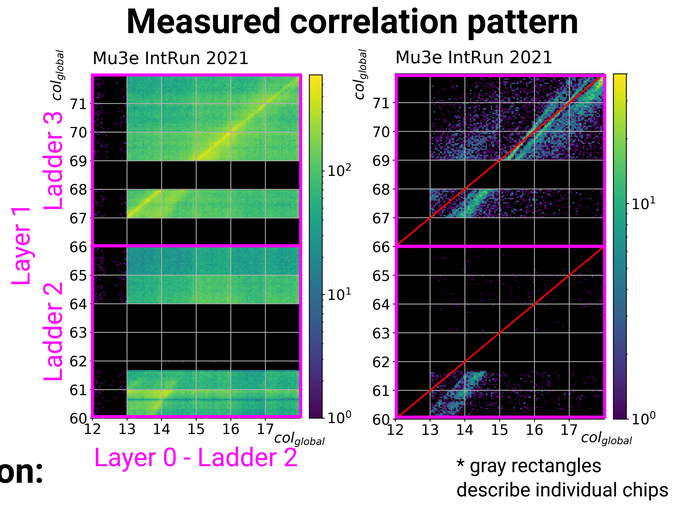
Successful operation of a 50 µm thin pixel detector with gaseous helium cooling:

- Mu3e integration run 2021 with around 70 functional MuPix10 chips (50 µm thickness).
- PCB-based ladders instead of thin HDIs (simplified geometry).
- Correlations between two tracking layers for two different target configurations

Simulated correlation pattern

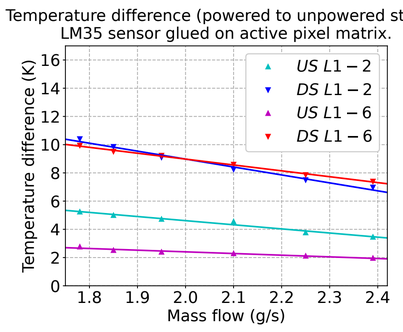


Measured correlation pattern



* gray rectangles describe individual chips

On-chip temperature during operation:



LM35 sensor on US L1-2

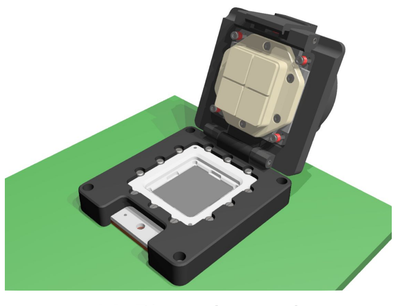
Disclaimer:

- PCB ladders behave as heat sinks differently than the final HDI ladders.
- Helium distribution not as in final detector.
- Results can't be directly compared to thermal-mechanical mock-up.

Vertex detector production:

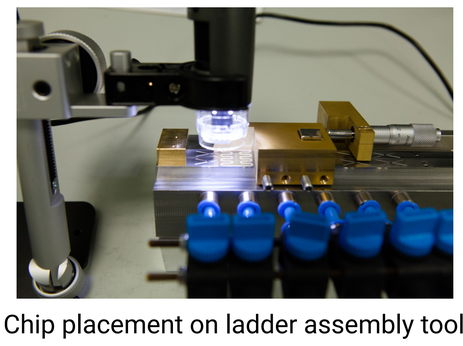
Quality control:

- Qualification of MuPix sensor before assembly by probe card
- Optical survey of all detector components by digital microscopes
- Pixel ladders and modules operated with final readout electronics in lab



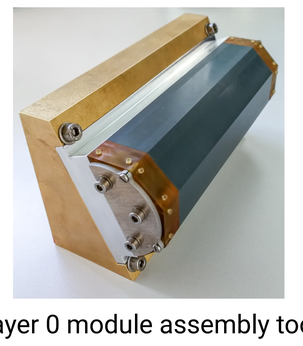
MuPix probe card

Ladder & module assembly:



Chip placement on ladder assembly tool

HDI glued onto 6 chips



Layer 0 module assembly tool