


Mu3e vertex detector prototyping

Thomas Theodor Rudzki for the Mu3e collaboration
Universität Heidelberg - Physikalisches Institut

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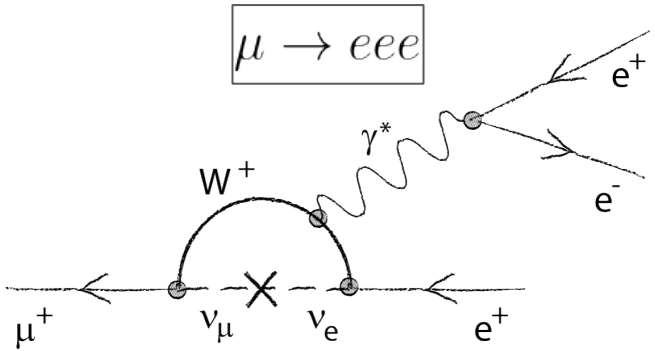
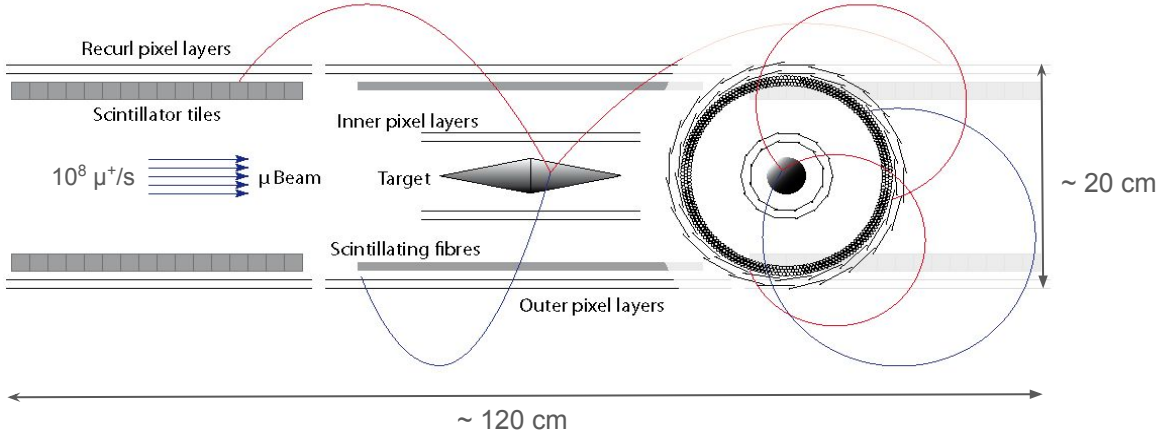
The Mu3e experiment





Standard Model branching ratio:

$$\mathcal{B}(\mu \to eee) \leq 1 \cdot 10^{-54}$$

Current limit (SINDRUM, 1988):

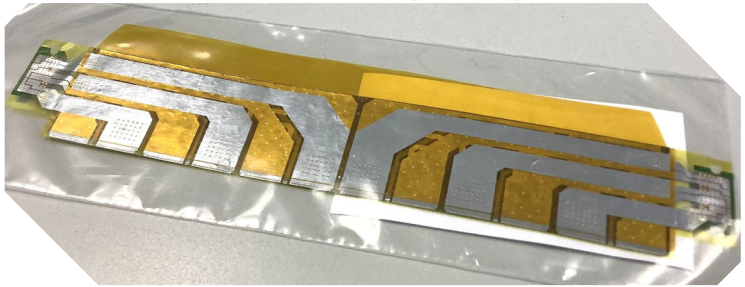
$$\mathcal{B}(\mu \to eee) < 1 \cdot 10^{-12}$$

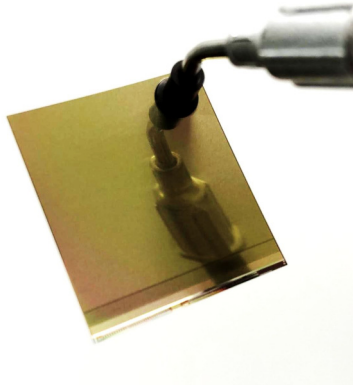
Aimed final single-event sensitivity :

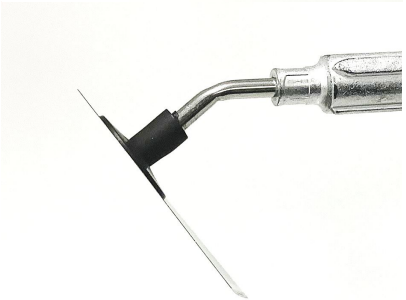
$$\mathcal{B}(\mu \to eee) \leq 1 \cdot 10^{-16}$$

The Mu3e experiment

- Muon decay at rest
  ➡️ Positron/electron momenta < 53 MeV/c
- Background dominated by multiple Coulomb scattering
  ➡️ Reduction of material budget
- Ultra-thin sensors (50 µm HV-MAPS, X/X_0= 0.054 %)
- High-density interconnects (HDI) as only support structure (polyimide + Al, 50 µm, X/X_0= 0.061 %)
- Gaseous helium as coolant (low Z)

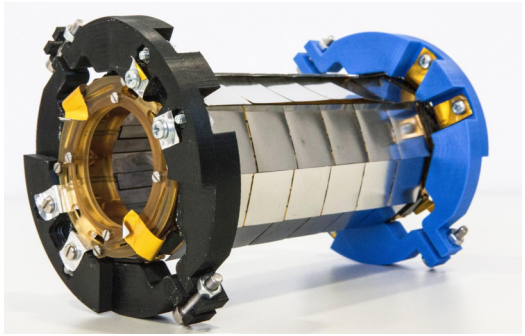


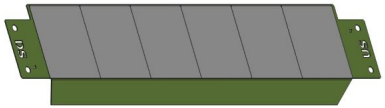




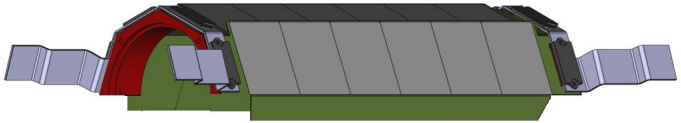
Vertex detector geometry

- 2 inner layers
  - 8/10 ladders each
  - 6 chips per ladder
- Target surrounded by inner layers
- Support (red) attached to beam pipes
- Electrical connections via flexprints
- Helium inlets on the faces

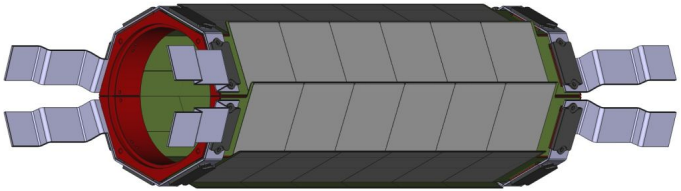




Ladder



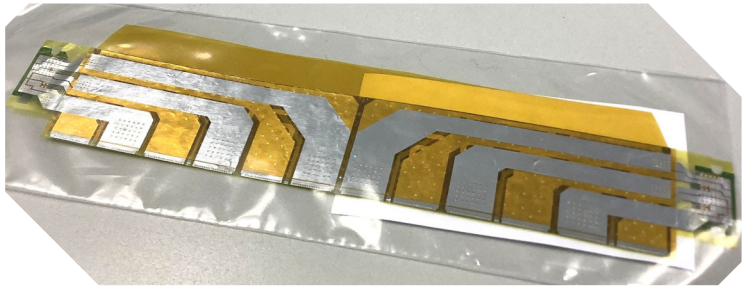
Module



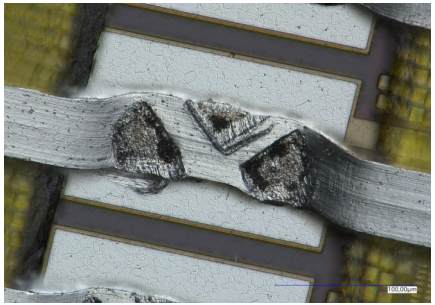
Layer

Prototyping

- Step to final materials/precision using silicon heater chips
- Silicon chips as active heating components
- HDI as support structure
- Electrical connection via spTAB
- Goals:
  - Verify feasibility of all working steps
  - Establish quality assurance procedure for final production



HDI for silicon heater chips



spTAB bond

Silicon heater chip

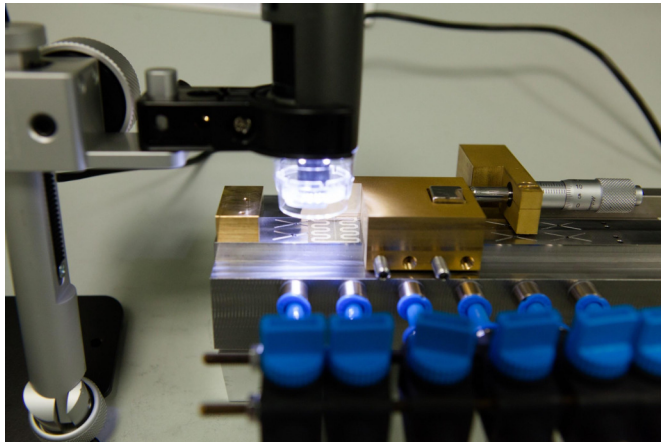
Layer stack of LTU hdi

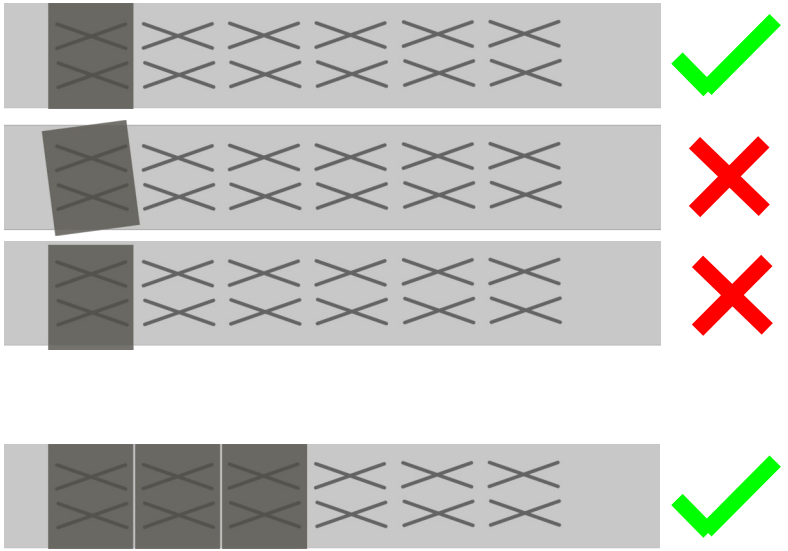
Ladder construction

- Placing 6x sensors in a row
- Apply glue
- Position hdi
- Putting weights on ladder + curing glue
- Bonding electrical connections

Sensor placement

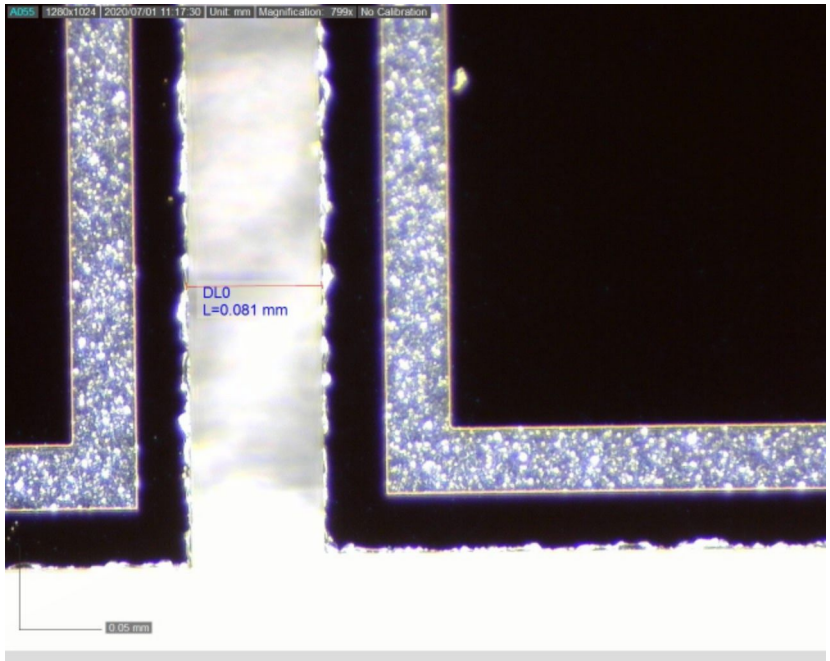
- Placement precision of 5 µm (chip-to-chip distance)
- Gap between chips: 80 ± 5 µm (Si heater)
  40 ± 5 µm (MuPix)
  Resulting of slight size differences
- Chip confinement while placing on chuck necessary





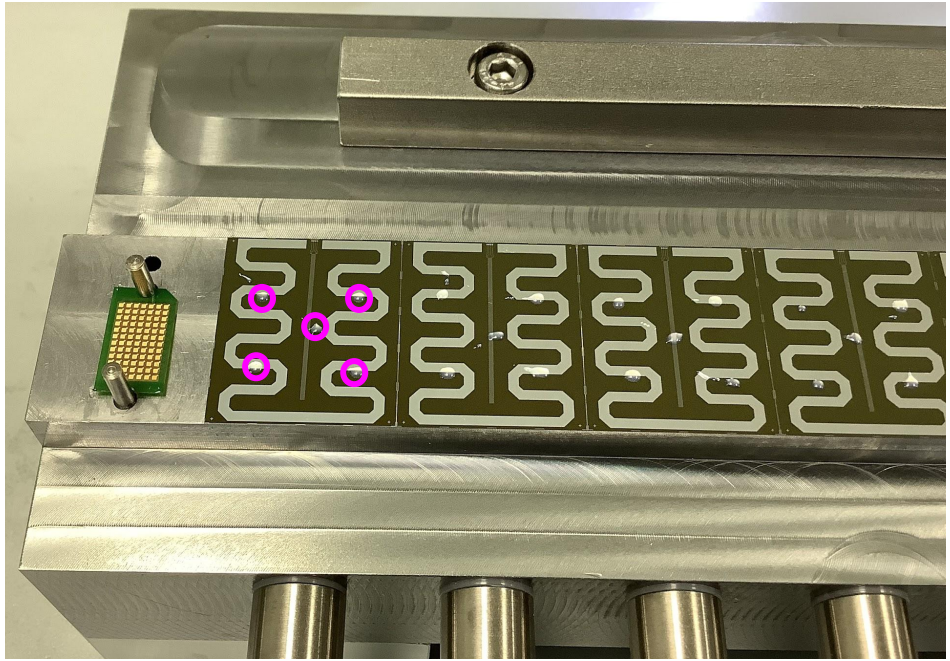
Sensor placement

- Manual placement with micrometer screw
- Measurement of distances via digital microscope
- Optical resolution of 1.5 µm
- Chip placement with σ < 5 µm well under control



Gluing

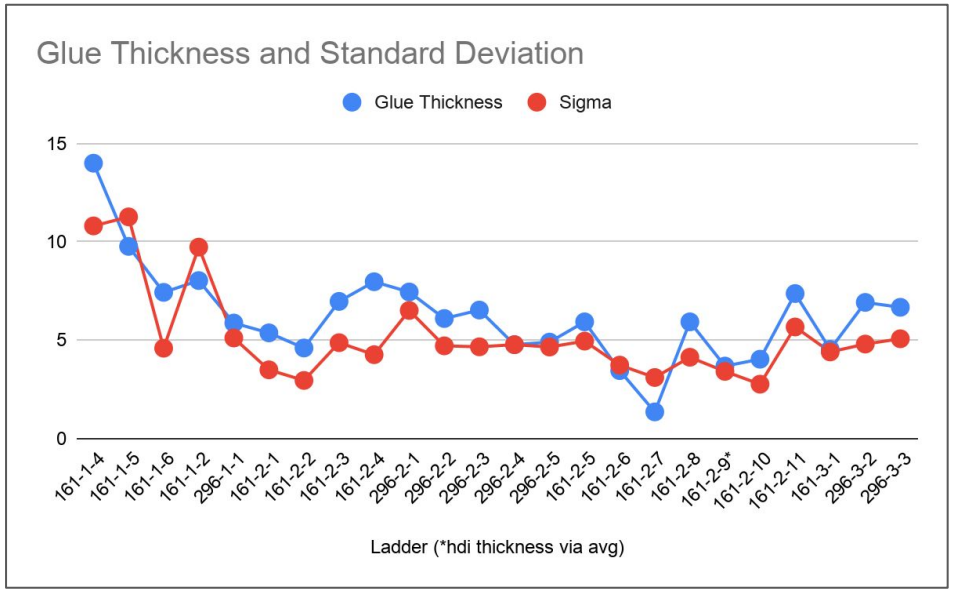
- Gluing by applying small glue dots using a toothpick
- Measured thickness of
  - Heaters
  - HDI
  - Heaters + HDI after gluing
- Obtain “glue thickness maps”

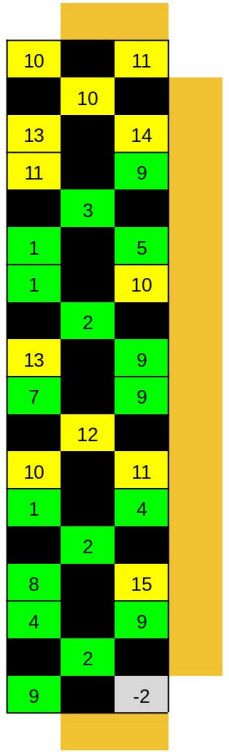


5-glue-dots pattern on each sensors

Gluing

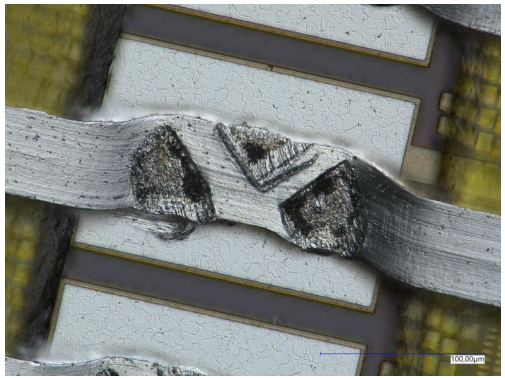
- Gluing by applying small glue dots using a toothpick
- Measured thickness of
  - Heaters
  - HDI
  - Heaters + HDI after gluing
- Obtain “glue thickness maps”
- Little material budget:
  - ~ 5 µm aimed thickness
  - After some practice glue thickness @ 5-7 µm
  - Satisfying results



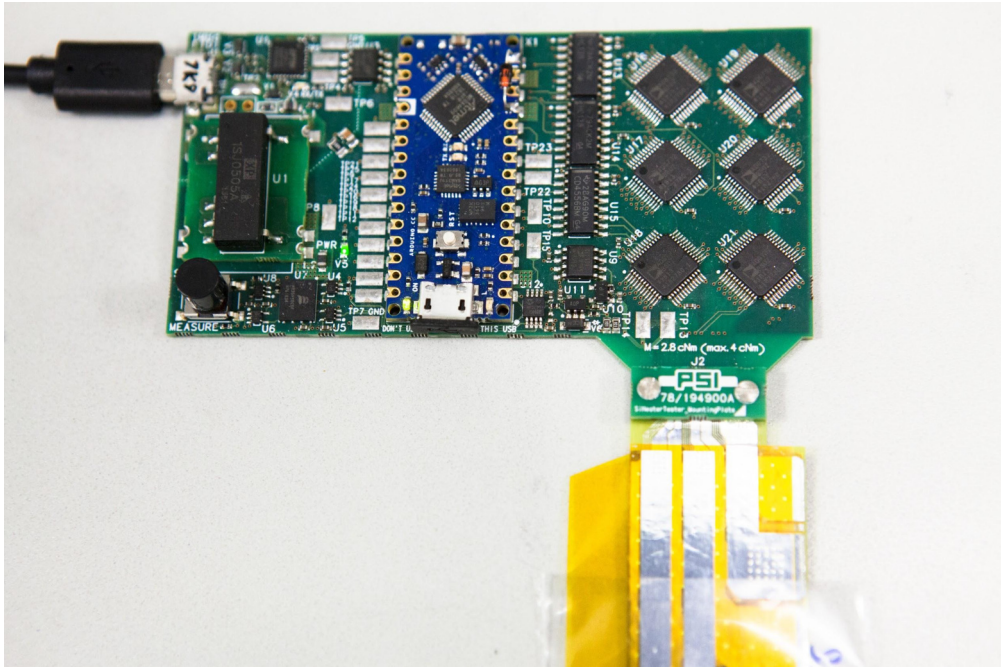


Si heater tester

- Arduino based test board
- Checks all connection within 1 second
- Rebonding if necessary



spTAB bond



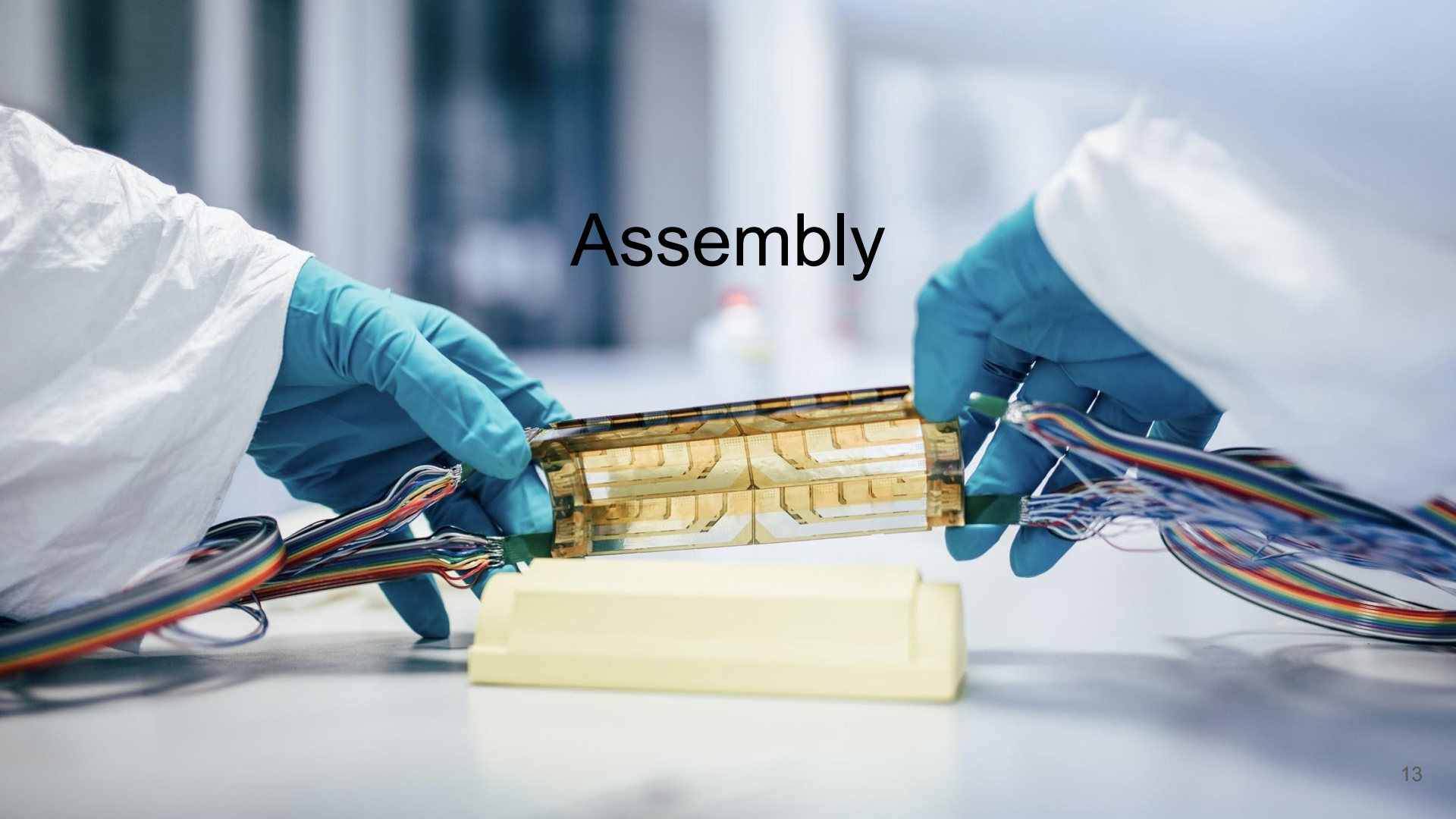
ladder	General remarks	thickness	distances	bad bonds
161-1-3	Some Si broke off at 1 sensor (maybe usable)	No Q&A	~ 100 µm	2x Power #1
161-1-4	Good to use	µ = 14 µm	~ 100 µm	Temp. #6
161-1-5	Two broken sensors	µ = 10 µm	~ 80 µm	Not tested
161-1-6	Good to use	µ = 7 µm	~ 80 µm	-
161-1-2	Good to use	µ = 8 µm	~ 80 µm	-
161-2-1	Good to use	µ = 5 µm	~ 80 µm	-
161-2-2			~ 80 µm	-
161-2-3			~ 80 µm	-
161-2-4	#		~ 80 µm	-
161-2-5			~ 80 µm	Temp. #4 (#37)
161-2-6			~ 80 µm	-
161-2-7			~ 80 µm	-
161-2-8	Goo		~ 80 µm	T.. #3 & #6 on chip
161-2-9	#		~ 80 µm	Power #6
161-2-10			~ 80 µm	Temp. #6
161-2-11			~ 80 µm	T. bonds offset large
161-3-1	Good to use		~ 80 µm	
296-1-1	Good to use	µ = 6 µm	~ 80 µm	-
296-2-1	Two broken sensors	µ = 7 µm	~ 80 µm	Not tested
296-2-2	Good to use	µ = 6 µm	~ 80 µm	-
296-2-3	Good to use	µ = 7 µm	~ 80 µm	-
296-2-4	#6 broken (might be usable)	µ = 8 µm	~ 80 µm	Temp. #6
296-2-5	Interposer Flex not correctly glued	µ = 5 µm	~ 80 µm	Not tested
296-3-1	Good to use	Not tested	~ 80 µm	Temp. #6

Yield:

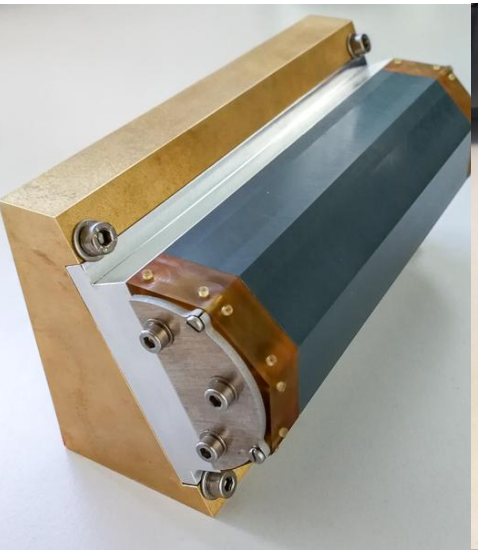
75 % of ladders used

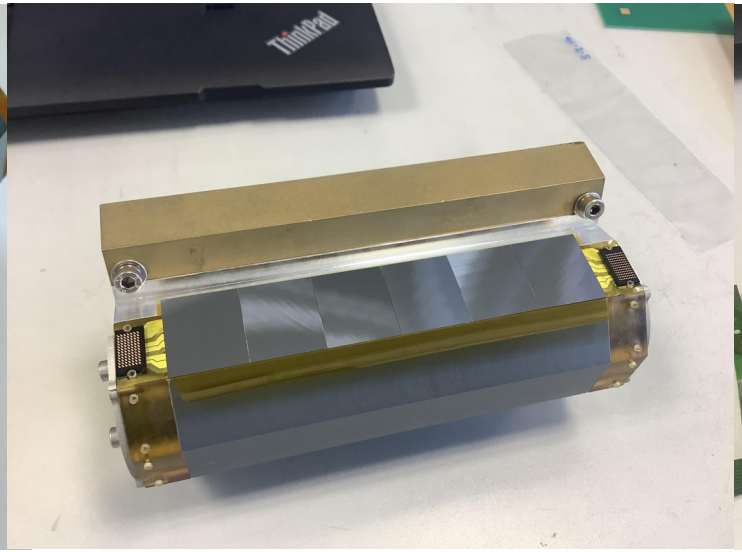
67 % would have been used for final tracker

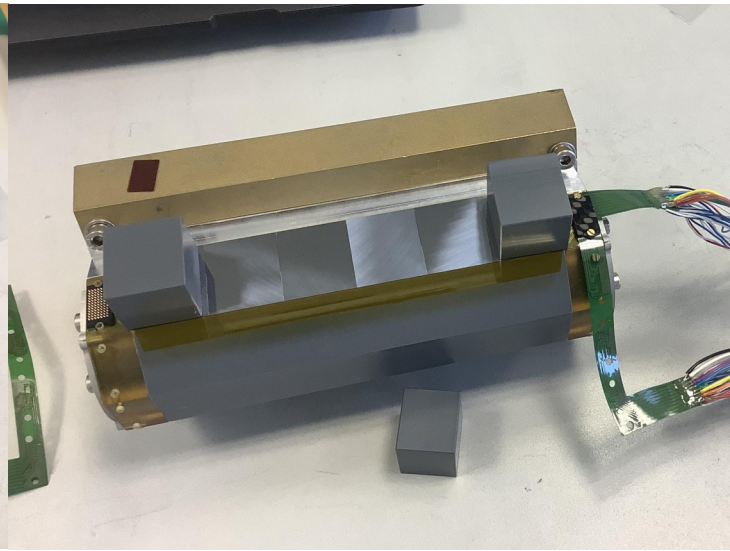
Assembly



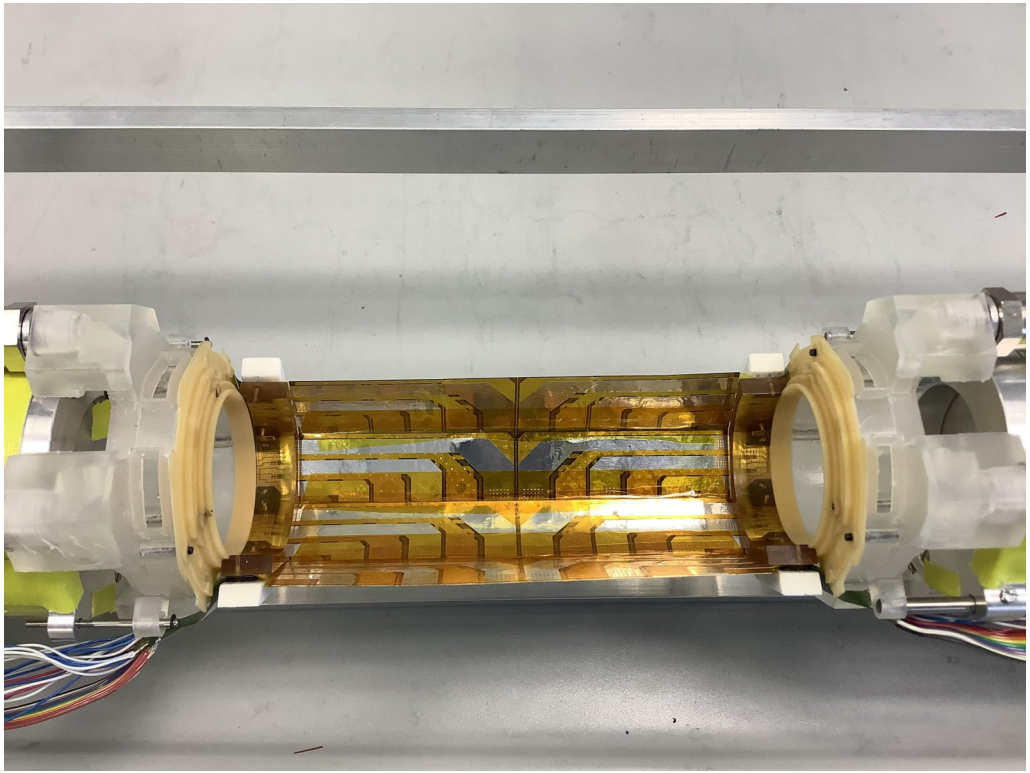
Final module construction







Construction of the vertex detector



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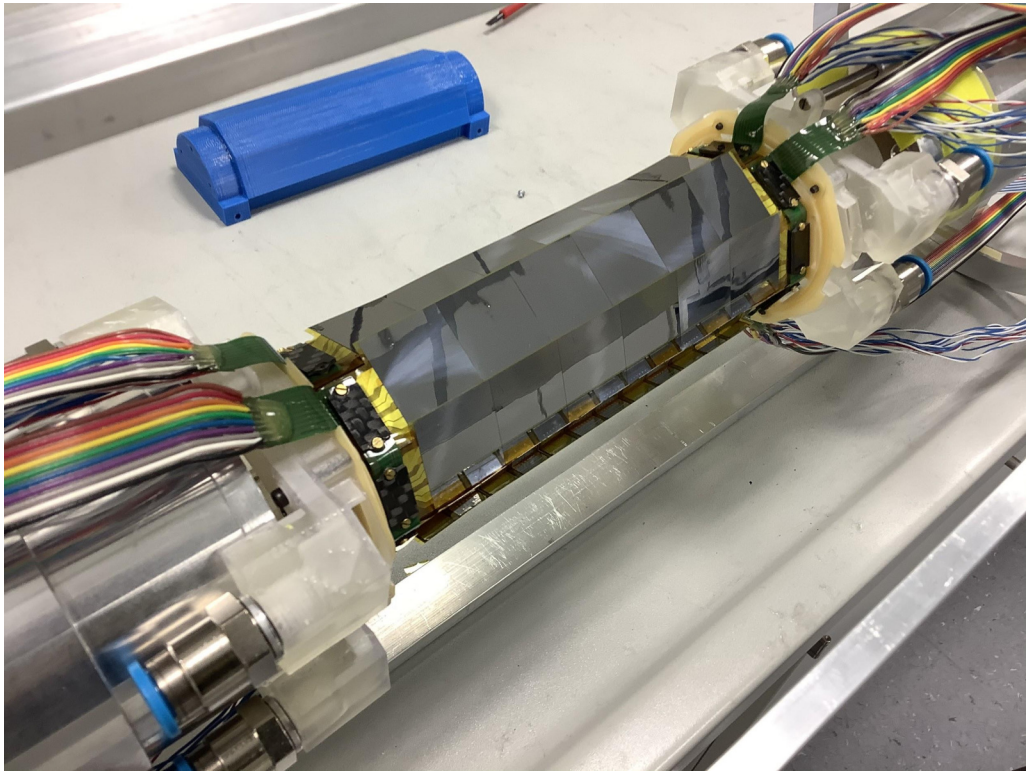

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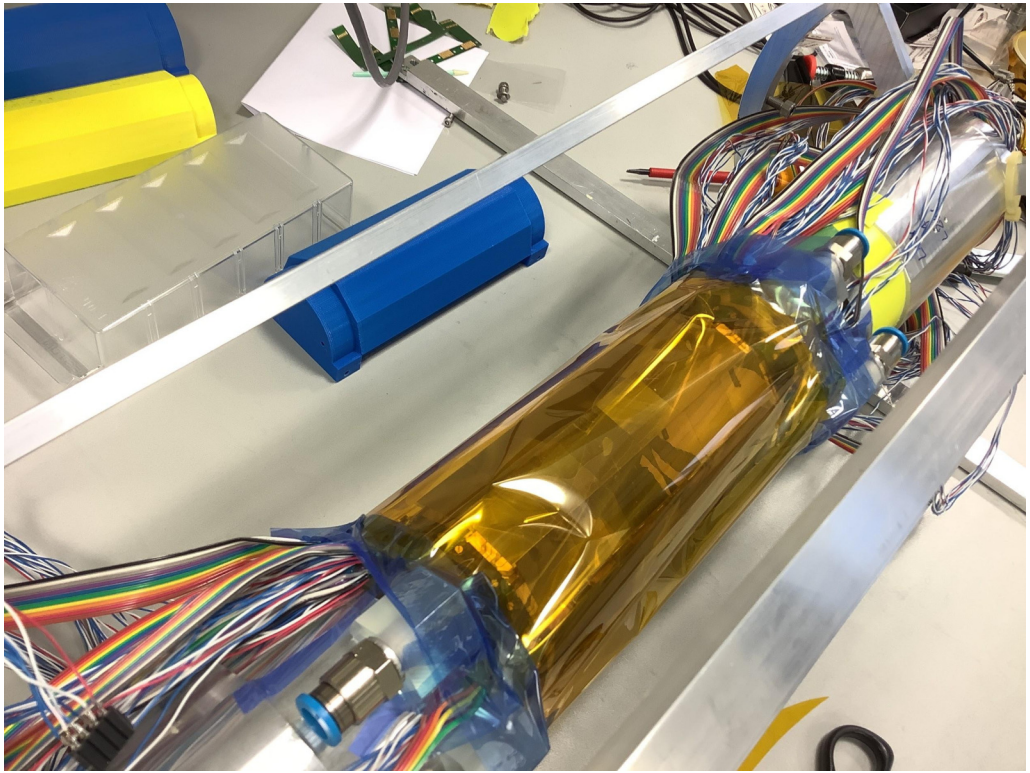
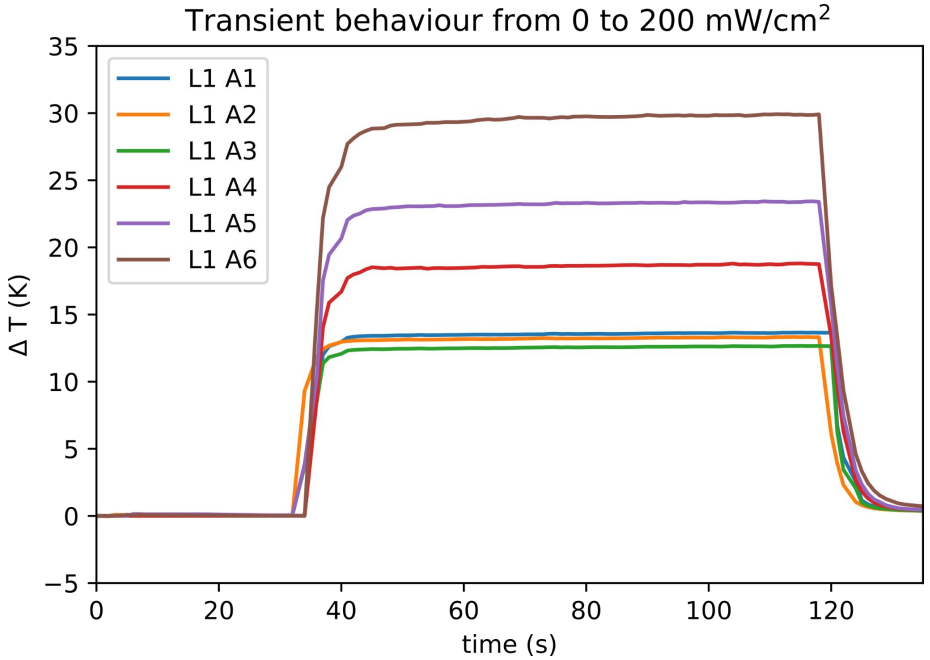


Cooling results

Thermodynamic behavior of the mockup:

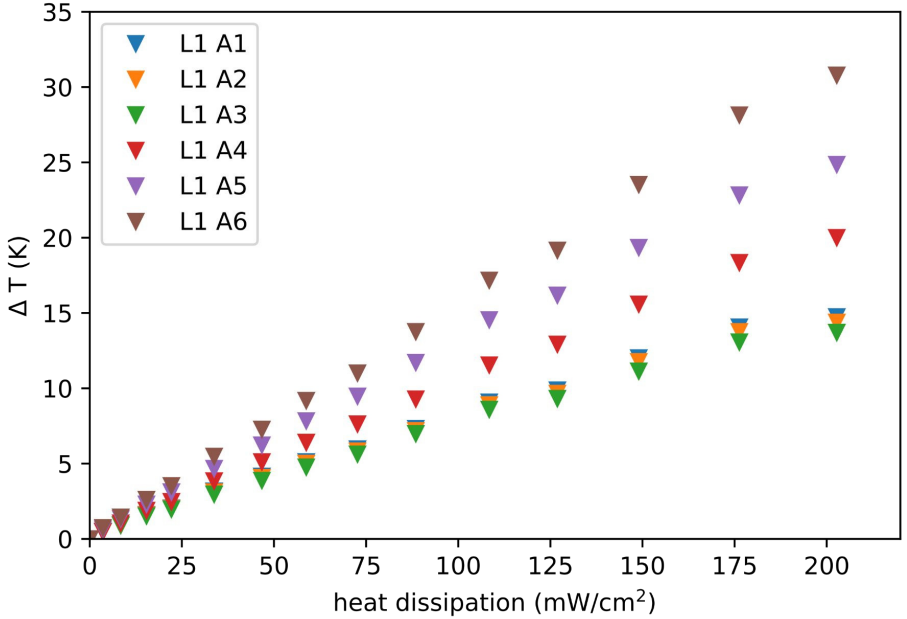
- Nominal heat load of 200 mW/cm²
- Temperature measured for 6 sensor on one inner ladders
- Equilibrium reached in seconds
- Maximum allowed temperature is 70°C
- Maximum ΔT ~ 30 K
  (foreseen inlet temperature ~ 5°C)



Cooling results

Measurement of temperature-to-power relation

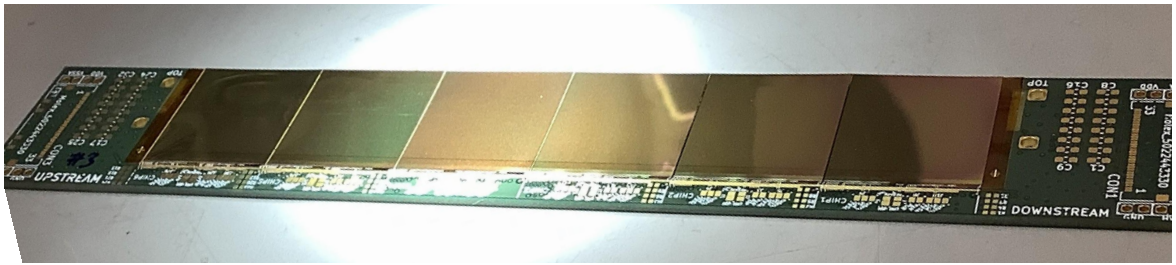
- Temperature difference linearly depending on heat dissipation
- Expected ΔT < 70 K for 400 mW/cm² (conservative limit)
- Cooling concept works ✔️



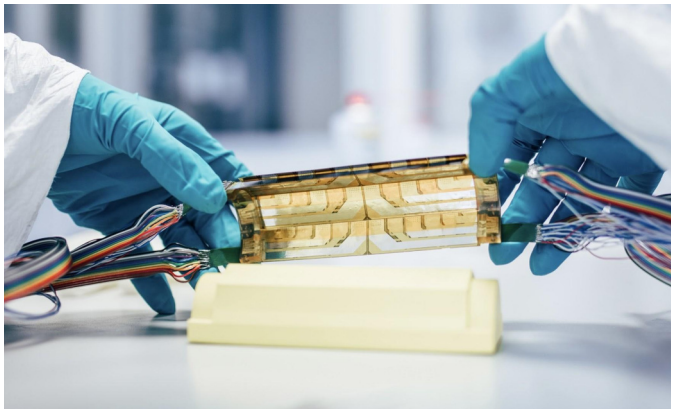
Summary & Outlook

- Feasibility of construction & functionality the cooling concept verified
- Mounting procedure ready for production in 2021/2022

- 1st ladders with 6 chips using PCBs will be tested in May 2021
- 1st ladders with 6 chips on HDI expected in summer 2021
- Mass production of final MuPix11 ladders in early 2022



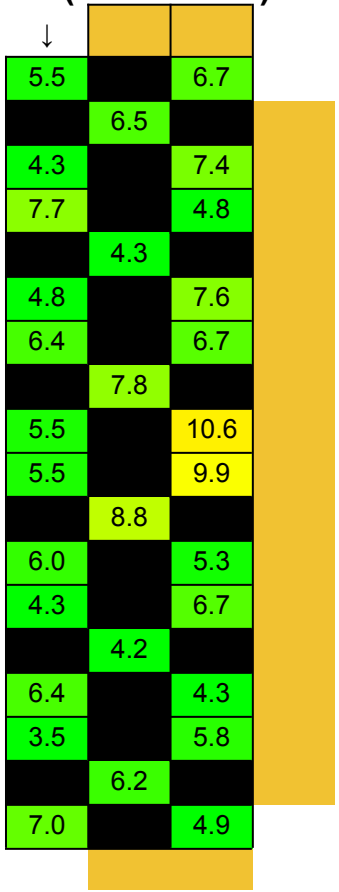
6-chip PCB for test run (summer 2021)



Backup

Systematic effects of tooling?

Average Thickness (all ladders)



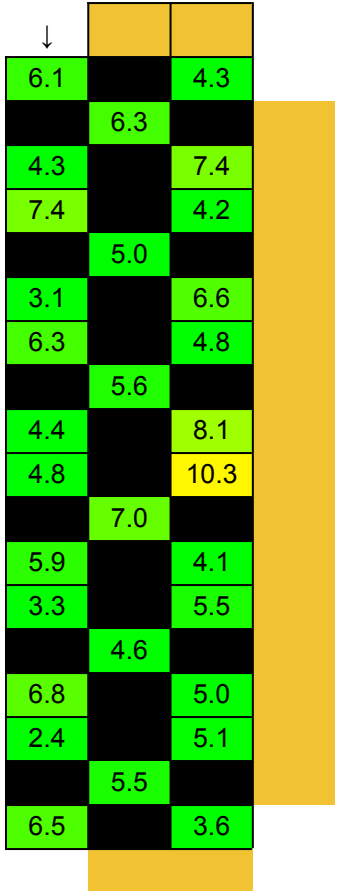
Overall average:
6.2 ± 1.7 µm

Sigma Thickness (all ladders)

- Local differences mainly from fluctuations

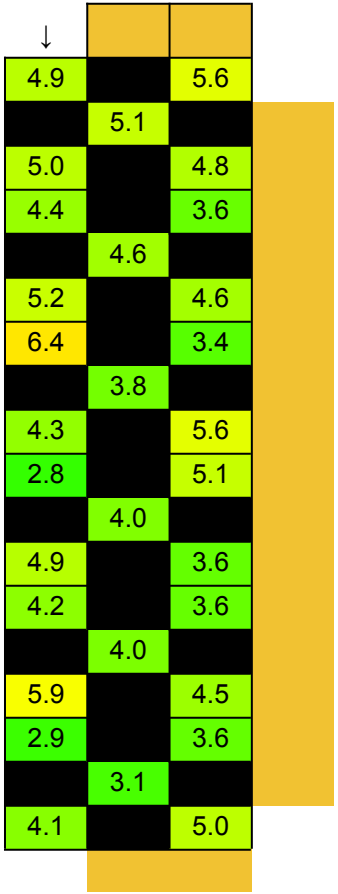
Systematic effects of tooling?

Average Thickness (excluded first 3 ladders)



Overall average:
5.5 ± 1.7 μm

Sigma Thickness (excluded first 3 ladders)



- Local differences mainly from fluctuations
- E.g. removing only first 3 ladders changes pictures
- $\sigma_{\text{glue spots}}$ = 4.7 μm
- Results are satisfying :-)