MANCHESTER 1824

The University of Manchester

The LHCb Mighty Tracker: Thermo-mechanical design and prototype testing

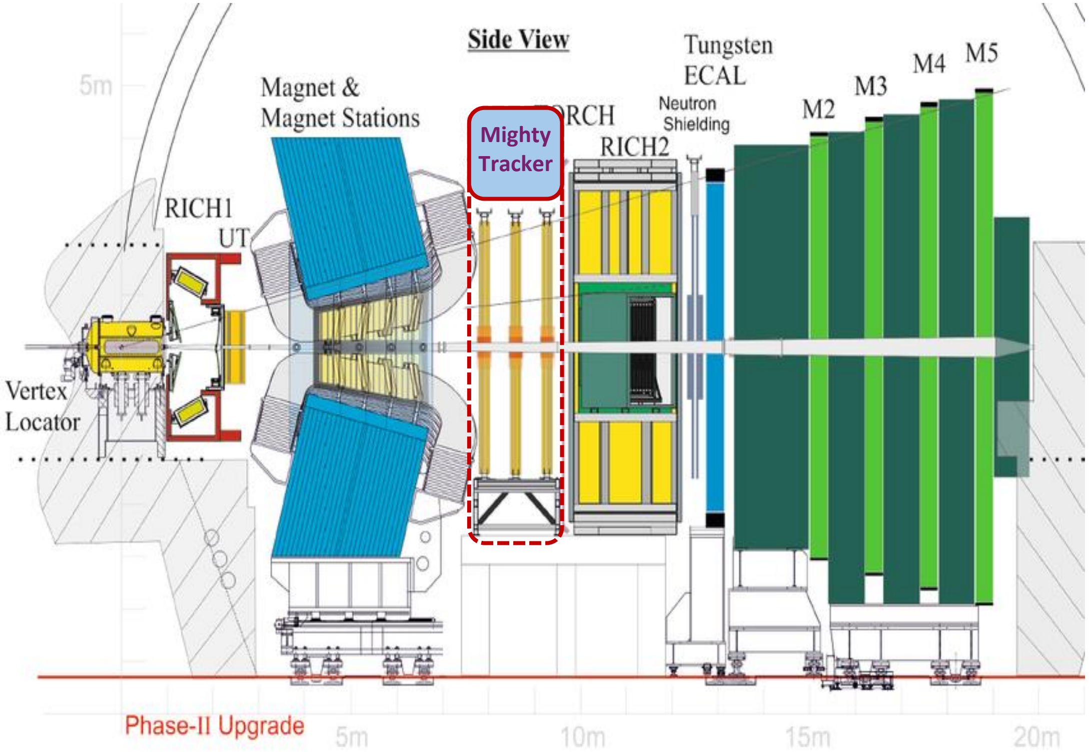
Bilal Ahmad Ganie

on behalf of the LHCb group Manchester

IOP Joint APP and HEP conference 2026 (Edinburgh, UK, 8-10 April 2026)

The LHCb Mighty Tracker

- Downstream tracking system for LHCb **Upgrade II**
- $\int\mathcal{L} = 300\ fb^{-1}$ ⟹significant fibre radiation damage in inner region
- $\mathcal{L}_{inst} = 1.5\times10^{34} cm^{-2} s^{-1}$
- ⟹ very high occupancy
- ⟹ SciFi is replaced near beam pipe to maintain the same (or better) tracking performance
- Solution: instrument the inner region with a pixel detector, while keeping scintillating fibres in the outer region.



Mighty Tracker consists of two parts:

❑ Mighty-Pixel

- HV-CMOS pixel sensors *(first HV-CMOS technology)*

❑ Mighty-SciFi

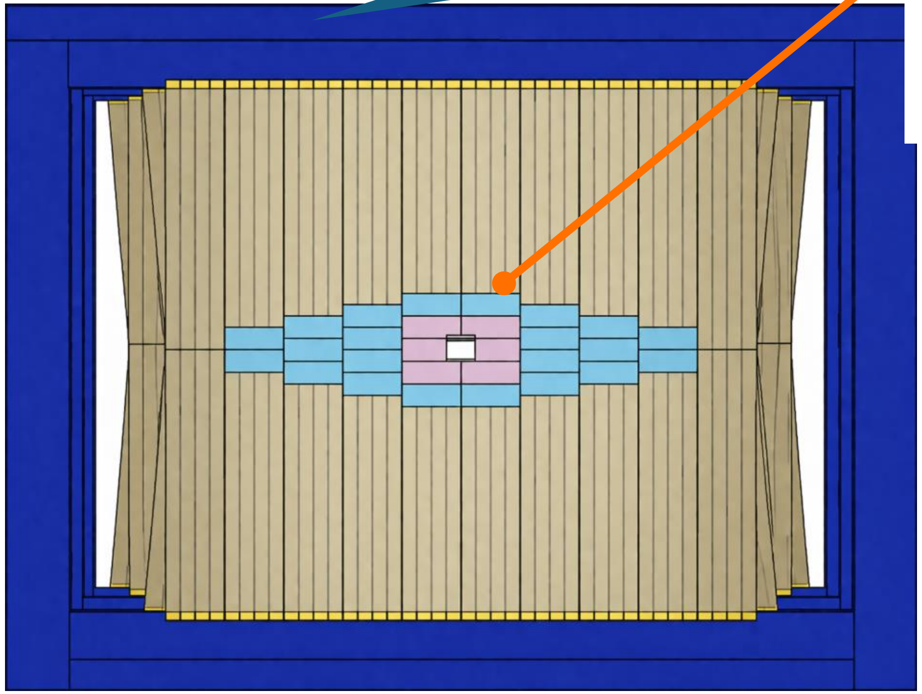
- Fibres: to improve the radiation hardness
- Cold Box & SiPMs: Cryo operation of SiPMs
- ReadOut Box: Updated components

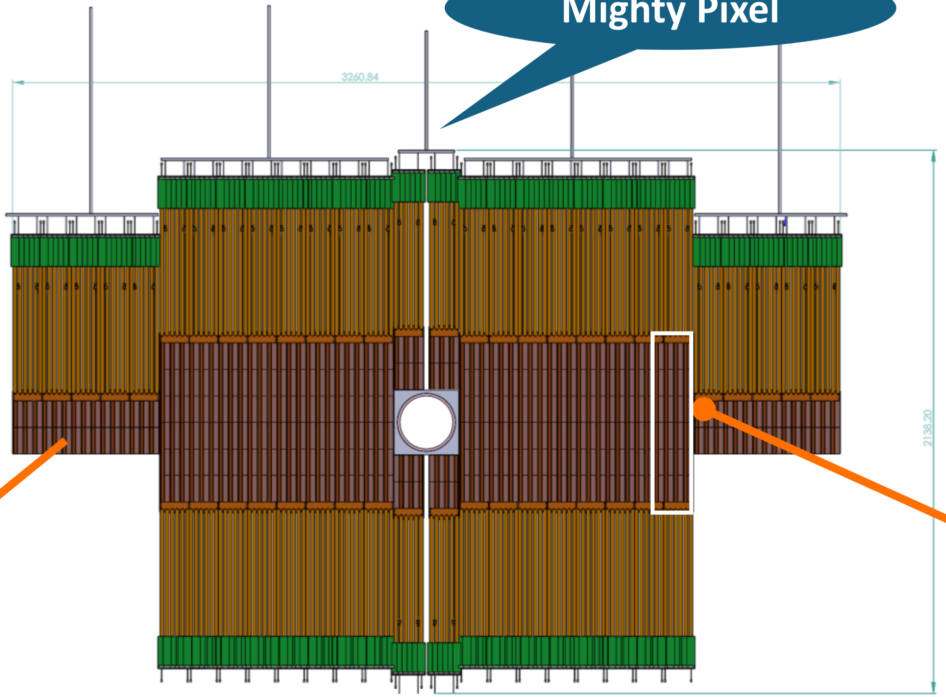
Mighty Tracker =
Mighty SciFi + Mighty Pixel

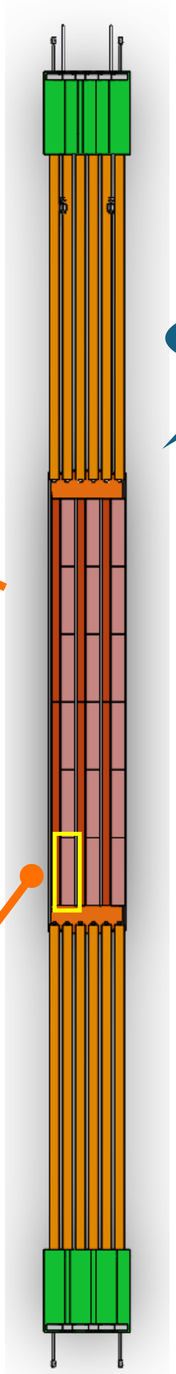
Mighty Pixel Architecture

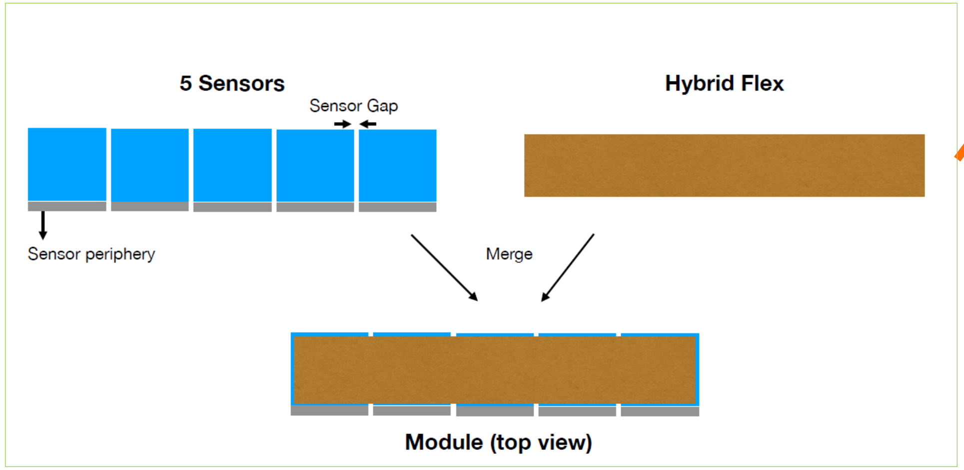
Stave topology:

- Elongated stave supports multiple monolithic CMOS sensors.
- Readout electronics is away from the high occupancy region.
- **6 layers of ~ 1.5 m^2 each layer: Total of ~9 m^2**







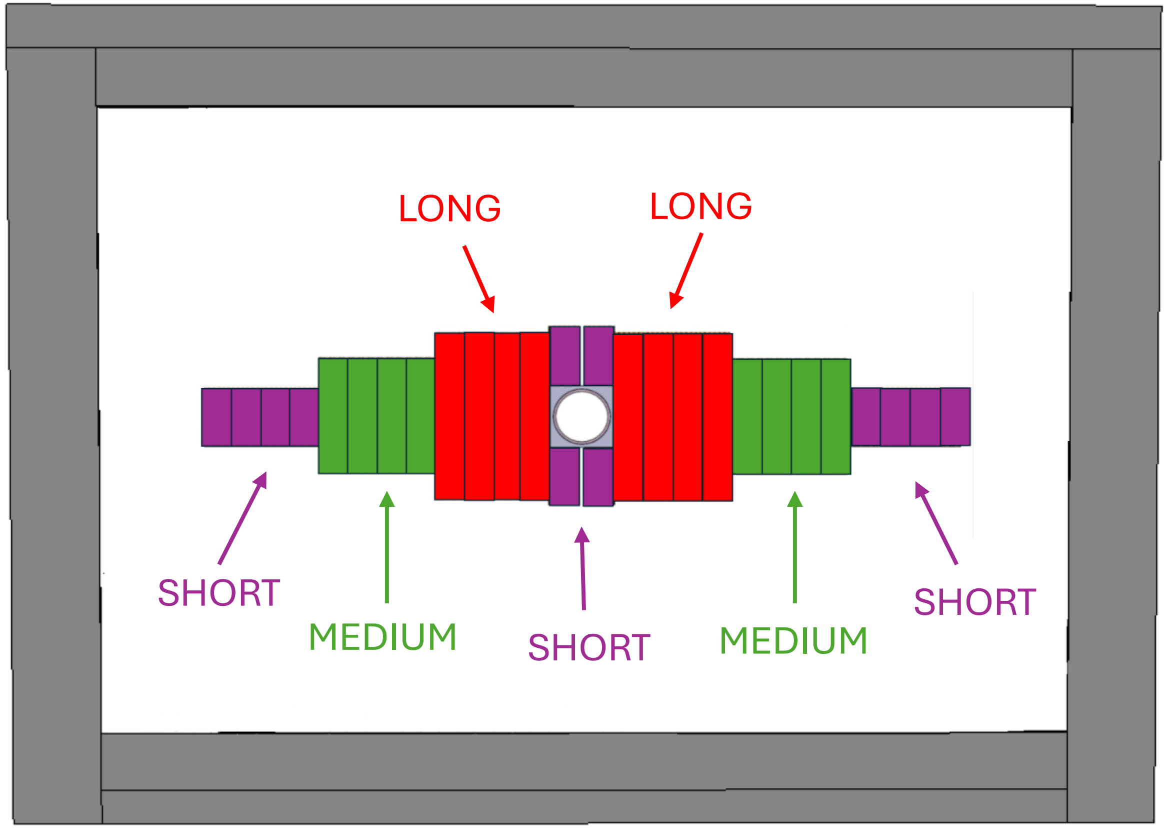


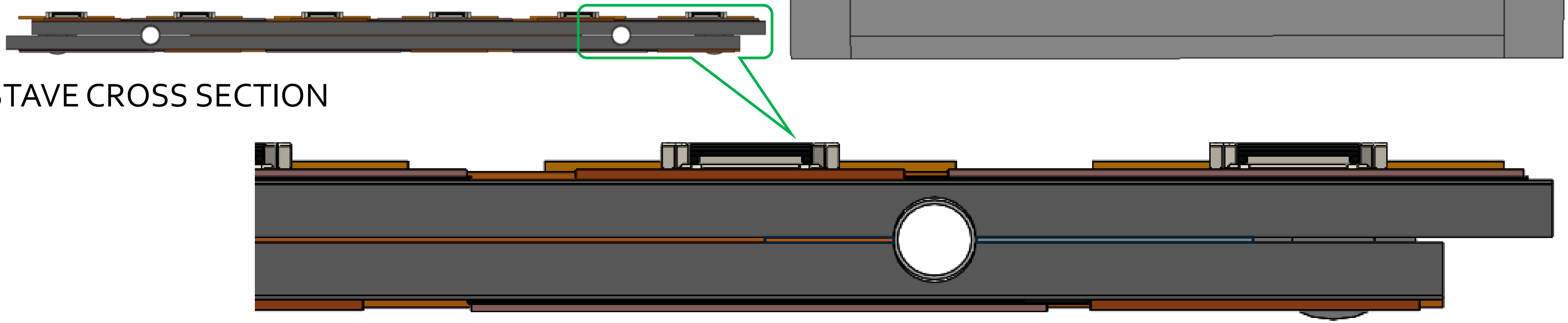
Mighty Pixel Staves

- **Building blocks: Staves**
  - 6 columns of pixel sensors - vary in length

- **Single layer contains:**
  - 12 **short** staves - 60-pixel sensors each
  - 8 **medium** staves - 120-pixel sensors each
  - 8 **long** staves - 180-pixel sensors each

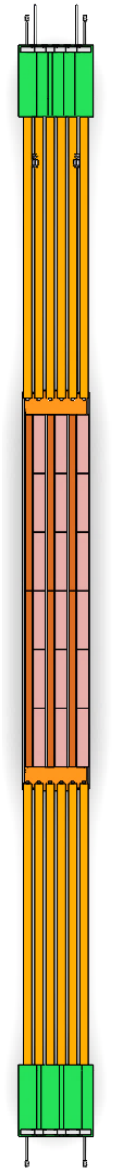
- **Chip columns are alternatively placed front and back.**

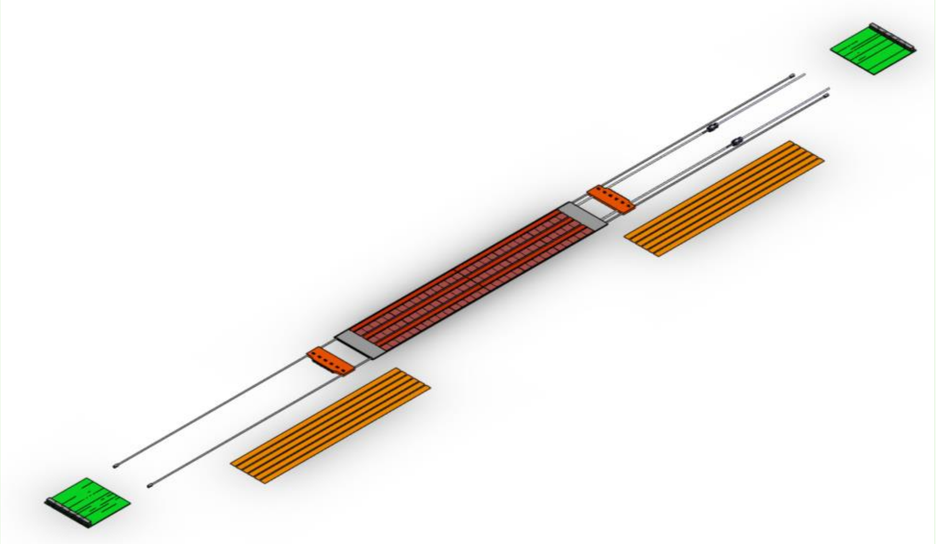


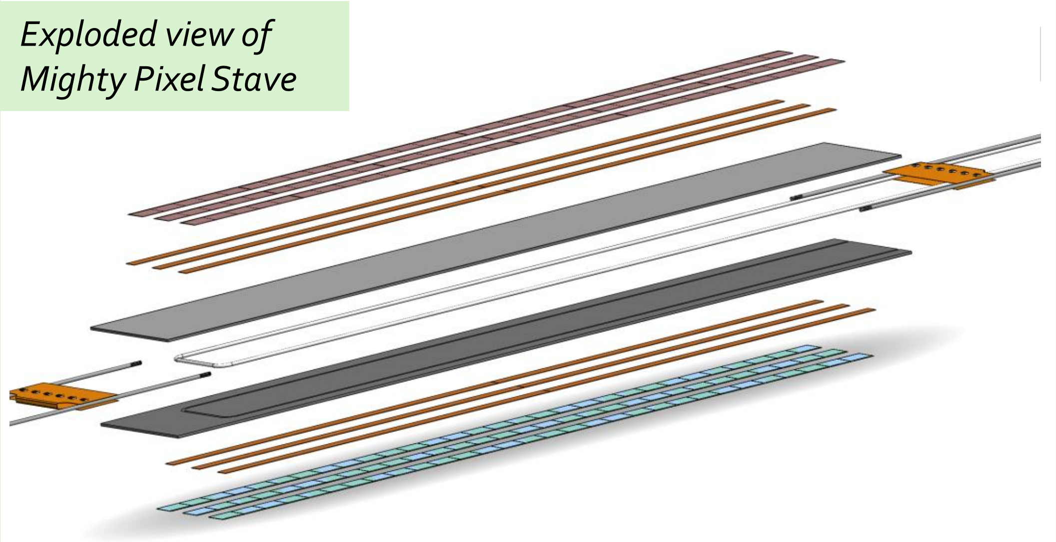


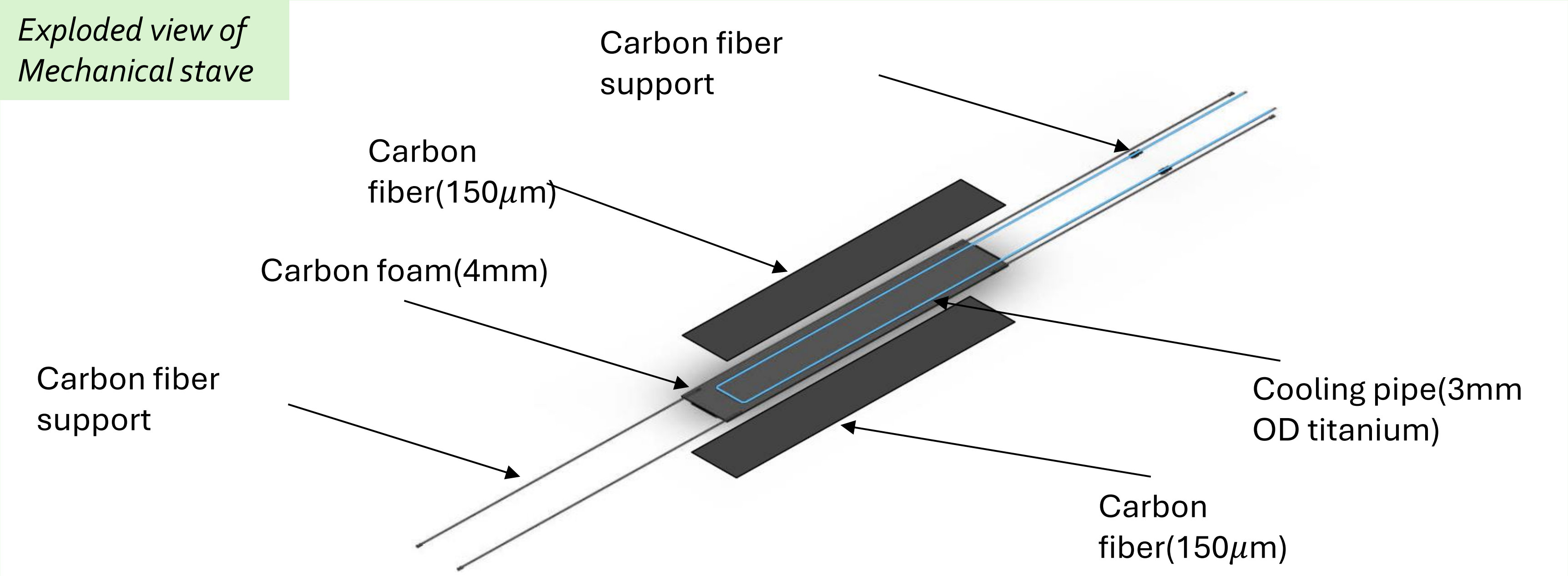
STAVE CROSS SECTION

Mighty Pixel Architecture

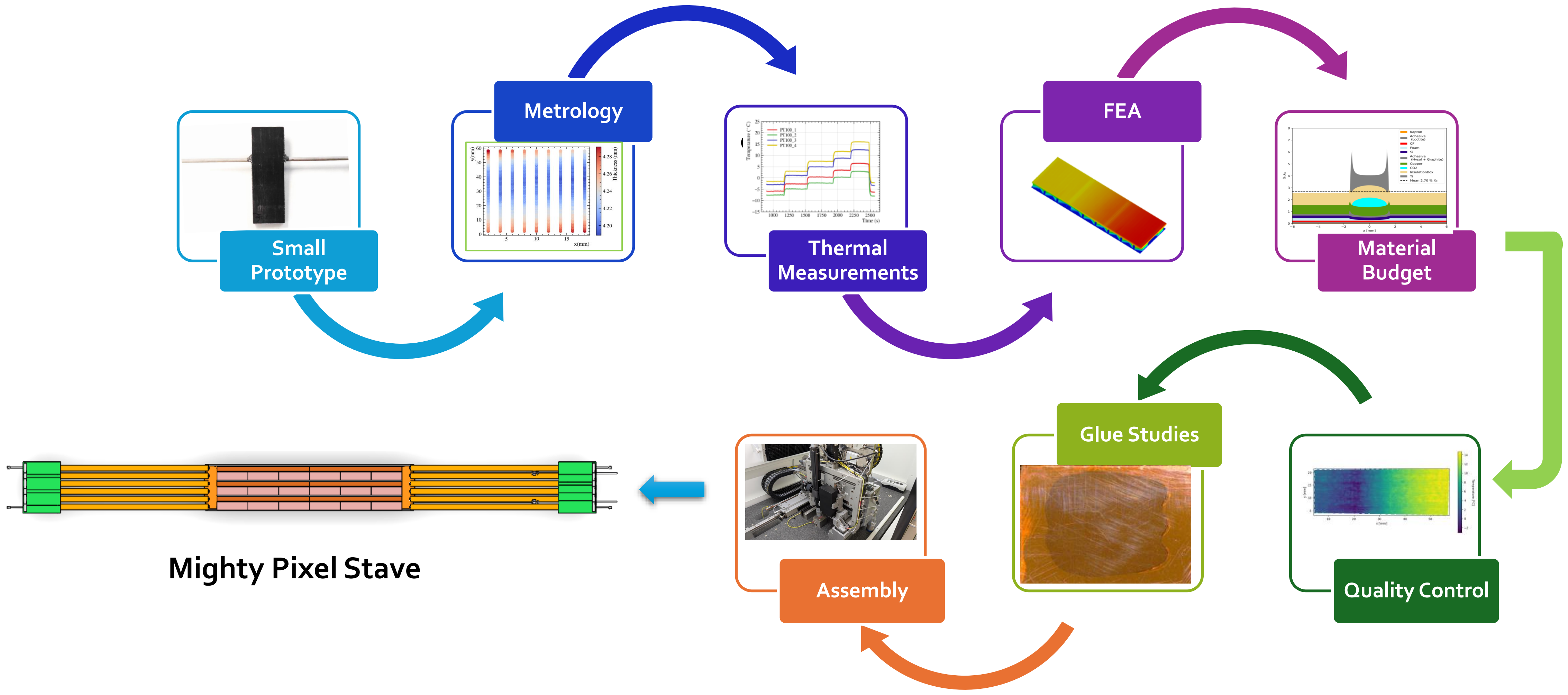




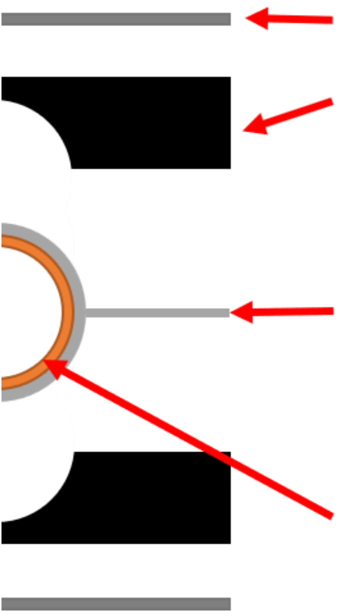




Stave Development Workflow



Small Prototype



Carbon fibre - Cocuring in Liverpool University (~150um)

Carbon foam

- Lockheed-Martin
- Alternatives such as PocoFoam and Honey comb structure being considered

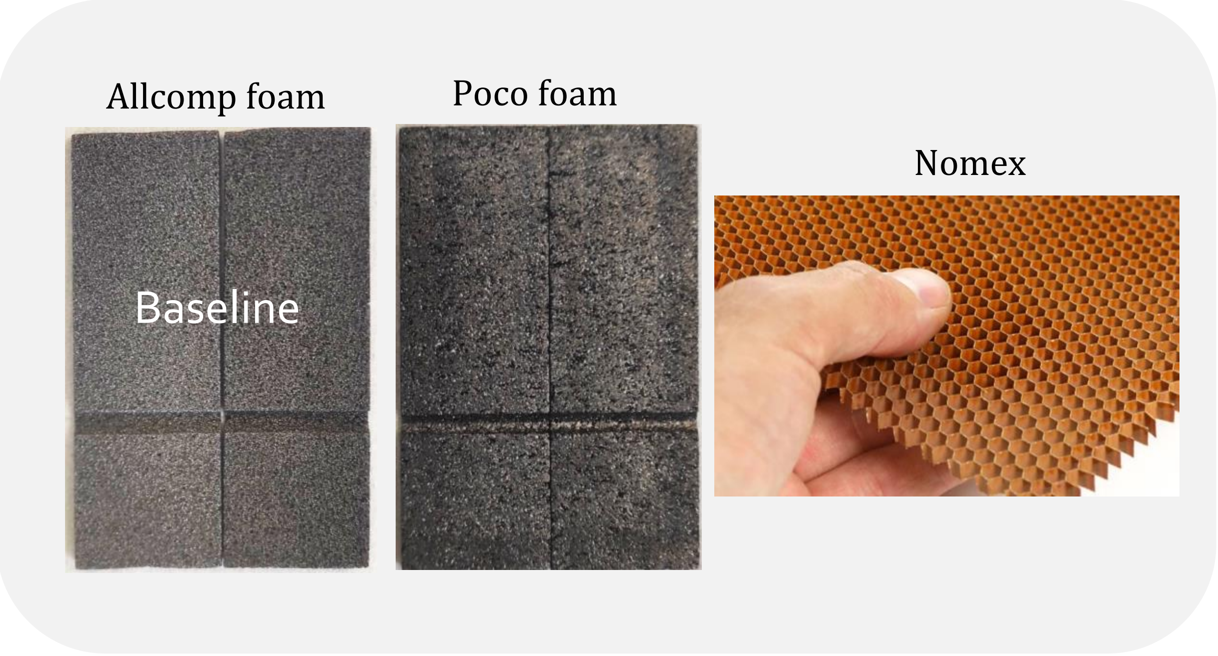
Carbon veil + Glue (Hysol)

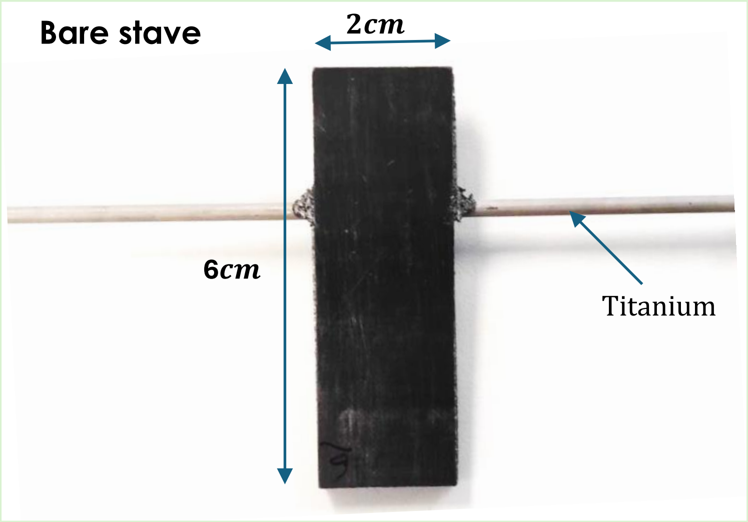
- **Foam-Foam attachment**

Glue around tube (Hysol+Graphite)

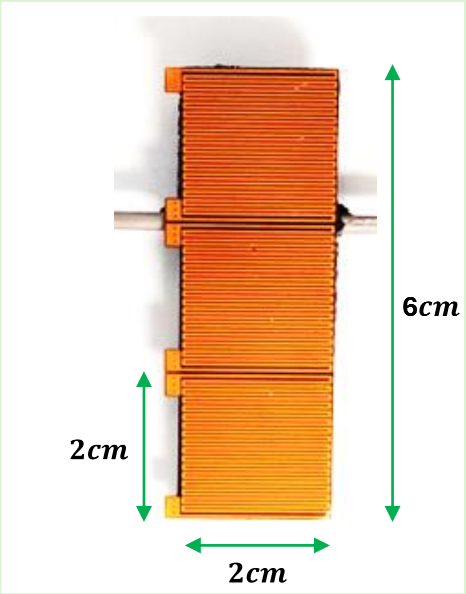
Tubes

Titanium tubes (baseline, Evaporative CO_2)





Stave with Electric heaters



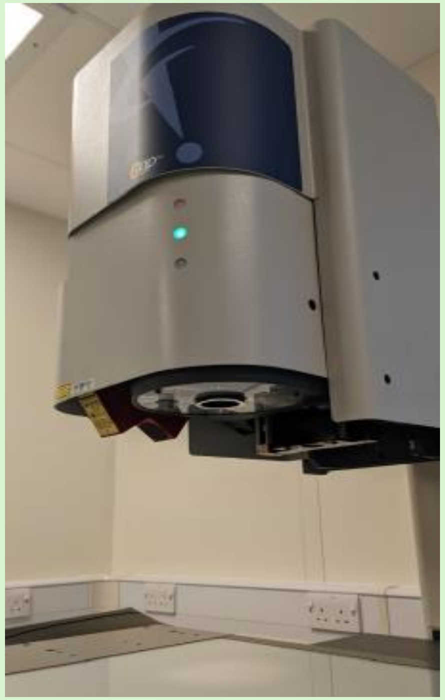
- Electric heaters are employed to reproduce realistic sensor heat loads
- The heaters are mounted along one side of the prototype

Metrology: Measuring with Precision

TOOL

OPG Smart- Scope Flash 300

High-precision optical system used to measure the mechanical prototype



WHY IT MATTERS

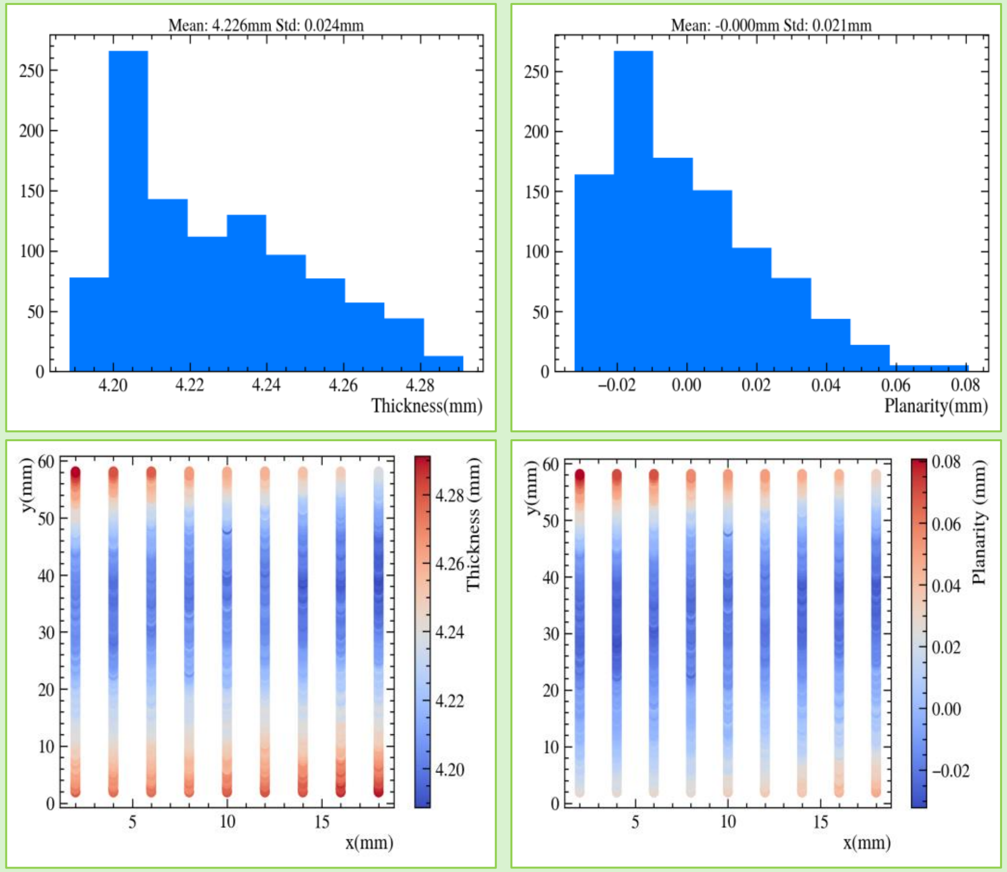
- Ensures prototypes are made to correct specifications
- Ensure accurate alignment for optimal detector performance
- Helps control the thickness of glue layers between sensors and support structure.
- Thickness is tightly controlled:
- **4.22mm** average with only
- **± 0.024mm** deviation

Small variation, confirming high manufacturing quality

KEY RESULTS

THICKNESS

PLANARITY



- **Accurate measurements are essential for building high- performance detector**

In Mighty tracker, metrology ensures precision, alignment, and quality

Thermal test and Monitoring

Test Environment

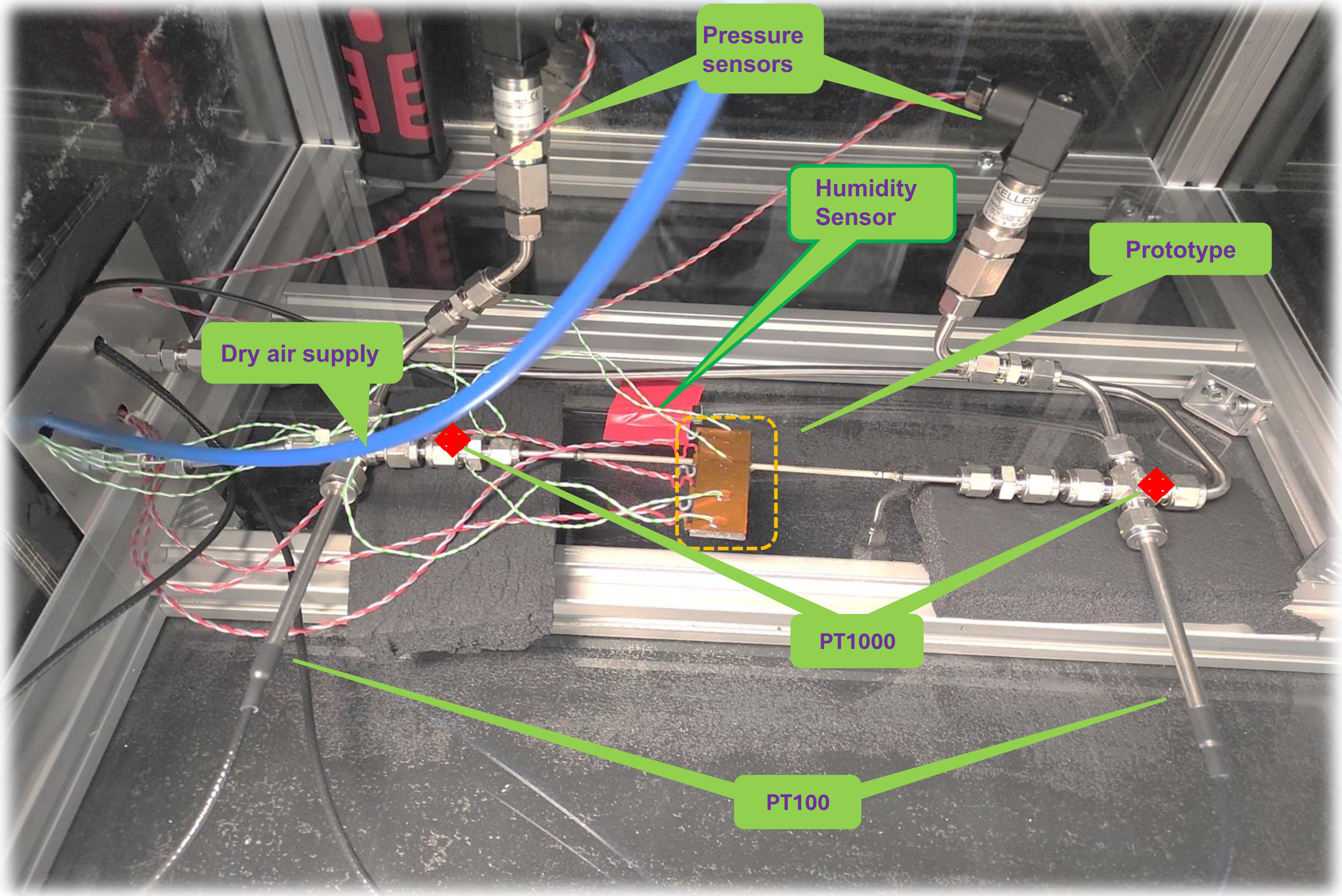
- Prototype installed inside the thermal box
- Dry air used to simulate the operational conditions
- Bi-phase CO_2 coolant is used.

What we measures

- Temperature at the multiple points along the prototype
- Cooling performance (Inlet & outlet)
- Environmental conditions (humidity)

Why it matters

- Ensure accurate and reliable thermal data
- Confirms systems behaviour under realistic conditions



The setup allows precise monitoring of temperature and cooling performance under controlled conditions

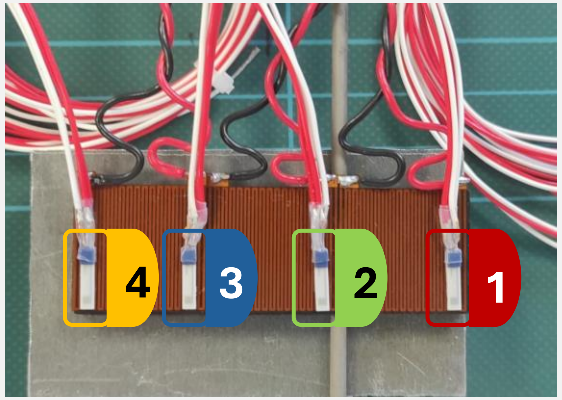
Thermal Performance

- Sample prototype with heaters on one side and internal cooling tube
- Four temperature sensors placed along the prototype
- Heaters are on one side of the porotype

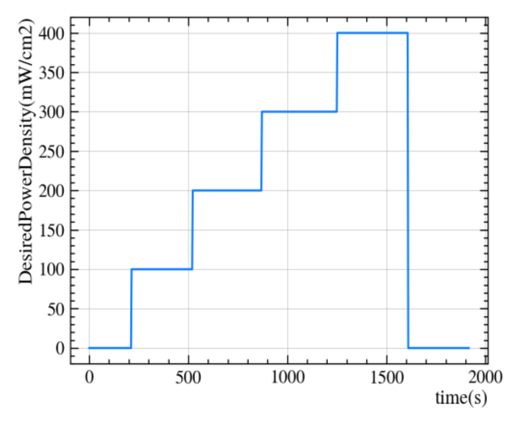
- Power increased step-by-step from zero to **400 mW/cm²** (Safety factor x2)
- Held at each power level to record how temperatures rise.

- Evaluates heat dissipation from the structure
- Determines temperature difference between hot regions and coolant
- Helps optimize coolant temperature for effective cooling
- Guides placement of cooling pipes within the structure

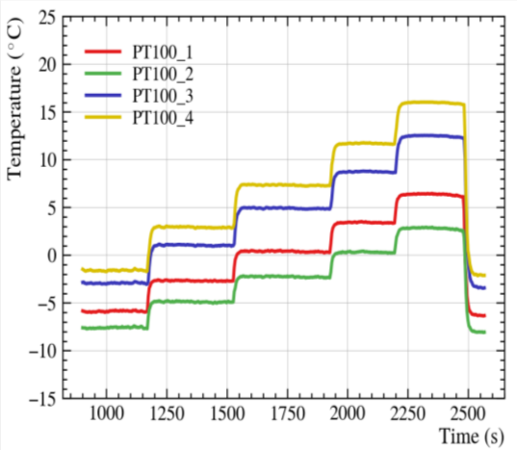
PT100's used to monitor the temperature along the prototype



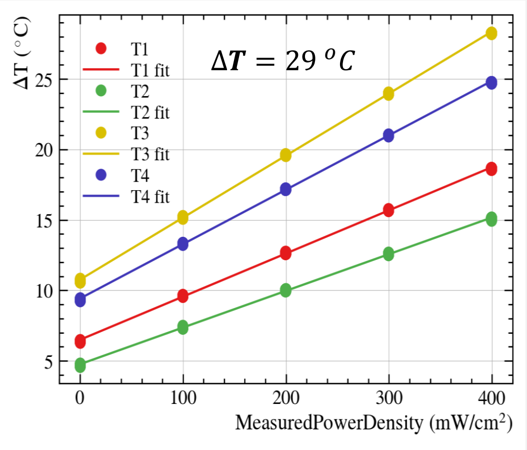
POWER DENSITY



TEMPERATURE PROFILE



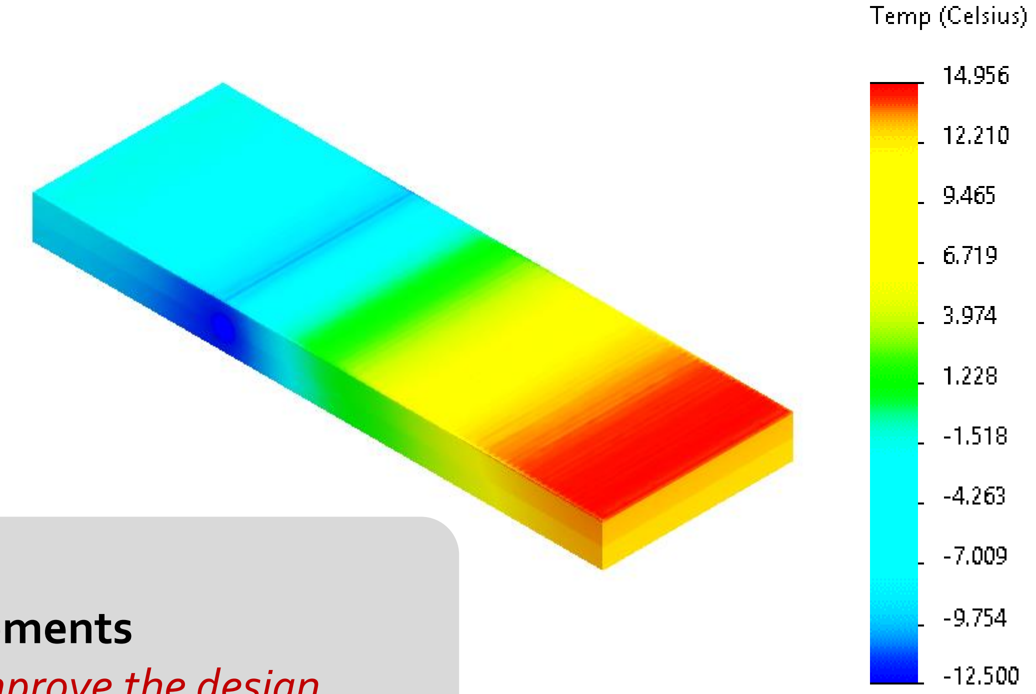
TEMPERATURE DIFFERENCE



FEA: Validating Thermal Measurements

Simulations

- Numerical method to predict system behaviour under real-world conditions
- We create a virtual version of our system
- The computer simulates how heat moves
- This gives us a temperature map



FEA Model

- The system is divided into many small elements
- Used to calculate heat flow
- Shows how heat flows through the system

Compare & confirm results

- **We compare the simulation’s temperature map with measurements**

  If both match → We confirm our system works well If not → We improve the design

Simulation + Measurement = Reliable Understanding of the System

Summary of measurements

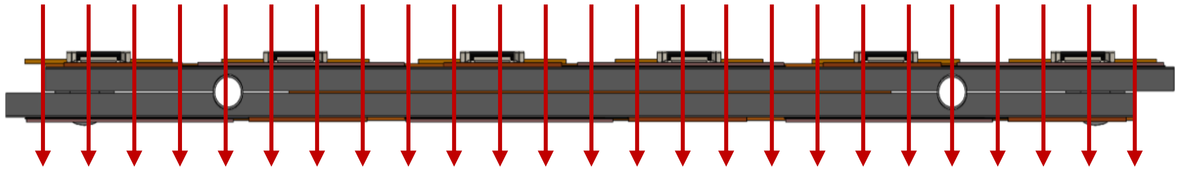
Prototype	Thermal conductivity $(W/m.k)$	Density (g/cm^3)	ΔT_{MAX} @ $200mW/cm^2$	ΔT_{MAX} @ $400mW/cm^2$	FEA (ΔT) @ $400mW/cm^2$
HTC Poco foam	$x/y/z$ = $245/245/70$	0.9	15^oC	25^oC	14^oC
Allcomp	20.3	0.2	20^oC	29^oC	27^oC
Nomex	0.1	0.048	25^oC	34^oC	40.7^oC

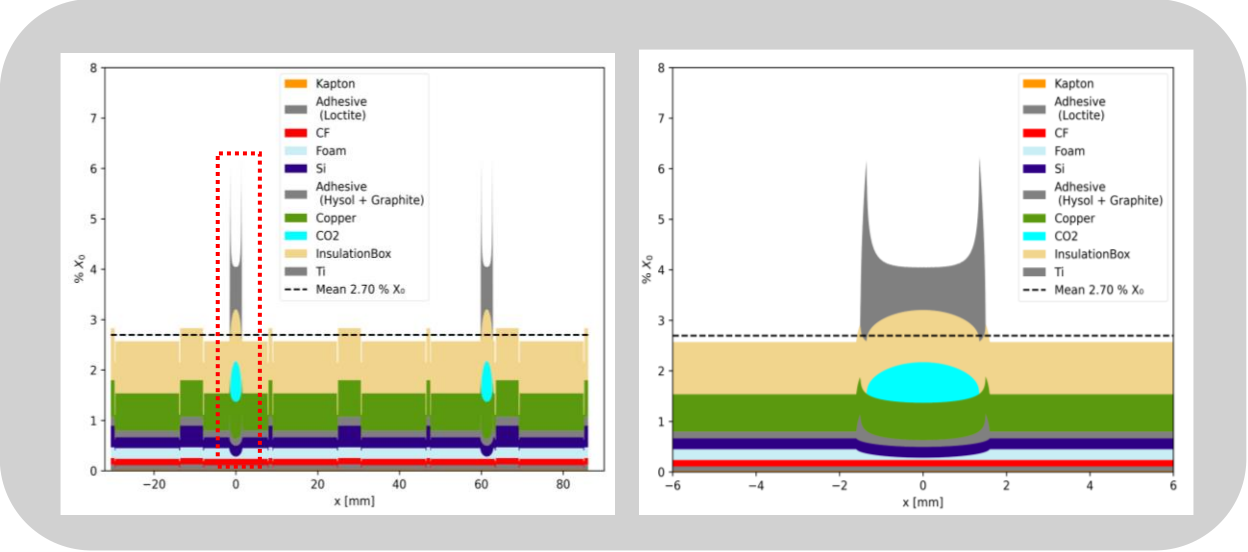
- ✓ The results are in line with expectations: more thermally conductive material ⇔ better thermal performance.
- ✓ At **200 mW/cm²** (nominal), all materials are expected to have their hottest location at T < **-10 °C** (assuming cooling setpoint is **-35 °C**).
- ✓ At **400 mW/cm²** (2x safety factor), all materials are expected to have their hottest location at T < **0 °C** (assuming cooling setpoint is **-35 °C**).

Material budget

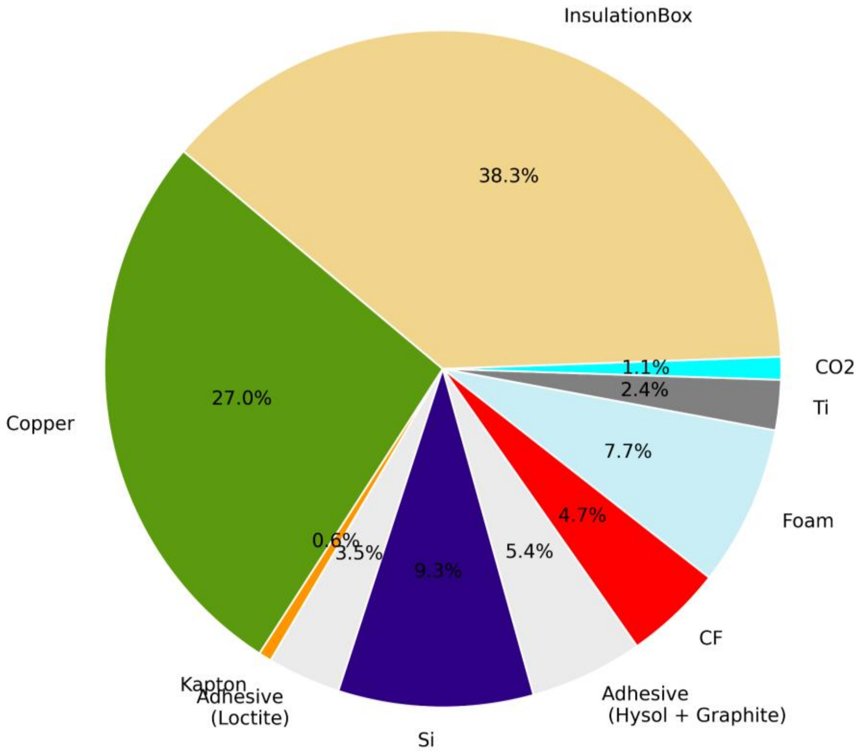
- Material budget = amount of material "seen" by particles
- Affects tracking accuracy (scattering, resolution)
- Expressed as fraction of radiation length (X_0)

Particle direction





Total Material Budget ≈ 2.7% X_0
(Low ⟶ good for tracking)



- ✓ Material is dominated by insulation box and copper layers in the electronics
- ✓ *Material budget identifies-* how much material is present and how it is distributed within the detector

Quality Control

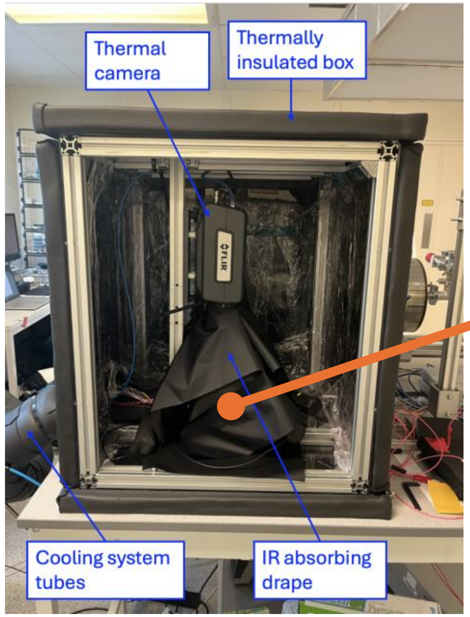
Investigating bare stave quality control using CO_2 thermal shock

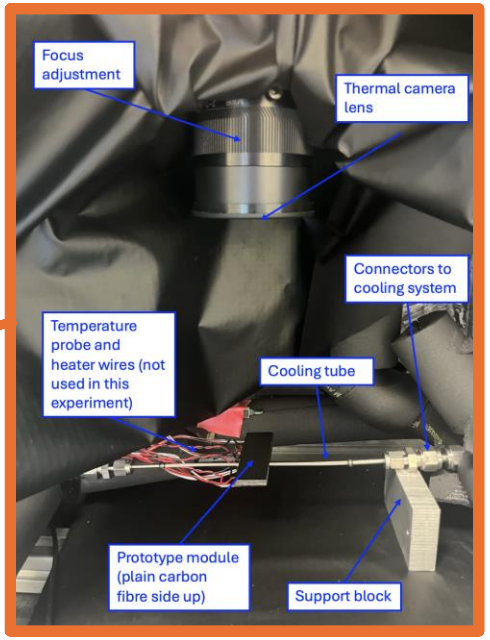
What would we like to detect?

- Imperfections in the glue layer around the titanium tube
- Large inconsistencies in the foam
- Delamination effects, …

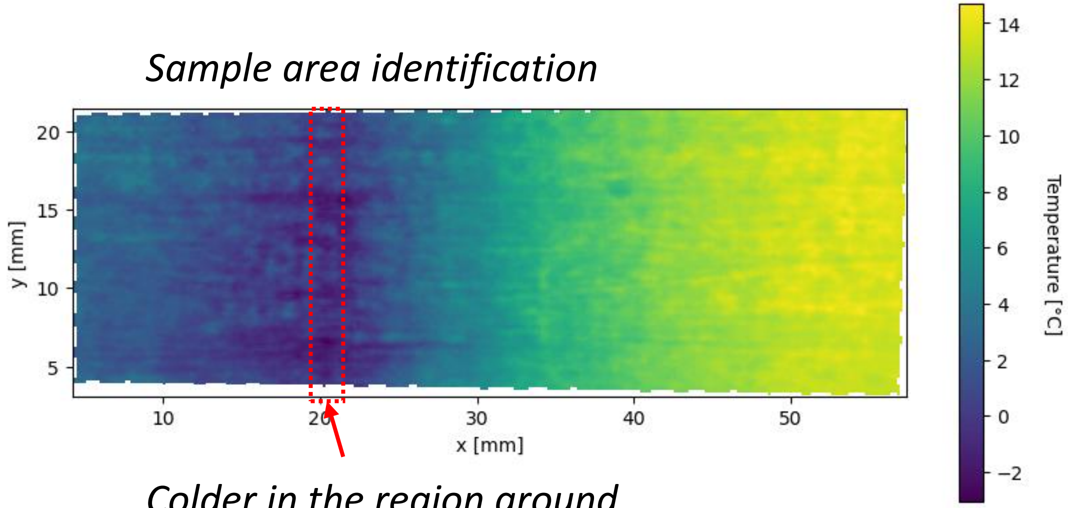
Procedure

- Perform a thermal shock with CO_2
- Select the frame with highest sample temperature standard deviation (maximize temp. differences)
- Fit the temperature surface and look for imperfections





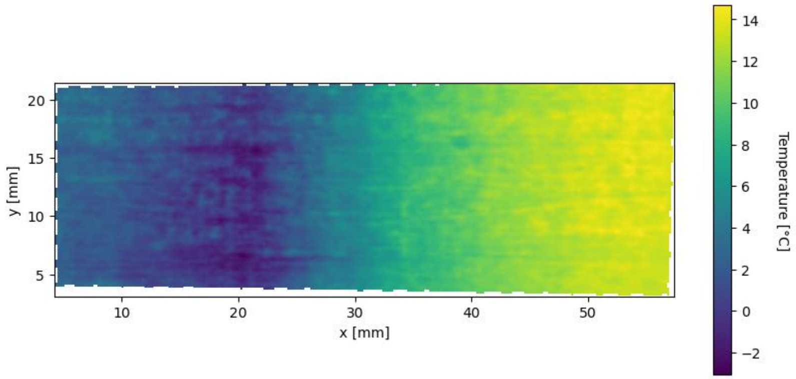
Sample area identification

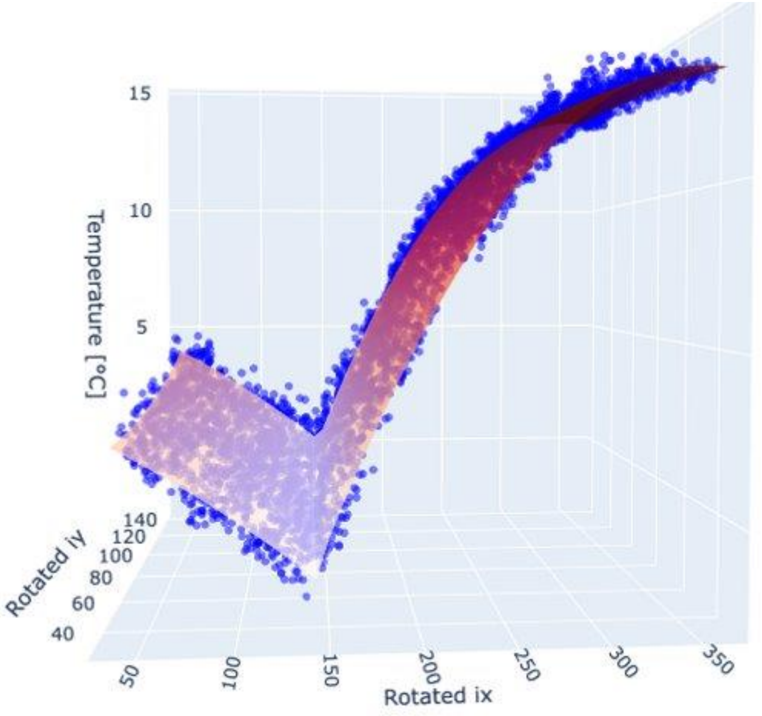


Colder in the region around the cooling tube

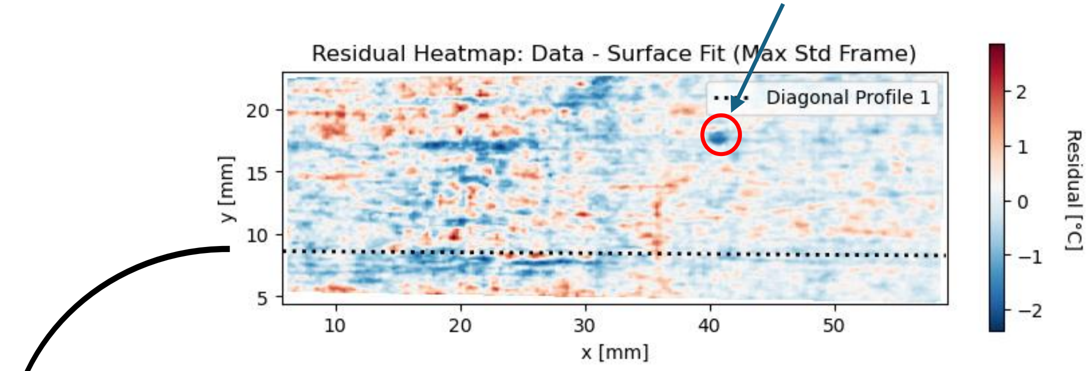
Quality Control

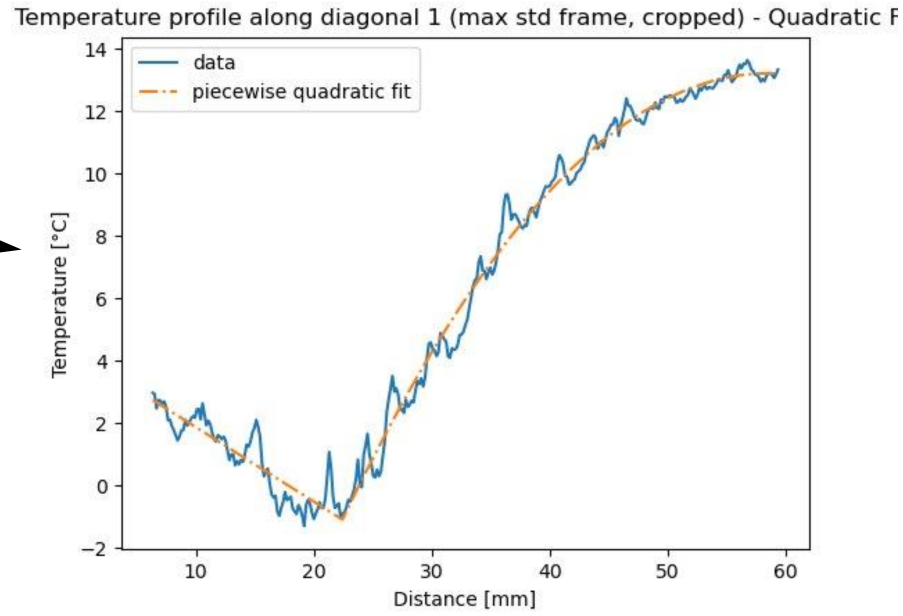
Surface fit using quadratic function for each side





Surface effects on the carbon fibre

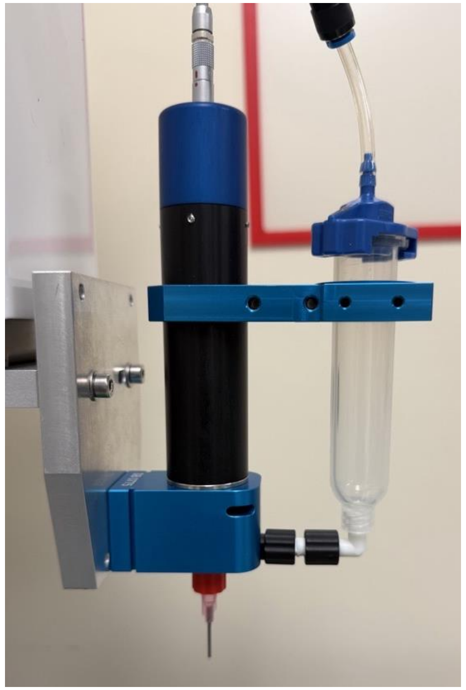


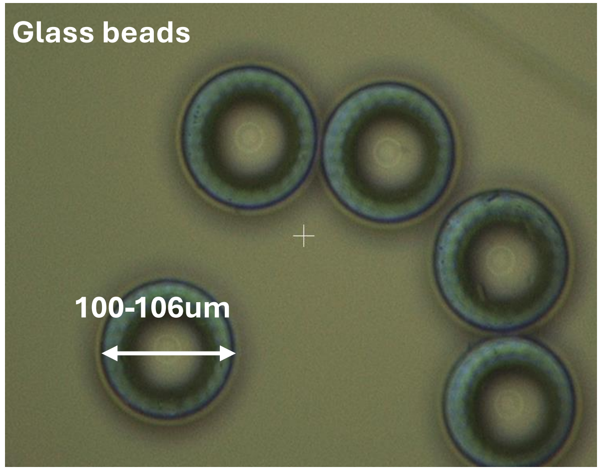


Hybrid & Readout Electronics: Glue studies

- Hybrid flex are attached to silicon sensors within the tracker.
- The hybrid processes digitizes and prepares the data.
- Readout flex cables transmit the digital data from the hybrid to the main electronics system.

- Testing ways to attach sensors to hybrid electronics modules with glue.
- Glue robot for the precise and controlled application of adhesive.
- Trying elastic glue layers to accommodate stress.
- Glue layer cures correctly and holds the sensor securely.
- ***Tiny glass beads → control thickness → consistent bond thickness.***





Kapton-Silicon sandwich

Testing Sensor Attachments

What We Test

- We test how strong the bond is between layers of materials in our sensor modules

Why We Test

- We need to know they can withstand real-world conditions, including movement and temperature changes
- We measure how the glue or adhesive behaves under stress

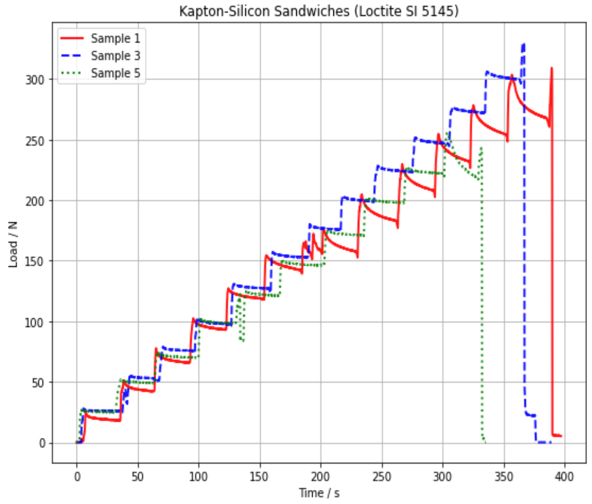
Pull Test

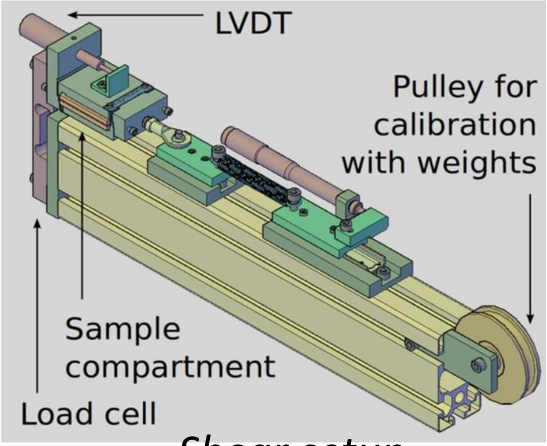
- Measures how much force is needed to pull layers apart

Shear Test

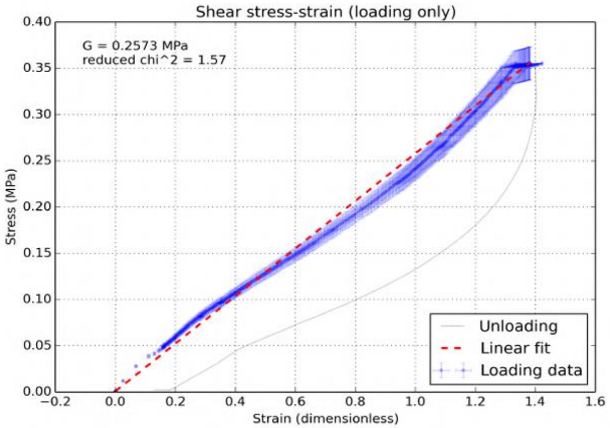
- Measures resistance to layers sliding sideways

Pull setup



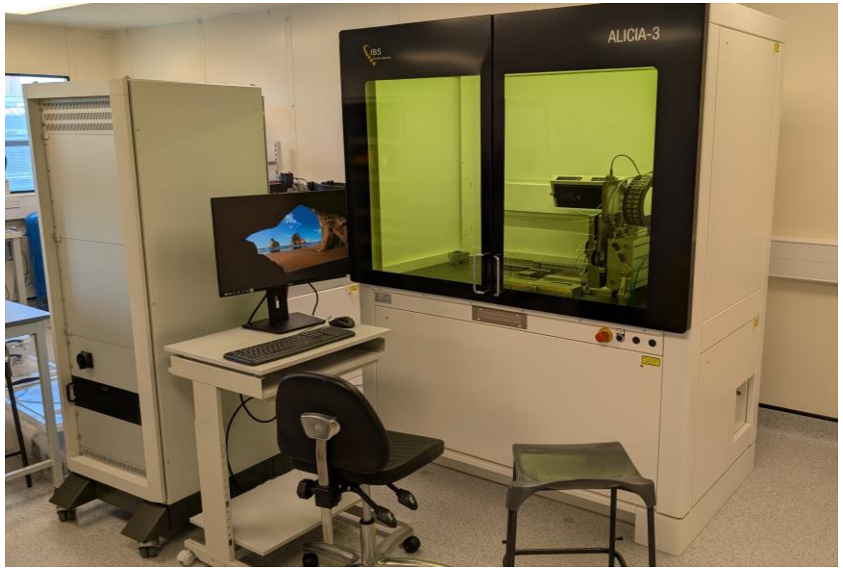


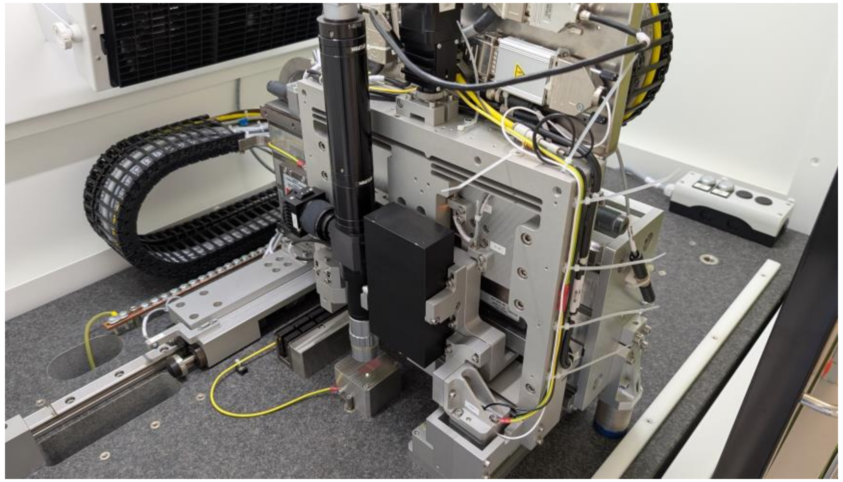
Shear setup

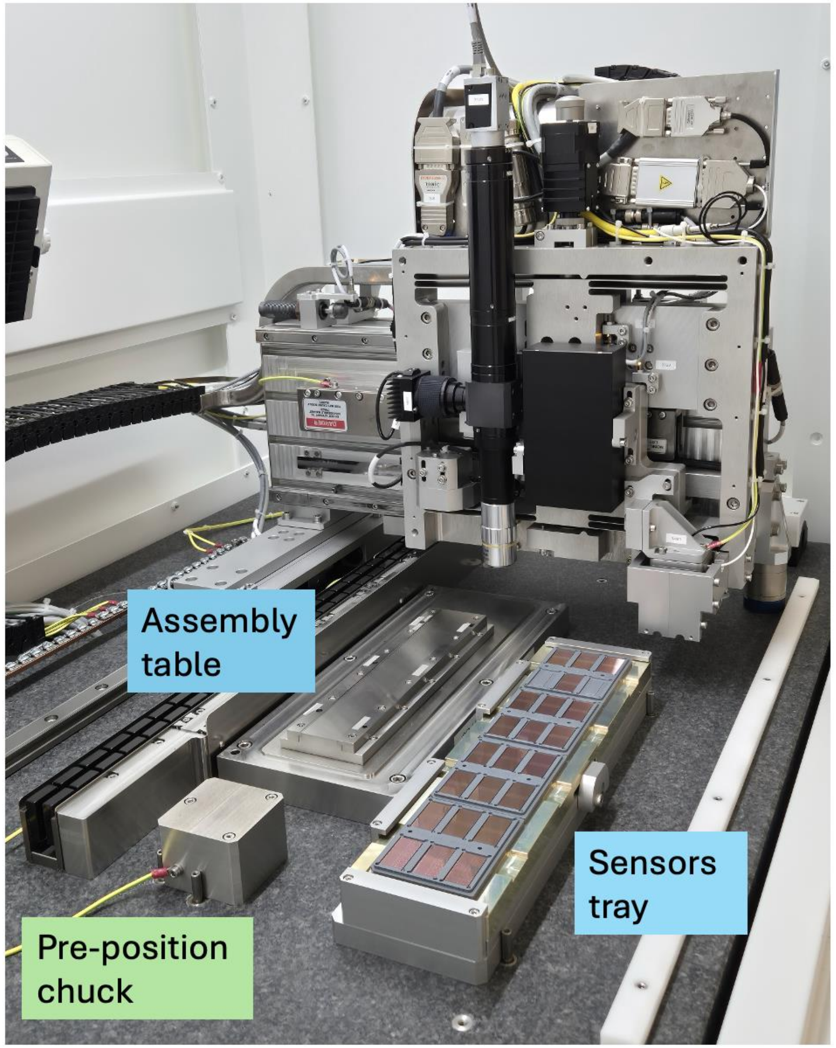


ALICIA: Pick and Place Machine

- System for precise sensors positioning





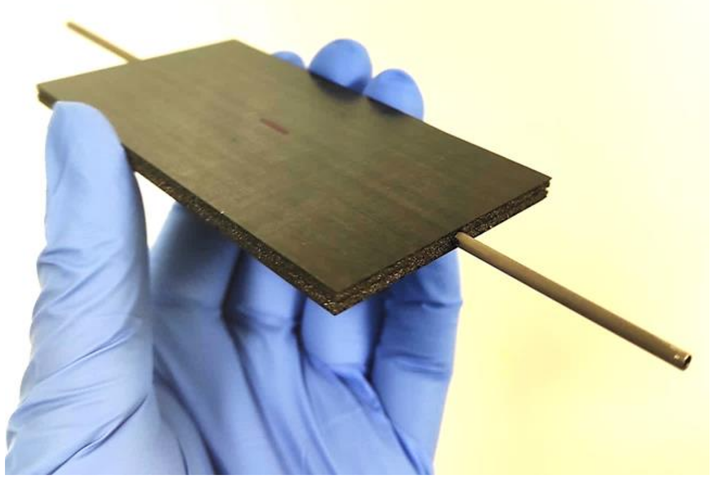


Summary

The LHCb Mighty Pixel Tracker

- ✓ Samples were fabricated using Allcomp foam, Poco foam, and honeycomb, each integrated with 1×3 heater prototypes.
- ✓ Metrology measurements were performed to quantify thickness uniformity and planarity.
- ✓ Thermal performance measurements were conducted and systematically benchmarked against FEA simulations
- ✓ Infrared thermal camera analyses were carried out for quality control.
- ✓ Adhesive studies were performed to evaluate flex–sensor adhesion reliability. Extended glue studies will be conducted on realistic hybrid flex–sensor assemblies
- ✓ A 3×5 sensor prototype has been assembled; new silicon sensors will be used for detailed analysis
- ✓ Preparation and assembly of a full stave(6×30 sensors) prototype will commence.

3×5 sensor prototype

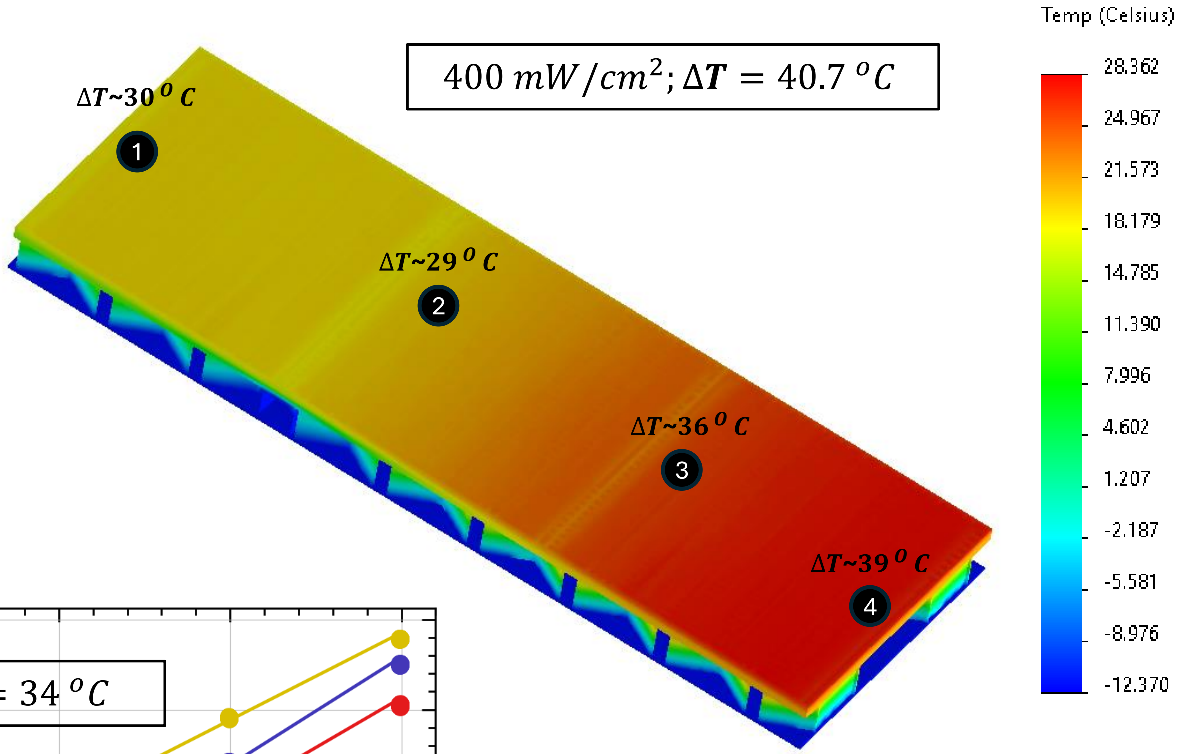


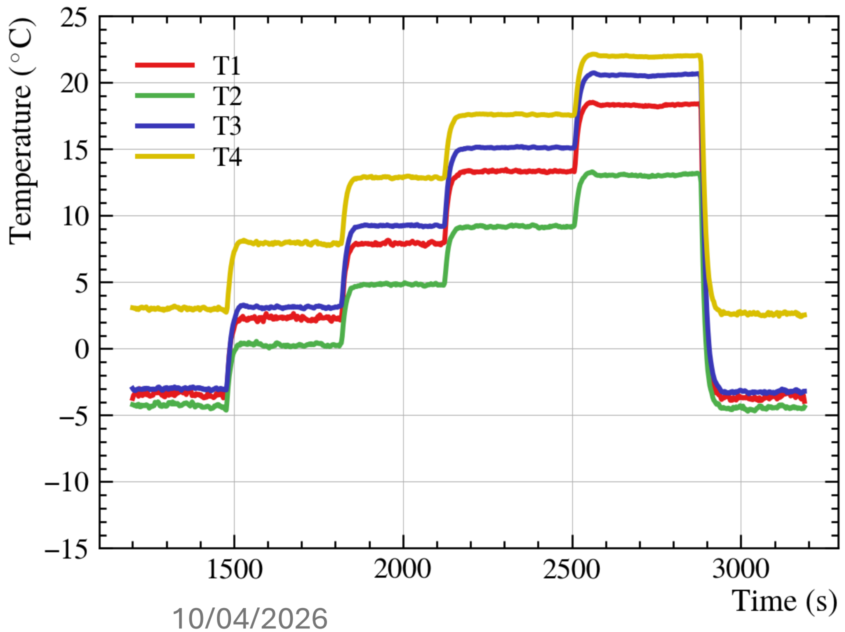
Back up slides

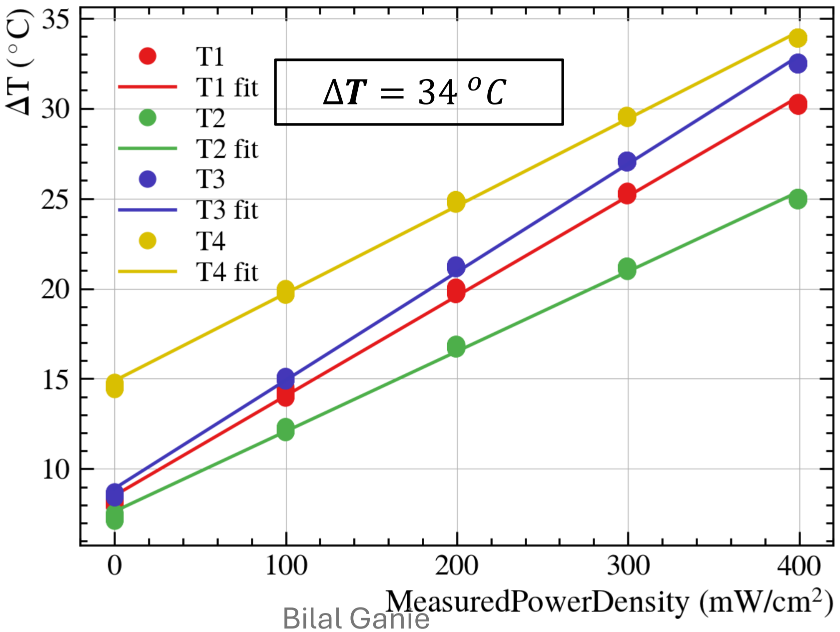
Experimental Methods and Validation

Finite Element Analyses (FEA): Conditions:-

- The coolant temperature (-12 °C) was applied as a boundary condition on the inner tube walls.
- Each heater was modelled to dissipate 1.6 W of thermal power.
- Simulation seems to be in better agreement with the measurements compared to the previous prototype.

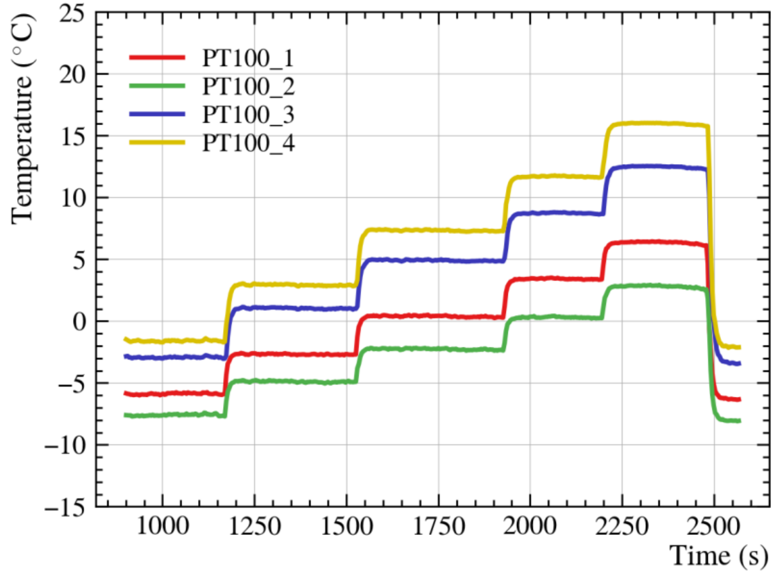






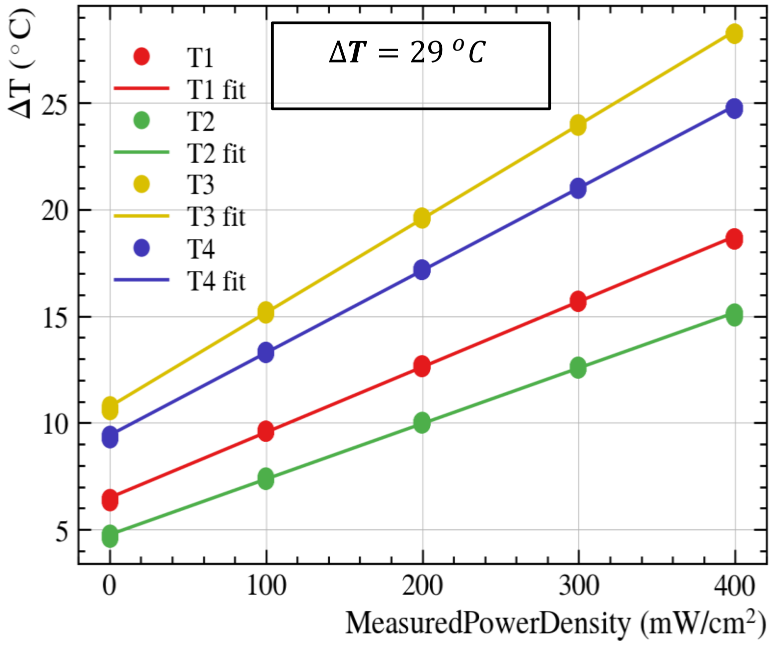
Experimental Methods and Validation

- At max power (400 mw/cm²), the observed max temperature difference (ΔT) between the heater surface and the coolant (@ -11 °C) is ~25 °C, in the T3 location.
- Unexpectedly, T4 is cooler than T3 at max power. We suspect that the T4 thermocouple is not properly glued or is malfunctioning.
- Dry air flow might also affect the measured temperature.



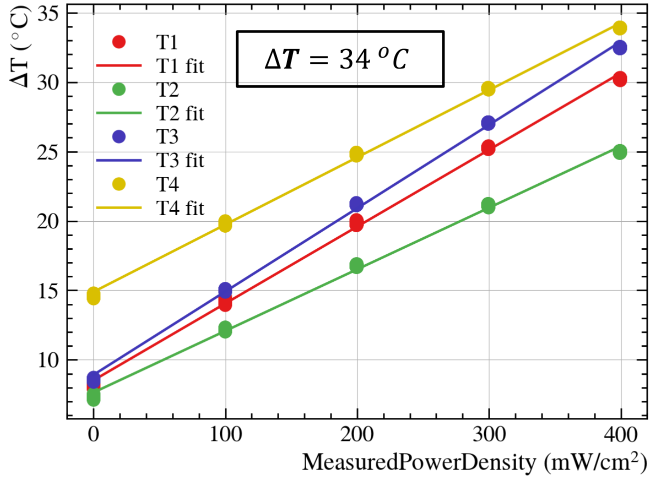
Additional structural Configurations tested

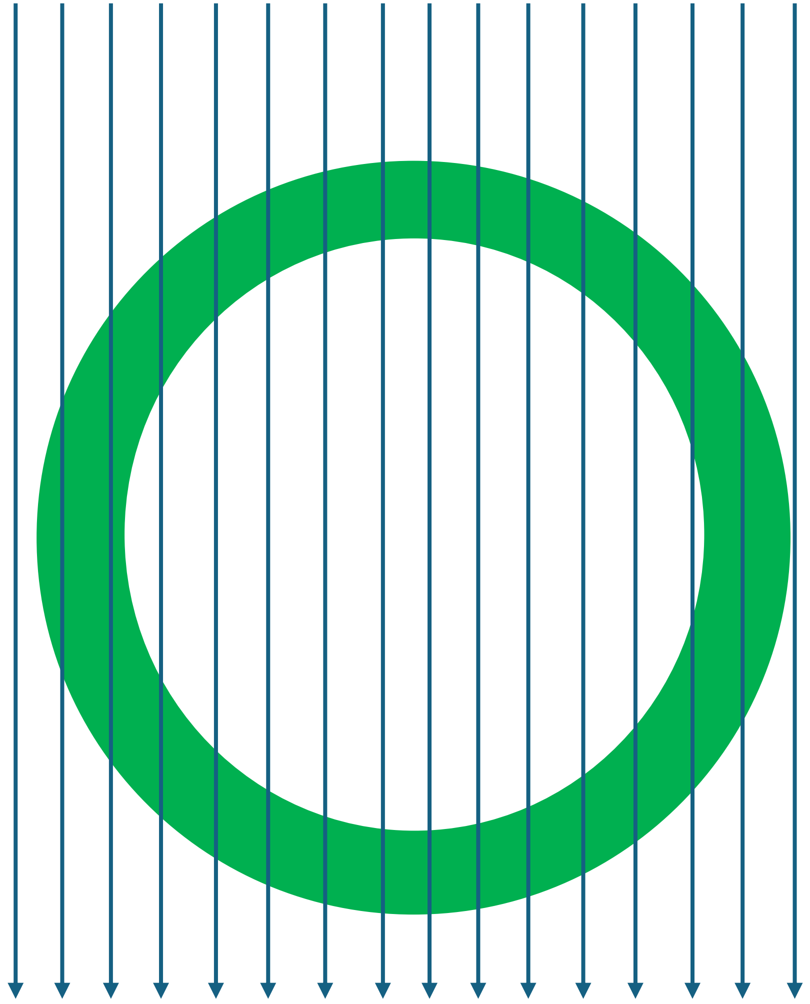
- Additional tests included alternative foam types like Poco foam as well as no foam configuration.
- A honeycomb structure variant was also evaluated.

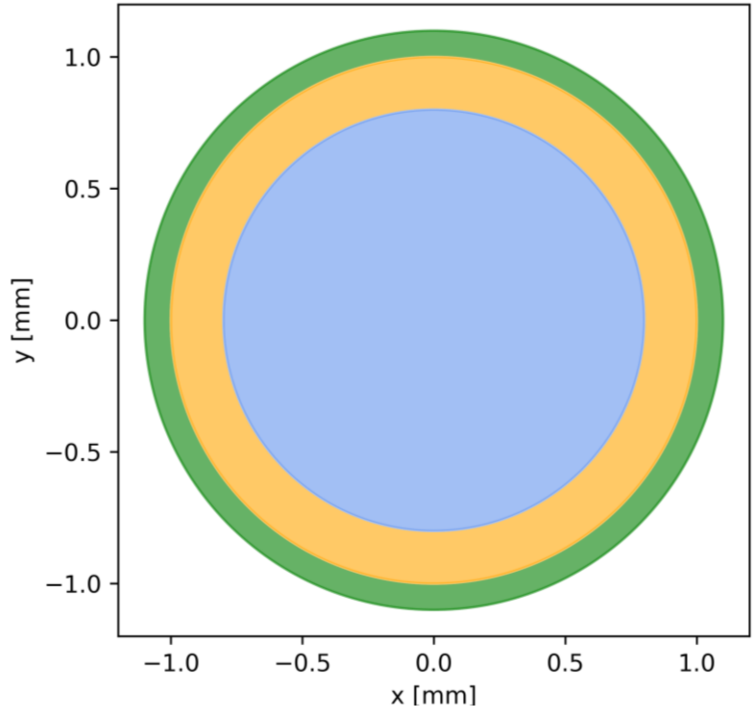


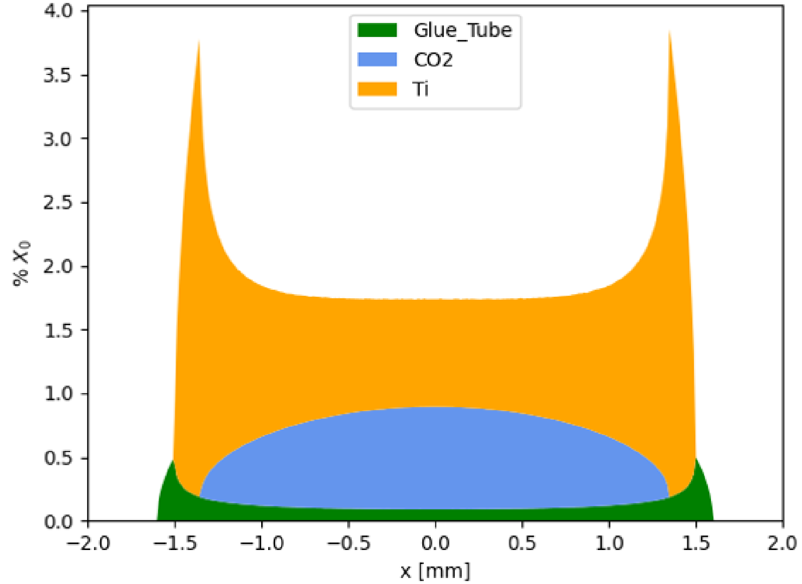
Honeycomb module

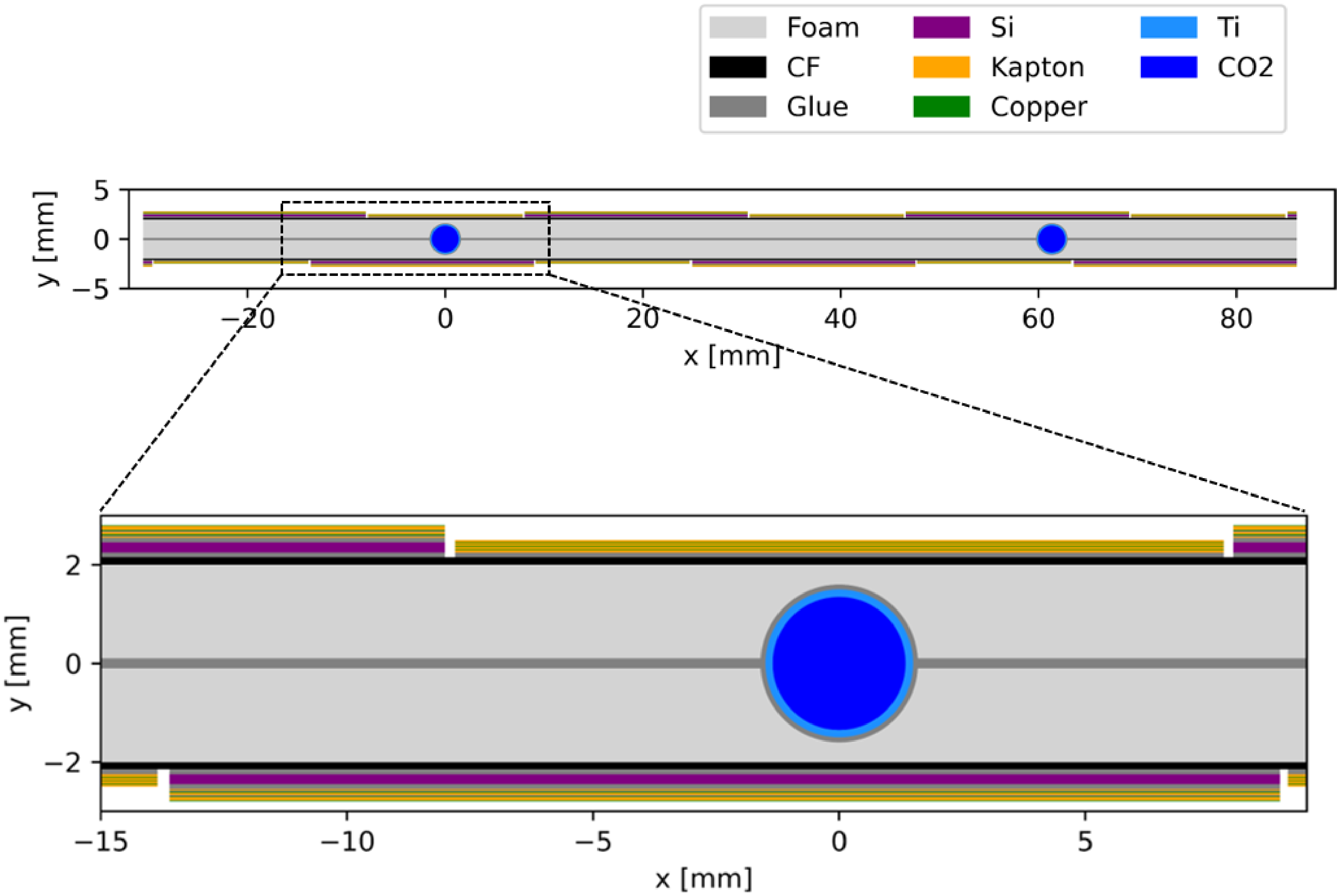
Very first trial!






1.0
0.5
0.0
−0.5
−1.0
y [mm]
−1.0
−0.5
0.0
0.5
1.0
x [mm]


Glue_Tube
CO2
Ti
% X_0
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
x [mm]



Foam
CF
Glue
Si
Kapton
Copper
Ti
CO2
y [mm]
5
0
−5
−20
0
20
40
60
80
x [mm]
y [mm]
2
0
−2
−15
−10
−5
0
5
x [mm]