Ultra-lightweight outer pixel tracker for the Mu3e experiment

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On behalf of the Mu3e collaboration

Forum on Tracking Detector Mechanics
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Probing the Standard Model with Mu3e:

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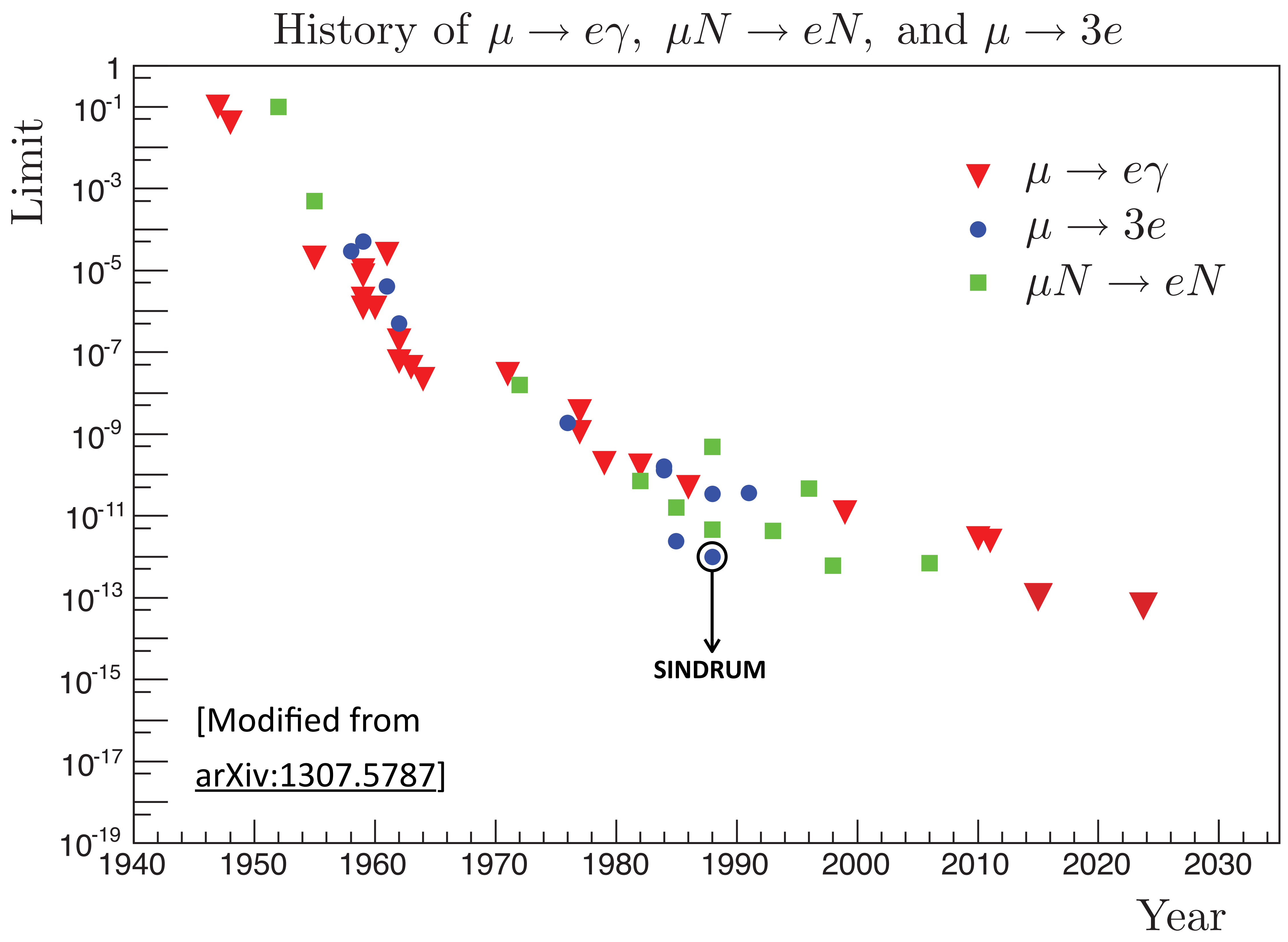
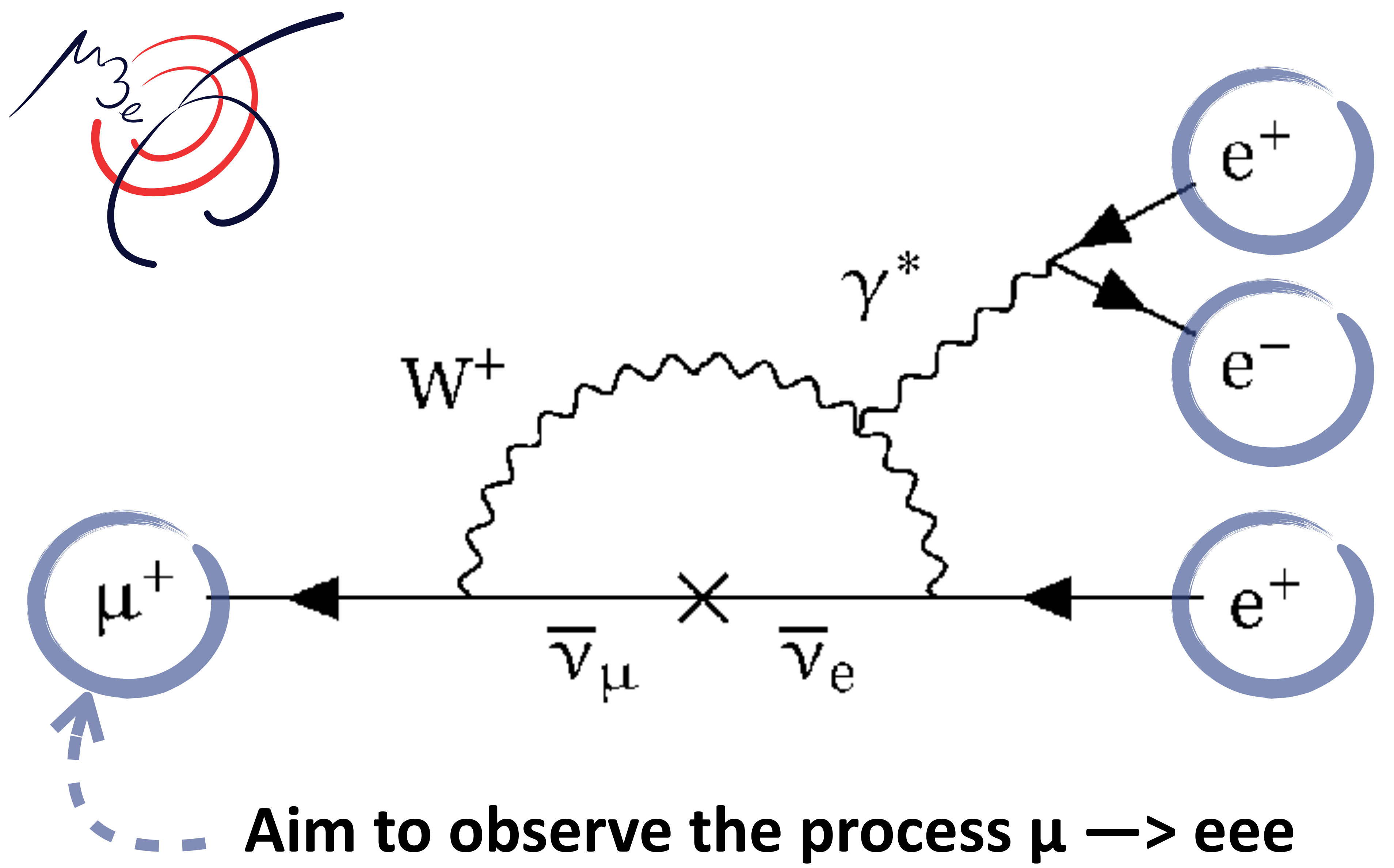
Muon decays (~100%) via: μ —> eνν̃

Highly suppressed BR for charged lepton flavour violating (cLFV) decays:

$$\Gamma \propto \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 \sim \mathcal{O}(10^{-54})$$





Aim to observe the process μ —> eee

BR(μ —> eee) < 10^{-12} (90% CL) from [SINDRUM (1988)]

- Complementary to other searches (@ LHC, or other muon modes)
- New BSM particles could appear in loop
- *New physics* models involving LFV **significantly enhance the predicted BR, to experimentally measurable levels**

Experimental considerations:

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Signal topology: three electron tracks

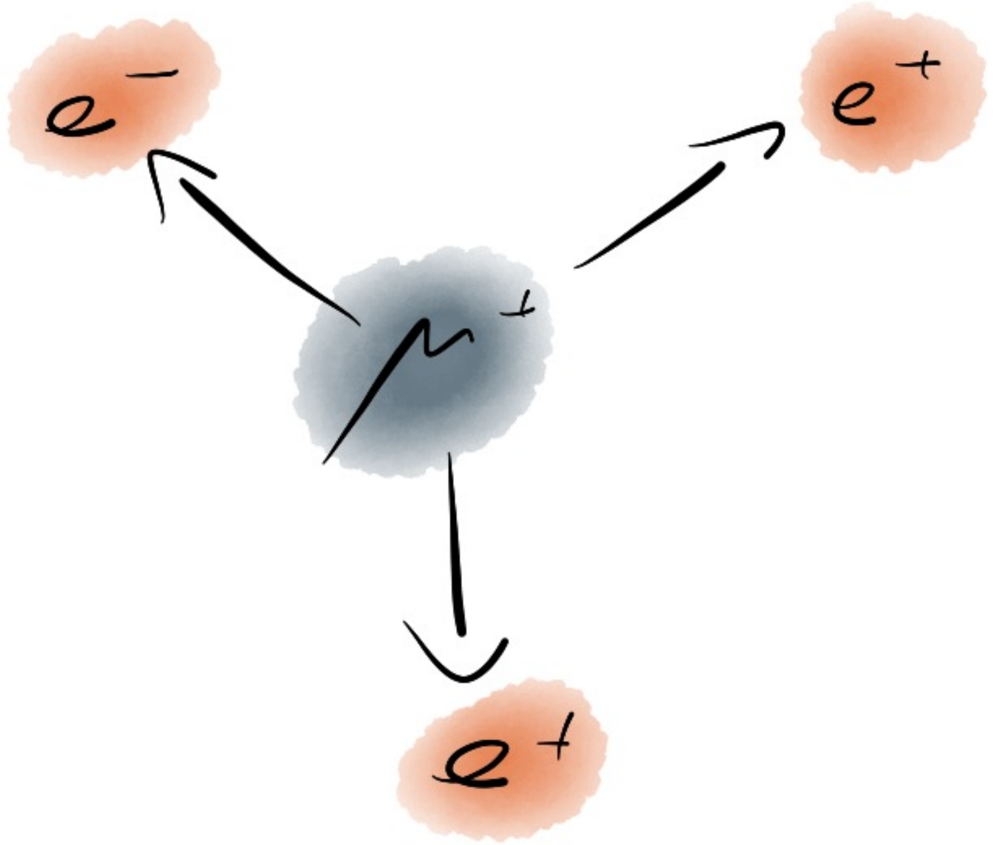
- Common vertex
- Time coincidence
- Energy sum = m_μ
- Decay at rest so $\sum \vec{p} = 0$

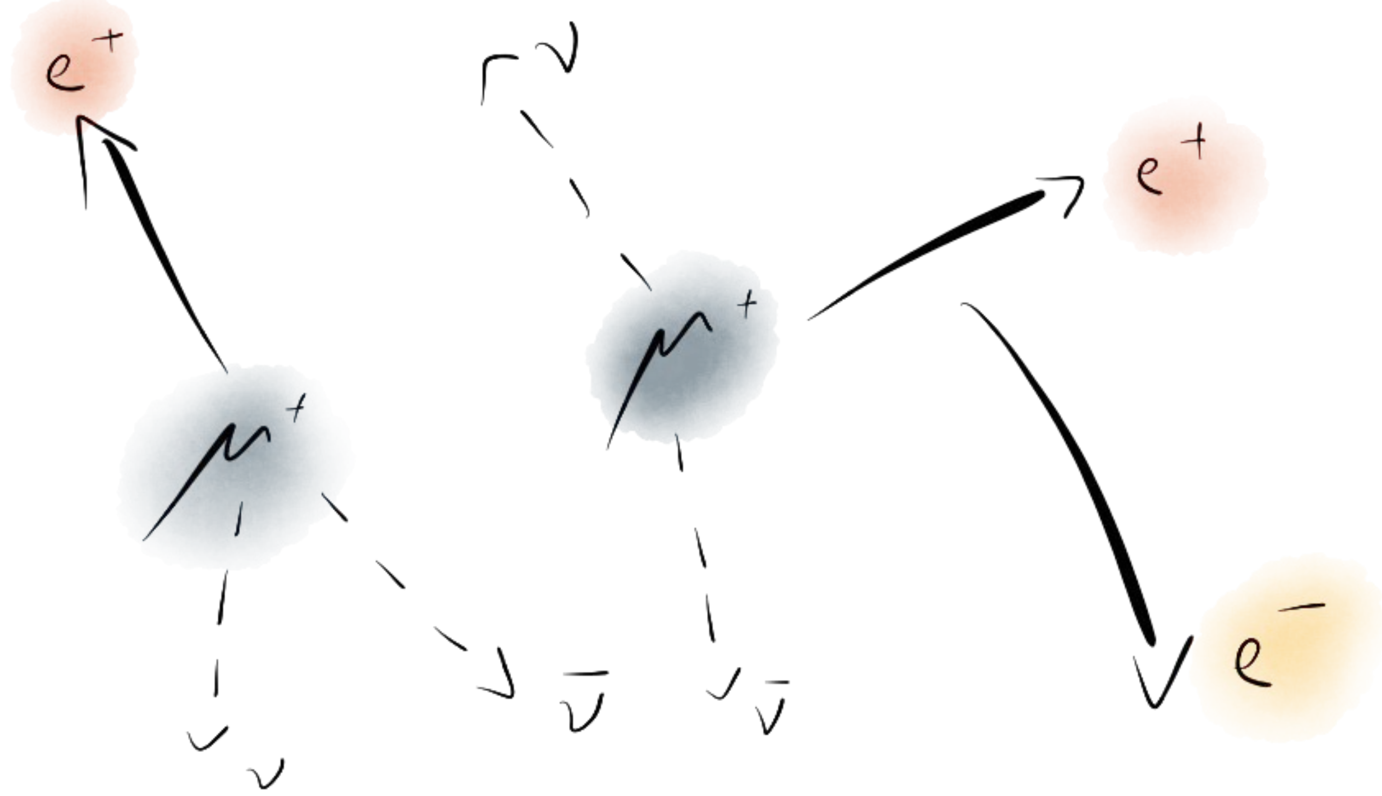
Main backgrounds:

- Internal conversion (small energy carried away by neutrinos):

  BR($\mu \to eee\nu\nu$) = $(3.4 \pm 0.4) \times 10^{-5}$
- Accidental: processes appearing to have $3e$ tracks.

  Can occur via: Misreconstruction, γ conversion, Bhabha scattering

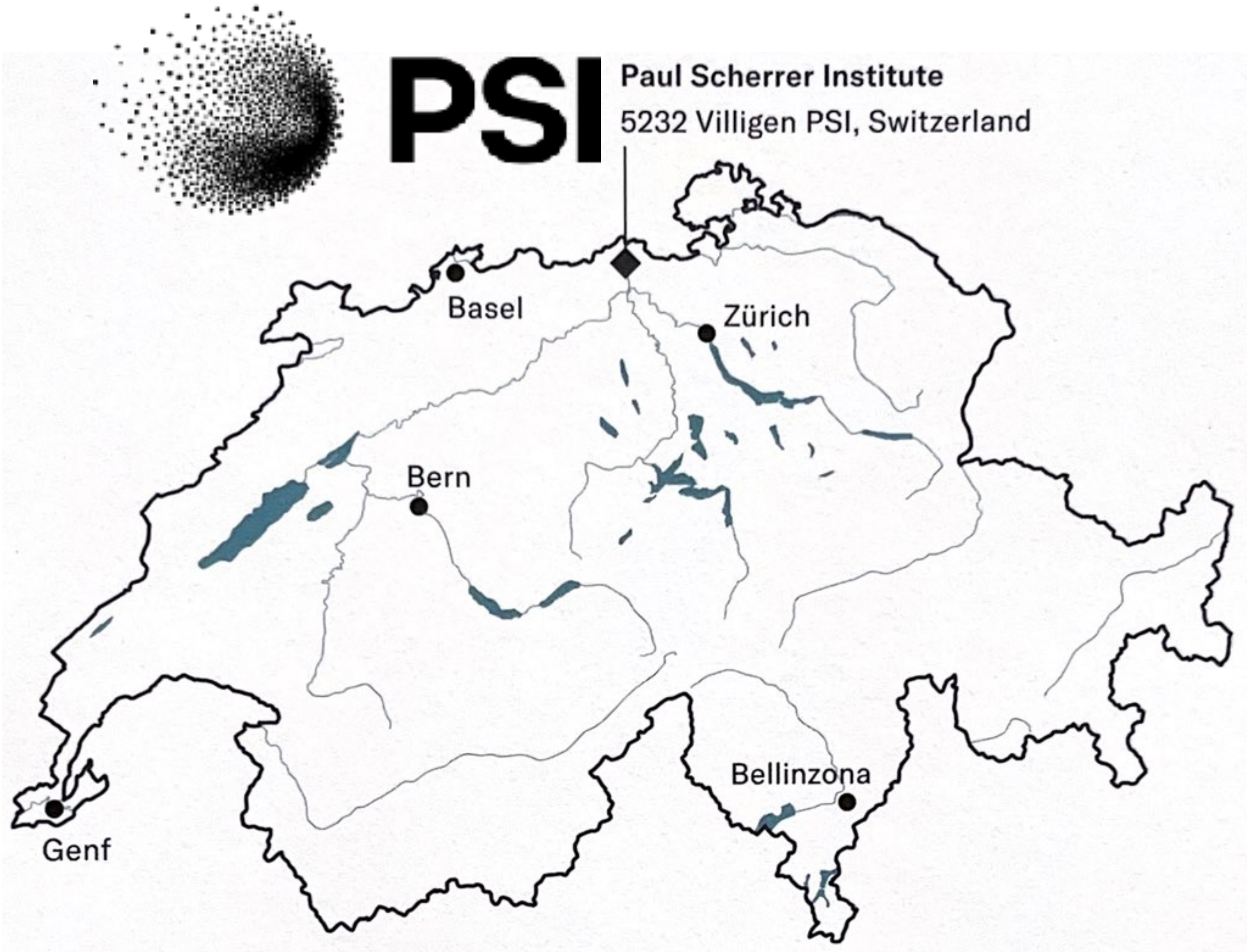


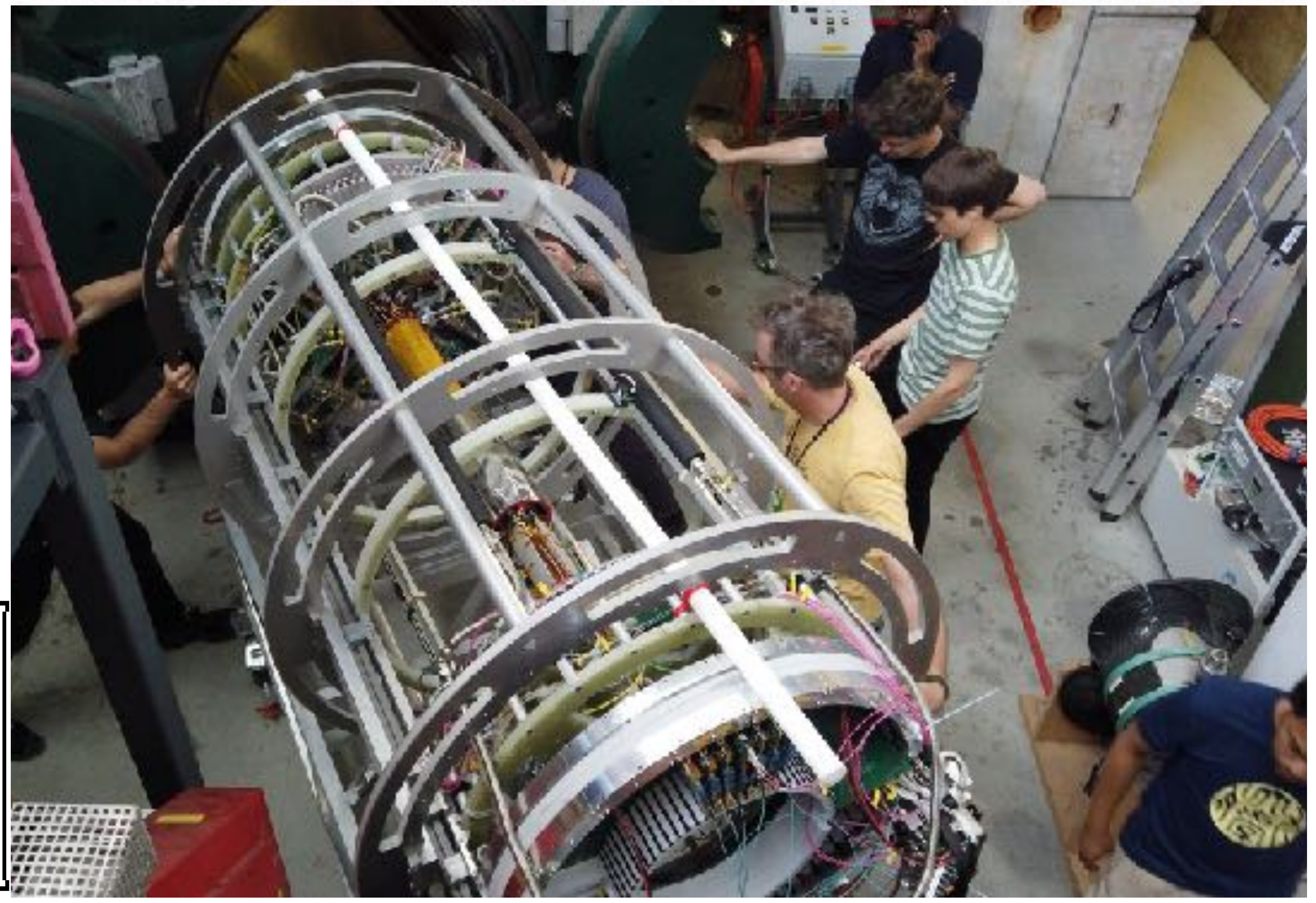


Detector requirements:

- Tracking in scattering-dominated regime: **low material budget**!
- Good timing and momentum resolution
- Large acceptance to capture electrons

Located along PIE5 beam-line at the Paul Scherrer Institute (PSI) near Zurich, CH





[Mu3e news]

Mu3e inside experimental hall

Collaboration $\mathcal{O}(100)$ people from 11 institutes (DE, UK, CH)

Expected to start taking physics data in 2026 (Phase I):

- PIE5 provides muon rates up to **10^8 muons/s** to Mu3e
- Target sensitivity: **BR (μ —> eee) < $2 \cdot 10^{-15}$**
- 290 days minimum running time required to achieve target

Phase II (> 2029):

- New High Intensity Muon Beam-line (HIMB), delivering up to **10^{10} muons/s**
- Target sensitivity: **BR (μ —> eee) < $2 \cdot 10^{-16}$**

Mu3e detector design:

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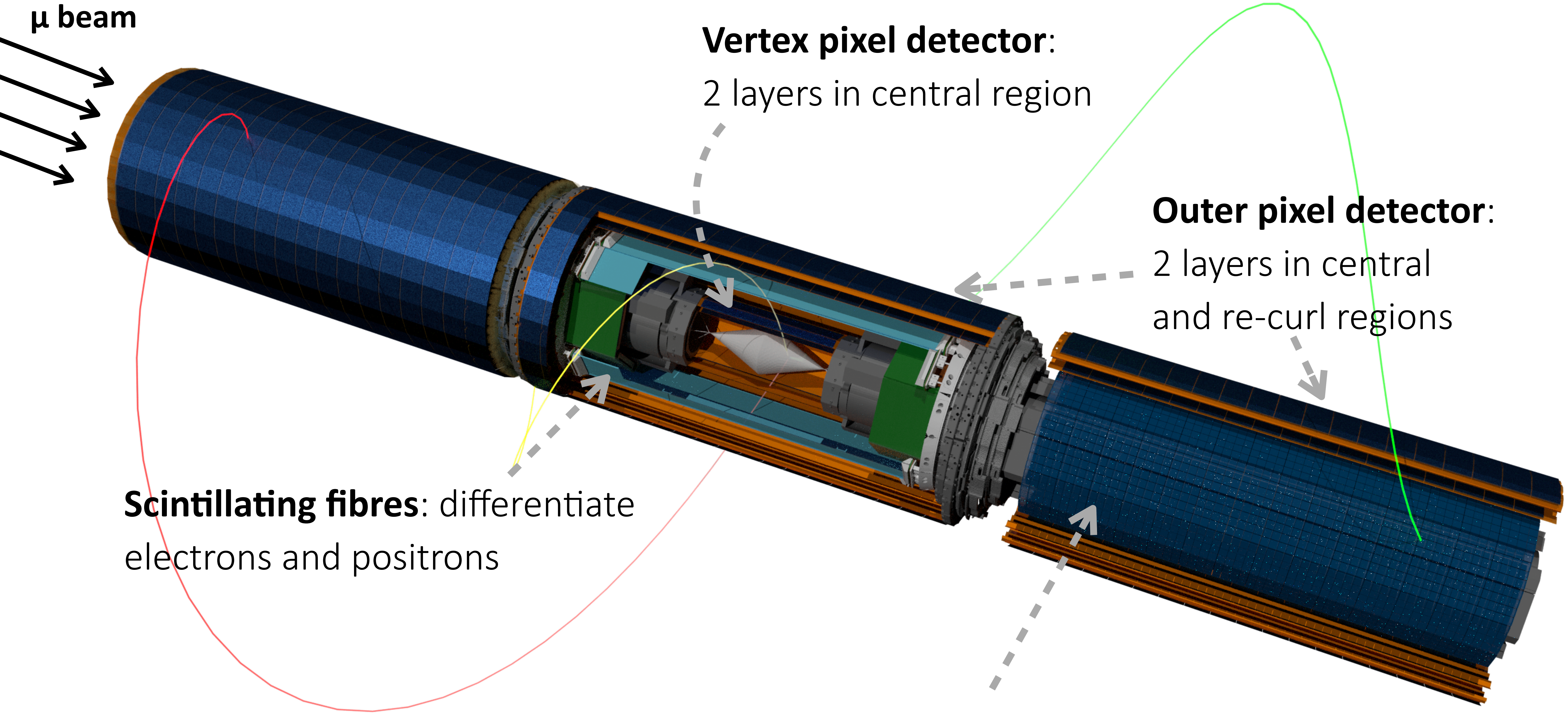
Detector geometry: **1 central + 2 re-curl regions**

- Homogeneous solenoidal magnetic field B = 1T
- Multiple scattering dominated: Momentum resolution dependant on number of detector layers and thickness



Material budget a key factor!

Tracking:

- 50-70 μm thick MuPix11 (Monolithic HV-CMOS) pixel sensors
- Per layer: ~ 0.1 % X/X_0

Cooling:

- Use gaseous He cooling (less dense compared to air)
- Flow rate 2 - 16 g/s

Inner pixel detector layers:

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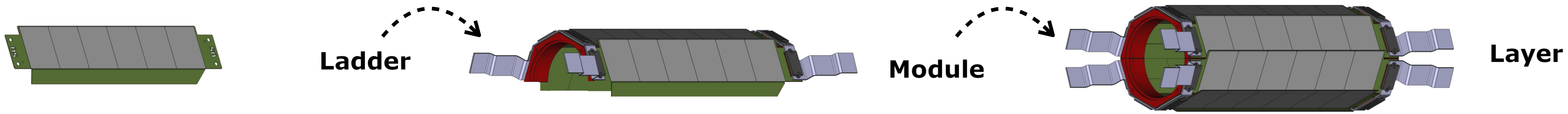
Basic building block for Mu3e pixel detector: **ladder**

Mechanical stability: primarily from 3D folded nature of vertex detector



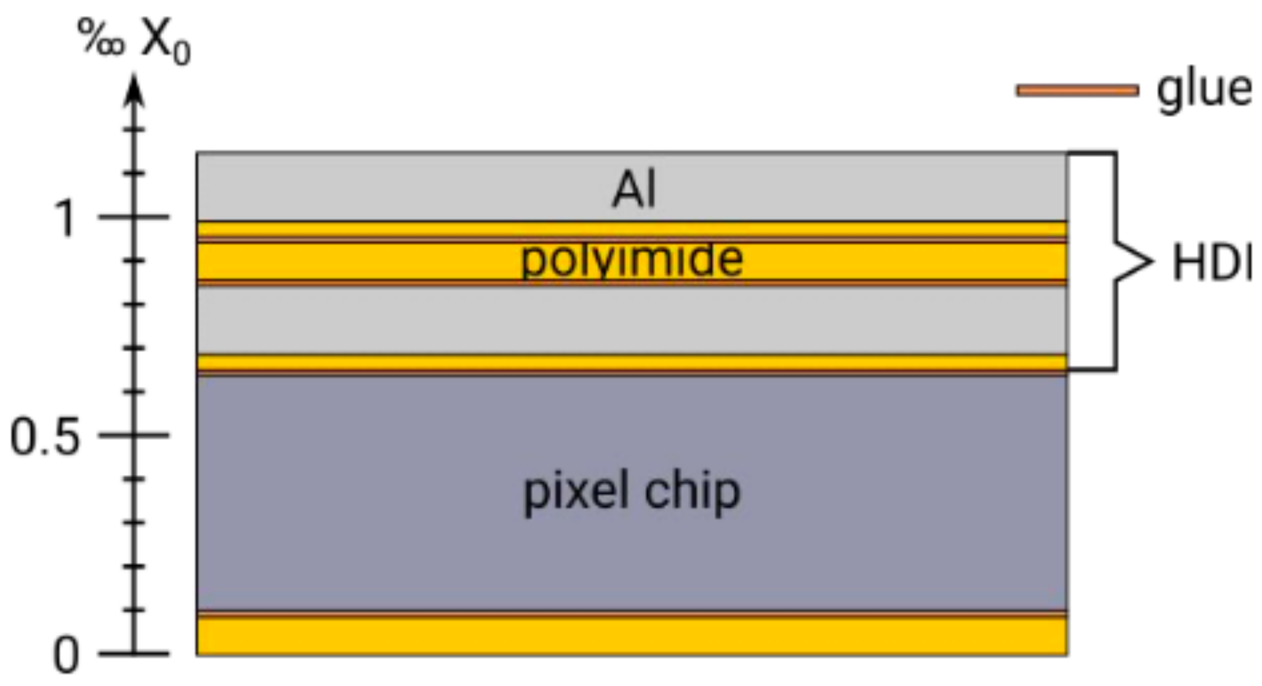
1 ladder = 6 x MuPix11 sensors

1 module = 4 ladders

2 modules = 1 layer

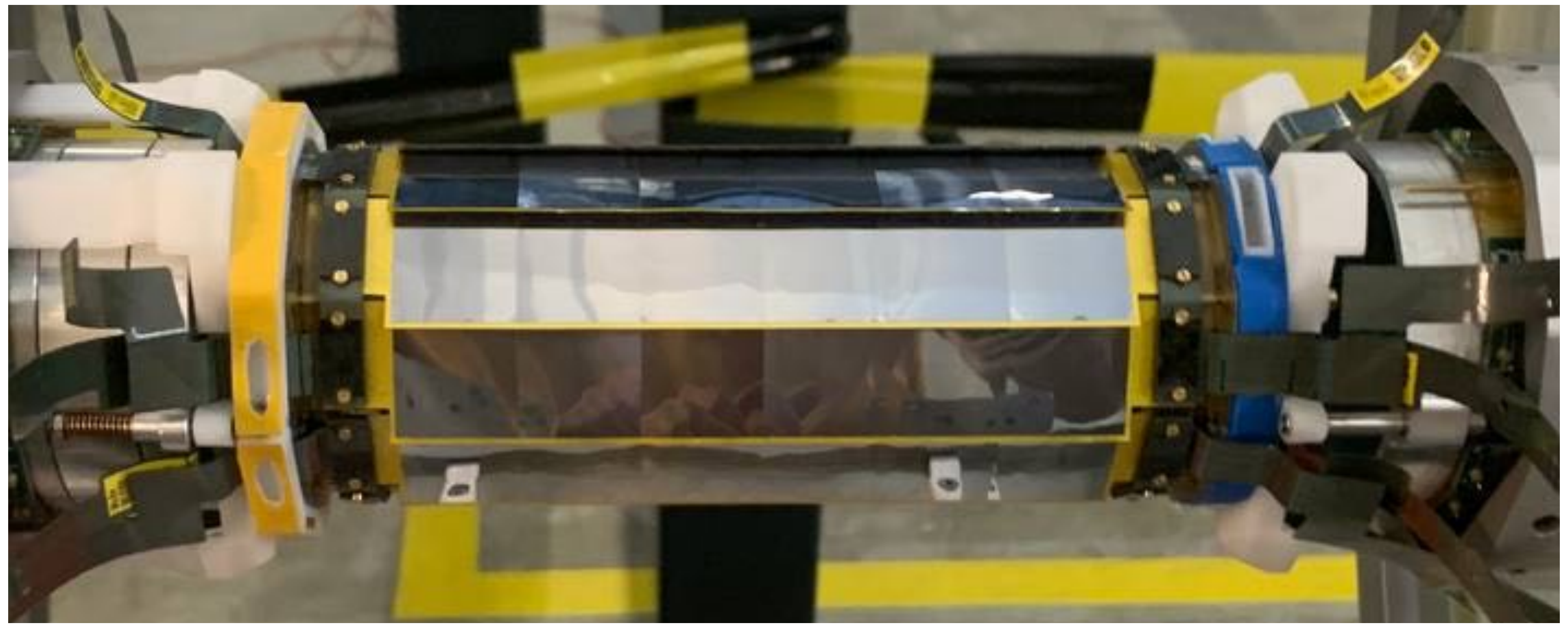
Comprised of:

- 50µm MuPix11 pixel sensors
- Alu/kapton high-density interconnect (HDI)
- 25µm kapton support
- Electrically connected via spTAB connections



spTAB connection:

- Trace width ~ 60 µm
- Pad size 200 x 100 µm^2



Vertex system (“version 1”) complete and <u>installed</u> in PIE5 for June 2025 beam-time.

Outer pixel detector layers:

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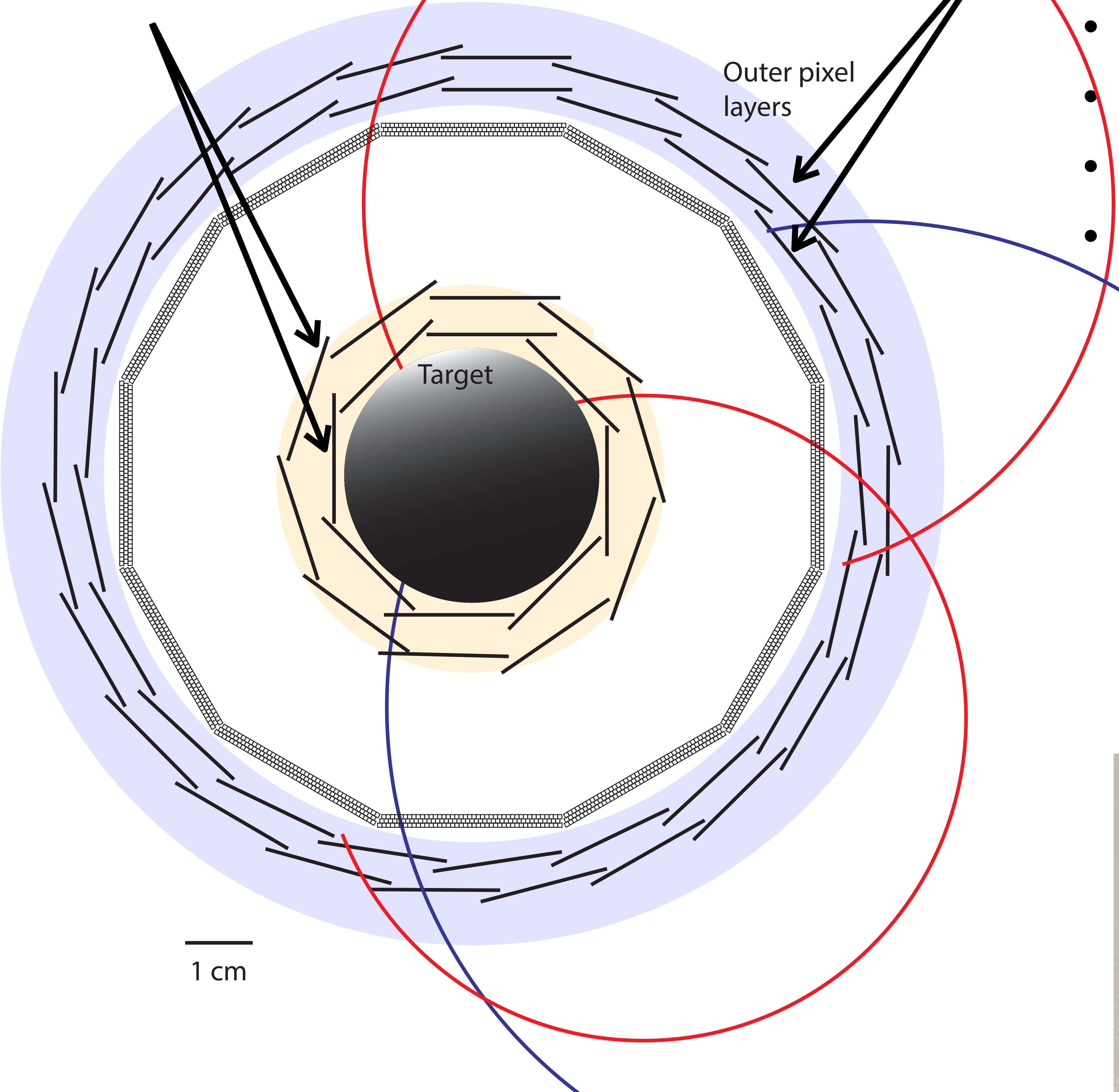
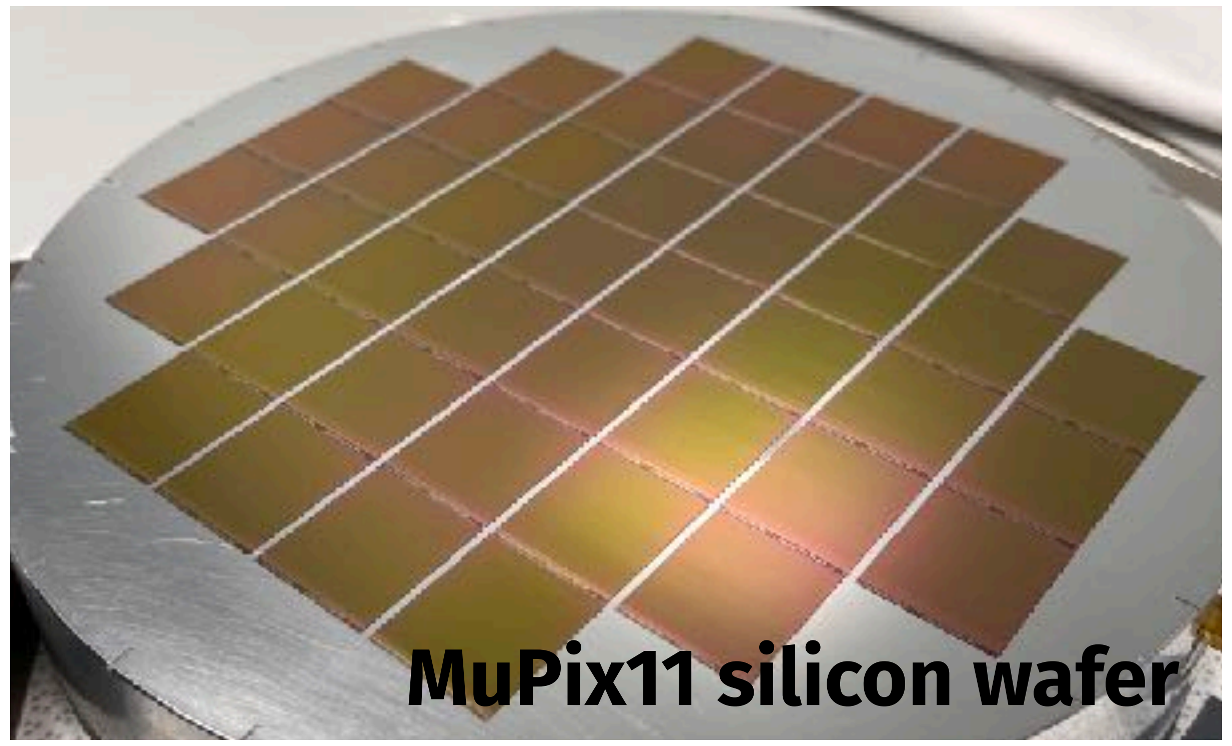
Inner pixel layers:
Layers 1 & 2

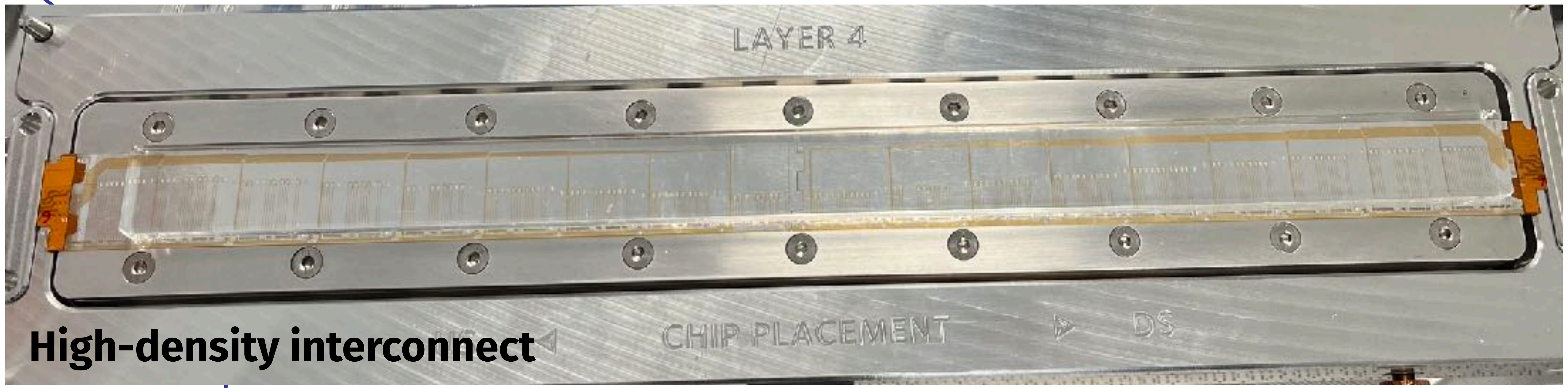


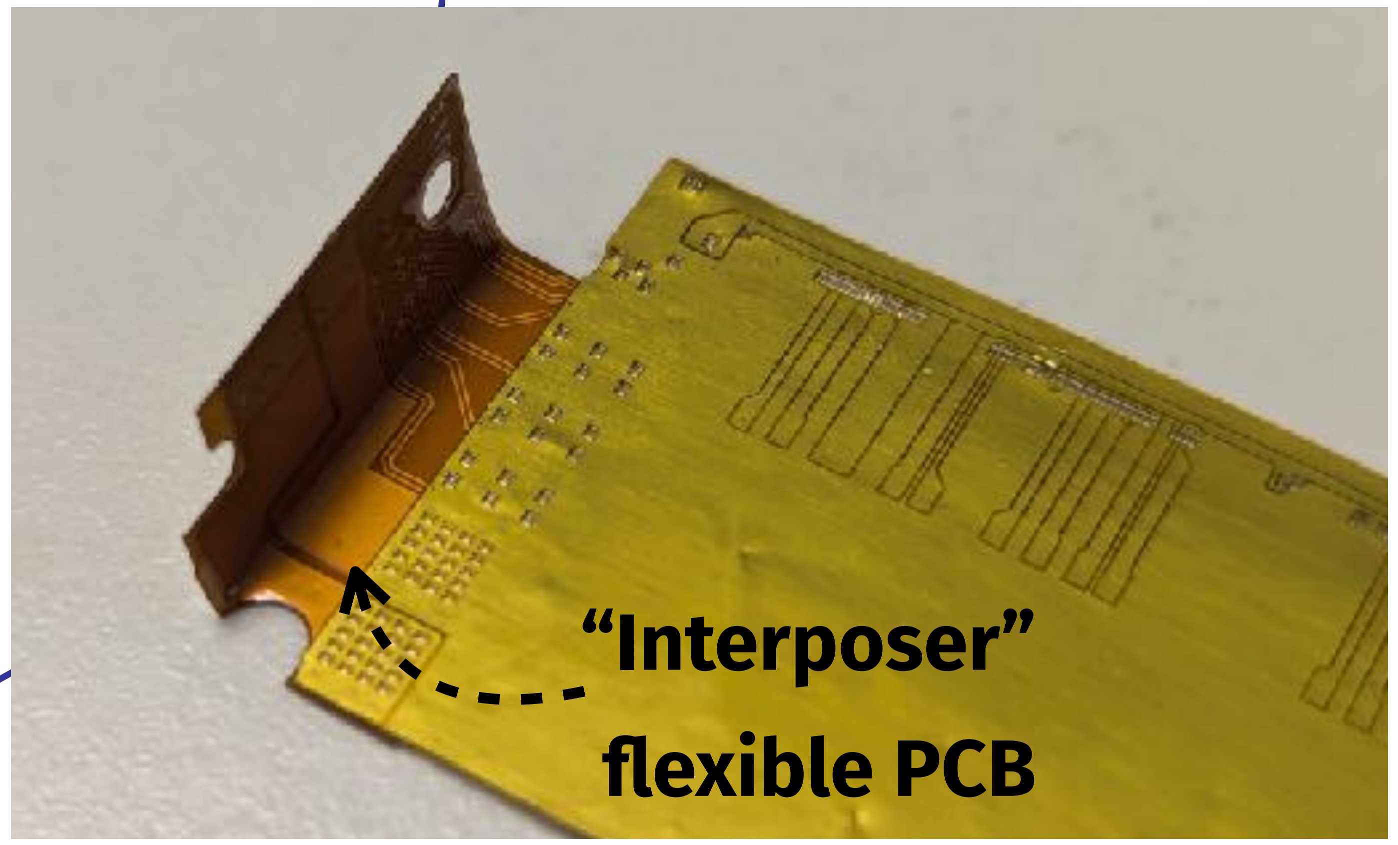
Outer pixel layers: Layers 3 & 4

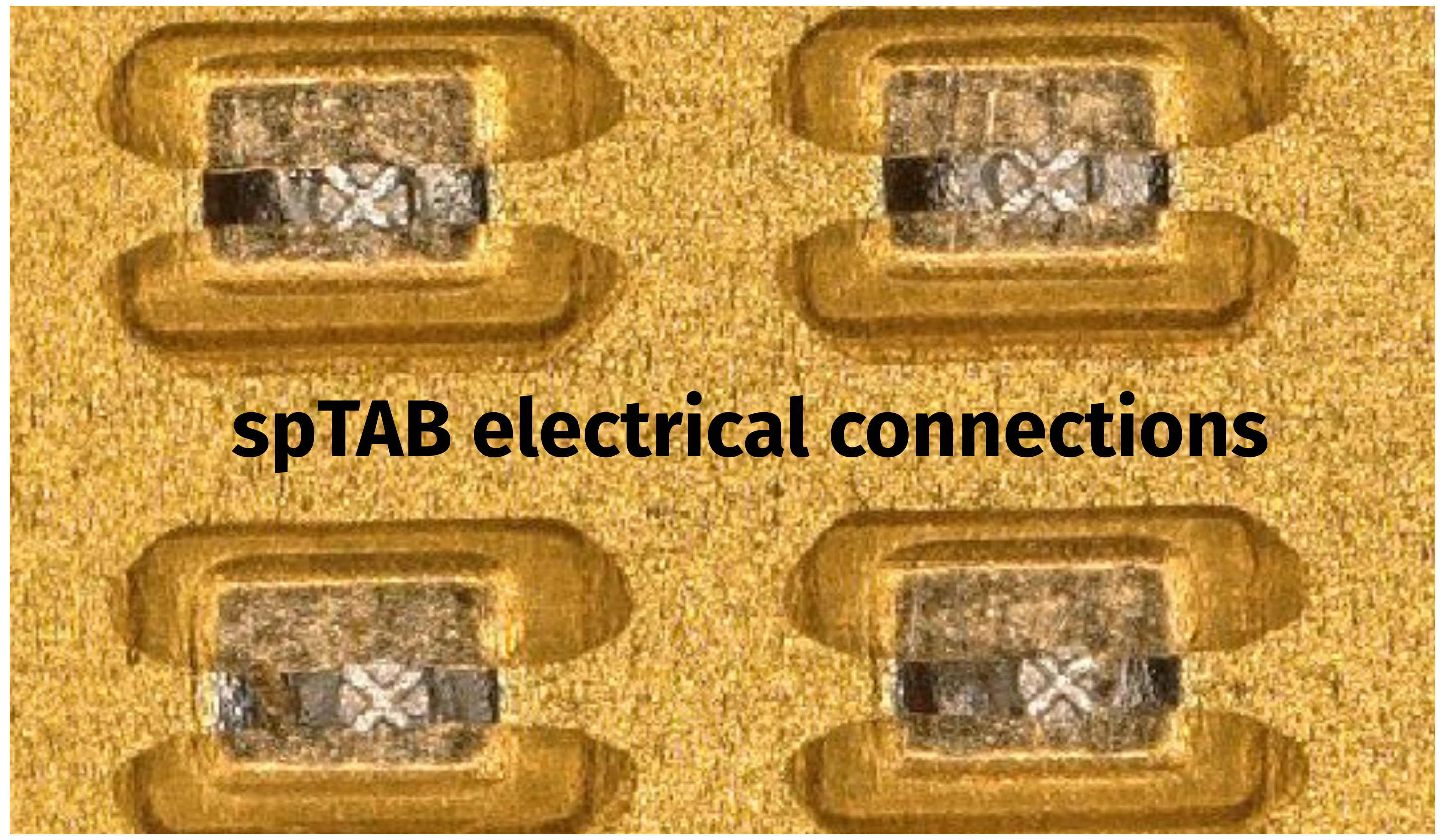
Ladders consist of:

- 17-18 70µm MuPix11 pixel sensors
- Alu/kapton high density interconnect (HDI)
- Flexible PCB ("interposer flex") either end
- Mechanical stiffener for support









Each ladder ~ 2 grams!
Despite it being over 300 mm long …

Mechanical support provided by either:

Kapton

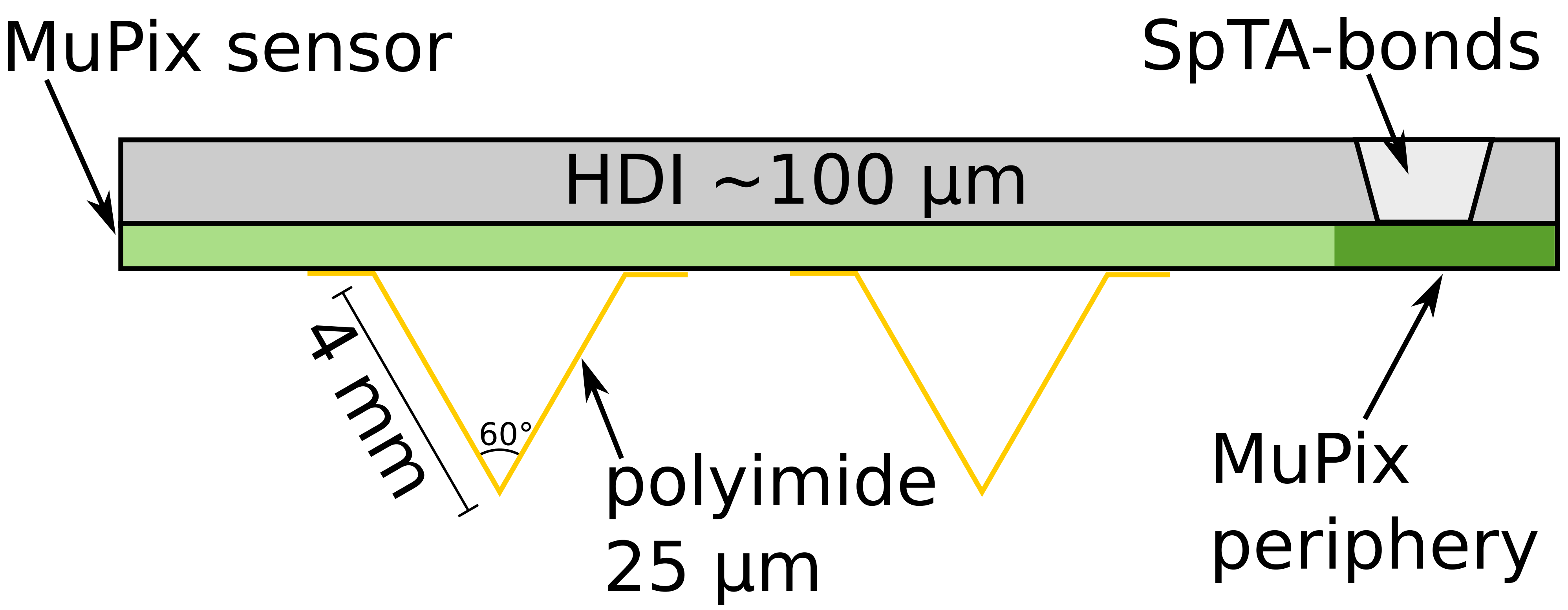
25µm thick kapton folded in two triangles,"*v-folds*":

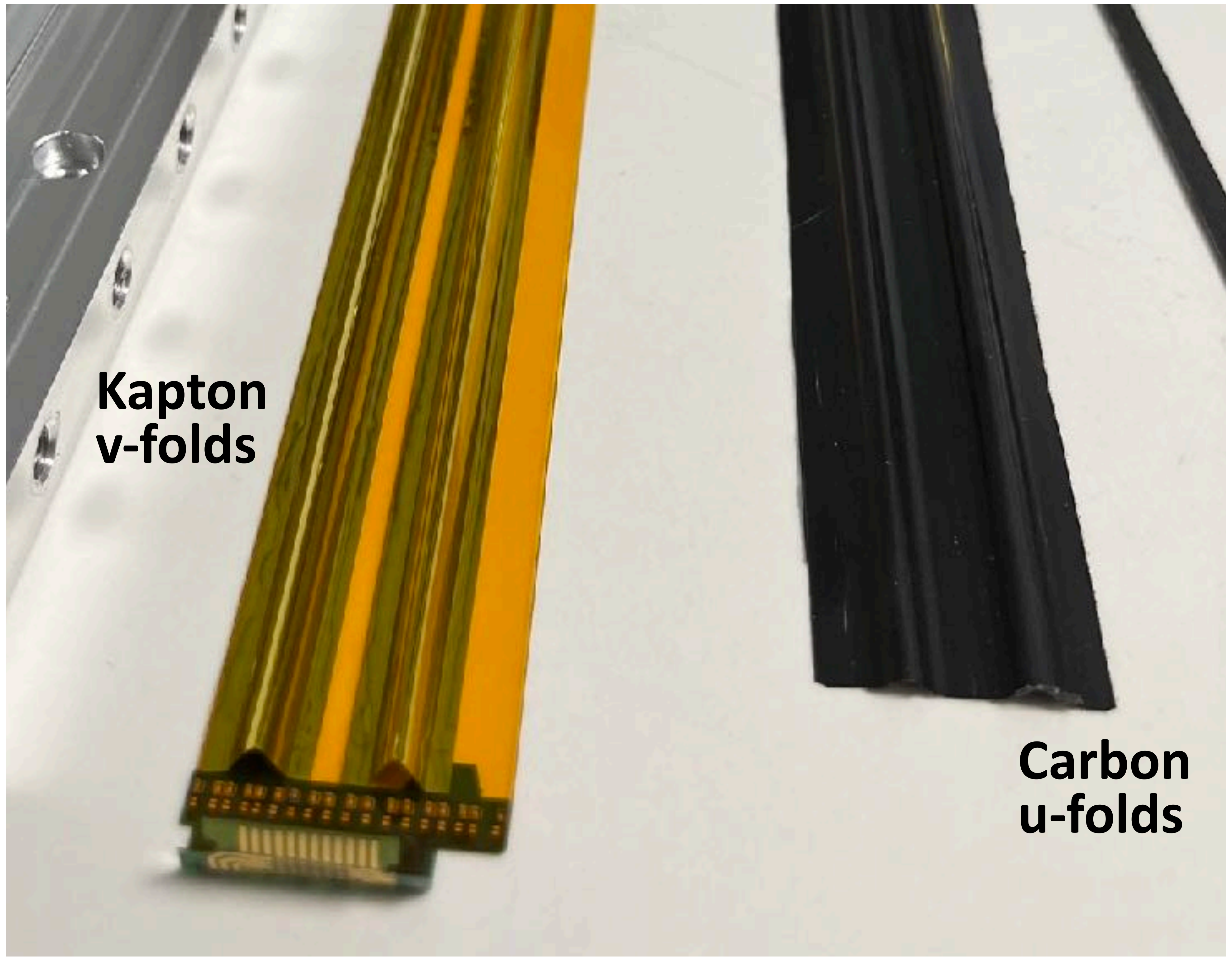
- Sensors mostly still visible underneath
- Quite delicate —> difficulties in transportation
- Seem to provide enough structural integrity for 18 chip ladders, but not more

Carbon-fibre

25 µm uni-directional carbon-fibre, with joined "*u-folds*":

- Moulded into double-u shape
- Co-cured kapton (8µm) backing - electrically seperate two halves
- Very stiff along length (impact on yield and transportation)
- Almost entirely covers sensors

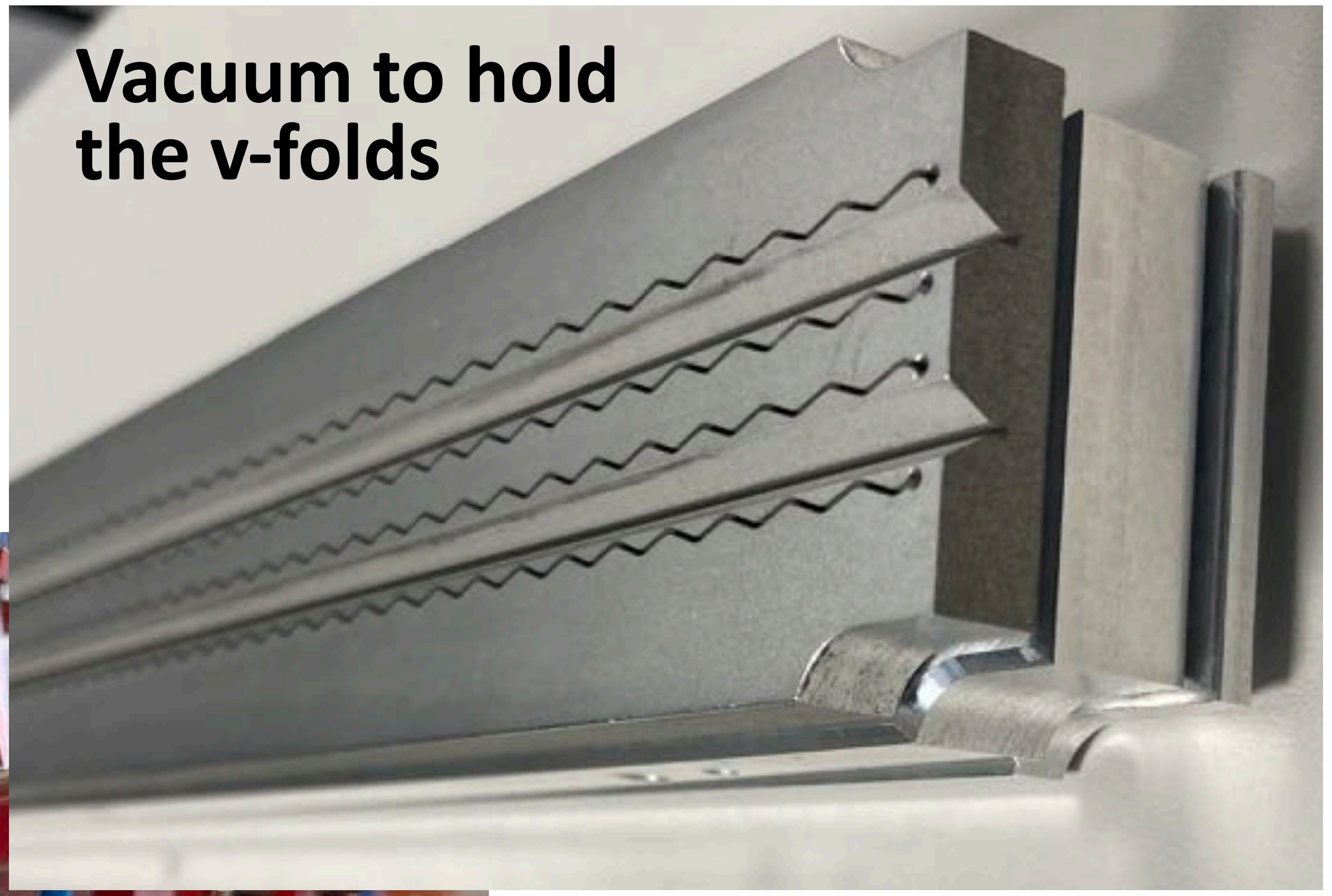


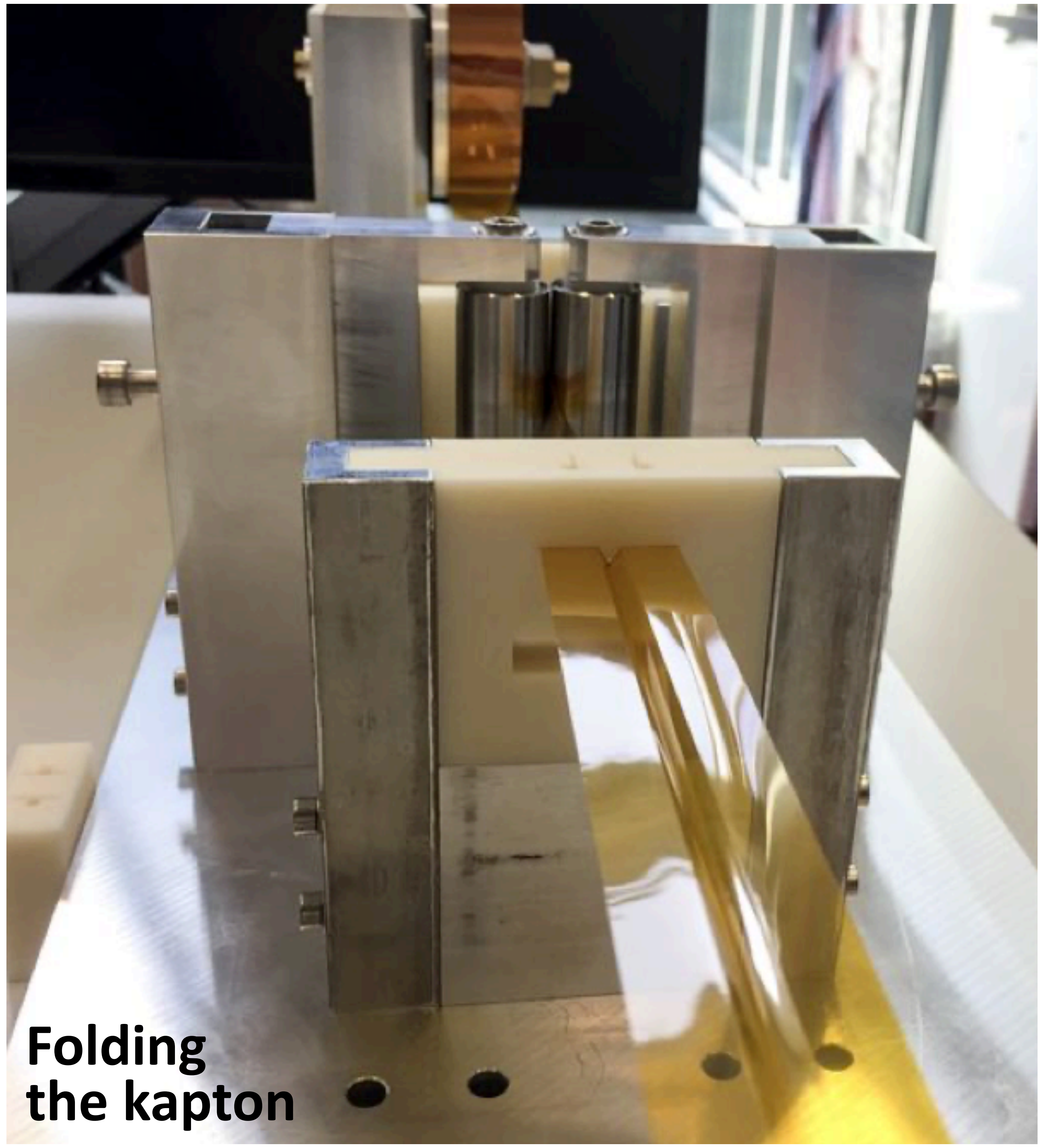


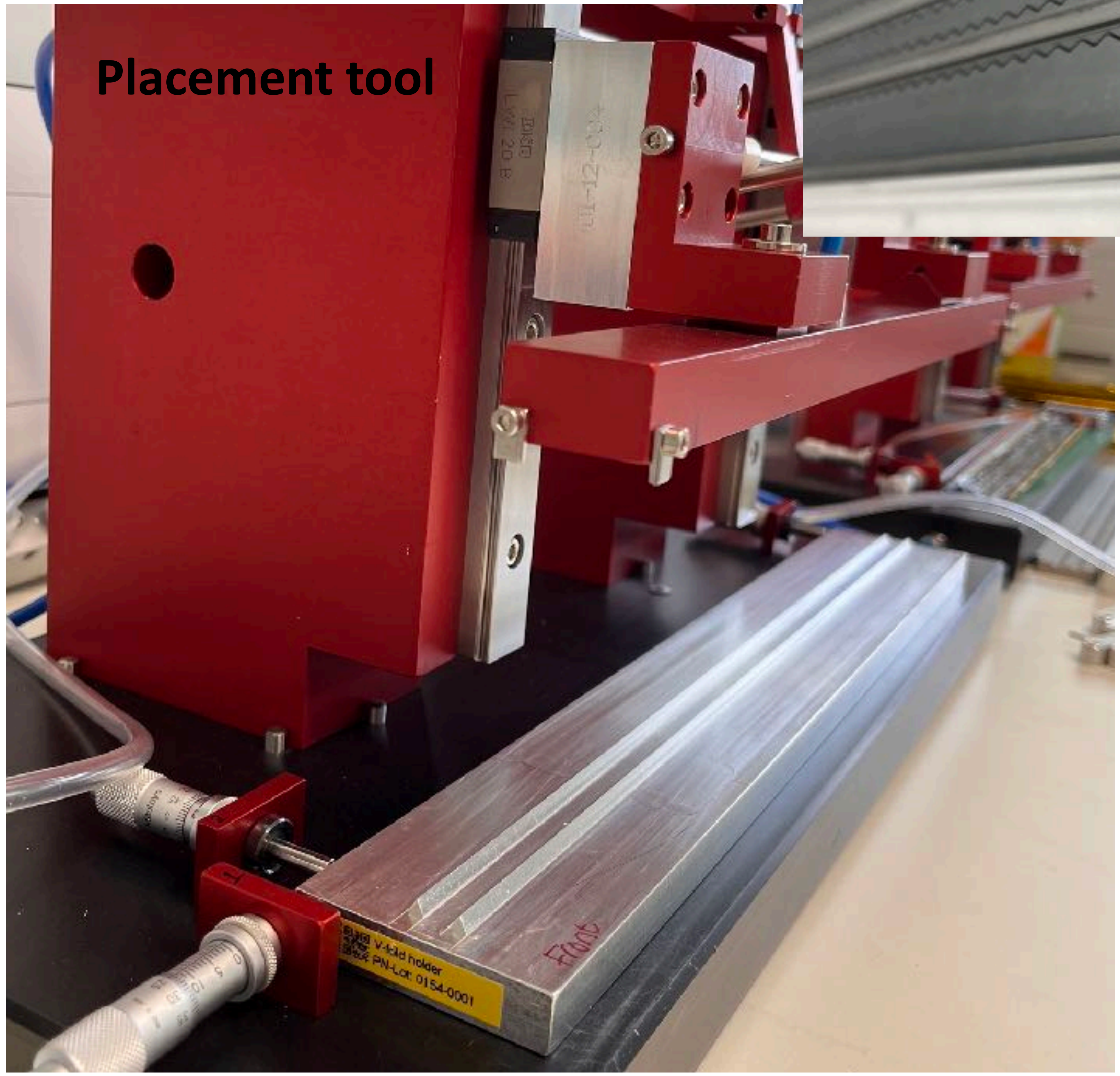
Fabrication of kapton support:

25µm thick kapton sheet folded in triangular shape: 2 per ladder

- Thin lines of glue along each of the v-folds
- Folded shape achieved by threading polyimide foil through "folding" machine


Vacuum to hold the v-folds


Folding the kapton


Placement tool

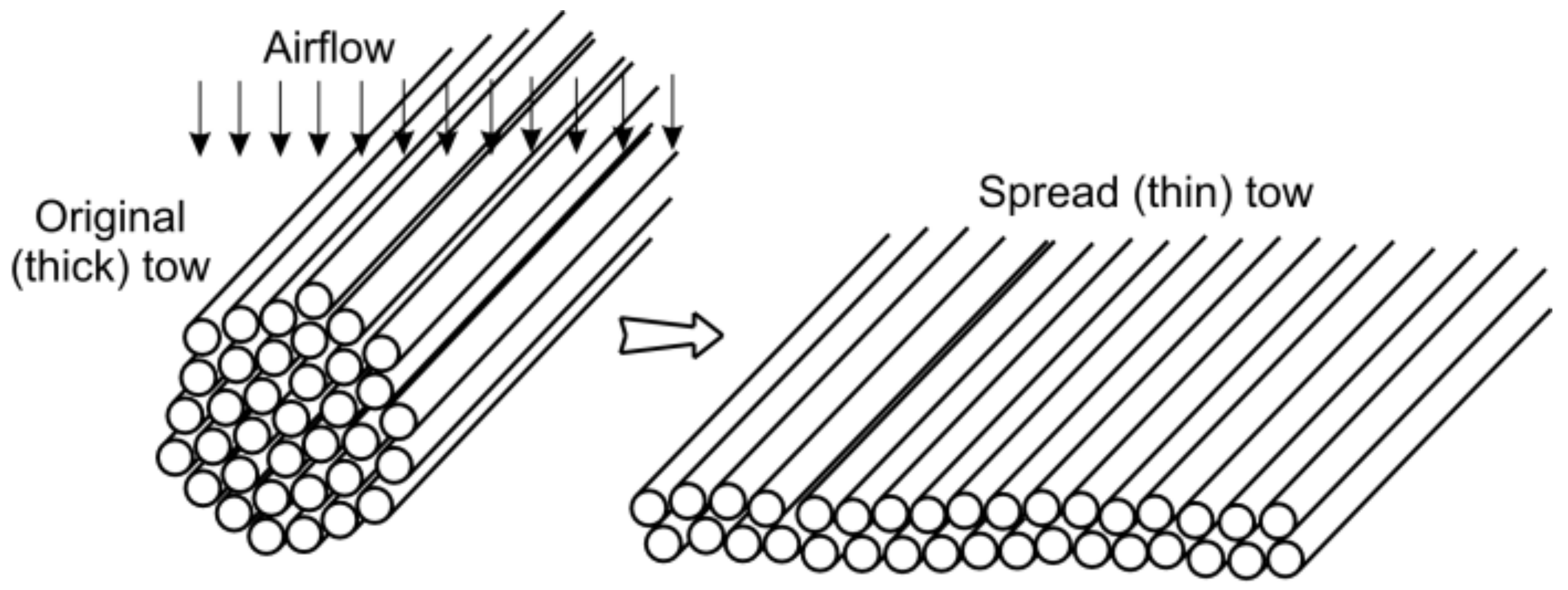

Completed ladder

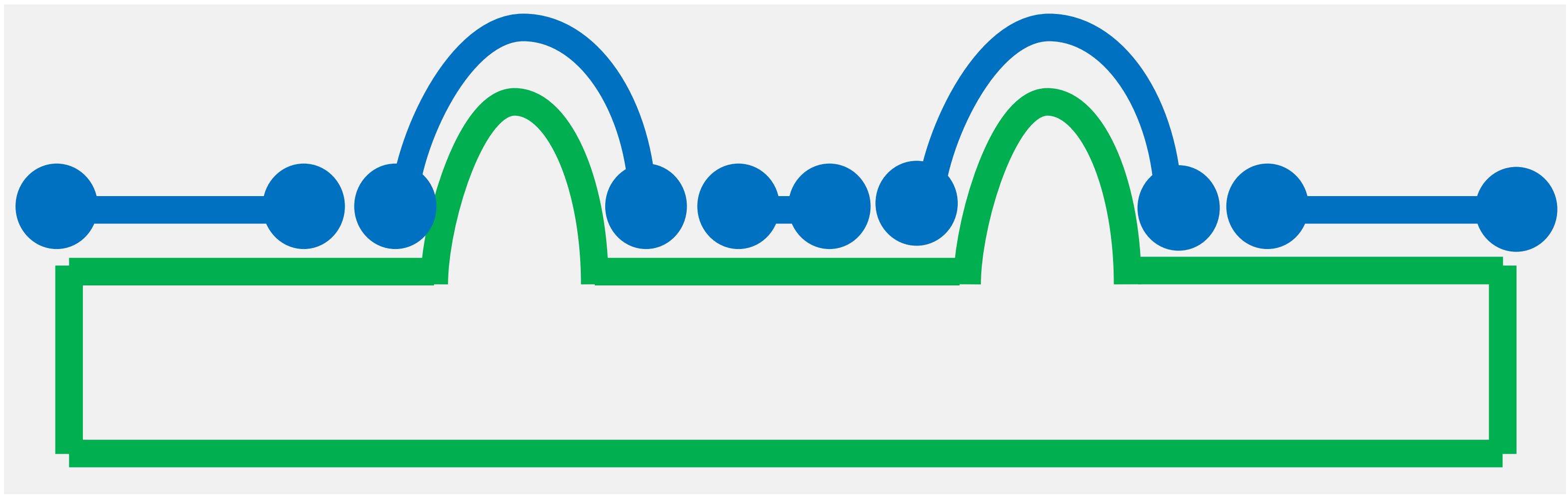
Fabrication of carbon-fibre support:

[doi.org/10.3390/polym15071767]

Uni-directional single-ply 25µm carbon-fibre sheet (40% resin content):

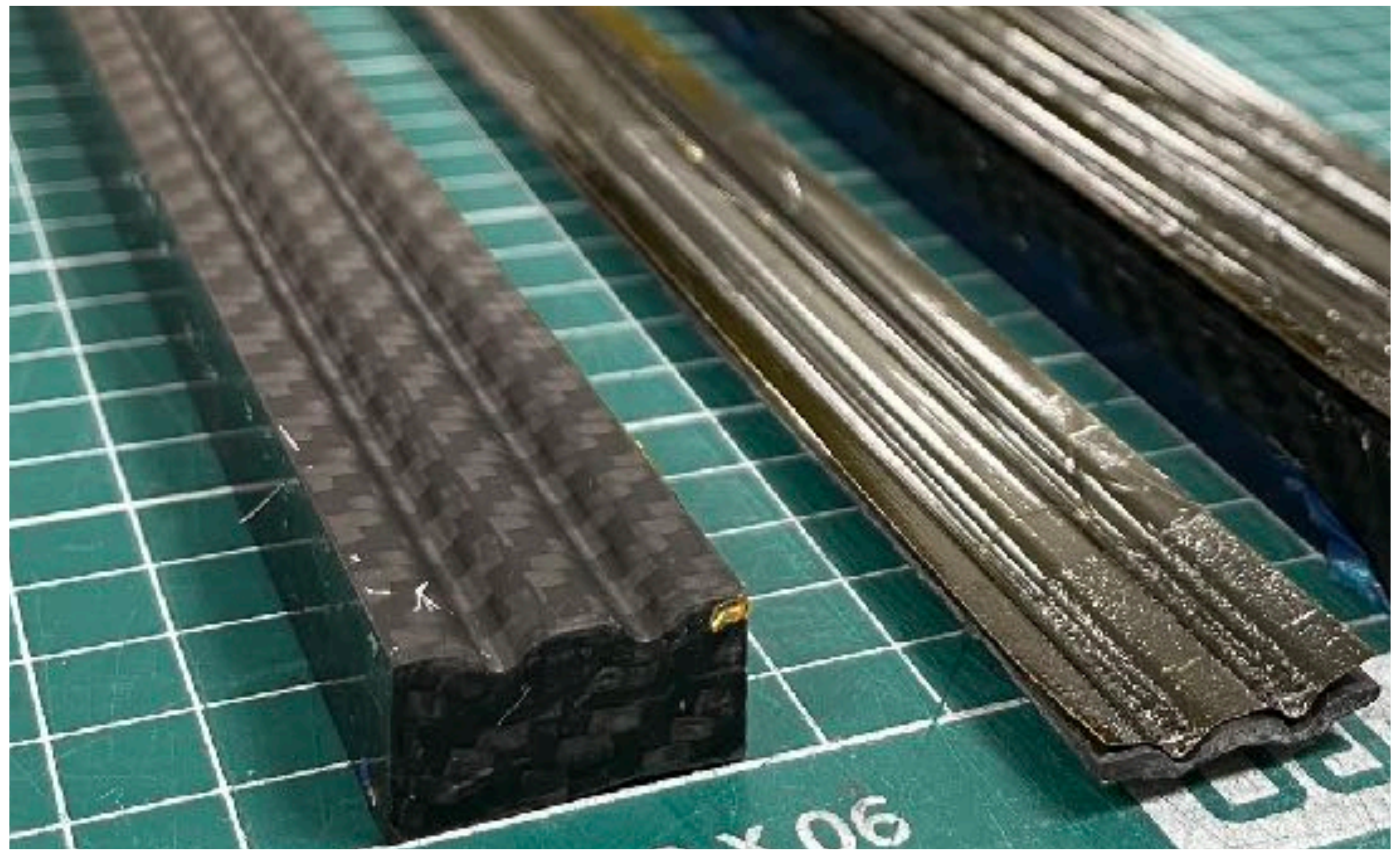
- **Spread-tow** Tairyfil TC33 fibre and SK Chemicals K51 matrix
  - Material developed for sails for America's cup yacht
  - Usually intended to be woven together
- Split-ply laid together: compliance during warm up/cool down, additional resin to bleed off
- Cured into double "u" shape

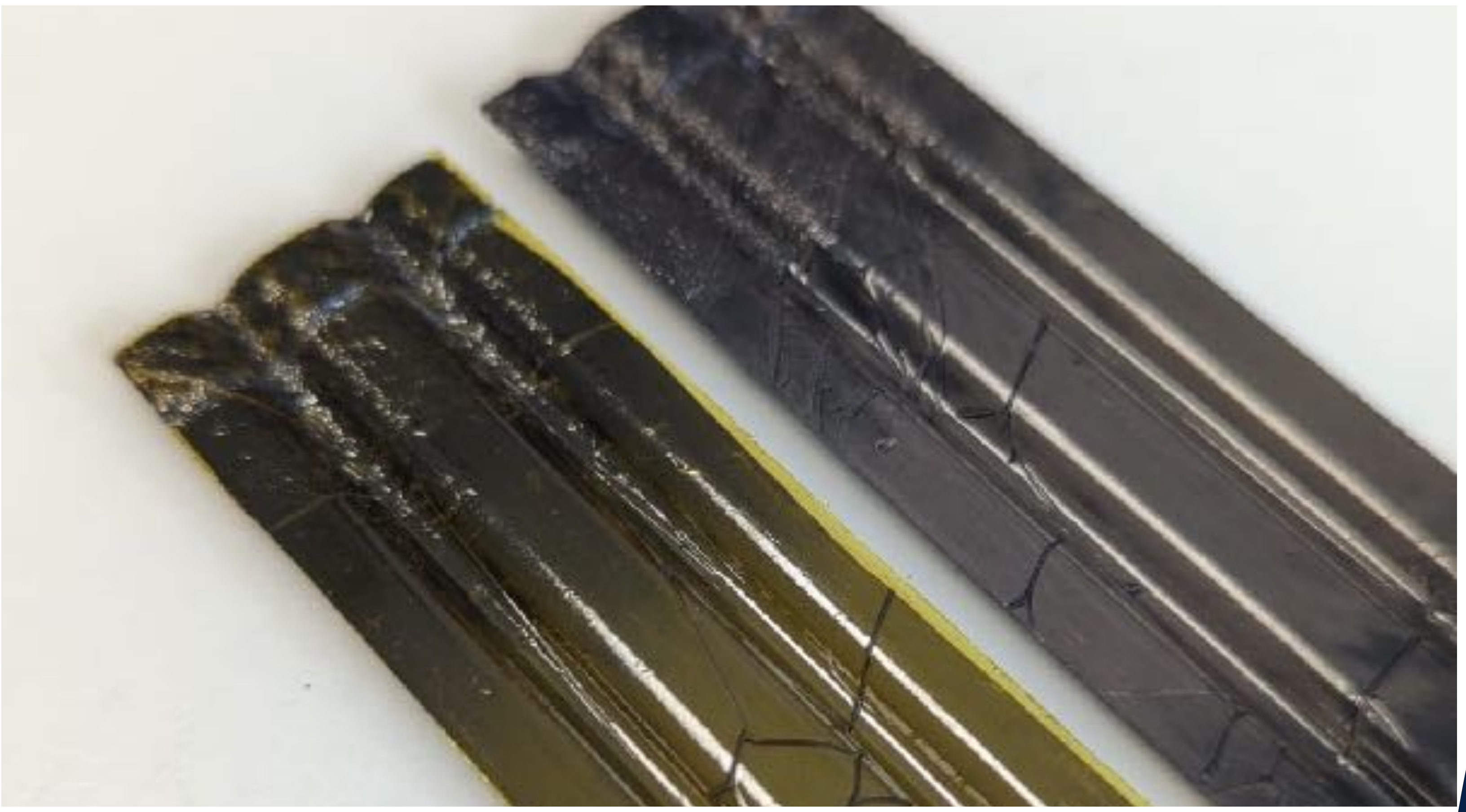




Very difficult to work with: 'chaotic' fibre pattern (due to single-ply UD spread tow), bowing issues, handling

- Challenges overcome by Adam Lowe + team through their laminating, tooling and fabrication techniques





Thermo-mechanical comparison studies:

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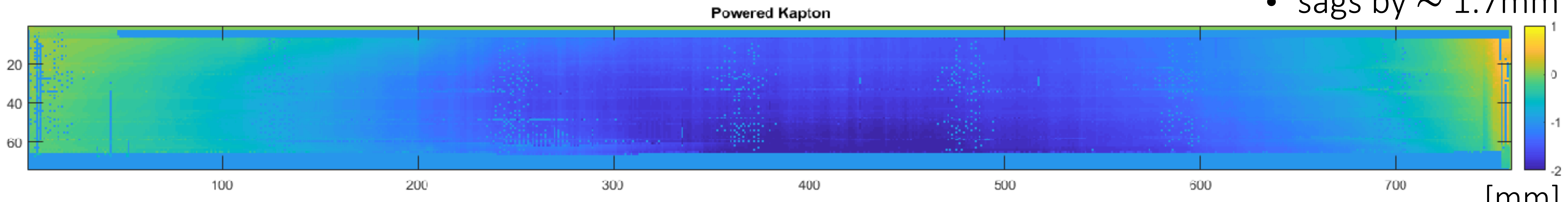
Investigations conducted to compare ladder performance (*using dedicated test objects*):

- Thermally induced out-of-plane deformations
  - Ladders resting freely but supported at either end
  - Neither ladder moved due to heat load

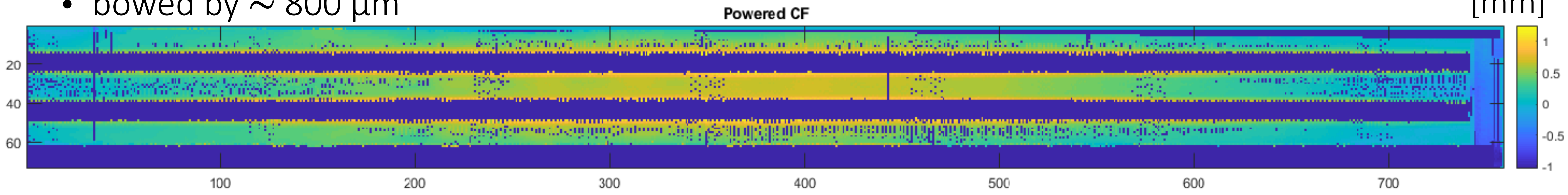
Ladder with **kapton** support:

- sags by ~ 1.7mm



Ladder with **carbon-fibre** support:

- bowed by ~ 800 µm



- Temperature uniformity
- Electrical connectivity stability through thermal cycling
- Vibration measurements

Thermo-mechanical comparison studies:

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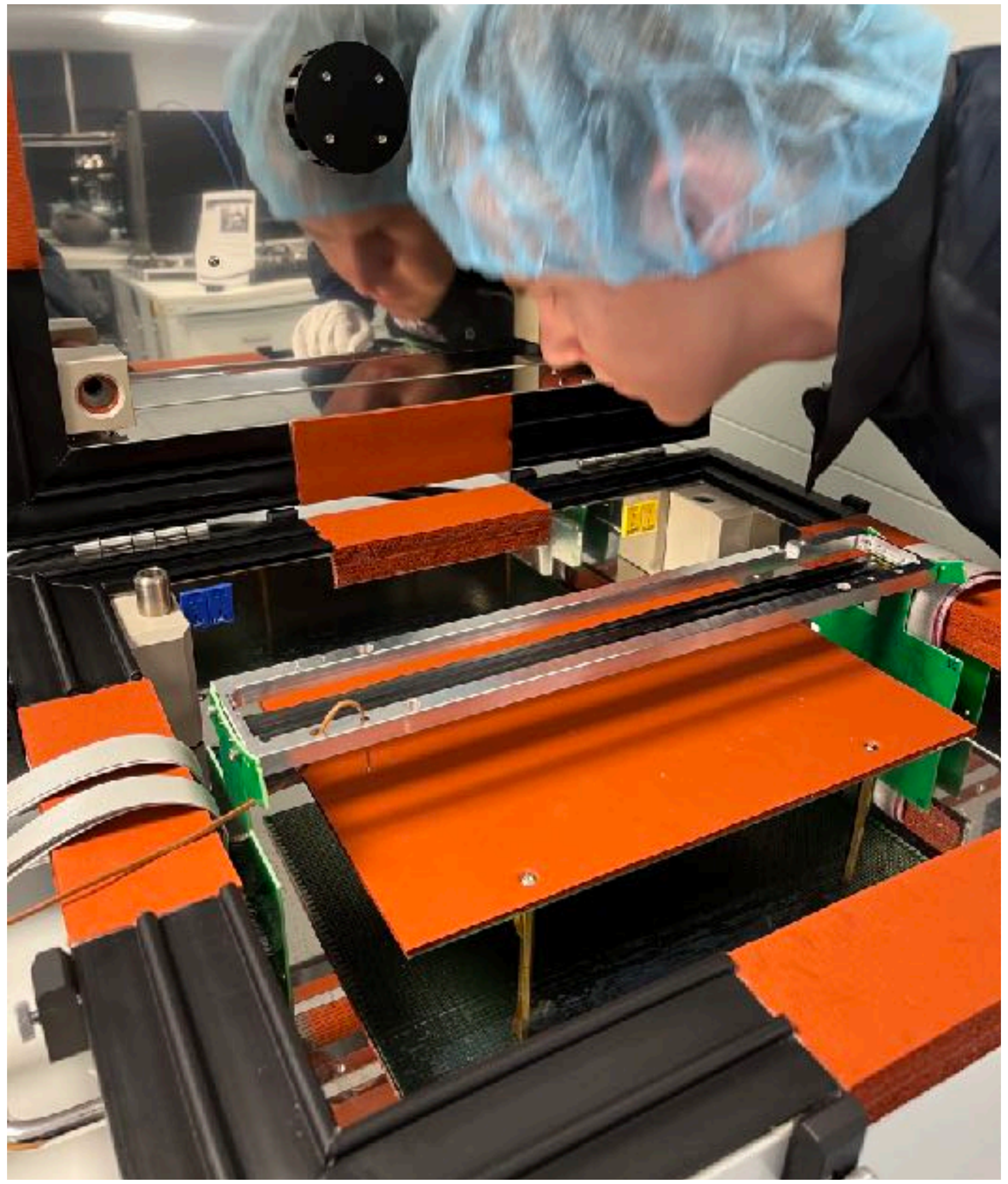
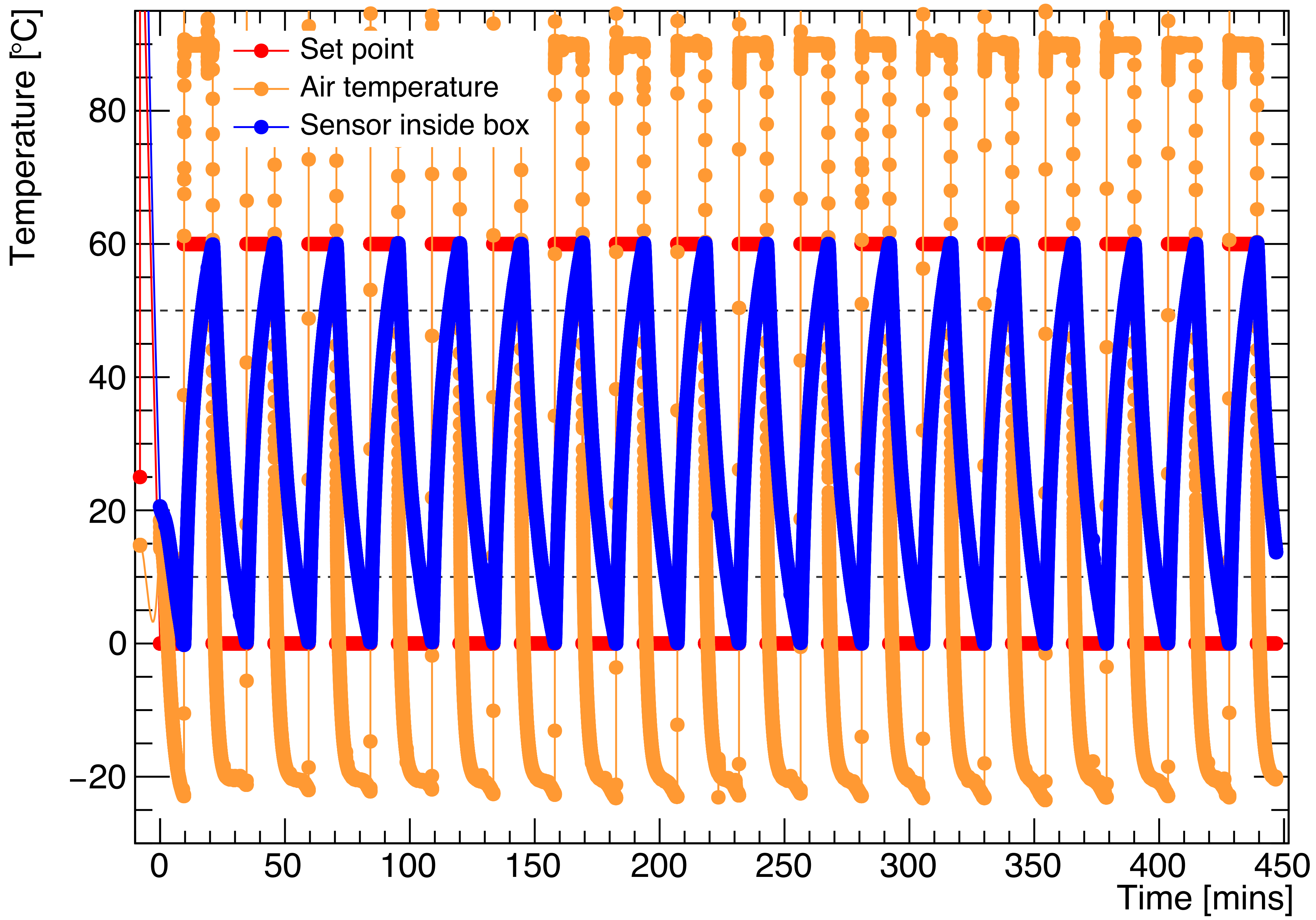
Electrical connectivity tested by thermal cycling (200 times) powered ladders between $\Delta T = 0$ —> 60°C:

- Large CTE mismatch between Si/kapton and carbon-fibre
- Carbon-fibre ladder general much stiffer --> more stress on Si/HDI

Thermally insulated box





- Kapton ladder: 2 failures seen per ~ 50 cycles
- Carbon-fibre ladder: no failures

Temperature uniformity and vibrations:

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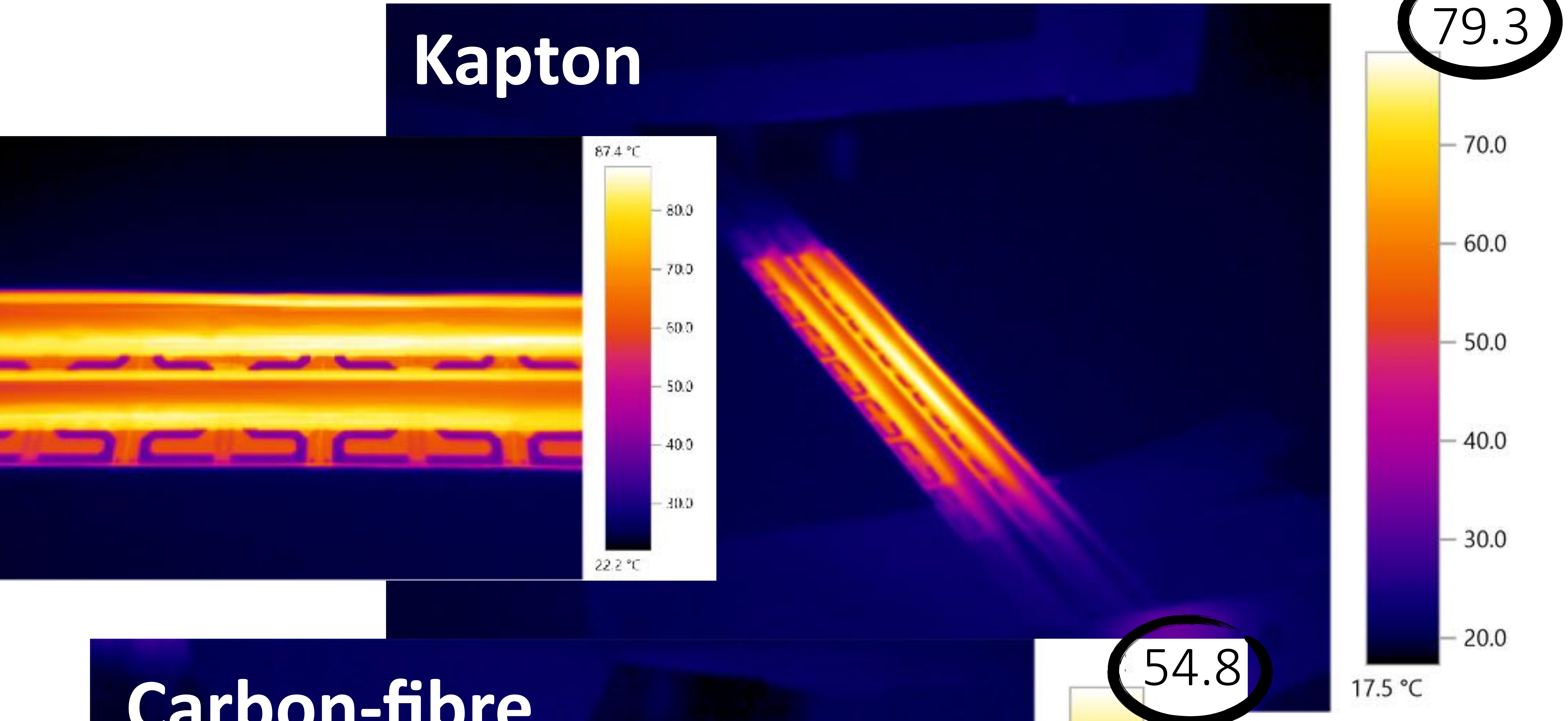
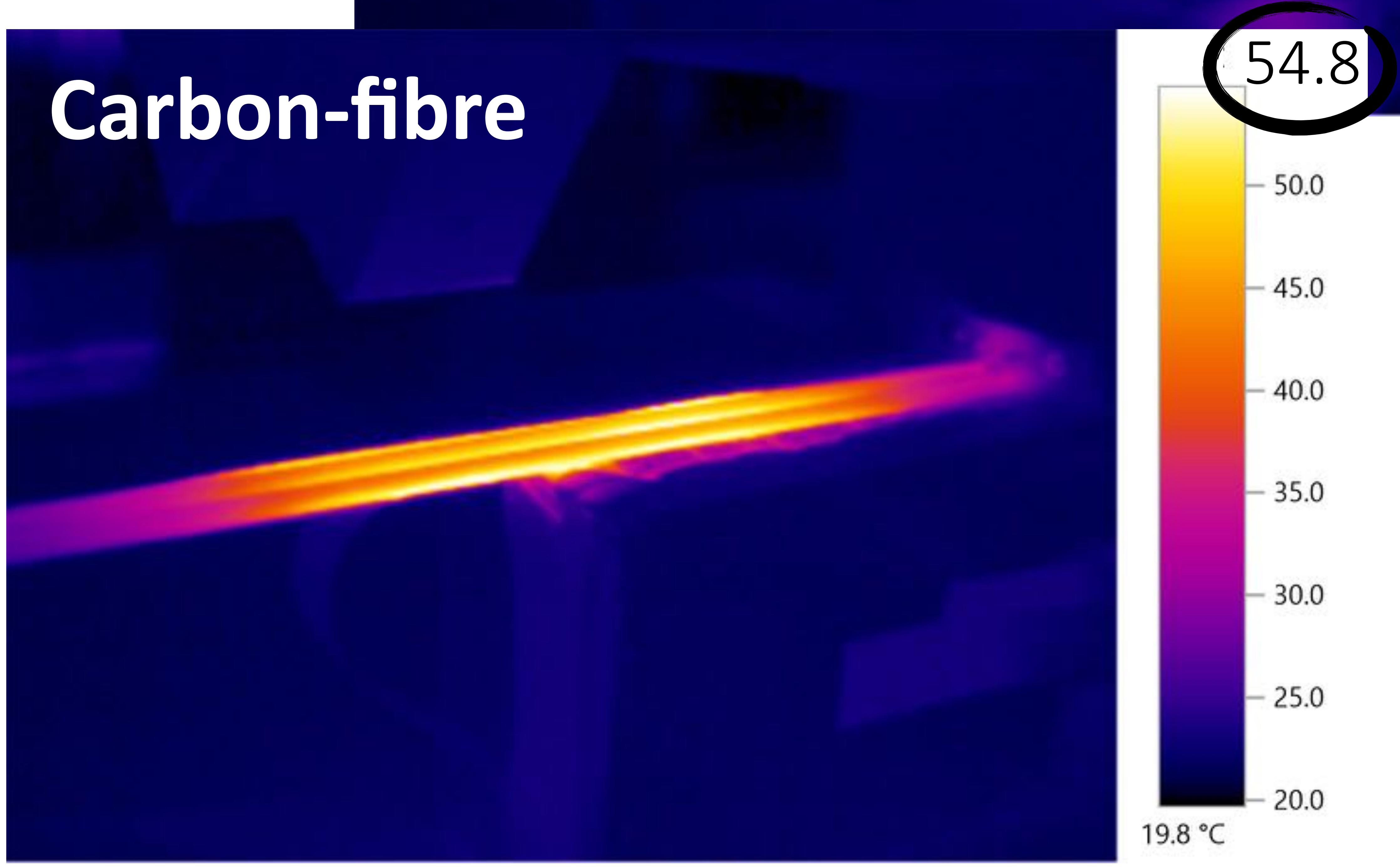


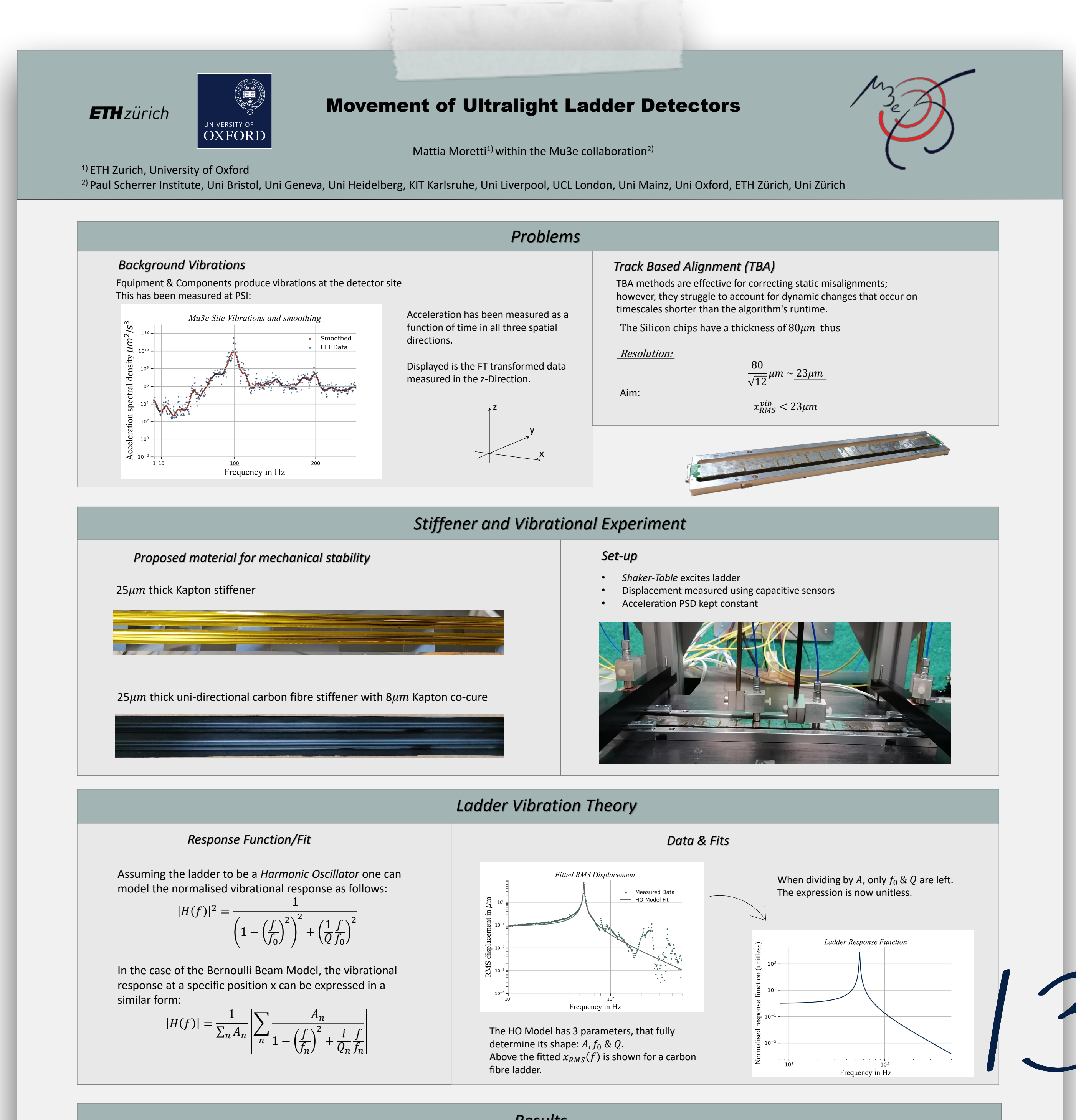


Measure **heat dissipation along ladder** when sensors are powered:

- Carbon-fibre better conductor than kapton: better at dispersing heat along the ladder length
- Carbon ladder reached much lower peak temperatures

Vibrations of ladders due to:

- Tension applied by module supports
- Environment: Helium compressors
- Gaseous flow



Fabrication procedure for outer pixel layers:

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Entire ladder production for the outer pixel tracker in Oxford cleanroom

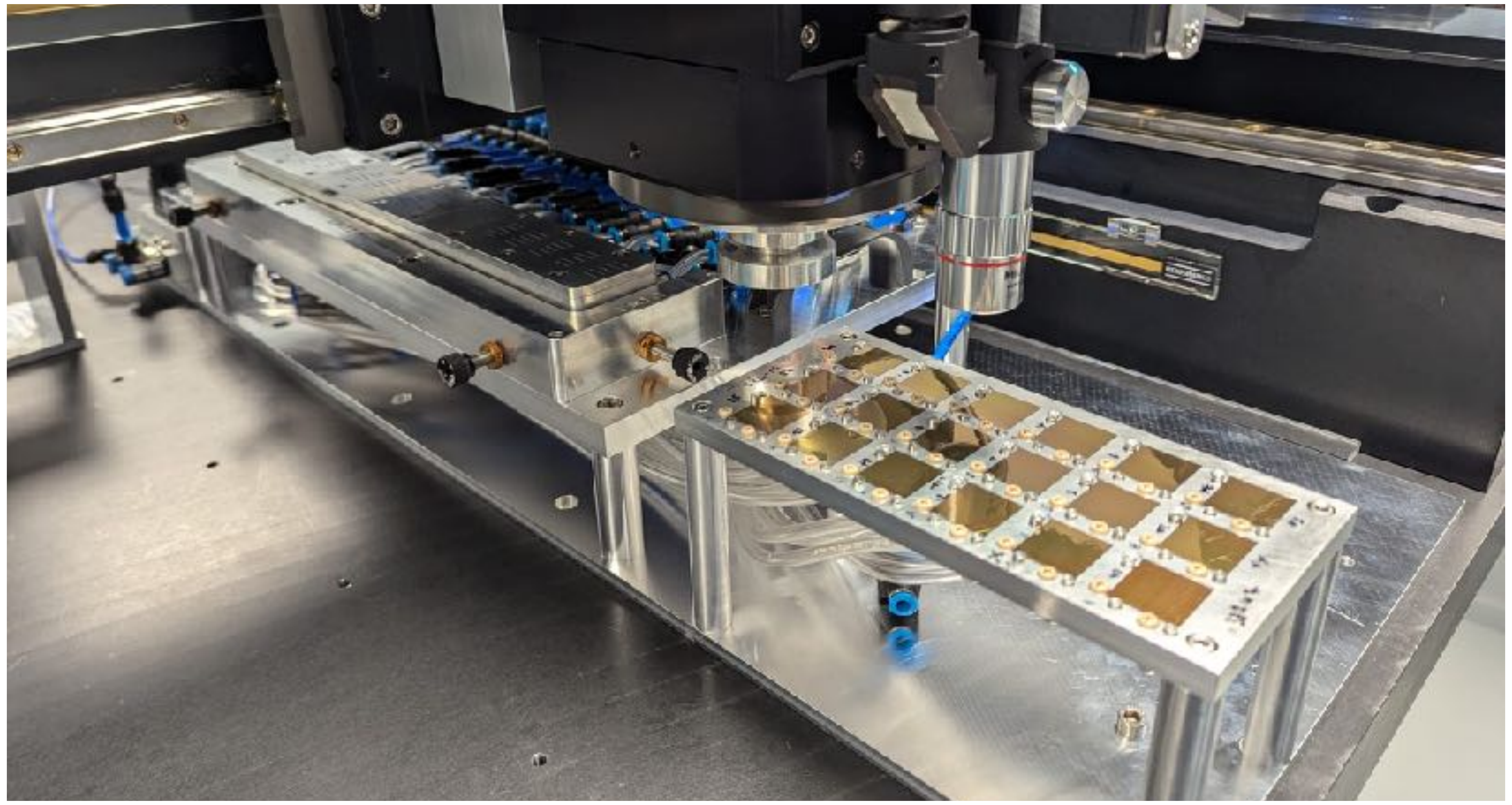
Ladder —> module —> layer:

- 17 (18) x MuPix11 sensors in layer 3 (4)
- 4 ladders per module
- 6 (7) modules in layer 3 (4)

Total per station: 52 ladders (912 sensors)

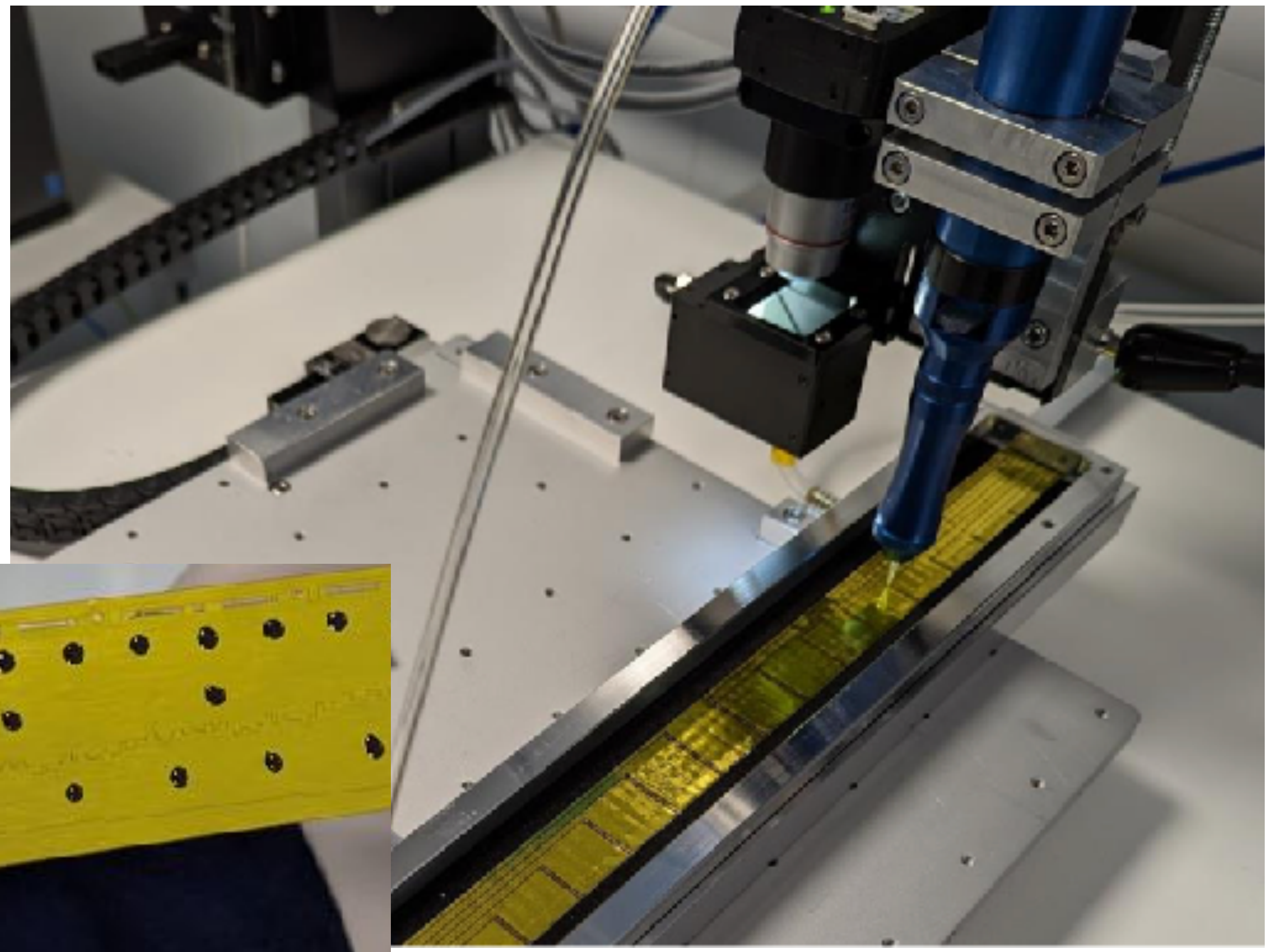
Automate ladder building procedure as much as possible:

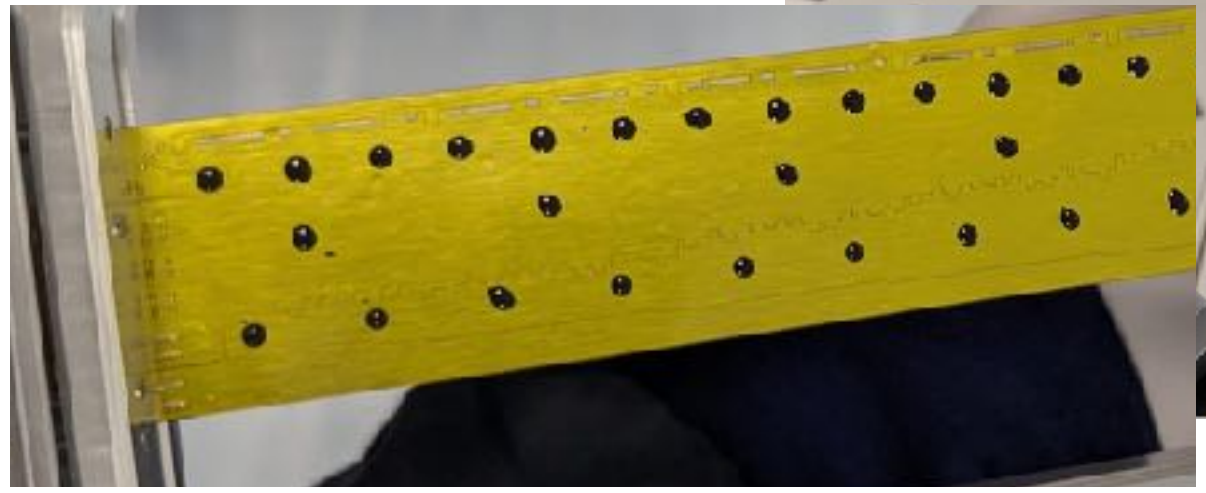
- Robotic gantry used for placement of chips



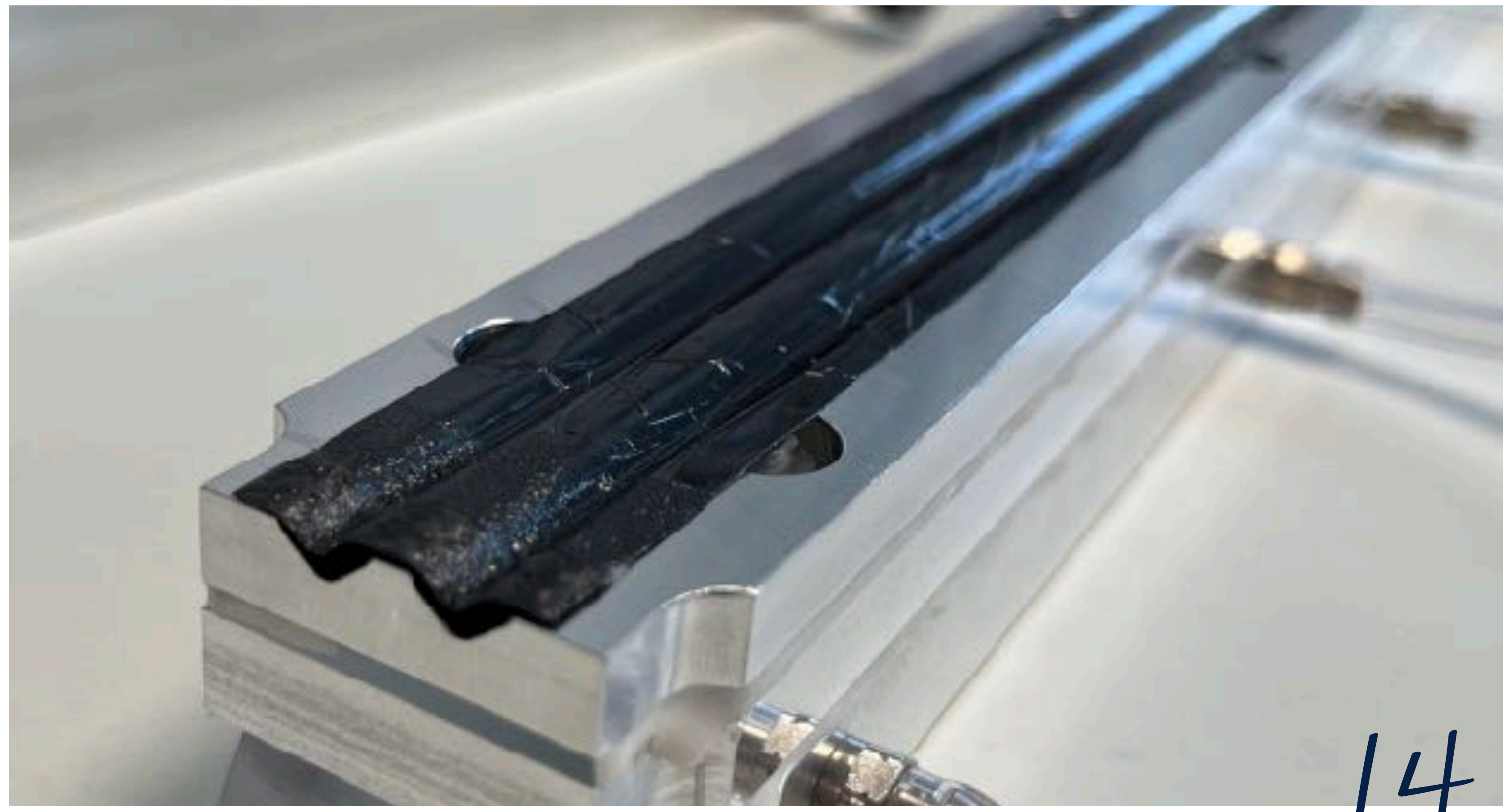
Glue-dispensing robot:

- Allows for precise placement and size of glue deposits





- Carbon-fibre stiffener vacuum held via suction cups:



Conclusions and outlook:

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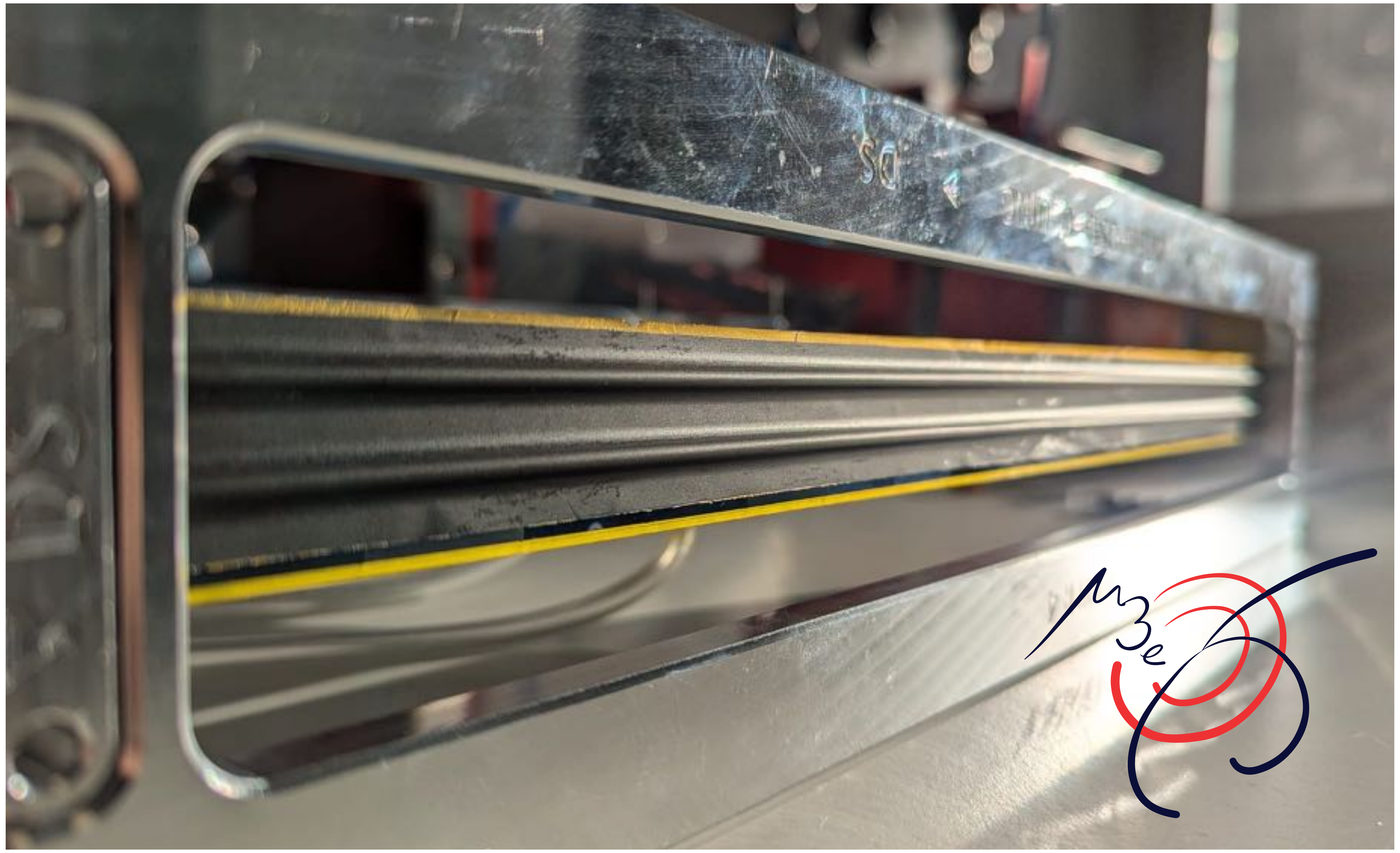

Mu3e on the cutting edge of ultra light-weight pixel tracking detectors!

Investigations into choice of stiffener material for the longer outer pixel ladders: **kapton vs. carbon-fibre**

- Carbon-fibre demonstrates favourable properties: thermally, stiffness, handleability

Production of outer pixel ladders on-going.

Expect physics data-taking to commence in 2026!

Stay tuned … !

[Mu3e collaboration] | [Oxford silicon detector group] | [ashley.mcdougall@physics.ox.ac.uk]