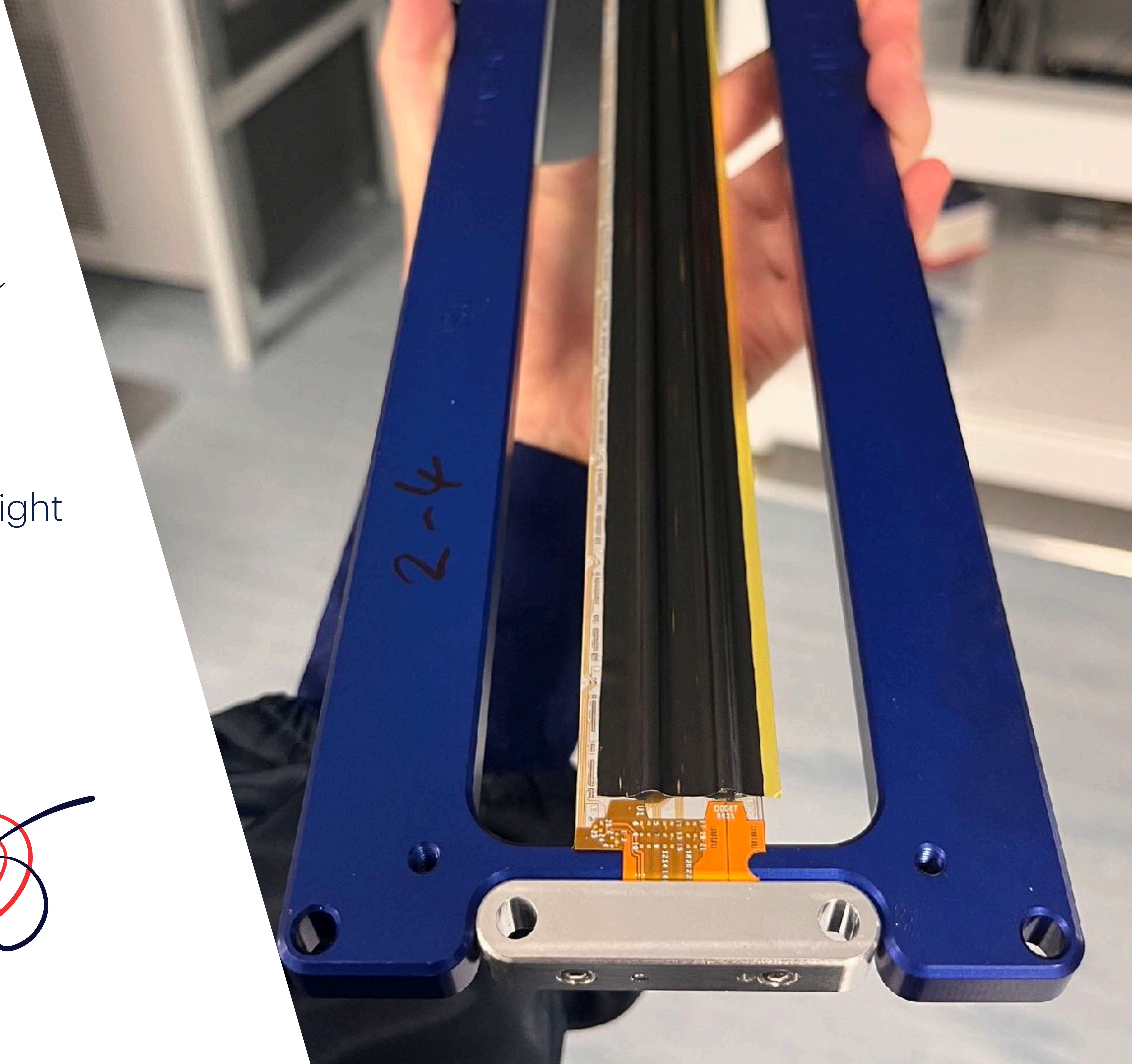
Ultralight UD structures for Mu3e pixel detector

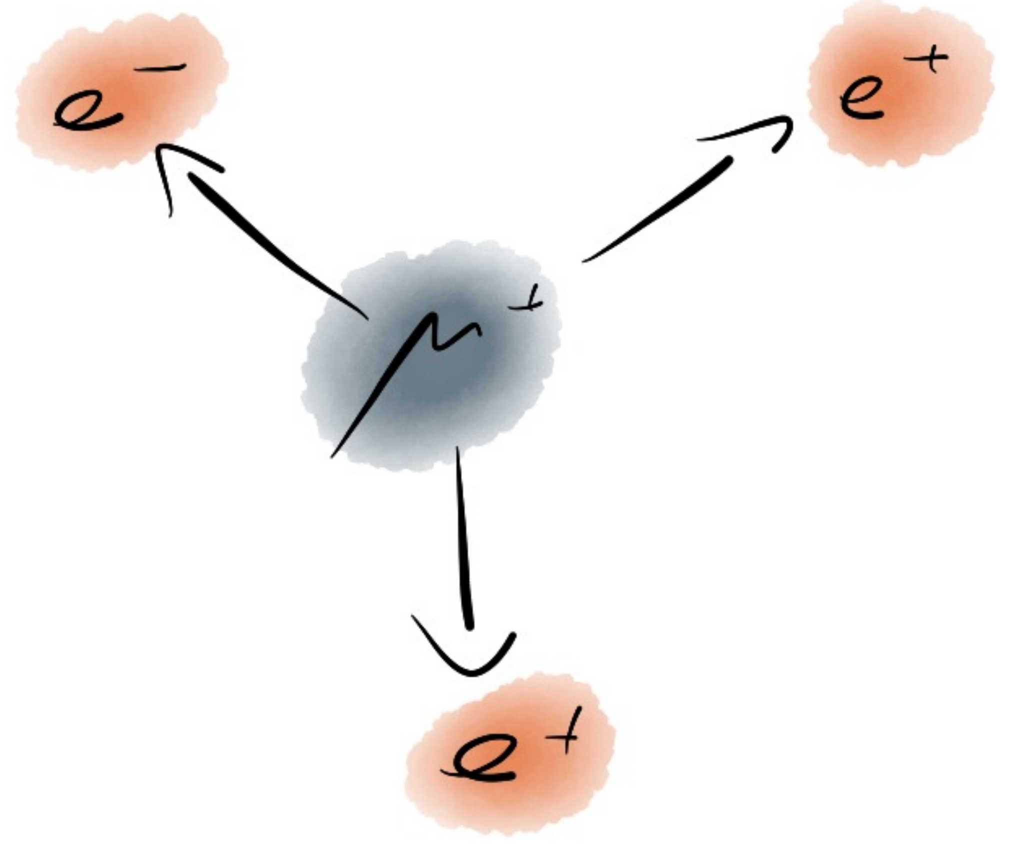
Ashley McDougall, Adam Lowe, Alex Knight

on behalf of the Mu3e collaboration

2nd DRD8 Collaboration Meeting
14.10.2025

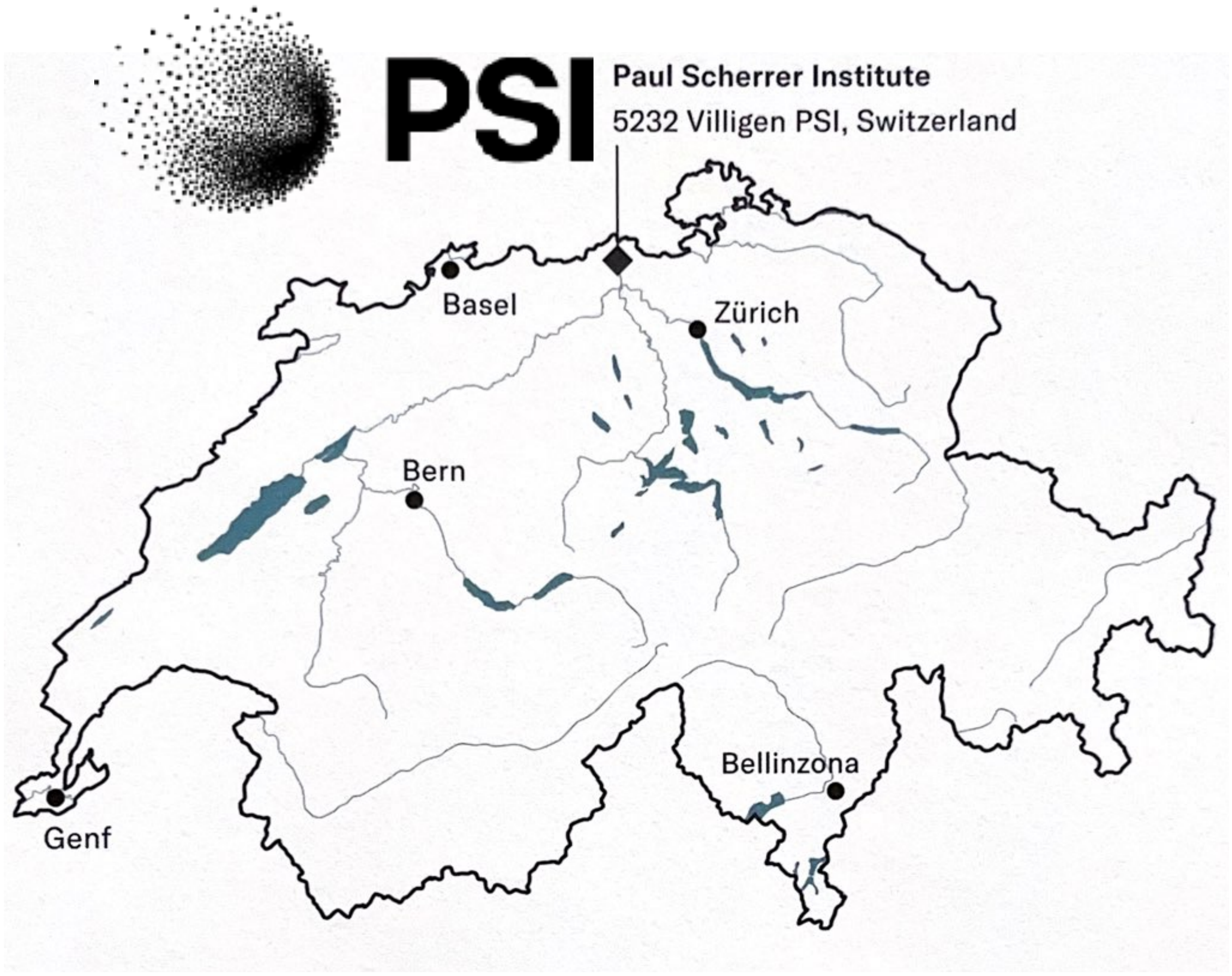


Signal:



Mu3e inside experimental hall

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



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

Physics data-taking in 2026 (Phase I):

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

Phase II (> 2029):

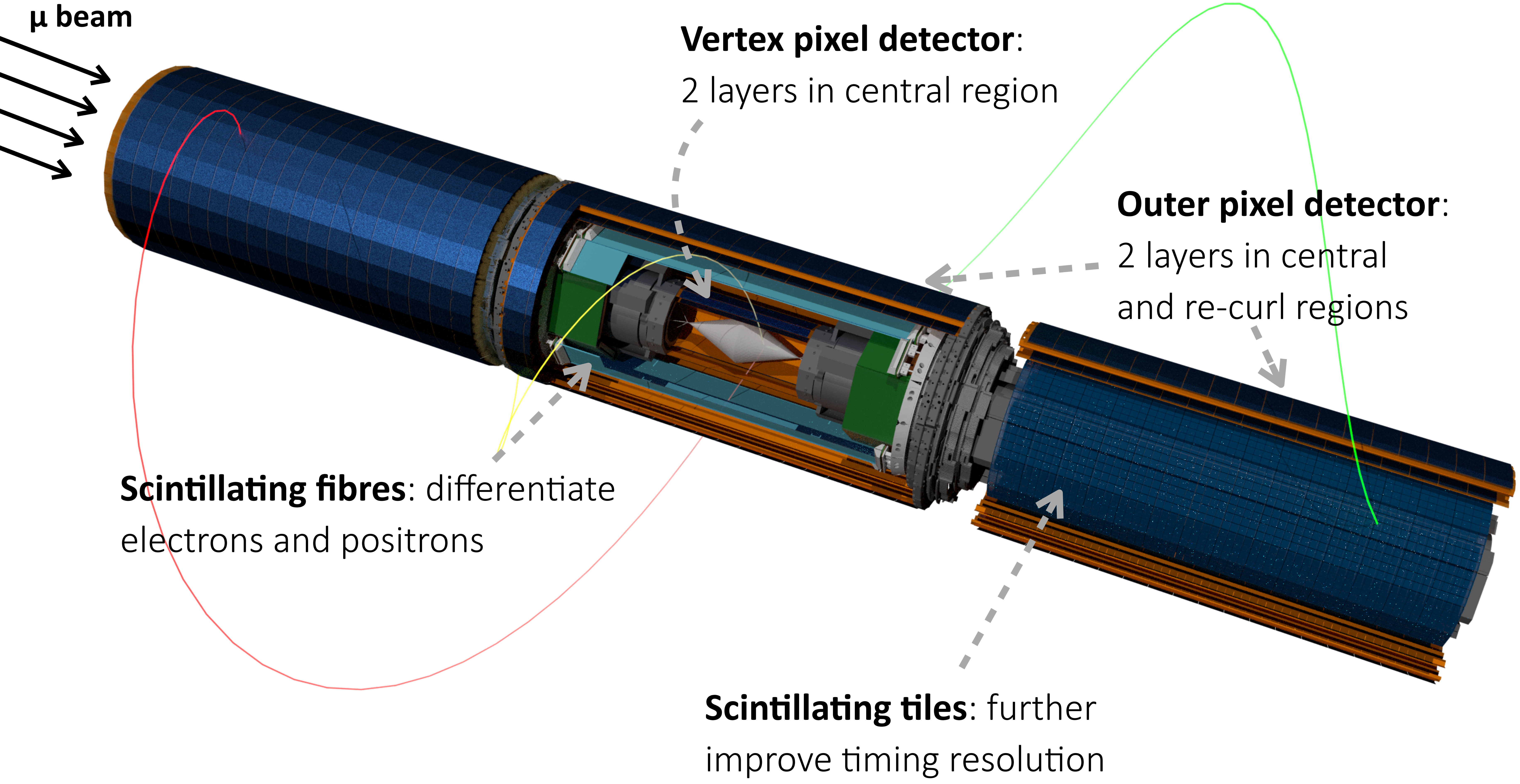
- New High Intensity Muon Beam-line (HIMB), delivering up to **10^{10} muons/s**
- Target sensitivity: **BR ($\mu \rightarrow eee$) < $2 \cdot 10^{-16}$**

Mu3e detector design:

A. McDougall

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:

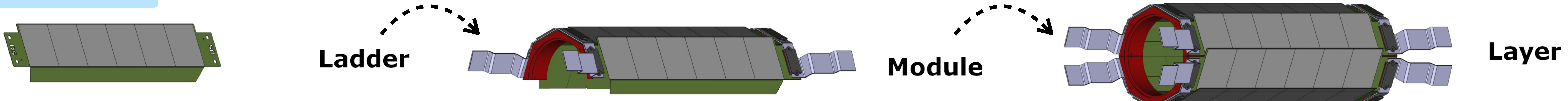
- 50-70 μm thick MuPix11 (Monolithic HV-CMOS) pixel sensors
- Per layer: ~ 0.1 % X/X_0

Cooling:

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

Vertex tracker:

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

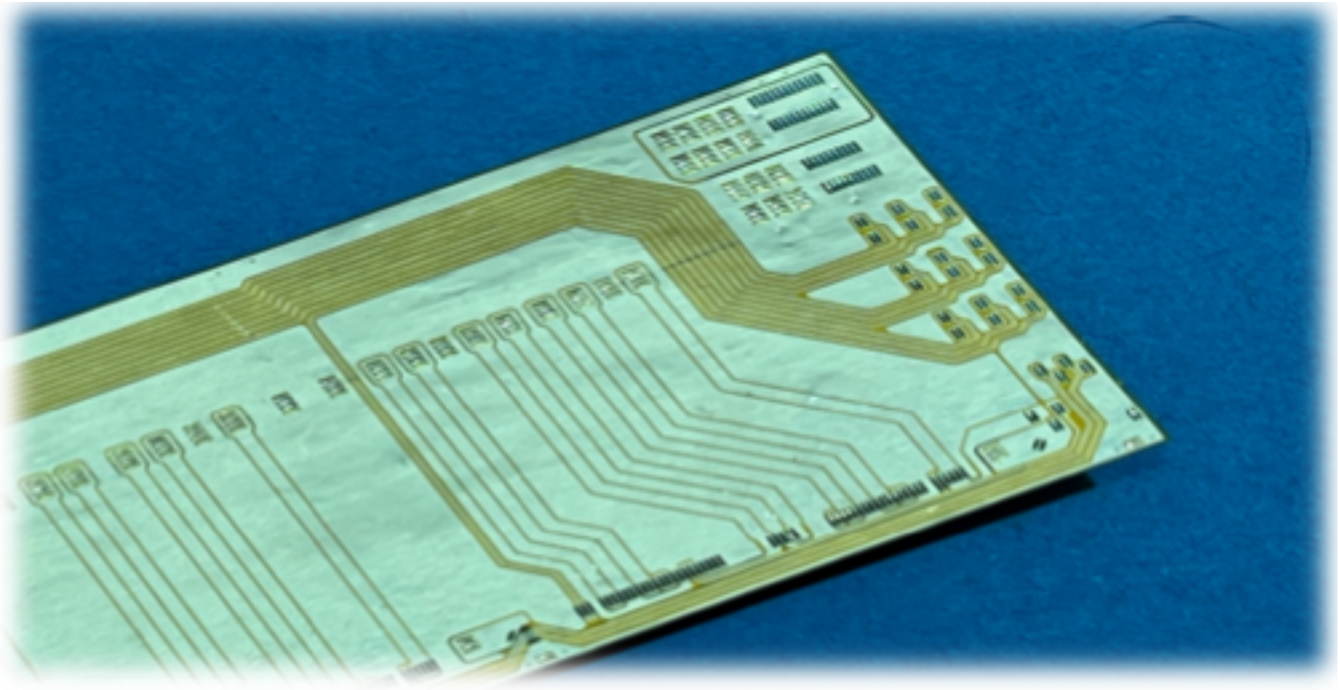


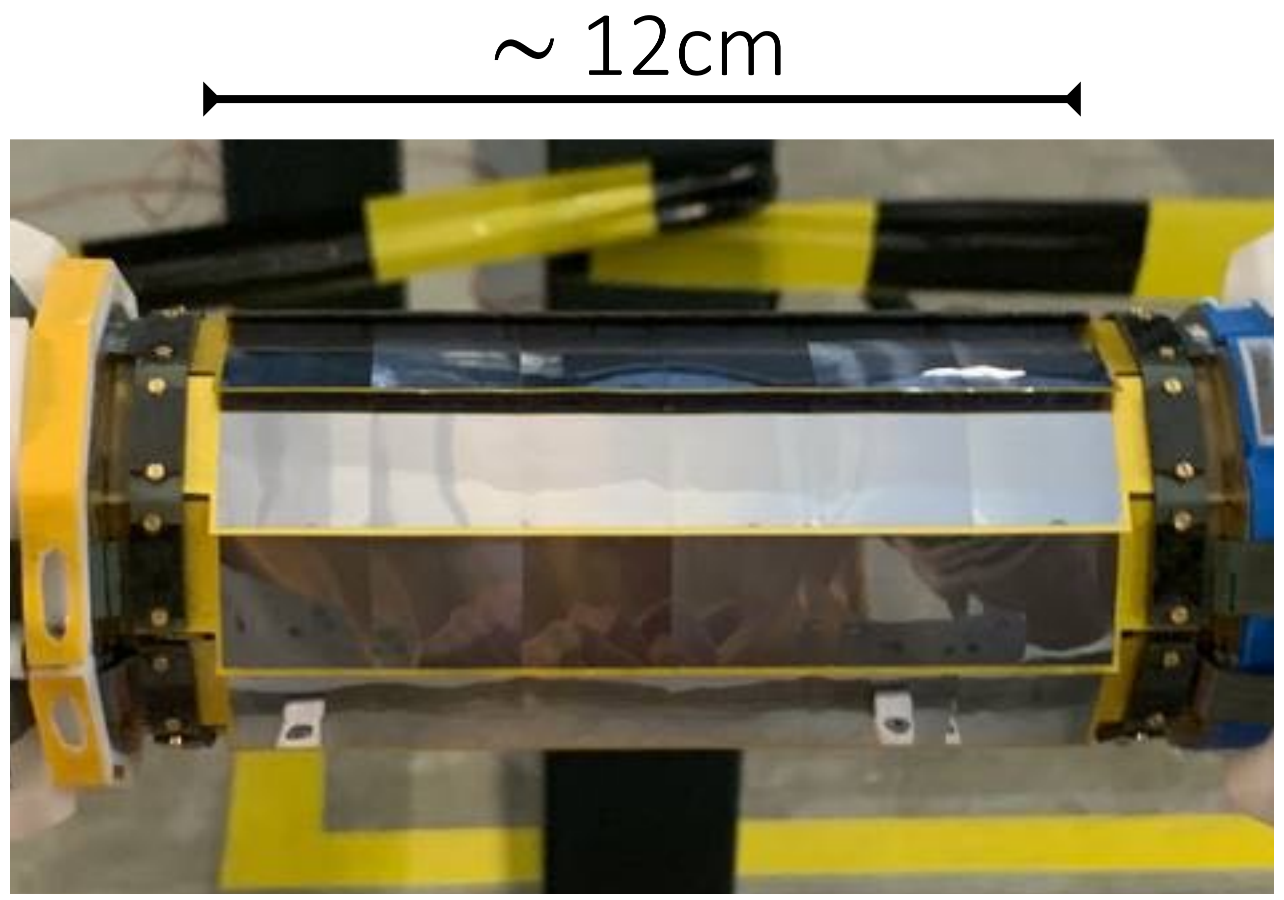
1 ladder = 6 x MuPix11 sensors 1 module = 4 ladders 2 modules = 1 layer

Comprised of:

- MuPix11 pixel sensors (50-70µm)
- Alu/kapton high-density interconnect (HDI), ~ 70µm
  - Produced by LTU (Kharkiv, Ukraine)
- Electrically connected via spTAB connections

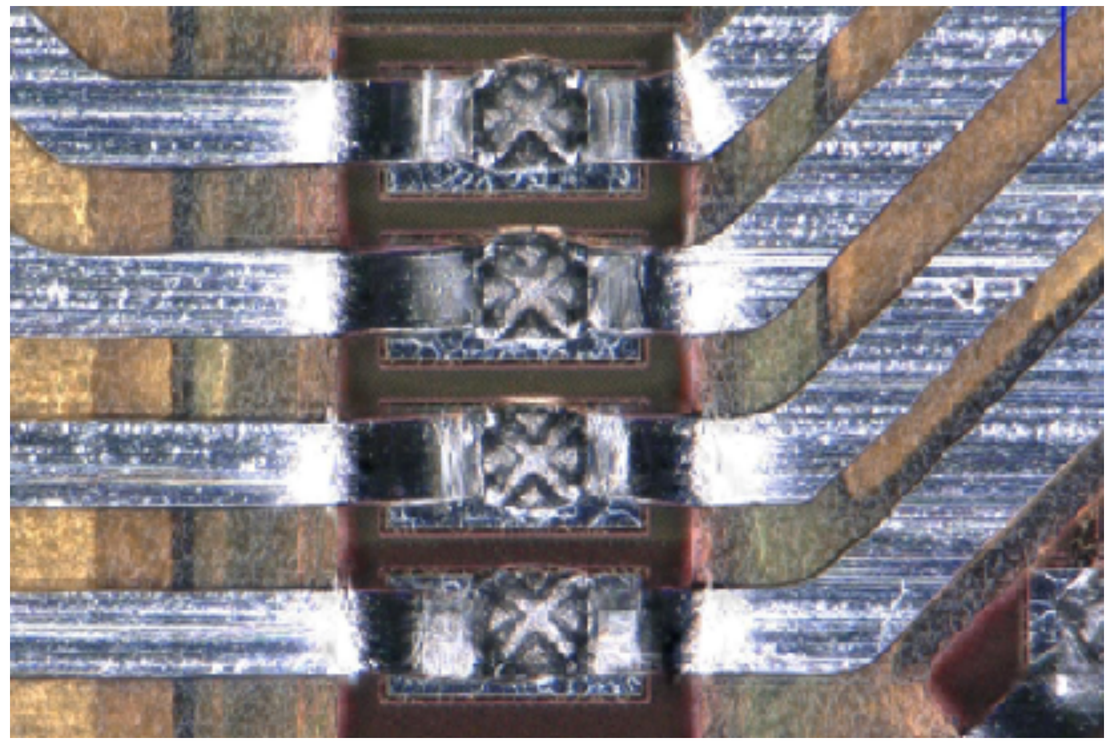
HDI:





Vertex system ("version 1") complete and installed in PIE5 for June 2025 beam-time.

spTAB (single point Tape Automated Bonding):



Outer pixel tracker:

- 17-18 x MuPix11 silicon sensors
- + additional mechanical support (stiffener)

Mu3e pixel tracker:

A. McDougall

Vertex tracker:

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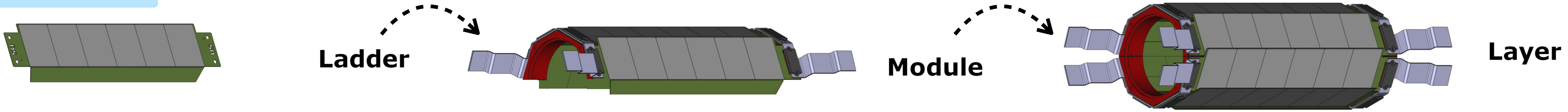

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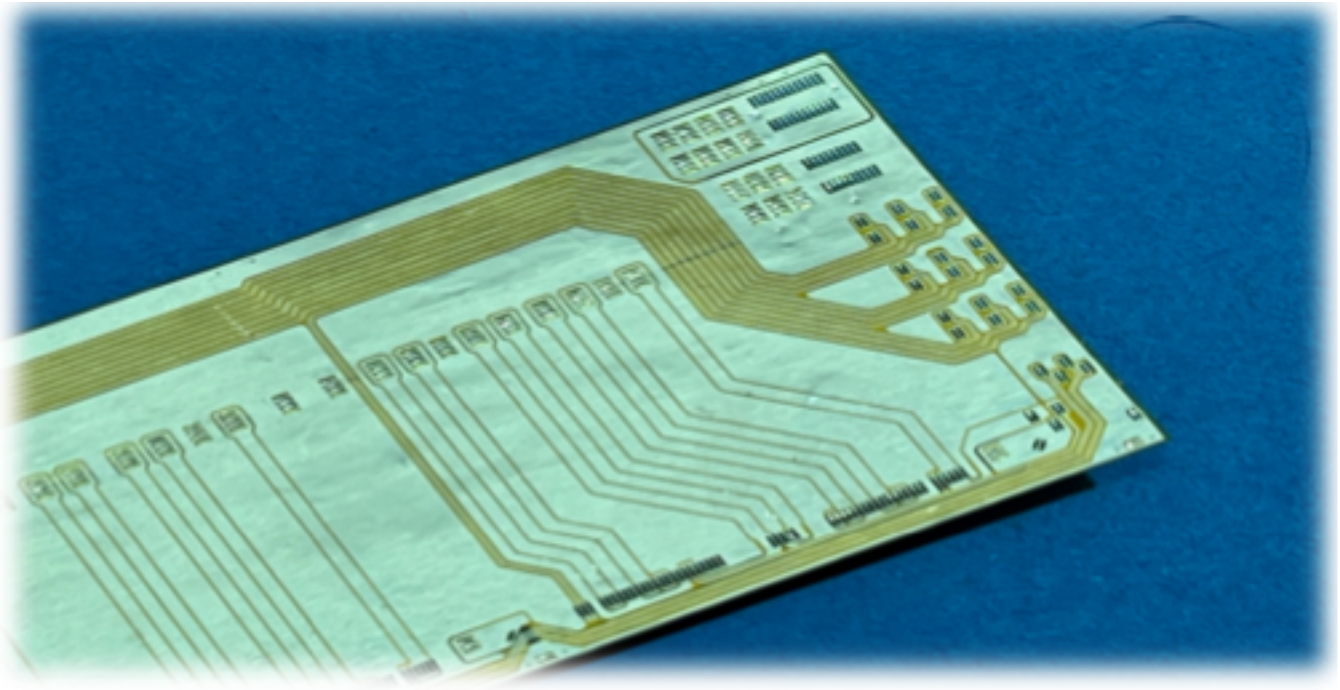
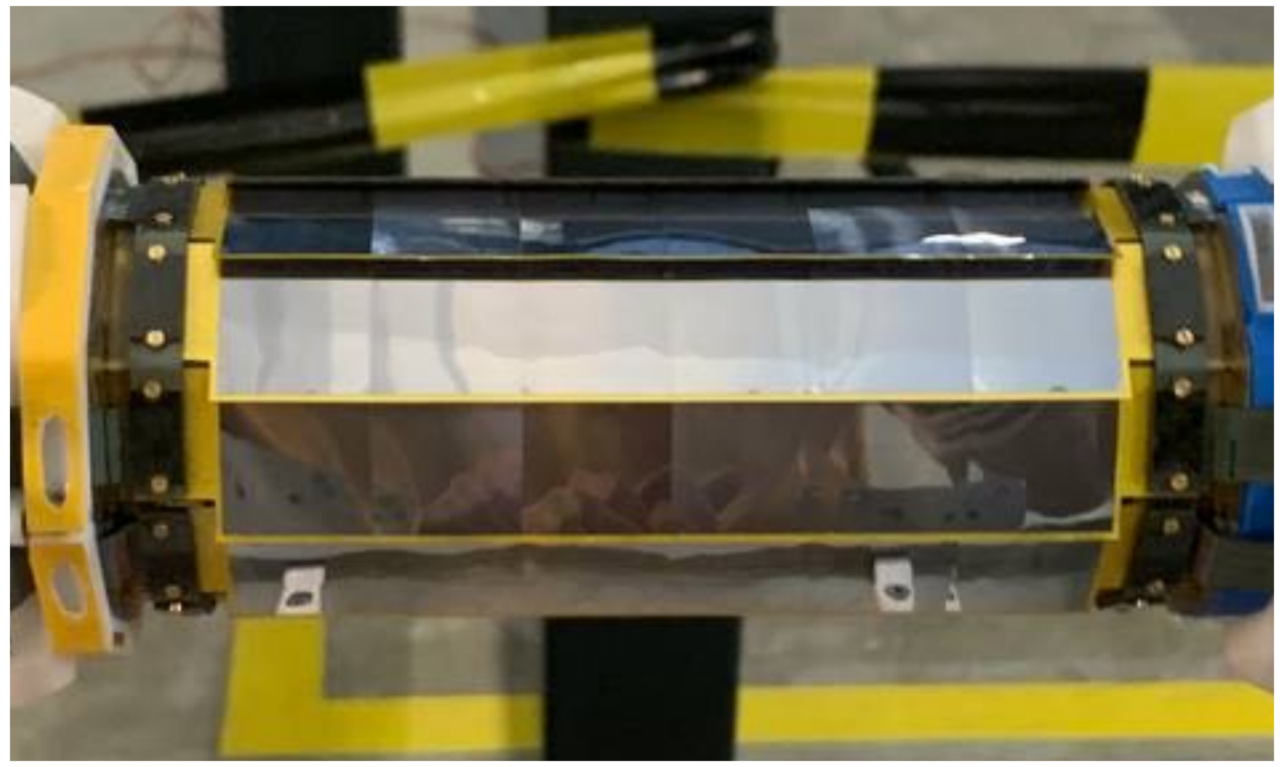
HDI:



~ 12cm



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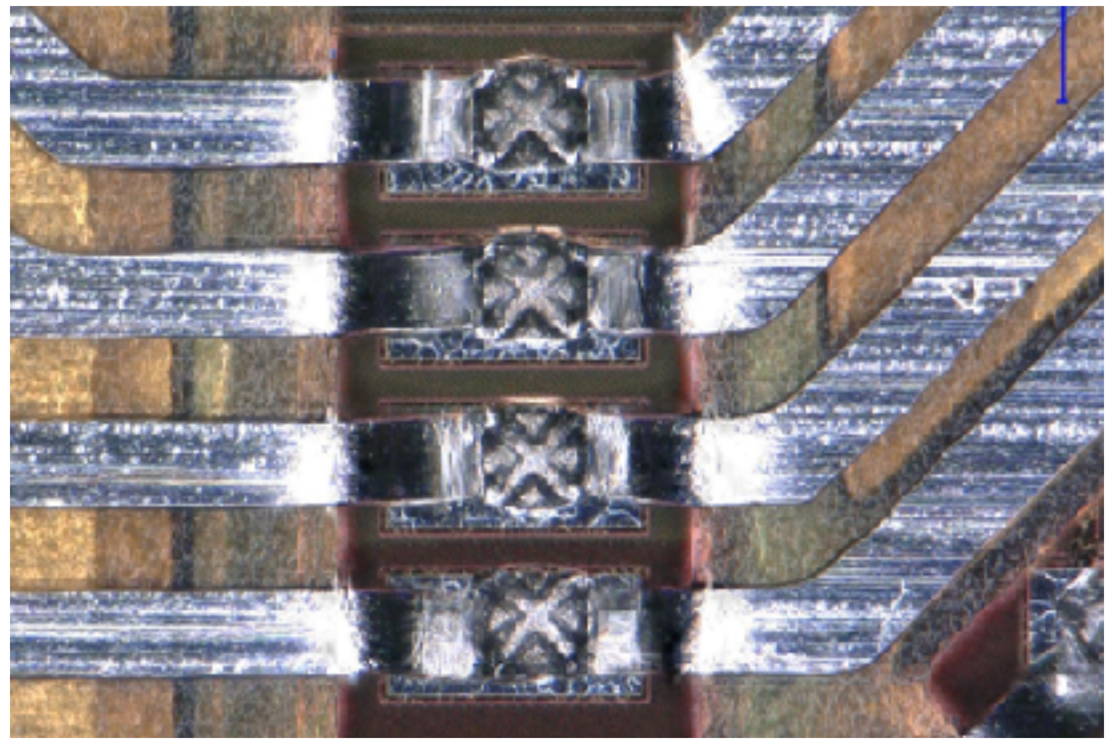


Outer pixel tracker:

- [redacted]
- + additional mechanical support (stiffener)

Focus of this talk

Mechanical support for the outer pixel ladders:

Mechanical support provided by either:

Polyimide film:

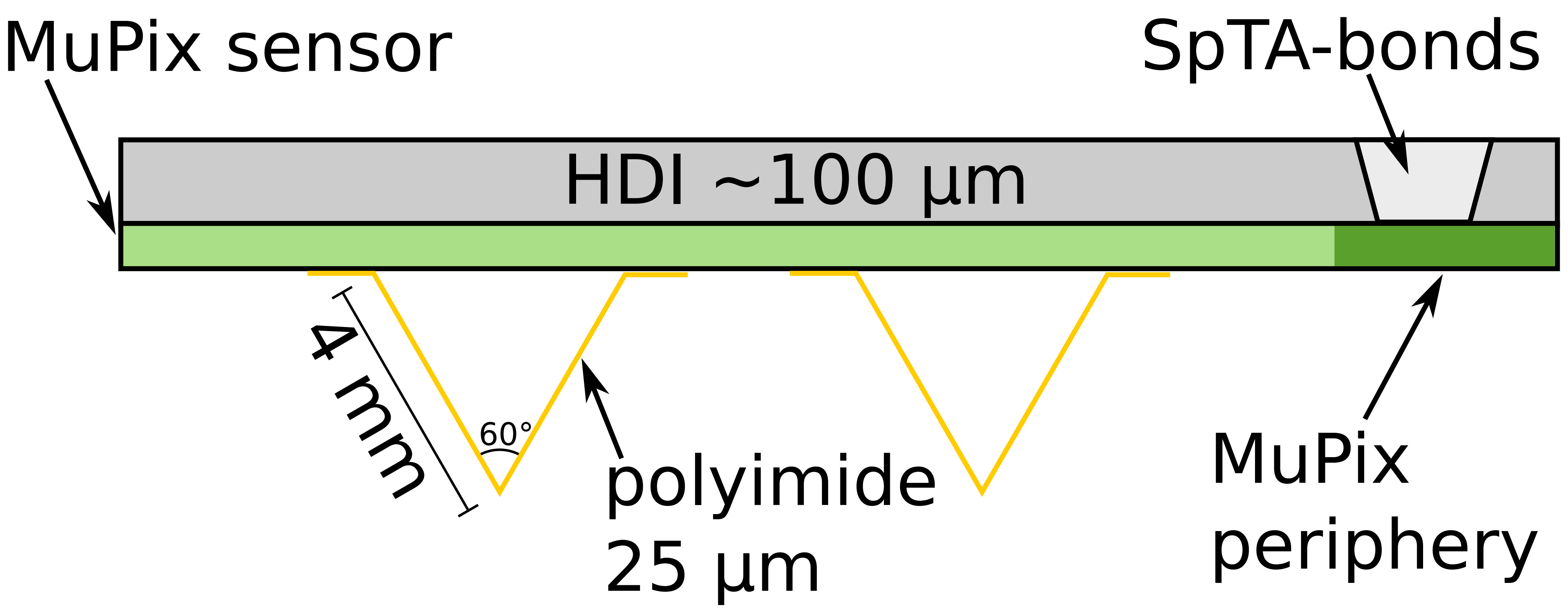
25µm thick folded in two triangles:

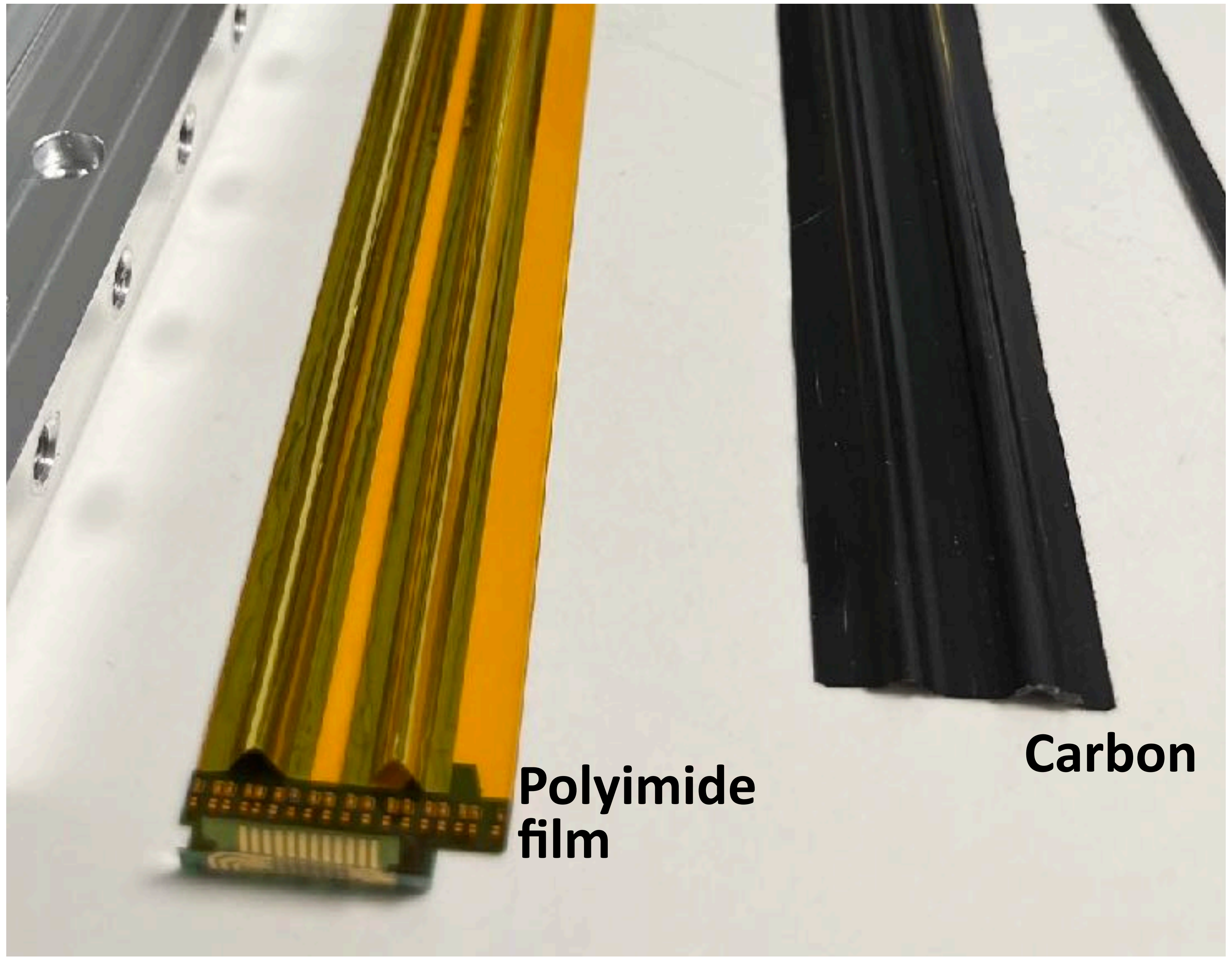
- Sensors/bonds mostly still visible underneath
- Quite delicate —> difficulties in transportation
- Barely enough structural integrity for 18 chip ladders

UD fibres (carbon, glass, kevlar):

25 µm uni-directional carbon-fibre, with joined:

- Moulded into double-u shape
- Co-cured polyimide film (8µm) backing - electrically seperate two halves
- Very stiff along length (improves yield and transportation)





Fabrication of polyimide stiffeners:

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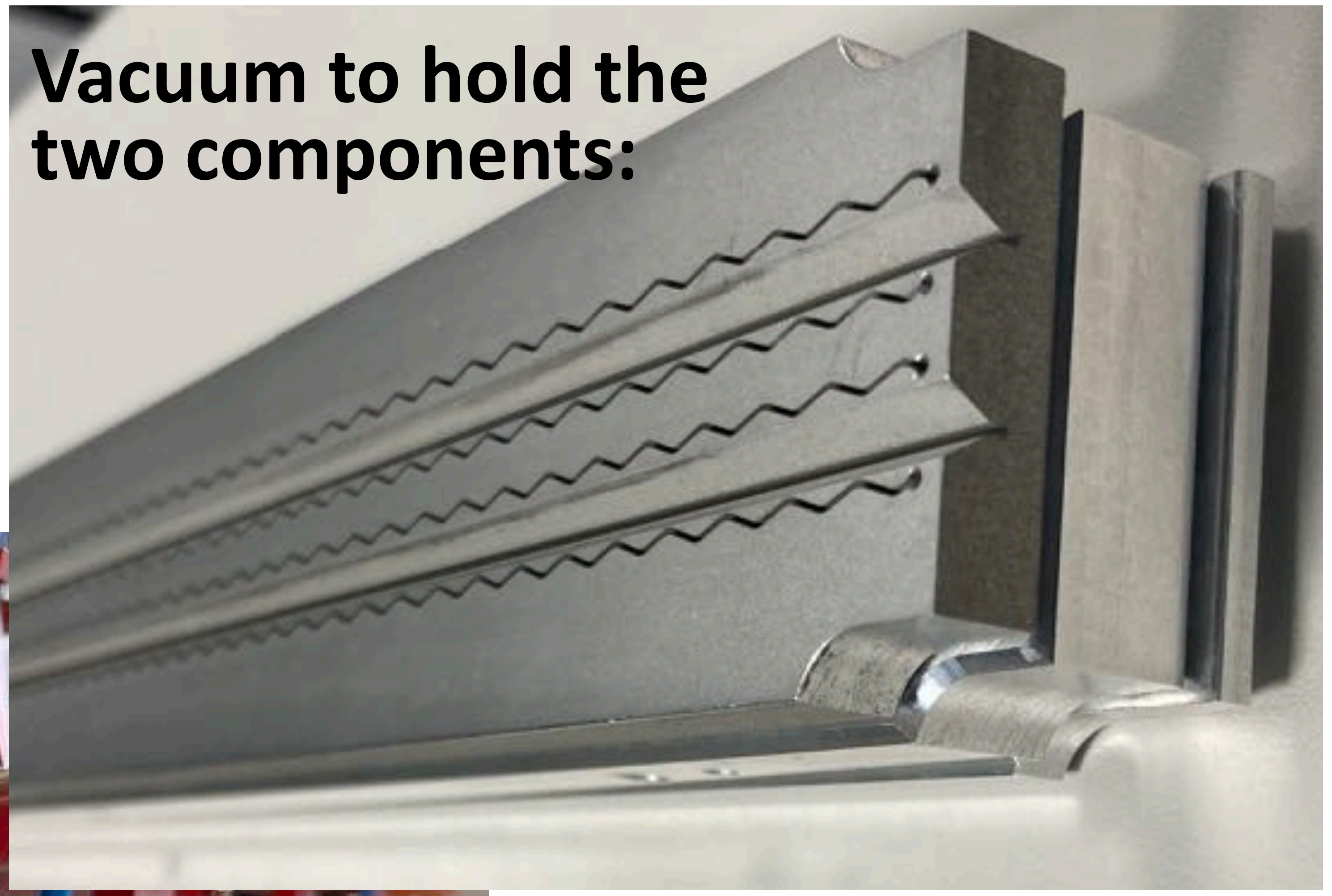
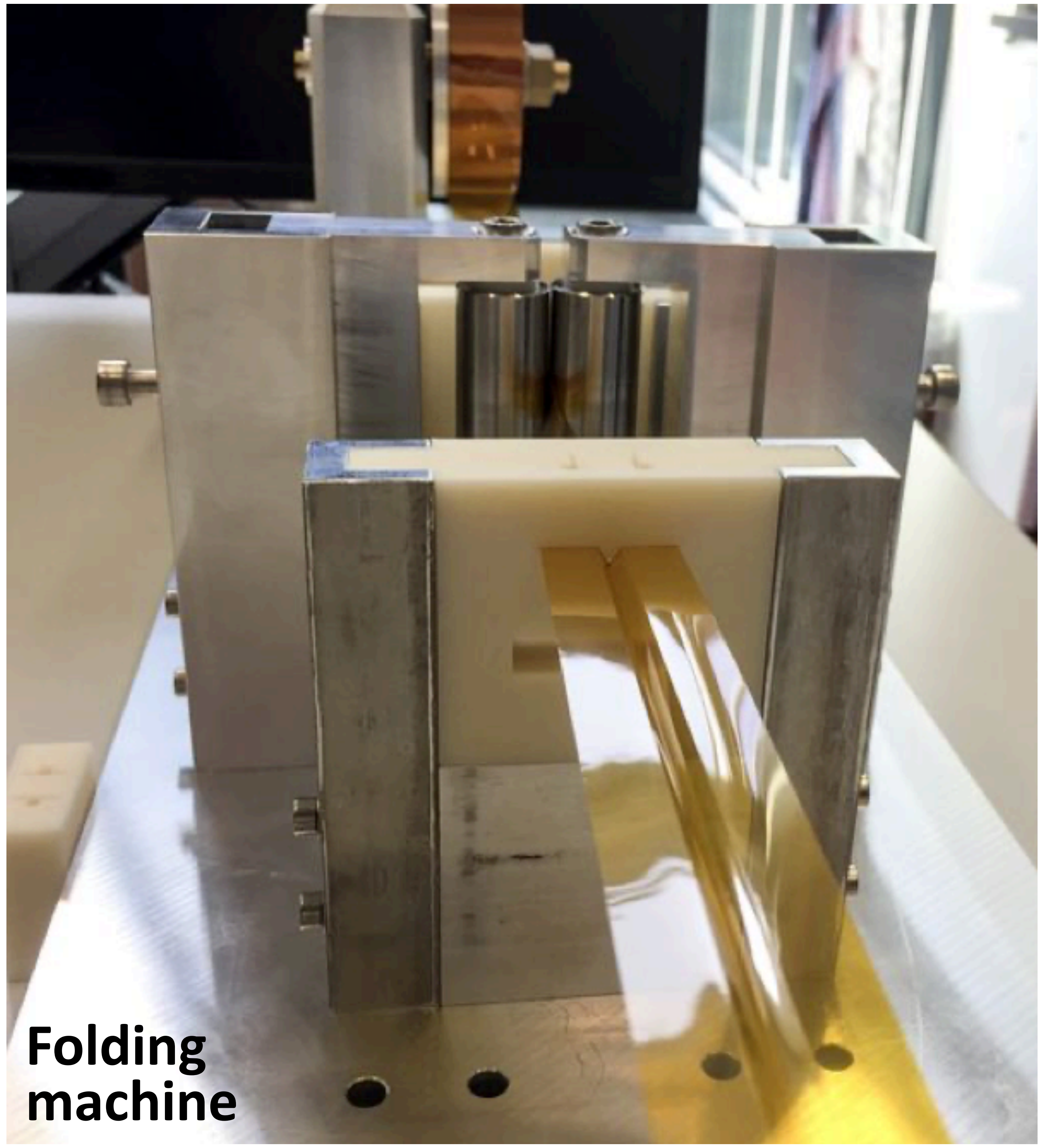
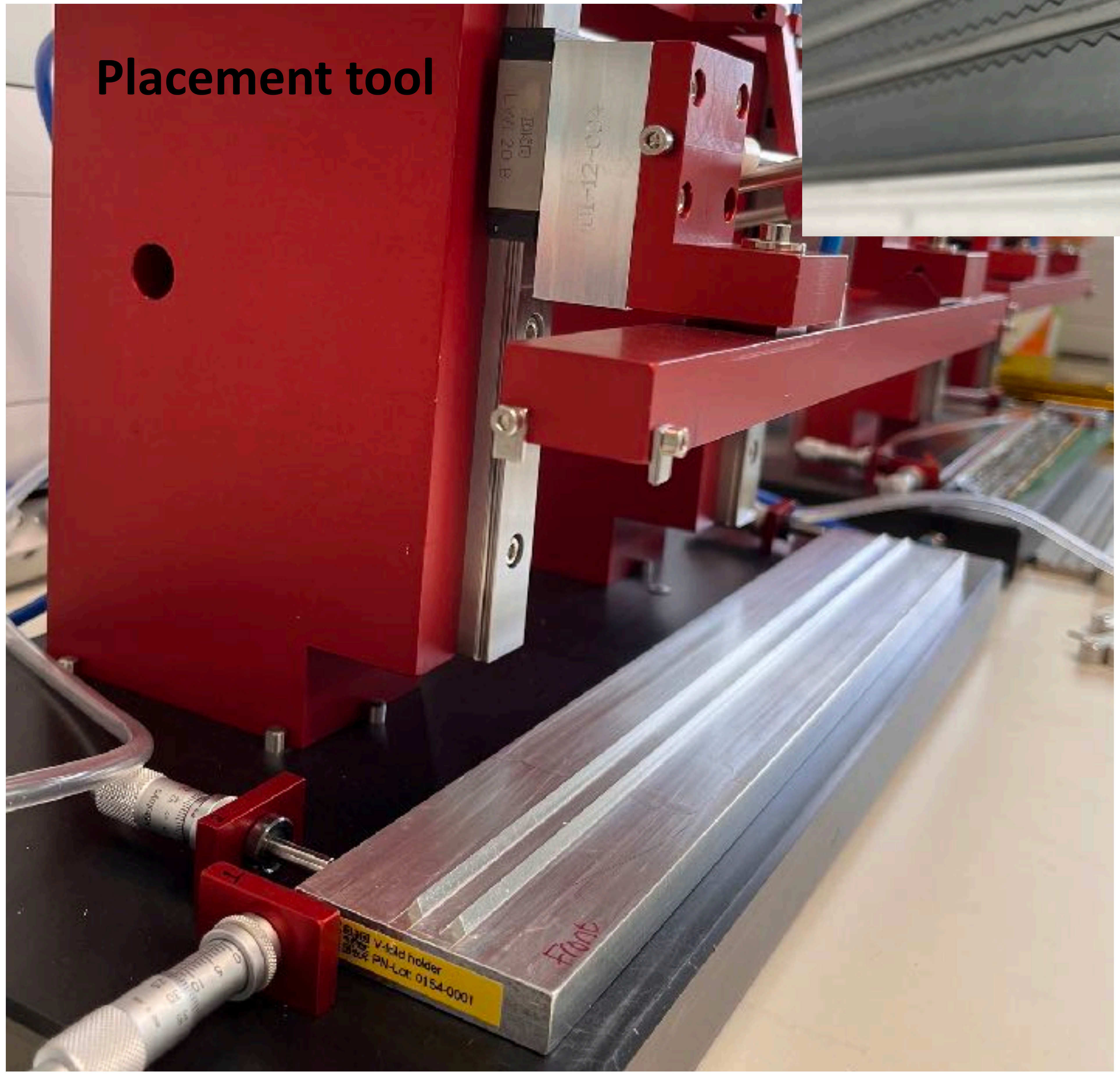
25μm thick film folded in triangular shape: 2 per ladder

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







Development of light-weight UD CFRP:

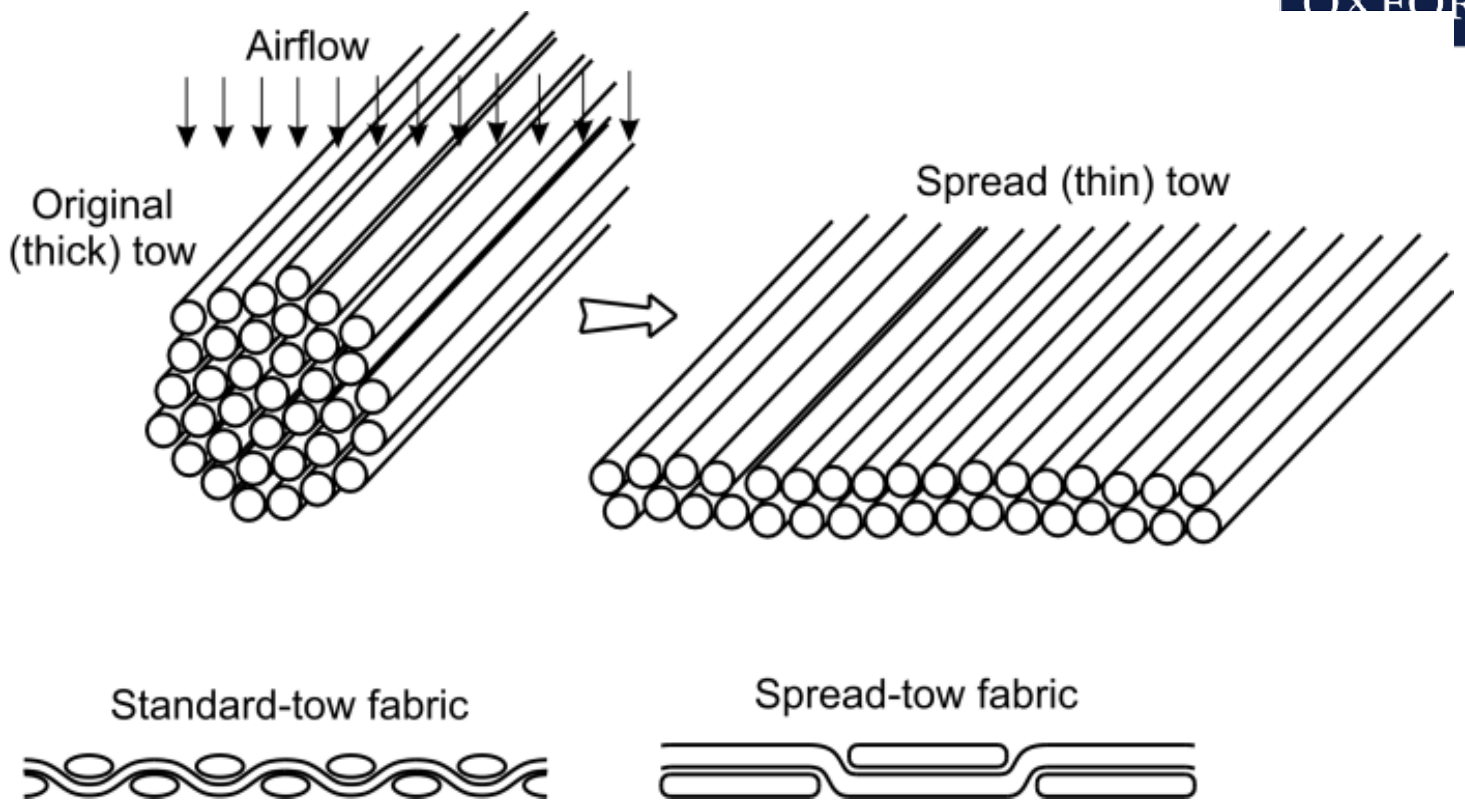
A. McDougall

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

- Tairyfil TC33 fibre and SK Chemicals K51 matrix
  - Material developed for sails for America's cup yacht (Allinghi)
  - Usually intended to be woven together

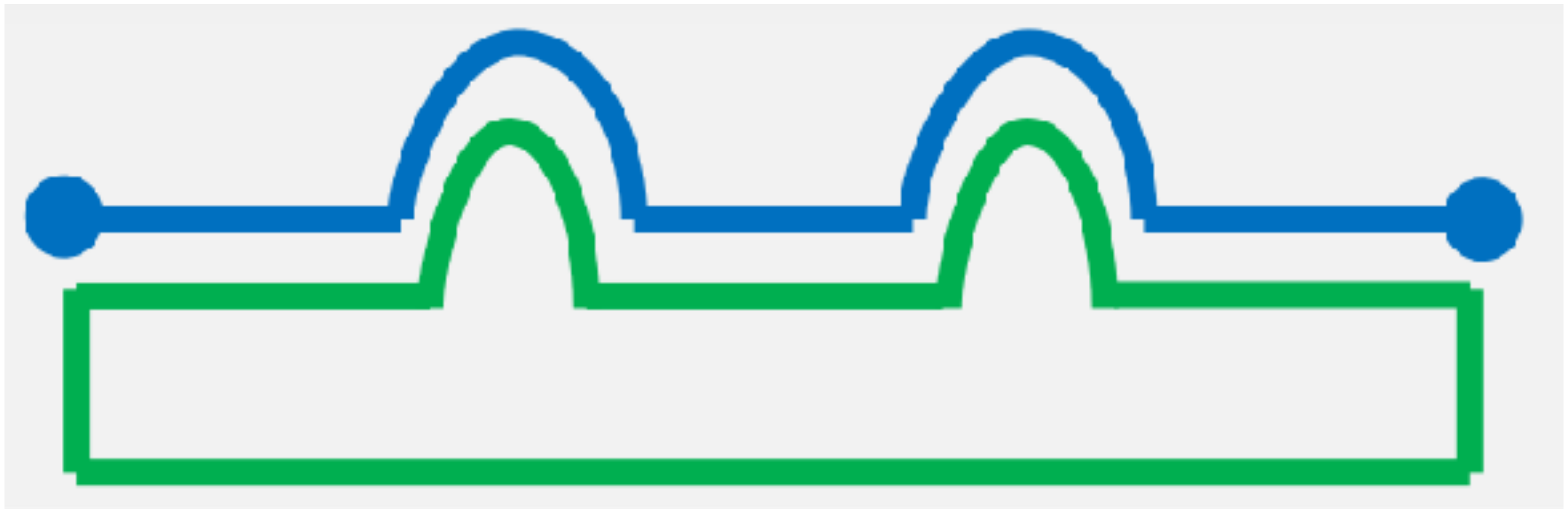
Mu3e design highly non-standard, no industry used case:

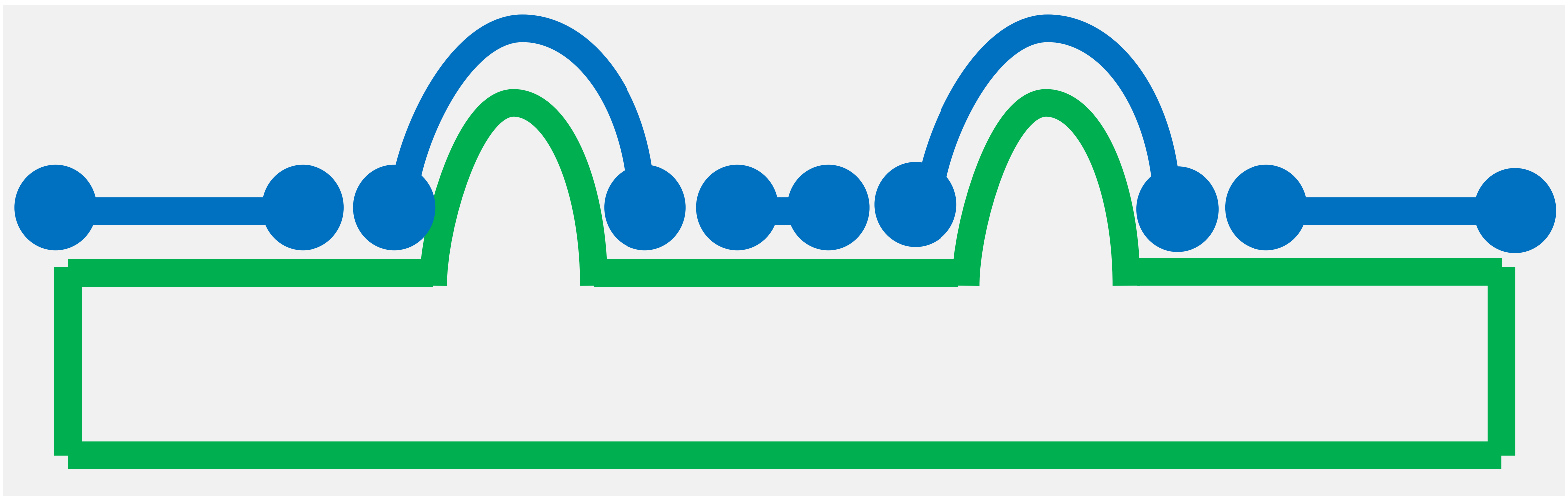
- **Spread tow**: results in much thinner ply- due to reduced tow thickness
- **Split-ply** laid together: compliance during warm up/cool down, additional resin to bleed off
- Material cured into double "u" shape, with 8µm polyimide film
- Average mass = 0.735 g



[doi.org/10.3390/polym15071767]

Single ply "normal" & logical approach:

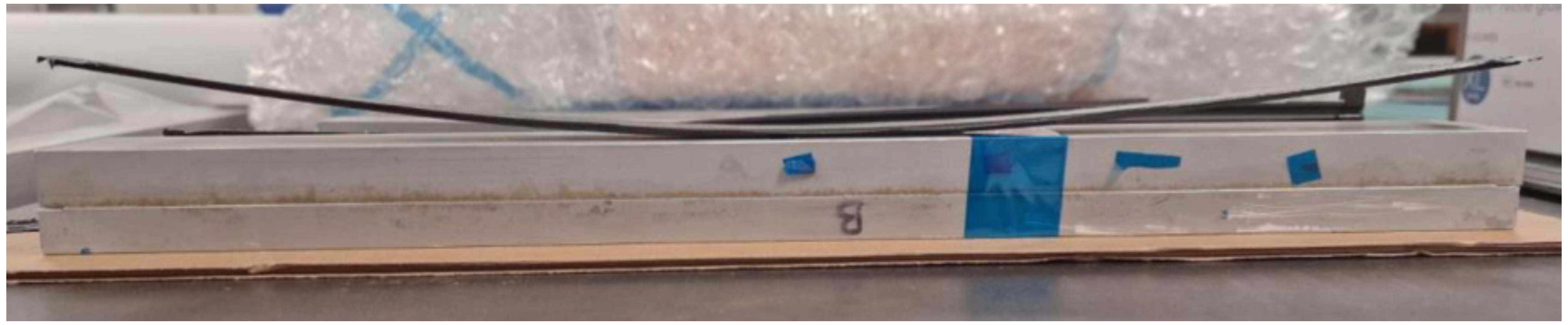


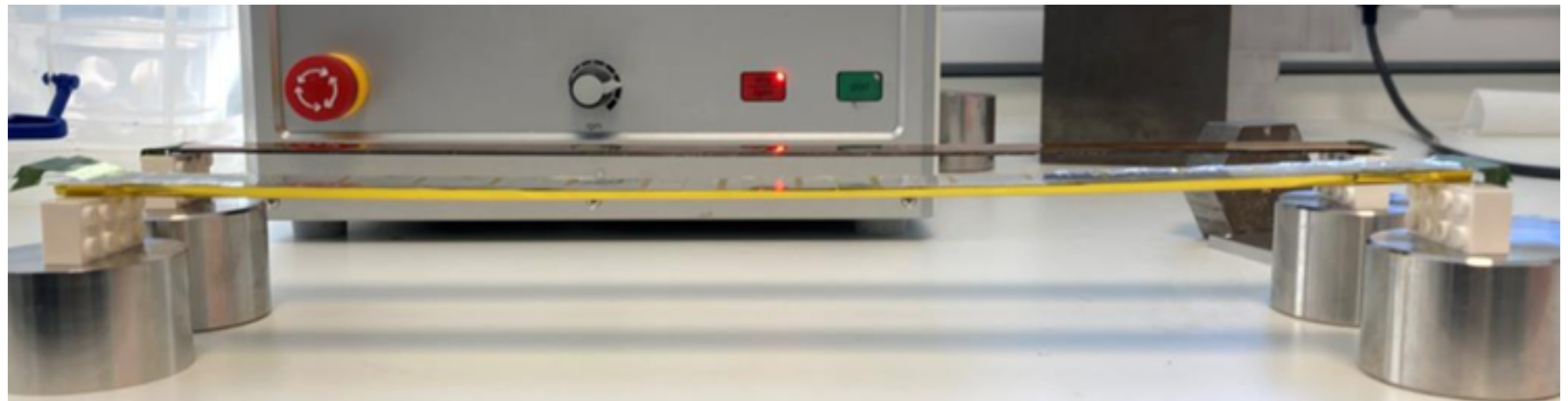


Fabrication of carbon-fibre support:

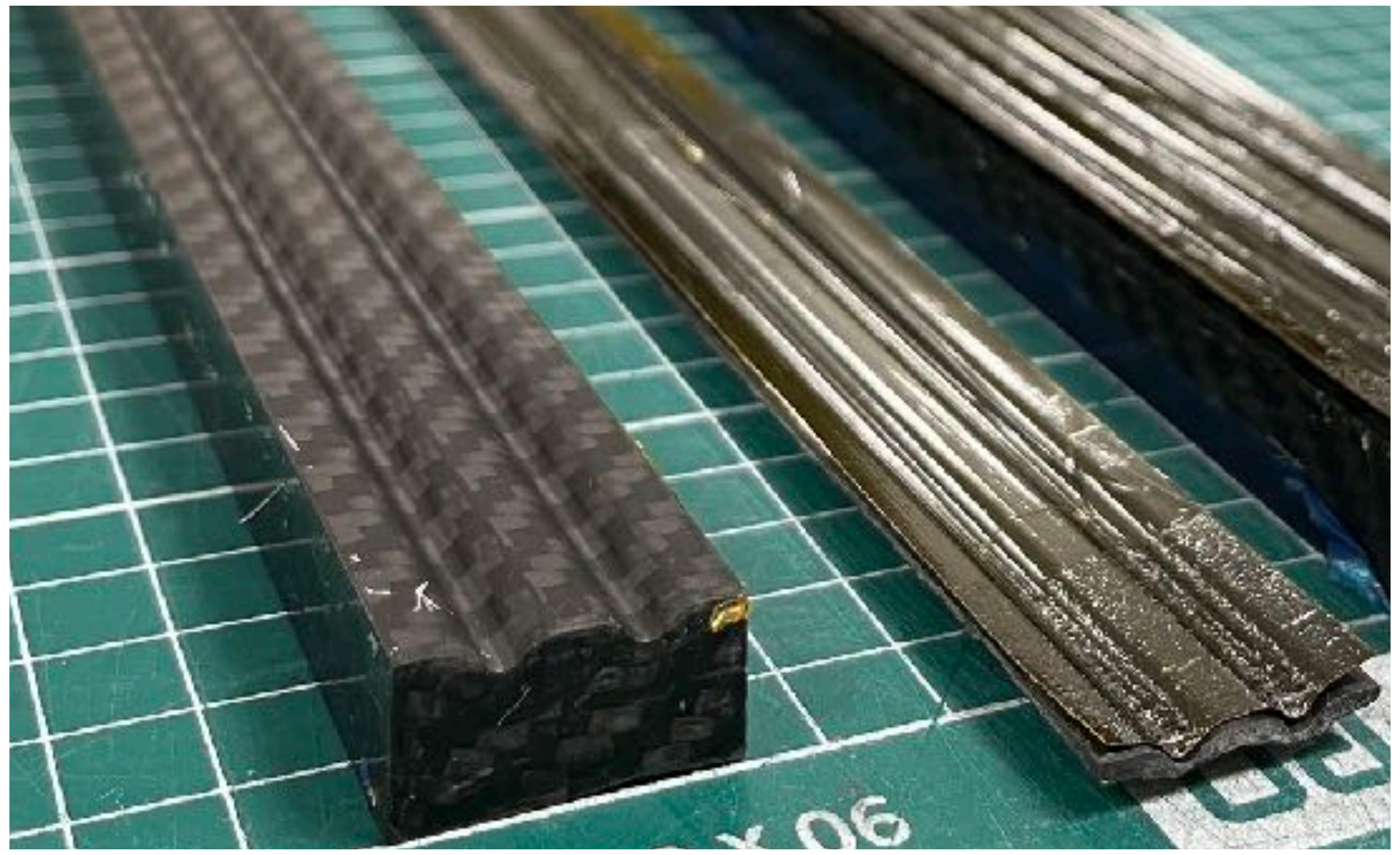
Very difficult material to work with; 'chaotic' fibre pattern:

- Lot of development on the fabrication and laminating tooling and techniques (Oxford Physics Mechanical Engineering Workshop + Brick Kiln Composites)
- **Bowing** one of main issues: resolved using carbon-fibre mould tooling
- Polyamide film co-cure: difficult to remove from vacuum bags, often resulted in tearing the film.

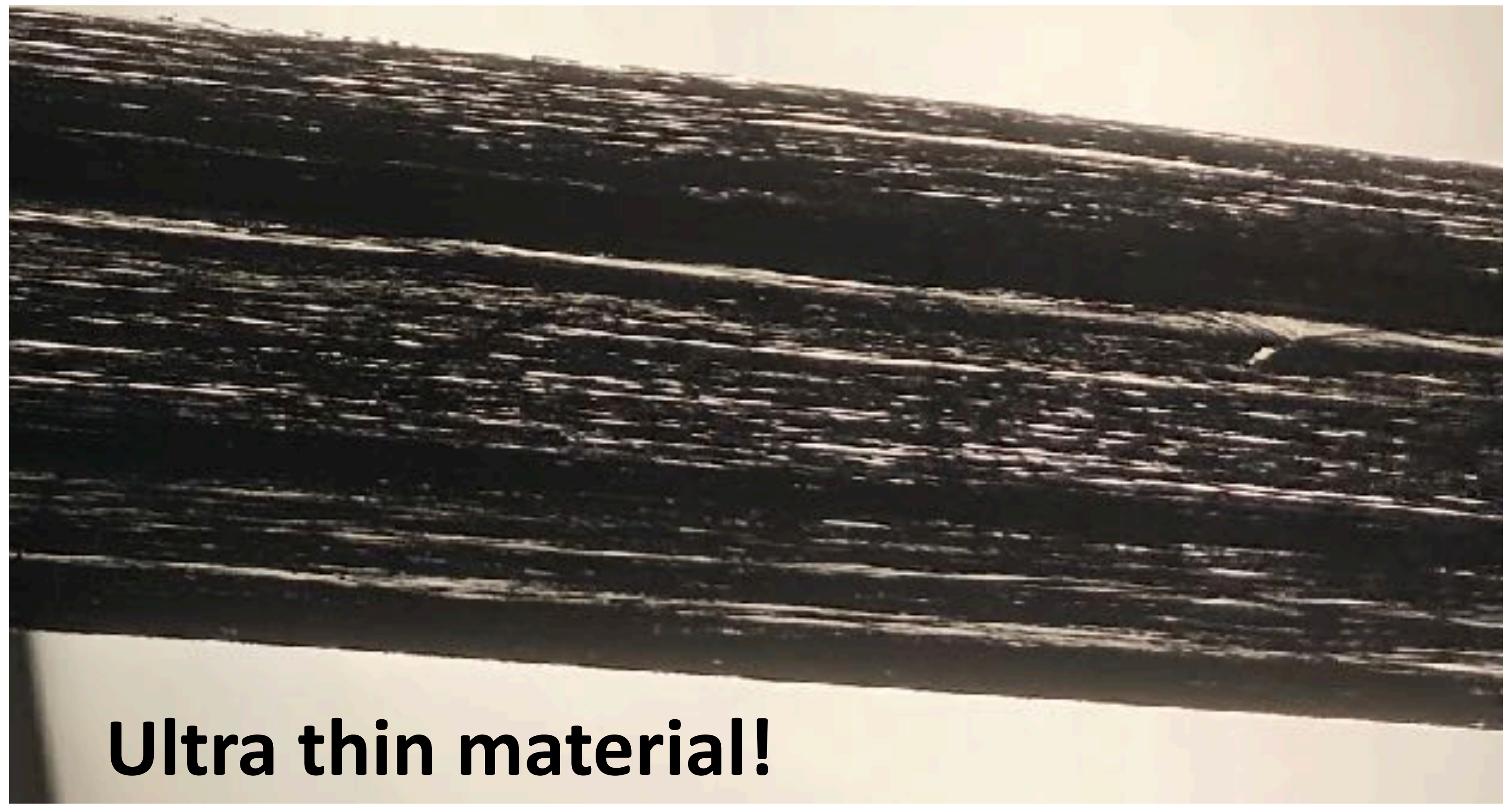




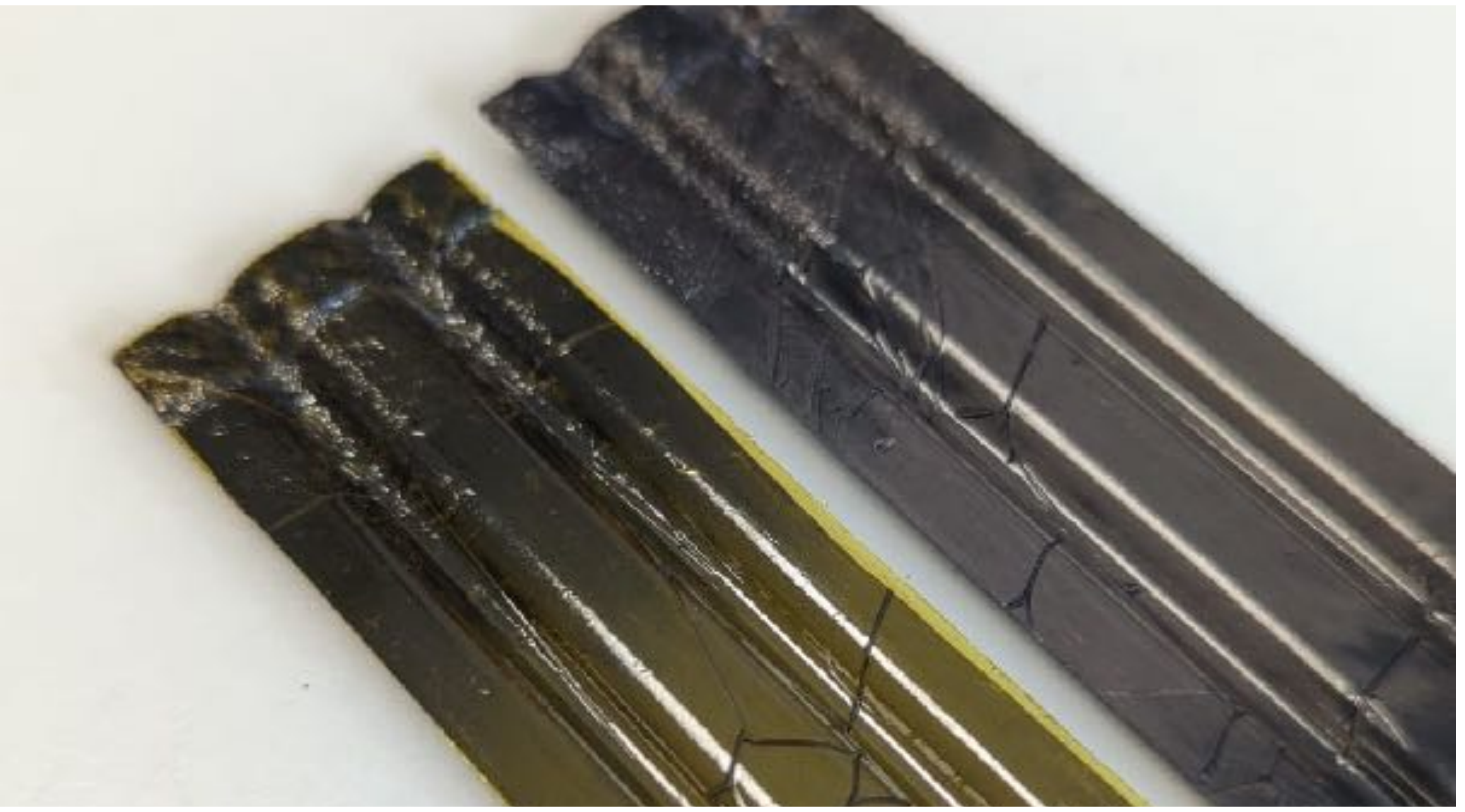
Stiffener comparison: polyimide v carbon-fibre supports



Carbon mould tool



Ultra thin material!



Stiffener placement & alignment:

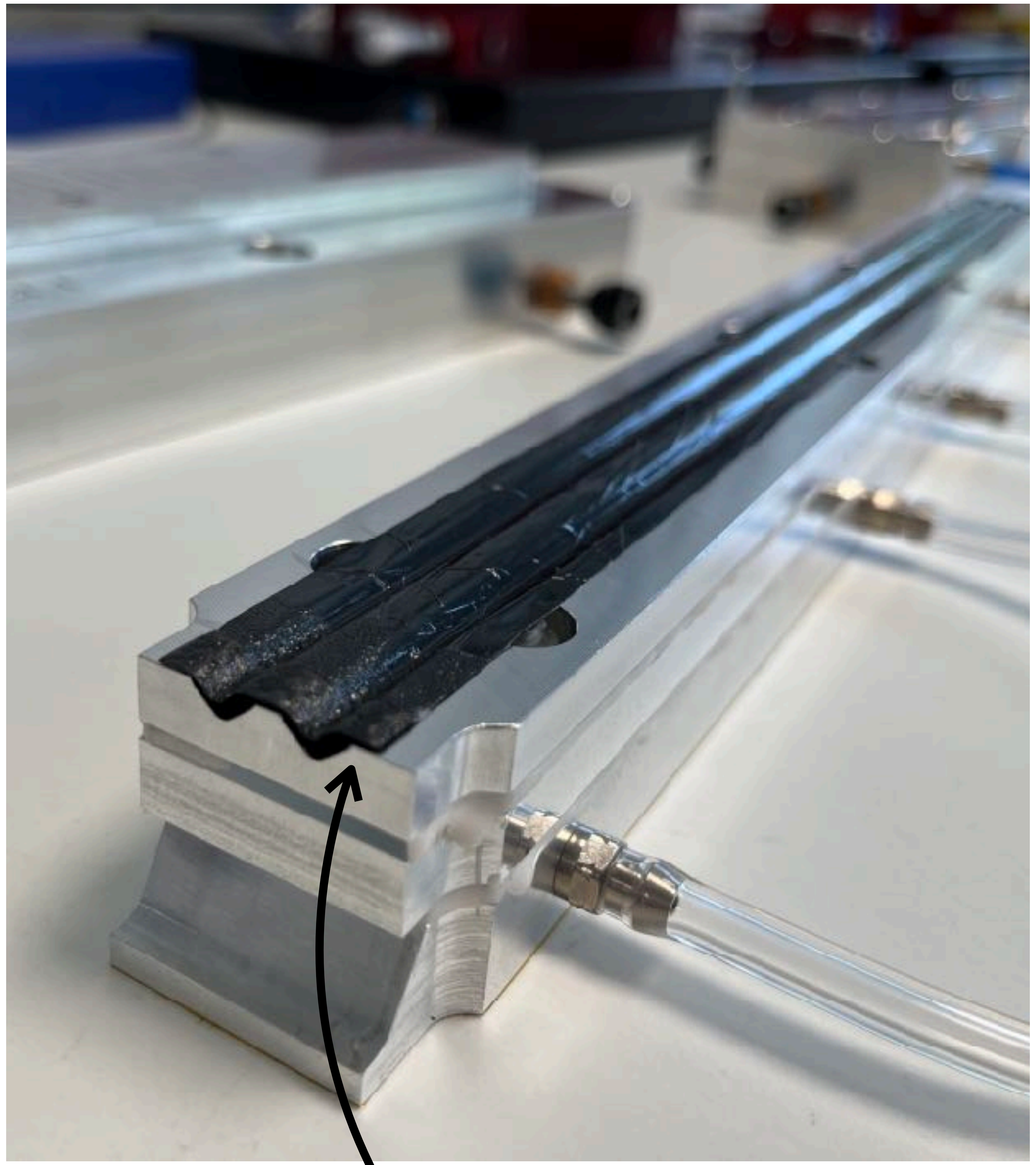
A. McDougall

Observed issues with kapton stiffener attachment:

- Due to flexibility of material, had to put pressure along the whole stiffener to ensure good contact for glue curing
- Tooling was bowed so caused silicon to break

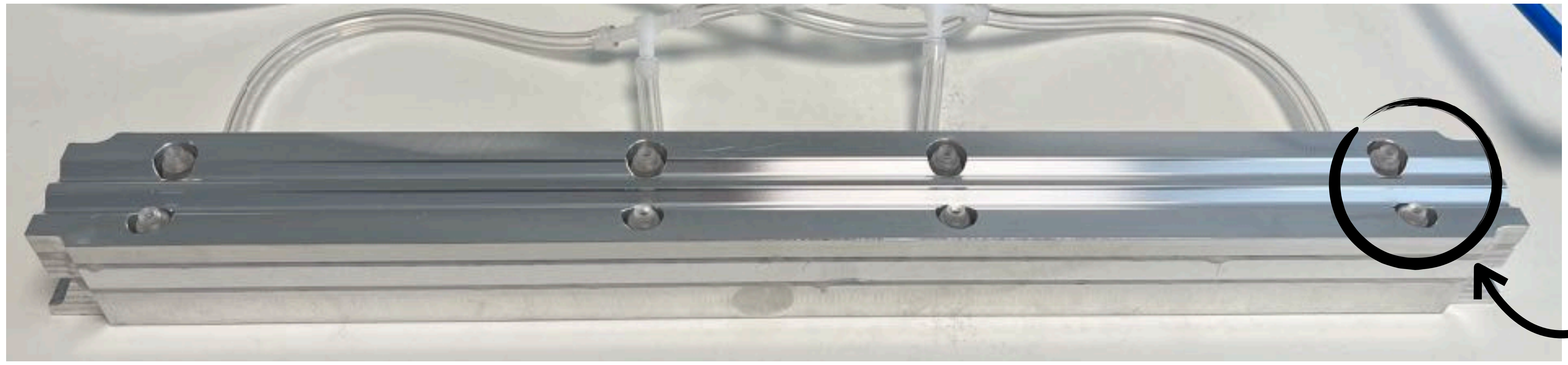
Carbon-fibre stiffener:

- Much stiffer; don’t need as many points of contact to be held together sufficiently well



Side-profile of stiffener

Tool to pick-up the carbon-fibre stiffener:



8 suction cups

Temperature uniformity comparison:

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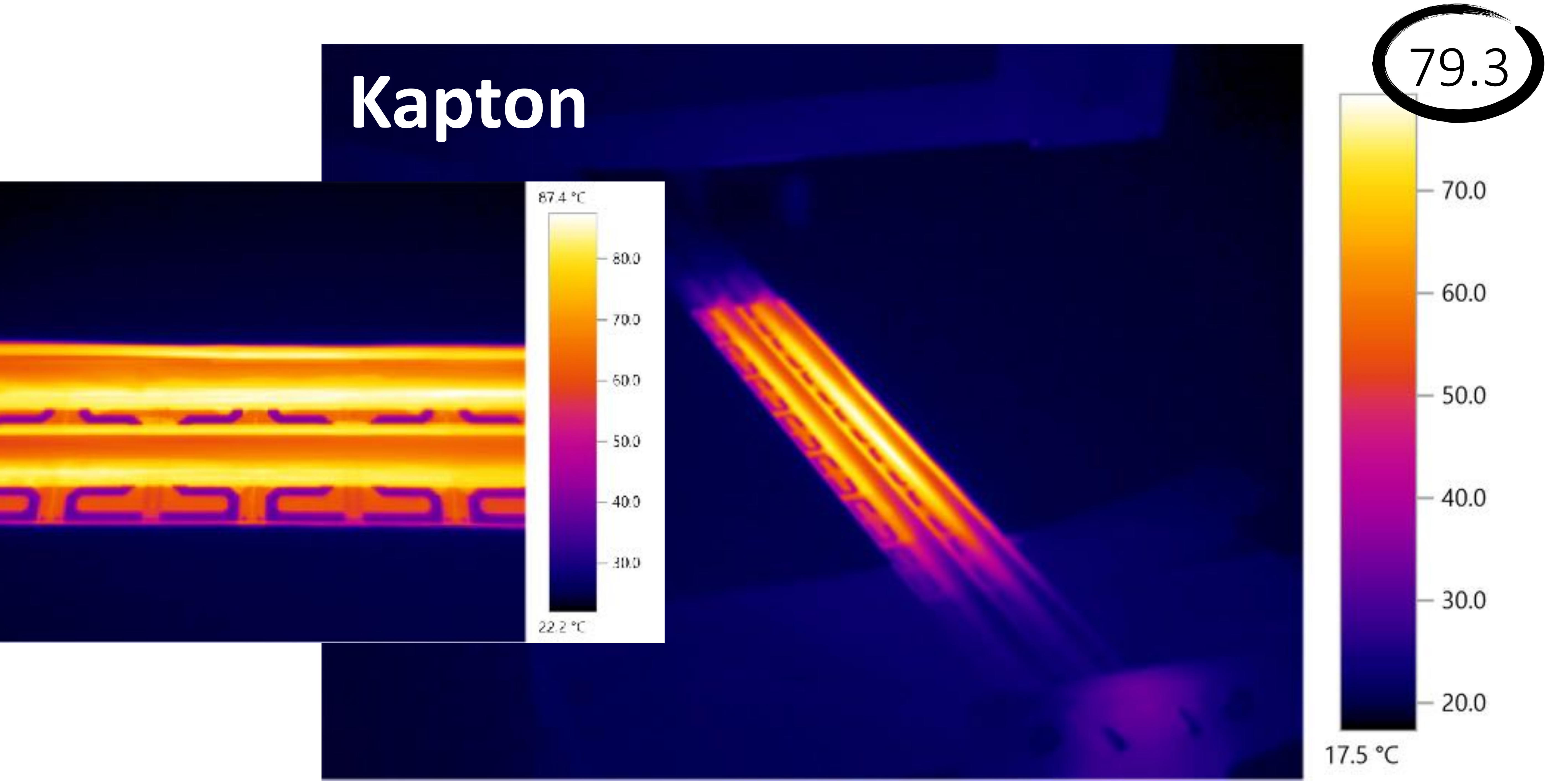

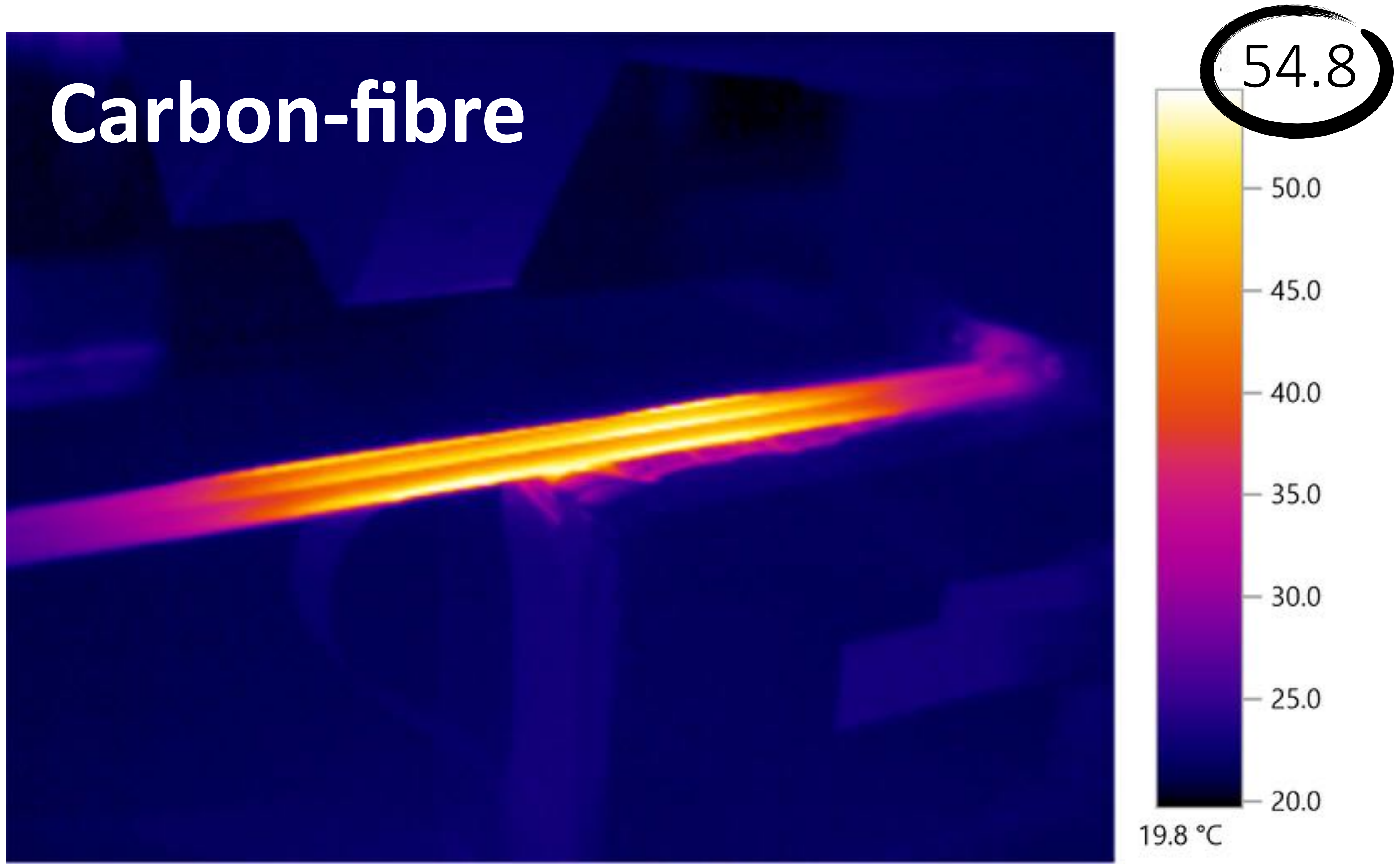

Measure **heat dissipation along ladder** when sensors are powered:

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

Electrical performance with carbon-fibre supports:

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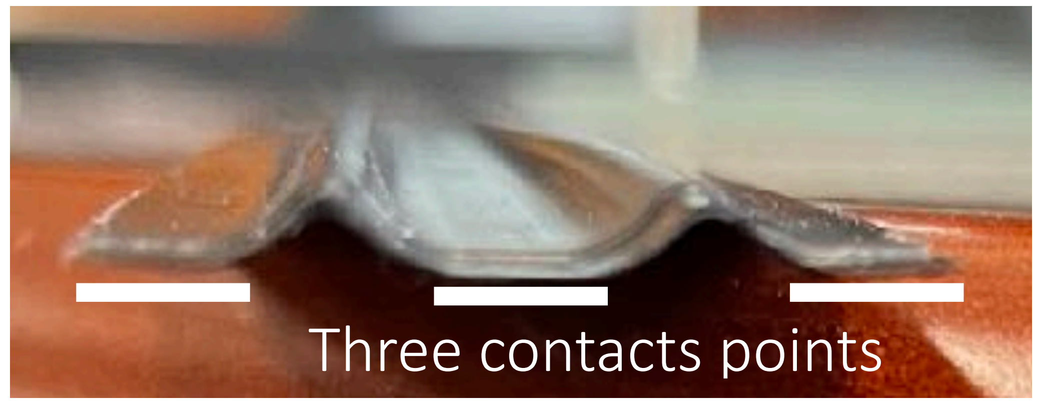
When taking data with nominal ladder design, observed very high levels of noisy pixels:

- Likely due to carbon-fibre being glued to back (biased) side of pixel sensor



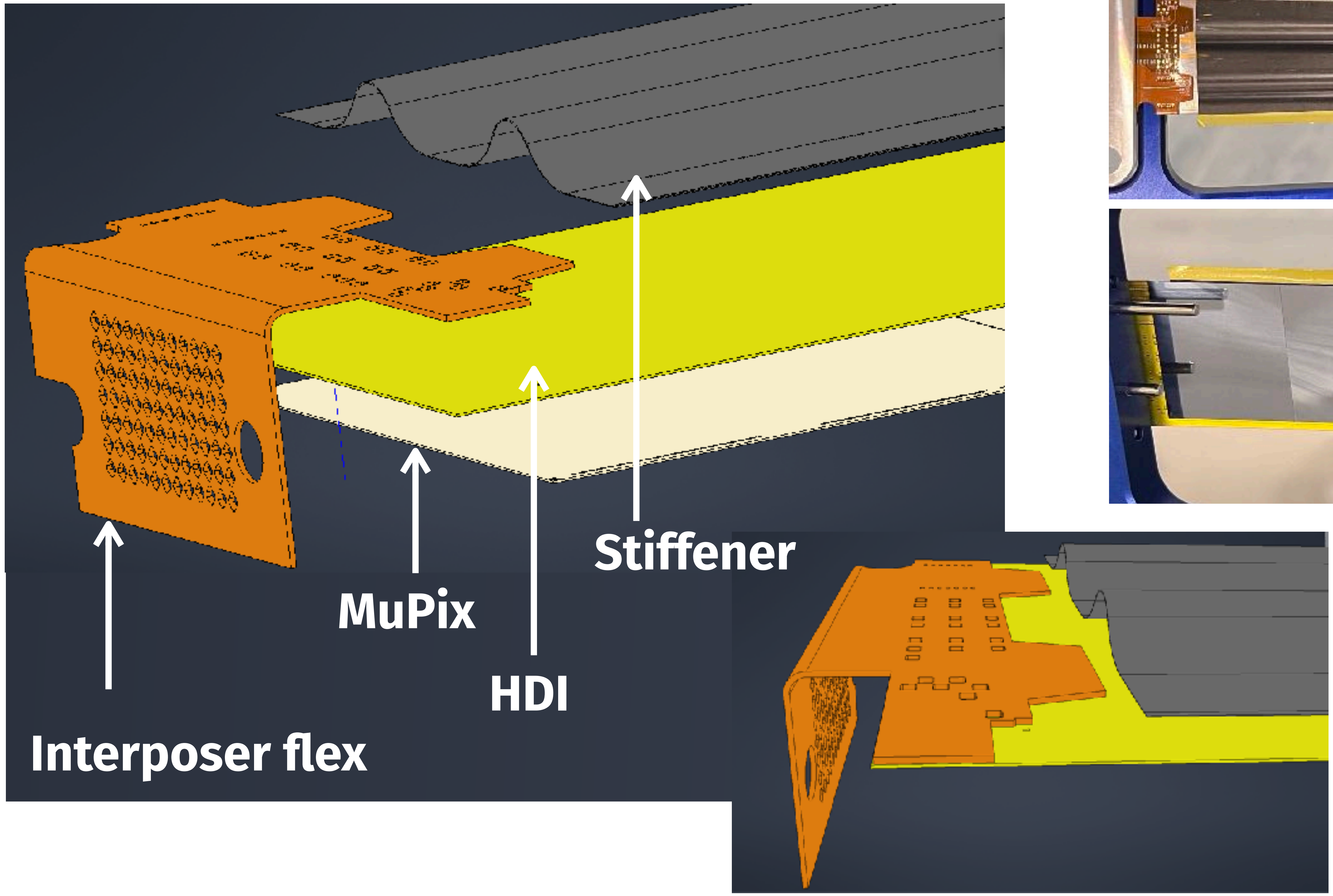
ThHigh @ 116, HV -30V

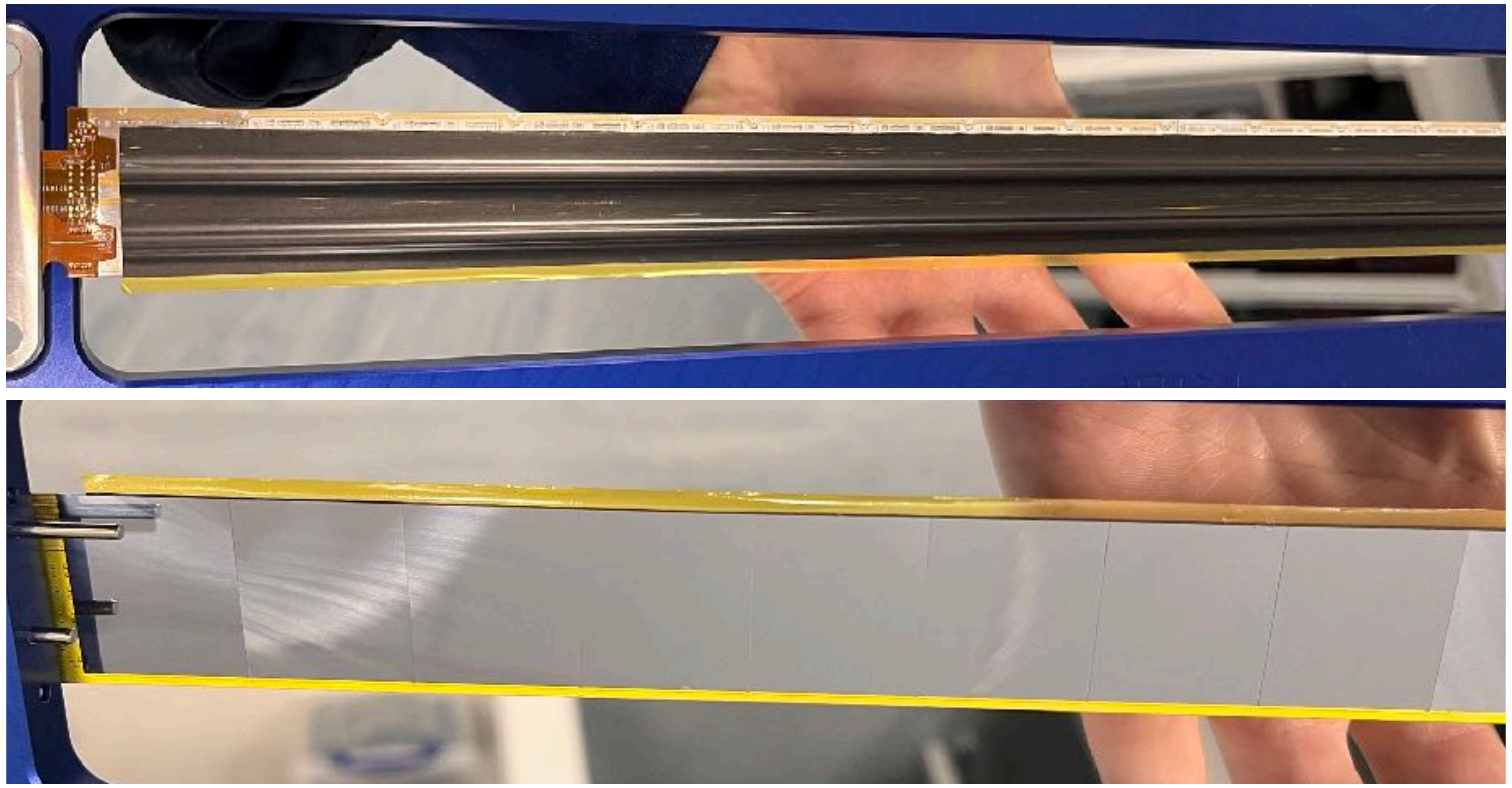
ThHigh @ 130, HV -30V

Carbon-fibre stiffener alternate placement:

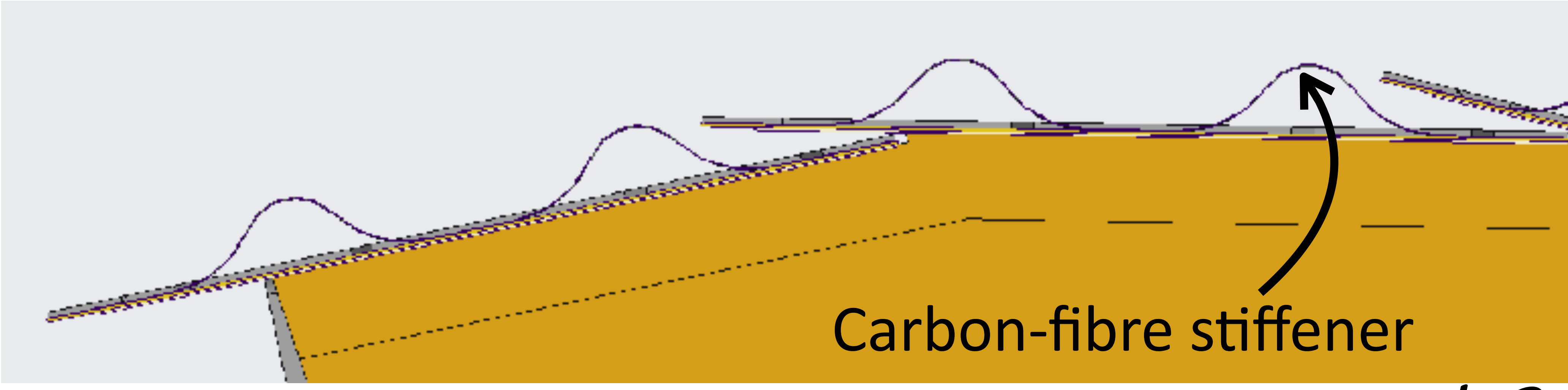
Place stiffener on other side of ladder:

- 25µm carbon-fibre + 8µm kapton
- Kapton glued to HDI surface





Side on view of the module:



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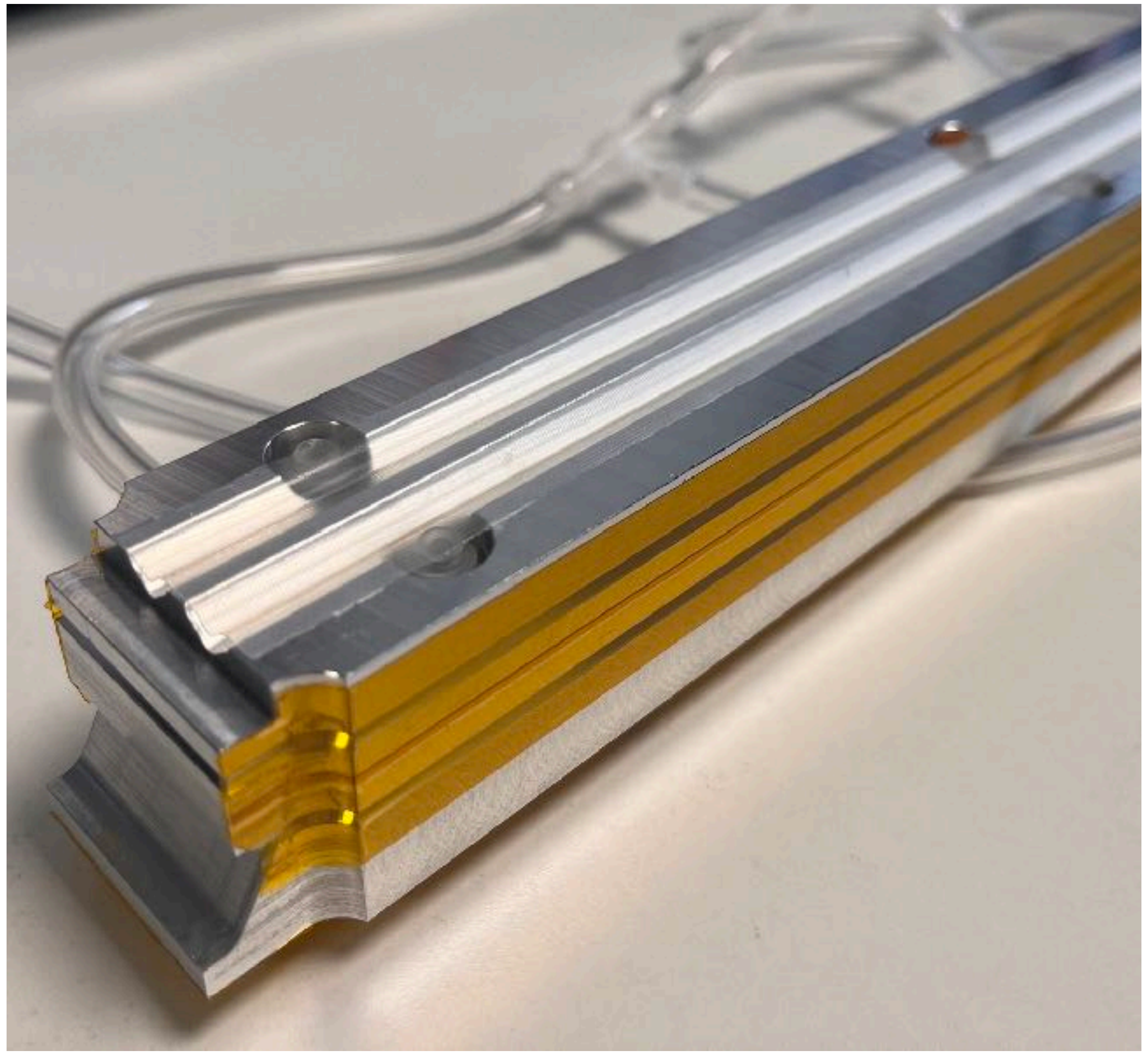
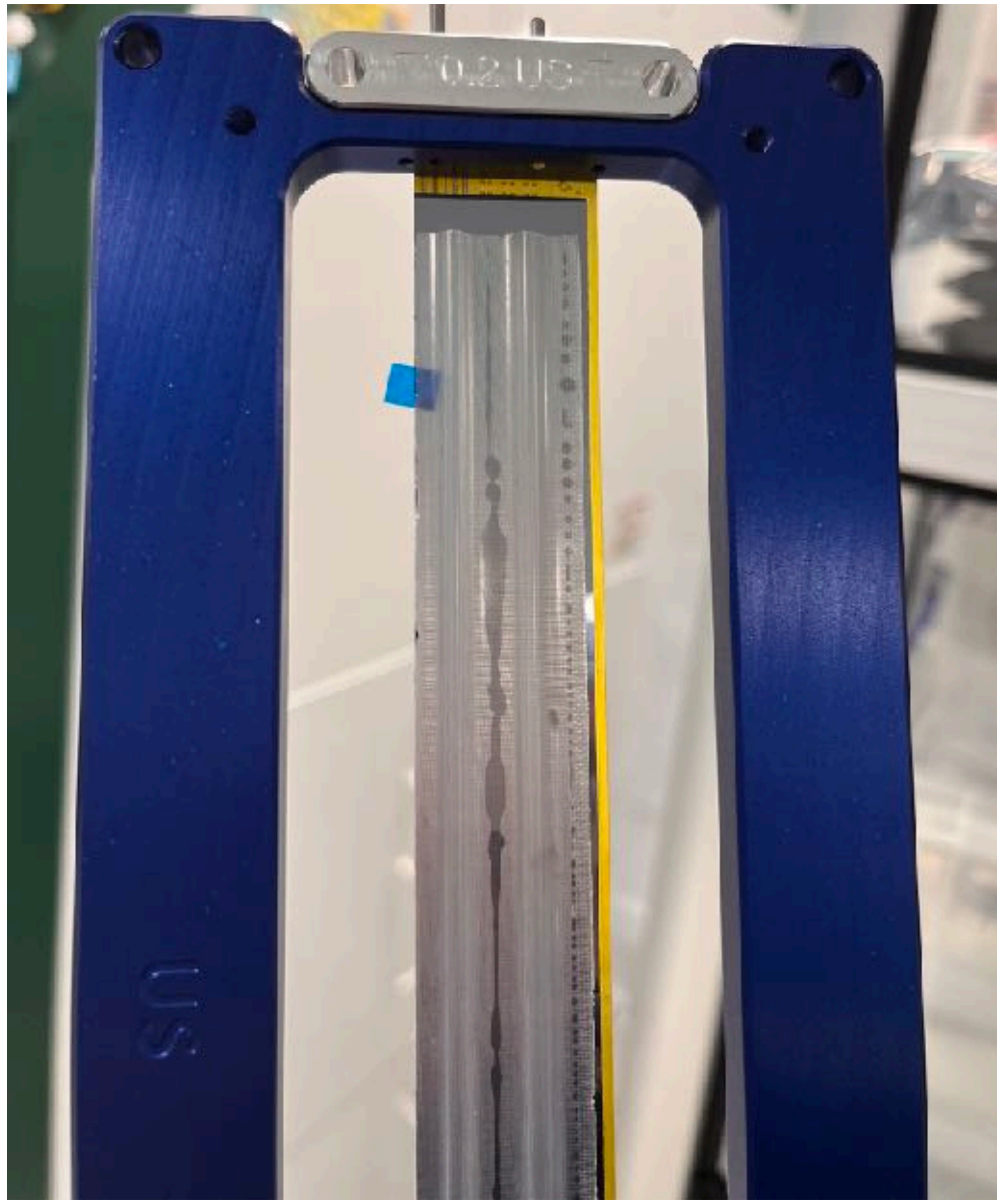
Alternatively to carbon-fibre, **stiffener made from glass fibres** (insulating material):

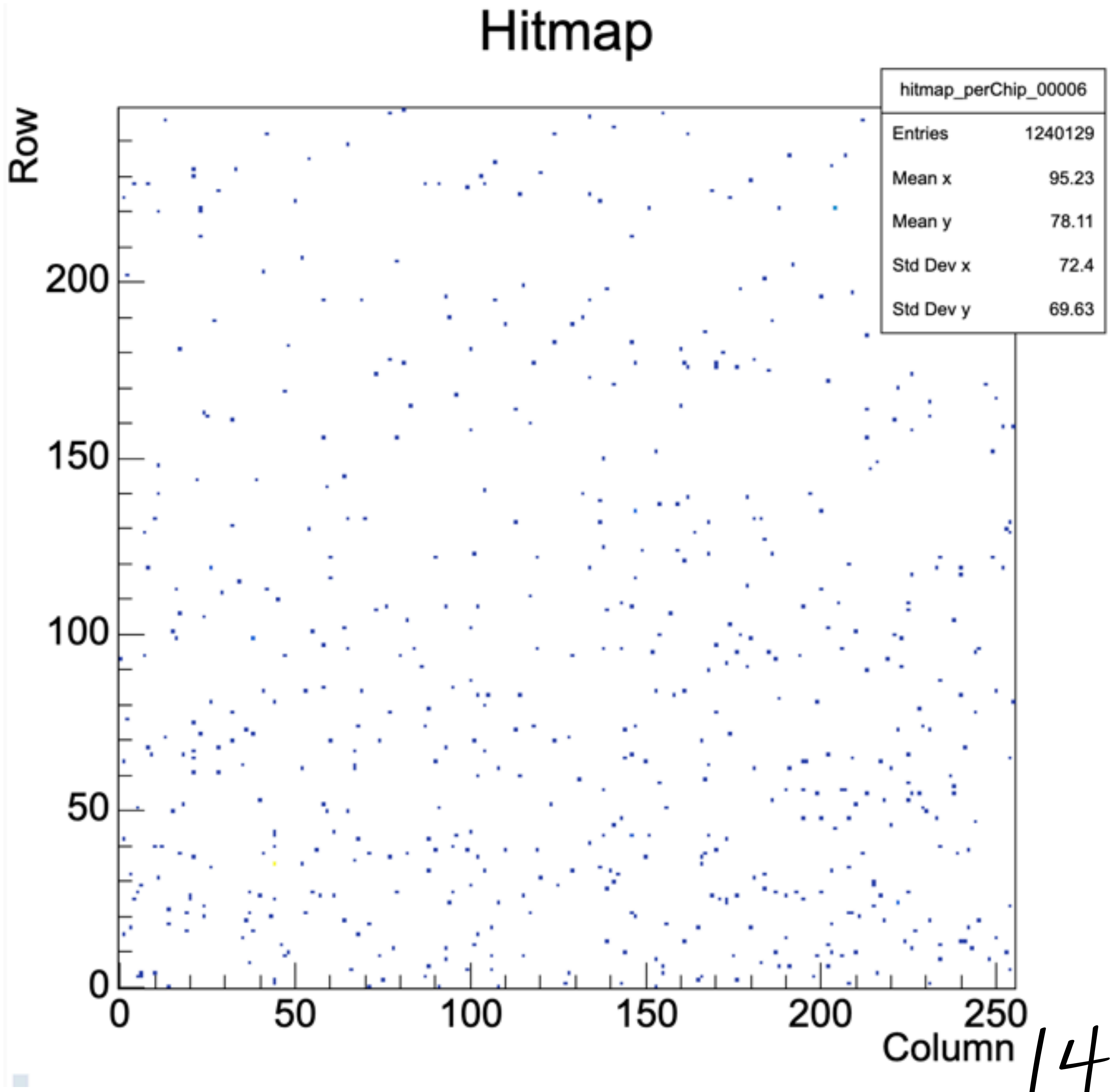
- First try with 60GSM (≈ 60µm) material, to see if same fabrication procedure viable (cross-weave instead of UD)

Production observations:

- Slightly bowed
- Material is quite flaky
- Difficulty picking up with "pick-up" tool (geometry)
- No issues with noisy pixels observed







Kevlar stiffeners

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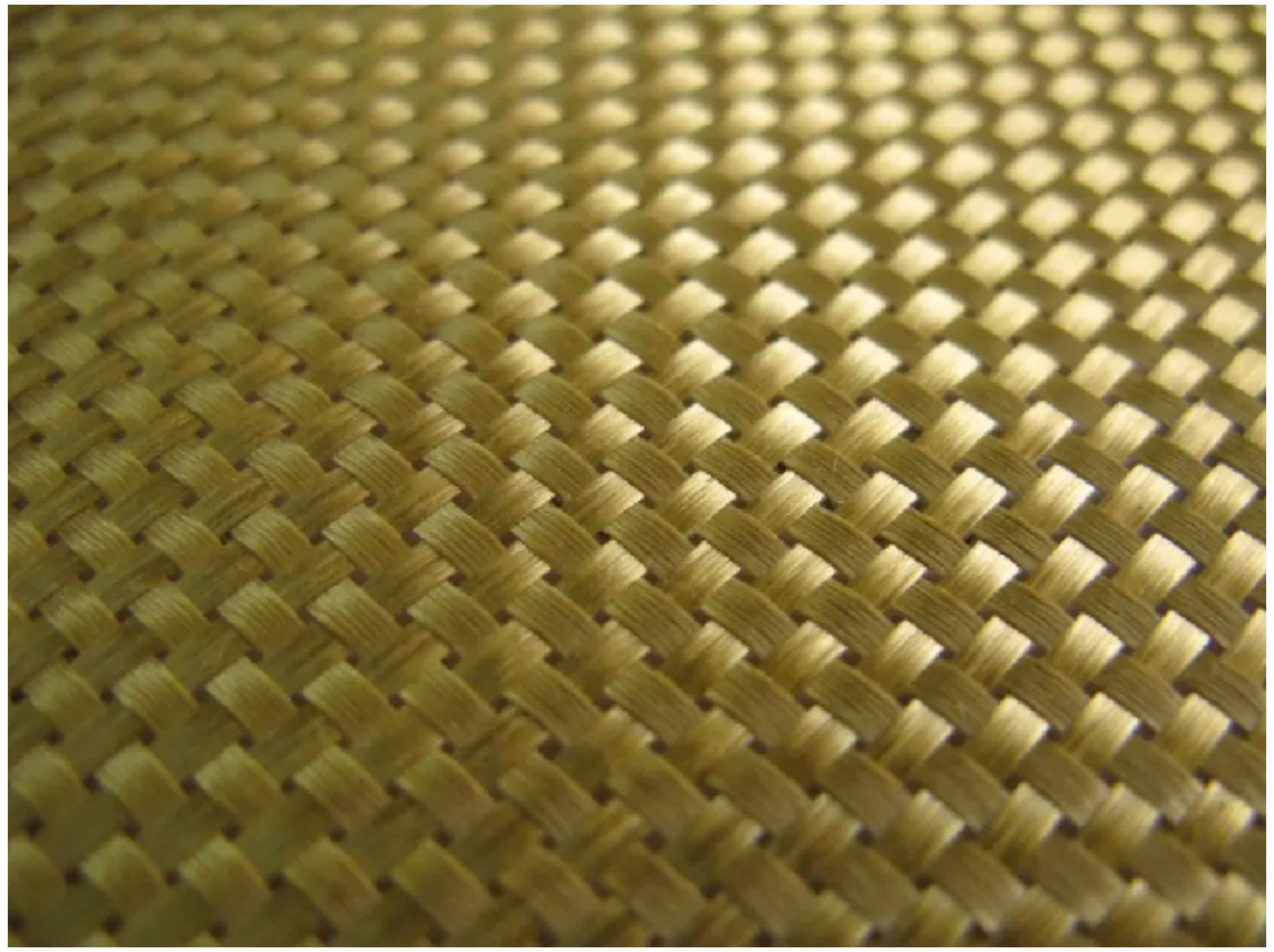
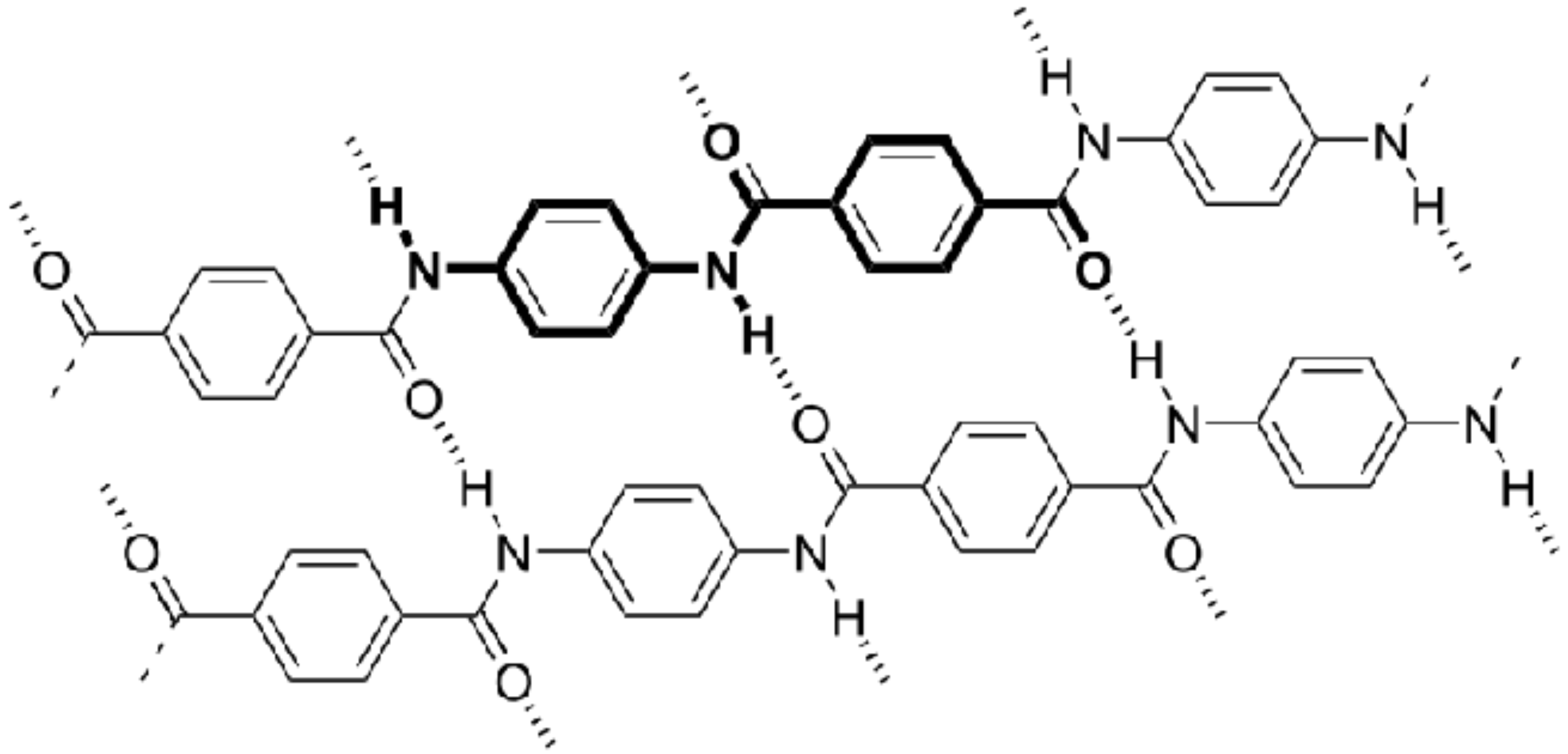




Properties:

- Material: Aramid (aromatic polyamide fibres), presence of aromatic rings of six carbon atoms
- Insulating material
- Available at **10µm** (thinnest possible option we've seen)

Strategy:

- 10 m^2 of material has been ordered (plenty for validation tests)
- Need to verify flatness requirement, and if any bowing occurs during manufacturing
- Continue with kapton co-cure
- Results to come!

Fabrication procedure for outer pixel layers:

A. McDougall

Entire ladder production for the outer pixel tracker in Oxford cleanroom

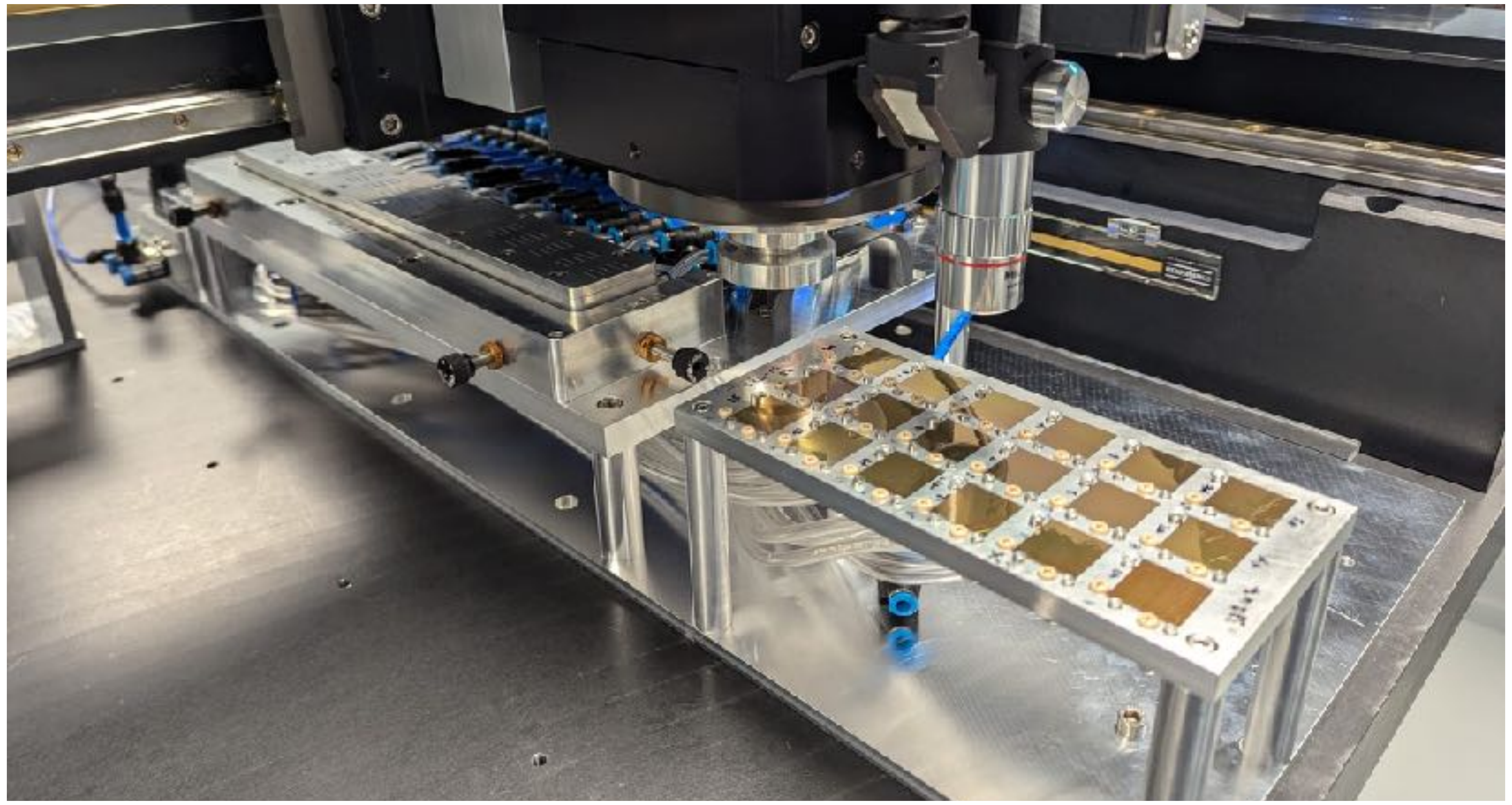
Ladder —> module —> layer:

- 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)

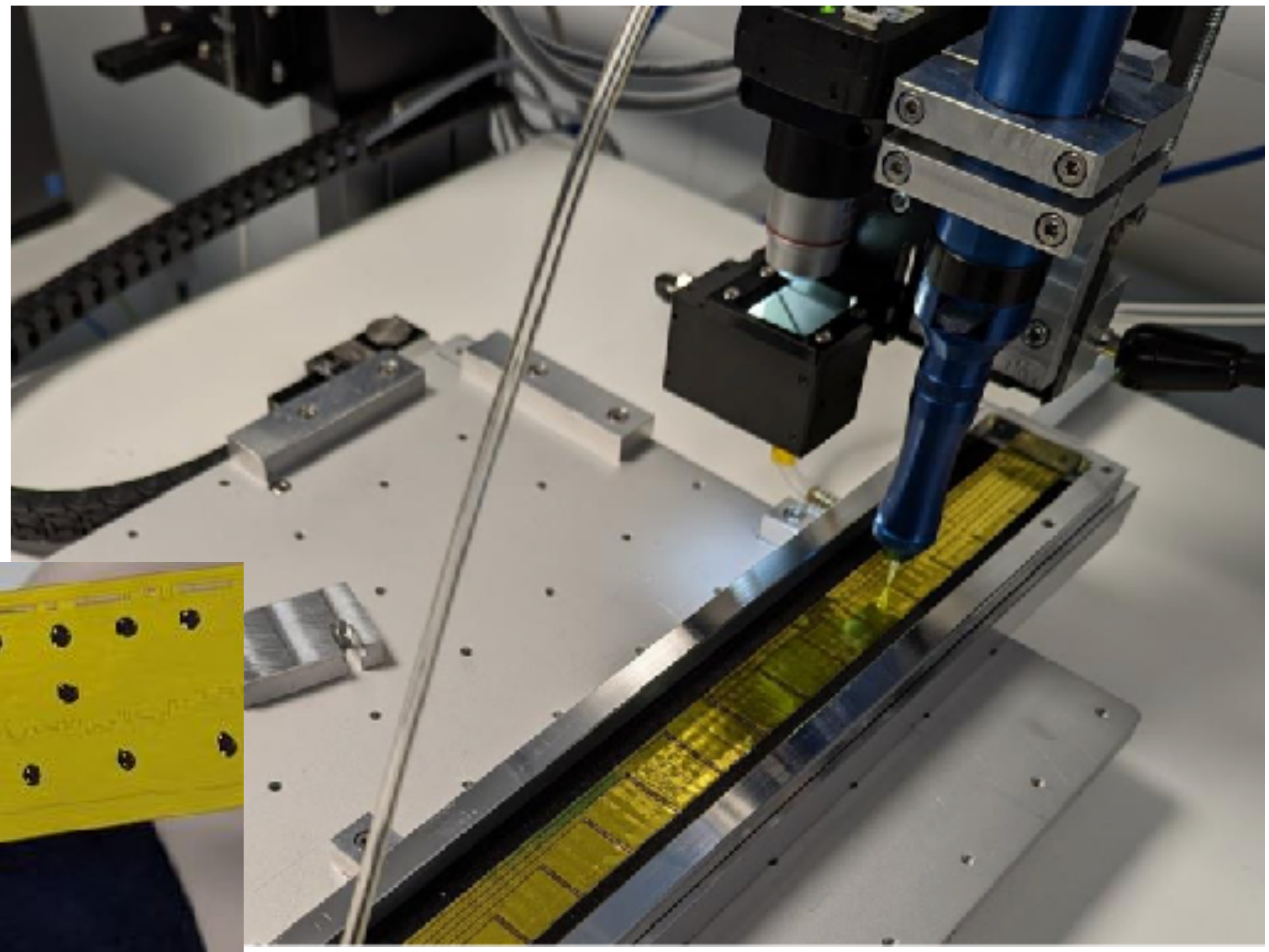
Automate ladder building procedure as much as possible:

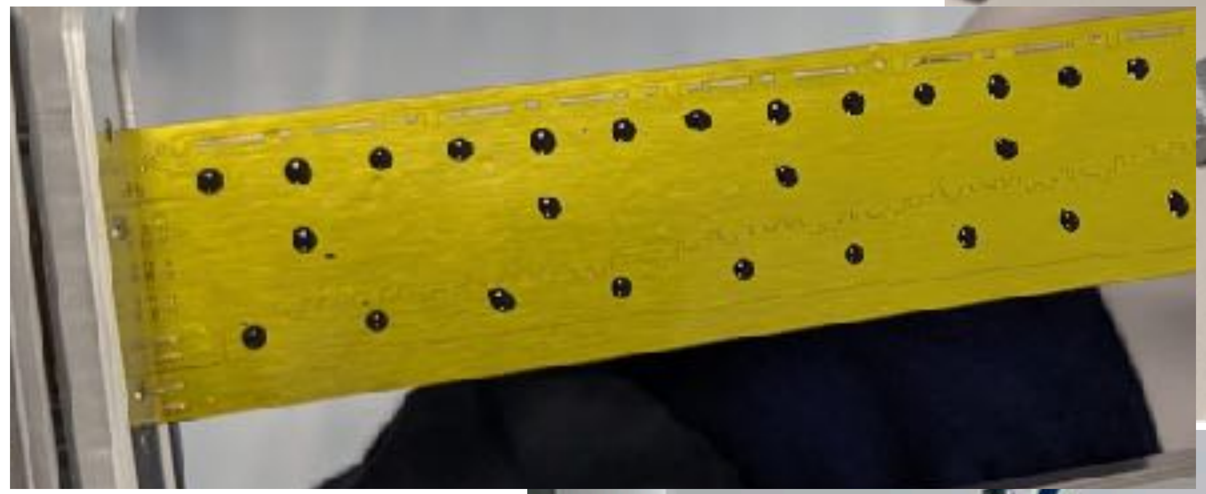
- Robotic **gantry used for placement of chips**



Glue-dispensing robot:

- Allows for precise placement and size of glue deposits





Vacuum assembly tooling for correct placement of components onto ladders:

Conclusions and outlook:

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

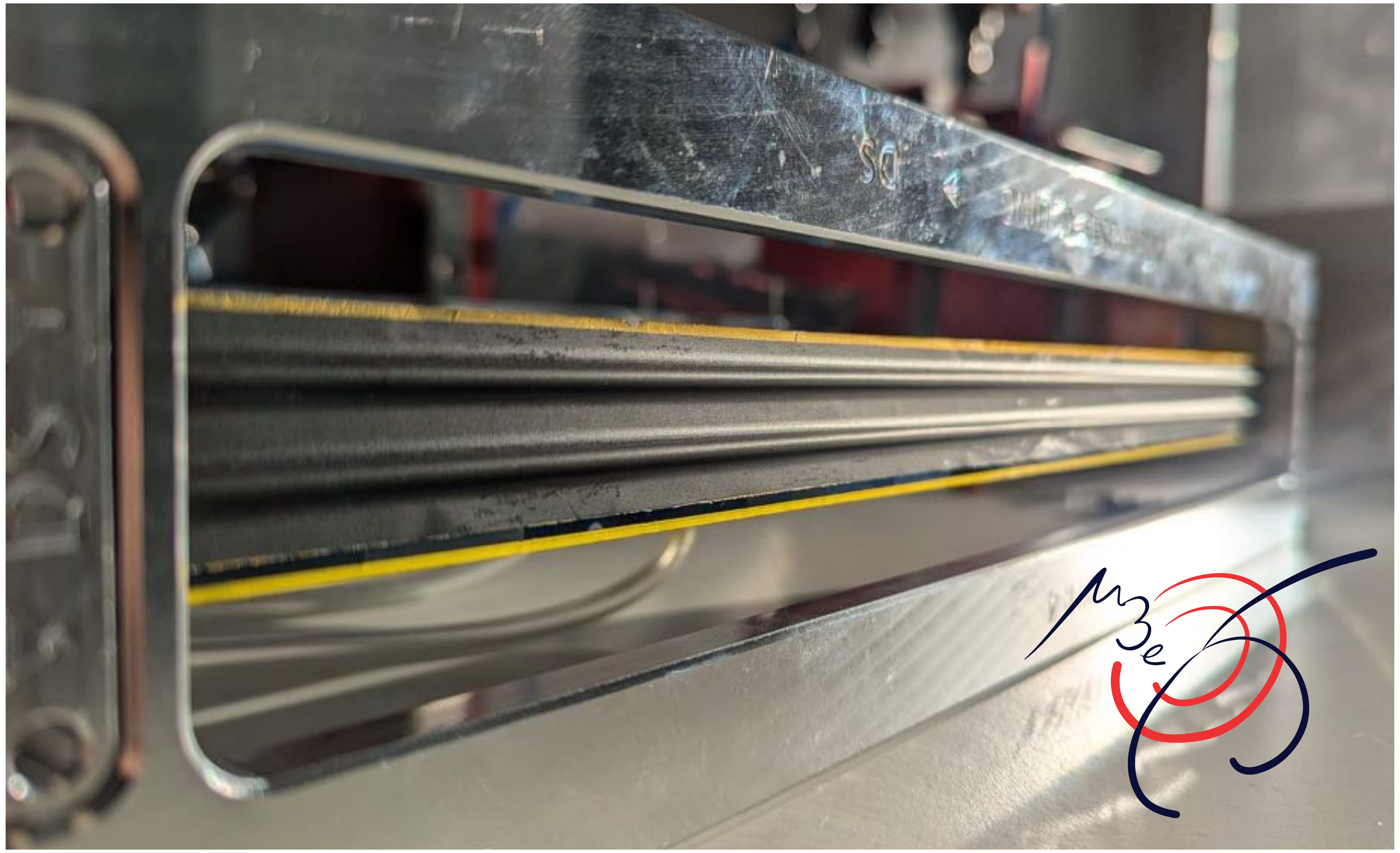
- Each ladder ~ 2 grams! Despite being over 30 cm long.

Investigations into choice of stiffener material:

- Polyimide film, UD carbon-fibre, glass fibres, UD kevlar all been studied.
- Carbon-fibre demonstrates favourable properties: thermally, stiffness, handleability; some noise issues observed
- Kevlar thinnest possibility @ 10µm!

Production of outer pixel ladders on-going.

Expect physics data-taking to commence in 2026!



Stay tuned … !

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