The Mu3e experiment: From pixels to particles

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On behalf of the Mu3e collaboration

Seminar talk: The University of Freiburg

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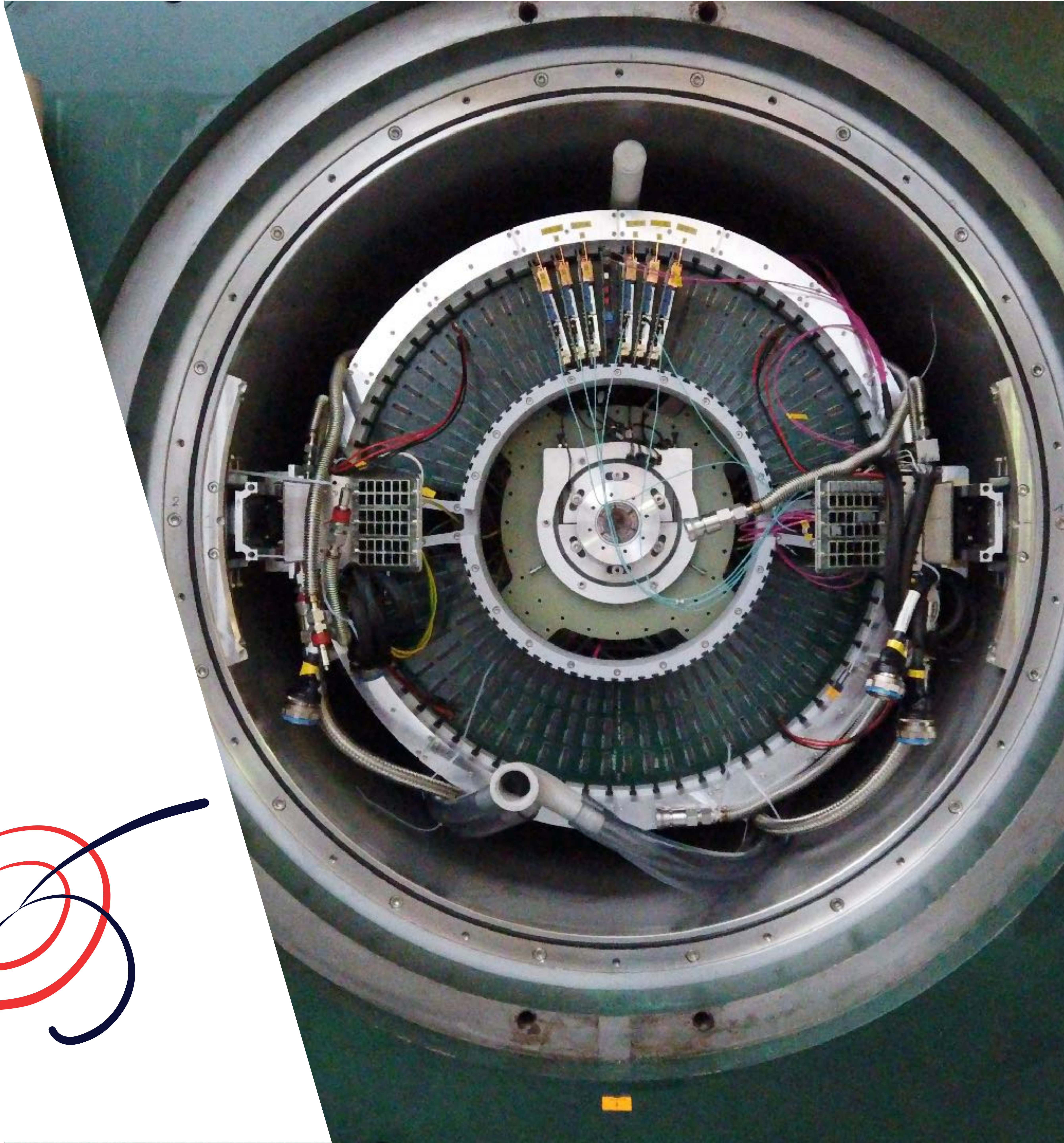
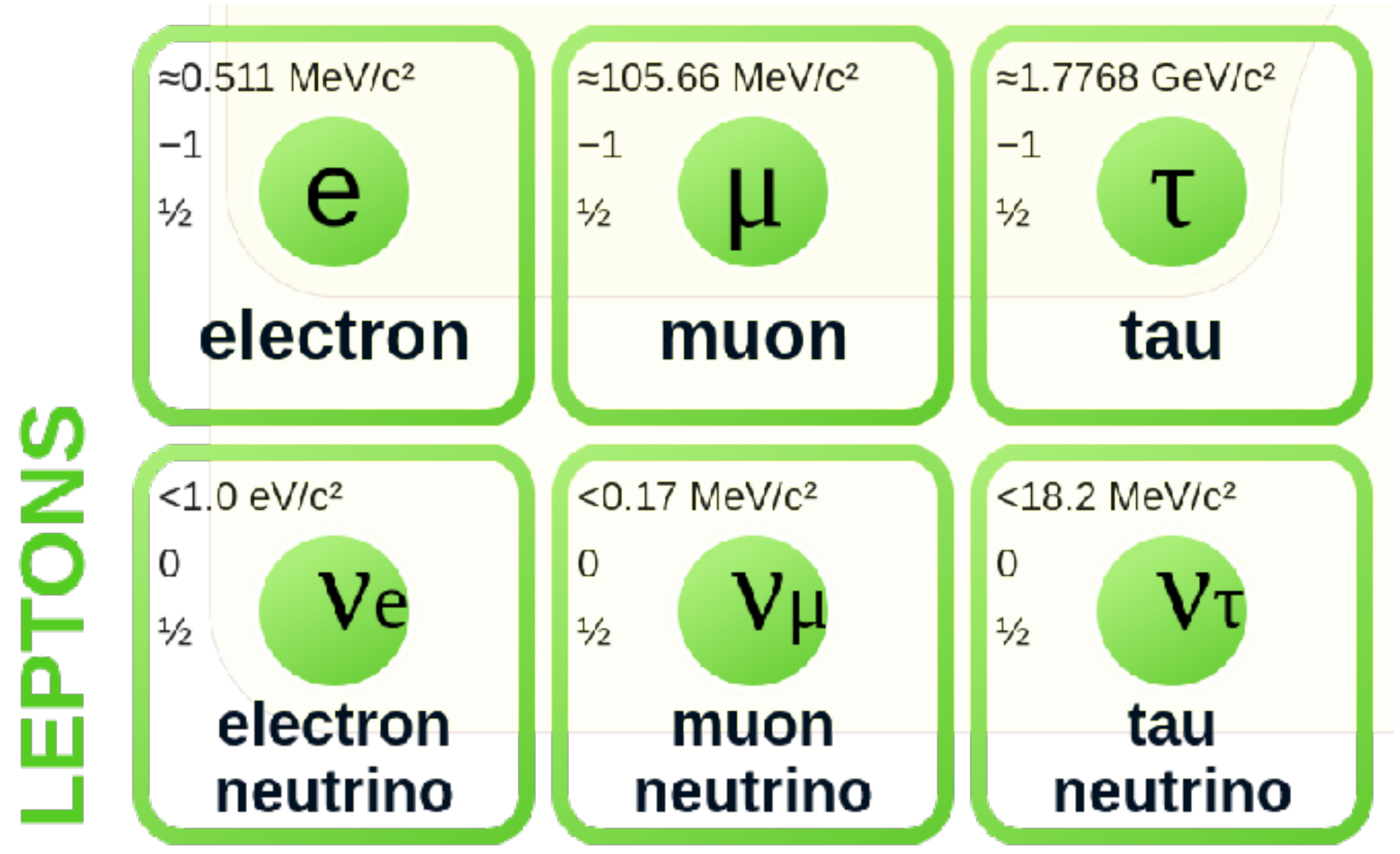
UNIVERSITY OF OXFORD



Lepton flavour in the Standard Model:



Lepton flavour: **accidental symmetry** of SM

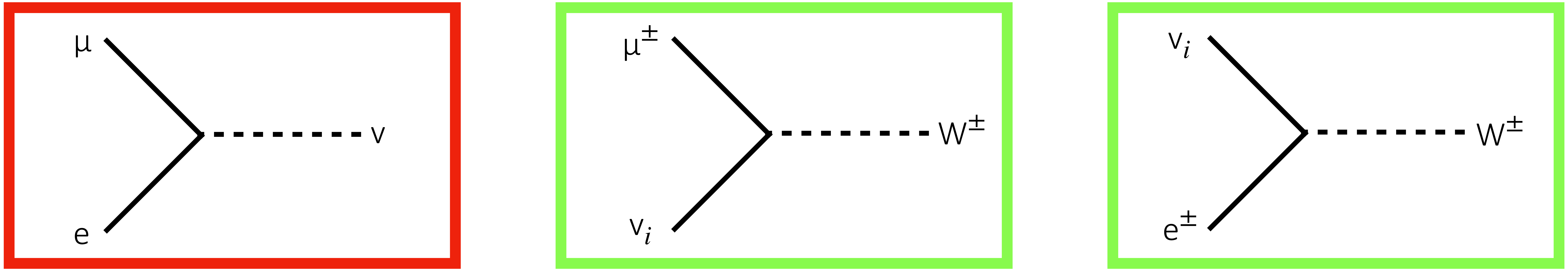
Lepton flavour violation (LFV): any process where lepton changes its flavour (e.g. $\mu \to e$ or $\tau \to \mu$)

- Neutrino oscillations ⇒ LFV occurs in nature

Muon decay almost exclusively via one channel: $B(\mu \to e\nu\bar{\nu}) \sim 100\%$

LFV with charged leptons highly suppressed in SM+neutrino-mixing:

$$\mathscr{B}_{\mu \to eee} \propto \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 \to \mathscr{B}_{\mu \to eee} < 10^{-54}$$



Forbidden in SM at tree level

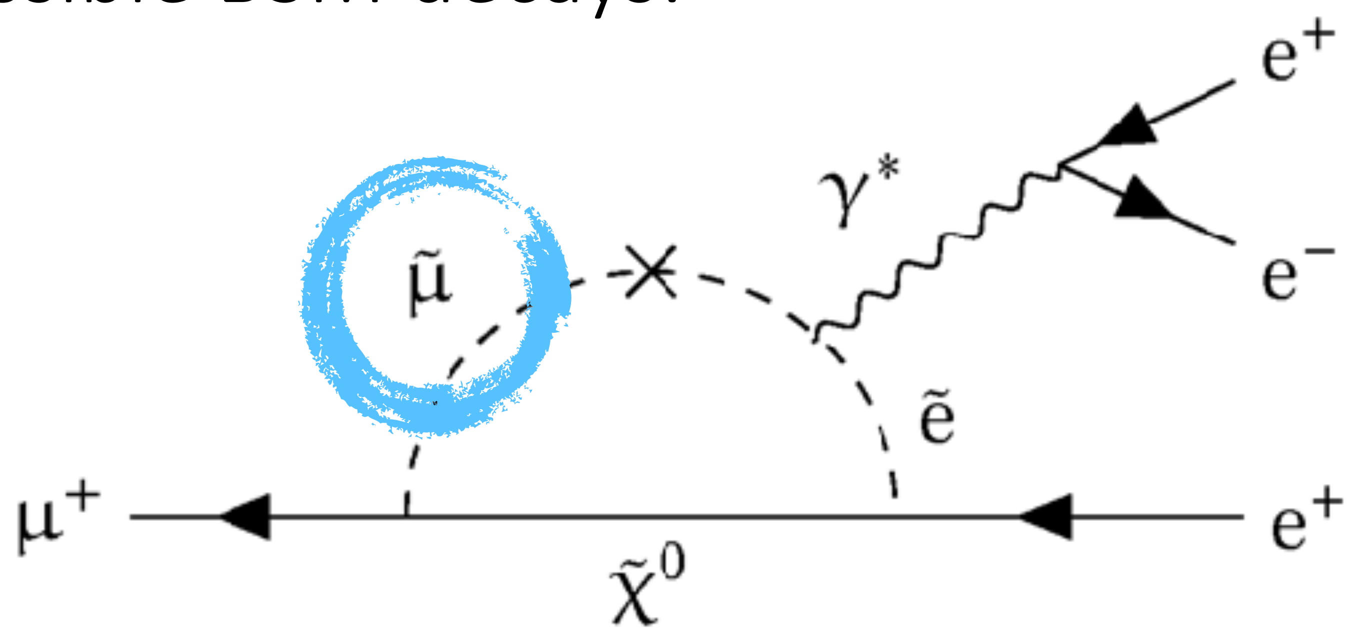
Allowed

Allowed

Why search for cLFV in the muon sector?

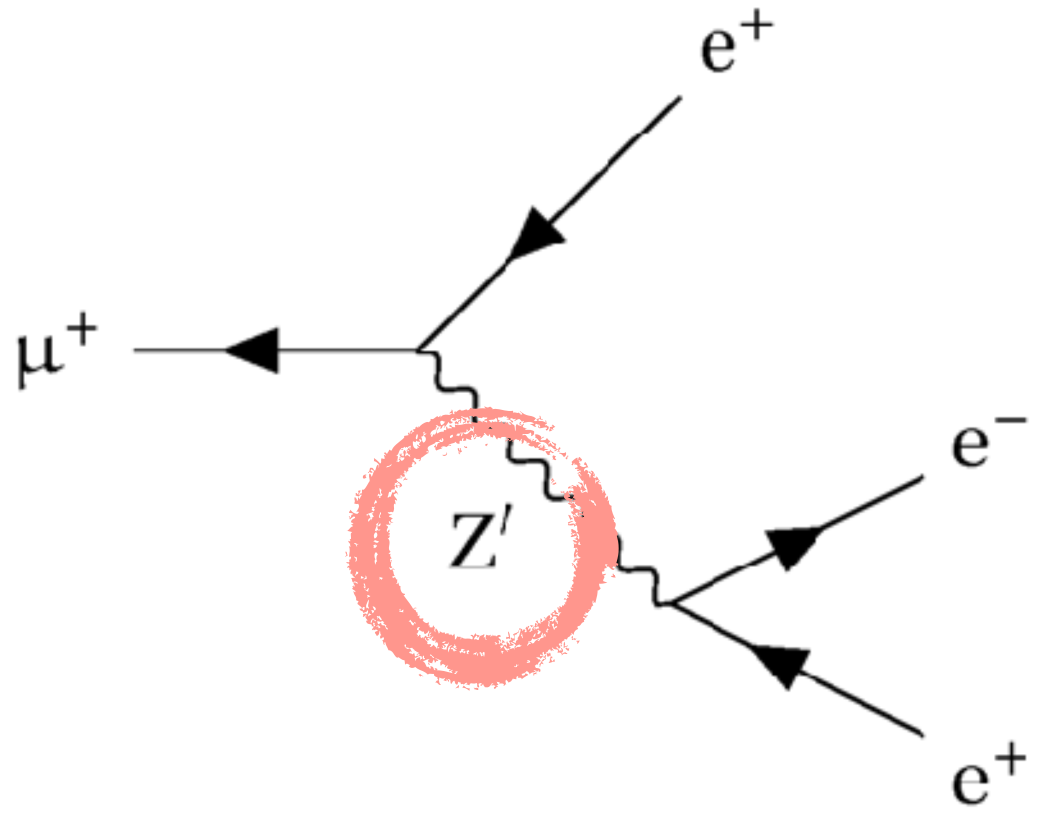
- Muons **ideal probes**: Extremely clean signatures (leptonic decay modes), SM background free
- **Available**: High intensity muon beam facilities: PSI, J-PARC, Fermilab
- **Low predicted BR**: any observation is **unambiguous sign** of physics beyond SM
- **Complementary** to other searches (e.g. LHC, neutrino experiments, tau decays or rare B decays)
- Many BSM theories generate LFV at **experimental accessible levels**

Example of possible BSM decays:



Heavy new particles in loops:

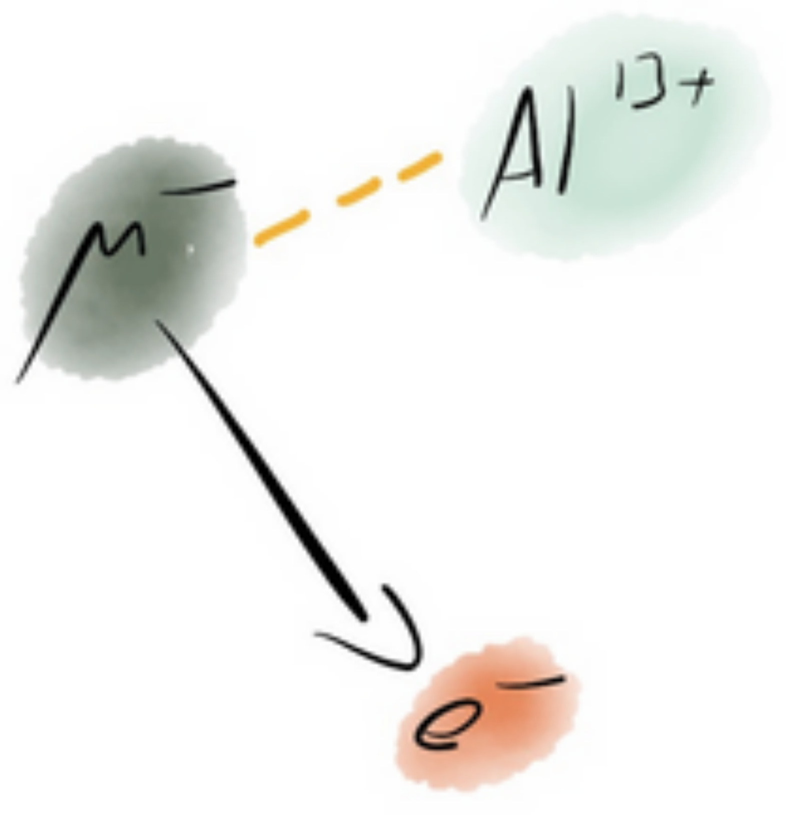
- Supersymmetry
- Little Higgs models
- Seesaw models
- Leptoquarks (GUT models)
- ...



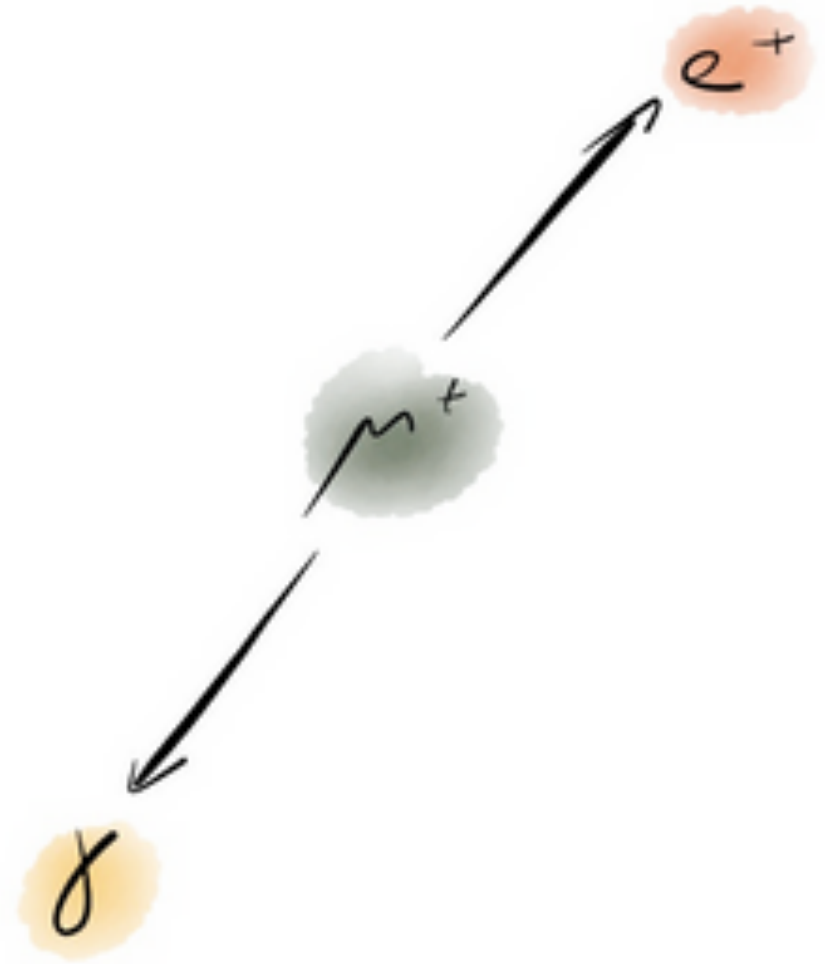
4-fermion interaction:

- New heavy vector bosons (Z’)
- Higgs Triplet Model
- Extra dimensions
- ...

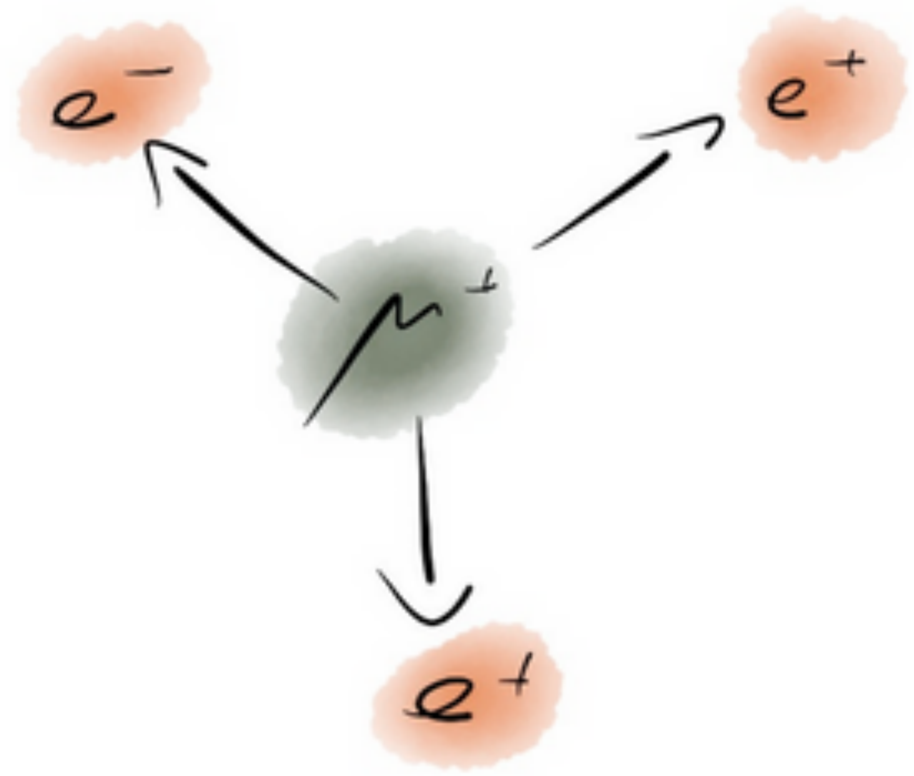
Muon golden channels:



$\mu^- N \to e^- N$



$\mu^+ \to e^+ \gamma$



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

SINDRUM II (PSI 2006)

- BR(μ^- Au $\to$ e^- Au) < $7{\cdot}10^{-13}$ (90% C.L.)

MEG / MEG II (PSI 2025)

- BR($\mu^+ \to e^+\gamma$) < $1.5{\cdot}10^{-13}$ (90% C.L.)

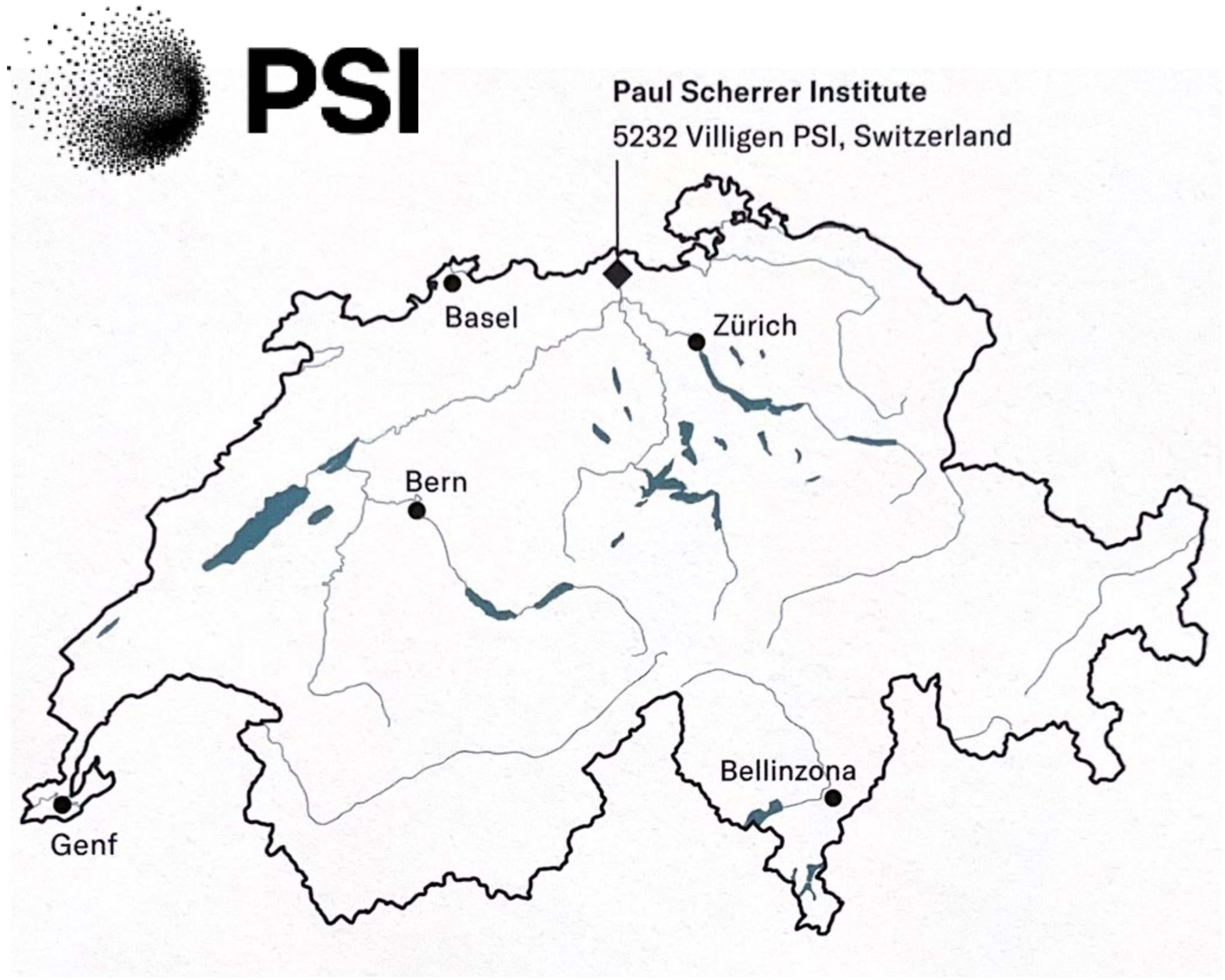
SINDRUM (PSI 1988)

- BR($\mu^+ \to e^+e^-e^+$) < $1.0{\cdot}10^{-12}$ (90% C.L.)

So far no observation!

The Mu3e experiment:

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



Collaboration $\mathcal{O}(50)$ people from 11 institutes (DE, UK, CH)

Mu3e inside experimental hall

Physics data-taking from 2026 (Phase I):

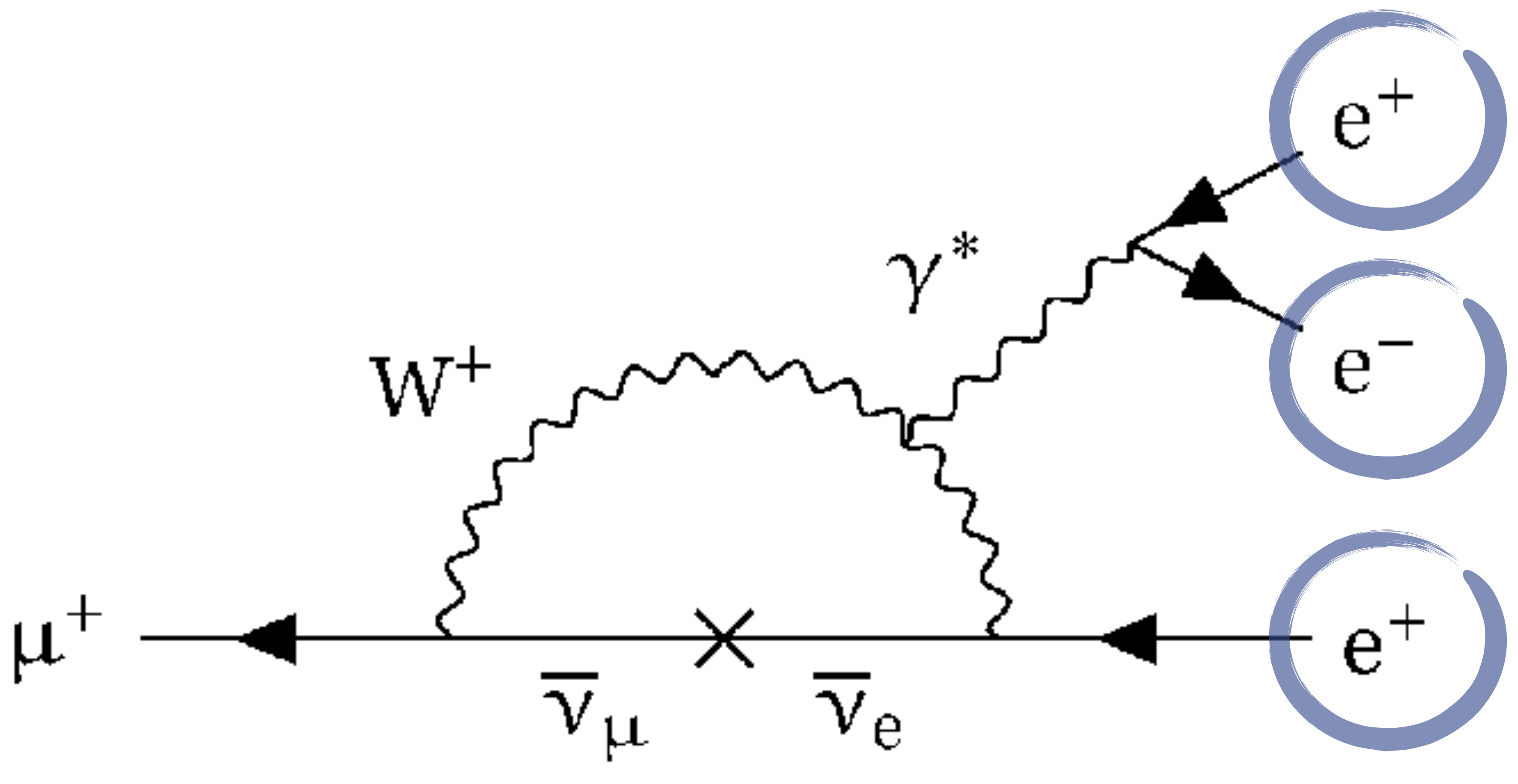
- PIE5 provides muon rates up to **10^8 muons/s** to Mu3e
- Target sensitivity: **BR (μ —> eee) < $2 \cdot 10^{-15}$**
- 290 days minimum running time required to achieve target

Phase II (> 2029):

- New High Intensity Muon Beam-line (HIMB), delivering up to **10^9 muons/s**
- Target sensitivity: **BR (μ —> eee) < $2 \cdot 10^{-16}$**

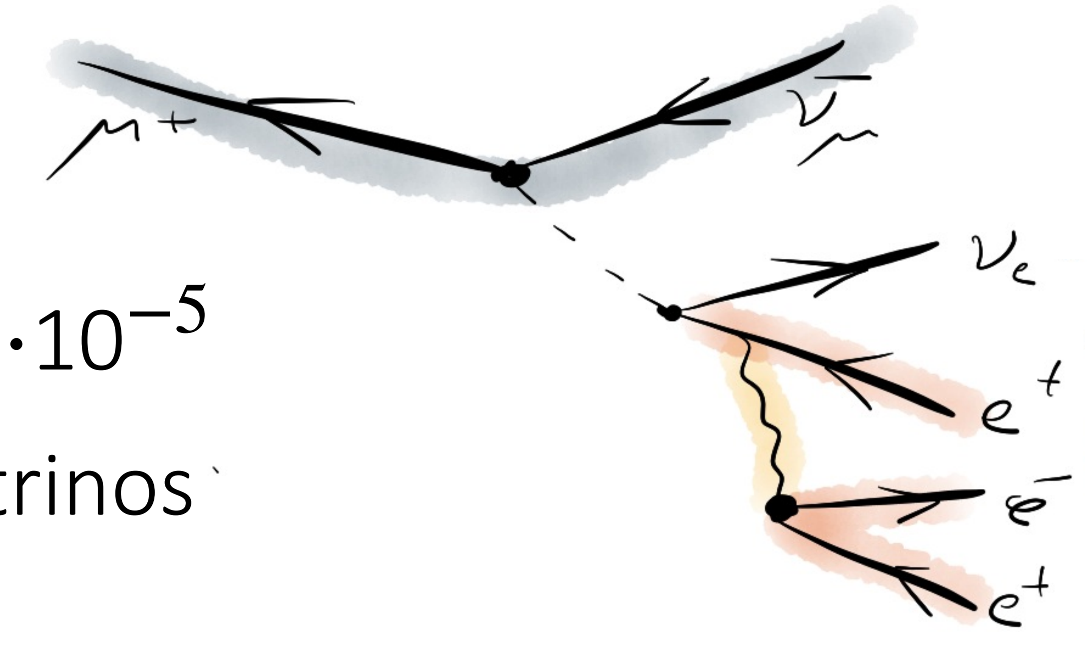
Muon decay topologies:

Signal:



Experimental signature: 3 electron tracks, common vertex, time coincidence, $\sum P_e=0$

Backgrounds:



Internal conversion:

- Rare muon decay: $BR(\mu^+ \rightarrow e^+e^-e^+\nu\bar{\nu}) = 3.4\cdot10^{-5}$
- Distinguished by momentum carried by neutrinos

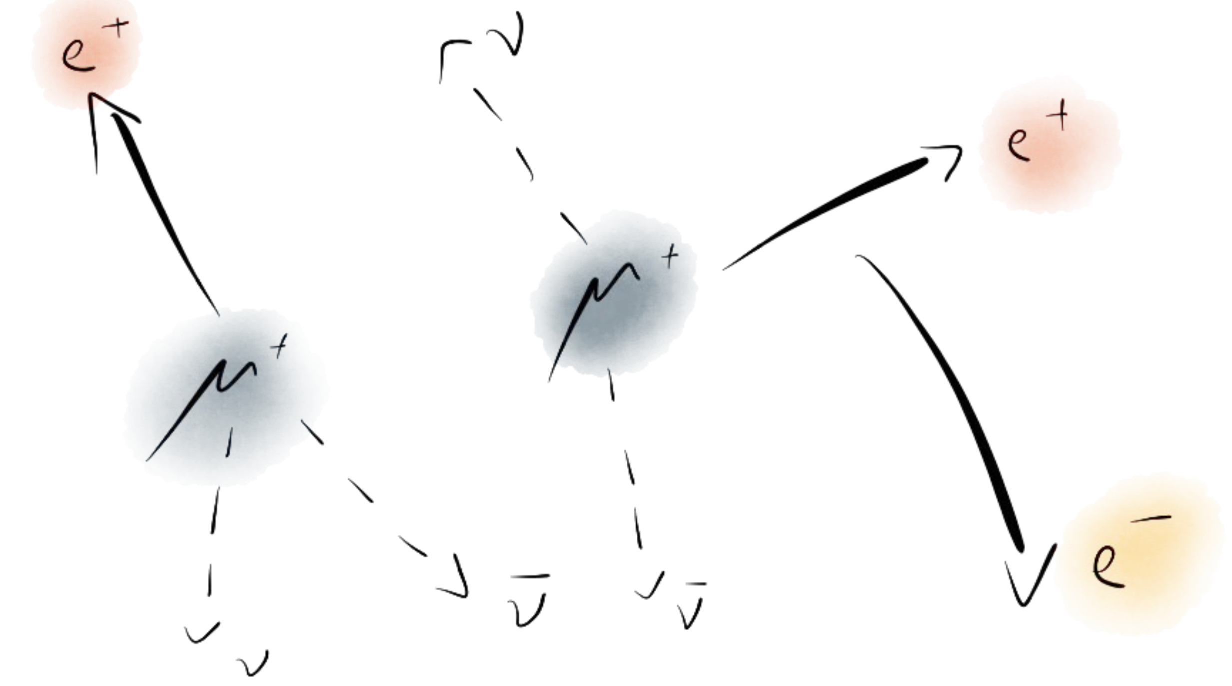
Excellent momentum resolution (0.5 MeV): crucial for detecting reconstructed peak at muon mass

Accidental combinatorial background:

Combinations of e^+ from $\mu^+ \rightarrow e^+\nu\bar{\nu}$ decay(s) with additional e originating from:

- Bhabha scattering
- Photon conversion
- Mis-reconstruction

No time coincidence/common vertex

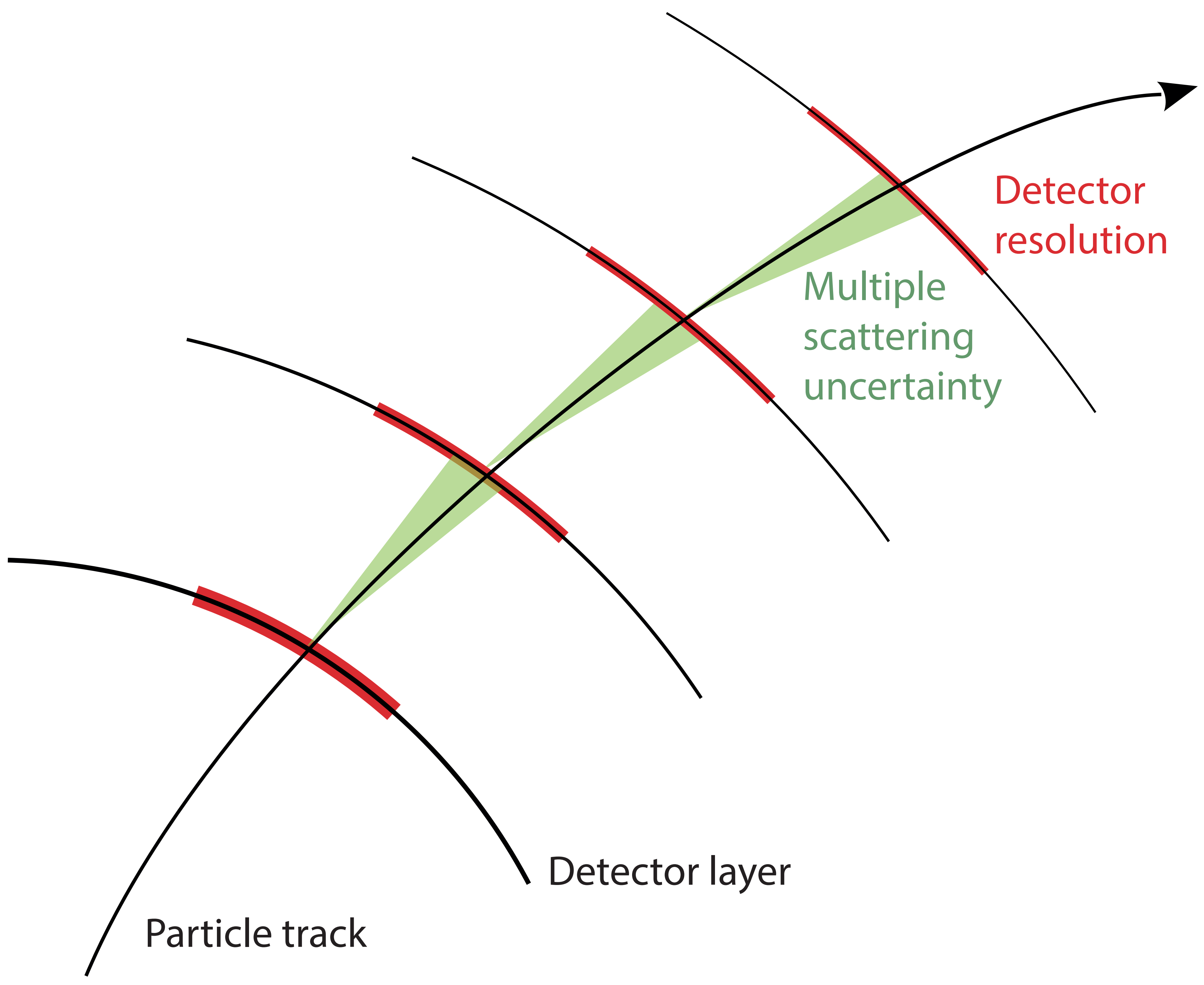


Good vertex and time resolution (100µm & 500ps)

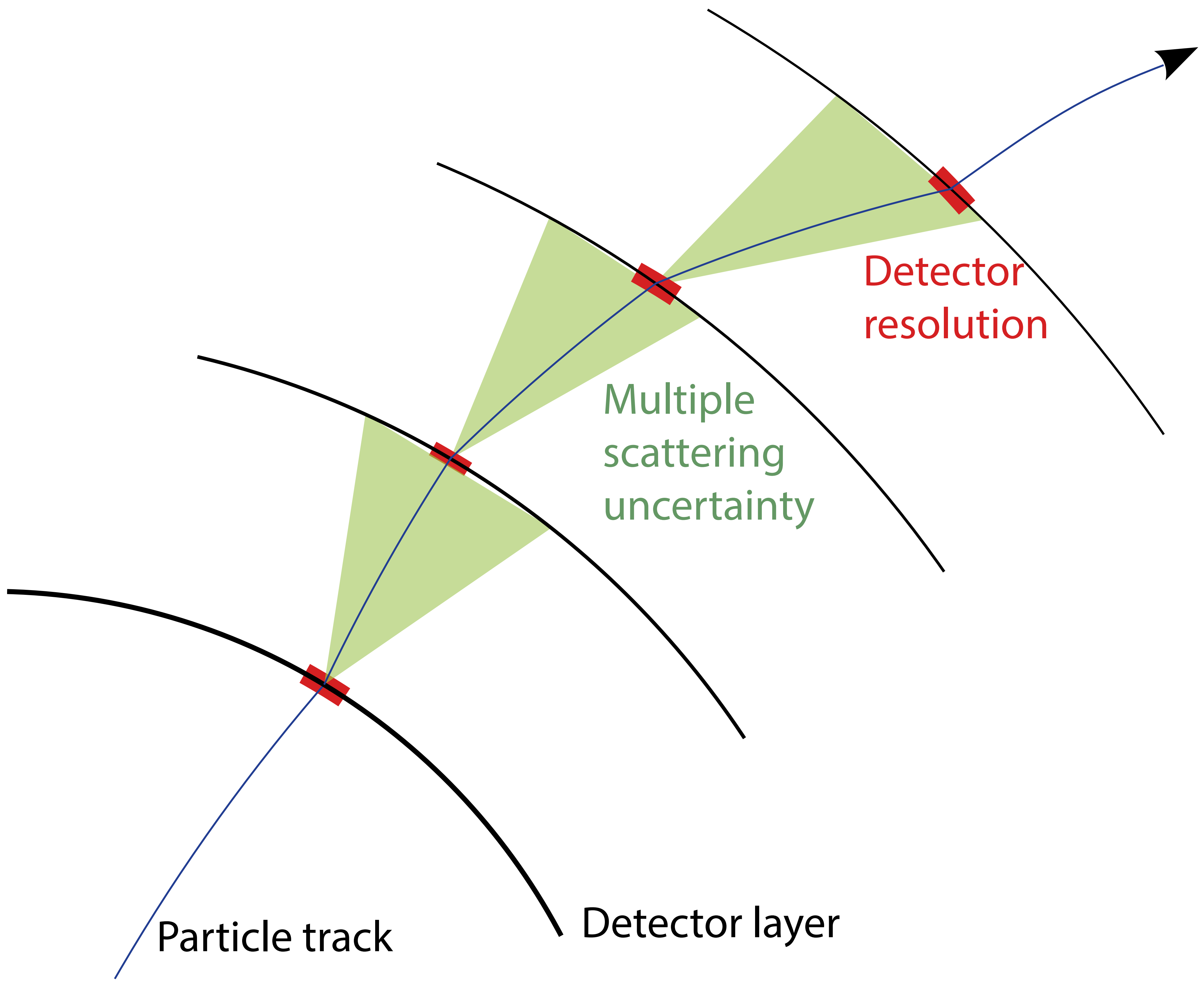
Multiple scattering regime:

Muons decay at rest: $\sum E = m_\mu$

- Small pixel sizes = hit resolution effects can be neglected
- Low (MeV/c) momentum regime: multiple scattering effects dominate



Spatial resolution dominates



Scattering dominates

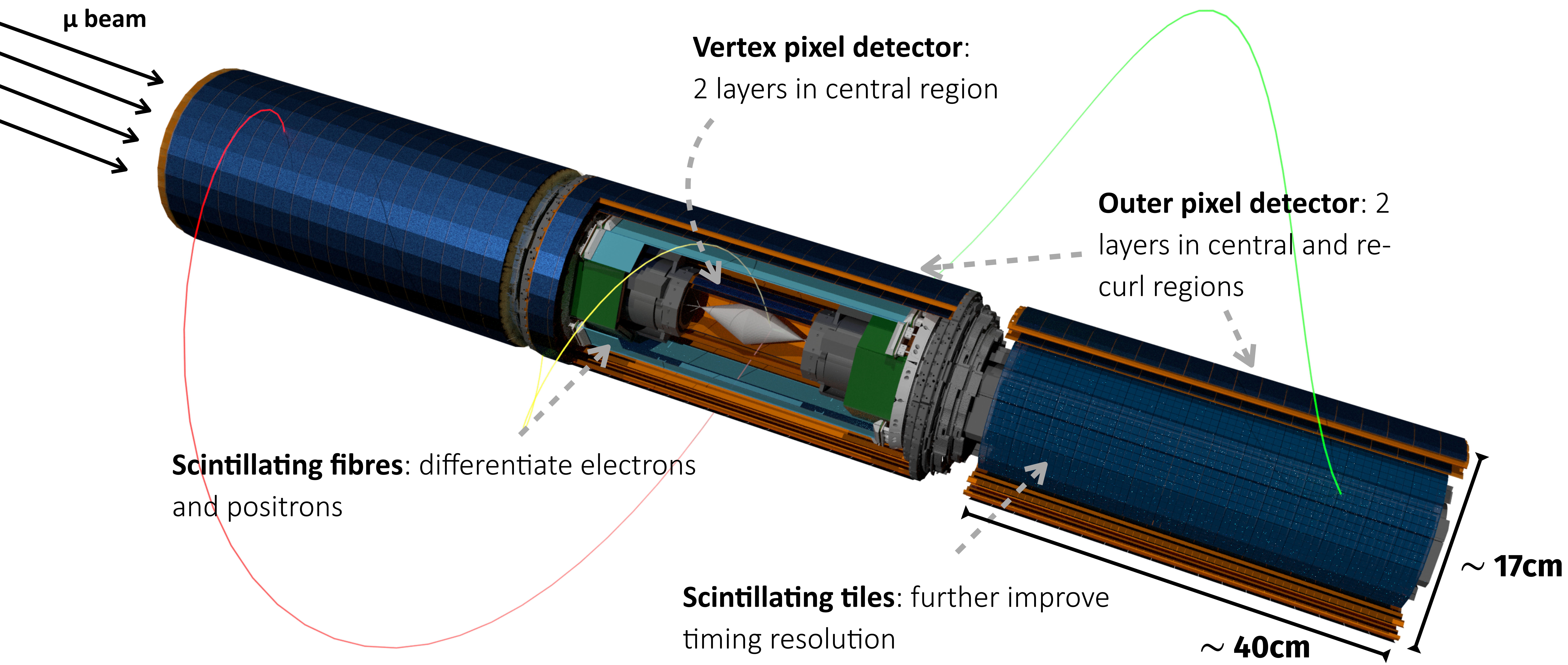
Mu3e detector design:

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

- Homogeneous solenoidal magnetic field B = 1T

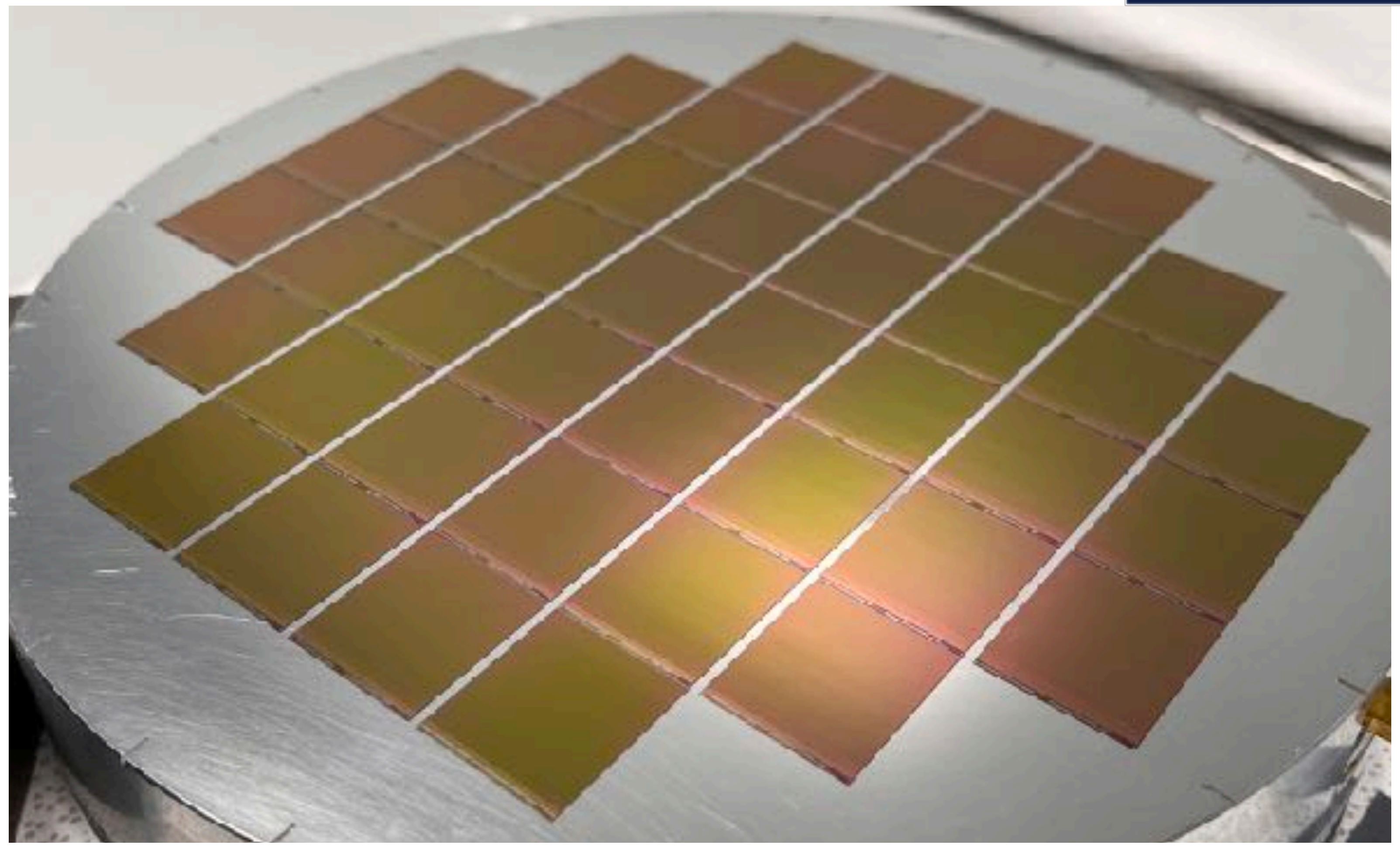
Design requirements:

- Minimise detector material in all layers
- Requires ultra-thin detectors + support structures
- Use gaseous helium cooling: forced convection



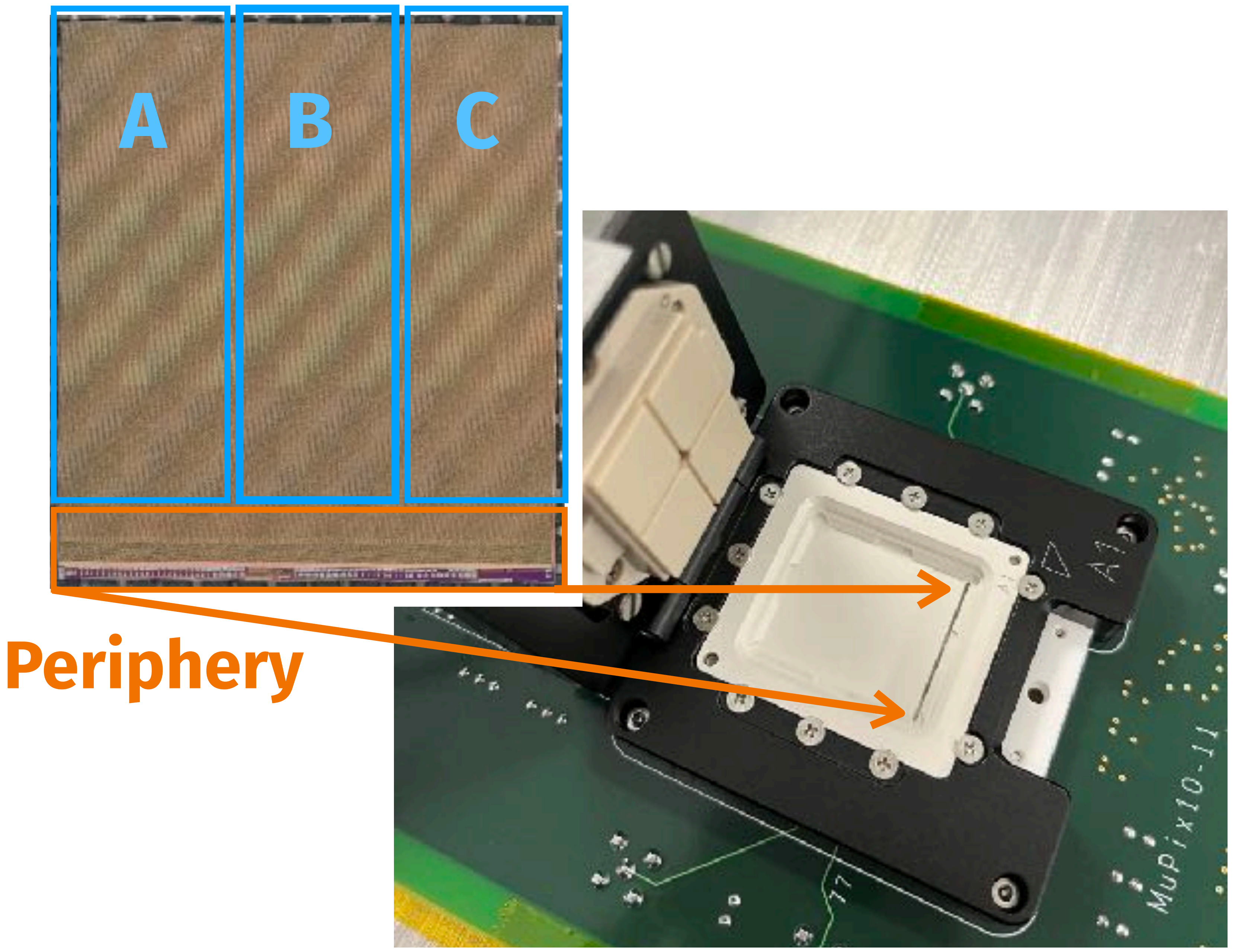
The MuPix sensor:

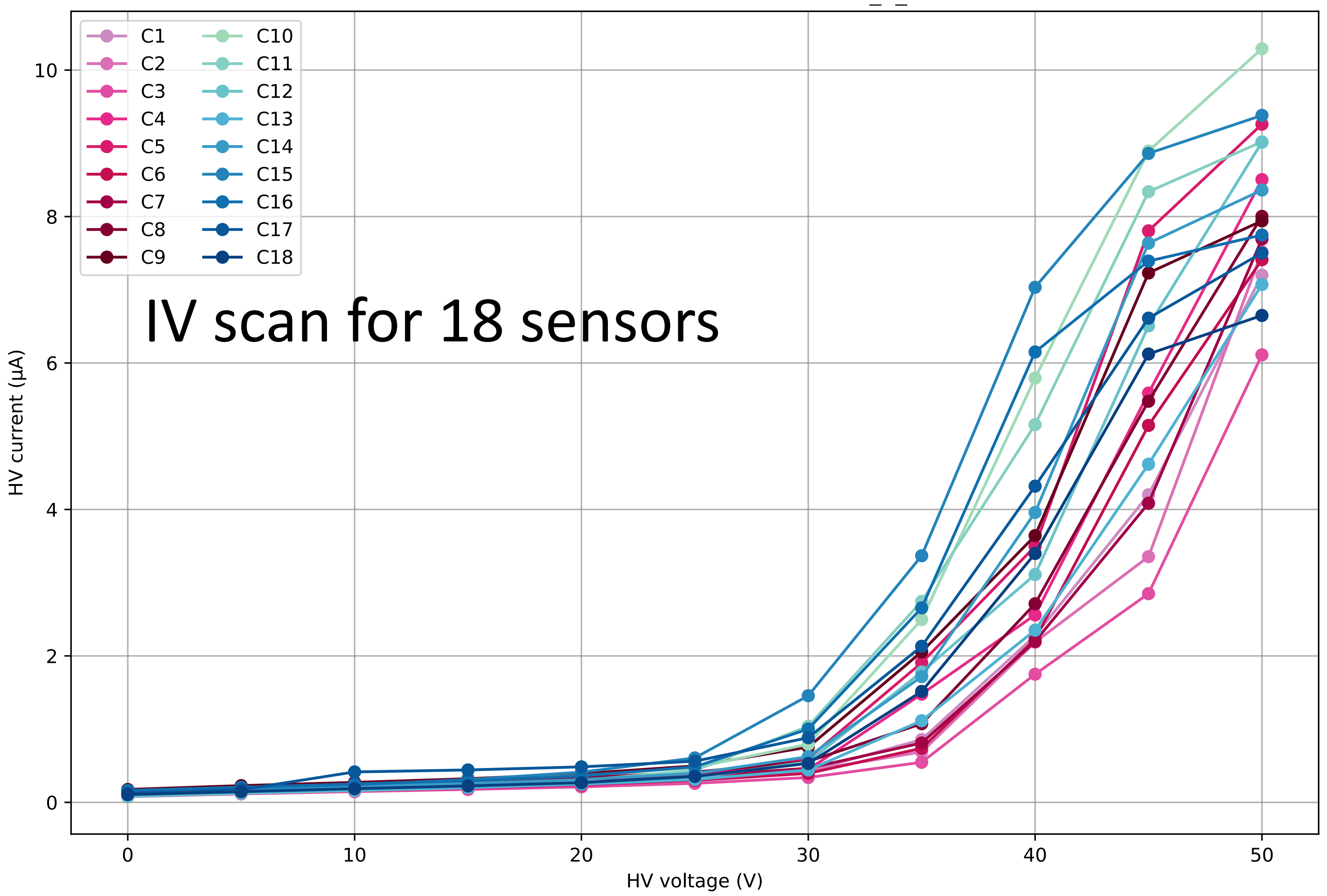
Custom **MuPix11** sensors: Monolithic HV-CMOS produced by TSI (Bosch) using 180 nm technology.



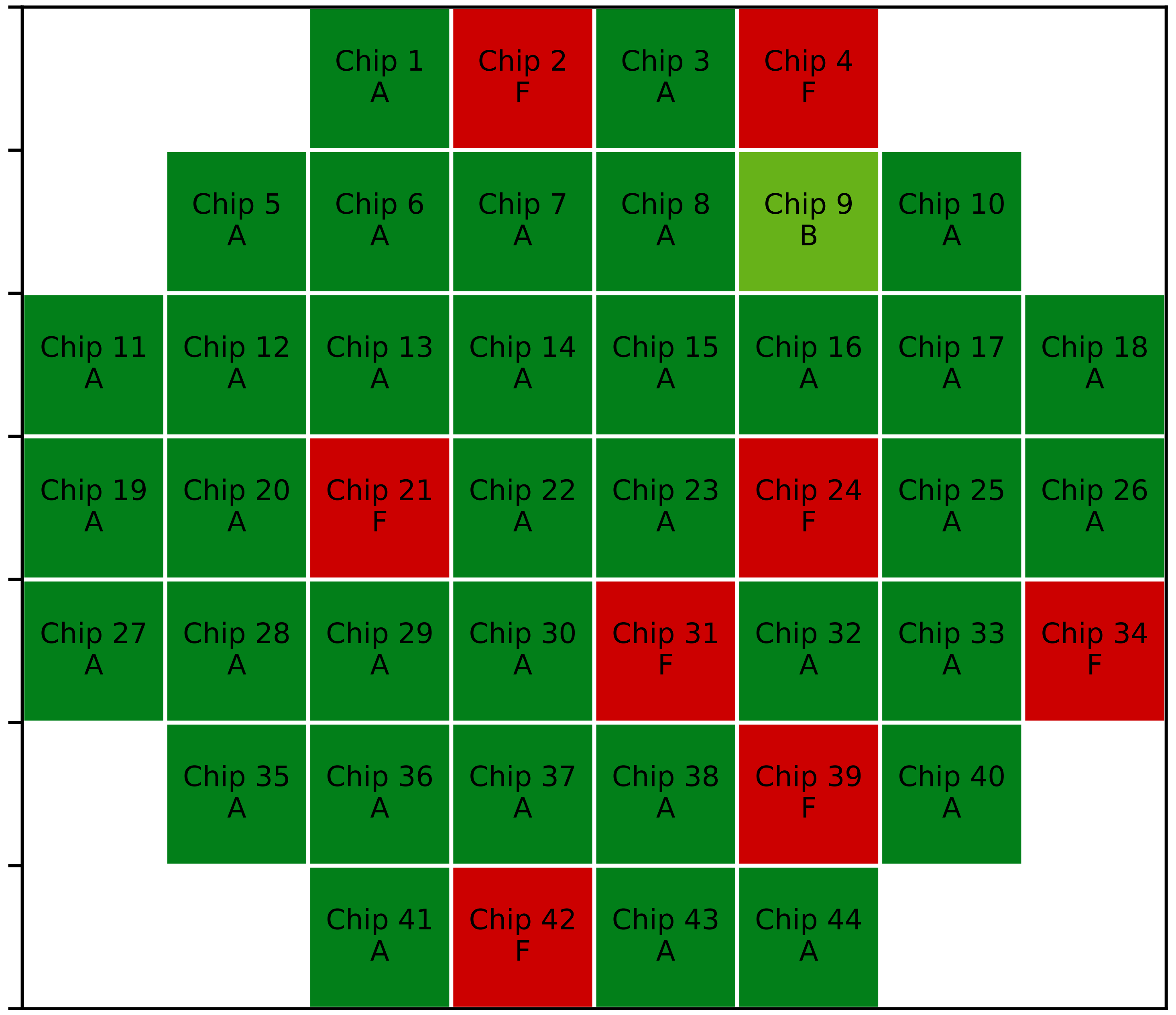
Sensor size [mm^2]	20.66 x 23.18	Data link	3 + 1 (MUX)
Pixel size [μm^2]	80 x 80	Data speed [Gbit/s]	1.25
Pixel matrix	256 x 250	Time resolution	< 20 ns
Thickness [μm]	50 & 70	Hit finding efficiency	> 99%

Single chip QC performed in house for all sensors (Oxford + Heidelberg)



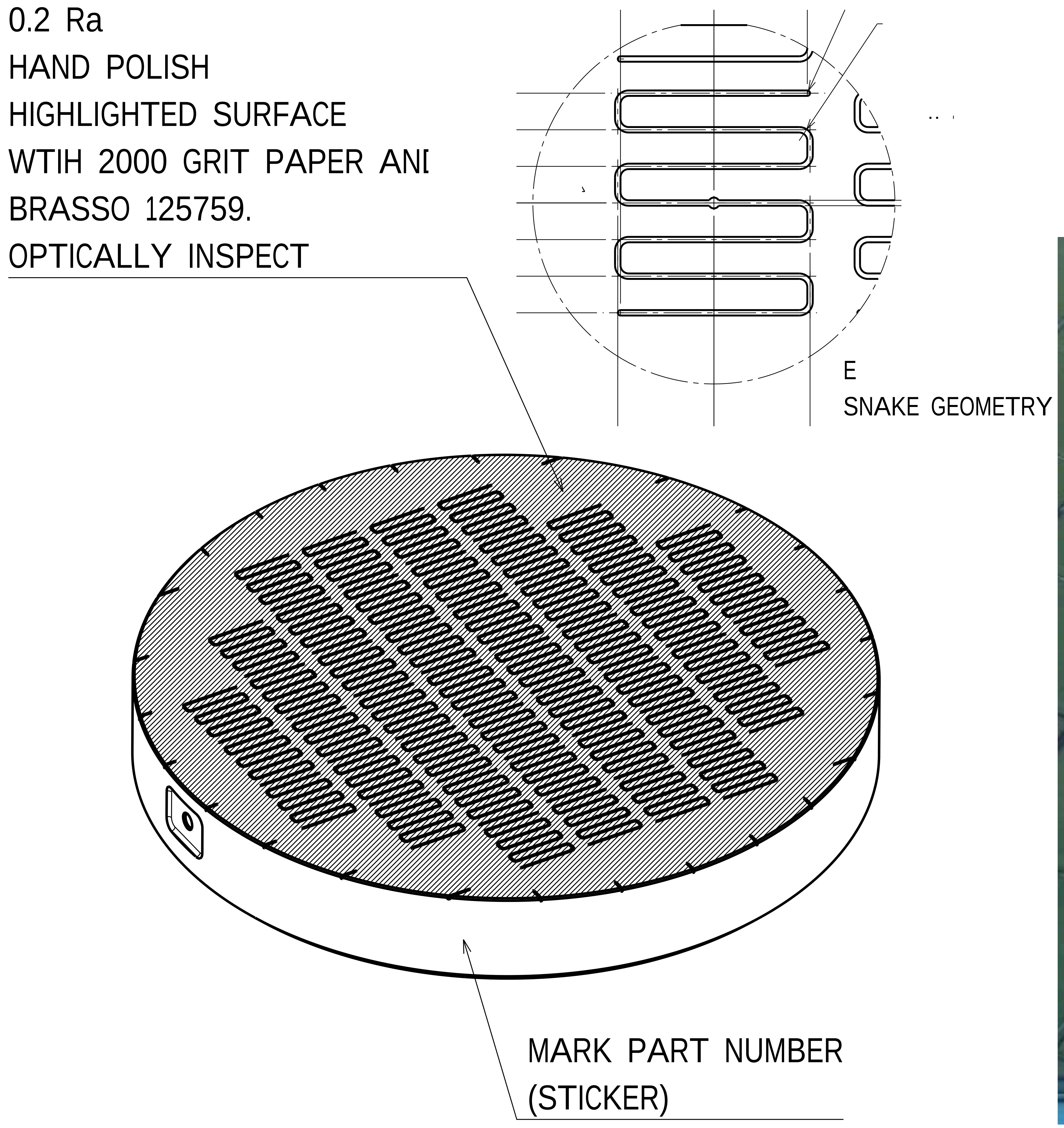


QC wafer plot [81.8% yield]

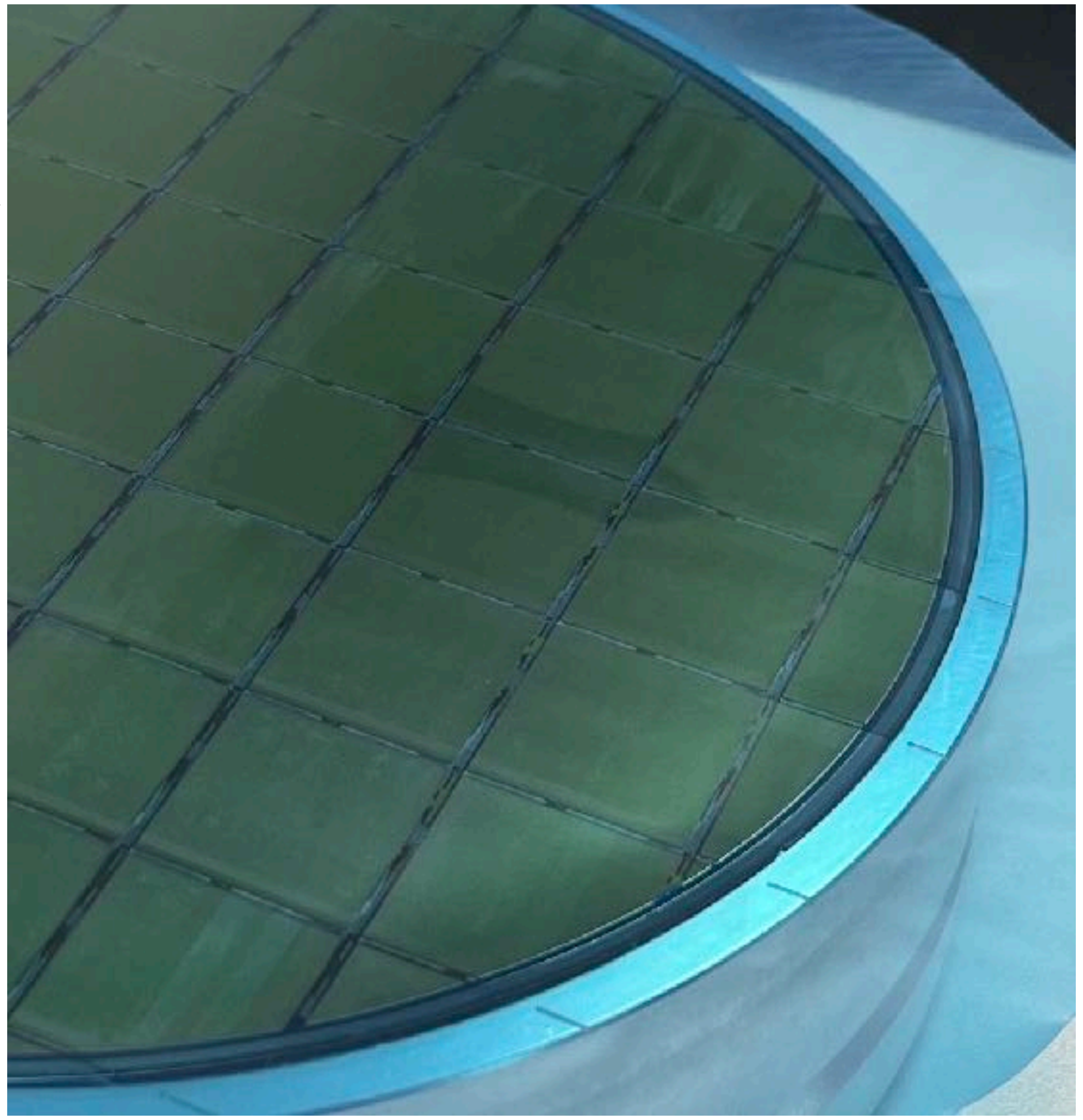


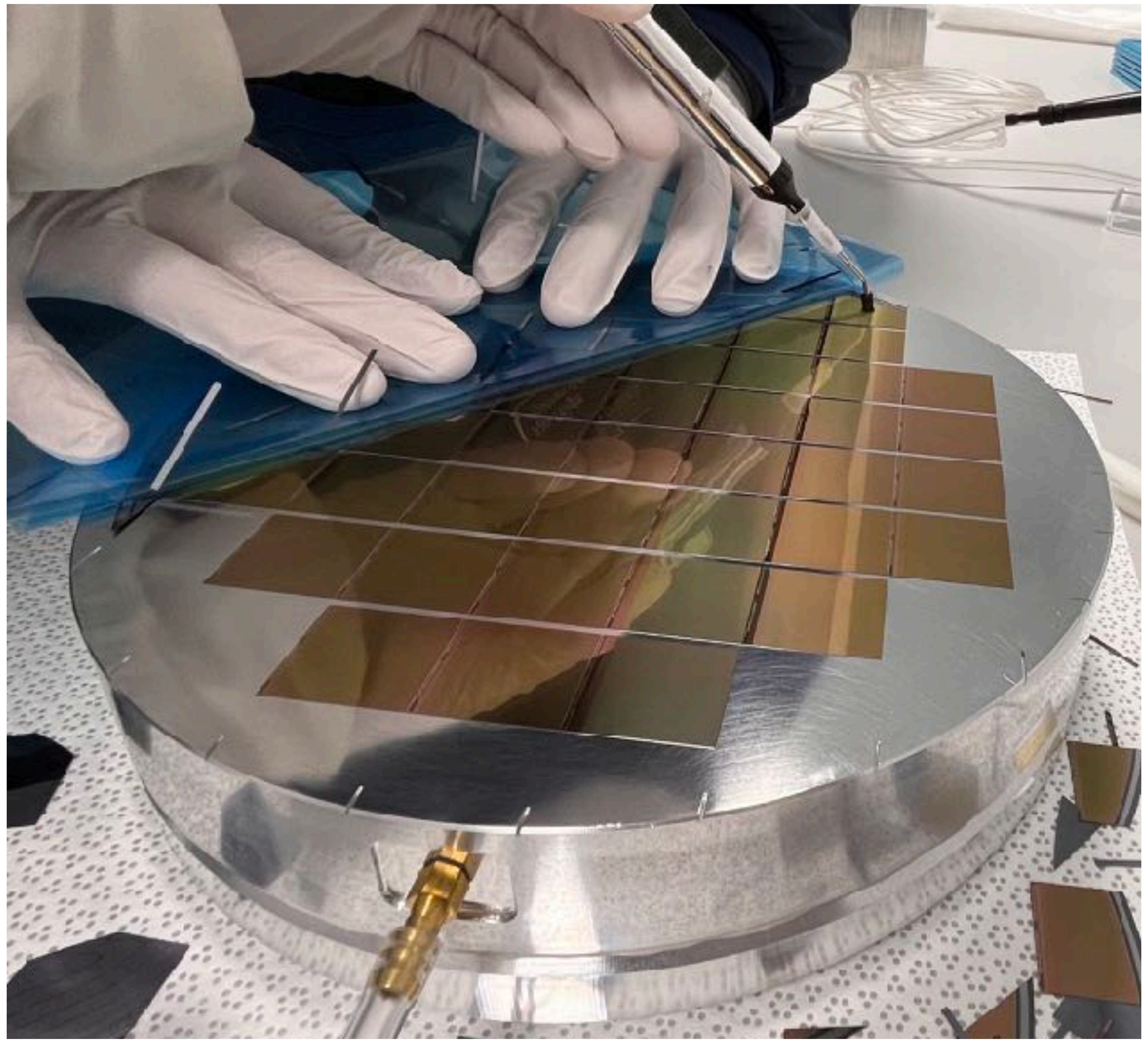
Silicon wafer peeling and picking:

In-house custom designed wafer peeling tool: polished aluminium



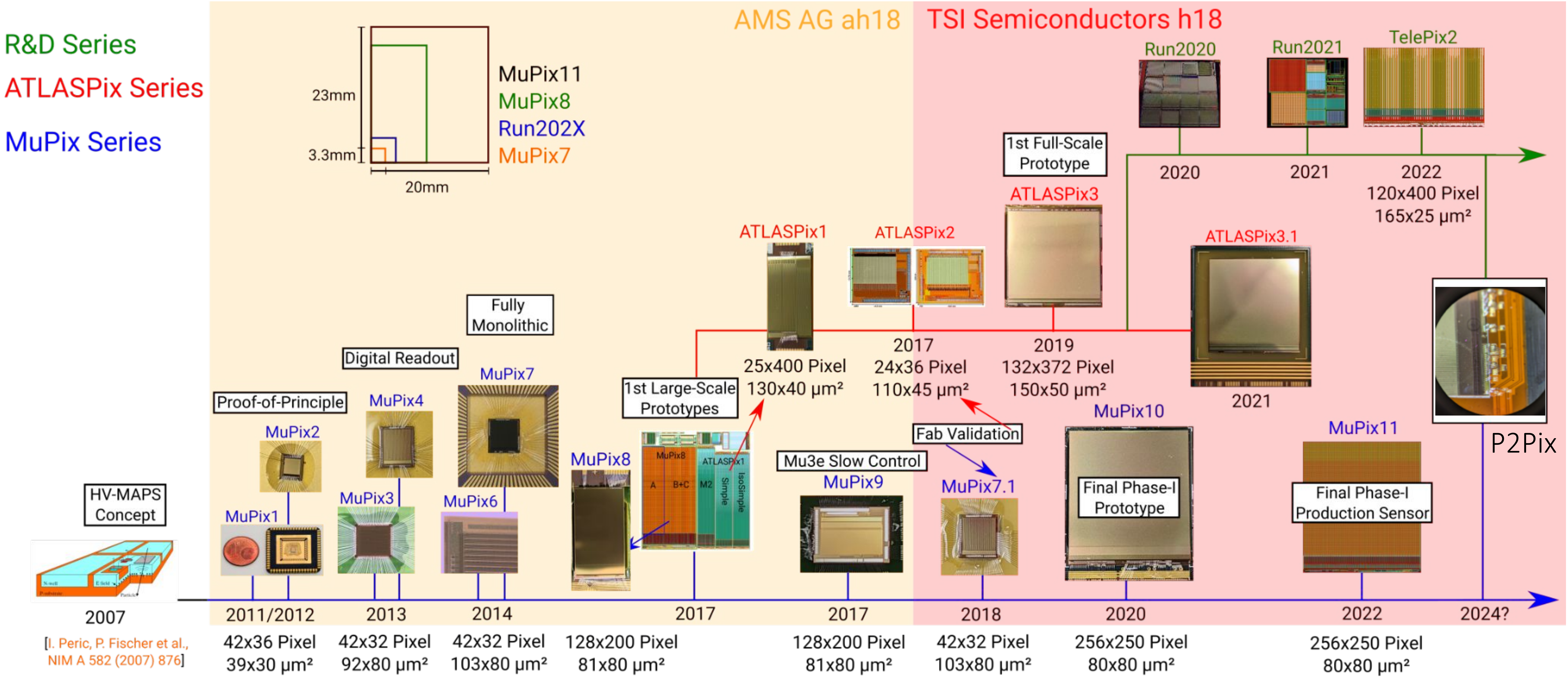
- When received diced sensors are attached with adhesive to blue protective film
- Requires UV light to detach (UV curing for 10 min @ 365nm wavelength)
- Needs to be removed within 2 weeks





MuPix/HV-MAPS R&D efforts:

[Image credit:Heiko Augustin]



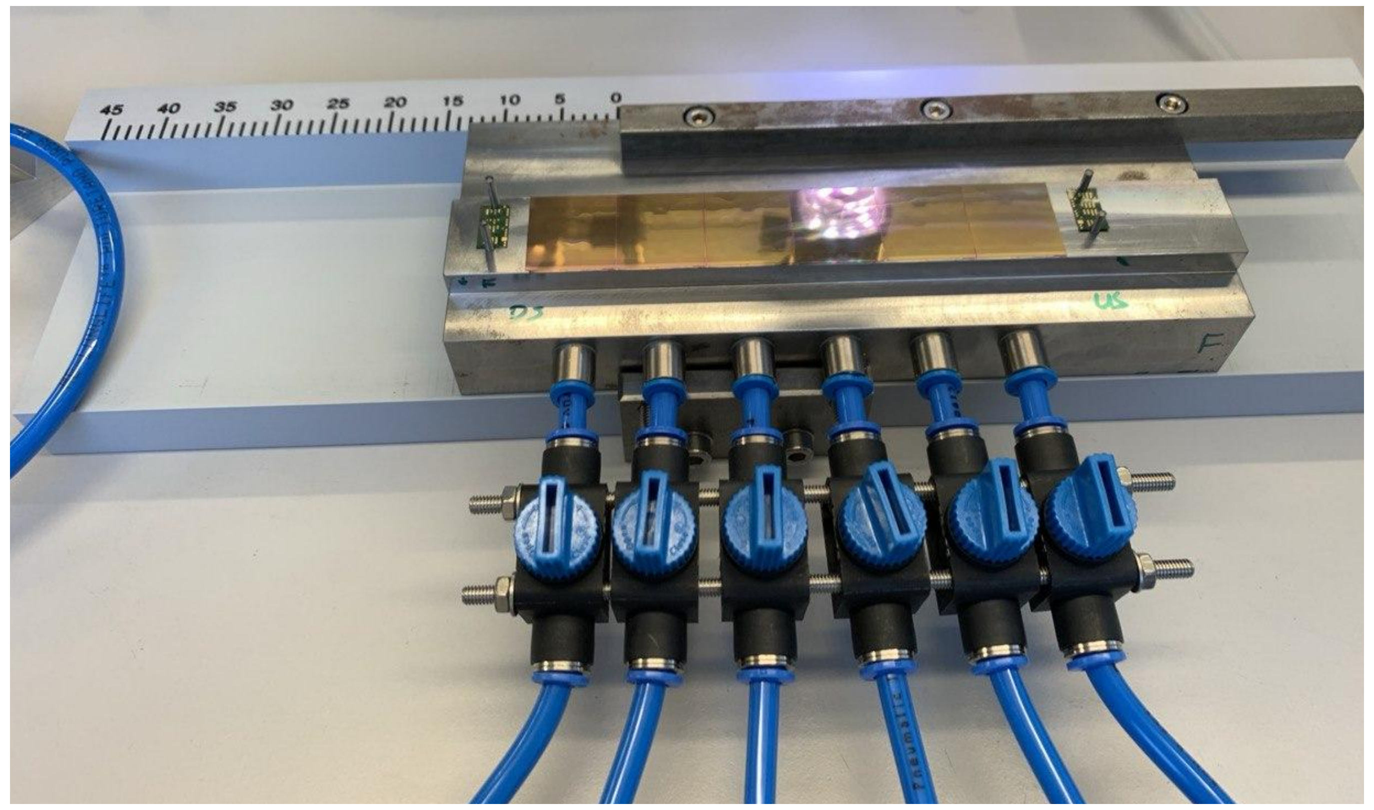
Vertex tracker components:

Ultra-thin pixel tracker for precise momentum reconstruction and vertexing

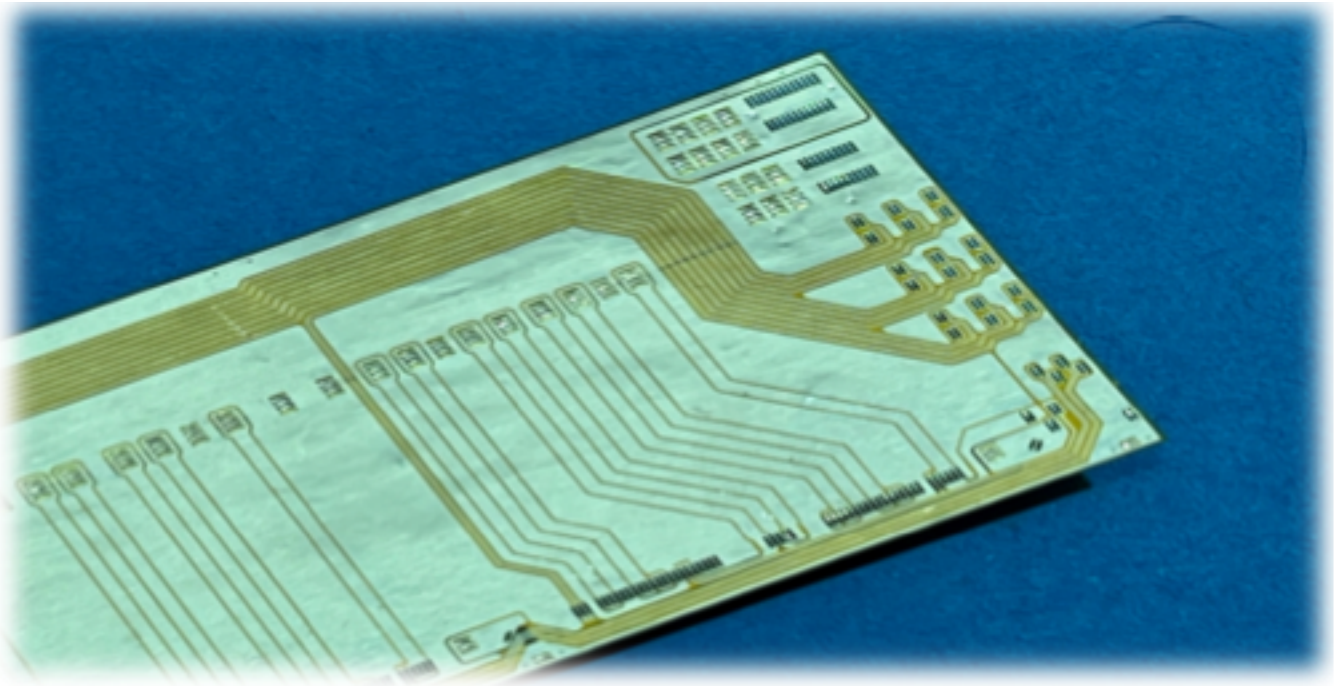
- Basic building block of Mu3e pixel tracker = “**Ladder**”
- Cooled by gaseous helium forced convection

Components:

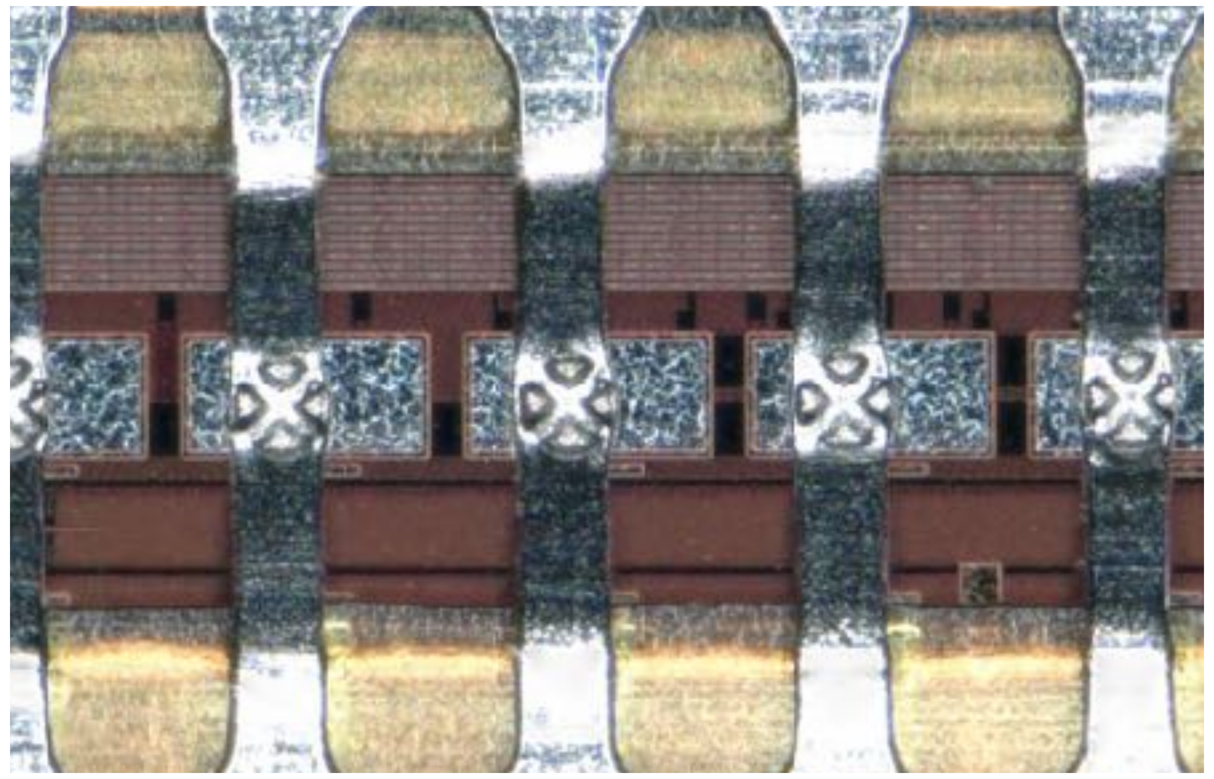
- **6x** MuPix11 pixel sensors, thinned to 50 µm



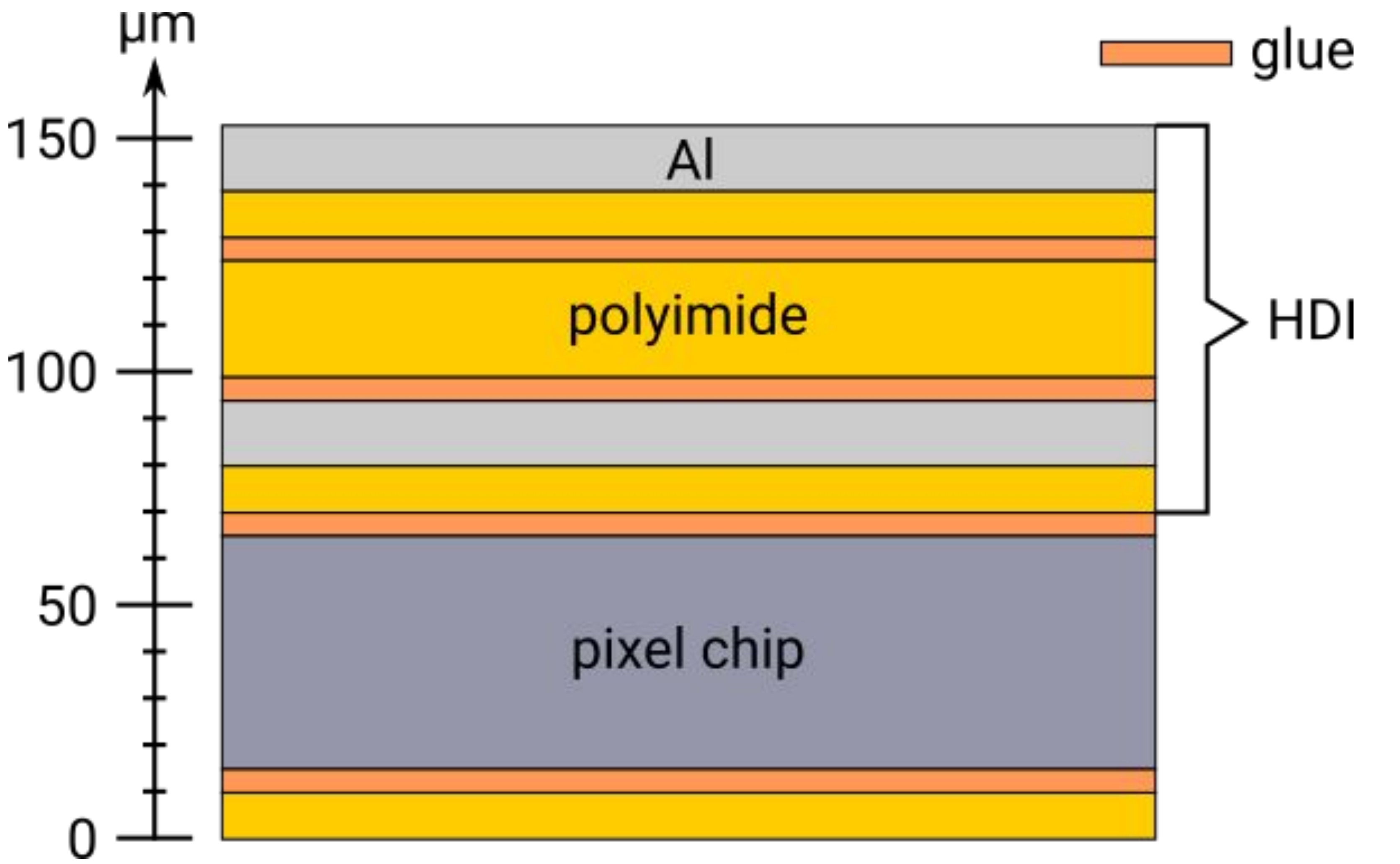
- Aluminium + kapton flexible PCB, ~ 70µm: can’t use copper, would be equivalent to XXXXX

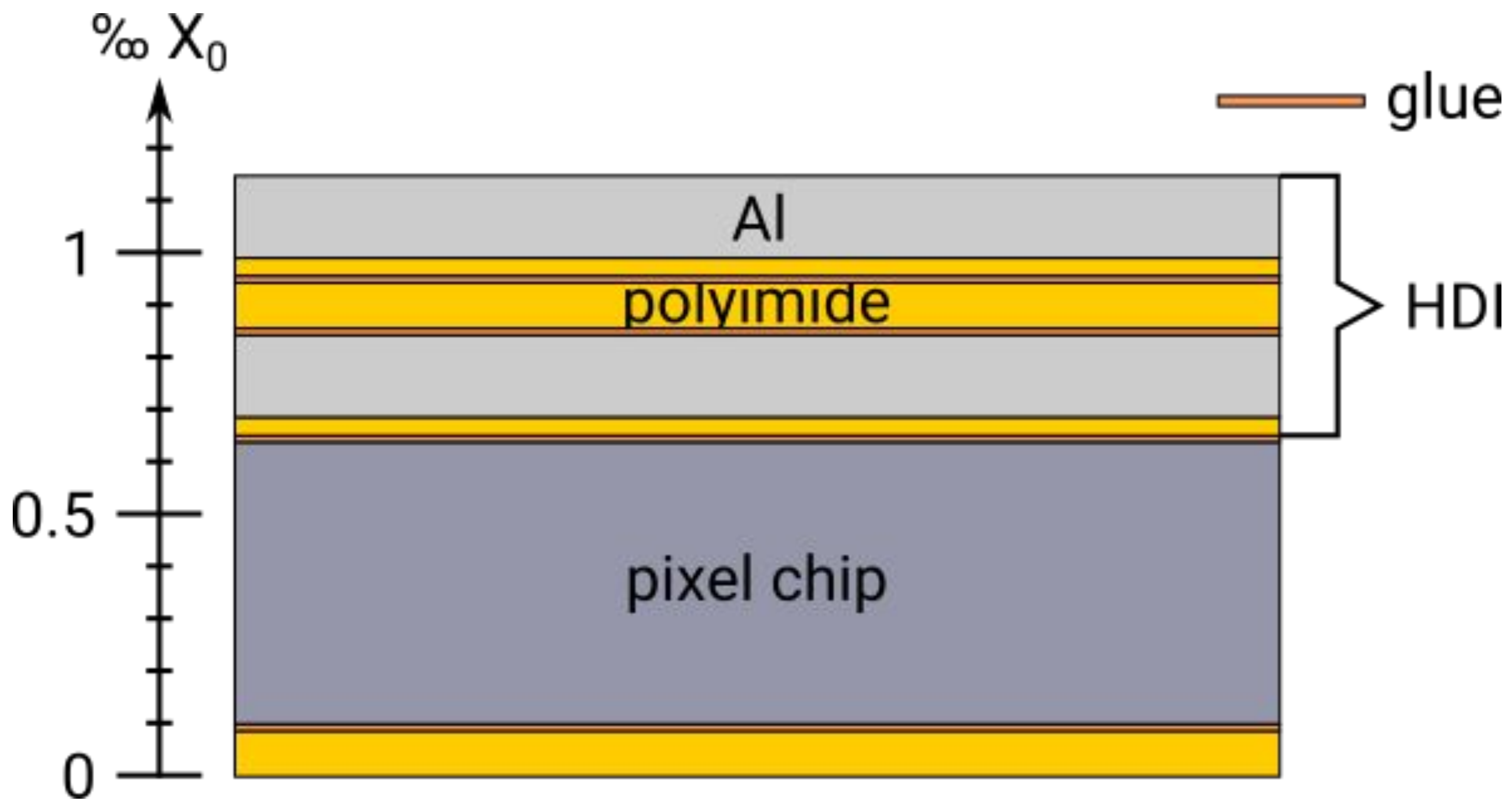


- Electrical connections via **spTAB** (single point Tape Automated Bonding):



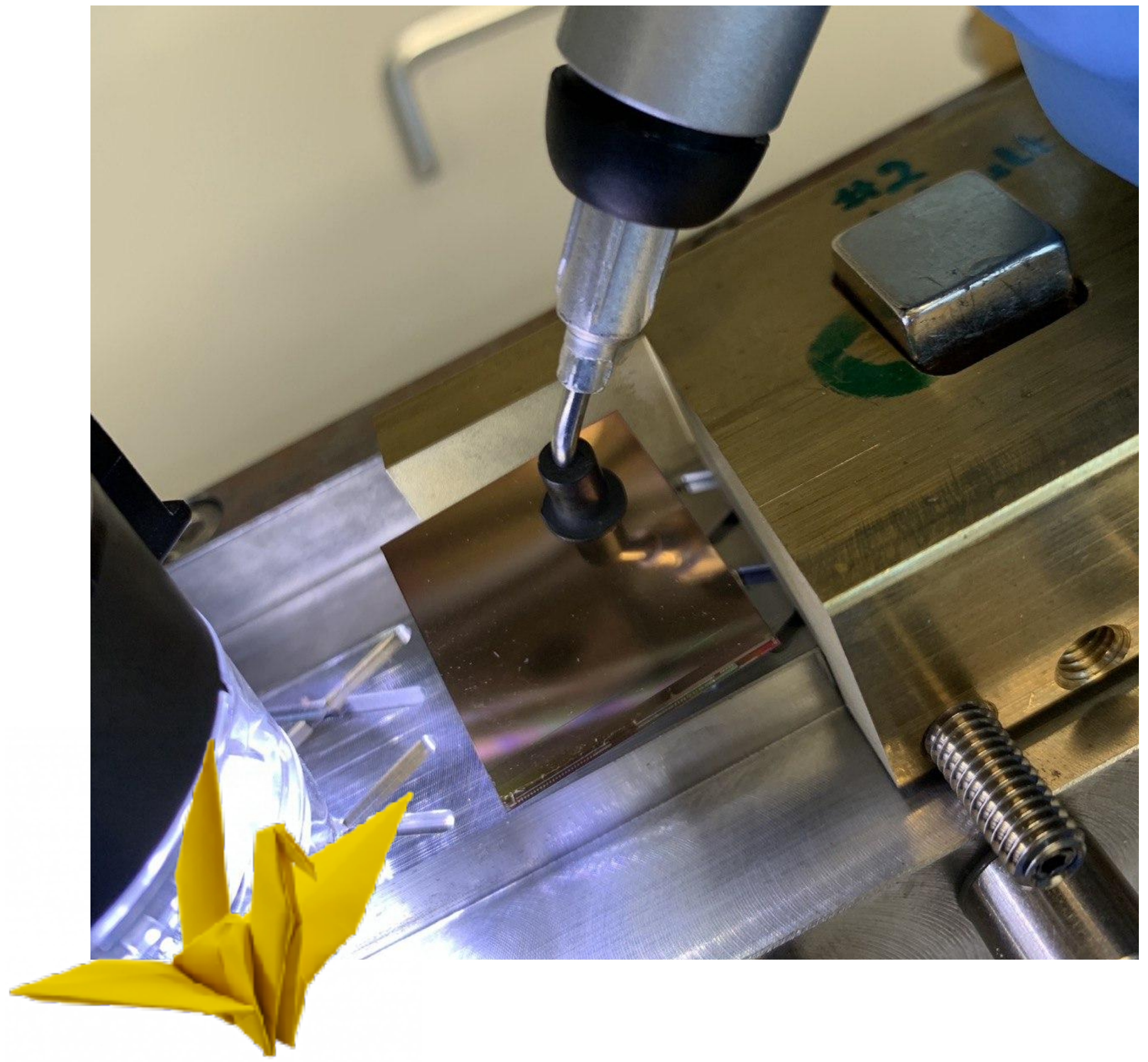
- Total radiation length = 0.115% per layer



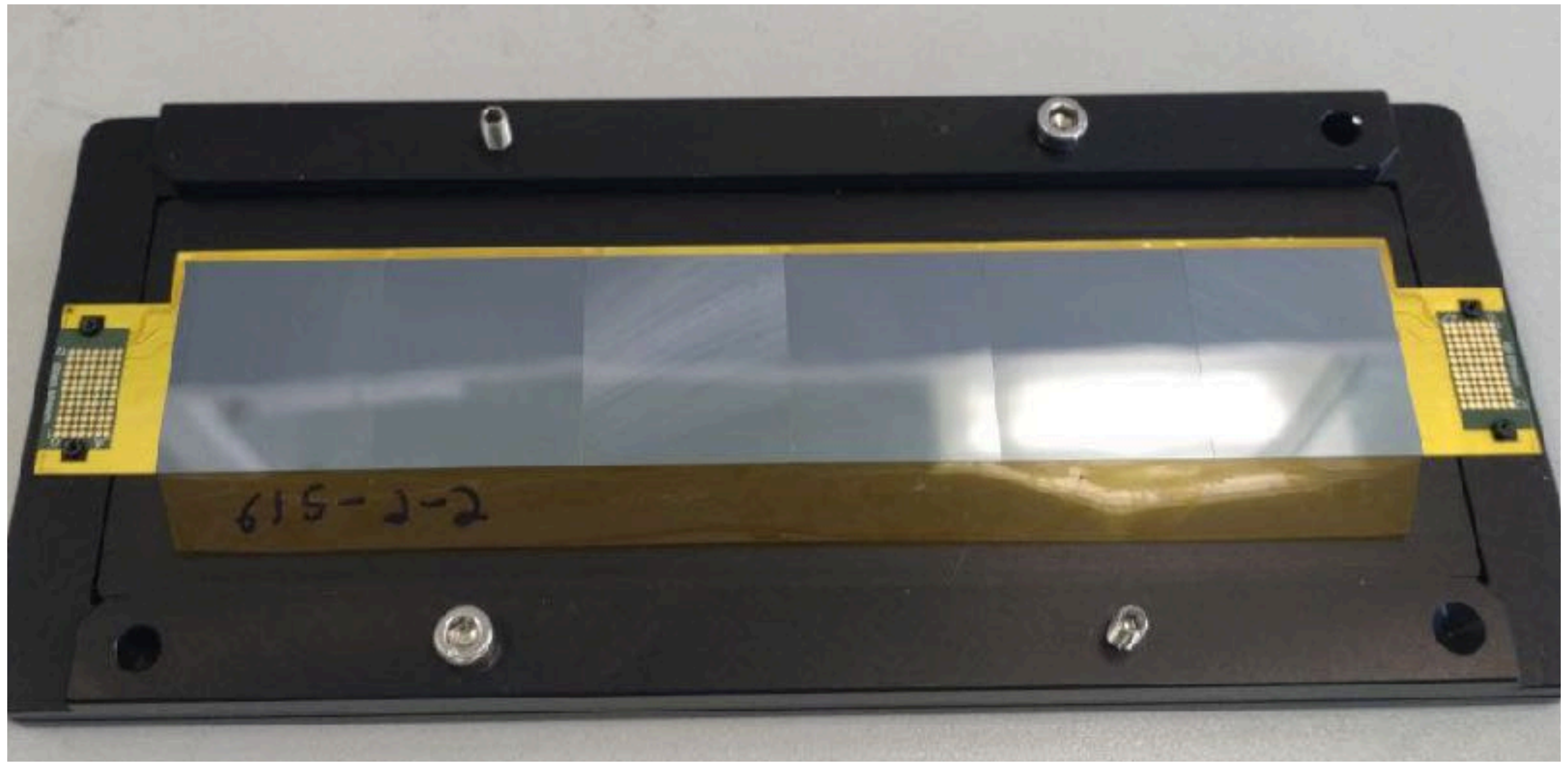


Vertex tracker production:

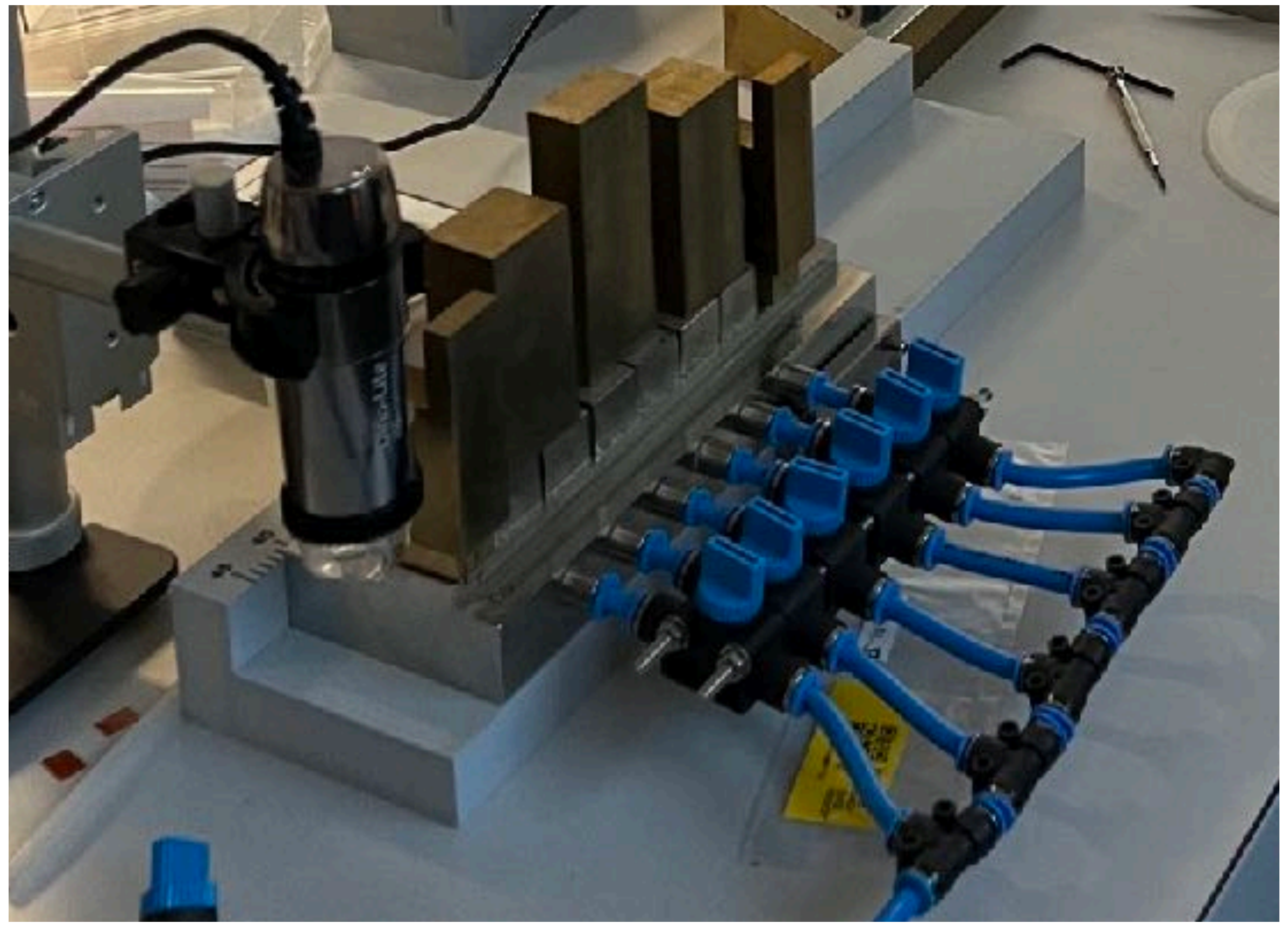
Sensors placed and glued manually on ladder



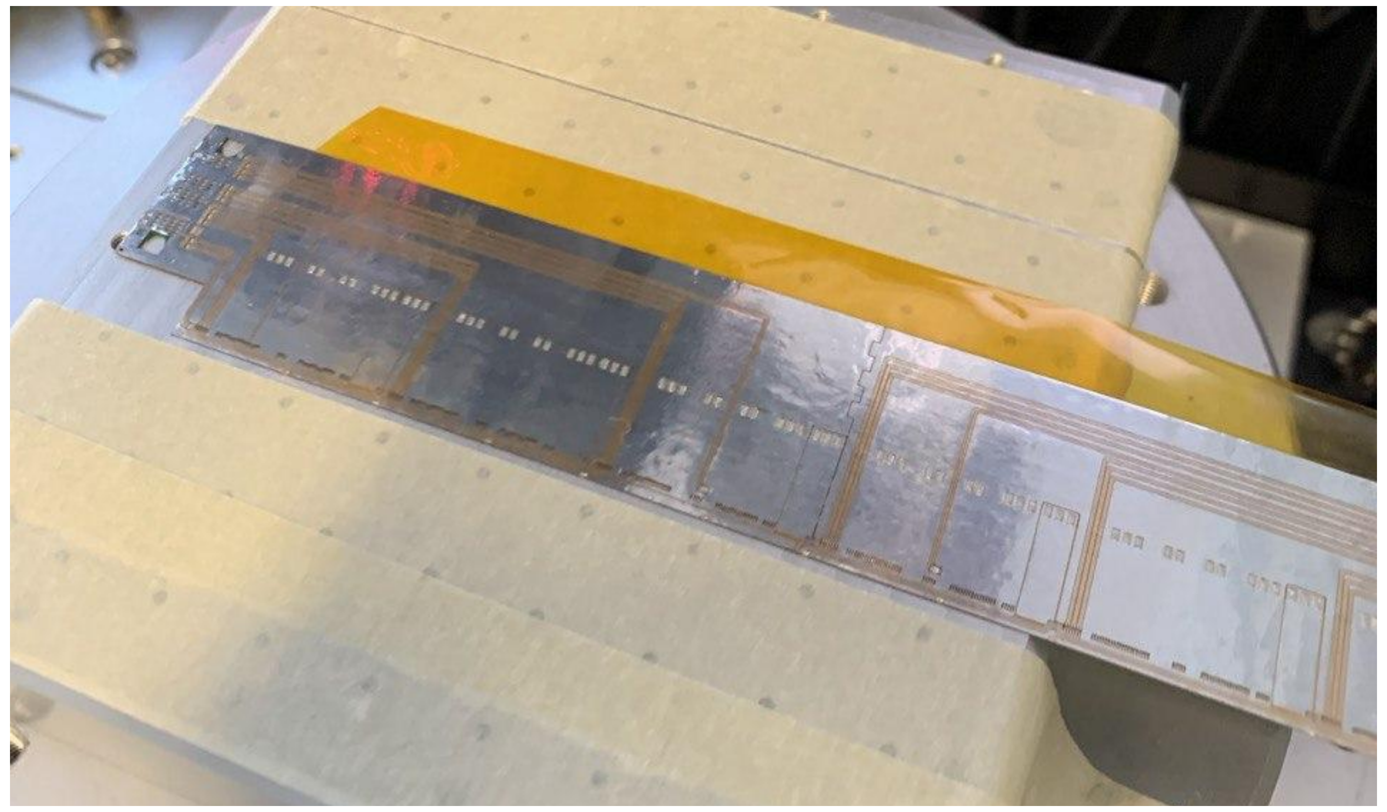
Additional small PCB (“interposer flex”) for ladder -> module

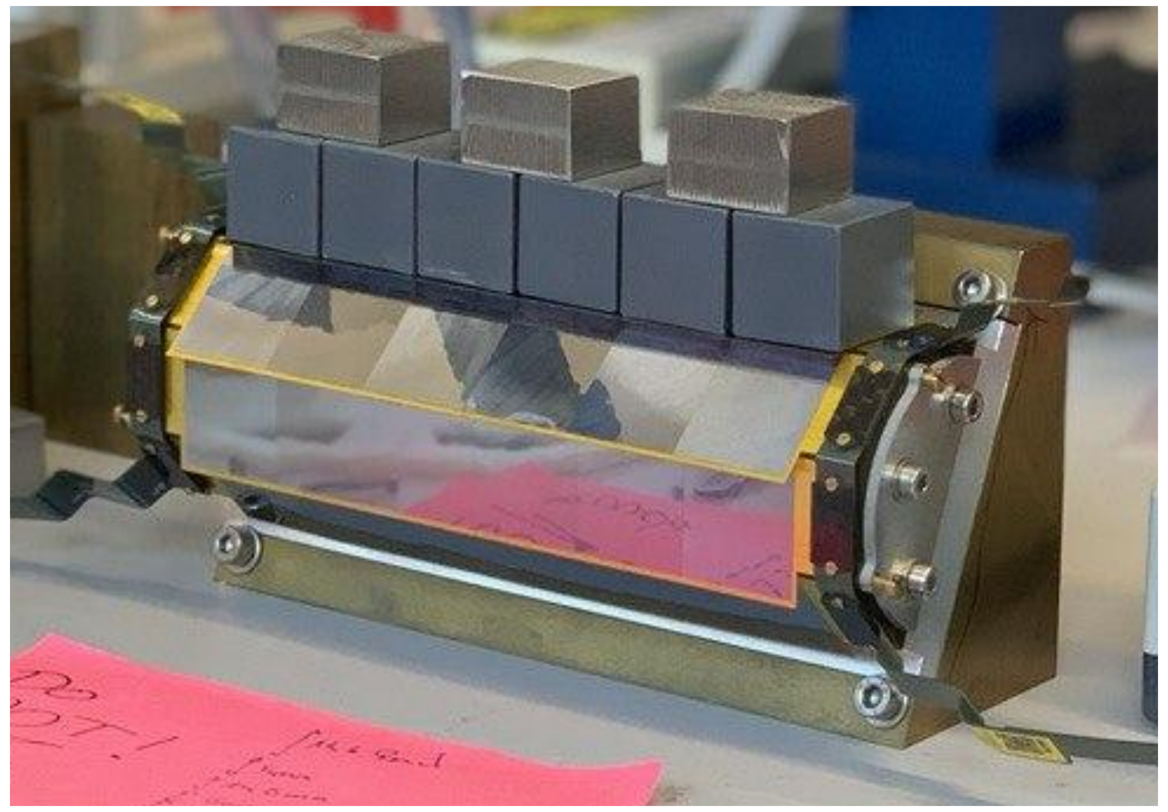


Weights for glue curing



- Kapton-flap allows ladders to be glued together
- Mechanical stability: from 3D folded nature of vertex detector





Flap glue curing in progress

Assembly of vertex pixel layers:

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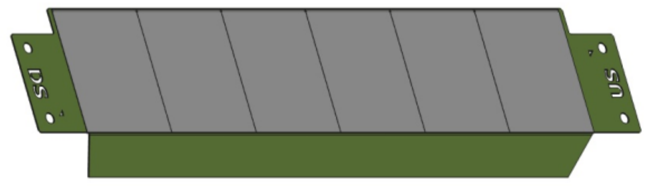
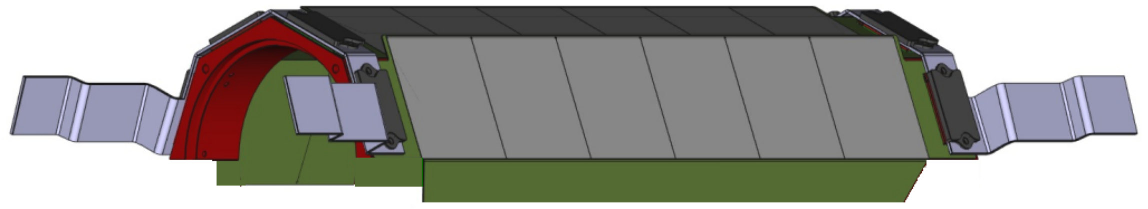


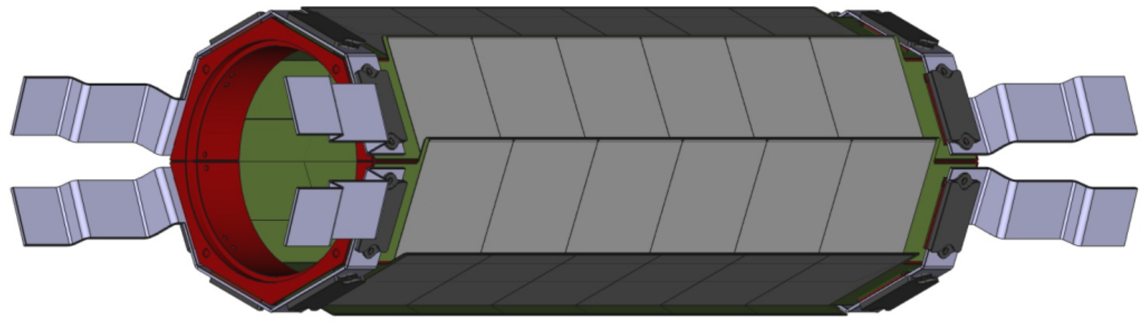
Ladder

1 ladder = 6 x MuPix11 sensors



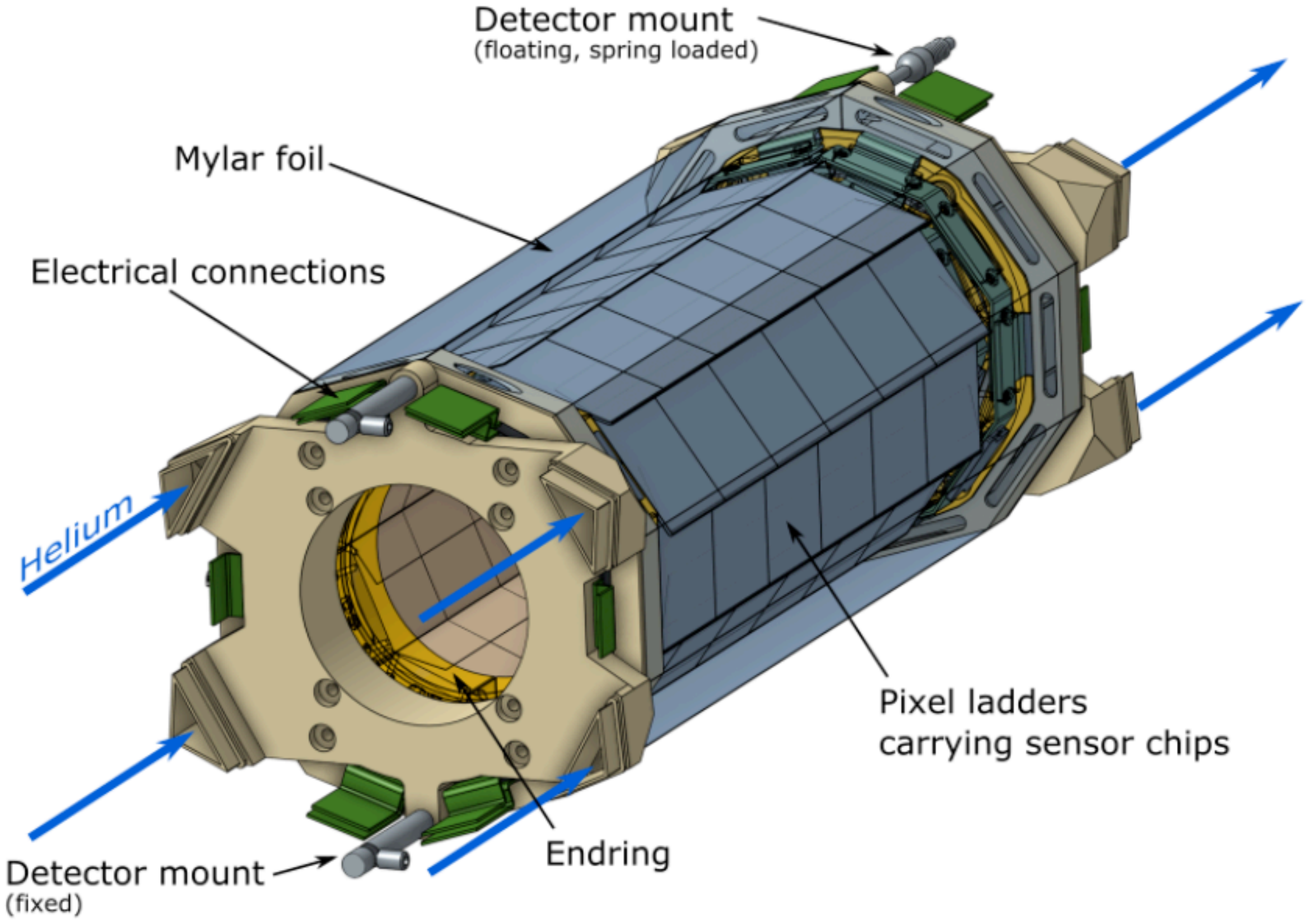
Module

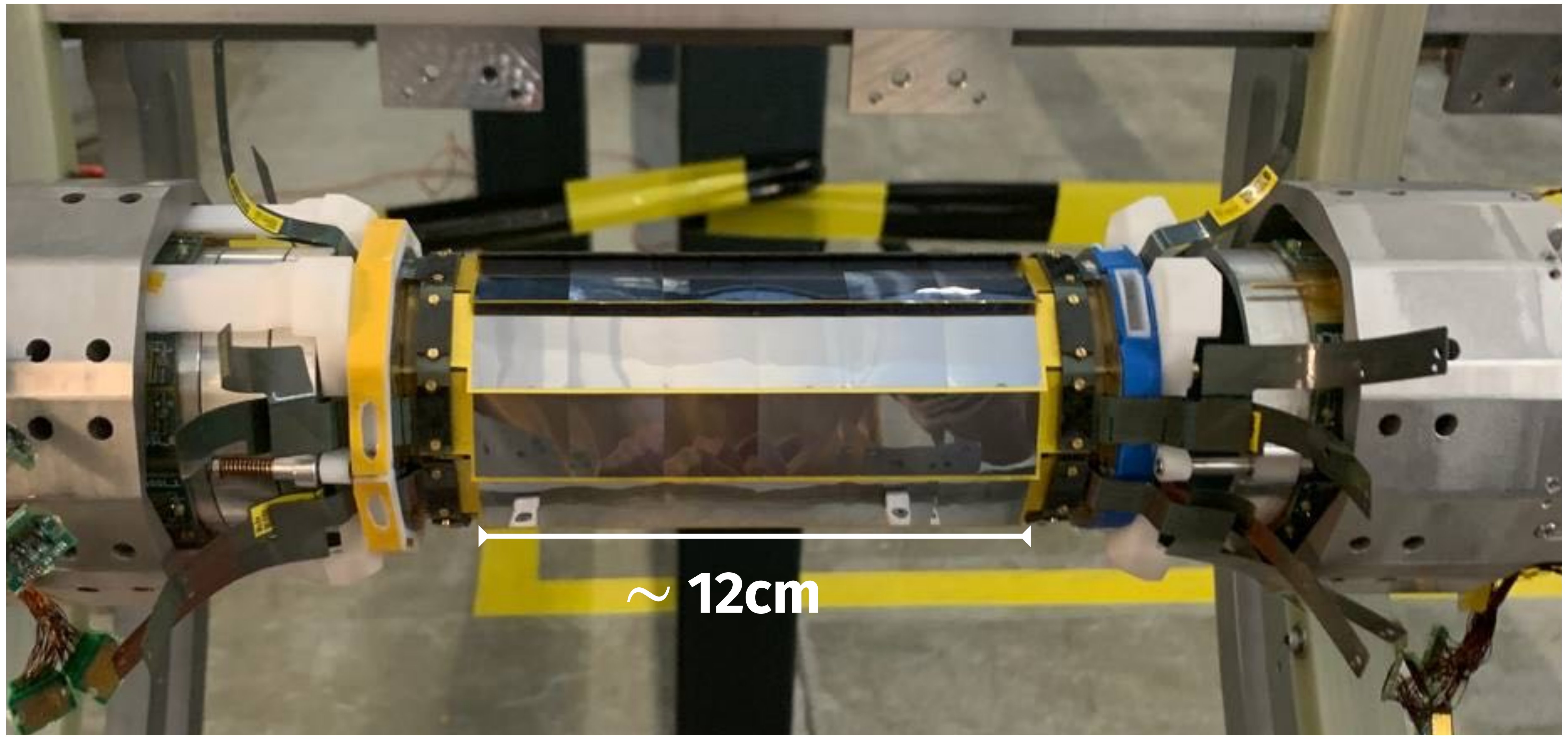
1 module = 4 ladders



Layer

2 modules = 1 layer





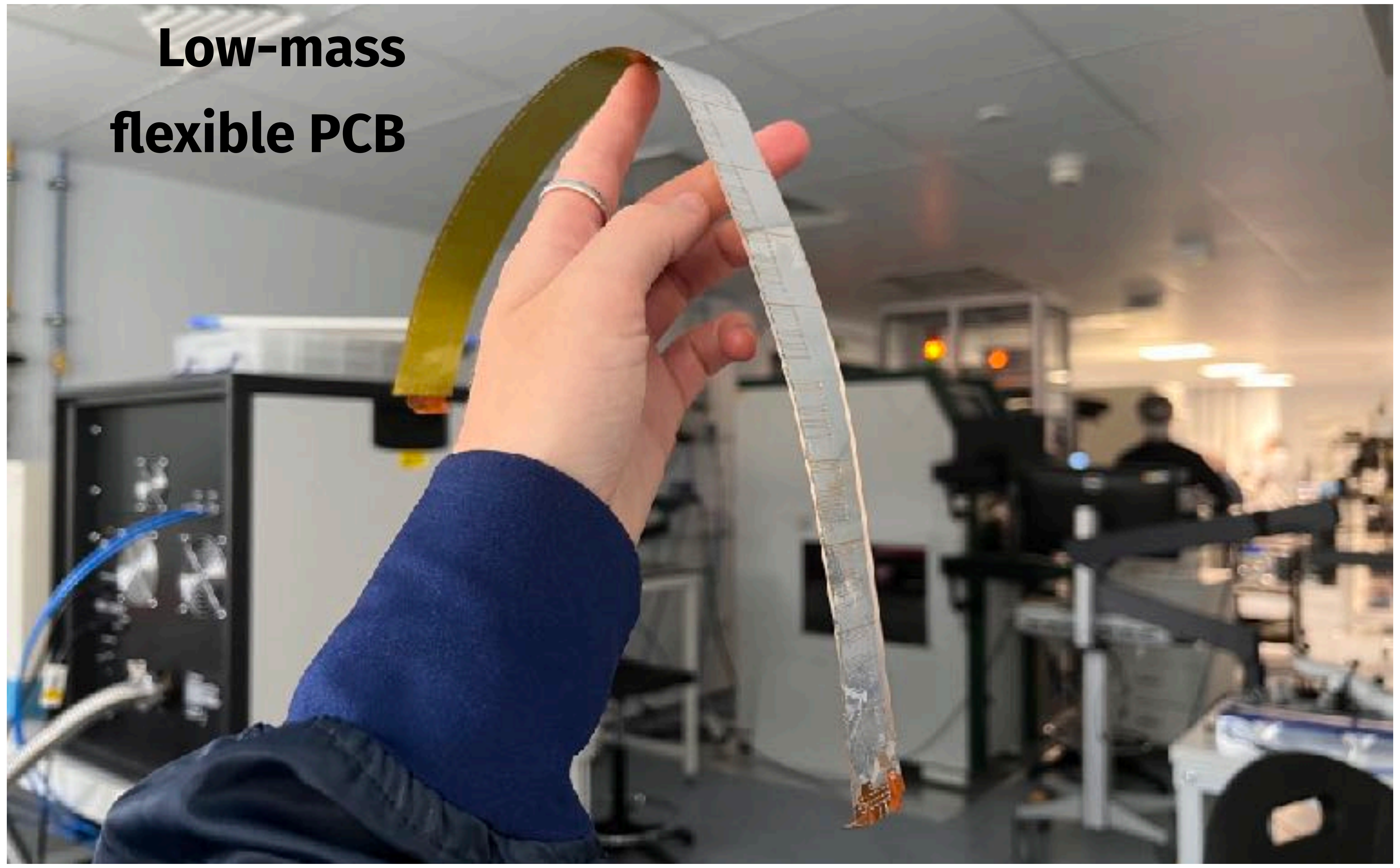
Fully assembled vertex detector!

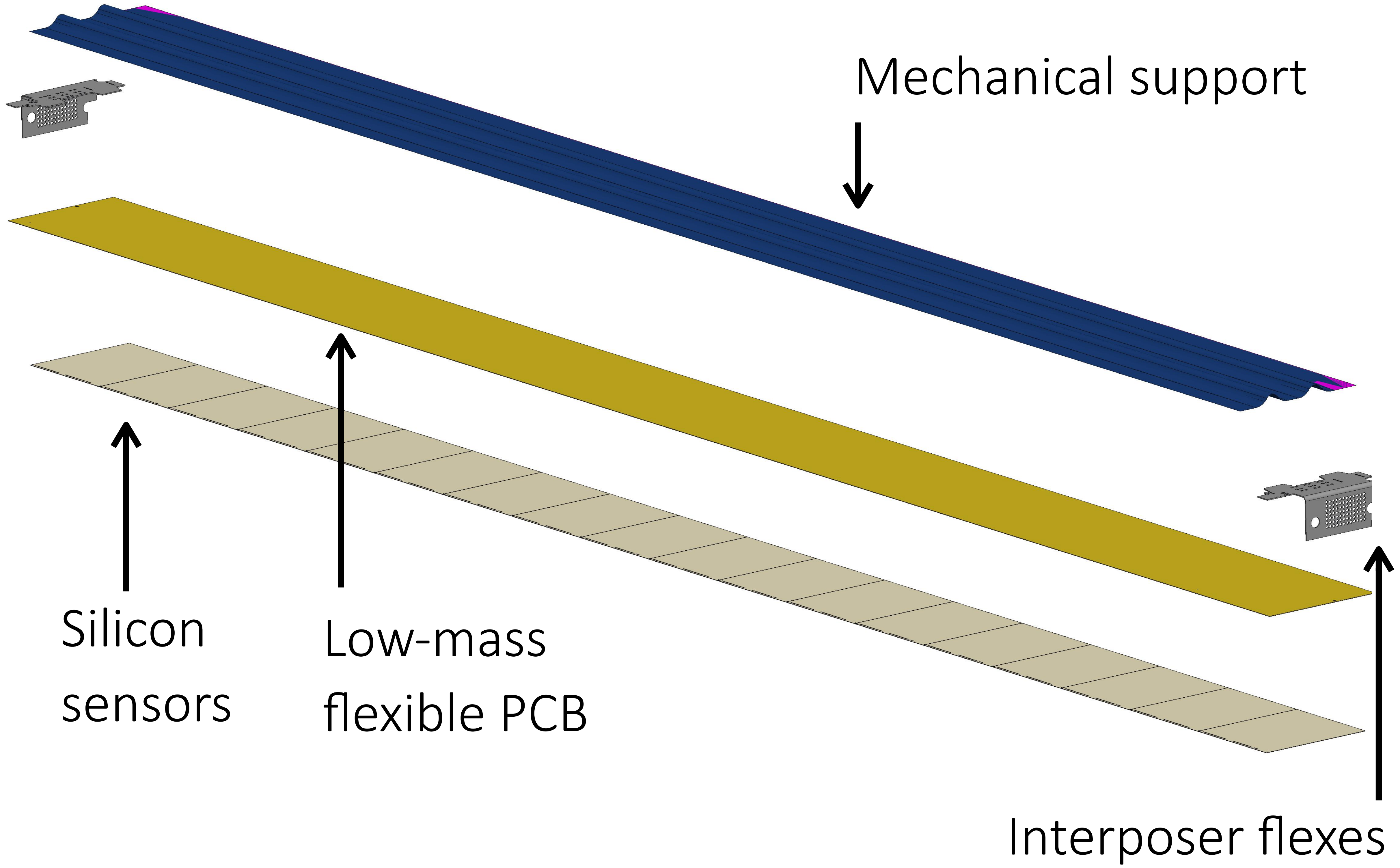
The outer pixel tracker components:

Same ladder components as vertex tracker:

- MuPix sensors thinned to 70µm: 17-18 per ladder
- Aluminium/kapton high-density interconnect, "HDI"
    - Only one company in the world can produce these, LTU in Kharkiv (Ukraine)

+ additional mechanical support





Ladder weighs ~ 2 grams and is 36.7cm long

Mechanical support for the outer pixel ladders:

Mechanical support provided by either:

Polyimide film:

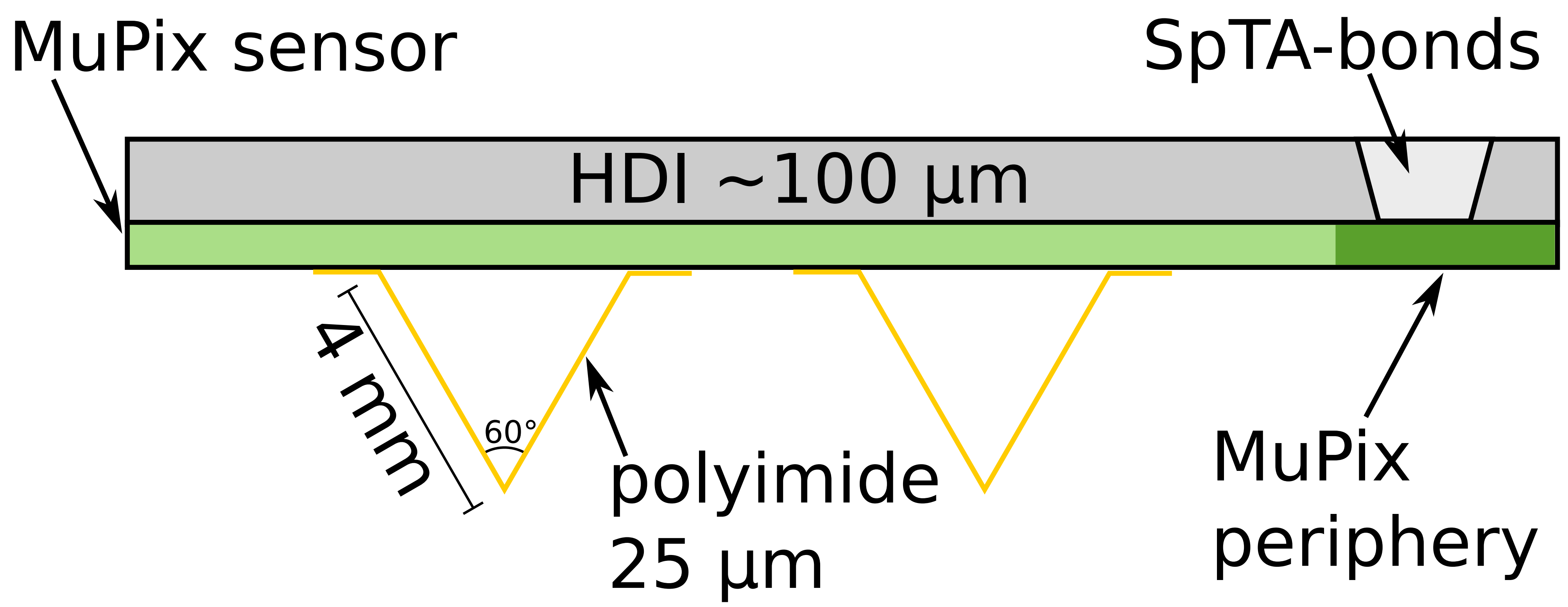
25µm thick folded into two triangles:

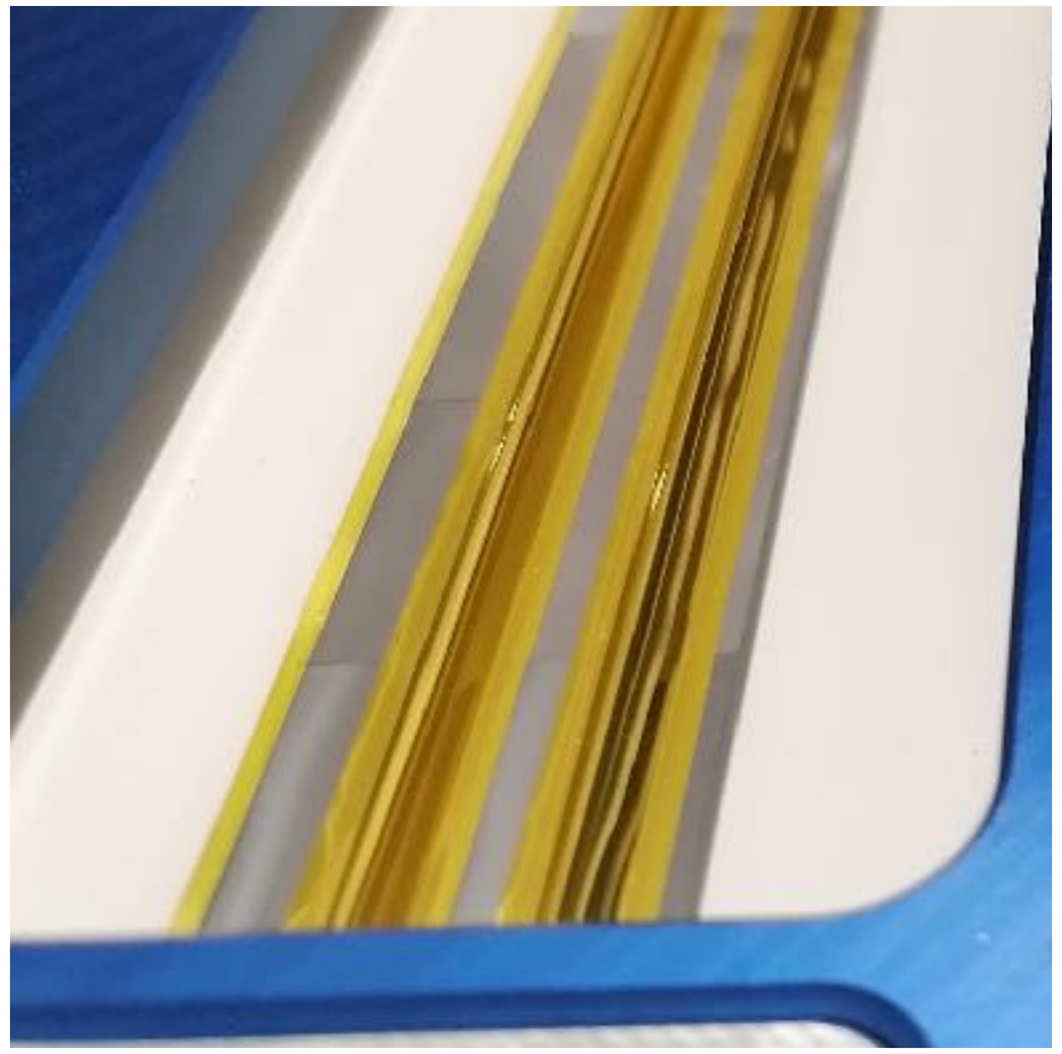
- Sensors/bonds visible underneath
- **Quite delicate** —> difficulties in transportation
- On the edge of providing enough structural integrity for 35cm long ladder

UD fibres (carbon, glass, kevlar):

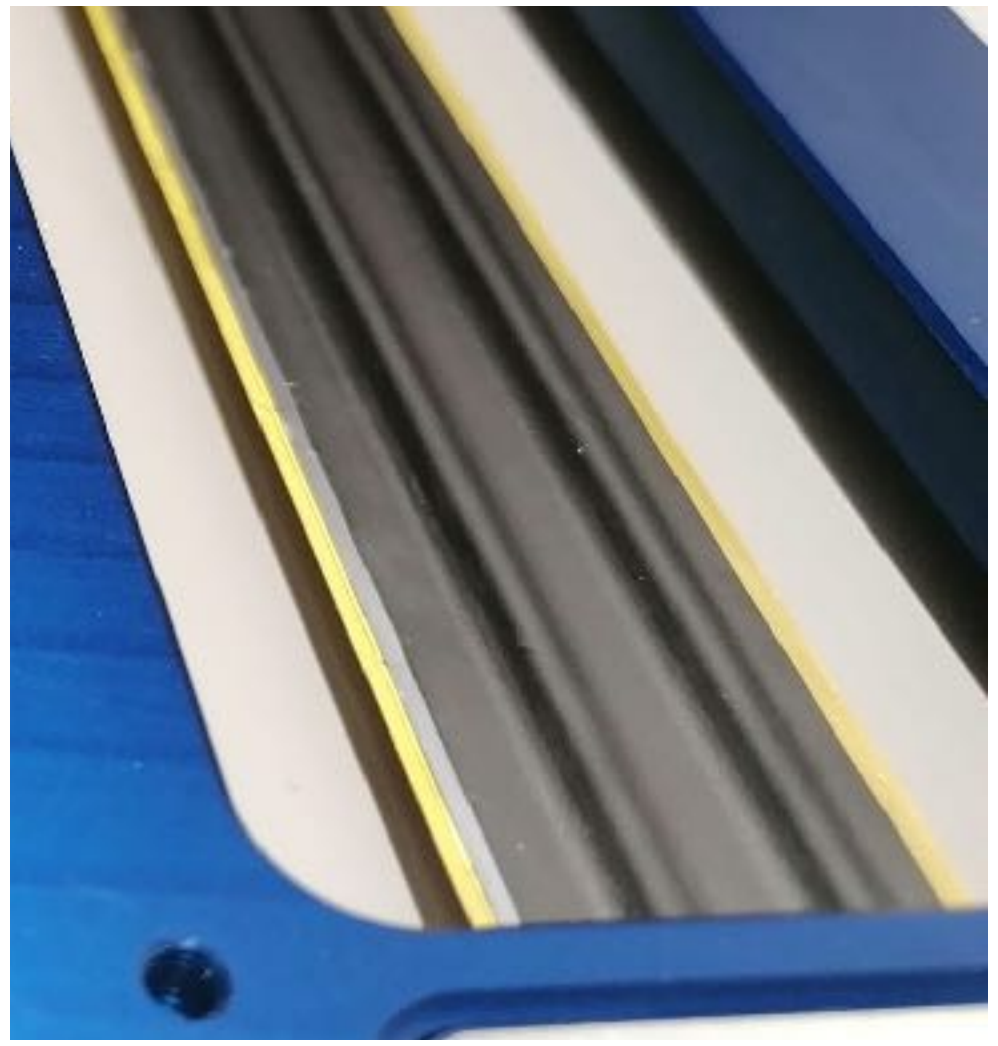
25 µm uni-directional carbon-fibre:

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





Polyimide film



Carbon-fibre

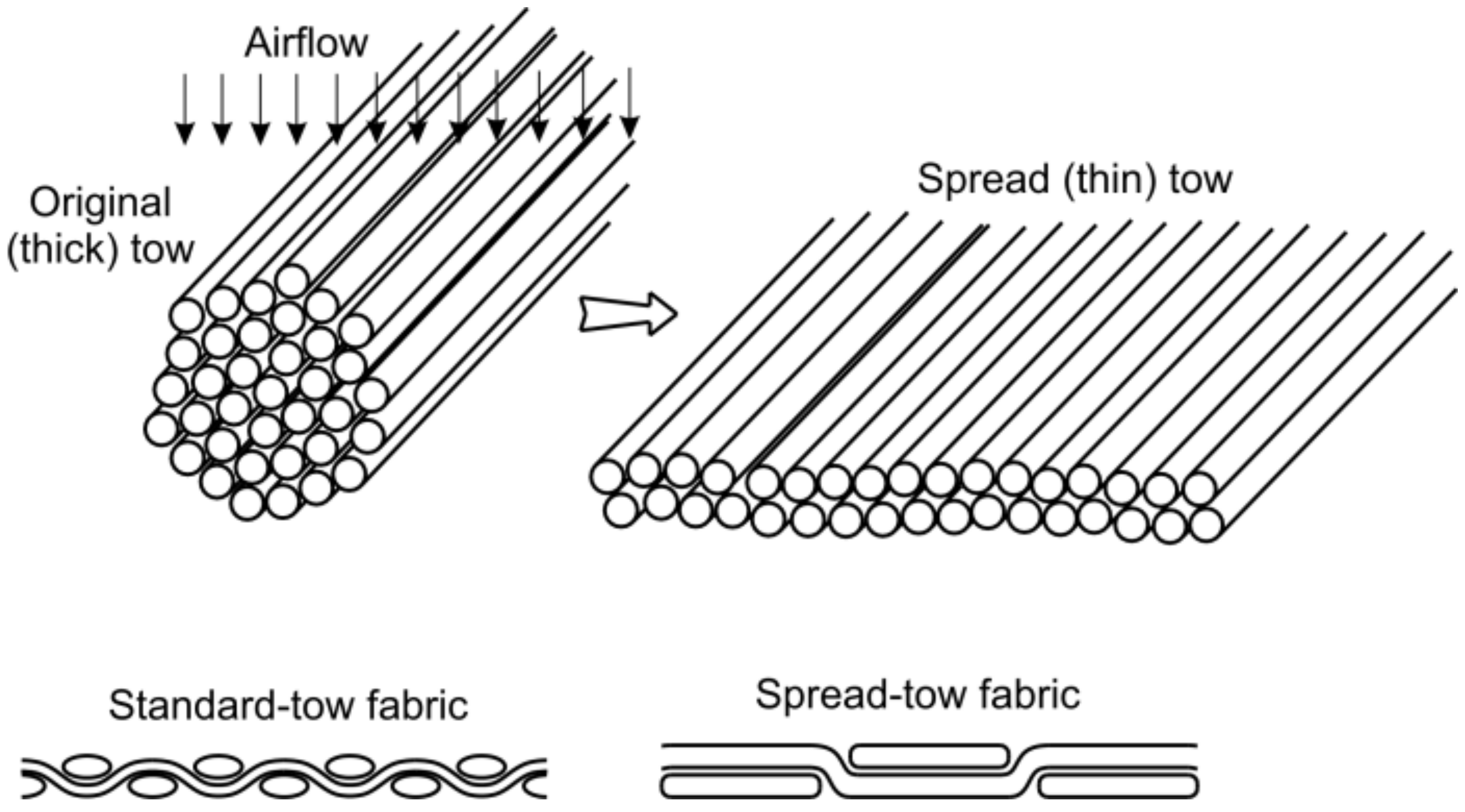
Development of light-weight carbon supports:

25µm carbon-fibre sheet (40% resin content):

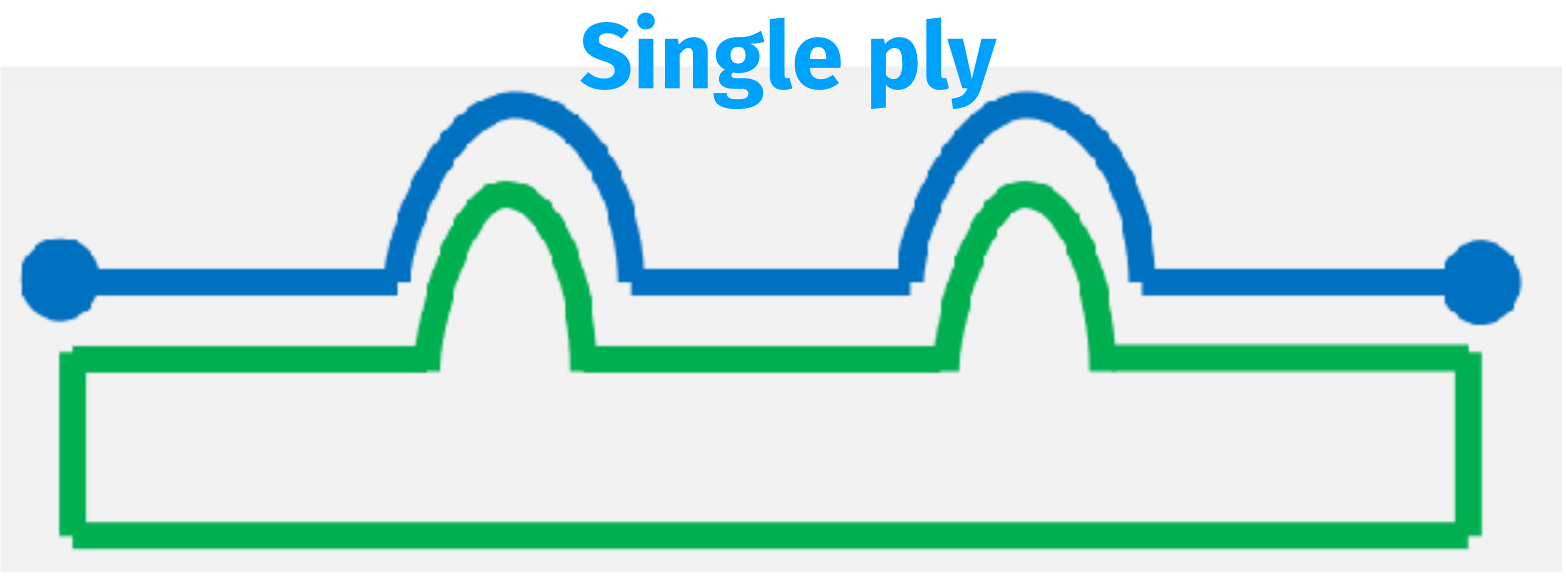
- Material developed for sails for America's cup yacht (Alinghi)

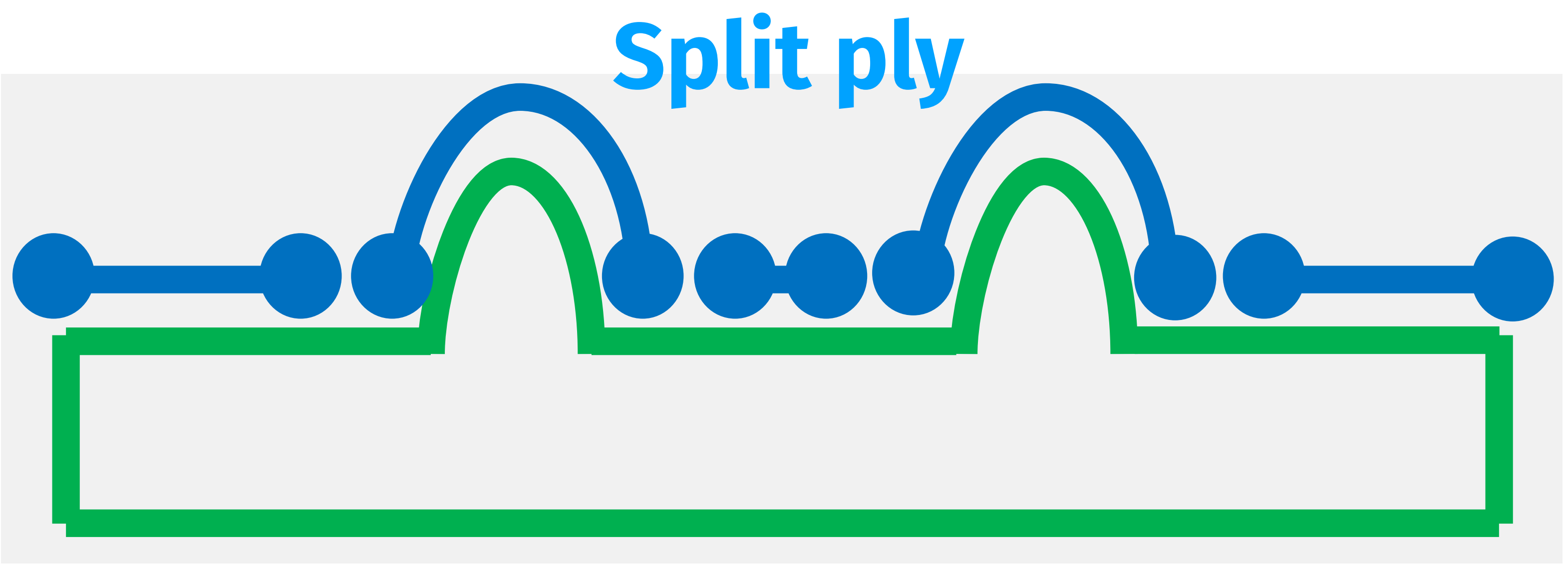
Mu3e design highly non-standard, no industry used case:
Design and fabrication development with mechanical engineers with composites background from F1.

- **Single ply uni-directional:** carbon-fibres usually woven together => too much material!
- **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



[doi.org/10.3390/polym15071767]





Fabrication of carbon-fibre supports:

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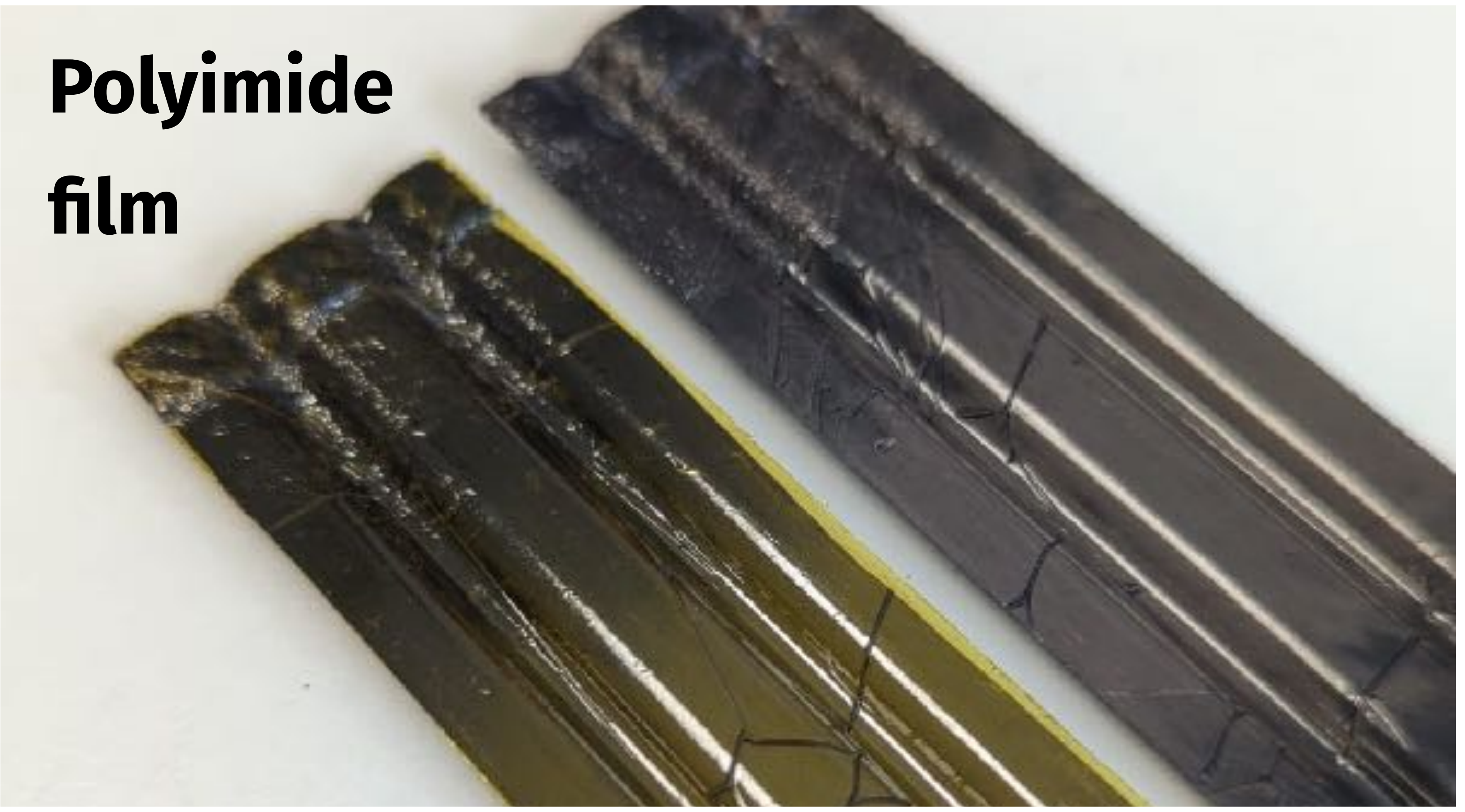
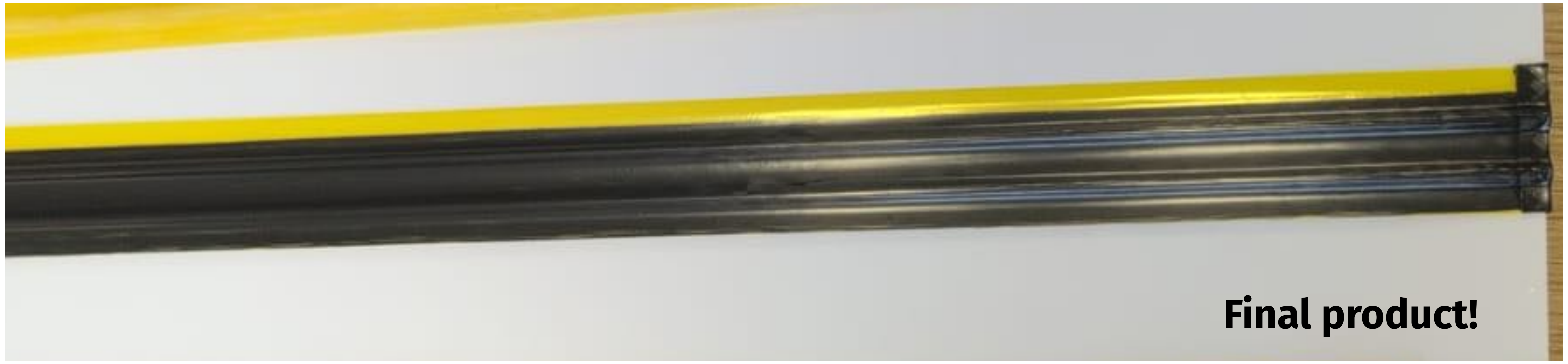
BRICK KILN COMPOSITES

Favourable thermal and mechanical properties deem carbon-fibre supports as best choice.

- Average mass = 0.735 g





Fabrication procedure for outer pixel layers:

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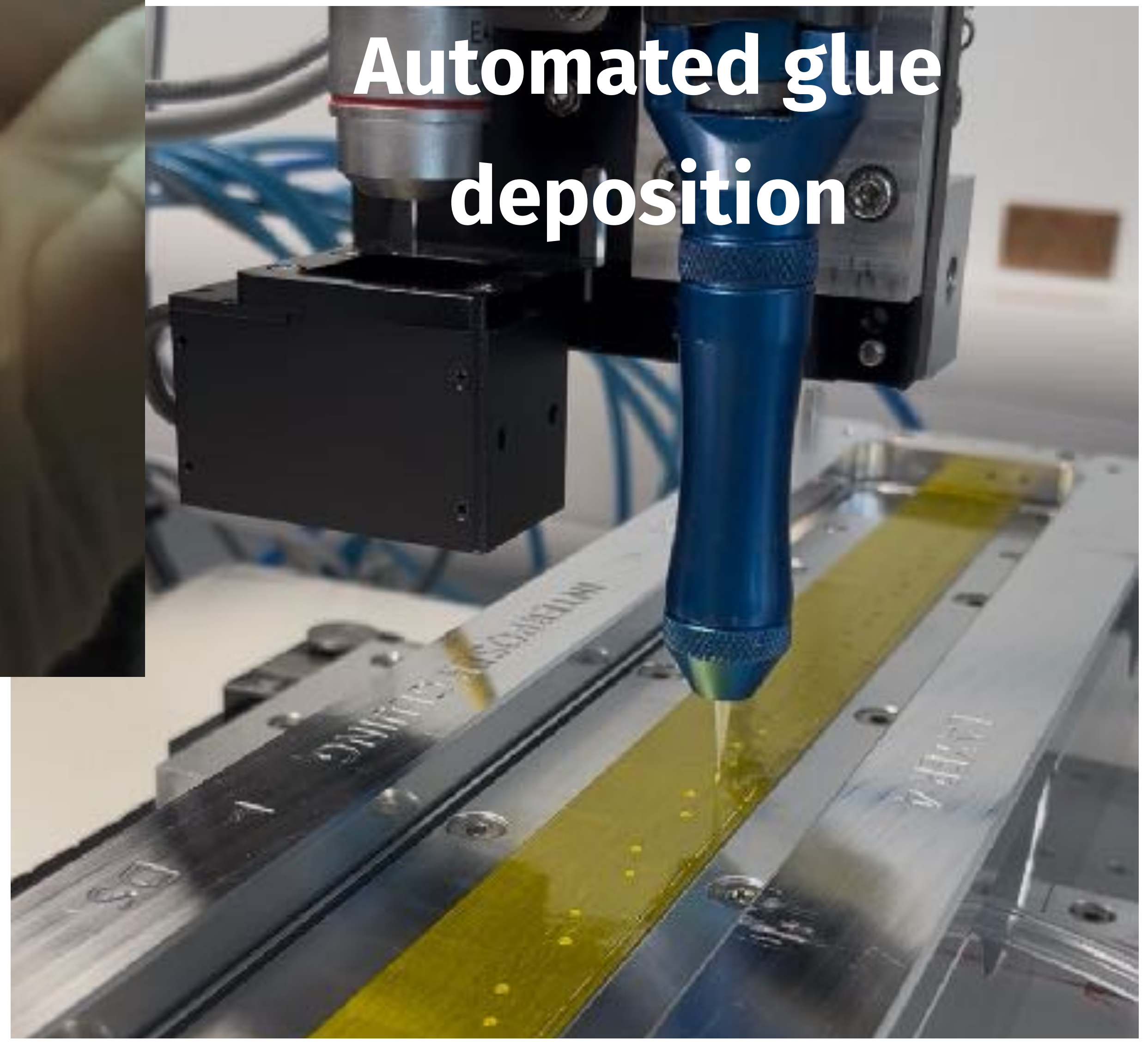
Total ladders: 156 ladders (~ 3000 sensors)

- Entire production and QC in Oxford cleanroom facility
- To cope with scale of production and accuracy required: automate build procedures
- Robotic gantry with pattern recognition used for placement of chips on vacuumed ladder tool.

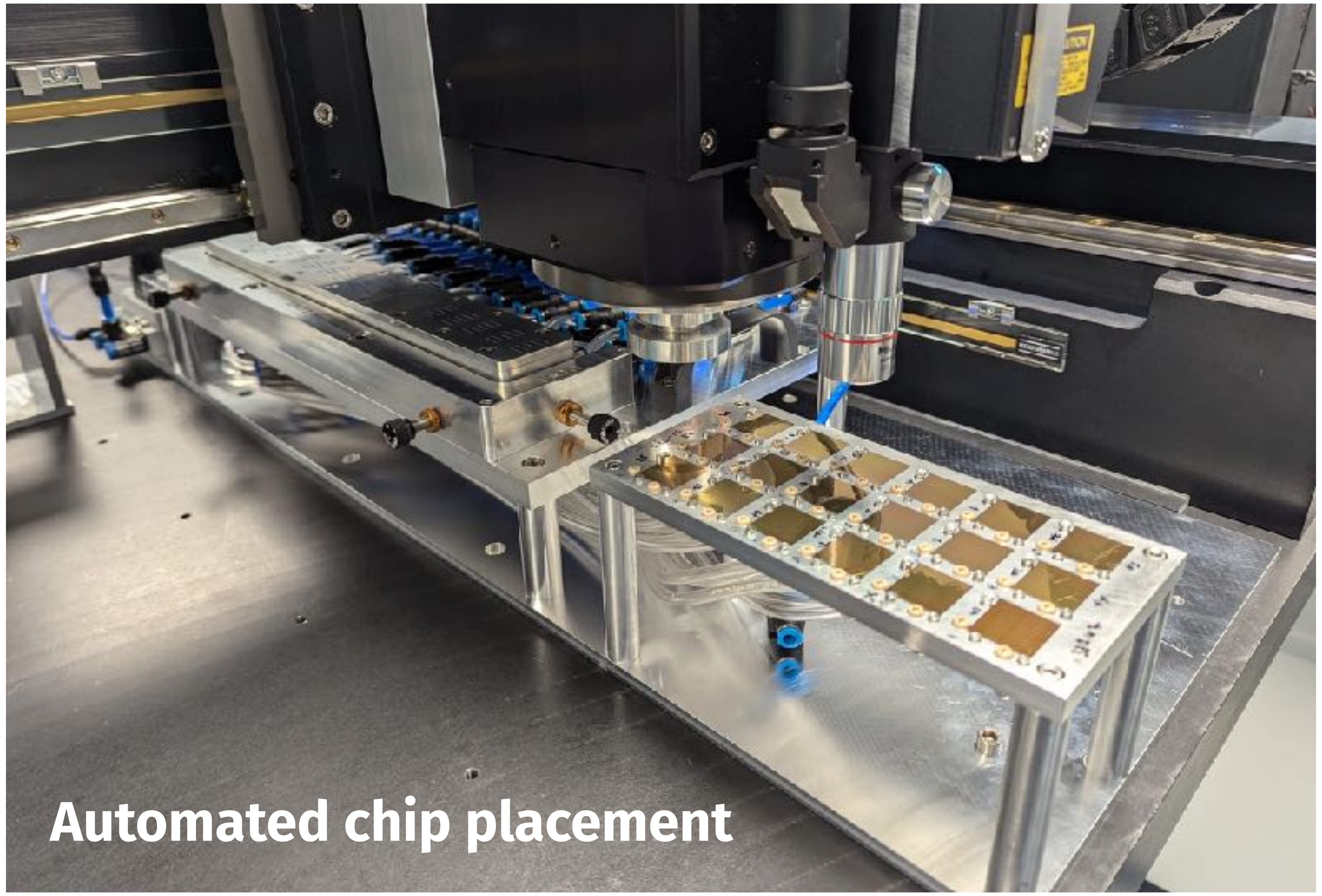
Production taking place @ Oxford

Tiny glue deposits



Automated glue deposition

- Automated glue placement to minimise excess material



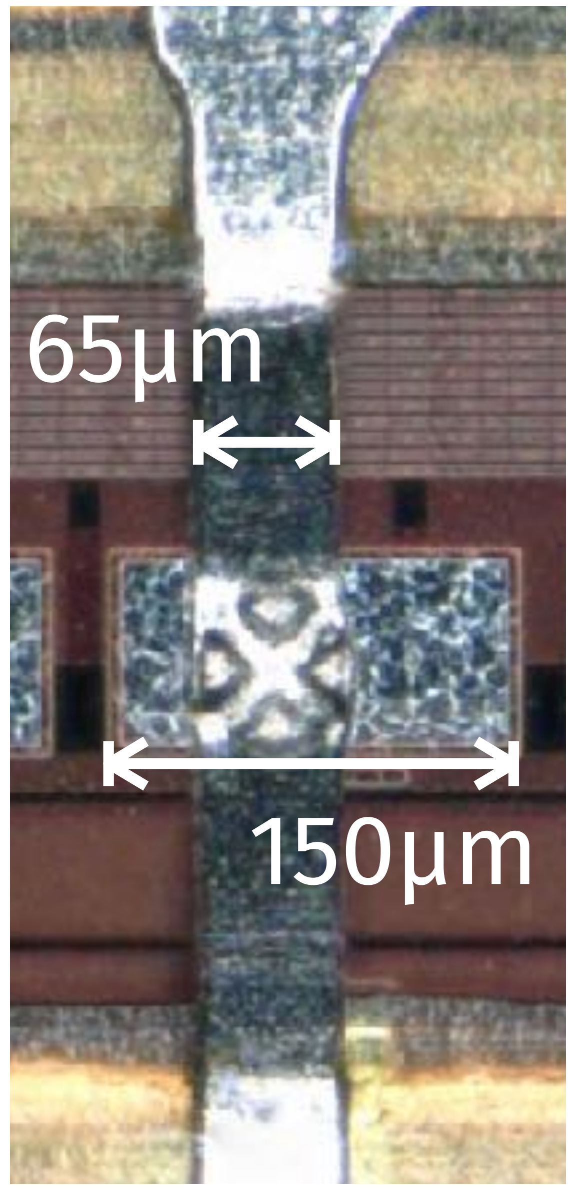
Automated chip placement

Sensor alignment precision:

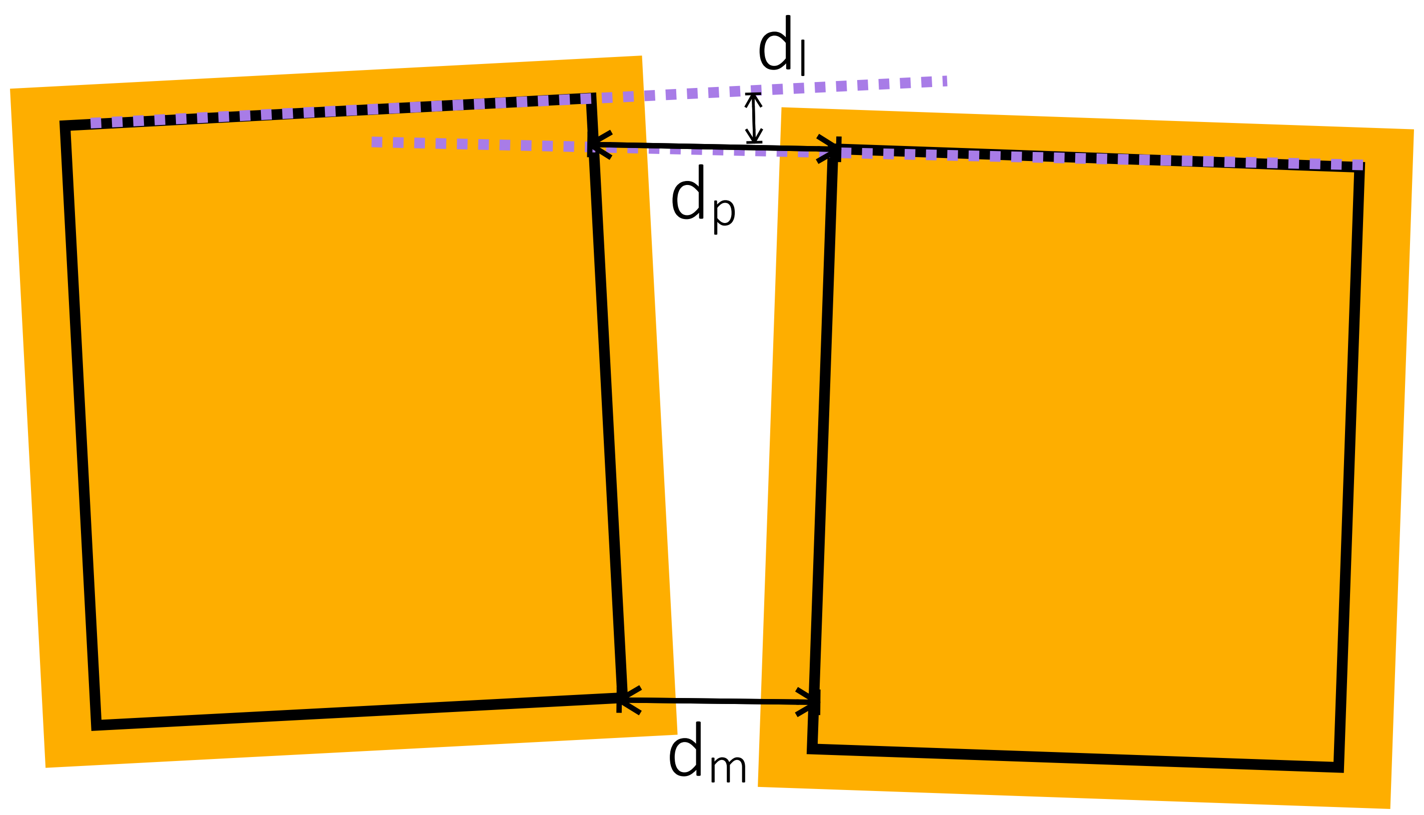
Outer pixel ladders have > 1000 spTAB connections each!

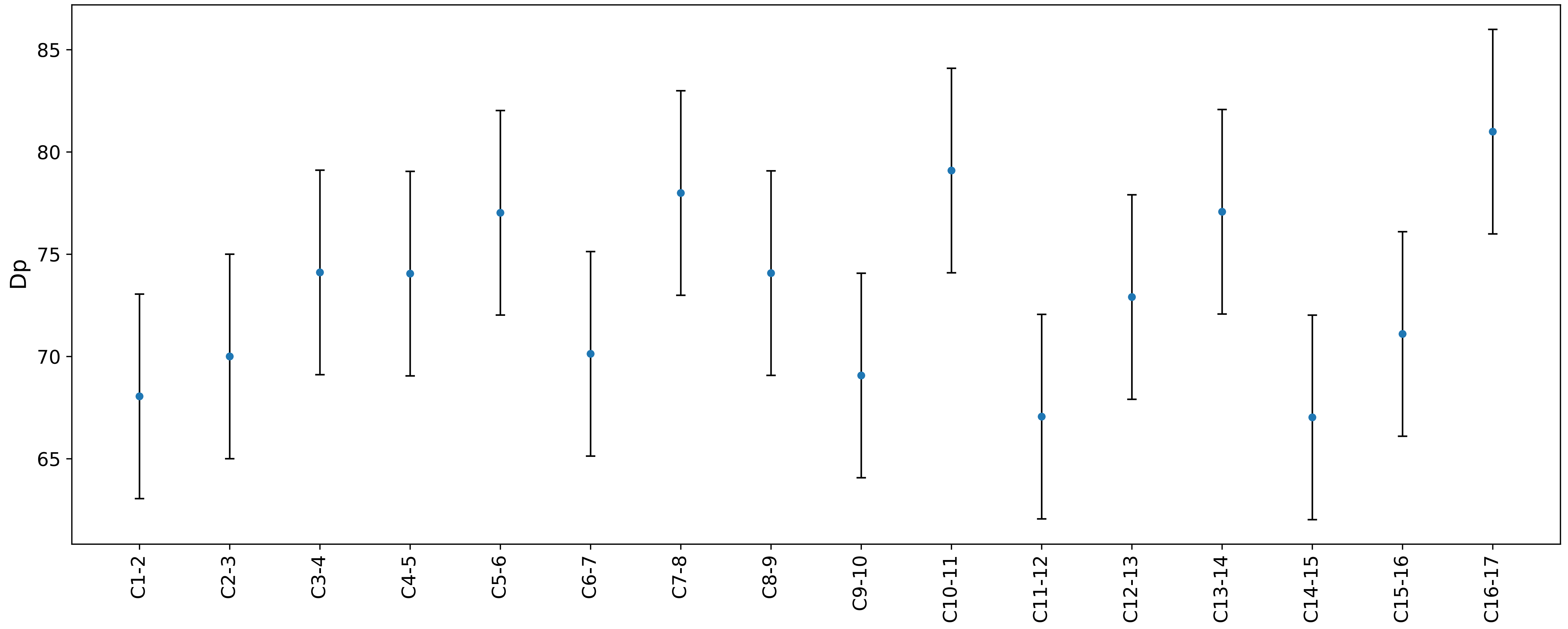
Sensors must be positioned very precisely (± 10 µm):

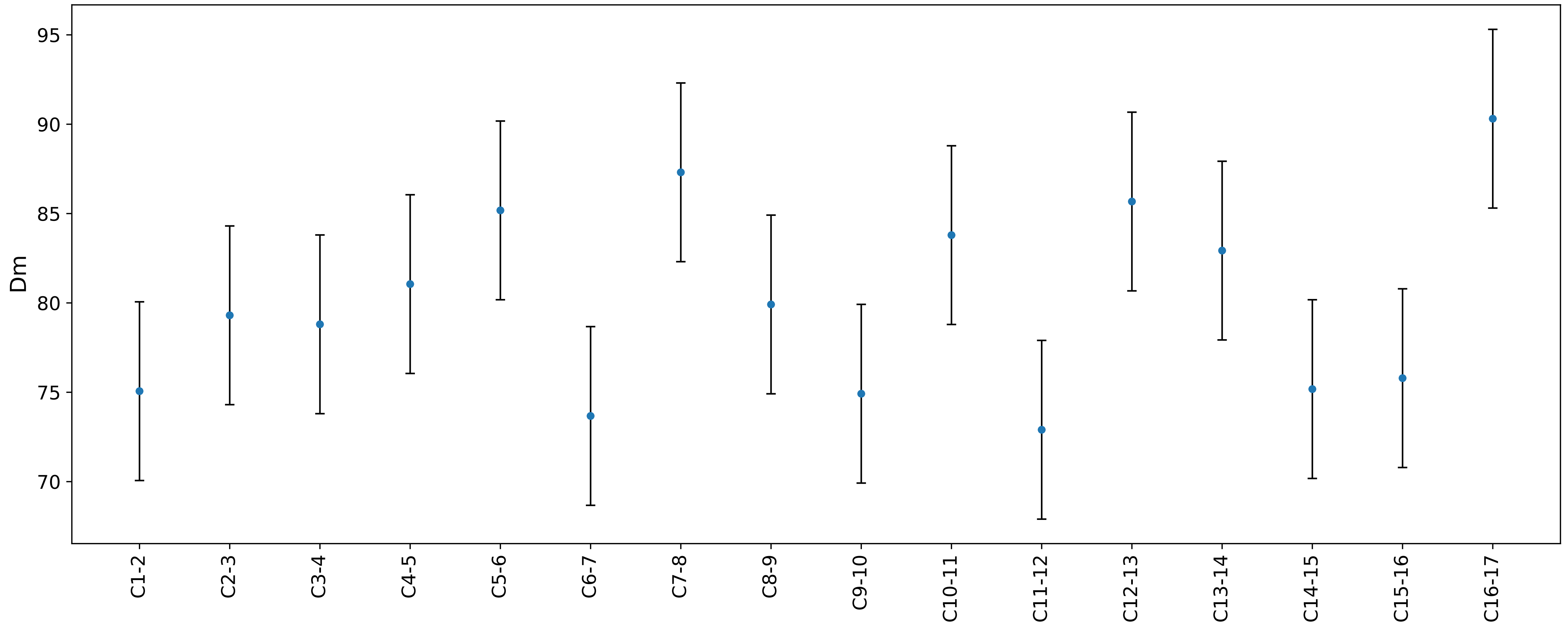
- To account for HDI length variations
- To ensure sufficient gap between sensors to avoid collisions due to thermal contraction during operations



Definition of alignment parameters:







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A completed ladder:

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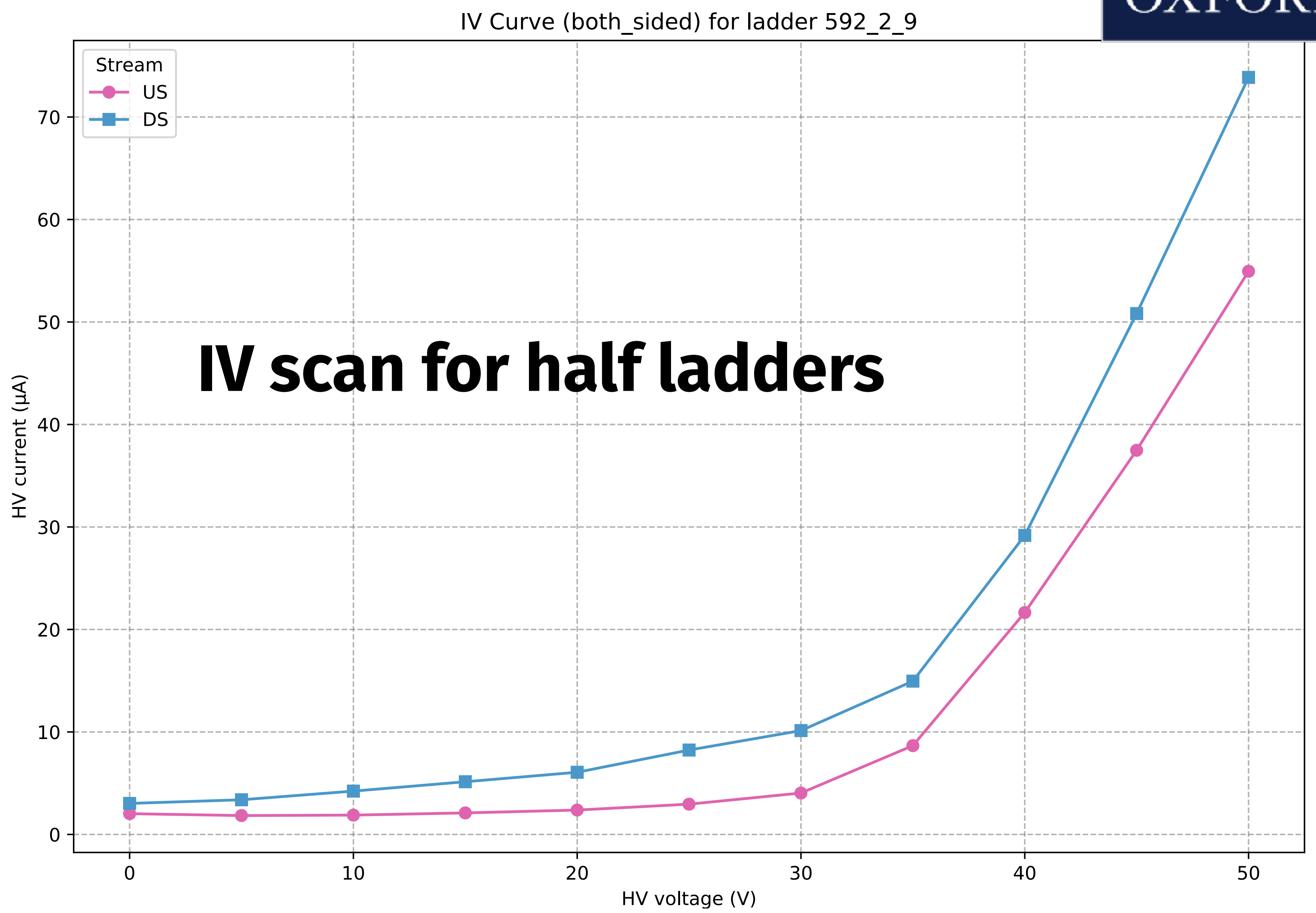
Qualification procedure for ladders:

After assembly, **each ladder is individually QC tested** before module assembly.

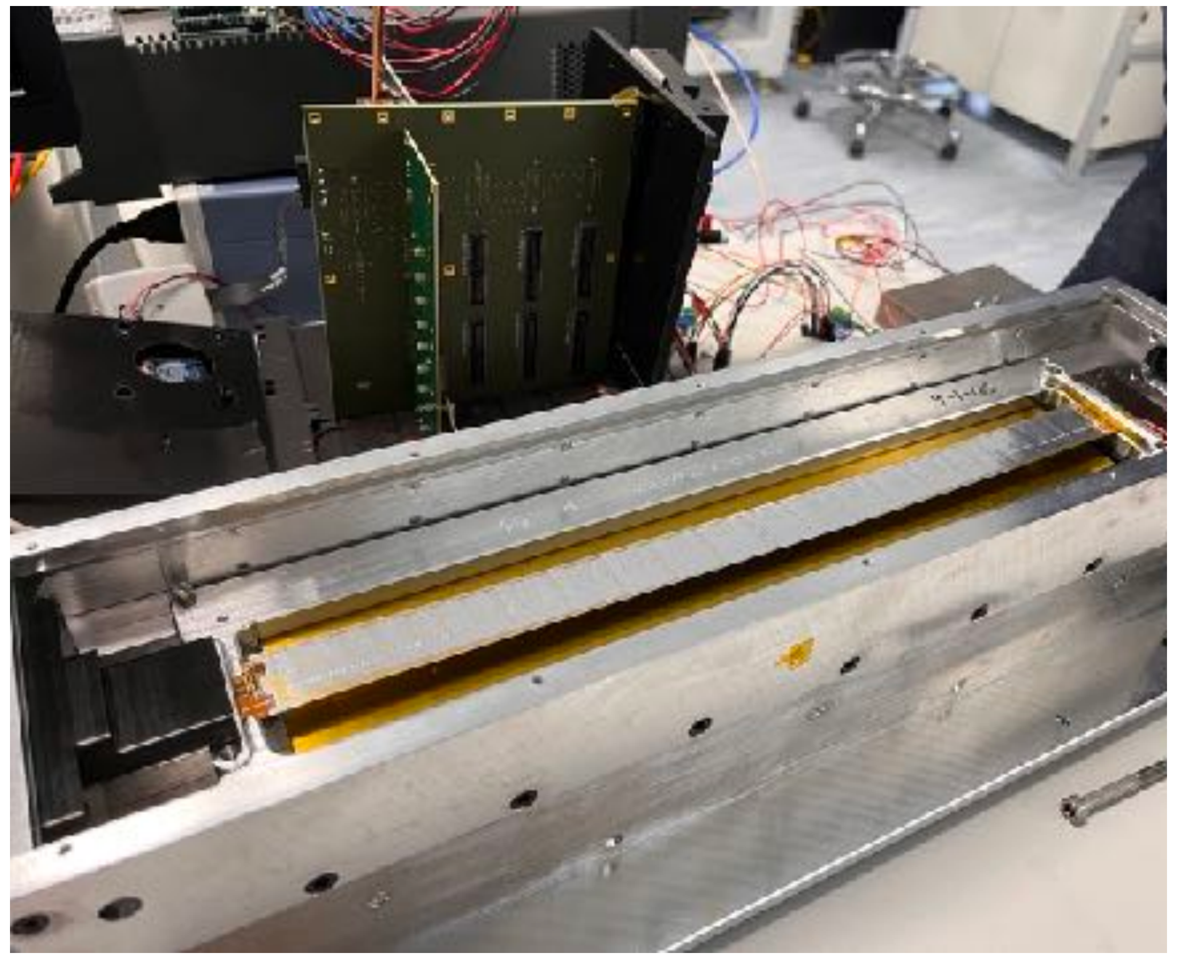
QC tests include:

- IV measurements
- Power consumption measurements
- On-Chip DAC response
- Data transmission stability
- Noise behaviour (pixel maskability)
- Response to radioactive source

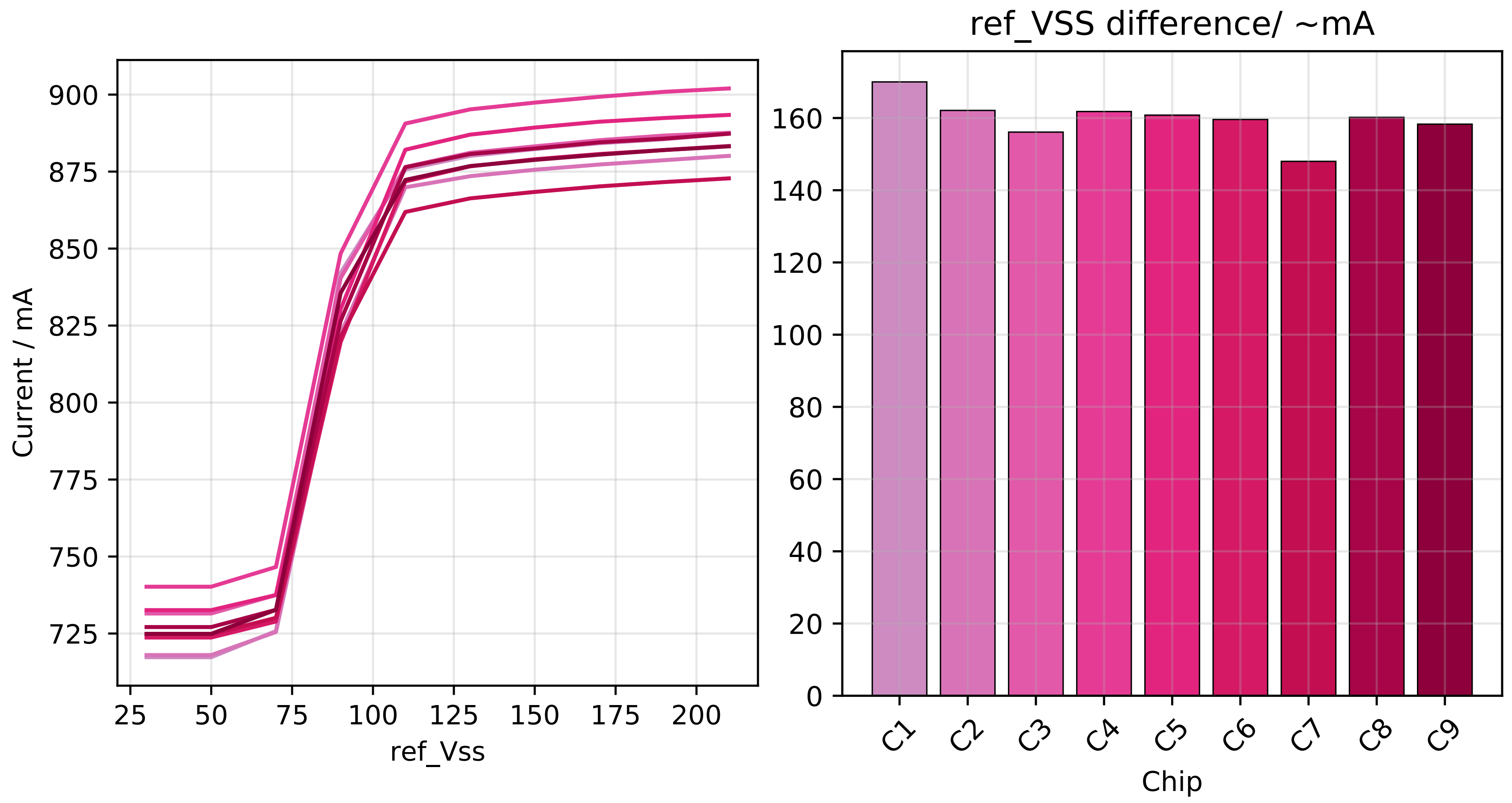


Production currently on-going: build rate ~ 5 ladders per week.

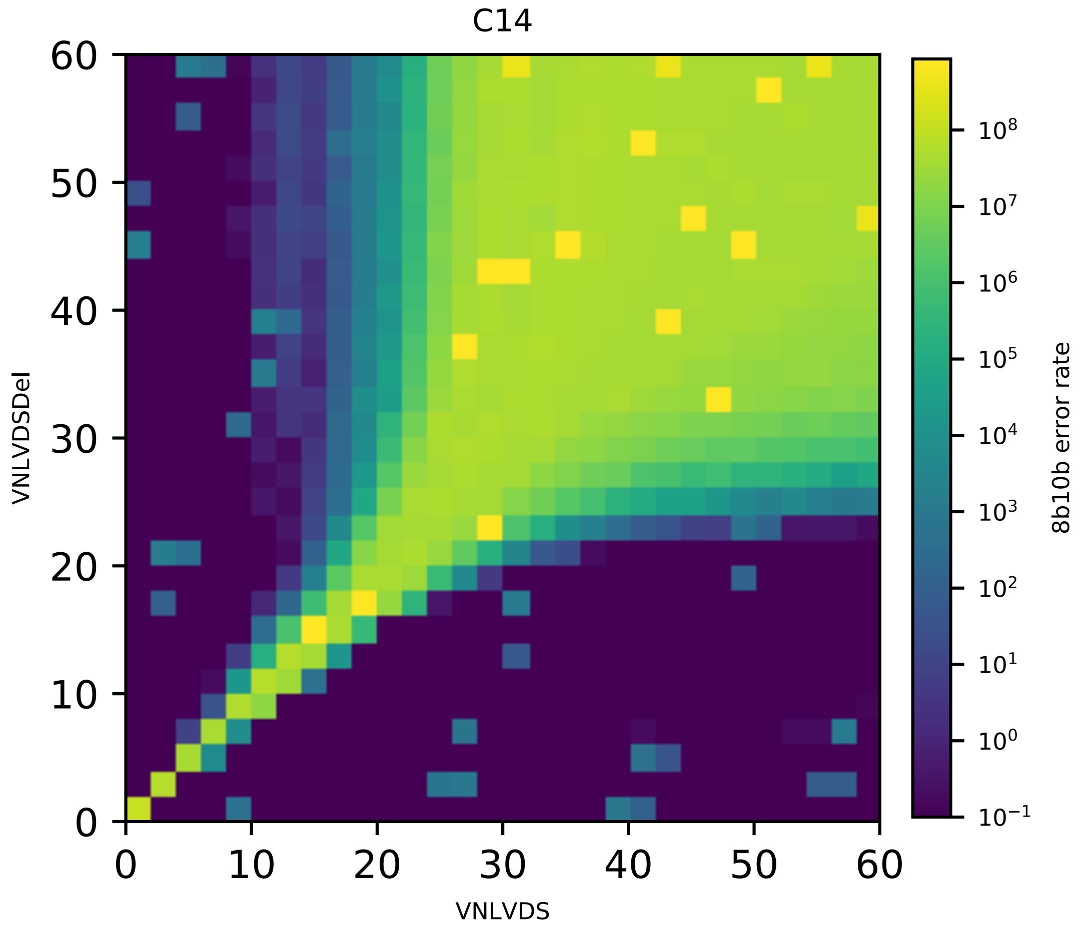
QC also undertaken once ladders mounted on modules.



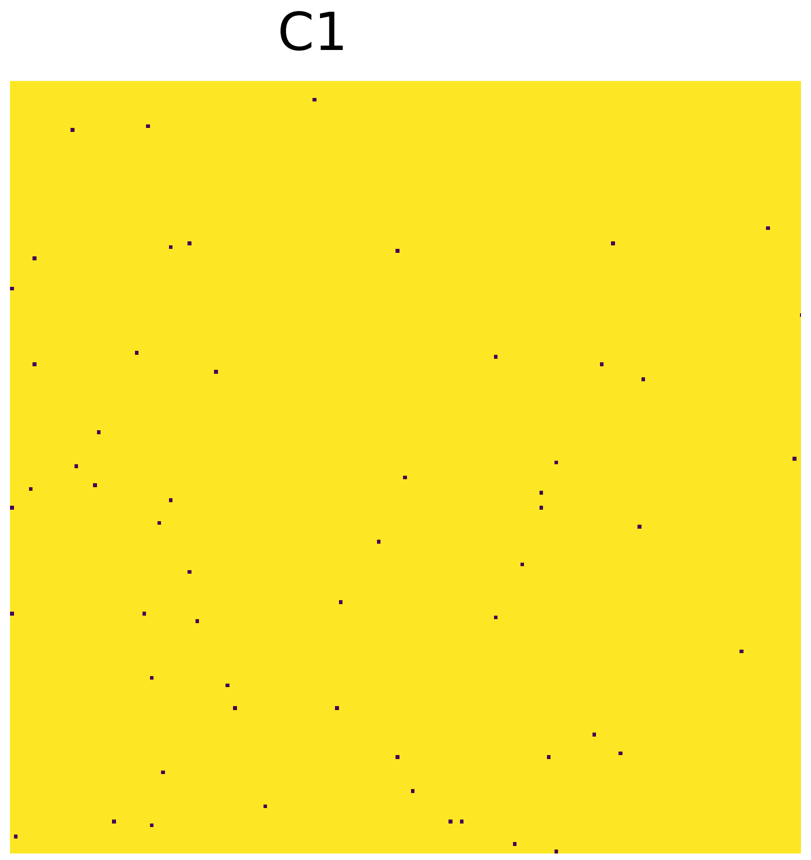
Ladder QC test box (cooled with cold dry air)



Current response to amplifier DAC



DAC values for error-free data transmission

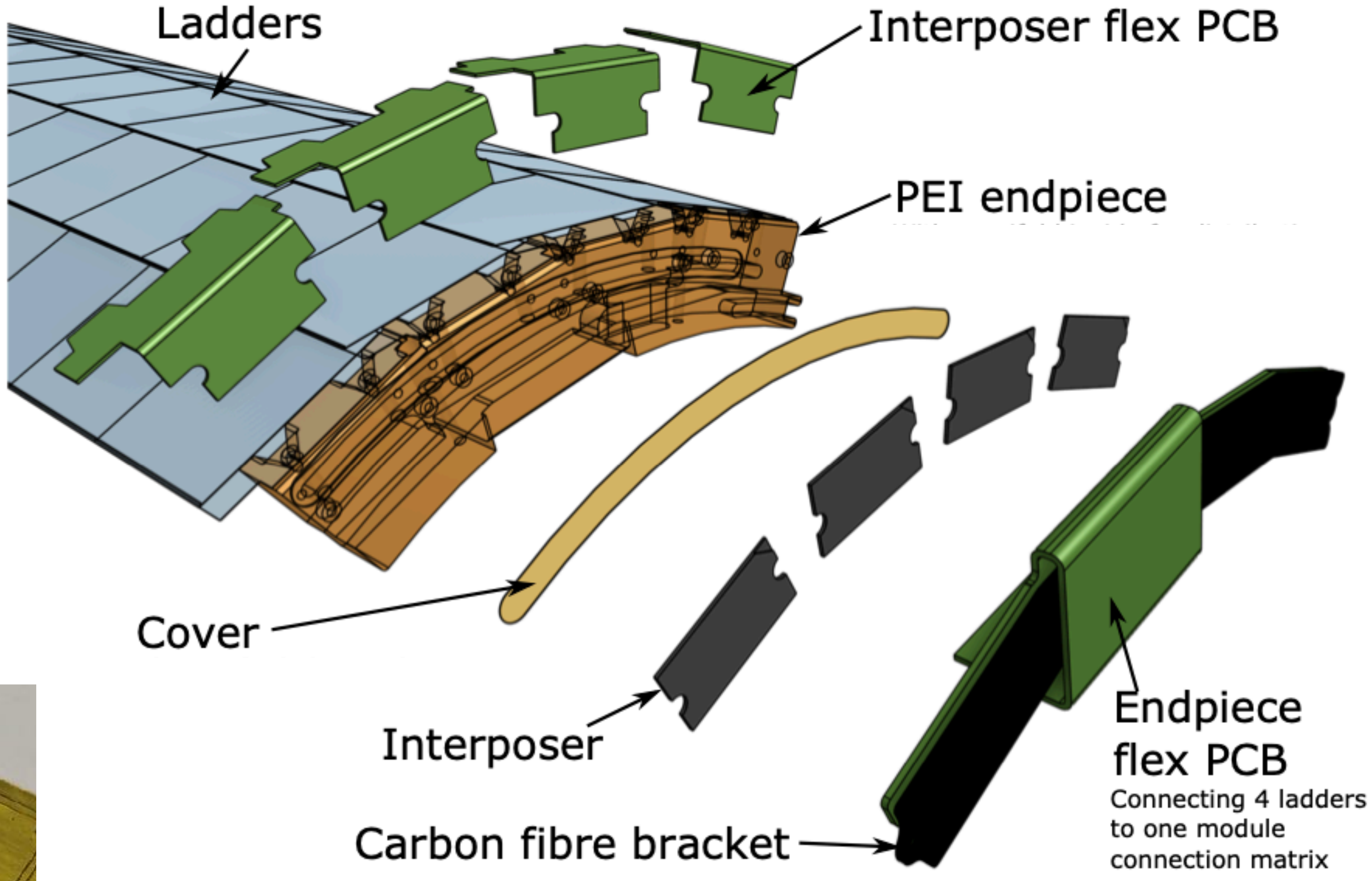


Tot masked pixels = 92 (0.14%)

Noise map of pixel matrix

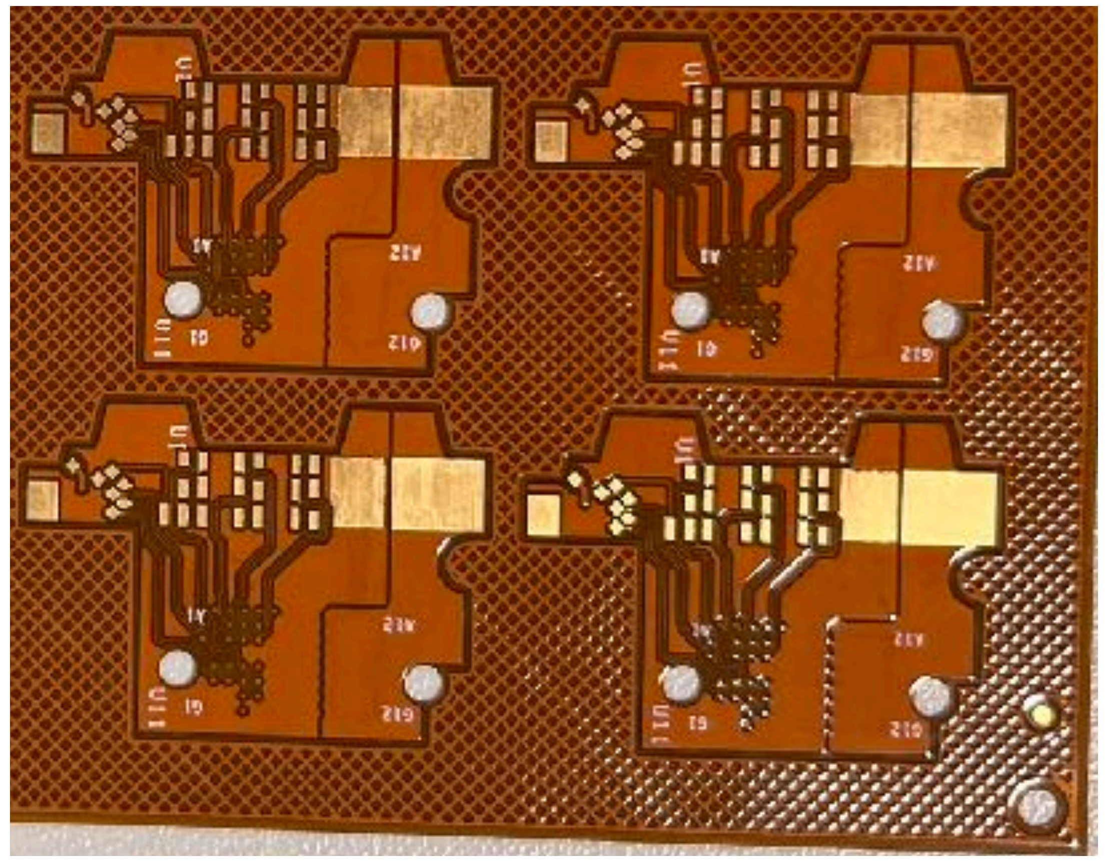
Assembly of outer pixel modules:

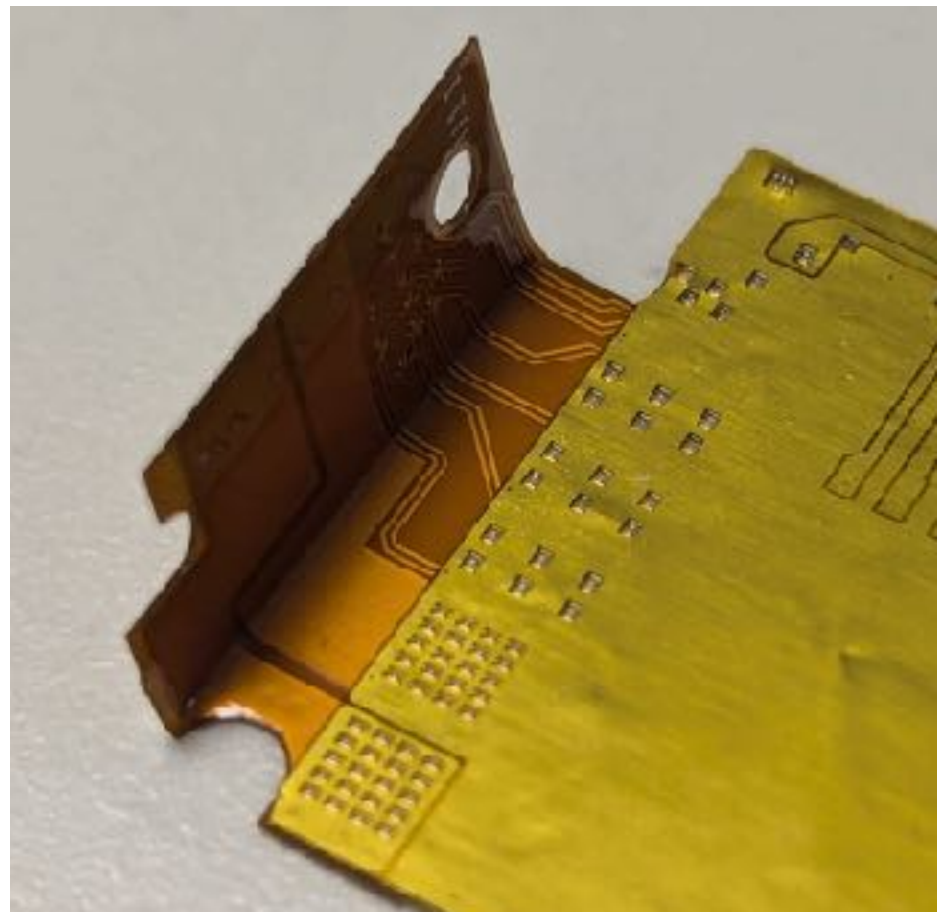
Layer	1	2	3	4
Number of ladders/modules	4	5	4	4
Number modules total	2	2	6	7
Number of ladders total	8	10	24	28
Number of sensors total	48	60	408	504



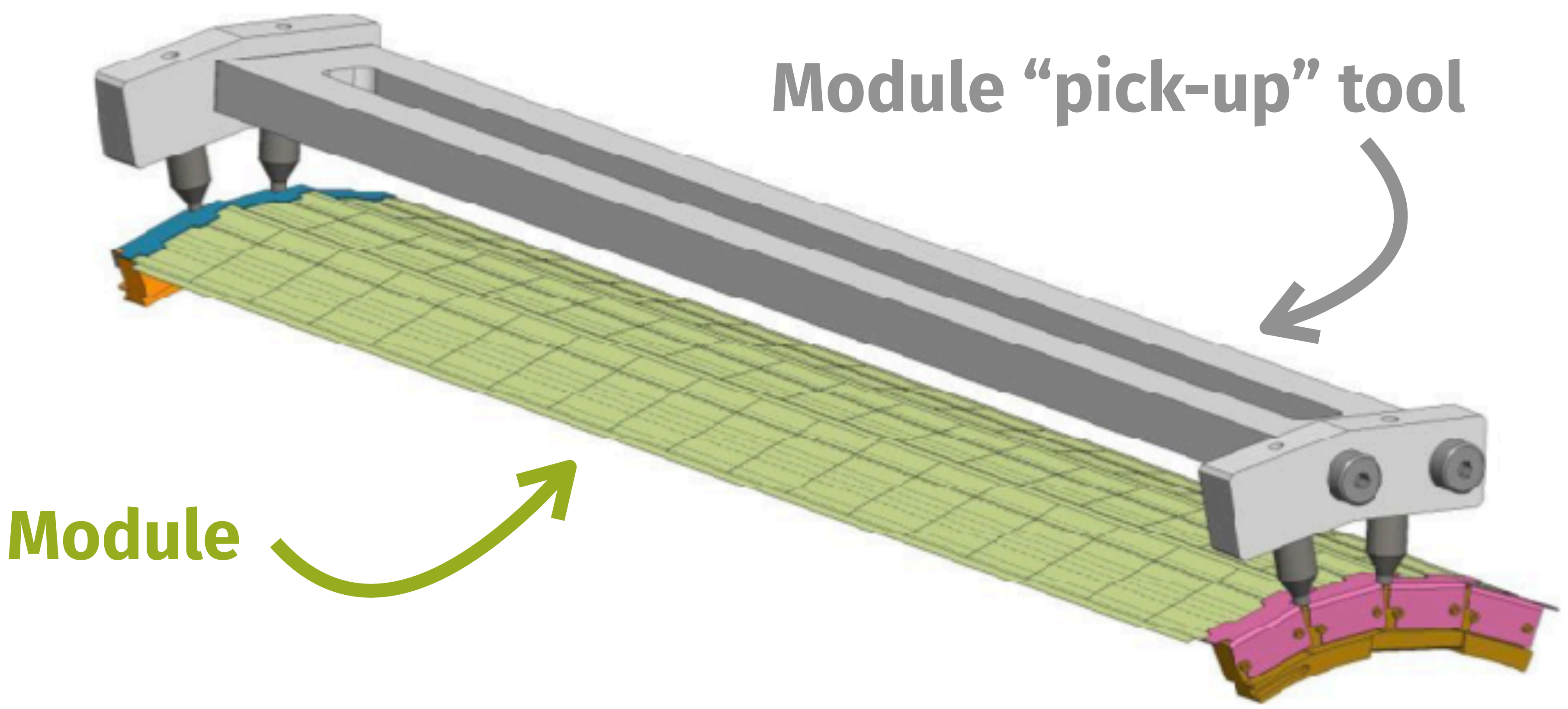
Due to space constraints — PCBs for read-out need to be bent into shape:

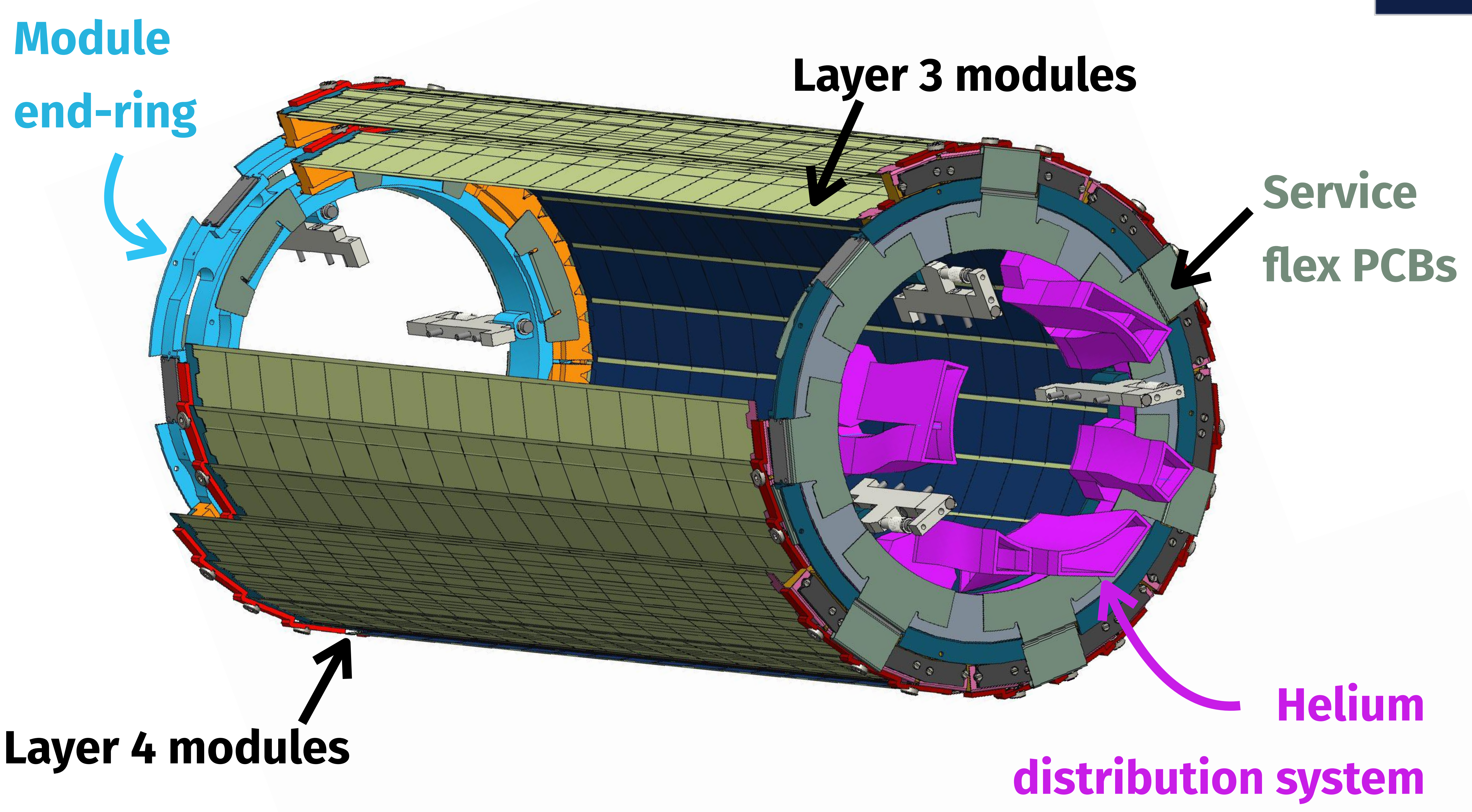
- 90° bent 4-layer copper “interposer flex” for ladder
- 180° bent end-piece flex for module





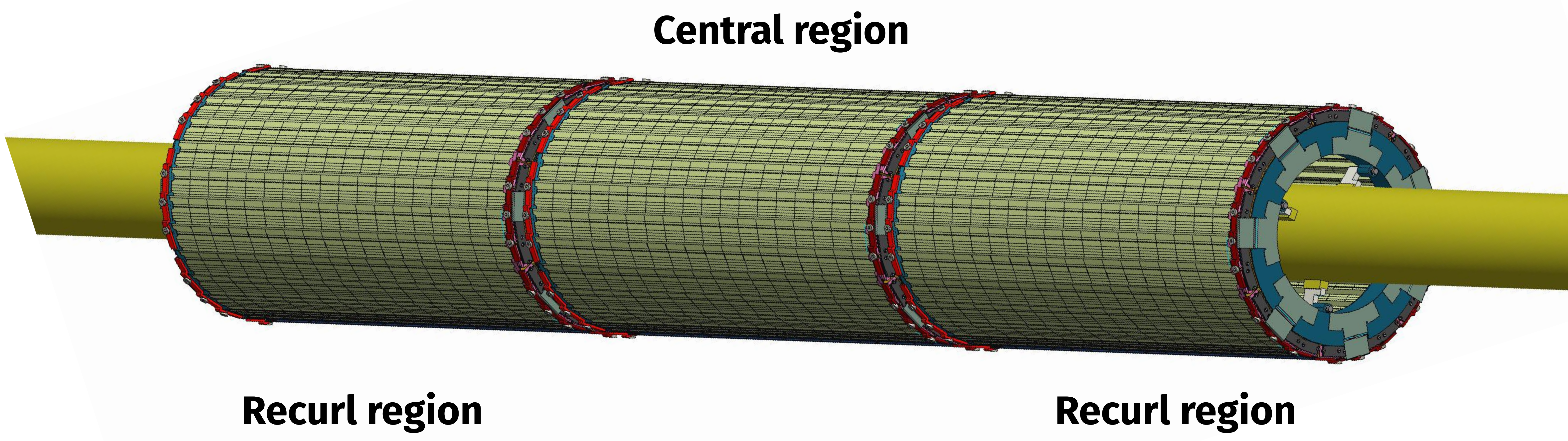
Outer pixel layers:





Modules mounted on each layer's end-ring (kapton)

- Module pick-up tool screws into module end-piece (kapton)
- All services (electrical PCBs and Helium system) attached to end-rings

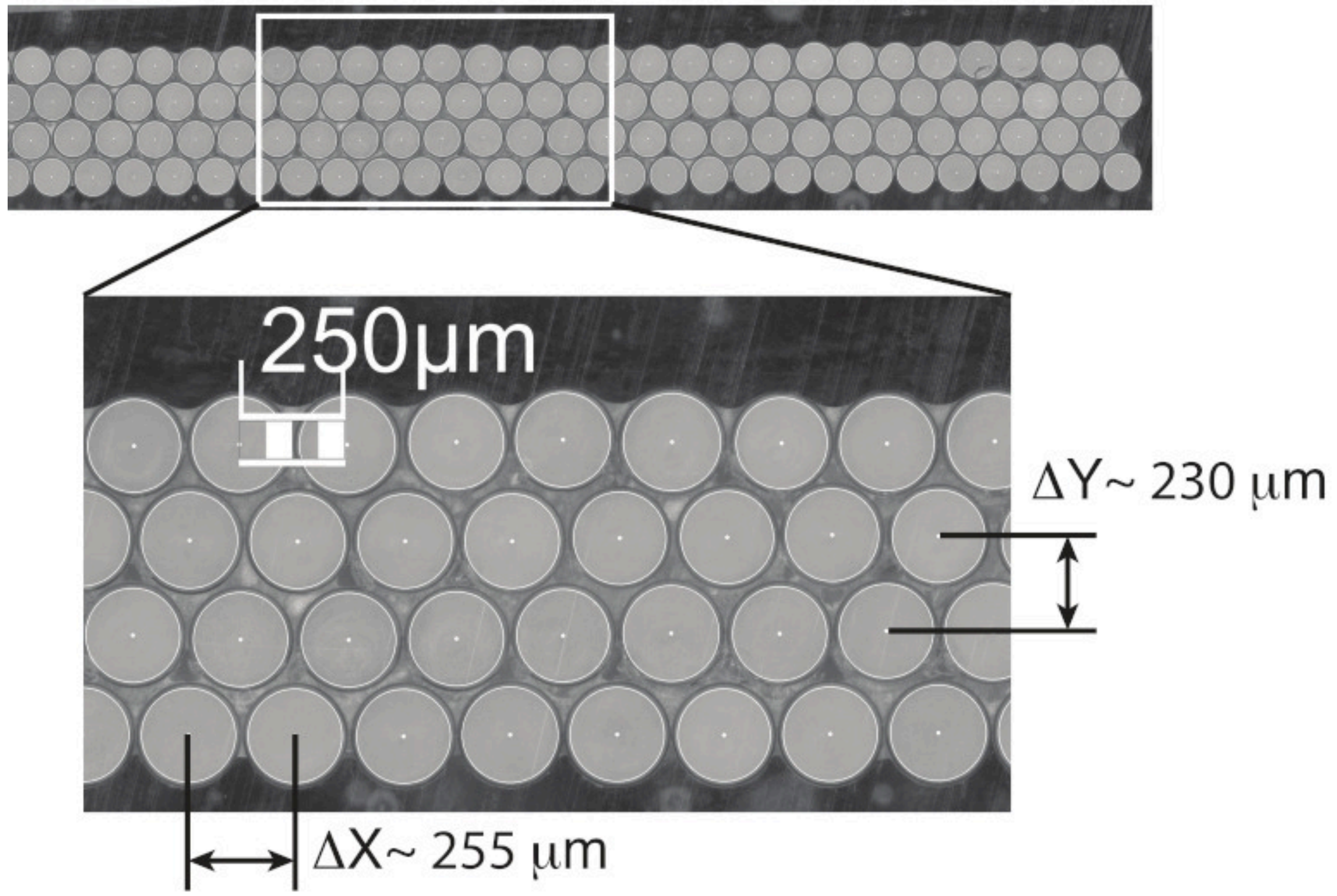


Timing detectors: scintillating fibres

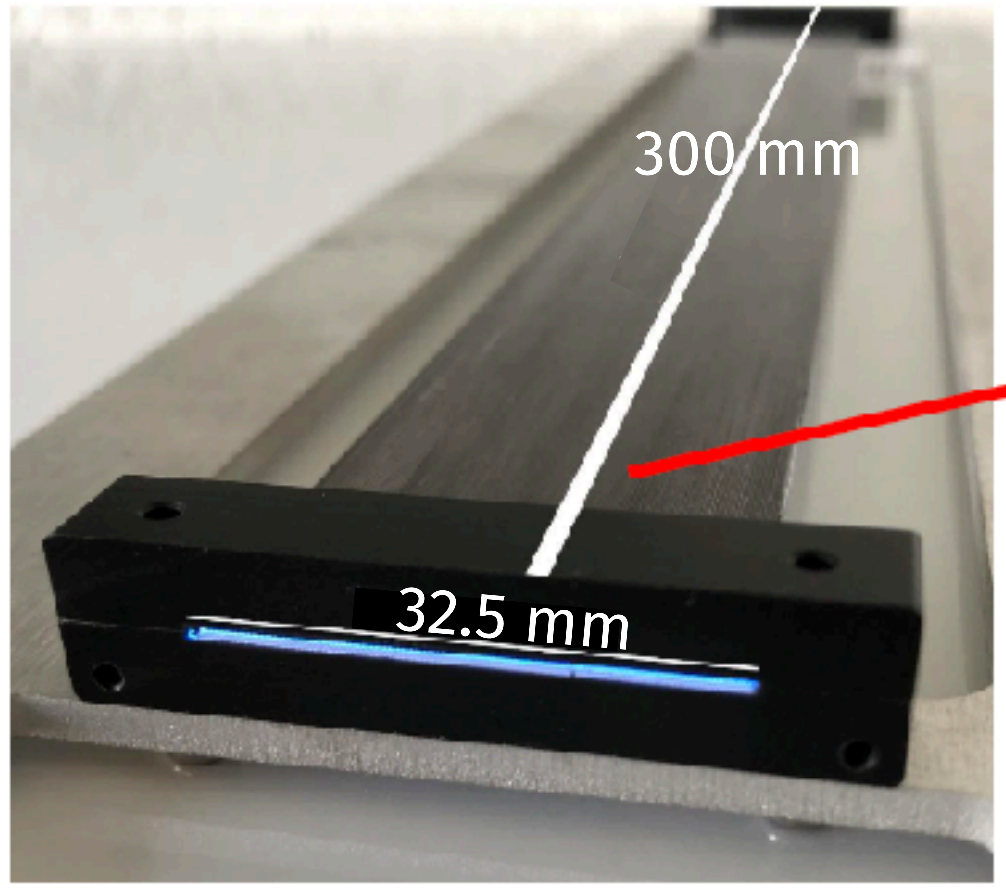
Scintillating fibres (SciFi): scintillating photo-multiplier tubes (SiPMs)

Used to **suppress accidental background** through additional timing information

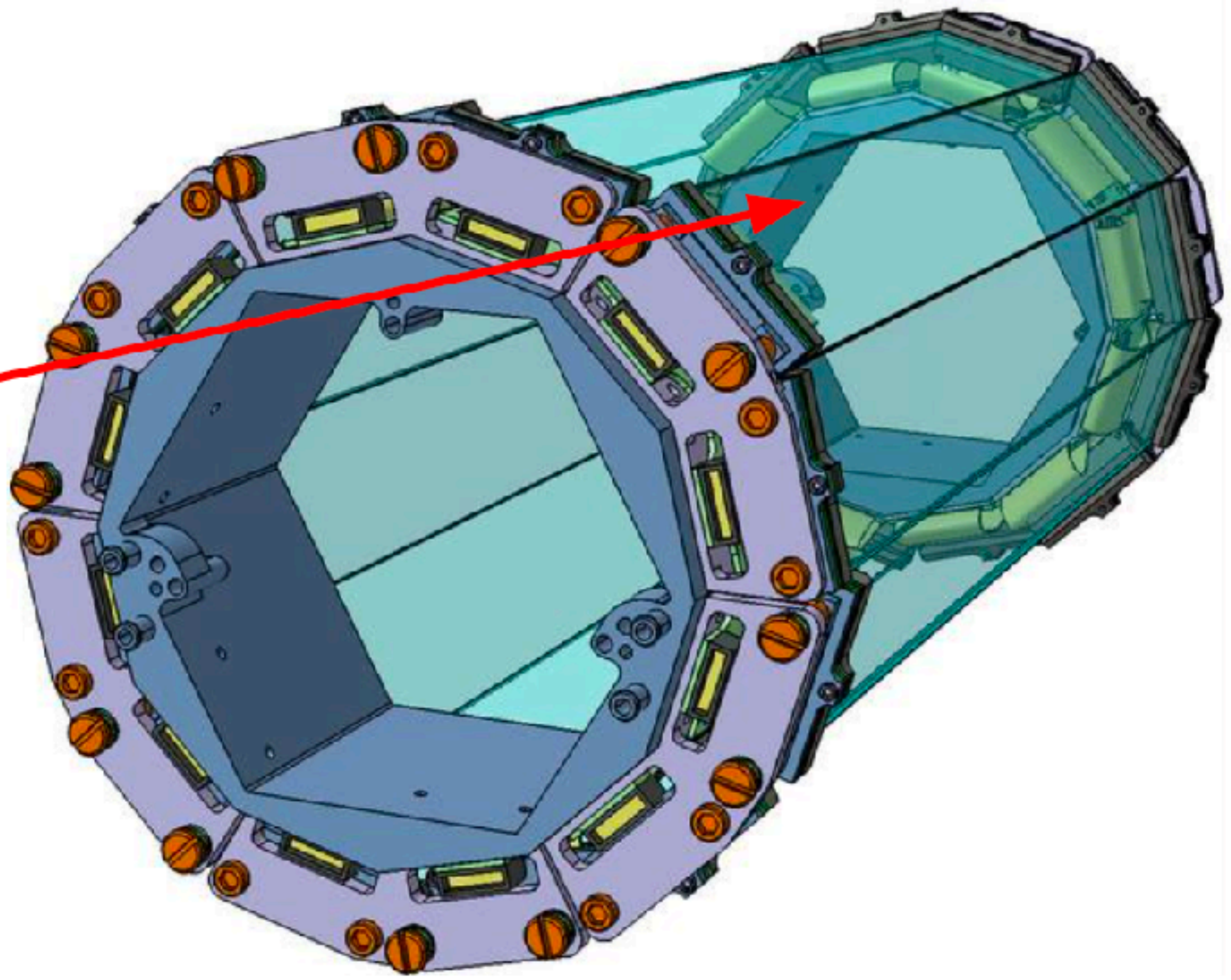
- 12 fibre ribbons, 30cm long, arranged in 3 staggered layers: surrounding vertex detector
- Fibres 250 µm thin: Material budget < 2% X_0
- Measured time resolution $\sim$ 250 ps
- Read-out through custom designed ASIC



Cross-section of 4-layer prototype



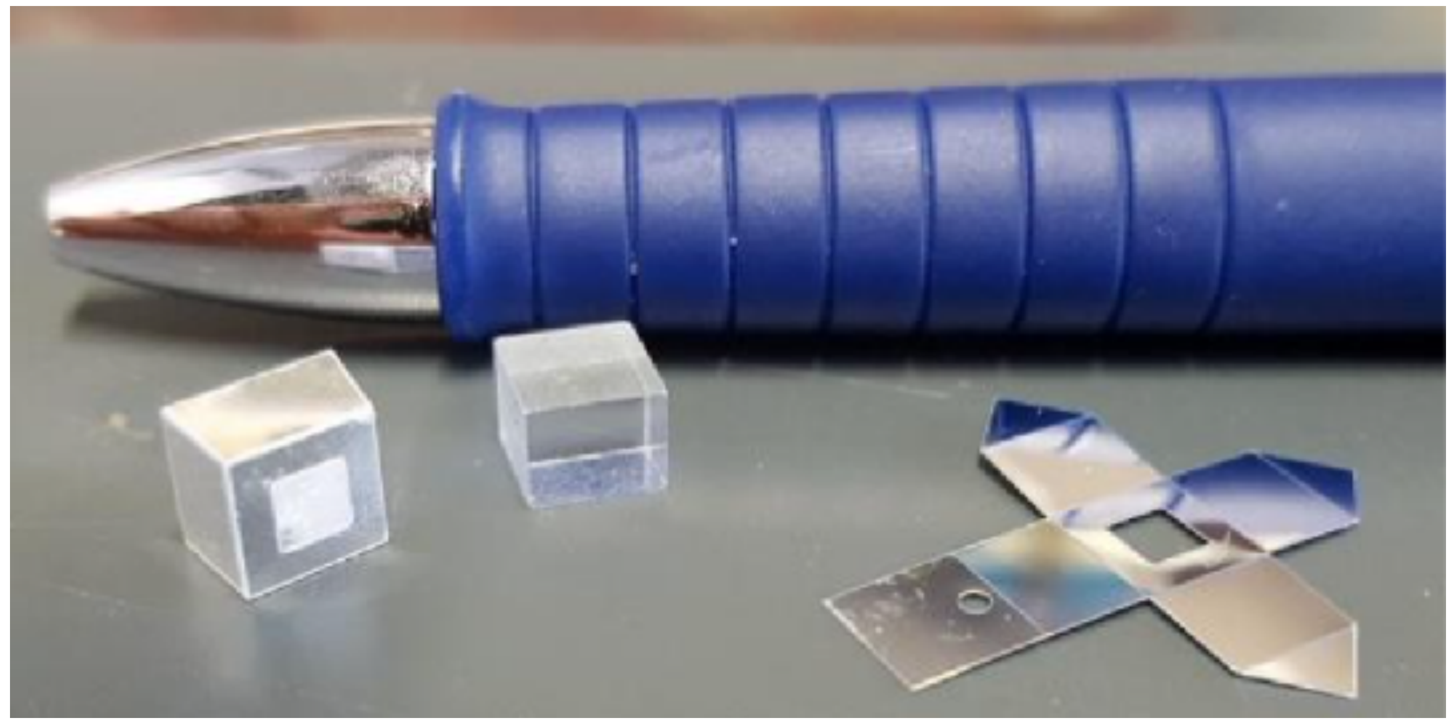
SciFi ribbons



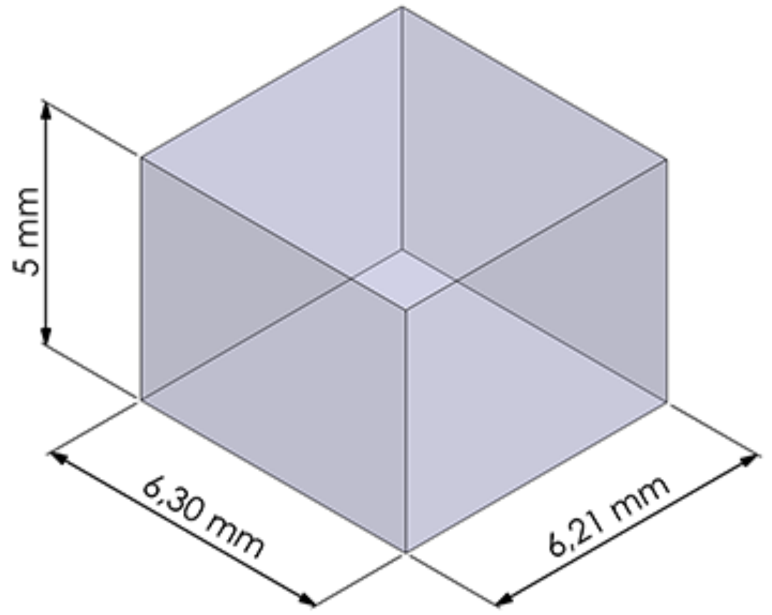
Timing detectors: scintillating tiles

Scintillating tiles: 6mm x 6mm x 5mm tiles with SiPMs in re-curl region

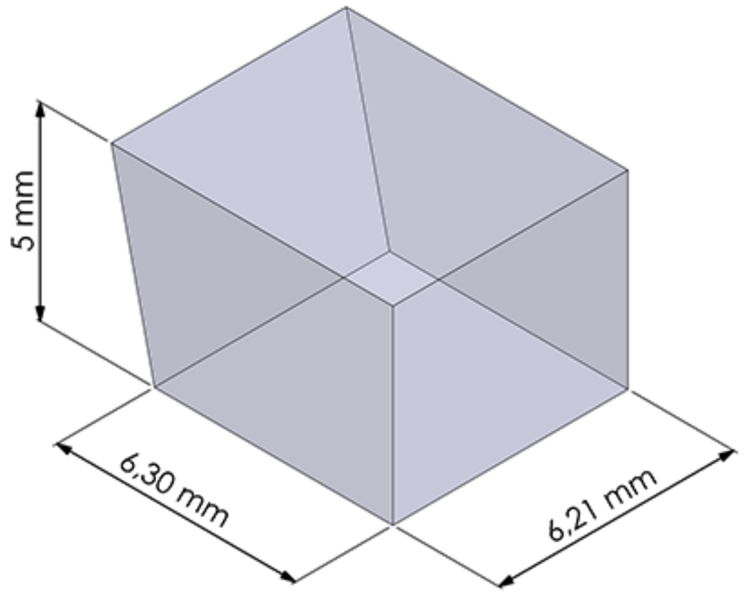
- ~ 6000 channels
- Measured single channel time resolution < 80ps
- Each tile individual hand wrapped with ESR reflector foil (optical isolation)
- Base unit = 32 scintillator and SiPM channels mounted on PCB
- Read-out through custom designed ASIC
- Intended to stop the electrons: no required material budget

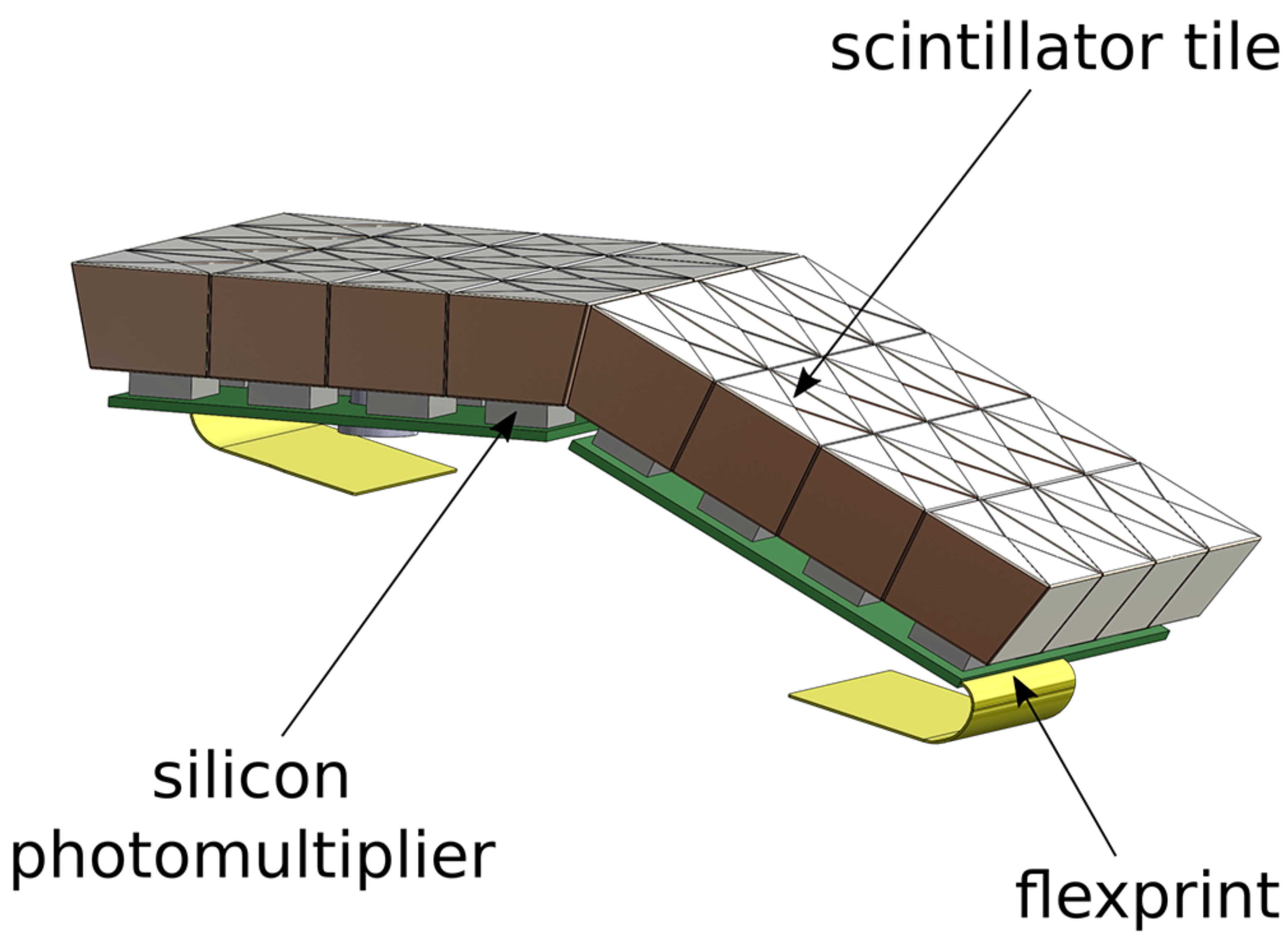


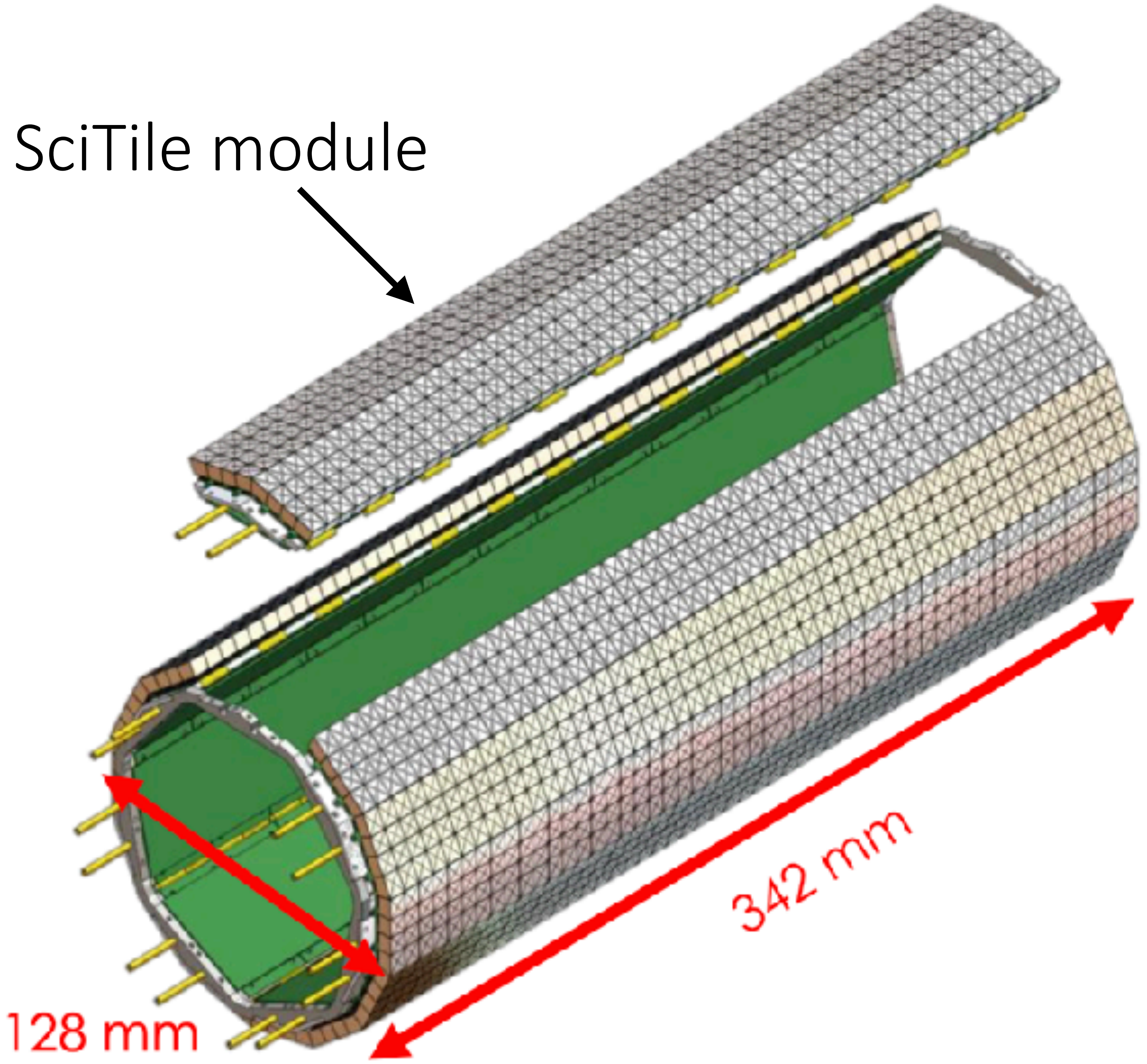
Central tile shape



Edge tile shape



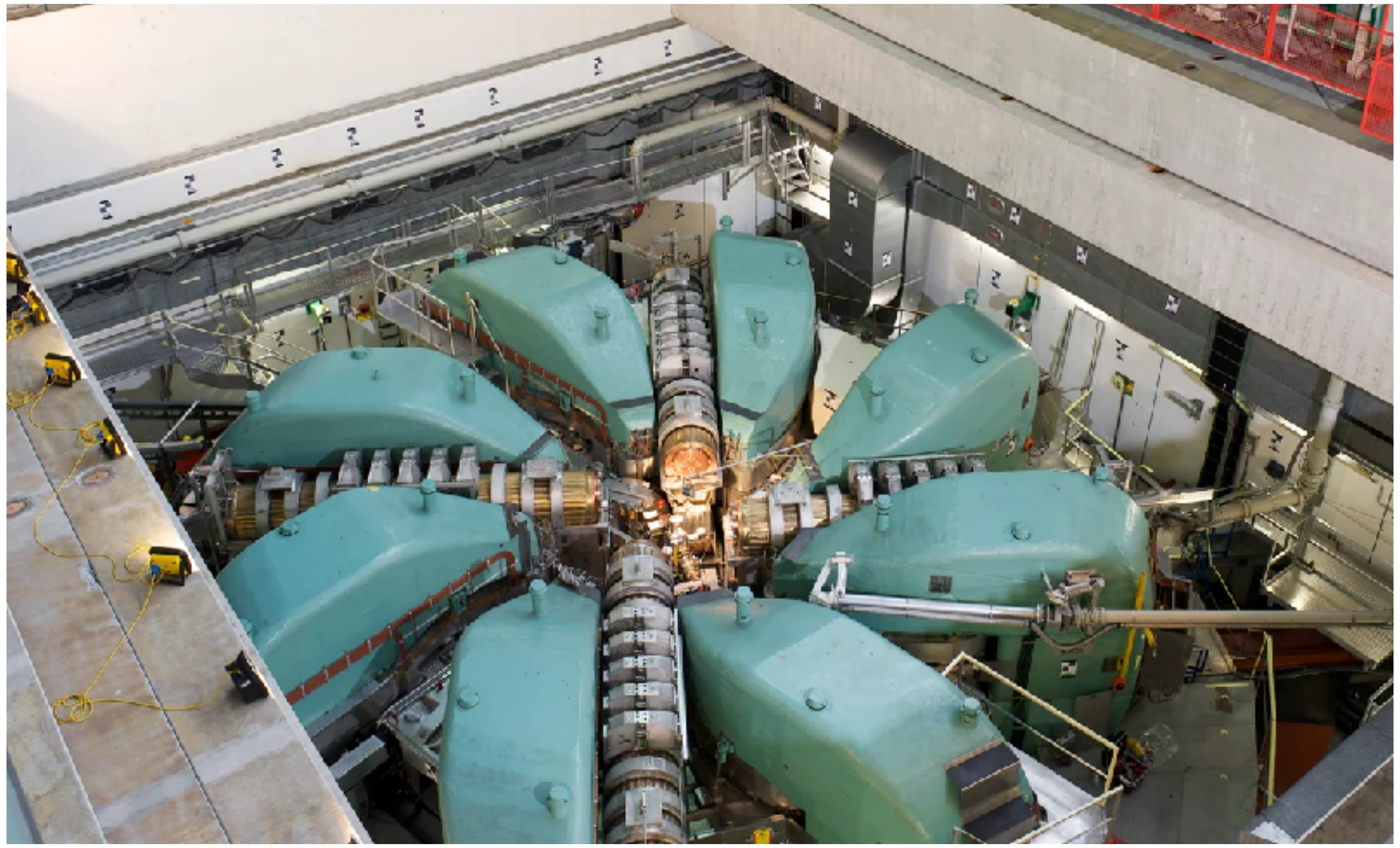




Muon beam & stopping target:

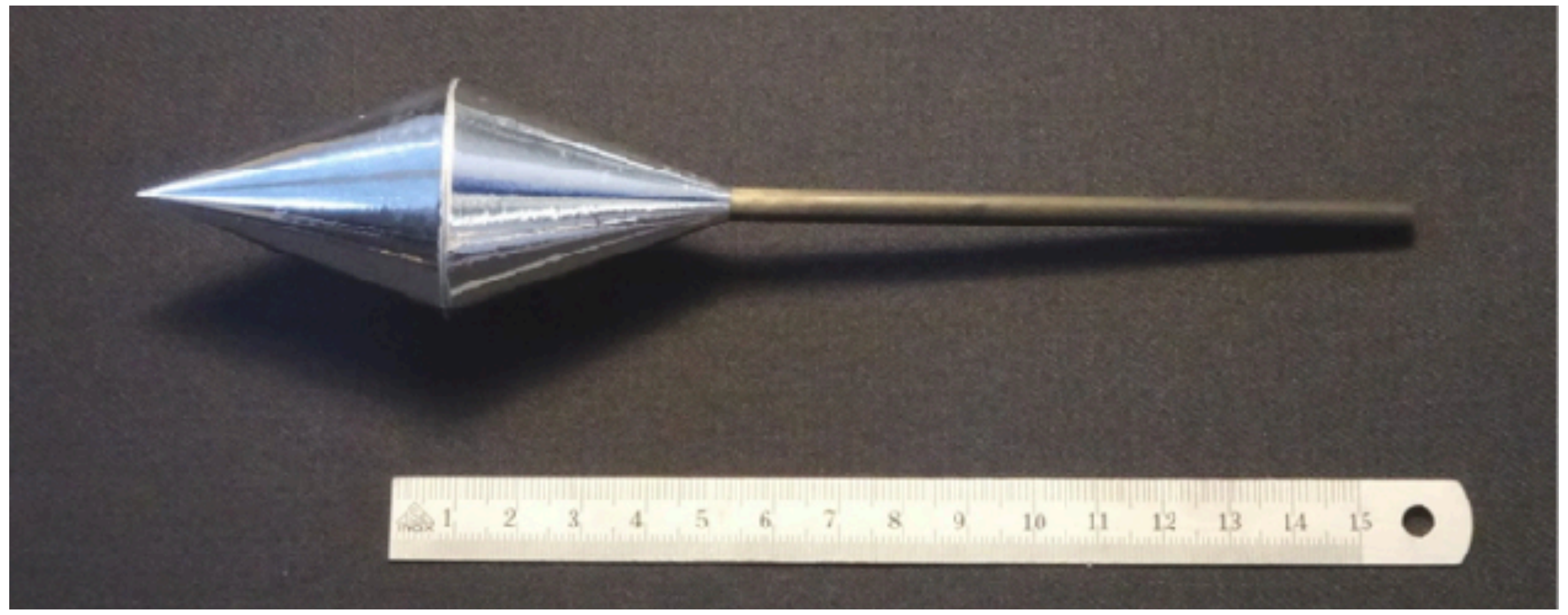
HIPA: High Intensity Proton Accelerator Facility @ PSI

- 1.4 MW continuous proton beam
- Fired onto graphite target: protons → pions → muons
- Muons guided by magnets to experimental stations
- Provides world's most intense DC muon beam
- PIE5 beam line: up to **10^8 muons/s**



Muon stopping target:

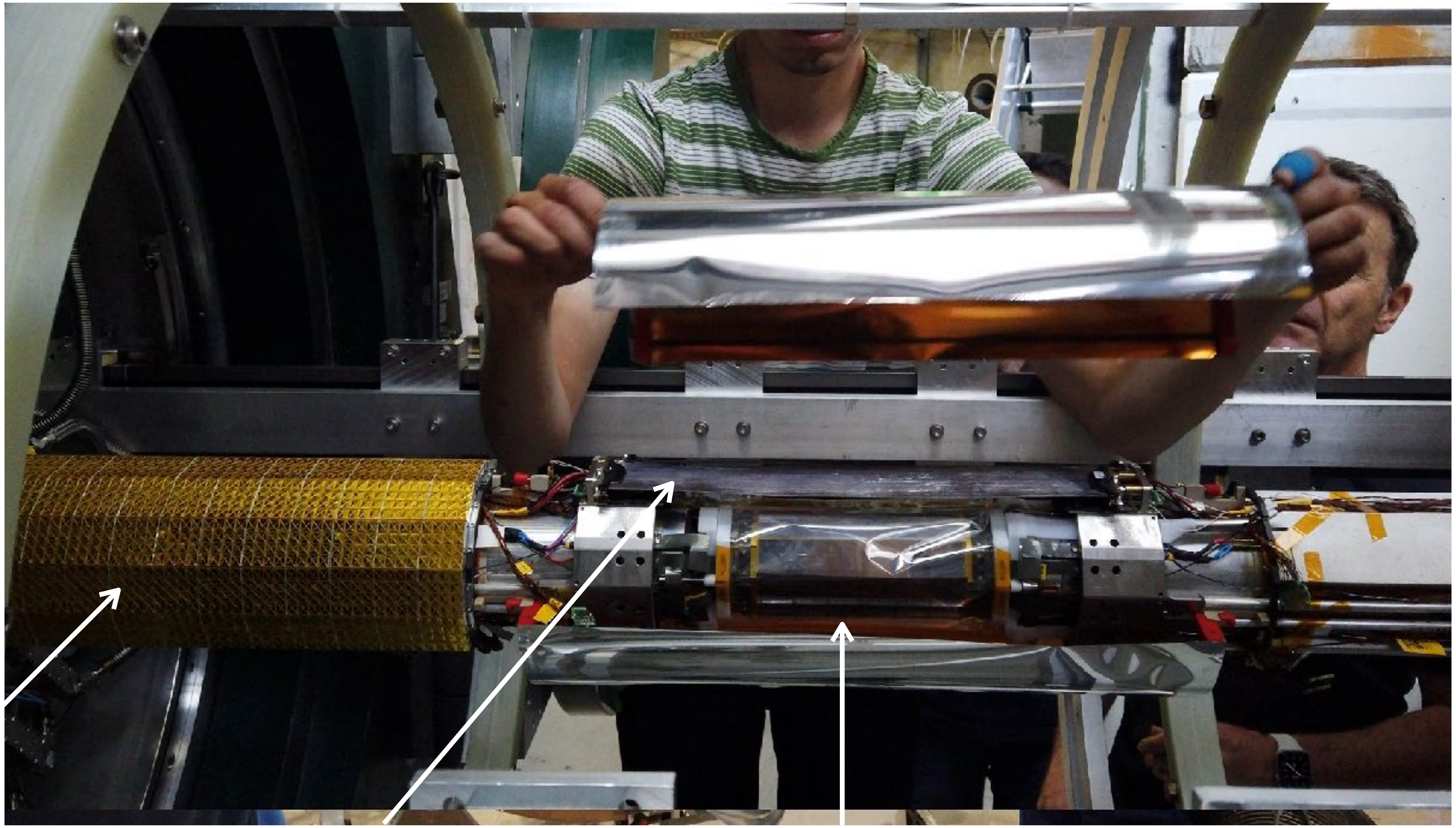
- Aluminised Mylar foil: ~ 95.5 % stopping efficiency
- Thin (70-80μm), hollow: minimal material budget
- Double cone: spread of decay vertices along beam direction



Successful commissioning run 2025:

Many firsts during installation and commissioning of detector during June 2025 beam time:

- Sub-system operations in beam
- Mu3e solenoid operational 1 T
- Gaseous helium cooling of vertex
- Liquid cooling of SciFi + SciTiles
- **Operation of world's thinnest pixel tracker!!**
- Analysis of results on-going



SciTile: 3/14 modules on side

SciFi: 2/12 ribbons

Vertex: Full layer 1 + 2 installed

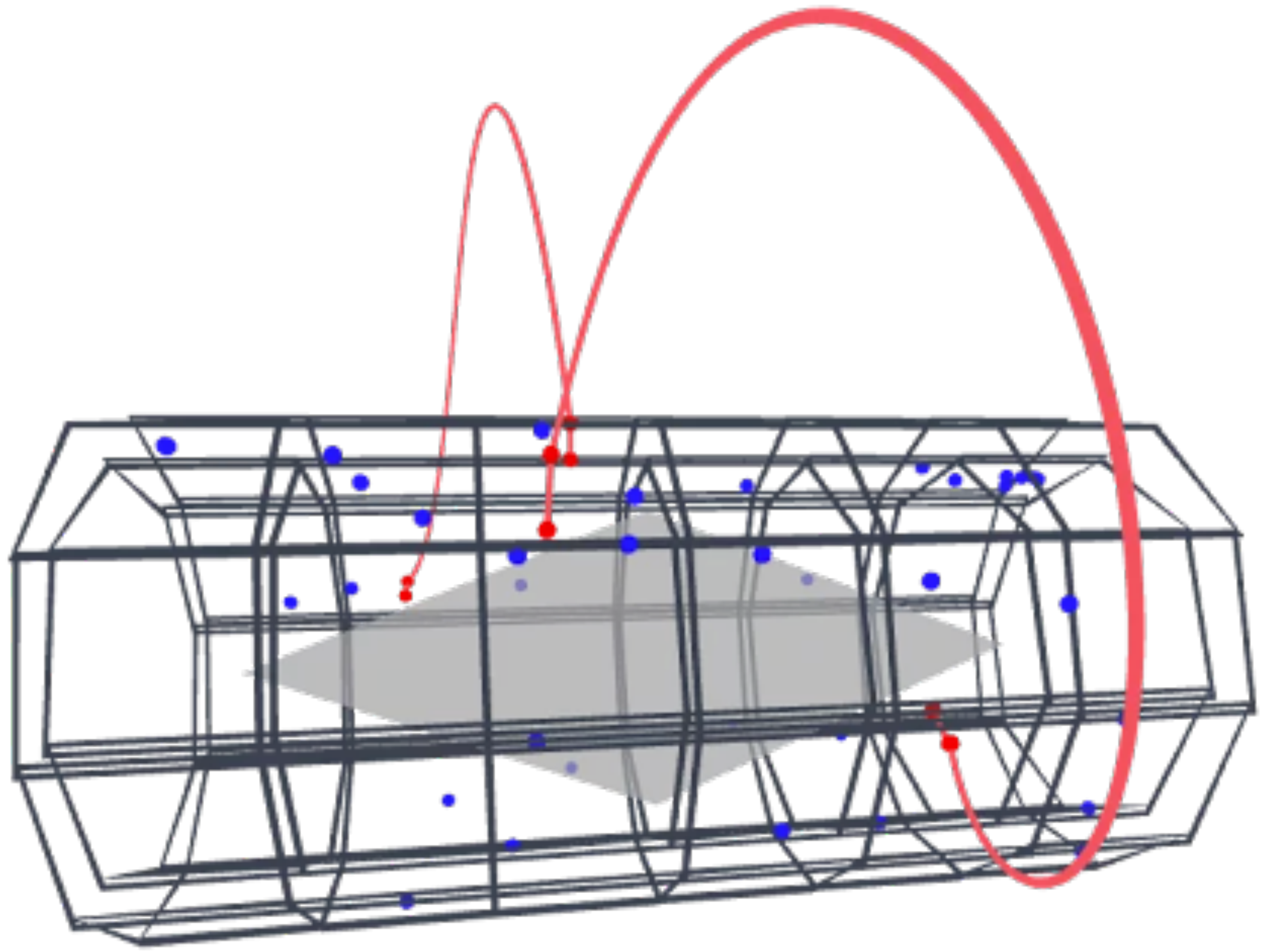
Operation of the vertex detector 2025:

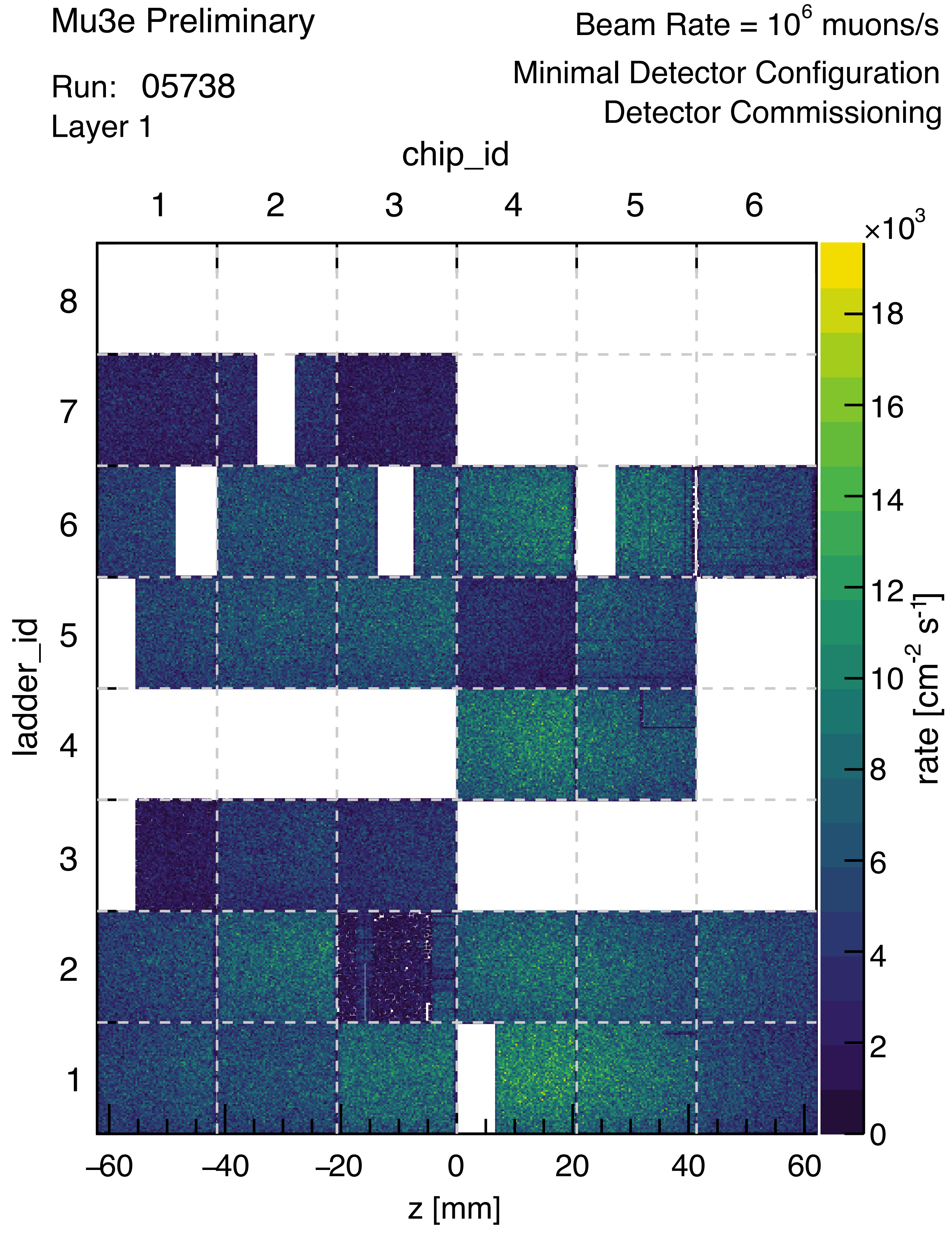
Full vertex detector installed:

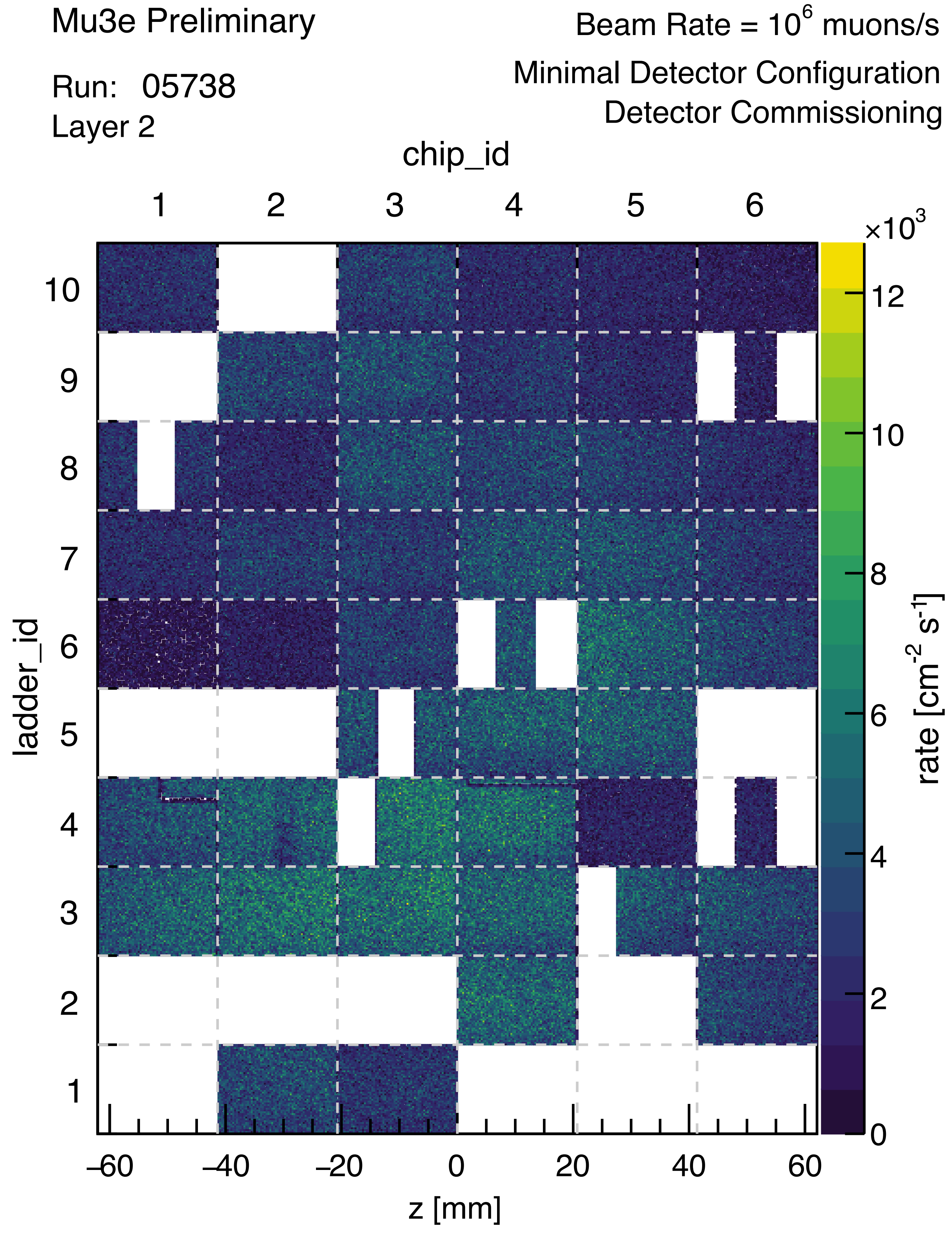
- Rate maps obtained for both layer 1 and 2: up to 10^7 muons/s stopped

Out of 108 MuPix11 sensors 24% sensors had issue

- Mechanically damaged
- Unstable data transmission



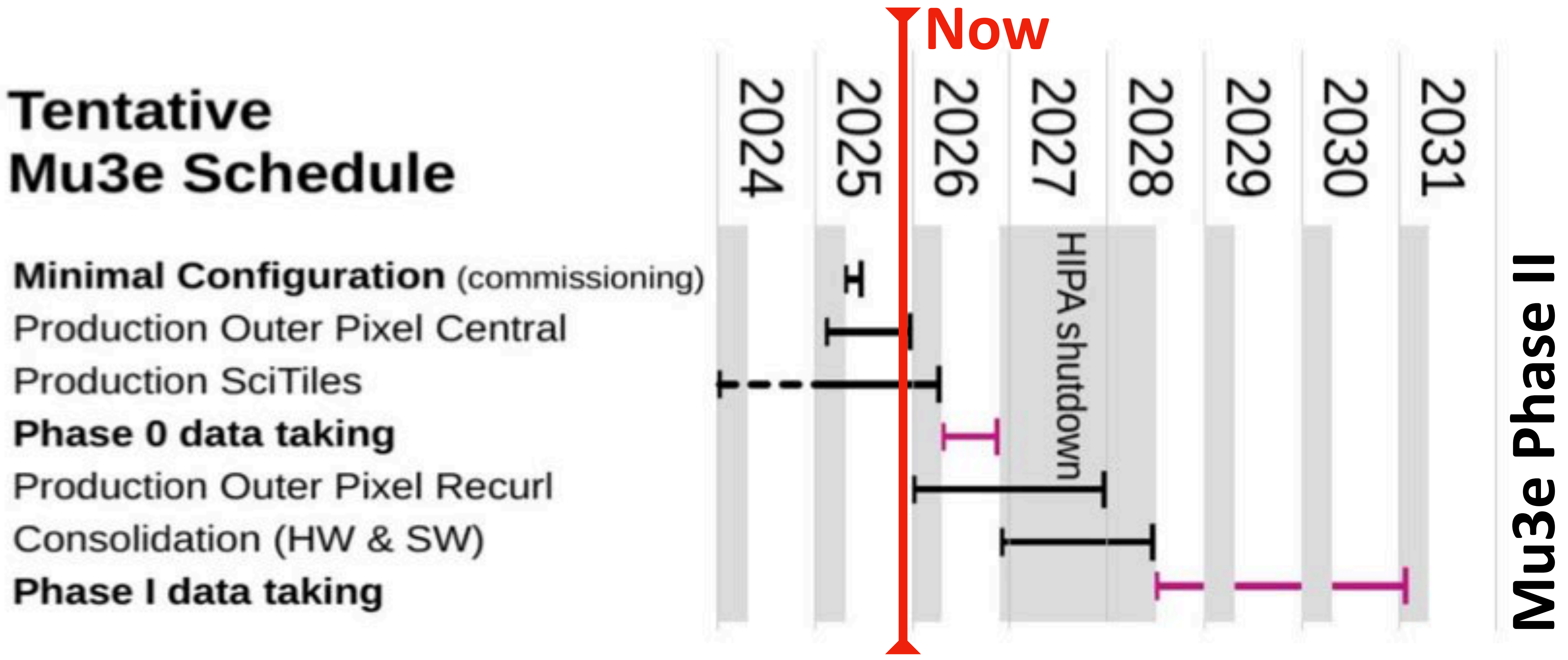


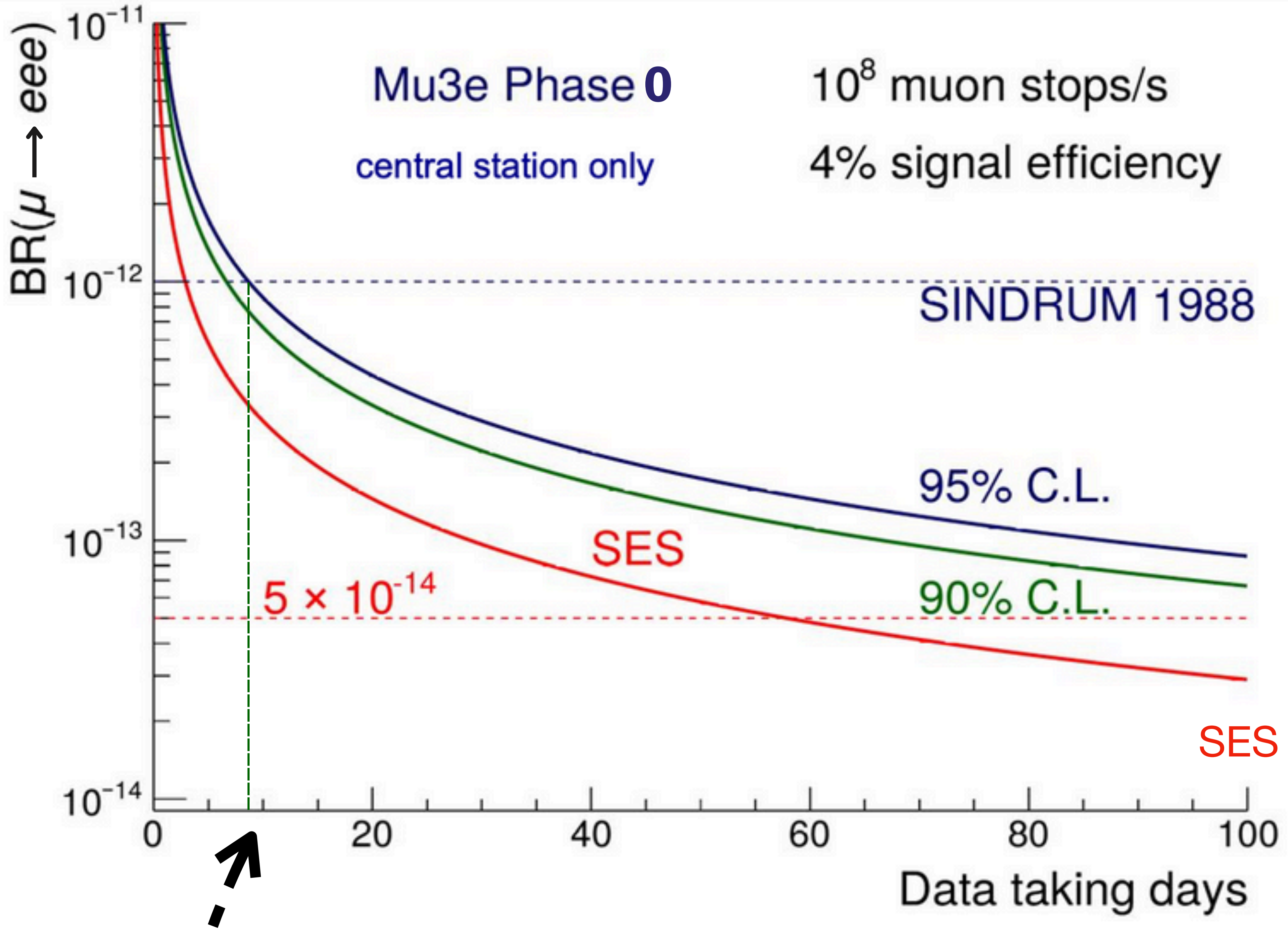


Looking to the future:

Preparing for physics data-taking in 2026!

- Production of all detector components on-going for 2026 beam time: including vertex “version 2” and outer pixel ladders for central station
- Result of BVR (“Benützerversammlung”) review to be held in Feb2026 will dictate 2026 beam-time duration





$$\text{SES} = \frac{1}{\epsilon \cdot N_\mu}$$

Phase 0 configuration likely to already surpass SINDRUM limit!


Stay tuned … !