Ultralight pixel tracker for the Mu3e experiment

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On behalf of the Mu3e collaboration

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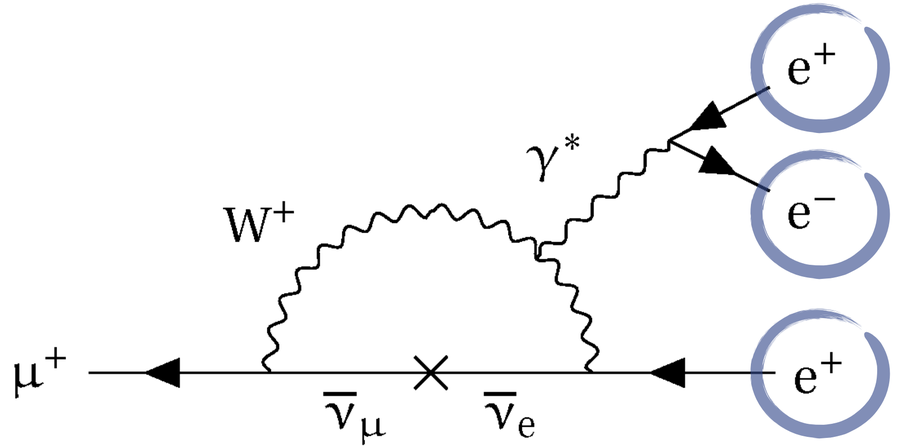
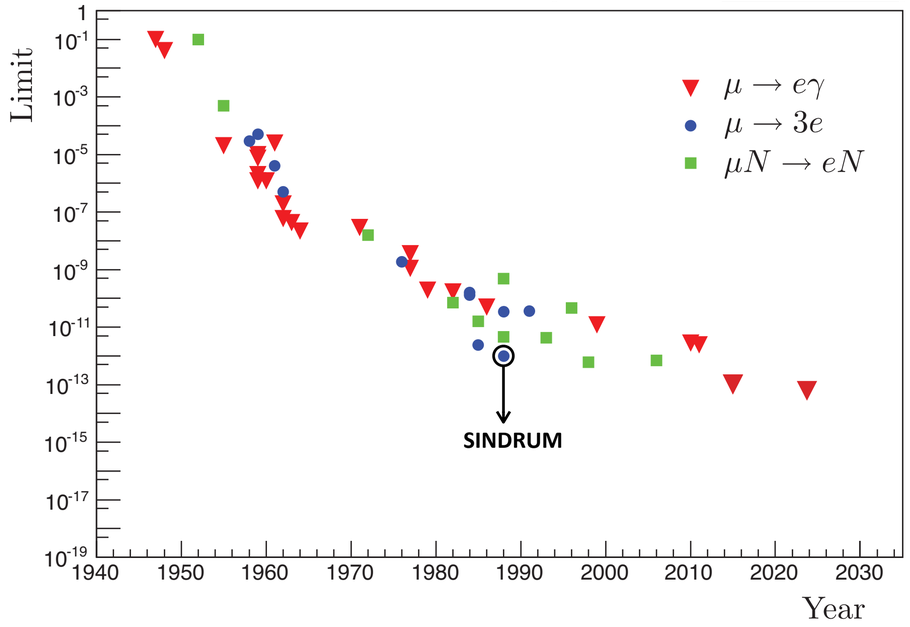
Search for the charged LFV decay $\mu^+ \to e^+e^-e^+$

- Highly suppressed in the SM+neutrino mixing, BR $\approx \mathcal{O}(10^{-54})$
- Best current upper limit $\approx 10^{-12}$ @ 90% C.L from [SINDRUM (1988)]
- Observation of cLFV in muonic sector = sign of new physics!



[Modified from arXiv:1307.5787]



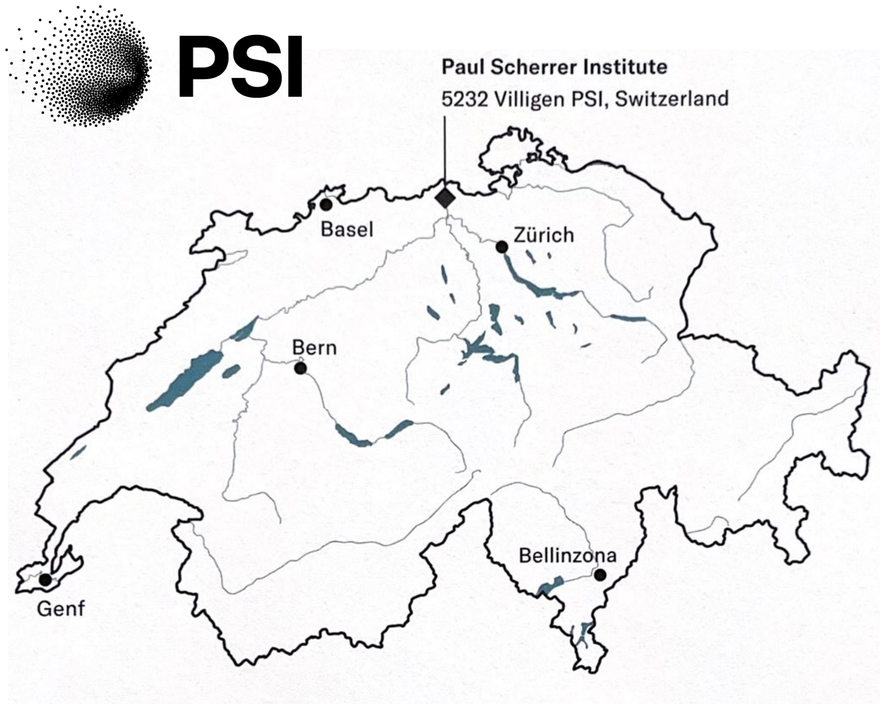
Experimental signature: 3 electron tracks, common vertex, time coincidence, $\sum P_e = 0$

Main backgrounds:

- Internal conversion: $\mu^+ \to e^+e^-e^+\bar{\nu}\nu$
- Accidental combinatorial background: combinations of Michel decays ($\mu^+ \to e^+\bar{\nu}\nu$), mis-reconstruction …

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)

Physics data-taking from 2026 (Phase I):

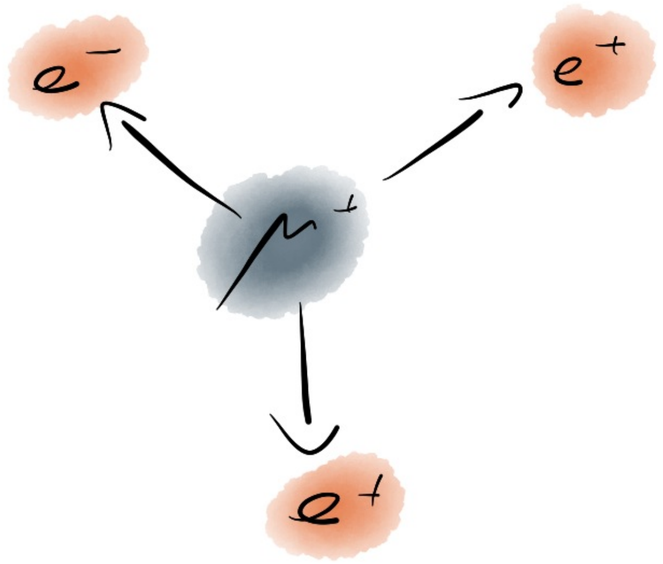
- PIE5 provides muon rates up to **10^8 muons/s** to Mu3e
- Target sensitivity: **BR (μ —> eee) < $2 \cdot 10^{-15}$**
- 290 days minimum running time required to achieve target

Phase II (> 2029):

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

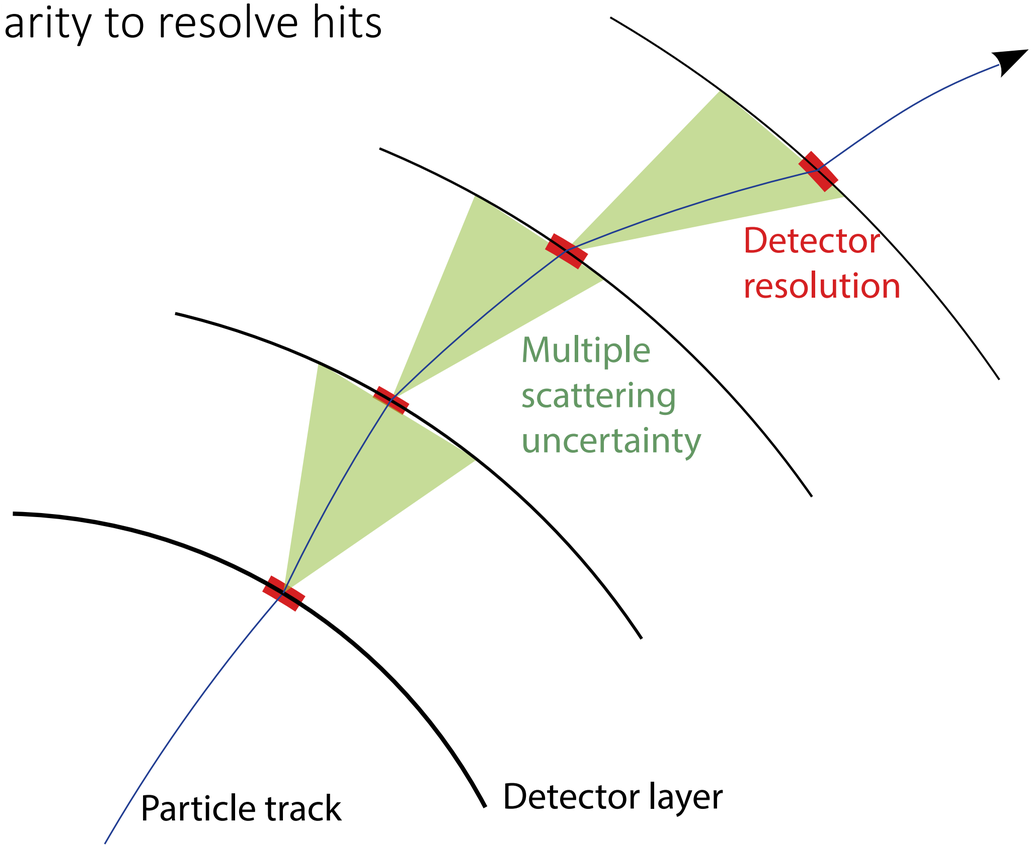
Achieving target sensitivities:

Signal:



Experimental sensitivity depends on ability to distinguish signal from background events — detector requirements therefore include:

- Excellent momentum resolution [$\sigma_p < 1.0$ MeV/c]
- Good timing resolution [~ ns]
- High granularity to resolve hits



Low momentum final state particles: regime where **multiple Coulomb scattering effects dominate**

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

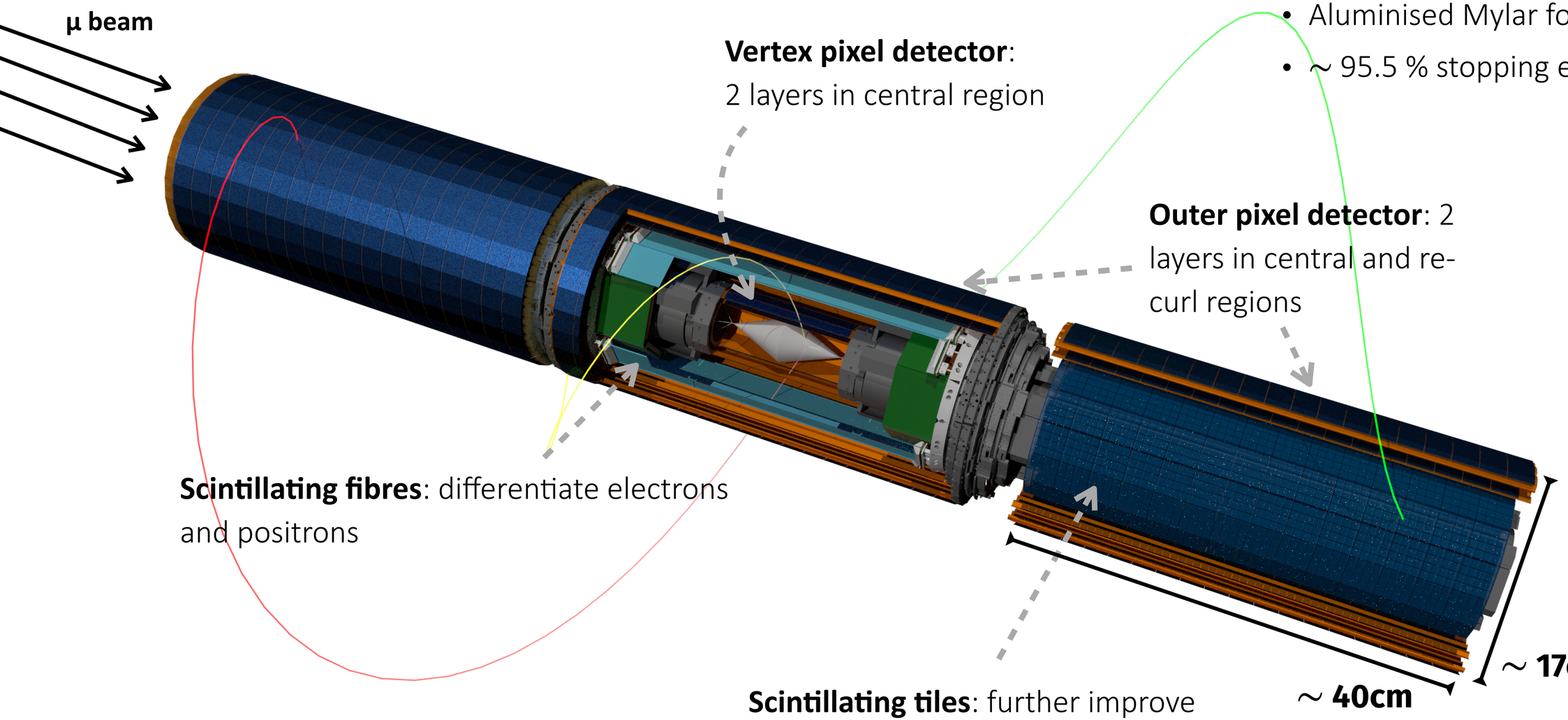
Mu3e detector design:

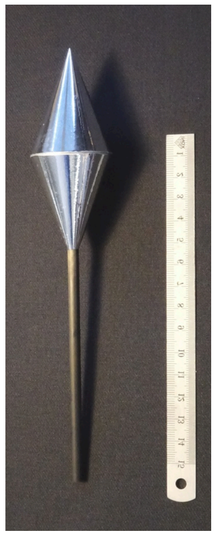
Detector geometry: **1 central + 2 re-curl regions**

- Homogeneous solenoidal magnetic field B = 1T

How do we stop the muons?

- Hollow double cone stopping target
- Aluminised Mylar foil 70-80µm
- ~ 95.5 % stopping efficiency

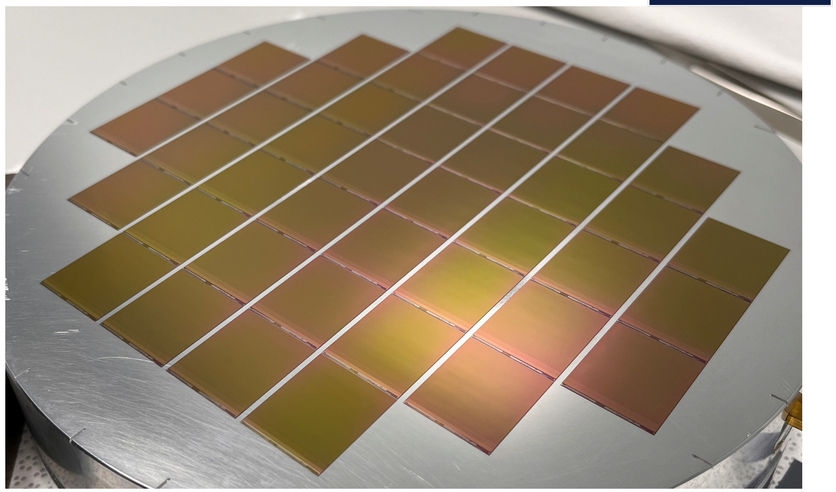




The MuPix sensor:

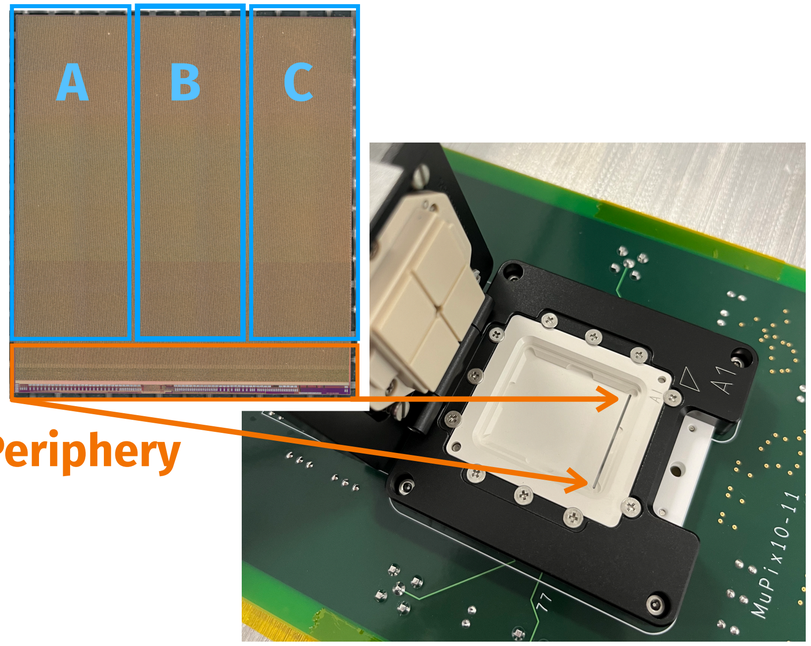
Custom HV-MAPS **MuPix11** sensors: produced by TSI using 180 nm technology.

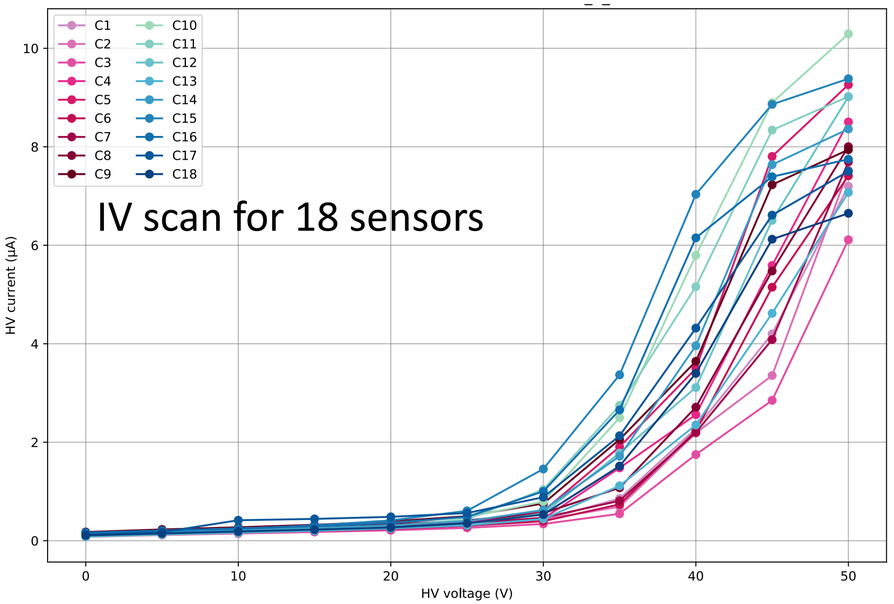
Sensor size [mm^2]	20.66 x 23.18	Data link	3 + 1 (MUX)
Pixel size [µm^2]	80 x 80	Data speed [Gbit/s]	1.25
Pixel matrix	256 x 250	Time resolution	< 20 ns
Thickness [µm]	50 & 70	Hit finding efficiency	> 99%



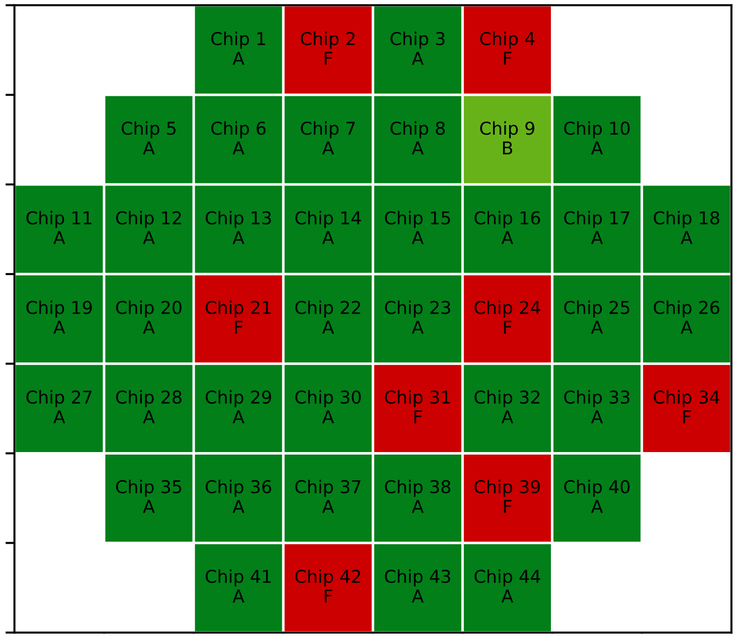
Wafer peeling and single chip QC performed in house (Heidelberg + Oxford)

- Need to test ~ 6000 sensors in total (so far completed ~ 1000)



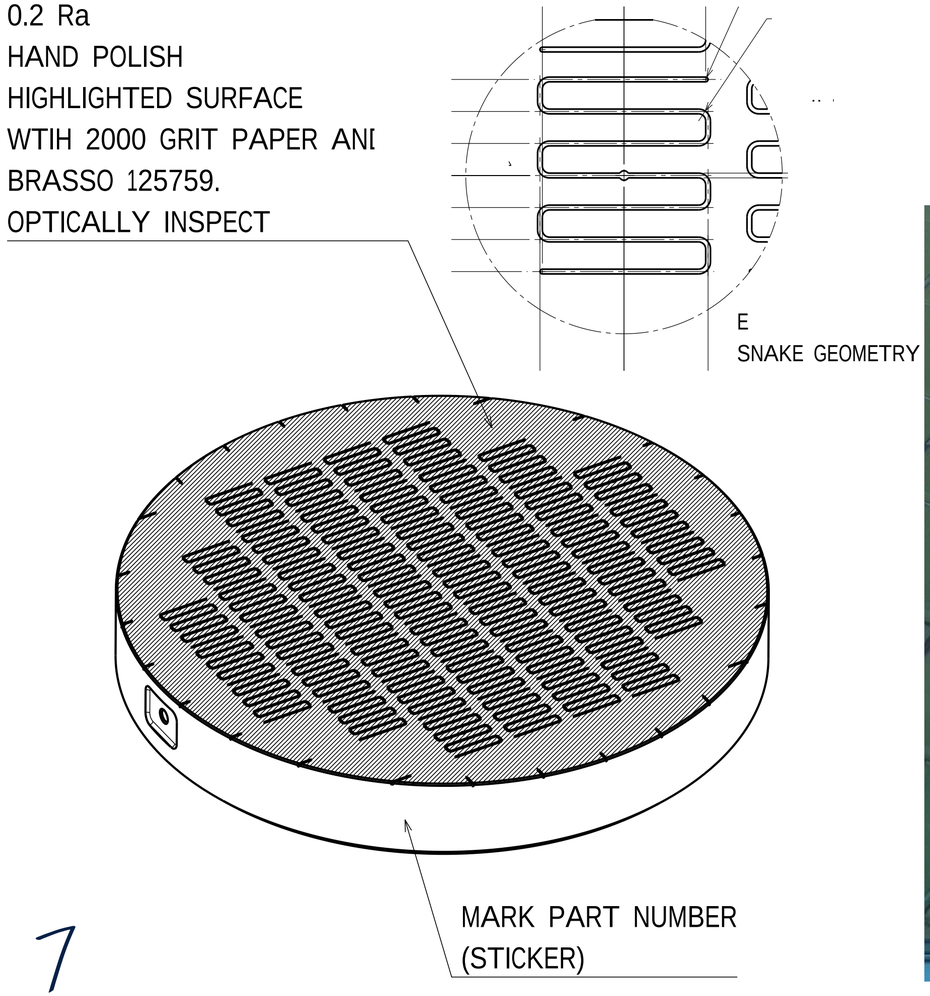


QC wafer plot [81.8% yield]

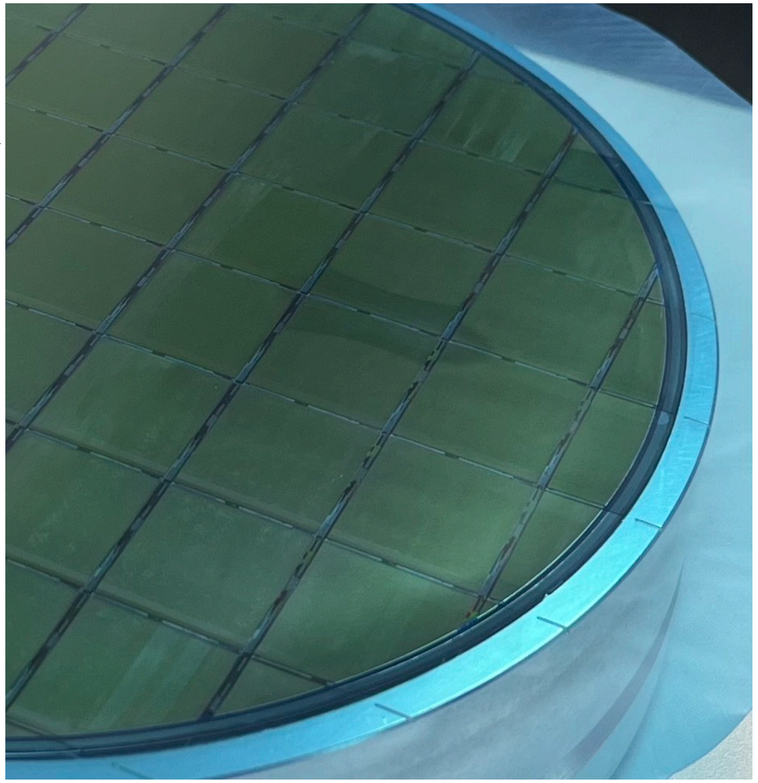


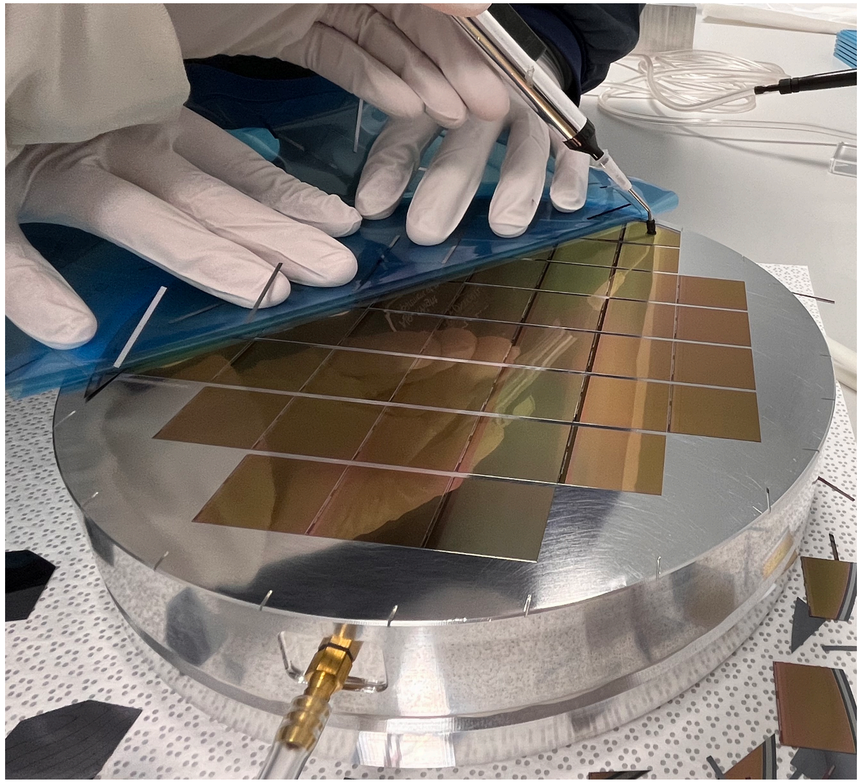
Silicon wafer peeling and picking:

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

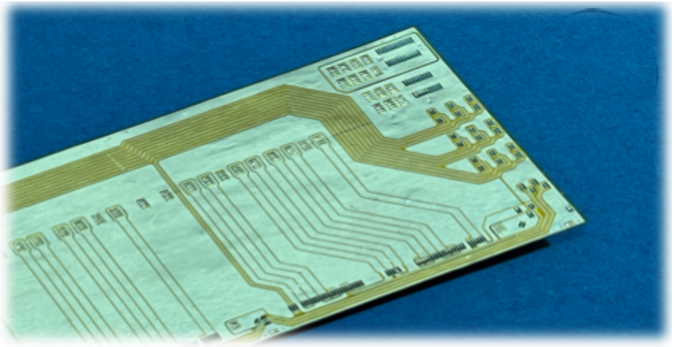




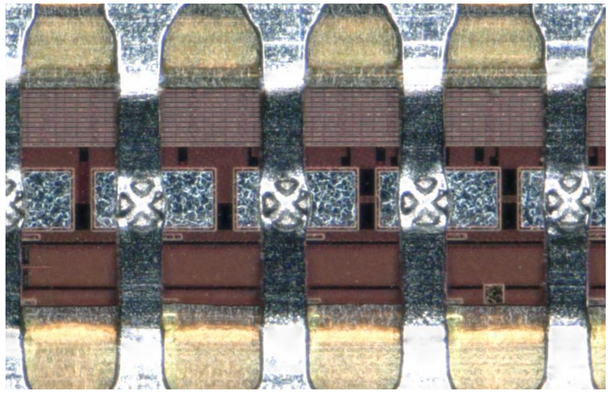
Basic building block of Mu3e pixel tracker = “Ladder”

Components:

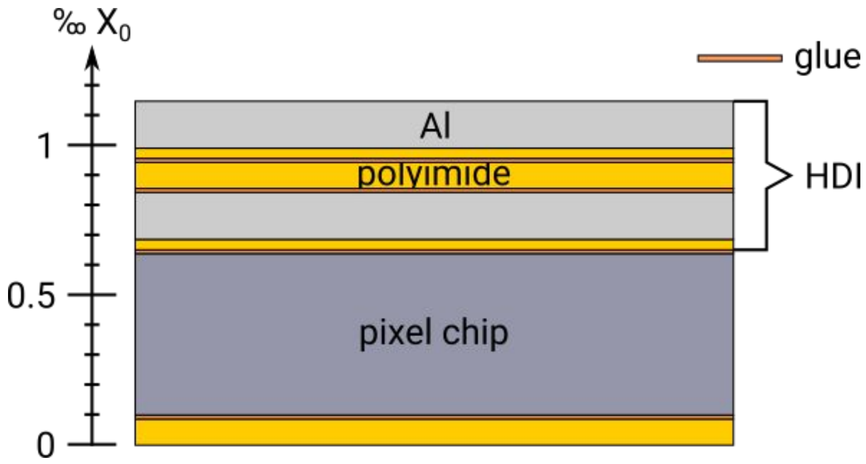
- MuPix11 pixel sensors (50 µm)
- Al/kapton high-density interconnect (HDI) flexible PCB, ~ 70µm



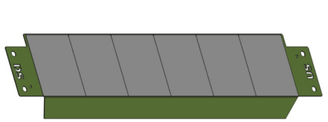
- Electrical connections via **spTAB** (single point Tape Automated Bonding):



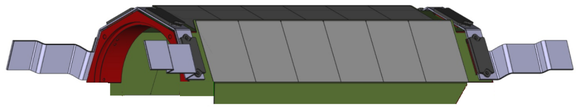
- Total radiation length = 0.115% per layer



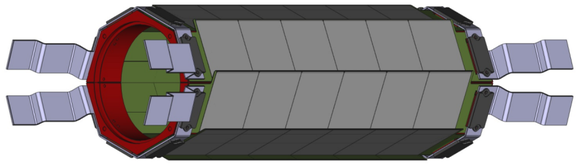
- Mechanical stability: from 3D folded nature of vertex detector



Ladder



Module



Layer

1 ladder = 6 x MuPix11 sensors

1 module = 4 ladders

2 modules = 1 layer

Successful commissioning run 2025:

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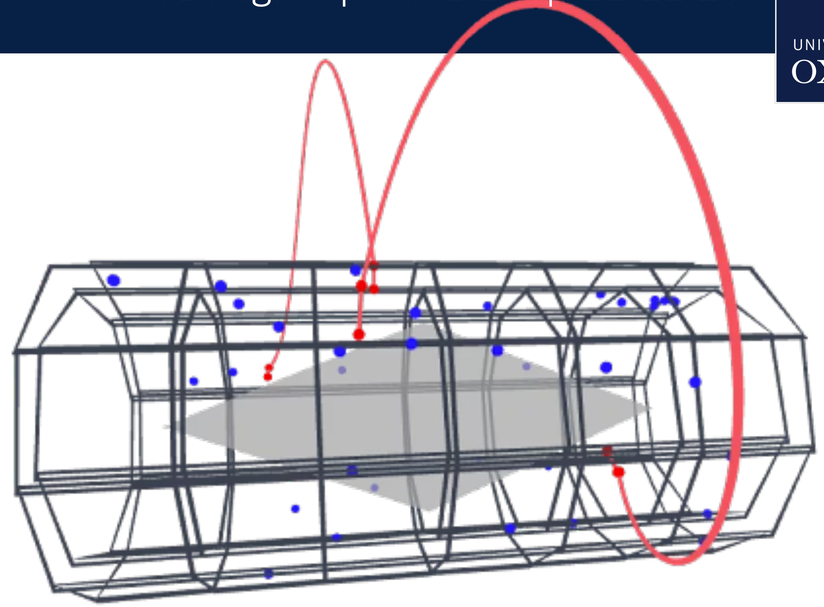
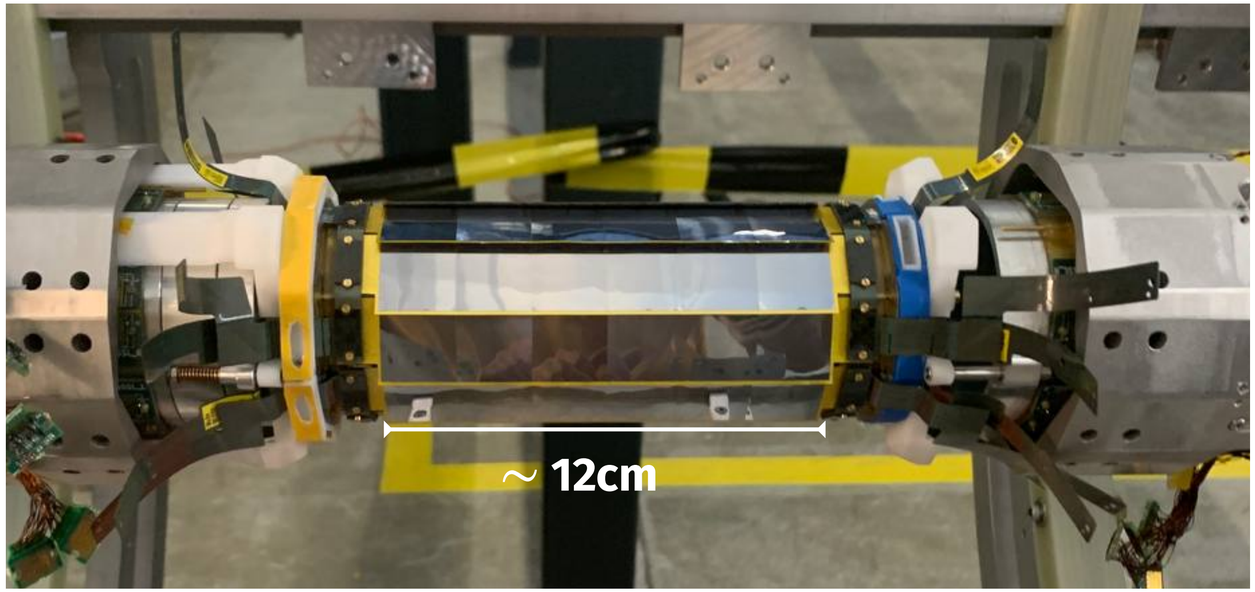
Many firsts during installation and commissioning of detector during June 2025 beam time:

- **Sub-system operations in beam, 1 T B-field, gaseous He cooling**
- Full vertex detector installed — rate maps observed for both layer 1 and 2: up to 10^7 muons/s stopped.
- **Operation of world's thinnest pixel tracker!!**

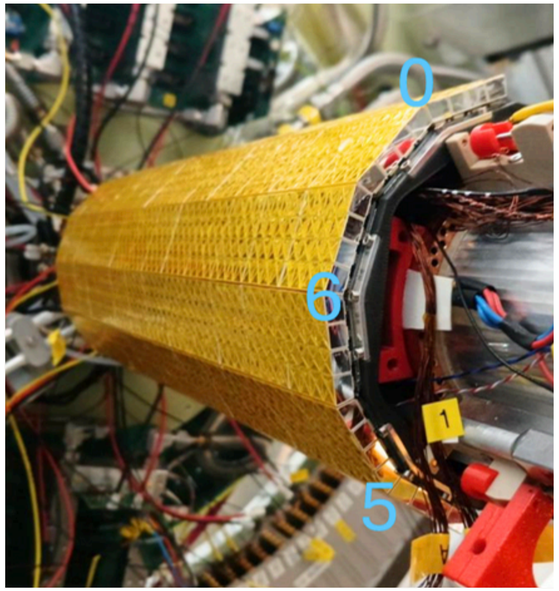


Vertex: Full layer 1 + 2 installed, 24% sensors had issues



SciFi: 2/12 ribbons

SciTile: 3/14 modules on DS



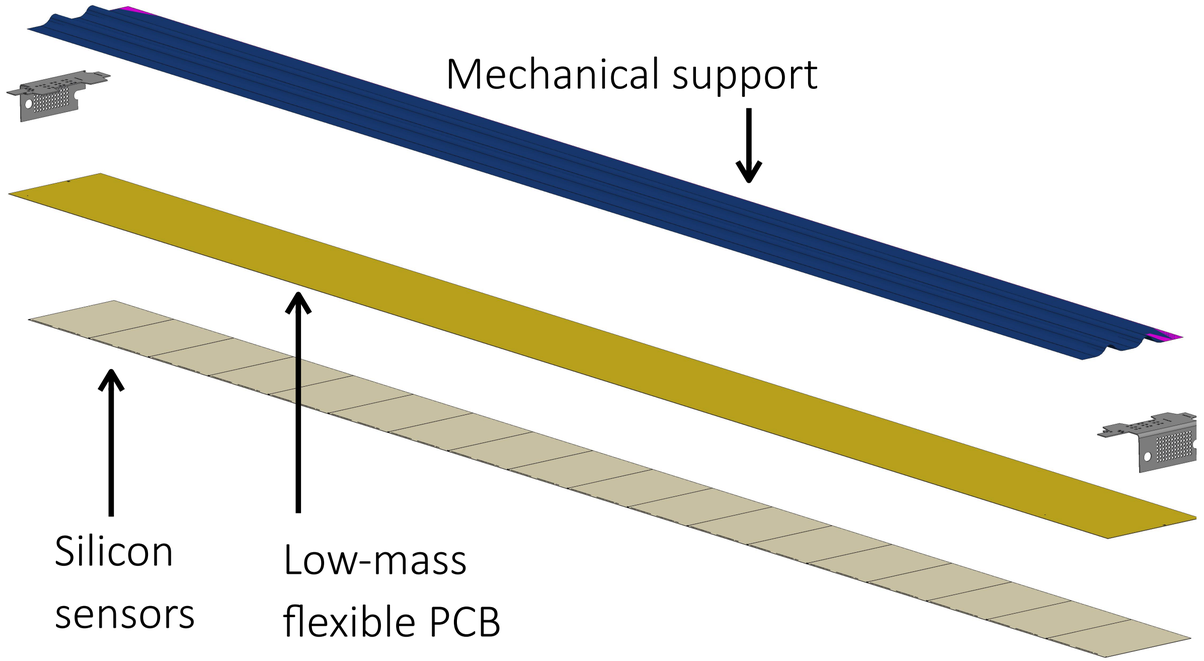
The outer pixel tracker:

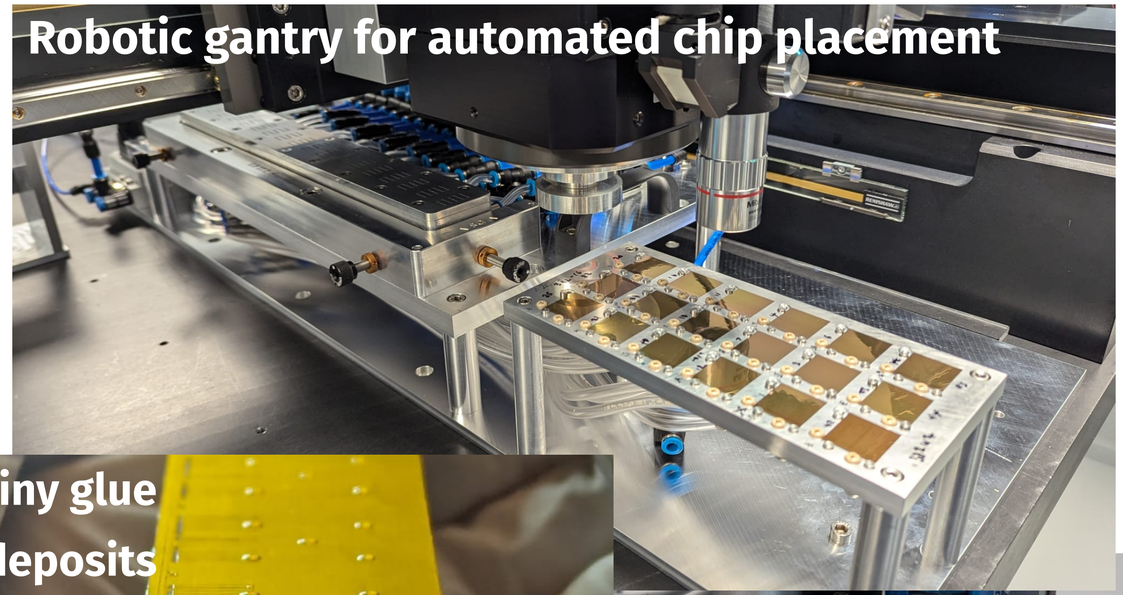
Same ladder components as vertex tracker **+ additional mechanical support**

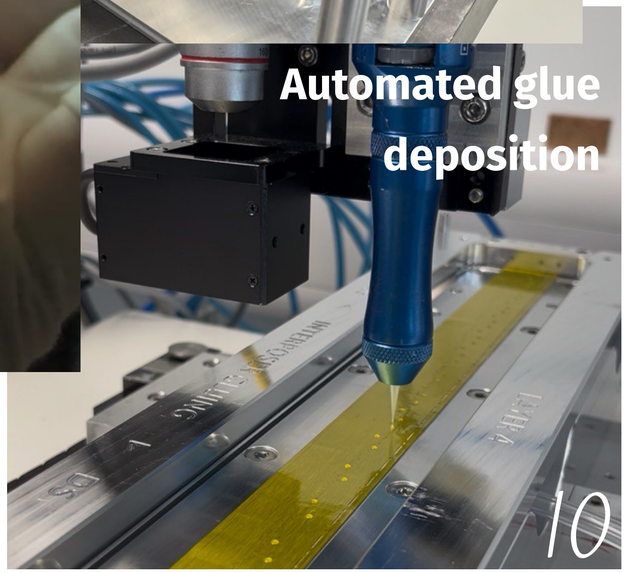
- 17 (18) x MuPix11 sensors in layer 3 (4) ladders
- 4 ladders per module

Total per station: 52 ladders (912 sensors)

- To cope with scale of production and accuracy required: automate build procedures







Ladder weighs ~ 2 grams and is 36.7cm long

Mechanical support for the outer pixel ladders:

Mechanical support provided by either:

Polyimide film:

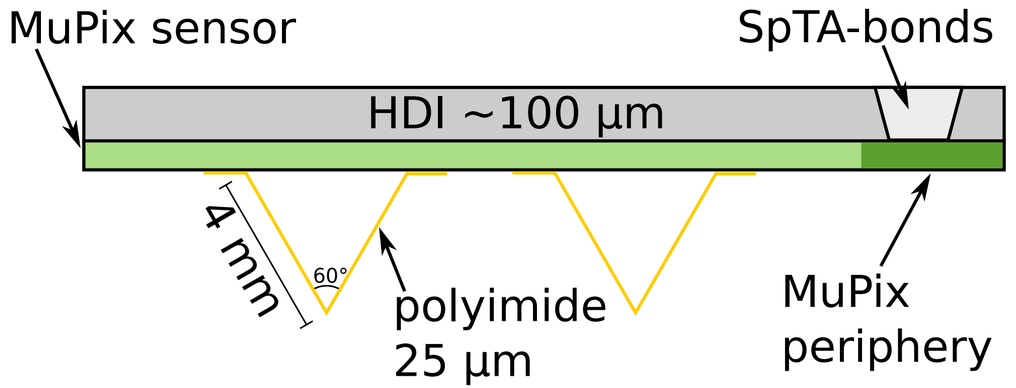
25µm thick folded into two triangles:

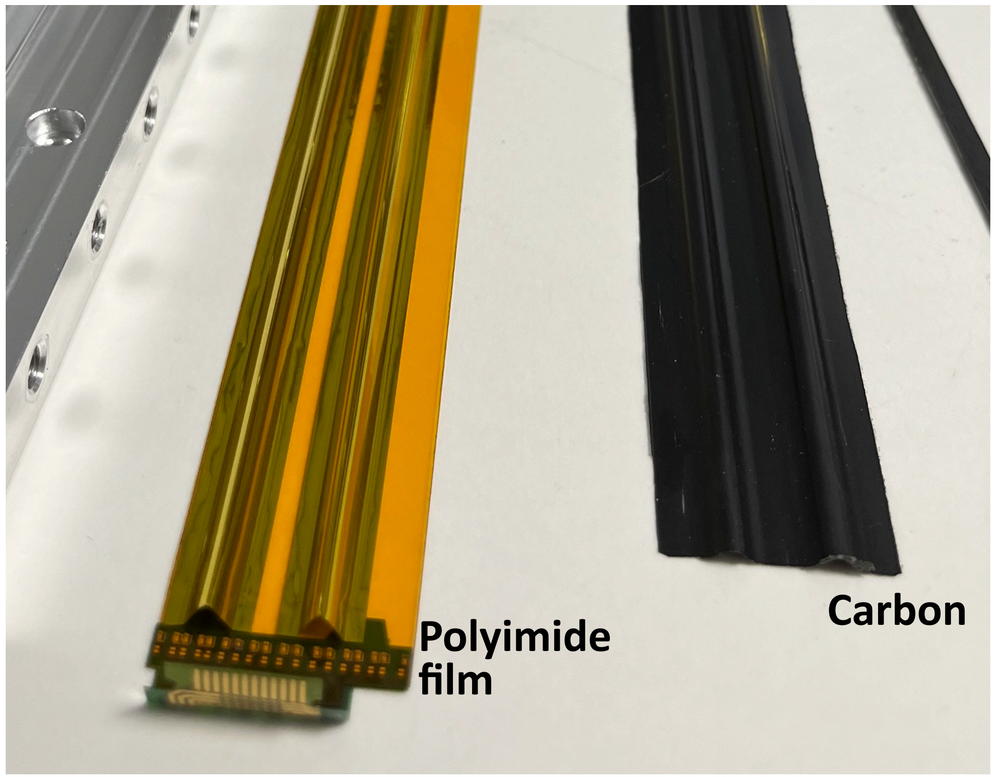
- Sensors/bonds visible underneath
- **Quite delicate** —> difficulties in transportation
- On the edge of providing enough structural integrity for 35cm long ladder

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)



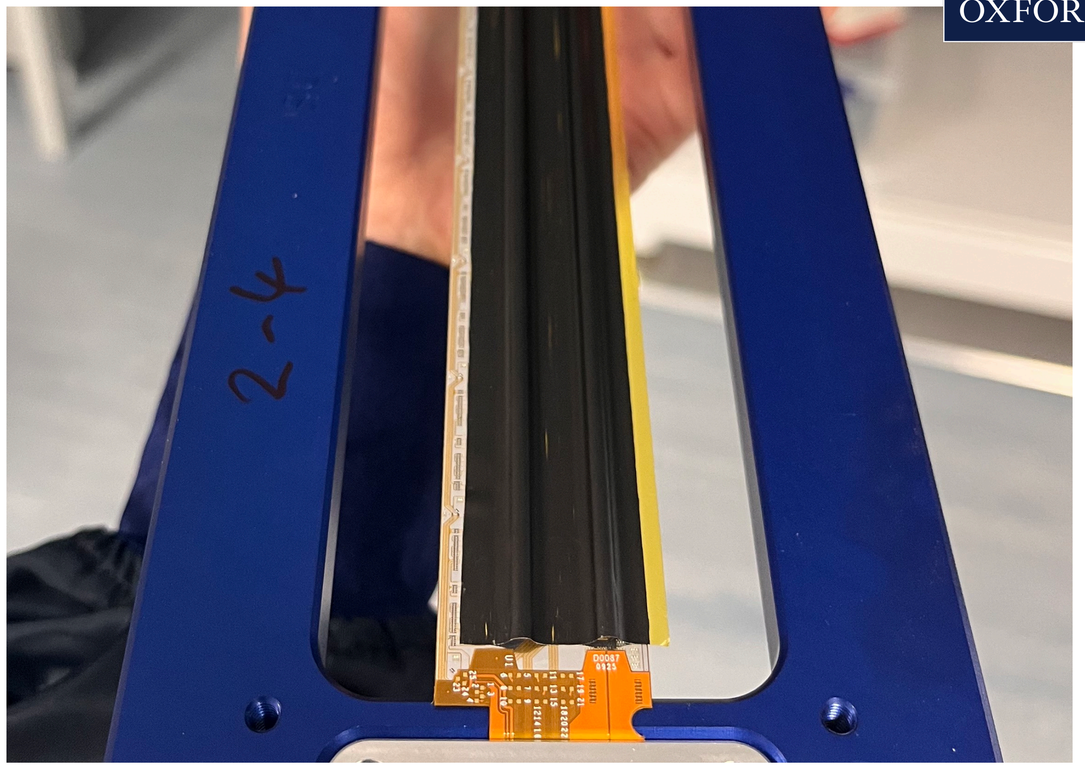


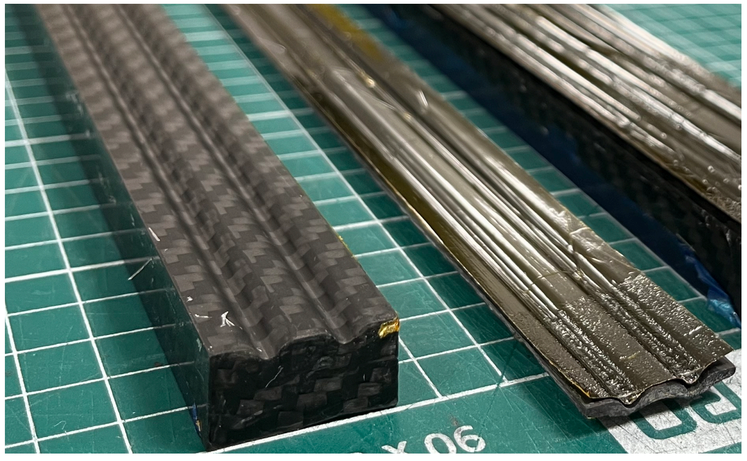
Fabrication of carbon-fibre support:

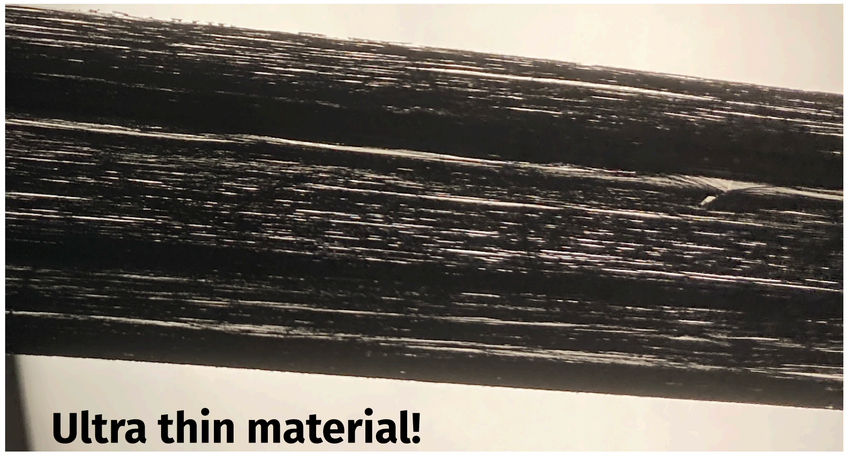
Uni-directional single-ply 25µm carbon-fibre sheet (40% resin content): highly non-standard material + fabrication techniques

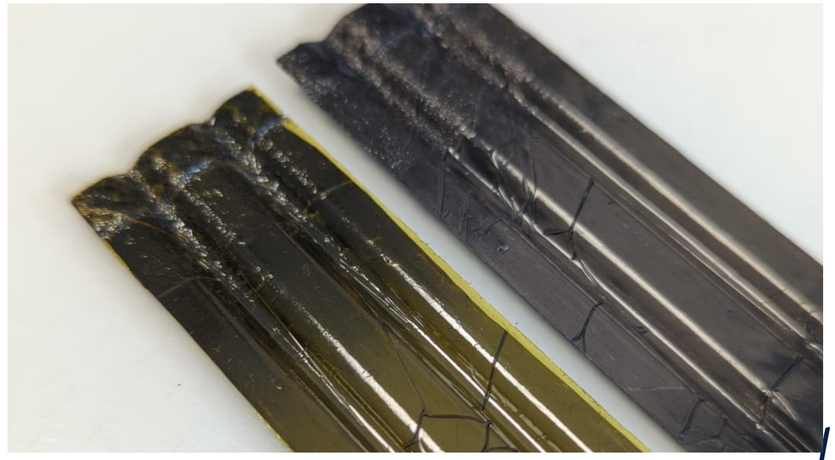
- **Spread-tow** fibres: usually woven together
- **Split-ply**: allows additional resin to bleed off
- Cured into double “u” shape with 8µm kapton backing: using carbon-fibre mould tool (to control bowing) + mossite intensifier for surface smoothness

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









Qualification procedure for ladders:

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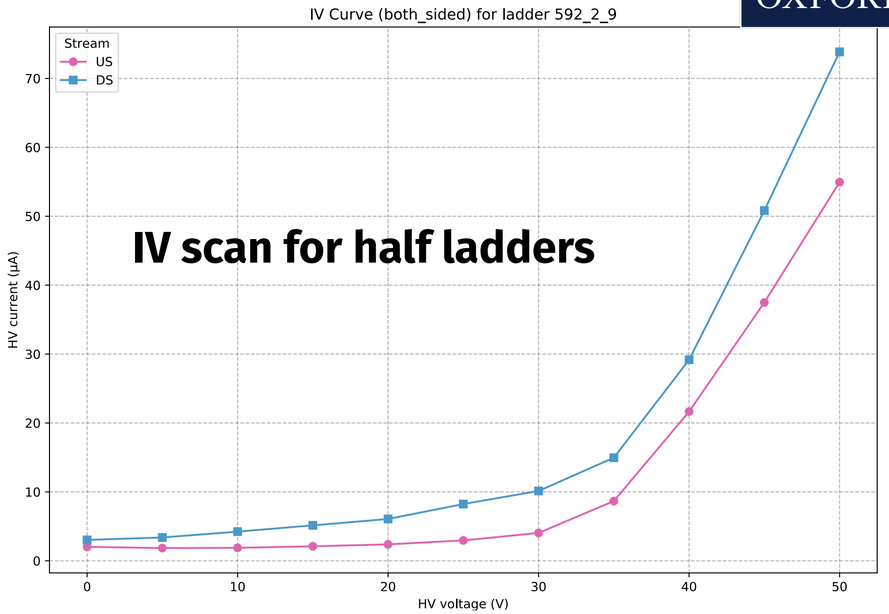
After assembly, **each ladder is individually QC tested** before module assembly.

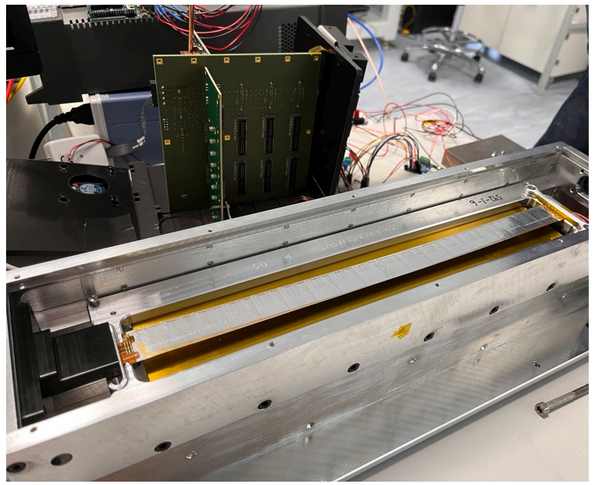
QC tests include:

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

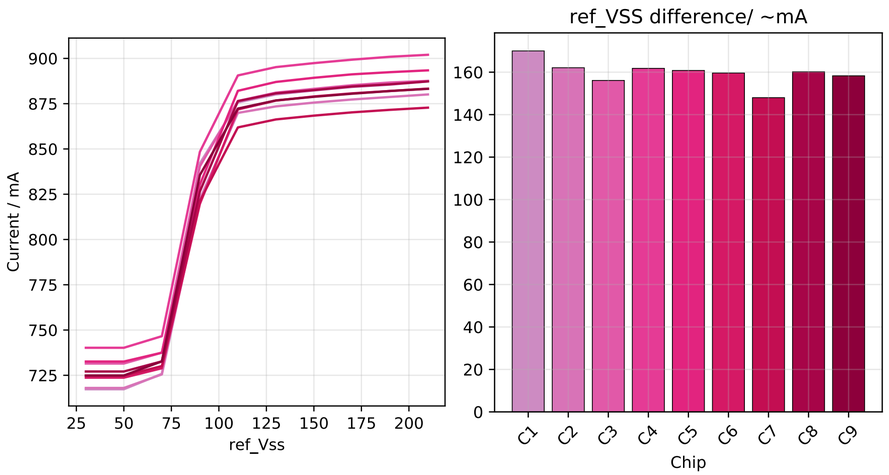
Production currently on-going: build rate ~ 5 ladders per week.

QC also undertaken once ladders mounted on modules.

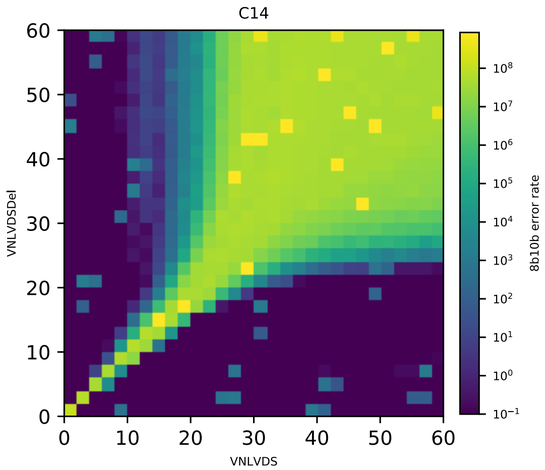




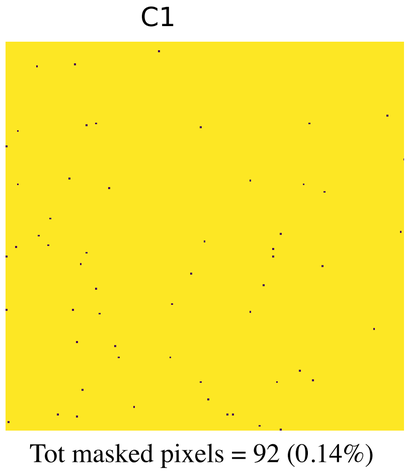
Ladder QC test box (cooled with cold dry air)



Current response to amplifier DAC



DAC values for error-free data transmission



Noise map of pixel matrix

Looking to the future:

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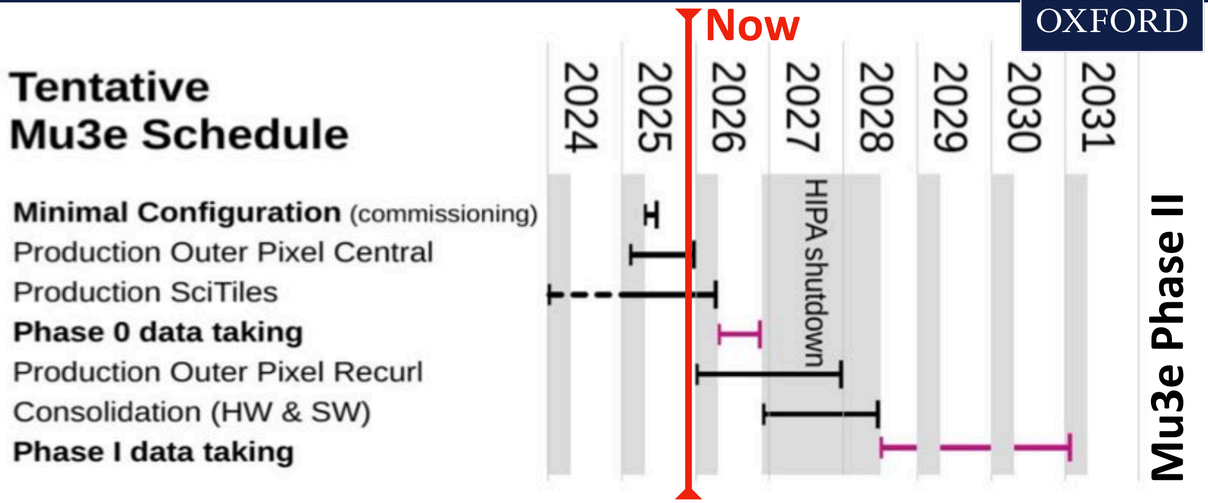
Successful operation of **world's thinnest vertex** detector!

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

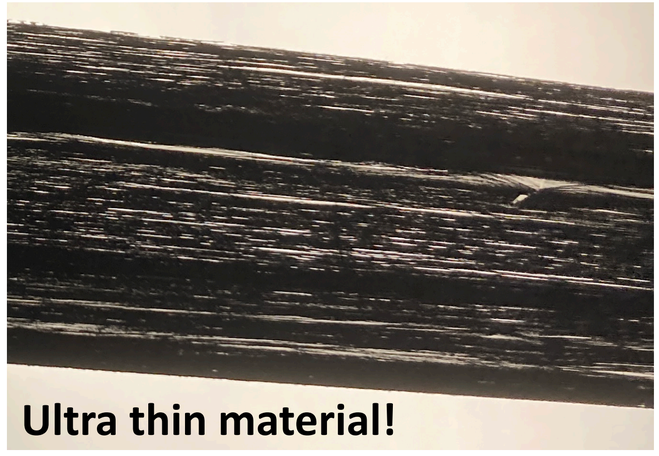


Additional material

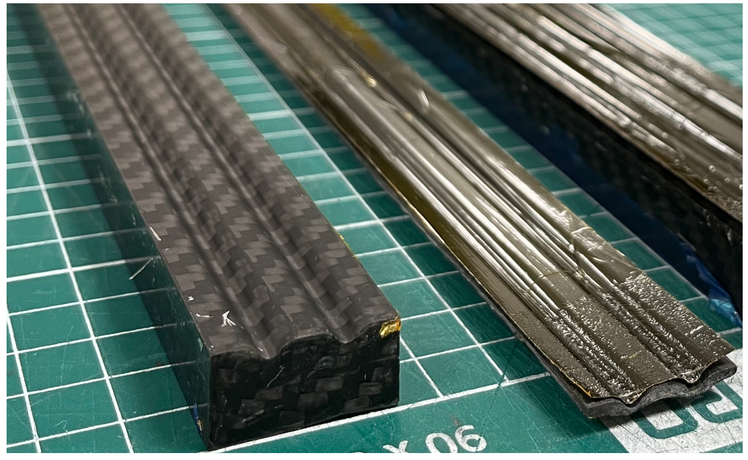
Fabrication of carbon-fibre support:

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 manually remove from vacuum bags, often resulted in **tearing the film**. Resolved by running small tubes of pressurised air into bags for more even breakout force.
- **Cured wrinkles in prototypes caused silicon to break**: **novel inflatable mossite intensifier** for polyimide side to ensure smooth surface.



Ultra thin material!



Carbon mould tool