Ultra-thin Mu3e tracker detector

DESIGN AND DEVELOPMENT

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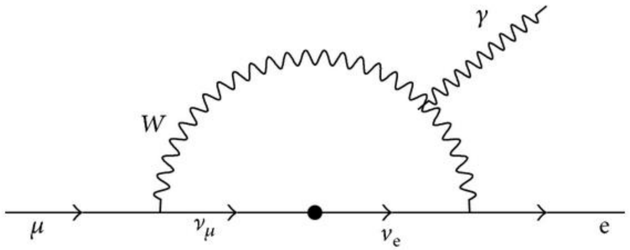
Outline

1. Charged Lepton Flavour Violation (CLFV) searches.

2. The Mu3e experiment.

3. Mu3e tracker design and roadmap towards construction.

Charged Lepton Flavour Violation (CLFV)



Example of CLFV process involving muons and neutrino oscillations.

BR$(\mu^+ \to e^+ + \gamma) \sim O(m_\nu/m_W)^4 \sim 10^{-54}$

New models (SUSY, extra dimension, etc) include new sources of LFV that lower the value of **BR** to numbers accessible by new experiments.

Muons experiments have proved to be the most sensitive among all the experiments on CLFV conducted so far. Current limits set by muon experiments:

C.L. 90% - BR($\mu^+ \to e^+\gamma$) < 4.2×10^{-13} MEG II

C.L. 90% - BR($\mu^+ \to e^+e^+e^-$) < 1×10^{-12} SINDRUM

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

Mu3e experiment

The Mu3e experiment, is under construction at PSI, Switzerland. It aims to find or exclude the muon decay into three e-leptons:

BR($\mu^+ \rightarrow e^+e^+e^-$)<2x10^{-15} (10$^8 \mu/s$ phase I)

BR($\mu^+ \rightarrow e^+e^+e^-$)<x10^{-16} (10$^9 \mu/s$ phase II)

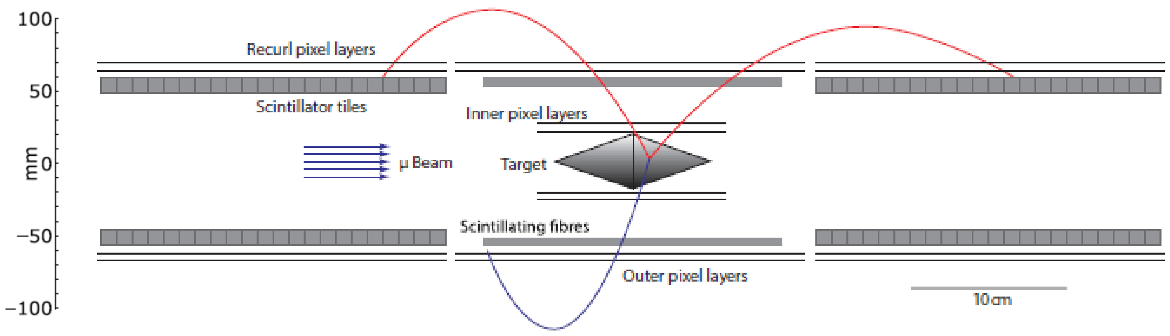
In its quest, Mu3e needs high muon rates, excellent momentum resolution to suppress background from internal conversion decay ($\mu \rightarrow eee\nu\nu$), and a good vertex and timing resolution to suppress combinatorial background.

To achieve that, Mu3e exploits an ultra-thin silicon pixel tracker and two timing detectors: tiles and scintillating fibres.

Detector design

Up-stream recurl station

Down-stream recurl station



Central barrel

The Mu3e tracker consists in:

- A central barrel including 2 inner layers (vertex detector) and two outer layers.
- Up- and down- stream recurl stations, with 2 layers each, for increased angular acceptance and improved the momentum resolution.

Inner layers | Outer layers

Layer	1	2	3	4
number of modules	2	2	6	7
number of ladders	8	10	24	28
number of MuPix sensors per ladder	6	6	17	18
instrumented length [mm]	124.7	124.7	351.9	372.6
minimum radius [mm]	23.3	29.8	73.9	86.3

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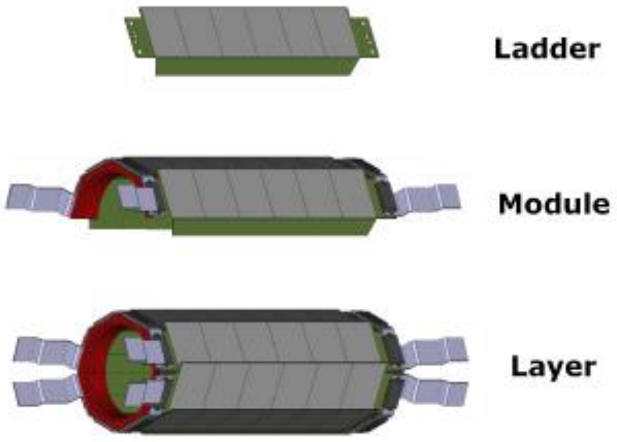
3D MODEL



Design and construction challenges

In Mu3e, the spatial and momentum resolution is limited by multiple scattering. This is reduced in a low-material budget detector i.e., thickness $X/X_o \sim 0.115\%$ per layer.

Mu3e exploits High-Voltage Monolithic Active Pixel Sensors (HV-MAPS). These chips integrate sensor and readout electronics and can be thinned to 50μm thickness (or 0.054% X_o).

The remaining material budget is used on the mechanical support structure, of which the High-Density Interconnect (HDI) flex circuit is an integral part.

CHALLENGES

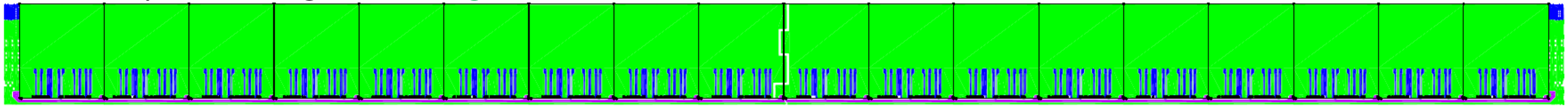
- **Mechanics**: the support of our detector ladder is a HDI flex thinner than a human hair.
- **Electronics**: high-density of traces in the HDI flex circuit (data lines, power, bias, for 18 chips).
- **HDI-production**: long fragile HDI flex, shrinking of the material, layers misalignment.
- **Tooling**: proper tooling for handling flex tapes and chips.

Mechanical structure: HDI flex tape

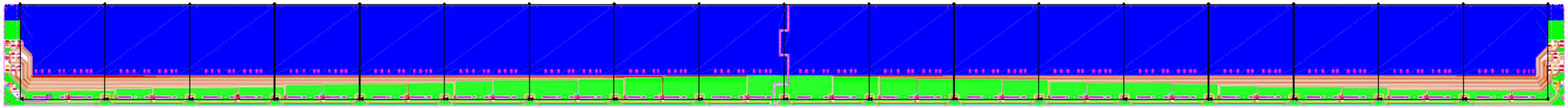
The HDI flex is a stack of two 14μm thick aluminium layers separated by 2 polyimide layers.

Total length: 380mm**, thickness**: 48um, **width**:24.7mm

Bottom layer, one single flex, for ground and HV line

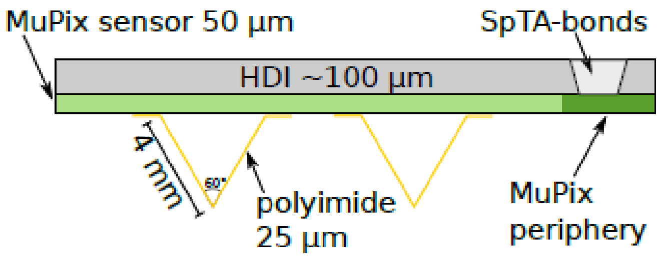


Top layer, split in 2 flexes, for power (+2V) and data lines.



The top layer is electrically and mechanically divided in half (right-left symmetry) and it is glued on the bottom layer**.** The middle cut helps the alignment of the layers during the production phase.

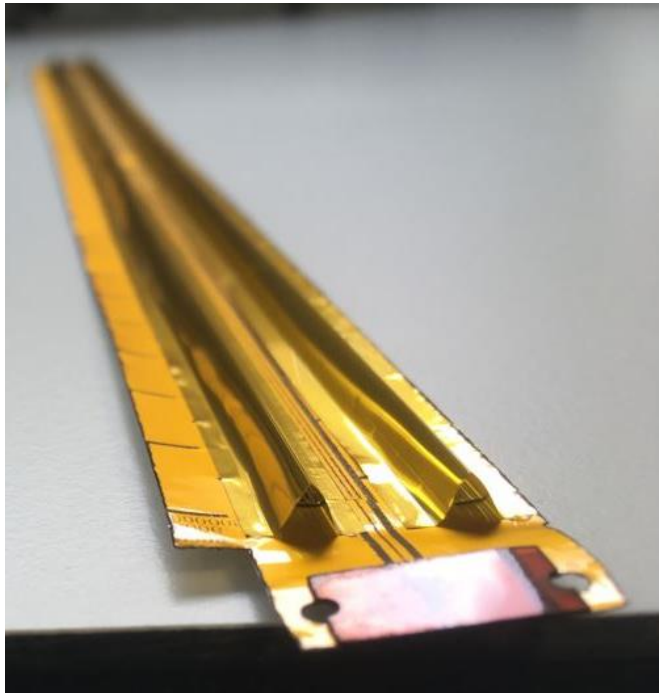
Mechanical support: V-folds



V-folds are made of 25μm thick polyamide layer with a V-shaped cross section. They run along the ladder longitudinal side, from end to end.

The 2 V-folds are glued onto the chips on the ladder. These give mechanical strength and stability against twisting and bending.

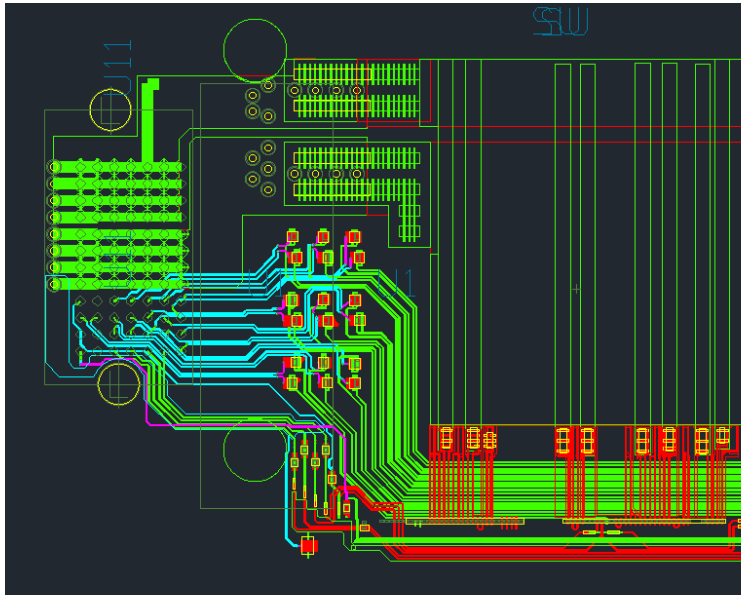
Originally, they were designed to carry coolant for the detector, now other solution are implemented (see next talk by Thomas).



Flex tape mock-up with V-fold (right).

Electrical connections: flex interposers

All data lines are sent to a connector mounted on a flex PCB, namely flex interposer. There are 2 flex interposers, one at each end of the flex tape.



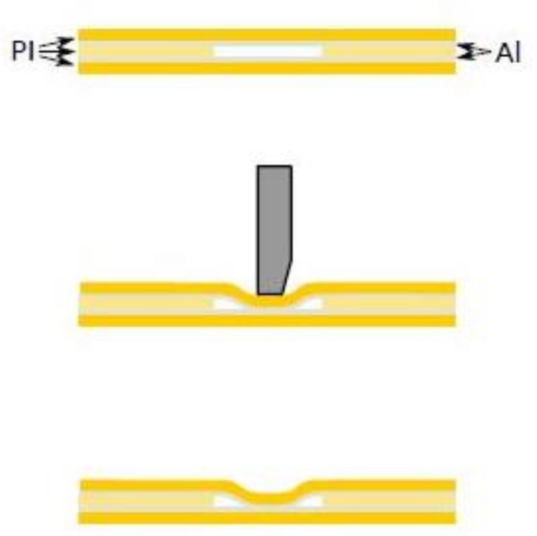
Flex interposer PCB

- This is a high-density track region. Therefore, the flex-interposer is separated in 4 different layers.
- In green (cyan) data lines to the sensors (to the interposer connector), purple HV, green power +2V.
- The flex interposer will be bent at right angle. To withstand the stress derived from the bending, lines in the flex interposers are made of Cu.

Single point automated tape bonding

Single Point Automated Tape Bonding (SpTAB) is a technique that allows to establish an electrical connection between two conductors without the need for additional bonding material, unlike the wire bonding technique that uses metal wires.

SpTAB is used to bond the Mu3e chips to the HDI tape as well as flex interposer to HDI.



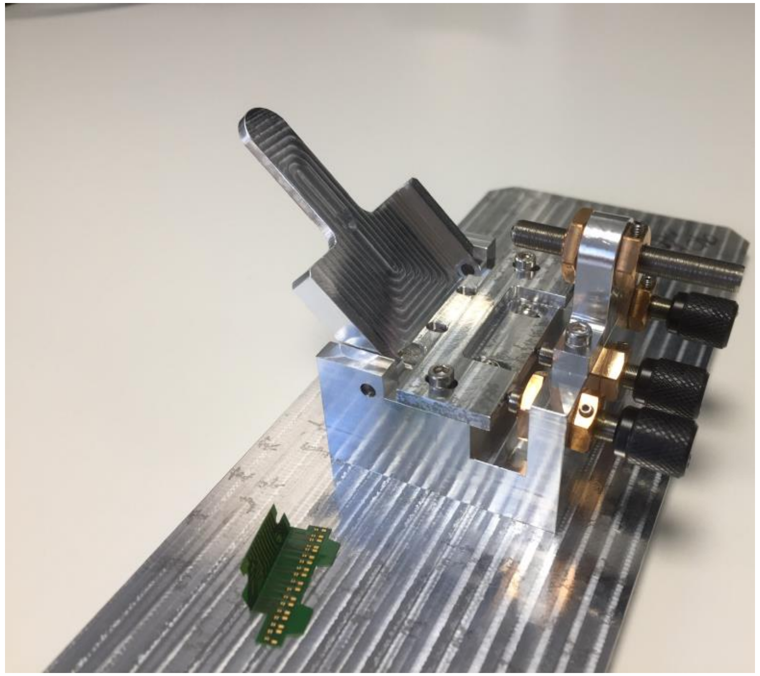
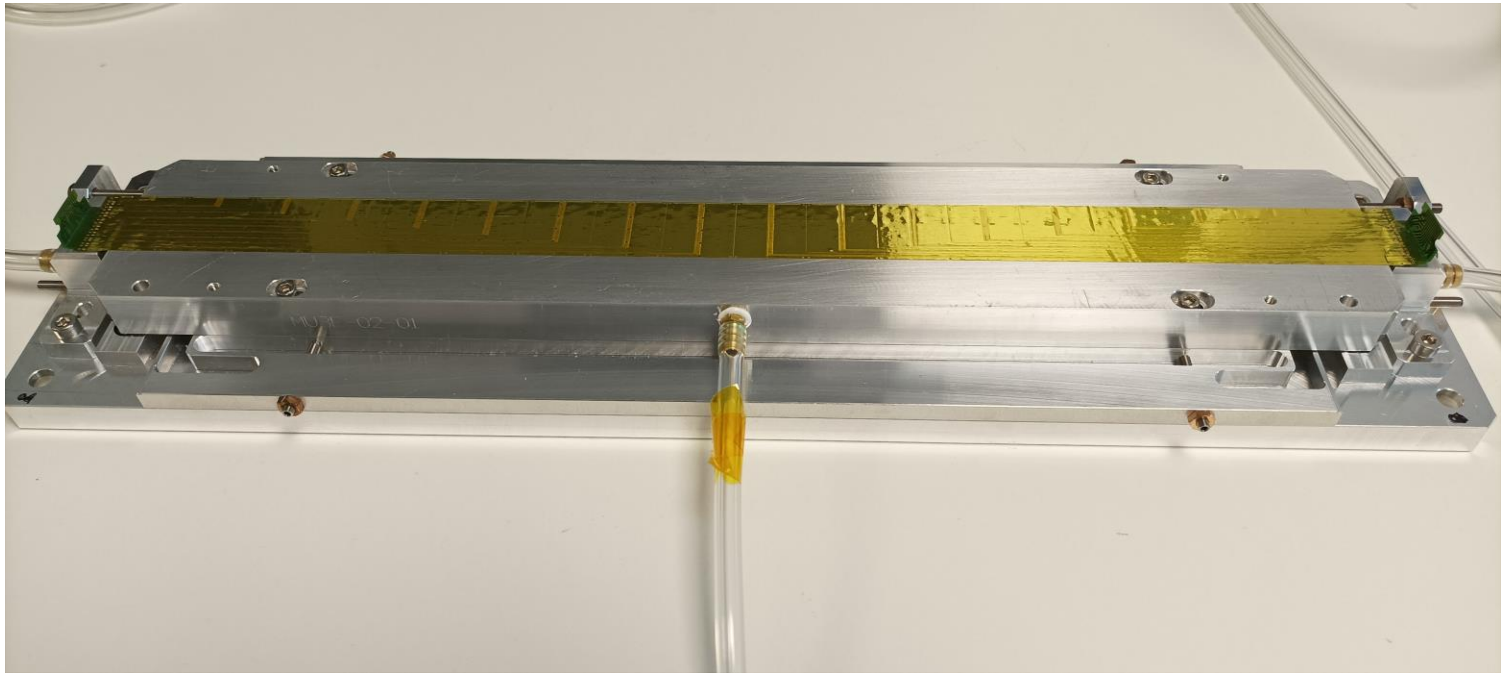
PI: Polyimide

1. Two Al layers separated by some insulating material, e.g., polyamide.

2. The tip pushes the top Al layer in contact with the bottom one through the punching window. Ultrasonic wedge bonding.

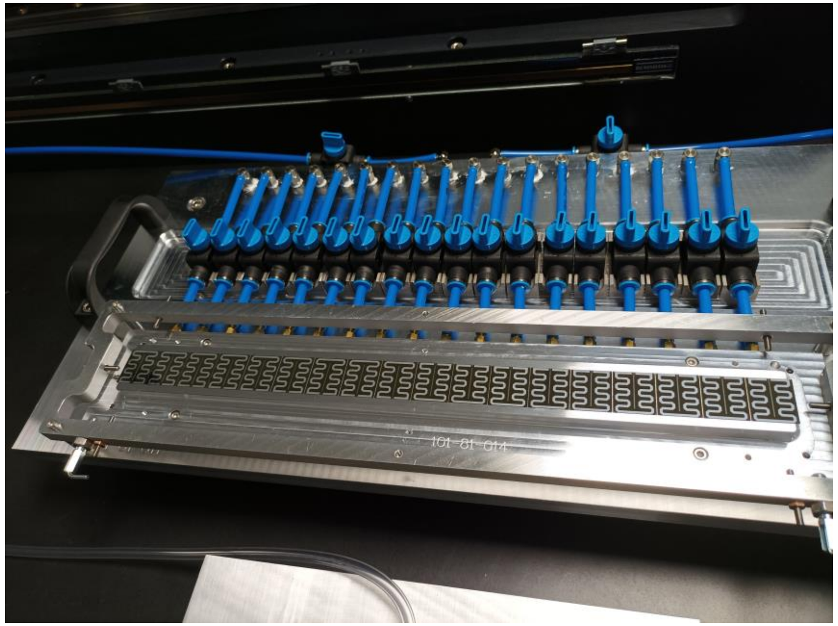
3. Bonding completed.

Tooling for the flex interposers

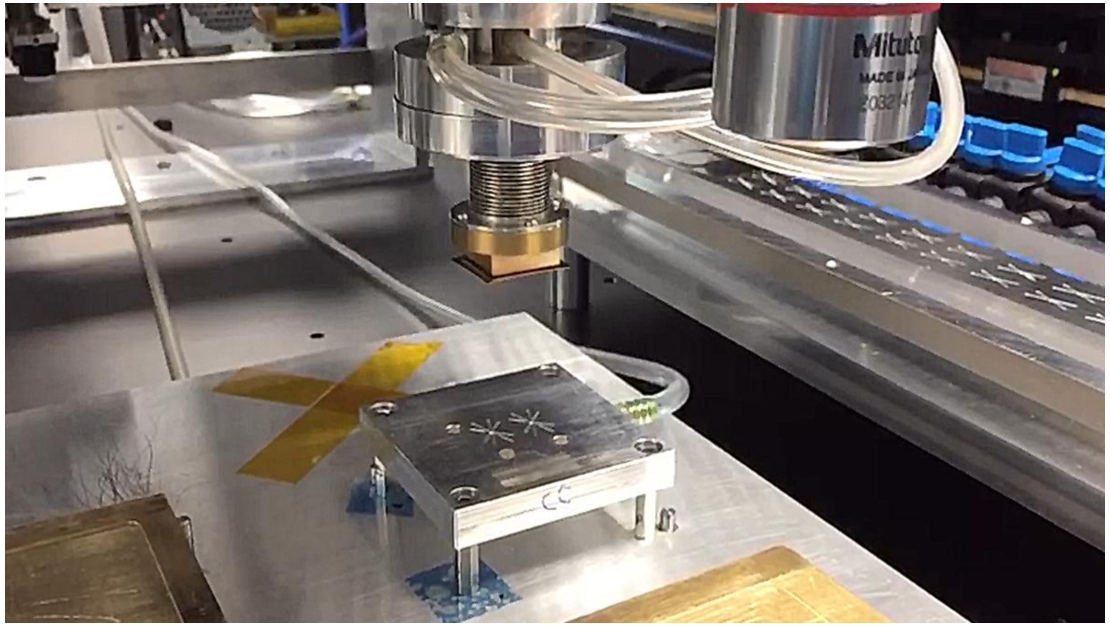



Left: flex interposer bending tooling. Right: the HDI flex is placed on a vacuum chuck and aligned against the flex interposers mounted at the ends.

Tooling for ladder production

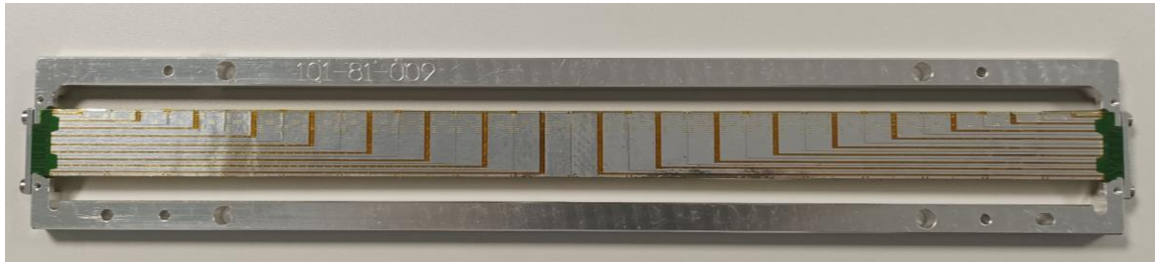


A series of 18 silicon chips aligned on the chuck. Alignment precision ~6 μm.

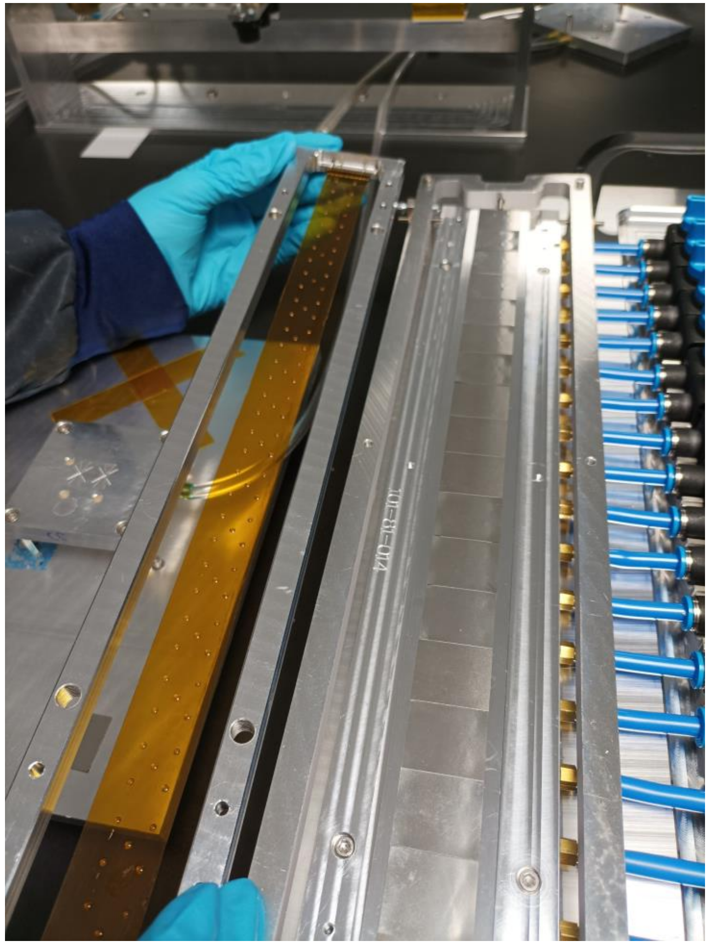


Gantry robot. Foreground: the chip base plate and the pick-up tool with camera; in the background the chip chuck.

Ladder production procedure

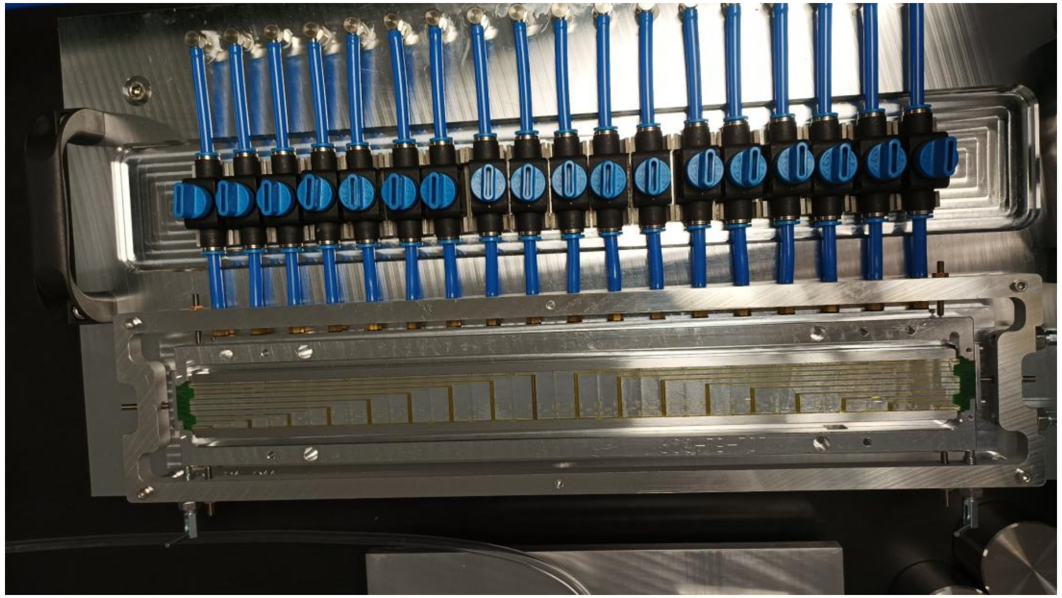


1) The HDI flex is installed on a ring frame and glue is applied at its back so that chips can be glued on it.

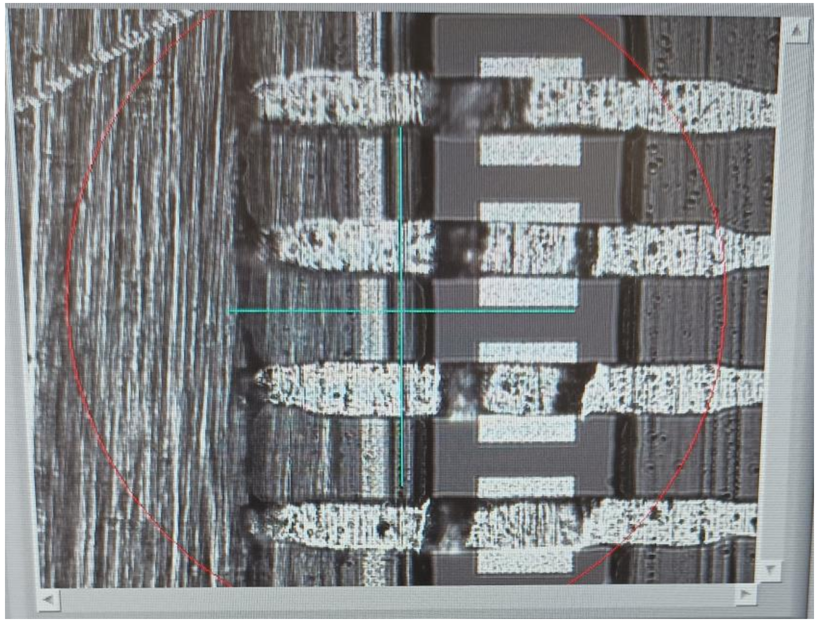


2) A mock-up flex made of a single Kapton layer with glue dots on it ready to be glued on top of mock-up steel chips.

Ladder production procedure



3) The ring frame is slotted in over the chips on the chip chuck.

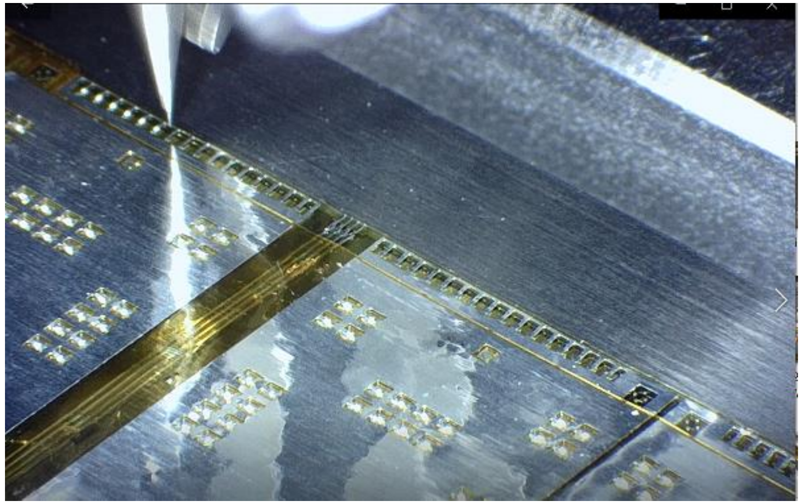


4) Fine alignment of Al traces on the HDI flex against the chip pads underneath.

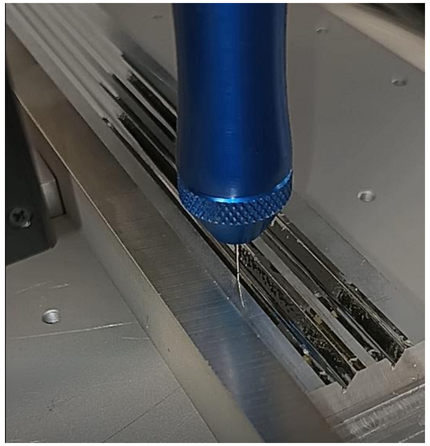
Ladder production procedure

5) Glue is let cure 12h under mild pressure.

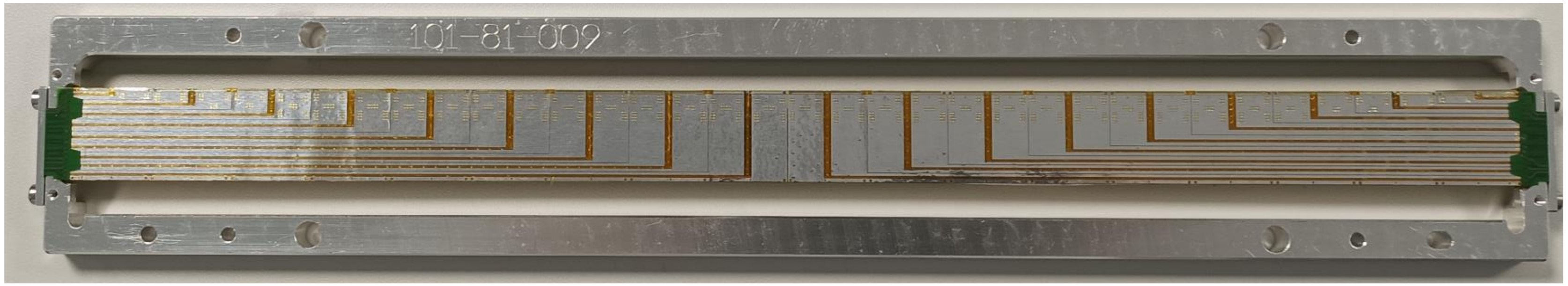
6) Tap-bonding of the flex HDI lines with the chip pads.

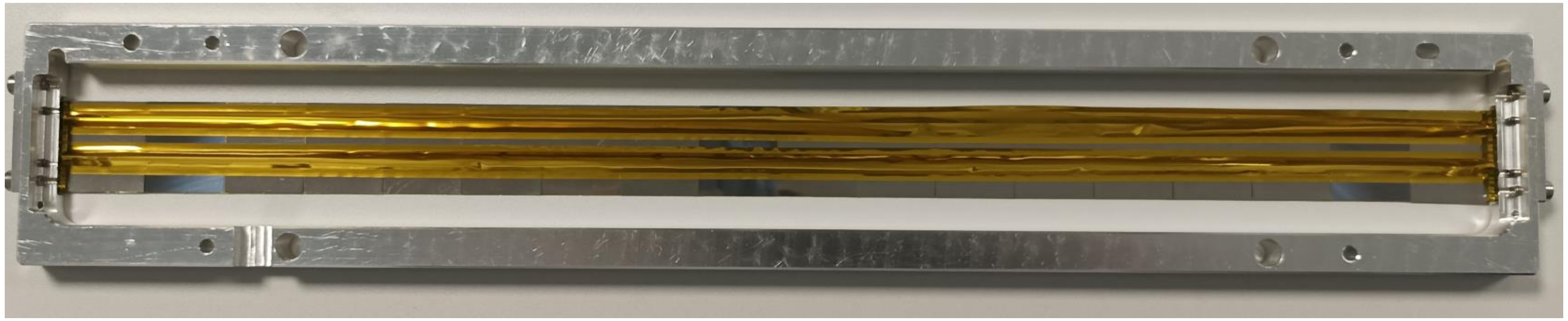


7) V-folds glue deposition on the glue robot .



Final ladder





Current status and outlook

1. Mu3e final chips (MuPix11) will arrive in summer 2022.
2. The design of the HDI flex tapes is complete.
3. The production of the MuPix10-11 HDI flex tapes is delayed. Our vendor is the Ukrainian company LTU.
4. Mock-up ladders with 18 chips have been built by using mock-up HDI flex tapes that run Al traces and Si chips with tap bondable fields.
5. Mock-up inner layers have been built using Mupix10 chips and rigid PCB boards. This detector prototype has been already tested PSI.

THANK YOU

Grazie

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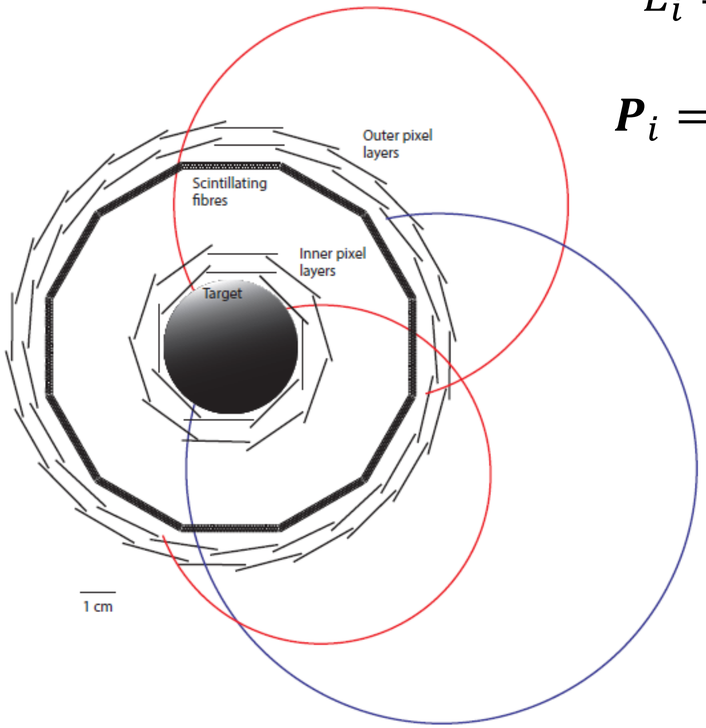
Спасибо

Experimental concept

By measuring the energy and momentum of the 3-lepton system in the final state we can discriminate a Mu3e signal from other standard model decays.

$$E_i = m_\mu c^2 = E_f = E_{e^+} + E_{e^-} + E_{e^+}$$

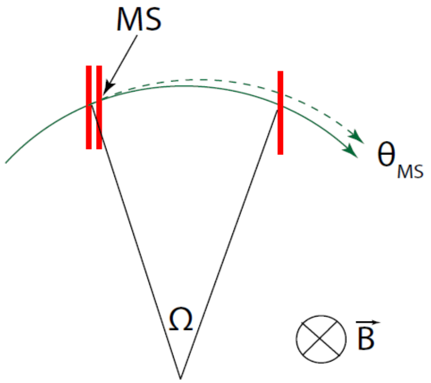
$$\boldsymbol{P}_i = \boldsymbol{P}_\mu = \boldsymbol{P}_f = \boldsymbol{P}_{e^+} + \boldsymbol{P}_{e^-} + \boldsymbol{P}_{e^+} = 0$$



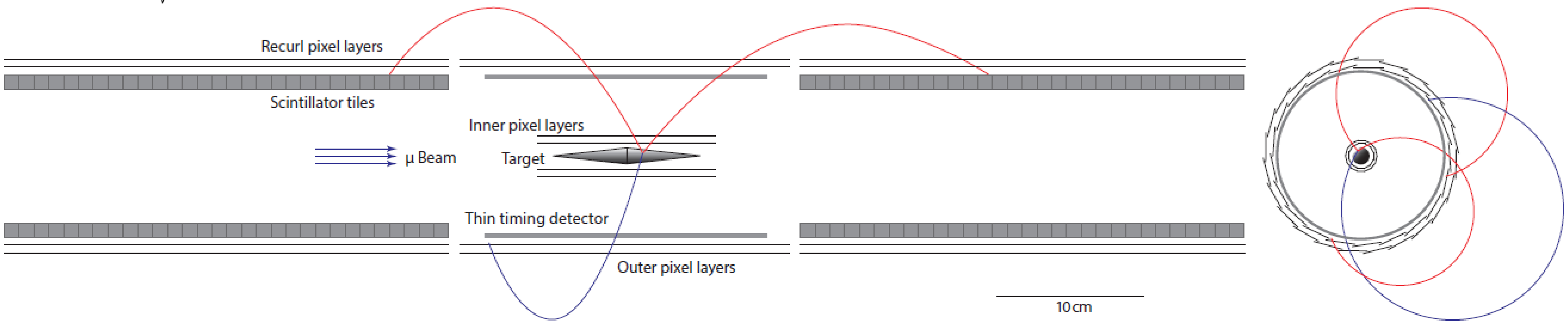
Momentum reconstruction is performed by fitting detector hits in triplets. From the fit, the curvature and thus the momentum of the track can be extracted.

Experimental concept

In Mu3e, the spatial and momentum resolution is limited by multiple scattering. For a given multiple scattering angle (Θ_{MS}) , the momentum resolution improves with the track curvature

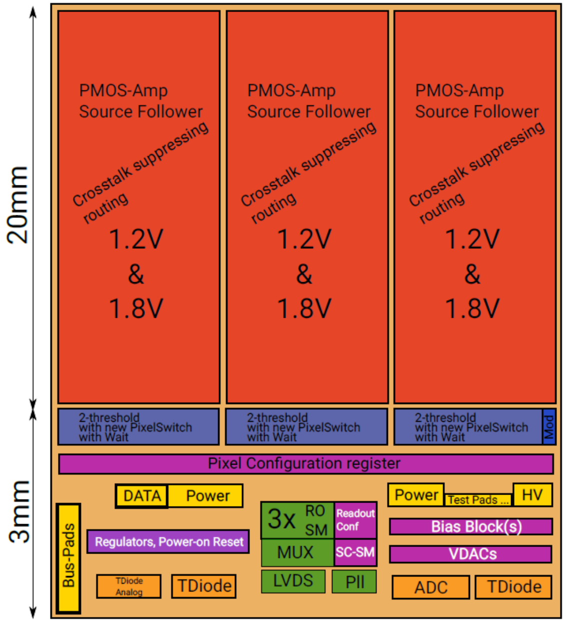


$$\frac{\sigma_p}{p} \propto \frac{\Theta_{MS}}{\Omega}$$



Mupix chips

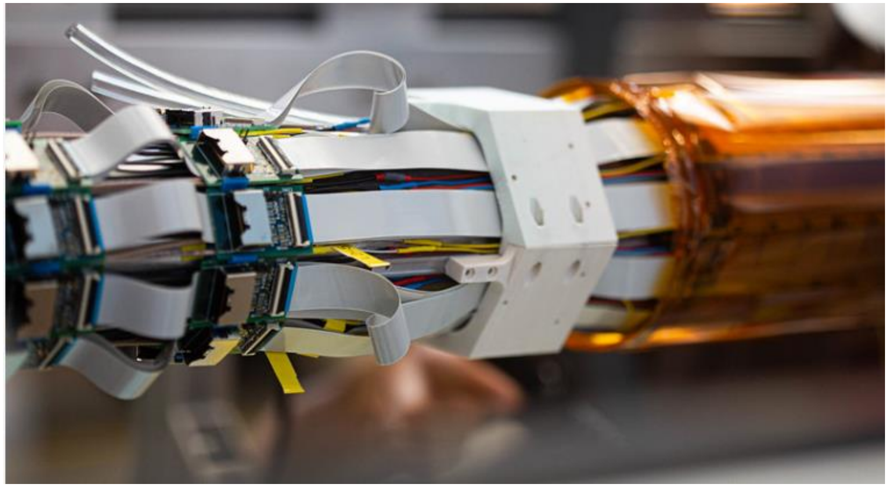
Mupix is a High-Voltage Monolithic Active Pixel (HV-MAPS) chip. It integrates sensor and readout together allowing the construction of a low material budget detector, i.e., $\frac{X}{X_o} = 0.054\%$.



sensor dimensions [mm^2]	$\lesssim 21 \times 23$
sensor size (active) [mm^2]	$\approx 20 \times 20$
thickness [μm]	$\lesssim 50$
spatial resolution μm	$\lesssim 30$
time resolution [ns]	$\lesssim 20$
hit efficiency [%]	$\gtrsim 99$
#LVDS links (inner layers)	1 (3)
bandwidth per link [Gbit/s]	$\gtrsim 1.25$
power density of sensors [mW/cm^2]	$\lesssim 350$
operation temperature range [°C]	0 to 70

256x256 pixels, 80x80 $\mu m2$. Each pixel has a sensor diode and a charge sensitive amplifier in it.

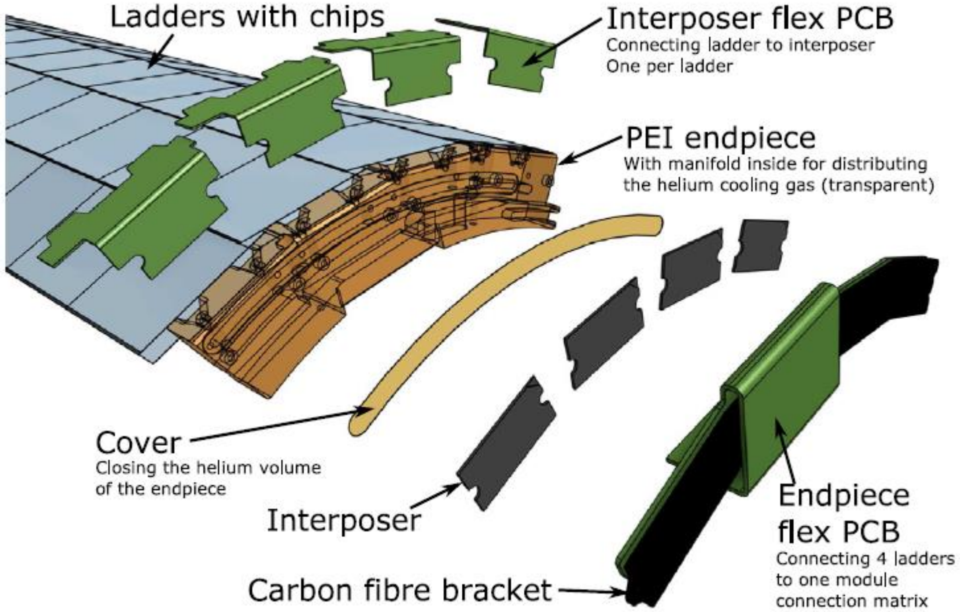
Ladder prototype



This is the inner module of the tracker detector in Mu3e. There are two layers made of 18 (8+10) ladders containing 6 chips each.

In this early prototype, the ladders were not built on HDI flexes. Instead, PCB were designed together with bus lines (white cables) and connectors.

Ladder mounting



Exploded view of the outer layer module assembly.

Ladders will be shipped to Liverpool where they will be assembled into modules.

A module is made of 4 ladders.