Mu3e ultra-low mass pixel detector mechanics

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On behalf of the Oxford Physics Microstructure Detector Laboratory and Mu3e Pixel Tracker collaboration
Introduction to Mu3e

• Search for rare decay of a muon into two positrons and an electron → evidence of a new physics beyond the standard model
• Detector design driven by need for:
  – Precise tracking (vertexing and momentum) → pixels
  – Good timing (coincidence, event separation) → scintillators
  – Minimal material budget (background suppression, multiple scattering)
• Muons are stopped on a target continuously, no bunch structure
• Rad-hard electronics not that important (~1 Mrad lifetime dose for pixel system)
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<td>50-100</td>
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<td>&lt;200</td>
<td>&lt;10</td>
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<td>Pixel positional stability (µm)</td>
<td>&lt;10</td>
<td>&lt;3</td>
</tr>
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<td>Sensor temperature range (°C)</td>
<td>0-70</td>
<td>20-50</td>
</tr>
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<td>Beampipe bake-out temperature (°C)</td>
<td>NA</td>
<td>120</td>
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<tr>
<td>Radiation max. dose (Mrad/year TID)</td>
<td>~1</td>
<td>3.4</td>
</tr>
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*measured value MuPix8 chip
Mu3e detector concept

Phase-I configuration:

- High rate: $10^8$ muon stops on target per second
- Time resolution (pixels): 20 ns
- Vertex resolution: about 200 μm
- Momentum resolution: about 0.5 MeV
- All inside a cryogenic 1 T magnet, warm bore I.D. 1 m
Let's focus on the pixels. Monte-Carlo studies led to the following geometry:

\[(B = 1 \, \text{T}, \, x/X_0 = 0.1\% \, \text{per layer})\]
MuPix detector concept

Identical copies of layers 3/4 will extend the detector in z to extend coverage for recoiling tracks.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Unit</th>
<th>units/layer</th>
<th>ladders/unit</th>
<th>chips/ladder</th>
<th>#chips</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>half shell</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>48</td>
</tr>
<tr>
<td>2</td>
<td>half shell</td>
<td>2</td>
<td>5</td>
<td>6</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>module</td>
<td>6</td>
<td>4</td>
<td>17</td>
<td>408</td>
</tr>
<tr>
<td>4</td>
<td>module</td>
<td>7</td>
<td>4</td>
<td>18</td>
<td>504</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1020</td>
</tr>
</tbody>
</table>
Material budget

**Perspective**

<table>
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<tr>
<th>Experiment</th>
<th>Ref.</th>
<th>$x/X_0$ per layer [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS IBL</td>
<td>[1]</td>
<td>1.9</td>
</tr>
<tr>
<td>CMS Phase I</td>
<td>[2]</td>
<td>1.1</td>
</tr>
<tr>
<td>ALICE upgrade</td>
<td>[3]</td>
<td>0.3</td>
</tr>
<tr>
<td>STAR</td>
<td>[4]</td>
<td>0.4</td>
</tr>
<tr>
<td>Belle-II IBL</td>
<td>[5]</td>
<td>0.2</td>
</tr>
<tr>
<td>Mu3e</td>
<td></td>
<td>0.1</td>
</tr>
</tbody>
</table>

- **Low-material mechanics** based on polyimide film
- **Aluminium flexes** to reduce $Z$
- **Interposers** to save space
- **Helium as coolant** – good compromise between cooling potential and radiation length

**Drill-down for pixel layers**

<table>
<thead>
<tr>
<th></th>
<th>Layer 1-2</th>
<th>Layer 3-4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>thickness [μm]</td>
<td>$X/X_0$</td>
</tr>
<tr>
<td>MuPix Si</td>
<td>45</td>
<td>$0.48 \times 10^{-3}$</td>
</tr>
<tr>
<td>MuPix Al</td>
<td>5</td>
<td>$0.06 \times 10^{-3}$</td>
</tr>
<tr>
<td>HDI polyimide &amp; glue</td>
<td>45</td>
<td>$0.18 \times 10^{-3}$</td>
</tr>
<tr>
<td>HDI Al</td>
<td>28</td>
<td>$0.31 \times 10^{-3}$</td>
</tr>
<tr>
<td>polyimide support</td>
<td>25</td>
<td>$0.09 \times 10^{-3}$</td>
</tr>
<tr>
<td>adhesives</td>
<td>10</td>
<td>$0.03 \times 10^{-3}$</td>
</tr>
<tr>
<td>total</td>
<td>158</td>
<td>$1.15 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
MuPix ladder and modules

Ladders:
- MuPix chips are mounted on thin Al-kapton High Density Interconnects (HDI) which incorporate signal, control and power lines.
- Material per layer: \( \sim 0.1\% X_0 \)
- Interposer flex mounted to HDI at each end to connect to interposer
- finally connections from several ladders are bundled together on the endpiece flex

Pixel modules:
L1/L2: 4 or 5 ladders make a half shell modules
L3/L4: 4 ladders to make an outer module
Inner layer half-shell prototypes

Components: flex heater circuits, endpiece flex and PEI endpieces (Heidelberg)

Ladder assembly:
- Steel chips and kapton spacers placed by hand under microscope.

Module assembly (ladder mounting)
- Custom tool for half shell assembly

Status Jan 2019:
- Full set of L1 / L2 flex heater modules produced

Next step Silicon heater modules:
- HDI and Silicon heater chips available
- Interposer/endpiece flexes ready for submission

Completed layer 1 flex heater half shell with steel chips.

Bare flex
II with spacer and steel chips.
III ends folded over

Custom tool for half shell assembly
Outer layer flex-heater ladder prototypes

**Components**: heater flex circuits, spacers and kapton v-channels (Heidelberg)

Oxford assembles these into ladders. Since the start of this programme many aspects the design, tooling and procedures have been optimised, both in Oxford and Heidelberg.

Improved control of alignment and glue deposition, achieving good seal of v-channels.

**Thermo-mechanical test stand needs ~ 52 ladders.**
Outer layer Si-heater ladder prototypes

Pick and place tooling in Oxford

Robotic gantry places 17 / 18 chips on a vacuum chuck.

Robotic pick and place gantry.

Chip holding chuck with 18 steel dummy chips

18 chips successfully aligned on dummy kapton flex to within about ±5 μm of the nominal positions
Outer layer module prototypes

**Components:** ladders (Oxford), endpiece flex (Heidelberg), endpieces and interposer clamp plates (Liverpool)

**Assembly:**
End pieces are mounted on a tooling stand before ladders are glued to the endpieces. The tooling stand set-up defines the module length. New tooling stand to optimise accuracy on the dimensions of assembled modules.

**Thermo-mechanical Mock-up** requires 13 modules.

*Image of tape heater ladders and connecting interposers.*
Flex circuits for Si-heaters modules L1 & L2

HDI: routes lines from 3 chips to either end. For each side 6 wide traces for power and ground, and 12 traces to monitor RTDs.

Interposer flex routes SpTAB bond pads to pads for the 7x12 interposer

Endpiece flexes (4 flavours, here L2 downstream) route lines from 7x12 interposers to solder pads.

SpTAB bonds

HDI circuits for layer 1 & 2 ladders received (LTU 2-layer Al-Kapton)
Interposer and endpiece flexes ready for submission (SwissPCB 4-layer Cu-Kapton)
Institutes geared and trained up on SpTAB bonding. Test samples successfully bonded.
Flex circuits for Si-heaters modules L3 & L4

HDI: 2 aluminium layers

HDI: 4 RTD monitoring lines, power and ground for each chip.

Modified transition HDI to interposer flex to gain more space for routing.

Interposer and Endpiece flex:
4 copper layers

Demonstration of concept for signal and power routing.
Same power and more independent lines than in final detector.

L4 Interposer flexes route the lines from 9 chips to the 7x12 interposer.

Endpiece flexes (2 versions):
- Downstream: power shared by 3 chips, and reduced RTD readout, to connect to single 10x20 interposer
- Upstream: all lines 9 chips routed to two 10x20 interposers
Pixel detector cooling

Sketch of supplies: electrical connectivity and cooling circuits.
Helium cooling system

4.5 (2.8) kW is dissipated in the full pixel tracker, based on 400 (250) mW/cm²

Gas flow in and around central pixel tracker

<table>
<thead>
<tr>
<th>Volume</th>
<th>Flow speed (m/s)</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap L1/L2</td>
<td>10</td>
<td>DS → US</td>
</tr>
<tr>
<td>Gap SciFi/L3</td>
<td>5</td>
<td>US → DS</td>
</tr>
<tr>
<td>V-folds L3/L4</td>
<td>20</td>
<td>DS → US</td>
</tr>
<tr>
<td>Gap L3/L4</td>
<td>10</td>
<td>DS → US</td>
</tr>
<tr>
<td>Global</td>
<td>0.5</td>
<td>US → DS</td>
</tr>
</tbody>
</table>
Verification of cooling solution

Simulation – Layer 1 & 2

Modelling
- Helium flow
- MuPix chips (108)
- Heat conduction in solid parts
- Heat transfer solid-fluid

Conditions
- $\dot{m} = 2 \text{ g/s} $ helium
- Inlet $ T = 0 ^\circ \text{C} $
- $ \dot{q} = 400 \text{ mW/cm}^2 $
Simulation - MuPix heat dissipation

- Results with $\dot{q} = 400 \text{ mW/cm}^2$
  - Scaled linearly

- Different heat loads in MuPix chip
  - Mockup $\rightarrow$ constant heat load
  - MuPix chips:
    - Periphery 50% of integral heat $\rightarrow \dot{q} = 1533 \text{ mW/cm}^2$
    - Detector 50% of integral heat $\rightarrow \dot{q} = 230 \text{ mW/cm}^2$

- Layer 2 temperature has high temperature increase due to uncooled periphery
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Simulation of Layer 1 & 2 – uniform heat chips

Original

Optimisation

Midplane

Flow direction

(a) Original slots geometry.

(b) Optimised slots geometry.
Simulation of Layer 1 & 2 – uneven heat chips

Mylar tube
Target

Optimisation with additional flow

Temperature
51.9
47.0
42.1
37.3
32.4
27.5
22.6
17.8
12.9
8.0
3.2
[°C]
Verification of cooling solution

Measurement – Mock-up Layer 1 & 2
Measurement setup – Layer 1 & 2

[Diagram showing measurement setup for Layer 1 & 2, with labels for measurement points and legend for process media.]
Comparison – CFD vs. Measurement

Layer 2 temperature
\( q = 400 \text{ [mW/cm}^2\text{]} \)

CFD - Optimisation

Measurements - Optimisation

Temperature

\[ \begin{array}{|c|c|c|c|c|c|}
\hline
\text{Temperature} & 75.0 & 67.5 & 60.0 & 52.5 & 45.0 & 37.5 & 30.0 & 22.5 & 15.0 & 7.5 & 0.0 \\
\hline
\end{array} \]

\( \Delta T \text{ [K]} \)

\[ \begin{array}{|c|c|c|c|c|c|}
\hline
\text{Temperature} & 70 & 60 & 50 & 40 & 30 & 20 & 10 & 0 \\
\hline
\end{array} \]

flow direction
Verification of cooling solution

Simulation of Layer 3 & 4

**Modelling**
- 5 x Helium flows
- Heat conduction MuPix (912)
- Heat conduction in polymide
- Heat transfer solid-fluid

**Conditions**
- Several helium flows
- 0 °C
- 400 mW/cm²

**Issues**
- No leakage flow modelled
- Limits reached of computational resources at ITFE
- Mesh size dependency unknown (Higher temperature may occur)
Simulation of Layer 3 & 4

Original

Optimisation

Temperature

Temperature

69.5
63.3
57.2
51.1
45.0
38.9
32.8
26.7
20.5
14.4
8.3
8.3
64.4
58.9
53.4
47.8
42.3
36.8
31.3
25.8
20.2
14.7
9.2

[°C]

[°C]
Detailed simulations: inclusion of gas distribution manifolds, realistic heat load distribution on chips, optimisation of inlet openings

ΔT simulation for L1/2 (left) and L3/4 (right)
- 400 W/cm² (MuPix8 ~250 W/cm²)
- Helium velocities as in final detector
- Thin mylar tube at r=67 mm to improve flow outside L2

Measurement challenges

**Layer 1 & 2**
- Measurement with unequal heat load
- Design mylar tube flow over layer 2
- Measurement with helium atmosphere
- Preciser measurement of heat load
- Improvement of instrumentation
- Improvement of simulation and measurements if needed

**Layer 3 & 4**
- Measurements with mockup
- Only with air due to high mass flows
- Simulation with leakage flow
- Adjustment of outlet geometry to minimise pressure drop
Positional stability of MuPix

- Ladders in modules and modules on end rings need to be equal length
  - Small variations lead to substantial out-of-plane bowing
  - Need accurate setup of tooling using dowel system
  - Need to assemble modules at same temperature (7.2µm per °K) and relative humidity (7.2µm per %RH)
- Modules are under spring tension applied to end ring
- Oscillations due to gas flow turbulence have been measured. Amplitudes were on micron level.
- Displacement depends on the differential pressure. Overpressure in one volume will ‘inflate’ → need to control the flows (and consequentially pressures) sufficiently precise and stable to be <10 µm displacement
- Main movements come from thermal changes
Silicon heaters

- We’ve prepared single silicon heater assemblies.
- Consists of heater (sputtered aluminium on silicon, thinned down to 50 μm) and a flex HDI (2 layers Al/polyimide). **Very close to final design.**
- Heater designed to dissipate up to 400 mW/cm².
- Has a 1000 Ω RTD on it
- Next set of slides: graph paper viewed reflected on back of silicon heater
Surface deformation experiment

Linear expansion coefficients:

\[ \alpha_{\text{Kapton}} = 2.0 \cdot 10^{-5}/K \]

\[ \alpha_{\text{Silicon}} = 2.6 \cdot 10^{-6}/K \]

Flat sensor at initial temperature

Deformation due to increased temperature
Sensor at 30 °C
Sensor at 40 °C
Sensor at 50 °C
Sensor at 60 °C
Sensor at 70 °C
Silicon heater deformation

Before you get too shocked:

- About the magnitude expected from CTE mismatch polyimide-silicon.
- Glue pattern has not been optimised yet.
- Will calibrate finite element simulations and optimise glue pattern in simulation.
- If detector is in thermal equilibrium and stable over time, track-based alignment can handle this.
- Thermal mass is small, hence equilibrium will be reached fast.
# MuPix / CEPC Pixel comparison

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*measured value MuPix8 chip*
Conclusions and Outlook

• **MuPix is a challenging, but exciting pixel detector project:**
  – Thinned silicon, monolithic, self-triggered pixels
  – Ultra-lightweight mechanics
  – Gaseous helium cooling
  – Readout using aluminium flexes, interposers and micro-twisted pair cables

• **Plans:**
  2019: Full thermo-mechanical mock-up using flex- and silicon-heater ladders
    Implement module assembly and test workflows
    Further electrical integration
  2020-21: Pixel ladder and module production
  2022: Integration at PSI beamline
Detailed overview (presented by Frank Meier at 2018 Forum on Tracking Detector Mechanics) at https://indico.cern.ch/event/695767/contributions/3014935/

Theses on helium cooling and thermal analysis at https://www.psi.ch/mu3e/theses

Video clips
- Inner layers
  - full assembly layer 1 (https://youtu.be/SBvlbvTk6Ac)
  - equipping two tape heaters with steel plates (https://youtu.be/CuNQZ7SVkO4)
  - mounting a tape heater (https://youtu.be/ioE6Pyc3i3g)
- Layers 3 & 4
  - aspects of the MuPix L4 ladder assembly - pick-and-place chips, dispensing epoxy on flexprints (https://www.youtube.com/channel/UCgqsa3w7as9x3auTFsQoekA)
References

Building L4 tape heater ladders for thermo-mechanical prototype

- Aligning/gluing V-folds and interposer stiffeners on metalized Kapton flexprints clamped on ring frame holders
- Performing metrology of V-fold locations w.r.t. alignment pin holes for interposers at ends of flexprints
  - most assembled ladders have V-folds <0.5mm away from design location w.r.t. the pin holes
- Ship L4 tape heater ladders to Liverpool for module assembly
Optimisation of tape heater ladder components, tooling and assembly procedure is ongoing

- Adopted a modified flexprint design with broader, tapered ends and circular holes instead of notches
- Modified ring frames to better support/avoid cutting into flexprint under clamps
- V-folds with closer to designed cross-section geometry (for better fit in double V-fold vacuum chuck) are being developed/manufactured at Heidelberg
- Designing test jig to aid connection to an electrical test station from Univ. of Bristol
- Clearance holes in ring frame at hole locations at the ends of the flexprint
- Ring frame is lowered onto plate that references the ring-frame-with-ladder to pins in each end of the plate. The pins are then in the correct locations for aligning interposers and external cables to make electrical connection to the ladder
- Alignment pins in the plate remove a requirement for high tolerance pins in all ring frames.
- Plate with alignment pins can be modified for cooling the V-fold side of the ladder
Mu3e @ Oxford

- Pictured here is an interposer aligned to the end of a tape heater flexprint by pins in a baseplate.
- Addition of two threaded holes in the ring frames, one to either side of the interposer, should be sufficient for clamping a ‘cable’ to connect to a ladder-in-ring-frame for electrical test.
Mu3e @ Oxford

Preparing for Silicon heater ladders

– Similar to final ladders, includes SpTA-bonds
– Test stand to measure R + calibration of Si heaters

Status:

- Designed and fabricated custom ‘front-end’ tools and programmed gantry positioning system for pick-and-place alignment of chips on a vacuum chuck
- Designed and fabricated tooling to align flexprint-in-ring-frame to chips arrayed on the vacuum chuck
- Programmed glue dispensing robot to deposit pattern of epoxy ‘dots’ on flexprint-in-ring-frame for chip attach
- Aligned and glued flexprint to arrayed chips on vacuum chuck → 1st attempt using stainless steel ‘chips’ looks good!
- Program with pattern recognition of chip fiducials is ready
- Replaced manual connections to vacuum supply with programmatic control using FESTO electro-valves
Mu3e @ Oxford

- Chip pick-up tool
- Chip alignment vacuum chuck
- Vacuum supply manifolds
Transferring a stainless steel ‘chip’ from single chip loading vacuum chuck to pick-up tool
Single SS chips pick-and-placed onto chip alignment vacuum chuck, progressively building an array of (up to 18) chips aligned within +/-10µm of ideal locations
Mu3e @ Oxford

18 SS chips aligned and vacuum clamped to the chuck, ready for optical survey and gluing to a flexprint-in-ring-frame

See videos of “MuPix L4 ladder” assembly on YouTube at https://www.youtube.com/channel/UCgqsa3w7as9x3auTFsQoekA
New outer layer ladder design

- New scheme for ladder flex - bent ‘flex interposer’ tabs with copper traces at ends + flat flexprint with aluminium traces
- Requires developing tools and procedures for aligning + gluing + SpTA-bonding flex interposers with pre-bend to flat flexprint
- Impacts almost all of our current tooling developed for tape heater ladder assembly → redesign of ring frame holders, alignment jigs, etc.
Challenges for new ladder design

• Very small areas for glue (to adhere interposer flex to flat flexprint) between openings/contacts for TAB bonding
• Consider adhesive film instead of liquid epoxy
Challenges for new ladder design

Old design had ~20µm gap between top of flexprint to bottom of chip in neighbouring ladder

New design (with addition of interposer flex) results in interference between neighbouring interposer flexes
Silvan has made changes to module end piece designs to accommodate the addition of the flex interposers, including increasing the angle between neighbouring ladders by 1 degree to avoid interferences.
Summary

- L4 tape heater ladder assembly is becoming (almost) routine – will refine based on feedback from experience from module assembly of the ladders at Liverpool
- Working with Bristol on connection of ladders to test station
- Preparation for pick-and-place assembly of Si heater chip ladders is advanced
- Several challenges for design, assembly and integration of ladders with pre-bent flex interposers
  - Flex designs submitted to LTU (flat flexprint with aluminium traces) and SwissPCB (flex interposers with copper traces)
  - Developing assembly sequence, tooling, and procedures to accurately align, bond, and handle new design ladders