Mu3e pixel chip “MuPix” and module construction design overview for the meeting with UK institutes

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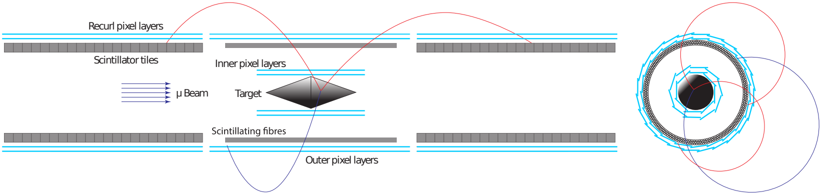
Overview

Introduction

The Mu3e experiment, Phase-Ib configuration:

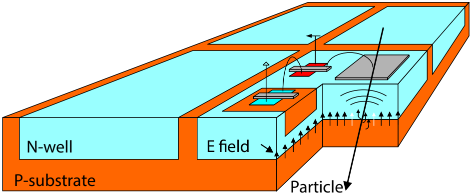


Key requirements:

- High rate: 10^8 muon stops on target per second
- Time resolution: 20 ns
- Vertex resolution: about 200 μm
- Momentum resolution: about 0.5 MeV/c^2
- Low material budget: 1‰ X_0 per pixel layer

Introduction

We use a High-Voltage **Monolithic** Pixel Sensor (HV-MAPS):



- HV CMOS technology used automotive and audio industry
- Reverse biasing up to $-90\,\text{V}$ (reliable)
- Thinning to $50\,\mu\text{m}$ possible and done
- Self-triggered, continuous readout (no shutter, darkframe etc.)

Introduction

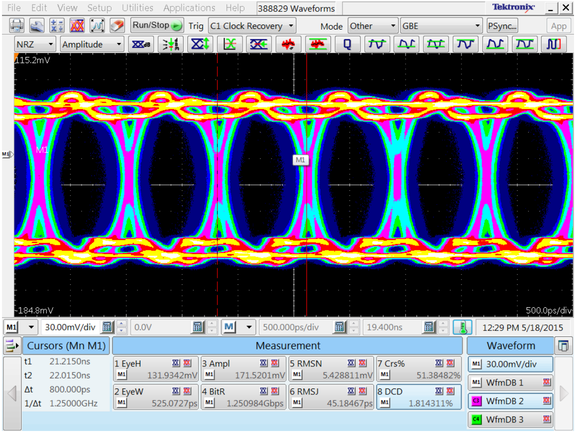
Several generations of MuPix chips realised:

Version	Year	Main features
MuPix1/2	2011/12	Analog prototype chips
MuPix3	2013	First digital readout
MuPix4	2013	Working digital readout and time-stamping
MuPix6	2014	Readout bugs fixed, double-staged preamplifier
MuPix7	2014	Fast serial readout (1.25 Gbit/s), internal state machine, internal clock generation

MuPix3–7 have an active area of $3 \times 3\,\text{mm}^2$, chip size is $3 \times 4\,\text{mm}^2$.
MuPix7 pixel size: $103 \times 80\,\mu\text{m}^2$.

MuPix7: Fast serial readout signal

Signal quality of fast readout signal at 1.25 Gbit/s is very good:

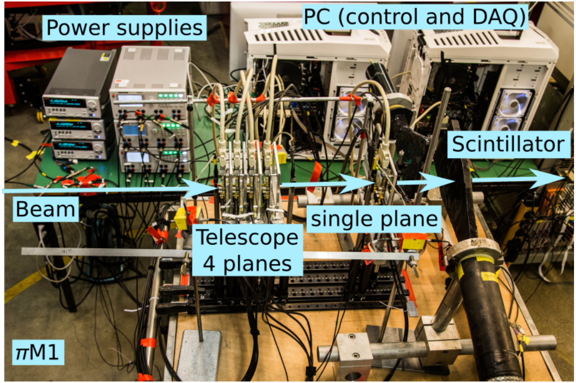


Clock is at 125 MHz, high speed clock internally generated.

Measured on test bench using chip on standard test board.

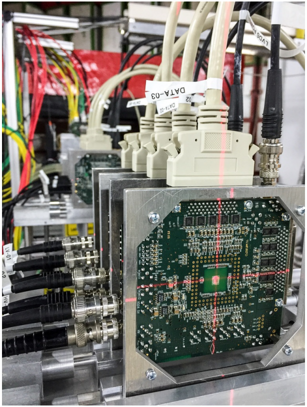
MuPix7: Telescope

Telescope setup, e.g. at PSI πM1:



Telescope with 4 MuPix7 planes, 1 plane elected as DUT

MuPix7: Test beams



Several MuPix7 testbeam campaigns during 2015:

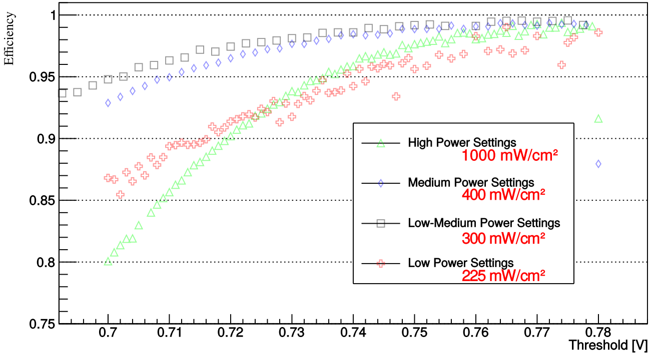
- Mainz MAMI, 1 GeV e^- (spring)
- CERN SPS, 180 GeV π (July)
- PSI πM1, 250 MeV π^+, μ^+, e^+ mix (October)
- DESY, 4 GeV e^+ (March, October)

Over this course, the setup became more reliable. Boards were debugged with MuPix6 already, which helped a lot.

What follows is a selection of results from those campaigns.

MuPix7: Efficiency

Efficiencies of DUT in a telescope:

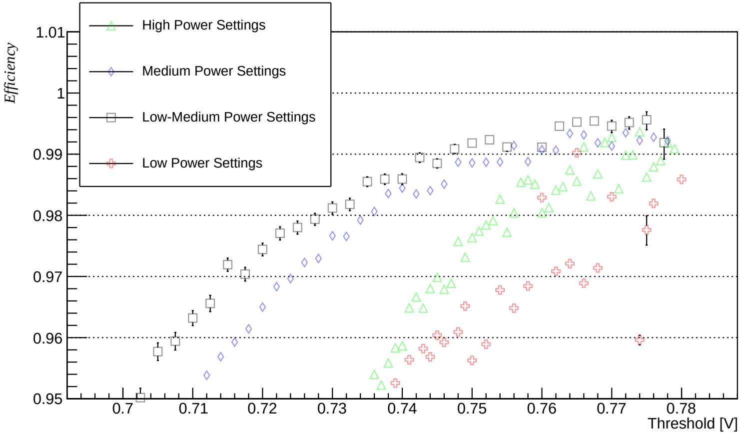


Technique: Extrapolate tracks to DUT. Comparing different power settings. Further optimisation planned.

Data taken at PSI

MuPix7: Efficiency

Efficiencies of DUT in a telescope:

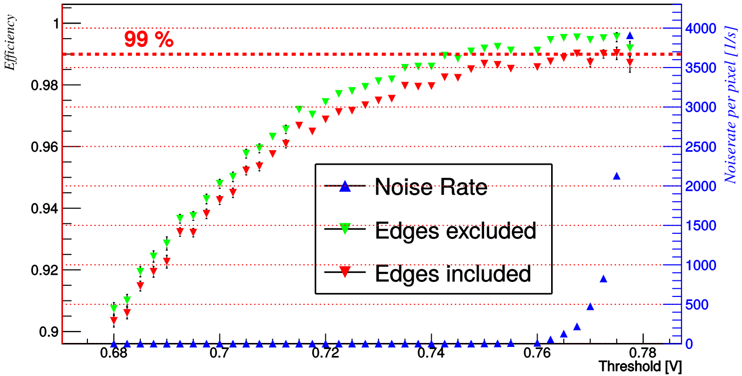


Same data, but zoomed in. Note: Hit rate is 300 kHz per chip.

Data taken at PSI

MuPix7: Efficiency

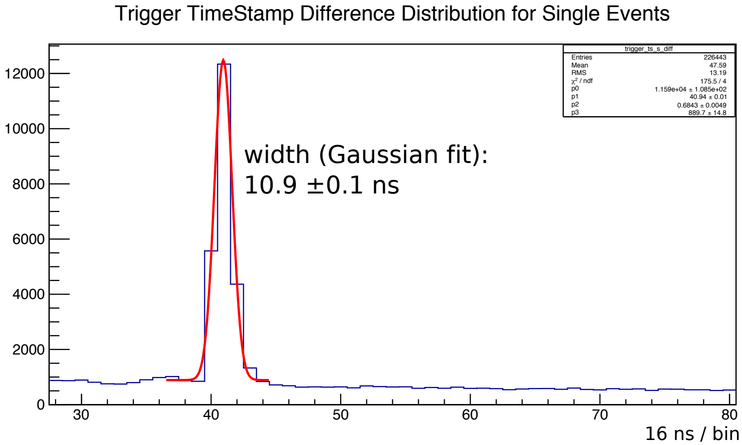
Efficiencies of DUT in a telescope:



One setting (intermediate power) as example with noise rate

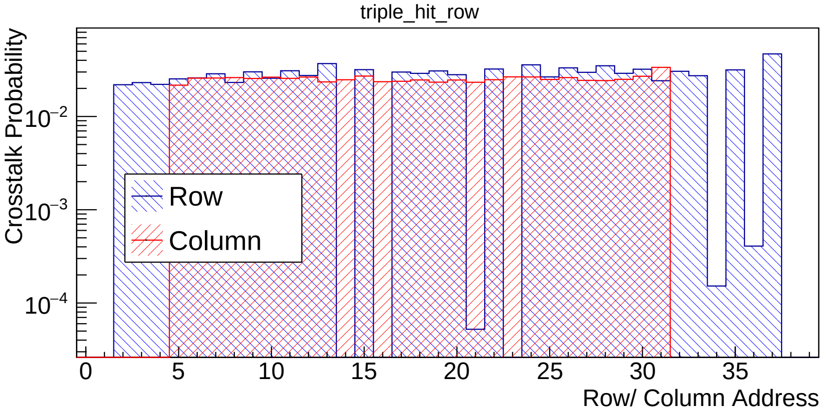
Data taken at PSI

MuPix7: Time resolution



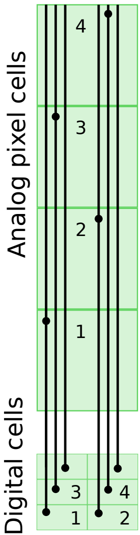
Technique: Scintillator coincidence signal as reference. Plotted timestamp seen in MuPix7.

MuPix7: Crosstalk



Method: Extrapolated track to DUT. Select events with 3 hits, center one matched to track. No entry: no such events found.
Do we understand the pattern?

MuPix7: Crosstalk



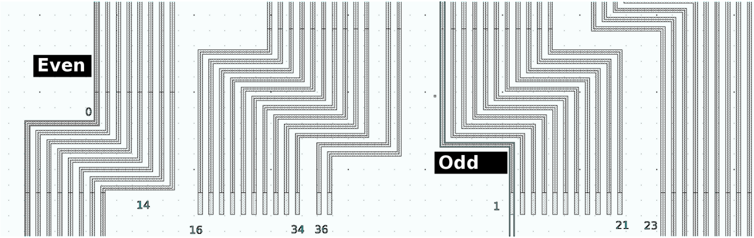
MuPix uses separate areas for analog and digital processing.

Pixel cells (sensor and preamp) are connected **point-to-point** to a corresponding digital cell (comparator, logic).

Long transmission lines can couple signals.

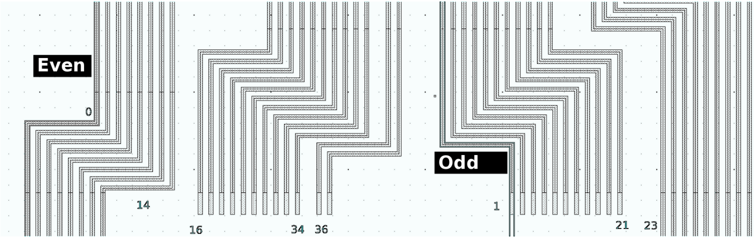
But still: Why the holes in the row-wise distribution?

MuPix7: Crosstalk



The space distribution between lines is not uniform. Does the pattern match?

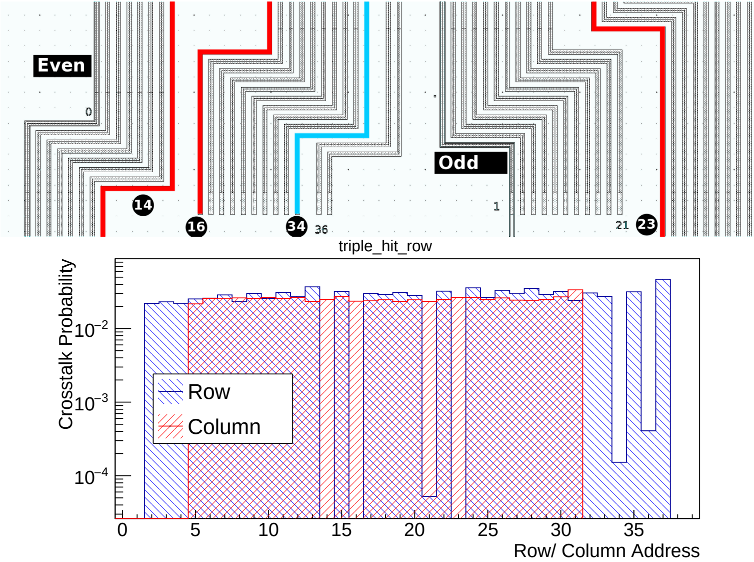
MuPix7: Crosstalk



Yes. Lines of pixels 14, 16, and 23 have bigger spacing to neighboring lines, no crosstalk seen.
Column 34 has intermediate spacing, lower crosstalk.

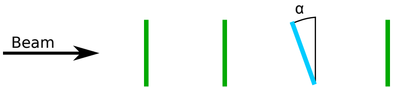
See next slide. . .

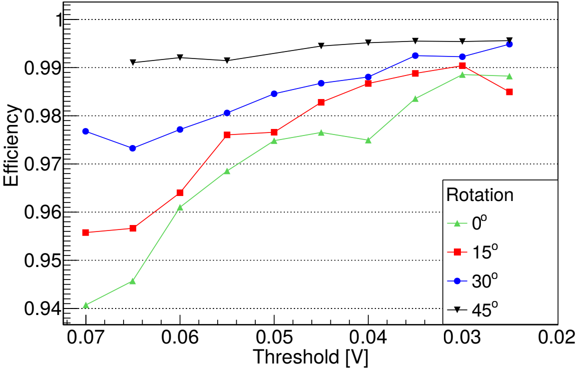
MuPix7: Crosstalk



MuPix7: efficiency of tilted sensor

Efficiencies with DUT under different angles:





Data taken at DESY

MuPix7: DAQ performance

- **CERN SPS**: MuPix7 run successfully at rates of about **500 kHz** (on chip)[1].
- Speed limit of MuPix7 telescope: about **1 million tracks per second**. Can be increased by optimizing DMA transfer.
- Fast data transfer and reconstruction demonstrated (simulation and at DESY).
  - Hits sorted on FPGA
  - Transferred to memory using DMA
  - Processed in GPU for track reconstruction.

  300 MB/s with simulated data achieved[2].
- **Three MuPix7 telescopes** (4 layers each) exist and proven reliable. Using own sensor and readout became a key advantage for efficient use of beamtime.

[1] Exact rate determination difficult due to fluctuating bunch filling rate.
[2] This is processing speed, not write to disk.

MuPix7

Fact check:

	Specification	MuPix7	Conclusion
Pixel size (μm^2)	80×80	103×80	$\rightarrow$ MuPix8
Sensor size (mm^2)	20×20	3×3	$\rightarrow$ MuPix8
Thickness (μm)	50	50	ok
Bandwidth per chip (Gbit/s)	3×1.25	1×1.25	$\rightarrow$ MuPix8
Hit rate (MHz/cm^2)	2.5	5.5	ok
Spatial resolution (μ)	< 100	$103/\sqrt{12}$	ok
Time resolution (ns)	< 20	11	ok
Efficiency (%)	> 99	99.5	ok
Signal to noise	> 20	$10 \ldots 15$	$\rightarrow$ MuPix8 (substrate)
Power (mW/cm^2)	≤ 300	≤ 300	ok

MuPix7

In summary, with MuPix7 we could show:

- We have a **fully functional HV-MAPS chip**, $3 \times 3\,\mathrm{mm}^2$
- **Specifications** met for key parameters that can be tested with MuPix7. MuPix8 is expected to cover the rest.
- Operation at high rates: 300 kHz at PSI πM1. We survived even higher rates of about 1 MHz at SPS.
- **Crosstalk** on setup under control, on chip seen. Mitigation plan exists (see MuPix8, later slides).
- We routinely operate systems of up to 8 chips in testbeams reliably.
- Data processing of one telescope (4 chips) at full rate on GPU demonstrated.

Towards MuPix8

Goals:

- **Scaling-up** from $3 \times 3\,\mathrm{mm}^2$ to $13 \times 20,\mathrm{mm}^2$ (active area)
- All **pads on one edge** (required for integration studies)
- **Submission** deadline: June 2016 (not earlier due to foundry capabilities)
- First chip suitable for **integration studies**
- Options for mitigating **crosstalk**:
  - Adjust ampllifier to optimize amplitude for strong signals
  - Place ground lines between signal lines
  - Switch from voltage to current signalling

  Chip designers are **confident** that space is sufficient to solve these issues. Next months will show.
- Foundry (AMS) provides **higher-resistivity substrate** ($20\,\Omega\mathrm{cm} \rightarrow 80\,\Omega\mathrm{cm}$). Will be explored with MuPix8 for the first time.

Towards MuPix8

Integration studies:

- Build a **prototype of an inner layer module**: 2×3 chips.
- Studies with different **flex print options** (1 signal layer, 2 power layers):
  - **Traditional:** 3 layer copper: conservative but reliable, too much material for final design (2‰ X_0)
    $\Rightarrow$ Electrical integration studies

Towards MuPix8

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Towards MuPix8

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  - **Baseline:** 1 copper layer (signal), 2 aluminium layers (power/GND), sandwiched (1.2‰ X_0 possible)
    $\Rightarrow$ Copper technology has nice spacing (10 μm feature sizes available)
  - **Optimal:** 2 layer Aluminium, if necessary with one additional layer. Uses pad-bonding (1‰ X_0)
    $\Rightarrow$ Technology implemented by ALICE. Riskier approach, new territory but promising.

See next page for an example layout.

Flexprint

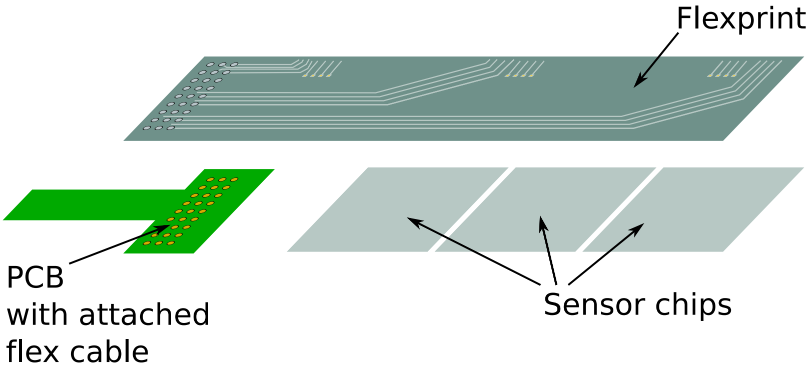
- Flexprints will be used to connect chips to DAQ.
- **Two designs** required (electrically split at center):

Layers	# chips	dimensions	channels per chip
1,2	$2 \times 3 = 6$	$20 \times 60\,\mathrm{mm}^2$	3
3,4	$2 \times 9 = 18$	$20 \times 360\,\mathrm{mm}^2$	1

- Material is a challenge, of course.
- Has to provide: Power, grounding, and signals:
  - **Acceptable voltage drop:** 20 mV. Remember: MuPix has no on-chip regulators (yet).
  - All signals as **differential pairs**, $Z \approx 100\,\Omega$
  - Minimal connection scheme per chip: 2 $\times$ power, HV, GND, Clk, Reset, Slow control, 3 $\times$ readout (1.25 Gbit/s)

Flexprint

Artistic sketch of a half-assembly fir layer 1,2:



Flexprint

Radiation lengths:

Material	1‰ of X_0 μm
Polyimide	286
Cu	14
Al	89
Epoxy	400
Silicon	93
Carbon	194

Flexprint

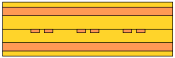
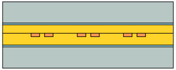
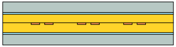
Electrical properties with radiation length in mind:

Material	X_0 cm	σ S/m	ρ $\Omega \cdot \mathrm{mm}^2/\mathrm{m}$	$\sigma \cdot X_0$ S
Cu	1.4	$58 \cdot 10^6$	$1.7 \cdot 10^{-2}$	$8.4 \cdot 10^5$
Al	8.9	$37 \cdot 10^6$	$2.7 \cdot 10^{-2}$	$33 \cdot 10^5$
Ratio Al/Cu	6.4	0.64	1.59	**3.9**

For our purpose, Al is better than Cu when it comes to powering.

Flexprint

Comparing Cu options:

	Demonstrator	Phase I	PhaseII
			
Kapton	45 μm	45 μm	45 μm
Kupfer	25 μm	4 μm	2 μm
Aluminium	0 μm	50 μm	25 μm
Epoxy	8 μm	4 μm	4 μm
Silicon	50 μm	50 μm	50 μm
Kapton support	25 μm	25 μm	25 μm
X_0	2.17 ‰	1.44‰	1.12‰

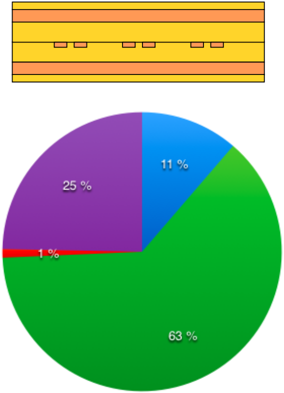
Notes:

- Sketches show only the flexprint, no chip, no support
- X_0 takes fill factor < 1 of certain layers into account
- For Phase-II, Si contributes about 50% to the material budget...

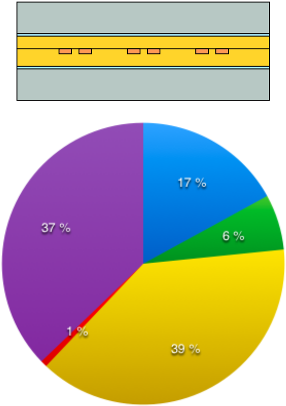
Flexprint

Comparing the relative contribution to X_0:

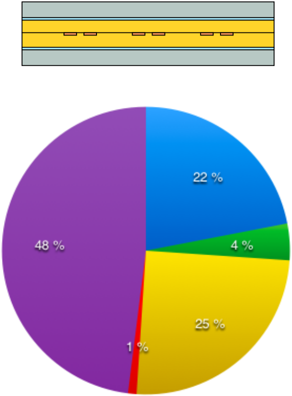
Phase 0



Phase I



Phase II

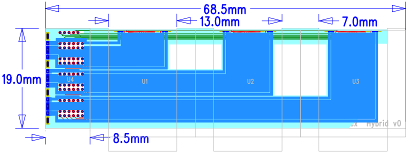


green: Cu violet: Si blue: Kapton yellow: Al red: Epoxy

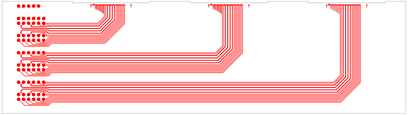
Flexprint

This is an example design for the two options using Cu layers (demonstrator):

All layers:



Signal layer 1:



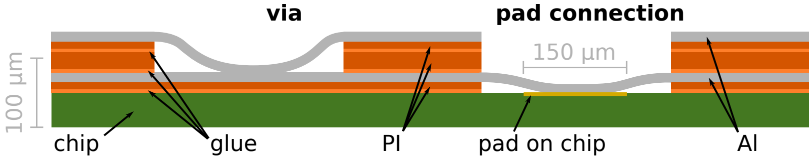
Signal layer 2:

Layer 1: point-to-point signals, layer 2: bus-type signals

Flexprint

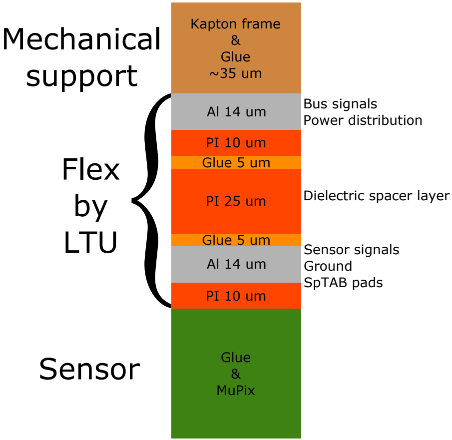
LTU technology:

- Base material (one layer) is Al 14 μm laminated to 19 μm PI
- Connections are made by tab bonding:



- No wirebonds but micro-ribbon bonds. Higher mass than wires, shorter connections. Assume no issue in B-field (needs testing).
- Mechanical sample to our drawings in hand.

Flexprint

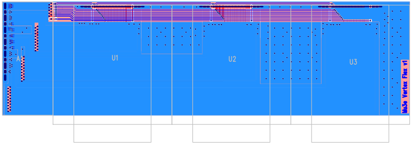


This shows the stack of a typical LTU flexprint made to our spec.

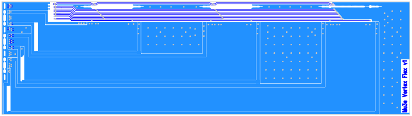
Flexprint

This is an example design for the two options using Cu layers (demonstrator):

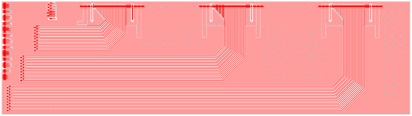
All layers:



Top layer:



Bottom layer:



Layers share power/signal. Voltage drop seems at edge, optimisation will be started soon.

Flexprint

Other things not mentioned so far:

- **Capacitors** for power: will be on PCB. Power traces have a quite some area and thin spacing, will use this as extra cap.
- **Encapsulation** of wirebonds with traditional approaches would use too much material. Tab bonding likely solves this or we need to determine resonance frequencies and suppress them electronically.

Conclusions

- MuPix shows a clear path of incremental improvements over time
- MuPix7 is a fully functional HV-MAPS chip showing performance to spec
- MuPix8 will tackle up-scaling in size and data-rate per chip
- First integration tests will be possible with MuPix8, effort started

(Almost) no results would have been possible without the great support at all testbeam facilities (CERN, DESY[3], MAMI, PSI).
We gratefully acknowledge the beamtime we received.

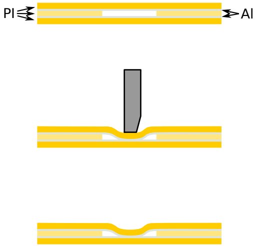
[3] a member of the Helmholtz Association (HGF)

BACKUP

Al flexprint

Layer-to-layer or Layer-to-chip bonding:

Via:



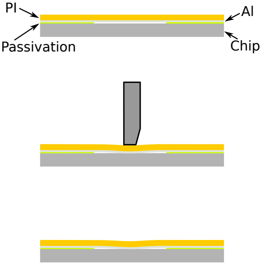
Stack of Al coated polyimide with spacer

Ultrasonic wedge bonding

Bond finished

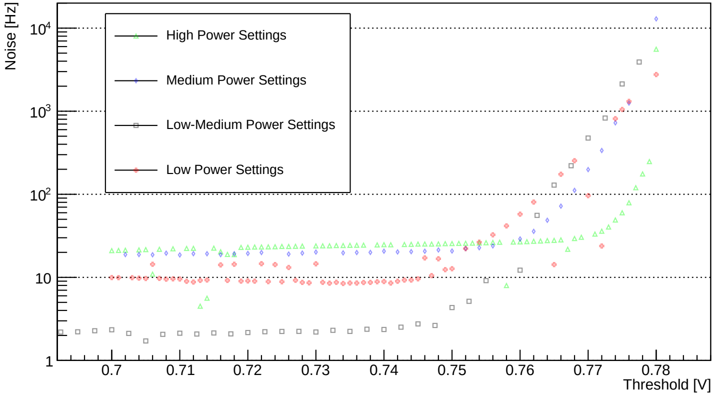
PI: Polyimide

Bond to chip:



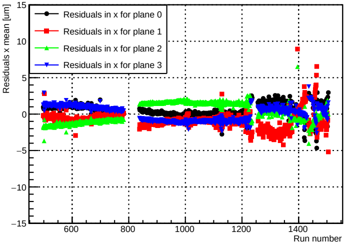
(Note: there is a small dip)

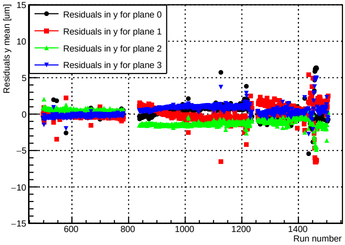
Noise per power setting

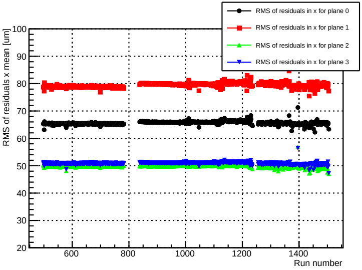


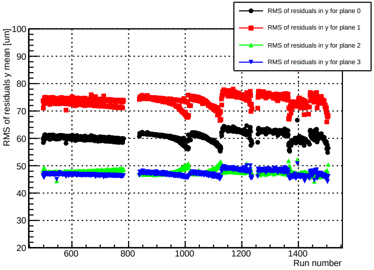
Same measurement as shown for efficiencies, noise shown here.

Telescope alignment



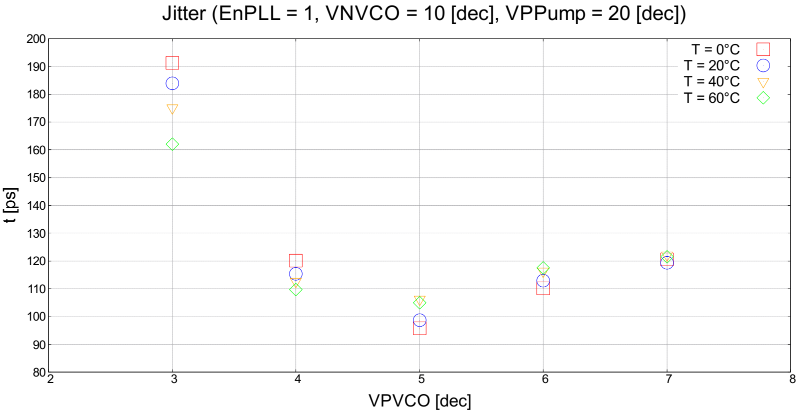






Data taken at DESY.

Jitter temperature dependence



Measured in a temperature chamber. Work in progress.