First Experience with the Mu3e Vertex Detector Construction

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University of Heidelberg

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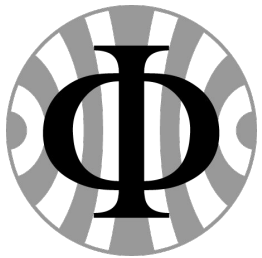
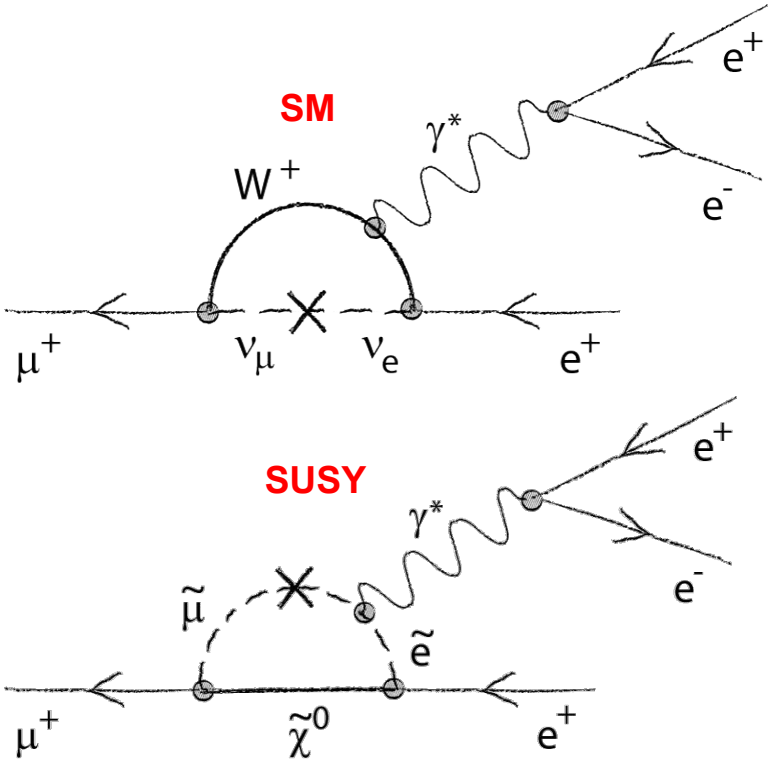


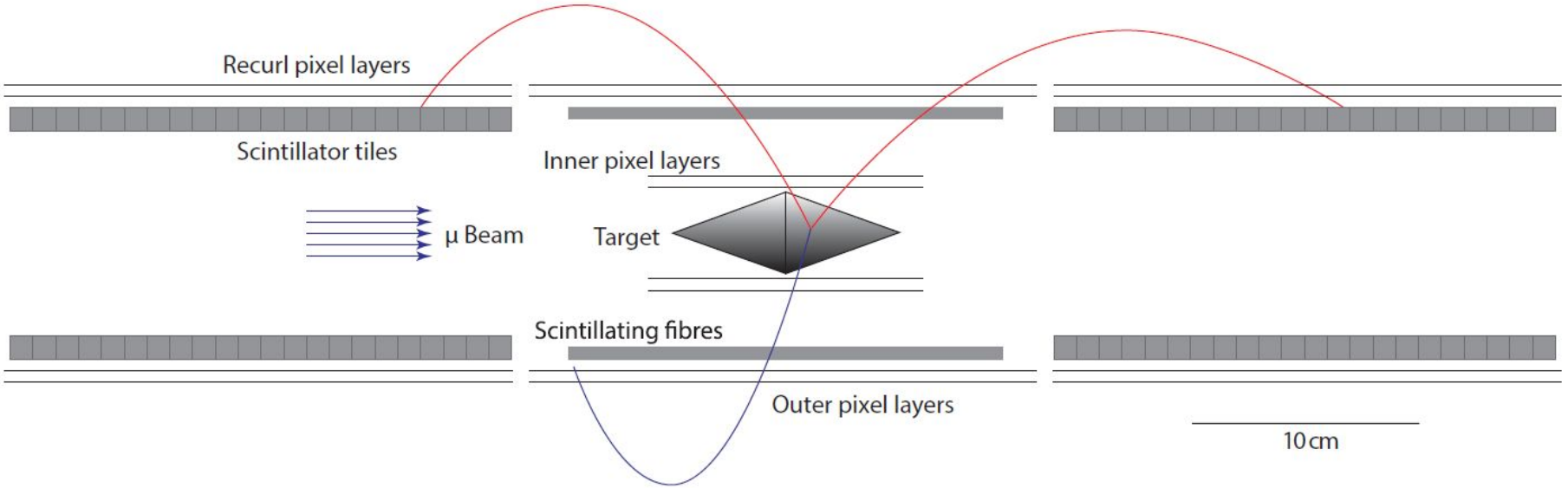
Mu3e: Physics Motivation

- Search for μ→eee
  - Standard Model: BR (μ→ eee) < 10^{-54}
- New physics might enhance BR
- Current limit:
  - BR (μ→ eee) < 10^{-12} (SINDRUM, 1988)
- Aimed single-event sensitivity:
  - BR (μ→ eee) < $2 \cdot 10^{-15}$ (Phase 1)
  - BR (μ→ eee) < 10^{-16} (Phase 2)
- Location: PSI muon beamline
- Phase 1: under construction
- Phase 2: PSI High Intensity Muon Beamline



Experimental concept

- Tracking electrons coming from muon decays (~10^8 Hz in Phase I)
- Magnetic field (1 T)



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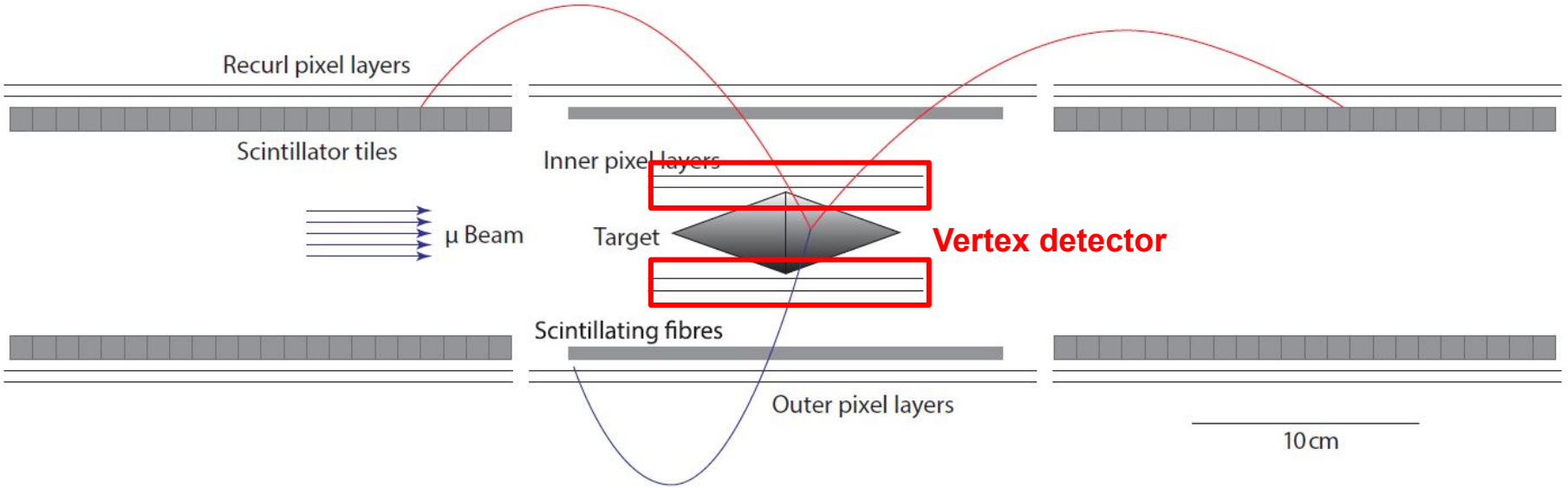

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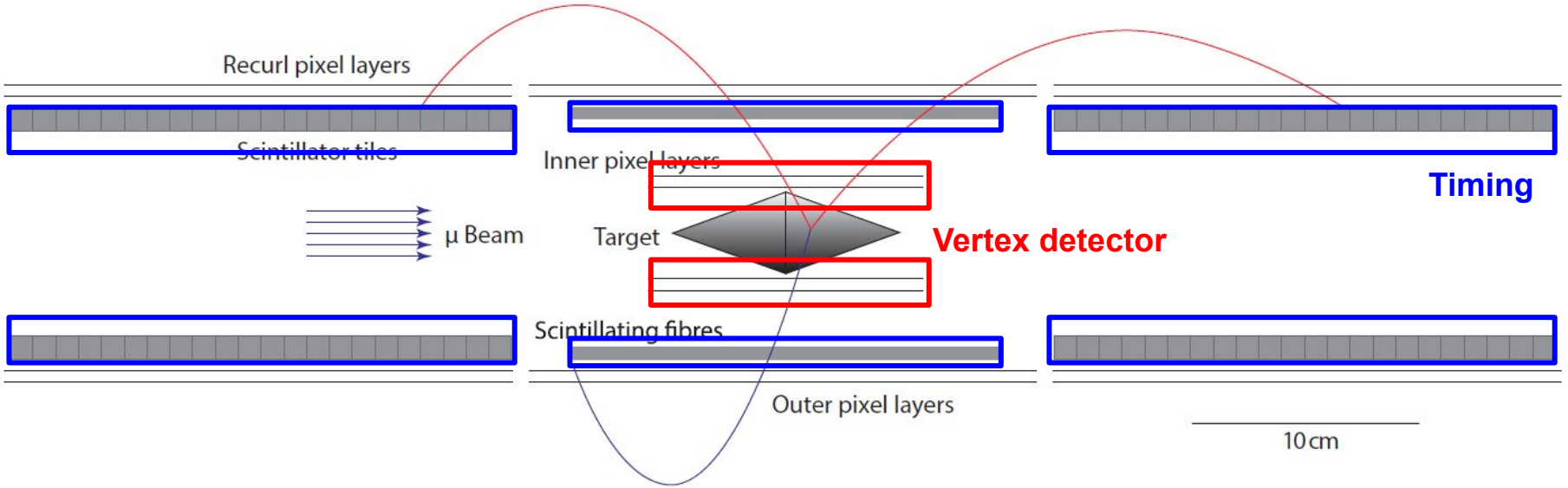

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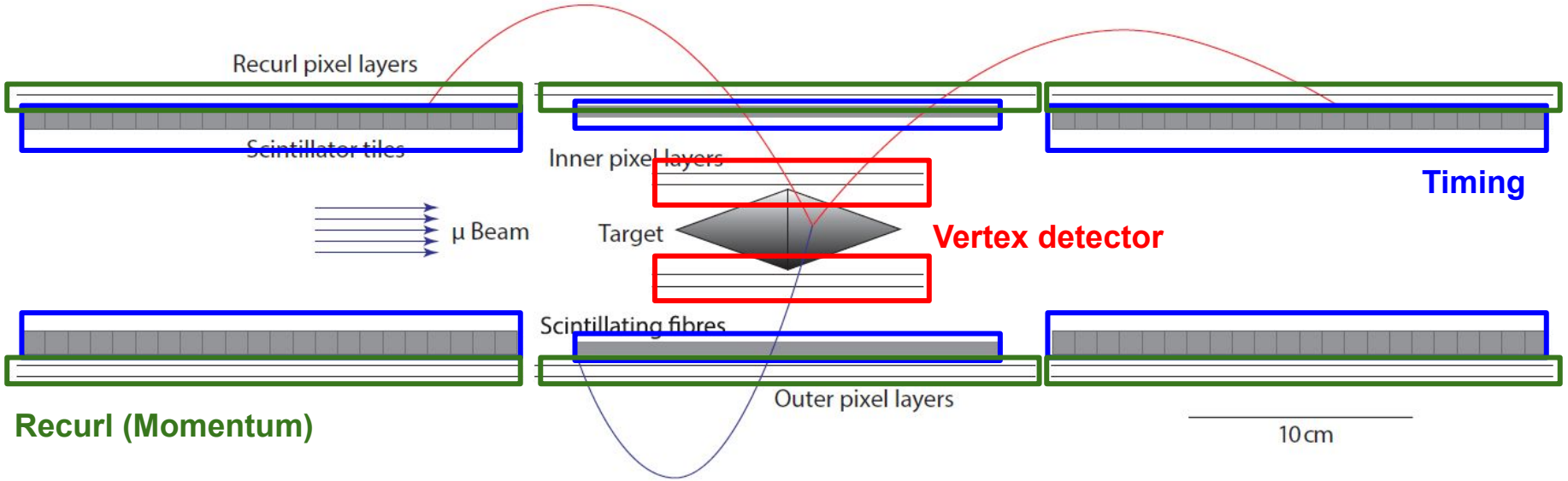

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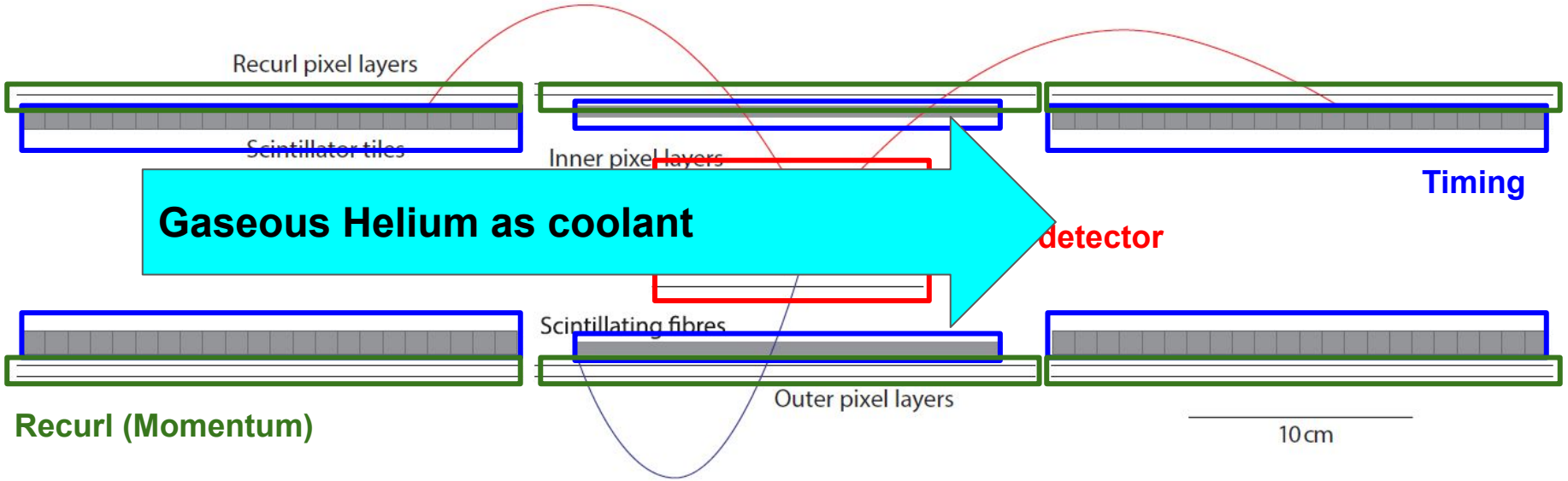
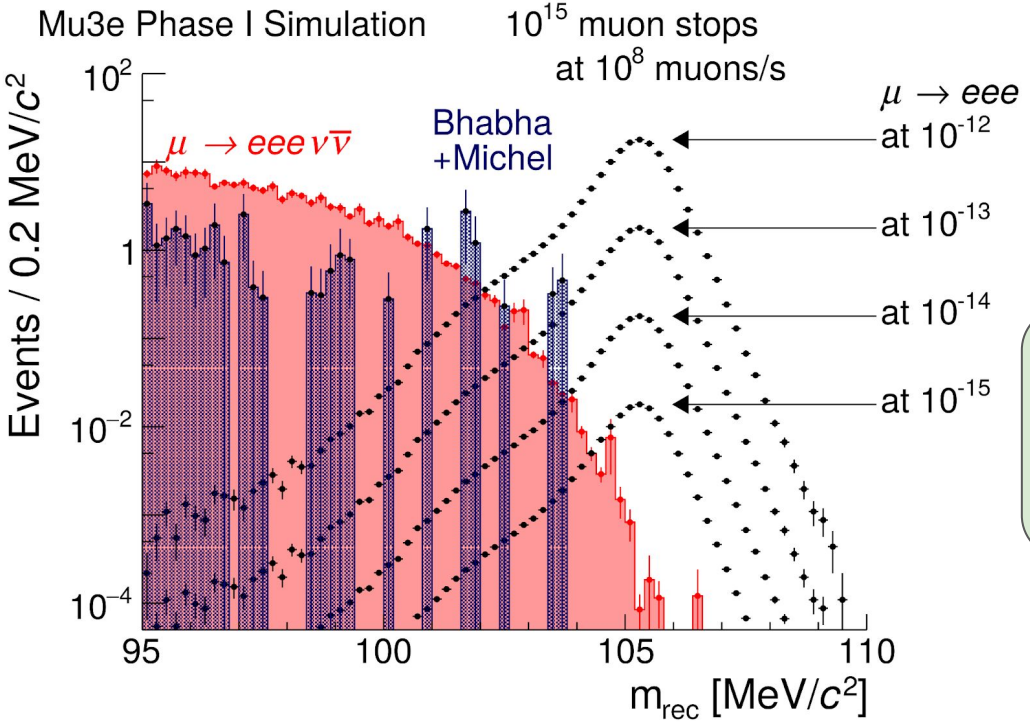


Experimental sensitivity



Invariant mass of signal decay, radiative decay and accidental background (Bhaba+Michel)

Momentum resolution crucial for detecting the peak at muon mass…

Material budget is key factor!

1 MeV resolution with 0.1% * X/X_0 per layer

Mu3e TDR at *Nucl.Instrum.Meth.A* 1014, 165679

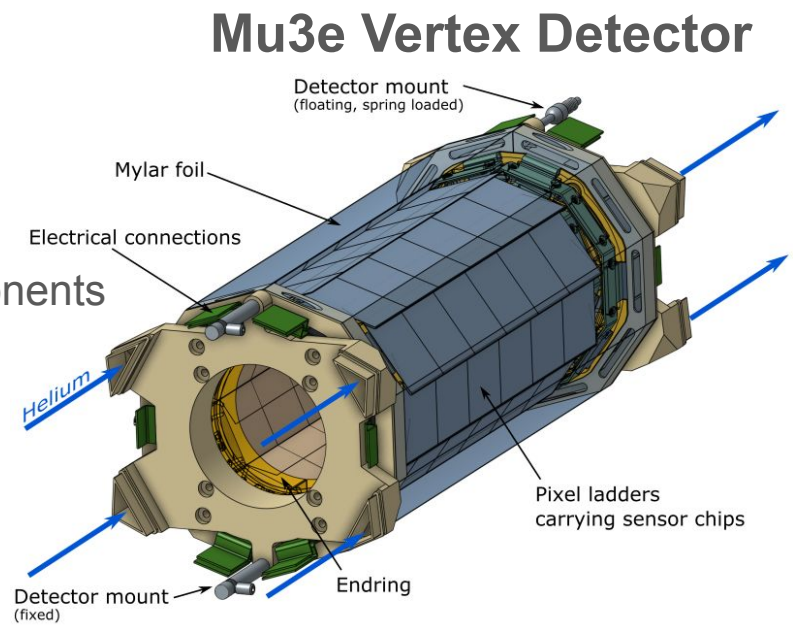
Experimental sensitivity

All done by a collaboration of 12 institutes in 3 countries

Invariant mass of signal decay, radiative decay and accidental background (Bhaba+Michel) [Mu3e TDR]

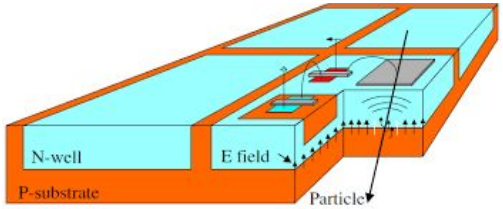
Construction challenges for the pixel detectors

- Thin chips
  - Post-processing and qualification
  - Handling
  - QC
- Thin Aluminum-Kapton HDIs
  - Both electrical and mechanical integration
  - Reduced number of lines, no electronic components
- Compact design
  - Cabling and routing
- Helium cooling system [not in this talk]
  - ~250 mW/cm^2
  - Helium plant
  - Flow control



Vertex collaboration:
Uni-Heidelberg, Uni-Zurich, PSI

Thin chips

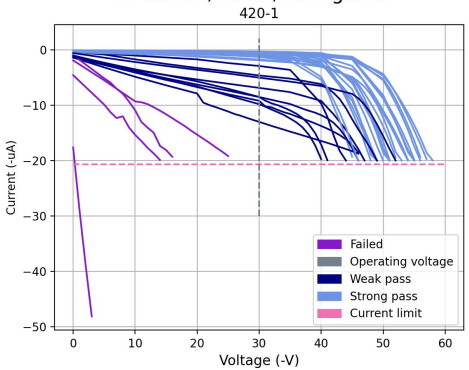


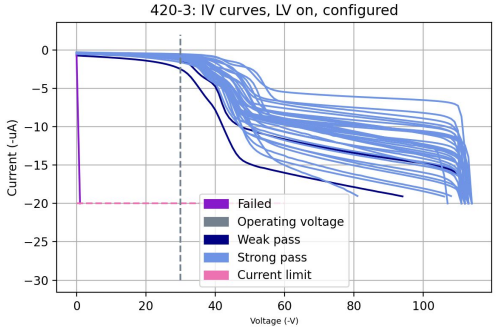
Mupix11 chips based on HV-CMOS technology
Thinned to 50 µm (Vertex)
80 Ωcm resistivity (380 Ωcm for first prototype modules)

W/O plasma etching

W/ plasma etching

IV curves, LV on, configured



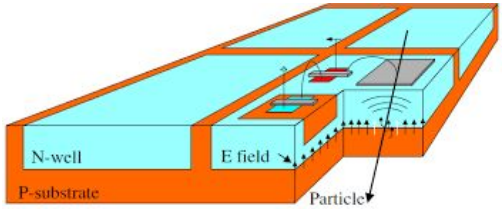


Post processing at Optim (Marseillle, France)

Small tolerance in dicing (11 µm)

Significant improvements with plasma etching

Thin chips



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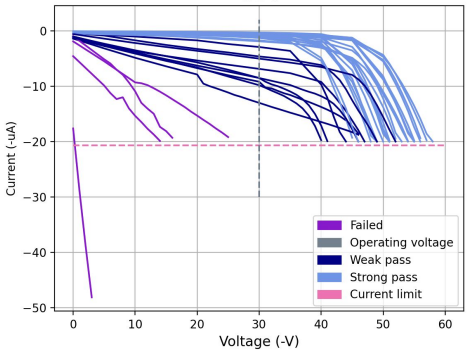
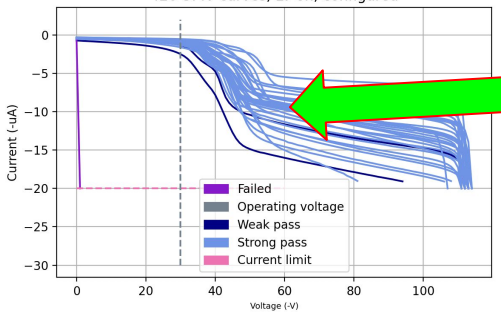
420-1



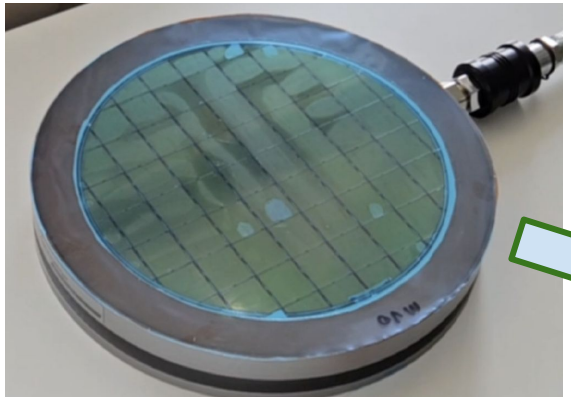
420-3: IV curves, LV on, configured



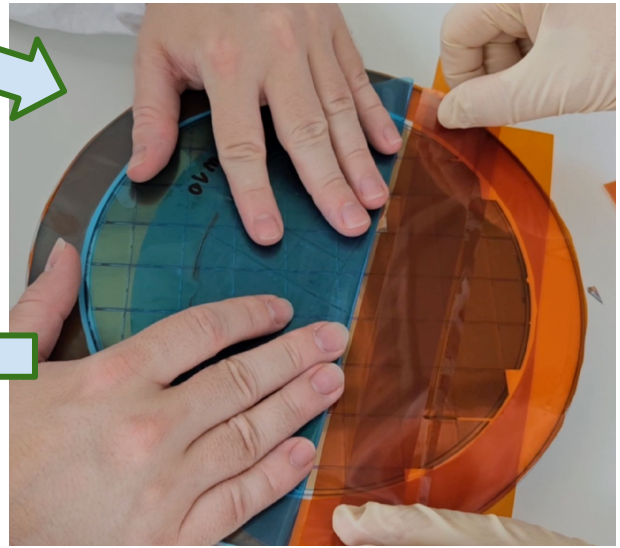
99.5 % efficiency
20 ns time resolution

After full depletion

Thin chips: handling

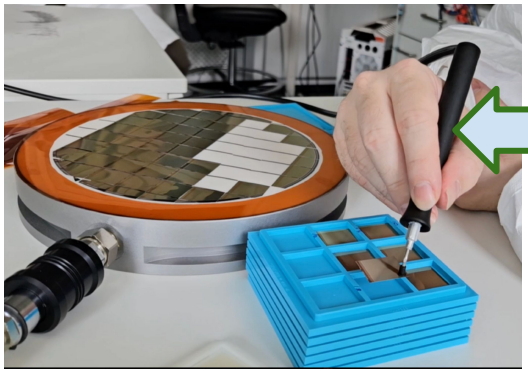


Wafers arrive diced and thinned on blue tape
Placed on ceramic vacuum chuck
→ uniform vacuum pressure

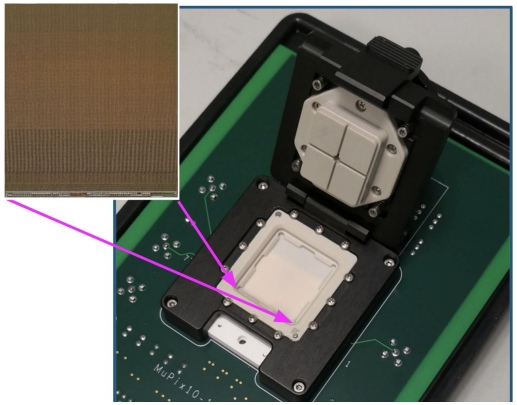


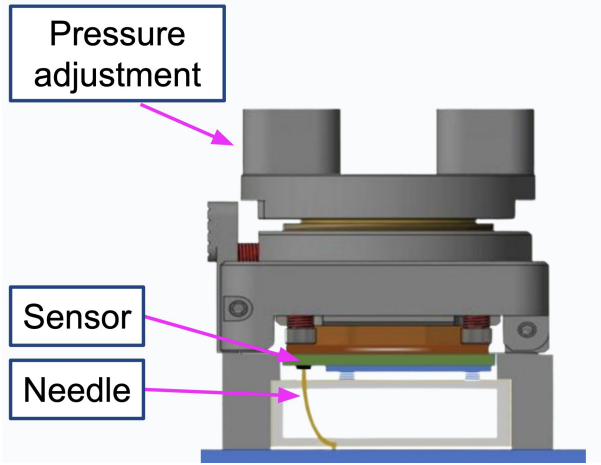
Careful peeling while vacuum on

Extra care for vacuum loss (here: kapton foils, next: tailor-made aluminum chuck)



Thin chips: QC





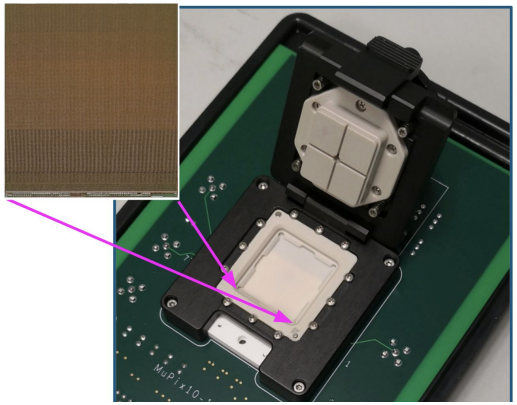
Probe card with manual actuator developed for the task

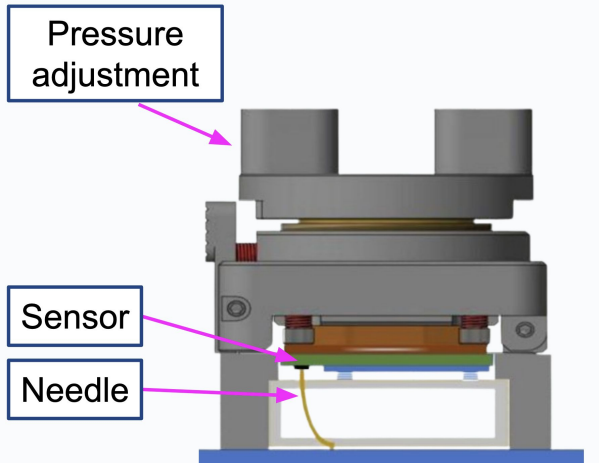
✅ Table-top system
✅ No dependency on probe stations
✅ Easy to transfer between institutes
❌ Manual procedure (training required)
❌ Slow throughput (2-3 minutes to replace chips)

Note: Mu3e Vertex detector consists of only 108 chips and is developed between Heidelberg and PSI

Several operational aspect investigated
(IV curve, powering, link stability, noise profile,...)

Thin chips: QC





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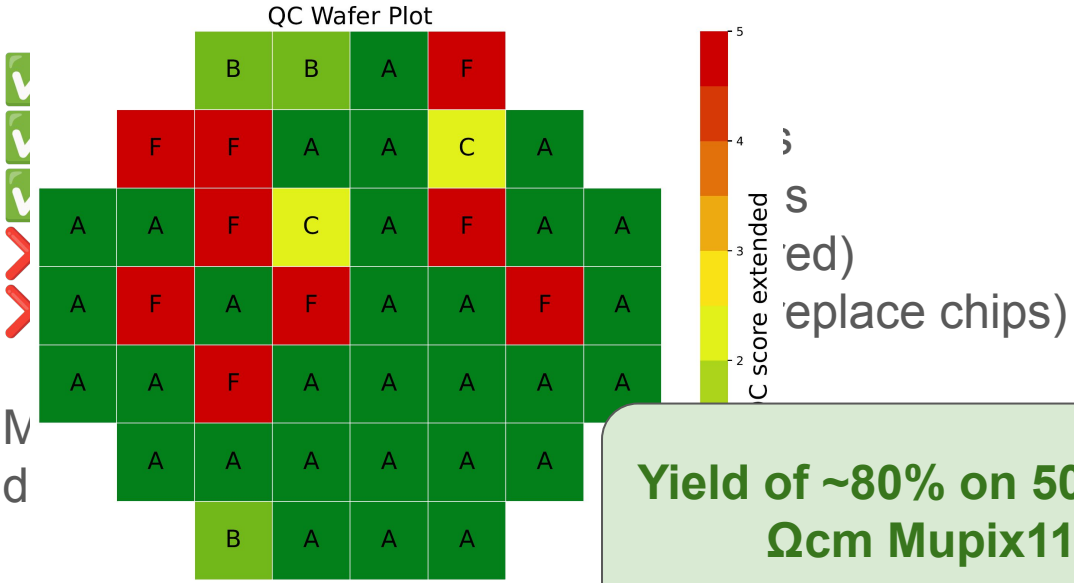


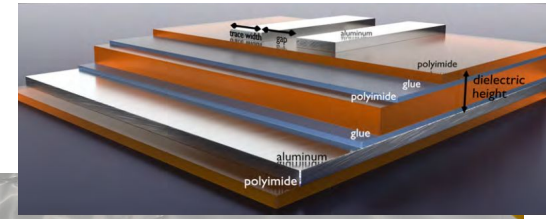
Yield of ~80% on 50 µm 80 Ωcm Mupix11*

*after some optimization iteration

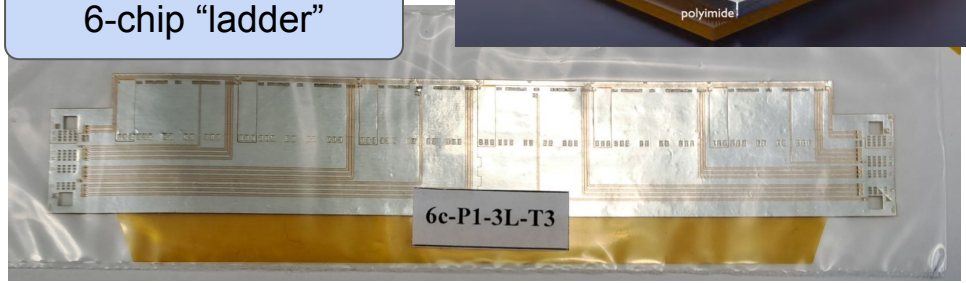
Thin HDIs

Katpon-Aluminum flexes produced by LTU (Kharkiv)

2 layers + spacer: stack and traces geometry optimized for LVDS transmission



6-chip “ladder”

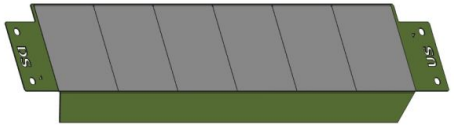


HDIs for multiple purposes: power, HV, signal in, data out, mechanical support

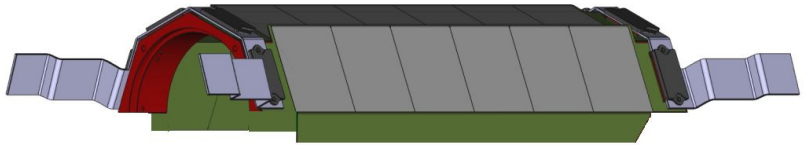
HDI + 6 chips + connecting flex = “Ladder” (see poster by T. Senger, with QC)

Long design and qualification stage needed.

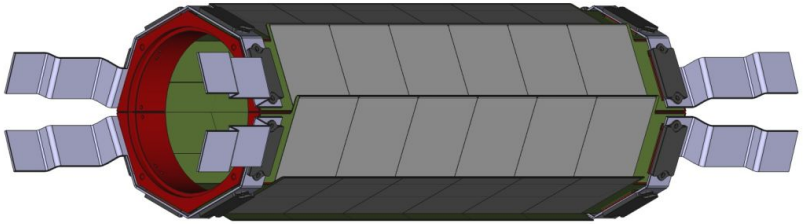
Modules



Ladder



Module

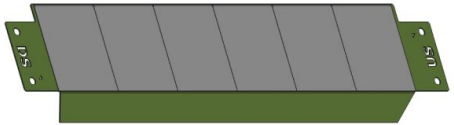


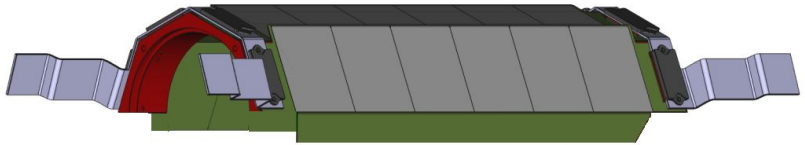
Layer

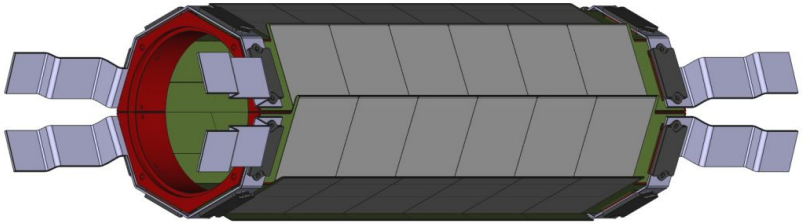
Design aims to be as modular as possible

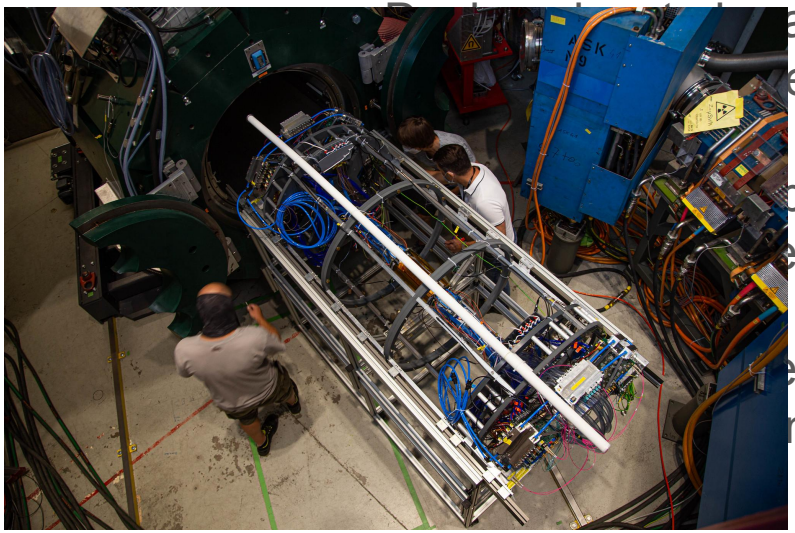
The module is the basic mechanical and electrical unit.
A module can be replaced without replacing anything else

Modules









as
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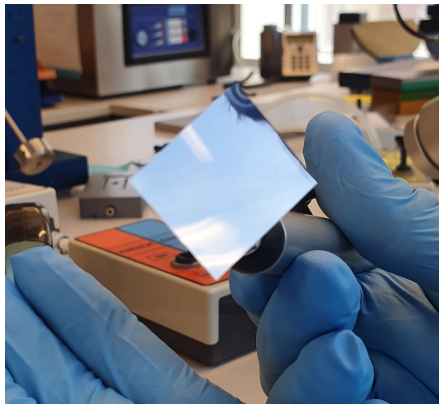
Layer

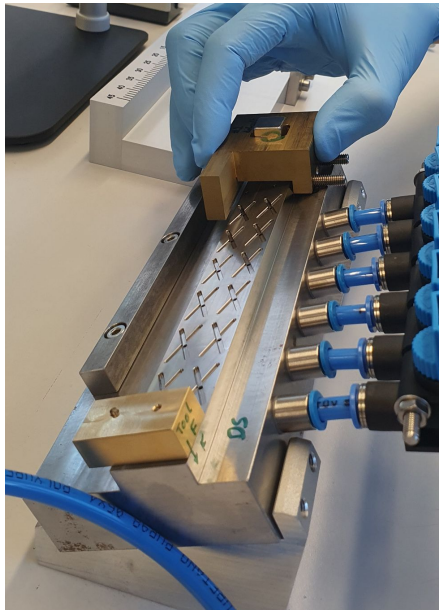
Note: Mu3e sits at ground level, relatively easy to access

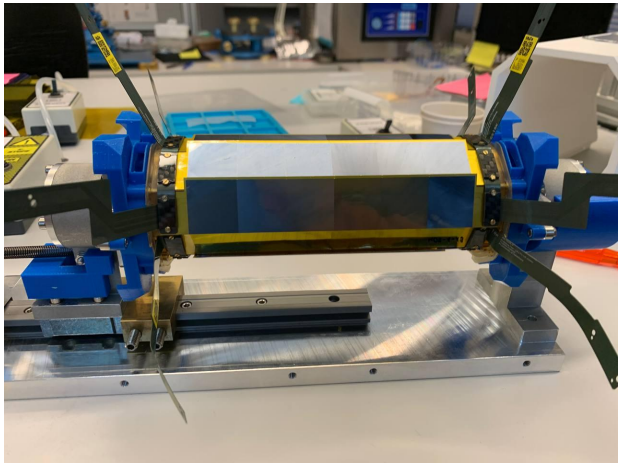
Thin HDIs: mounting

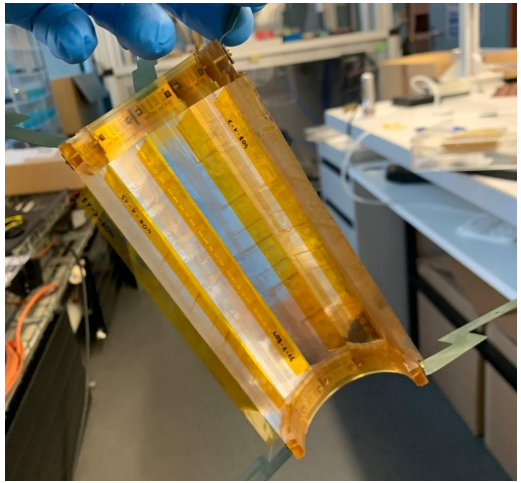
Manual procedures:

- Aligning chips
- Glueing
- HDI overlay
- TA-Bonding
- Module assembly



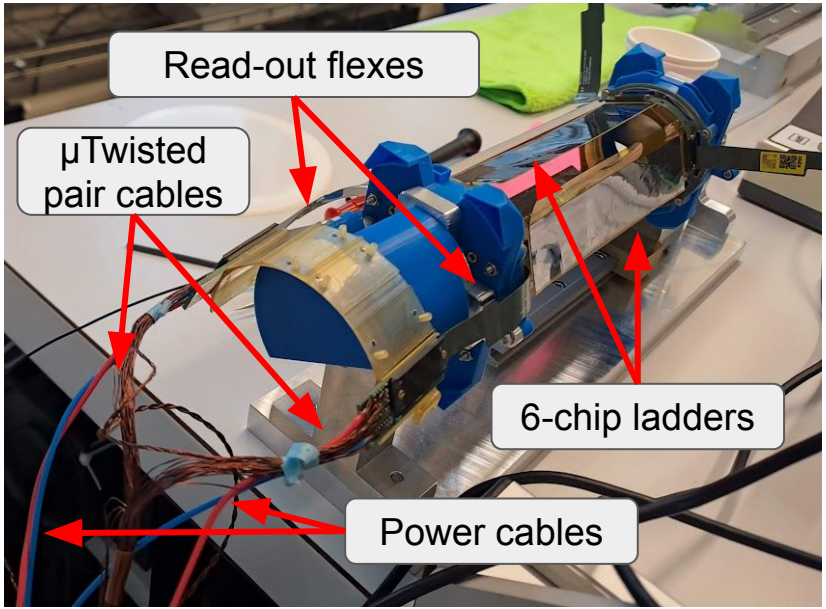




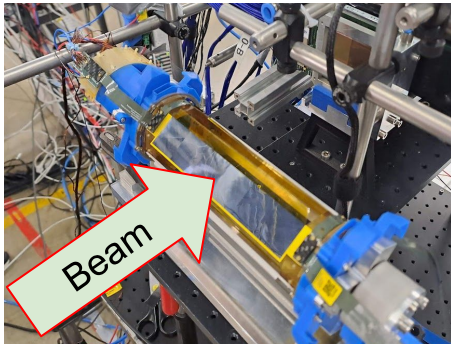


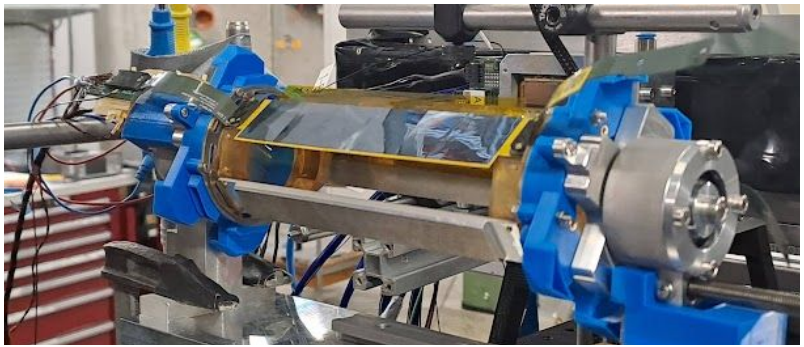
Thin HDI qualification

In the lab



In the testbeam area





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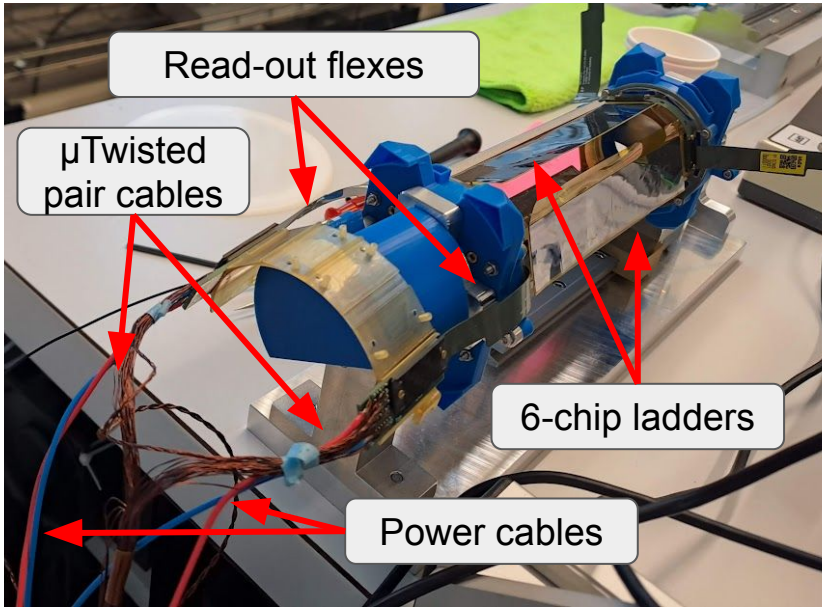

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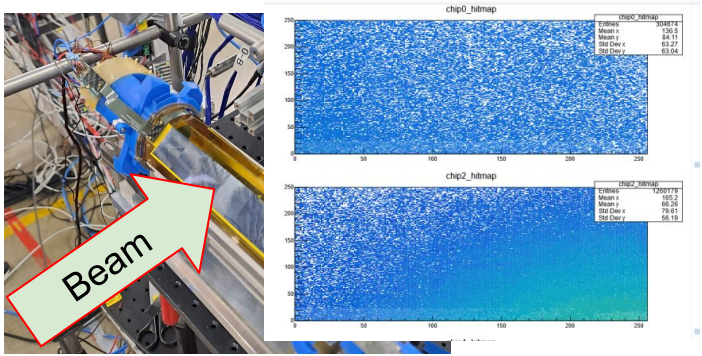
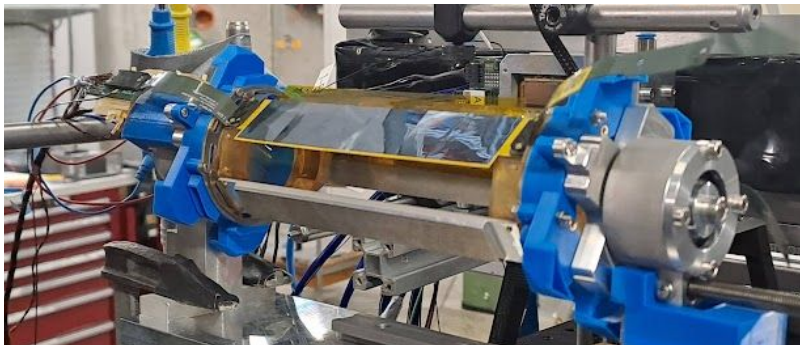
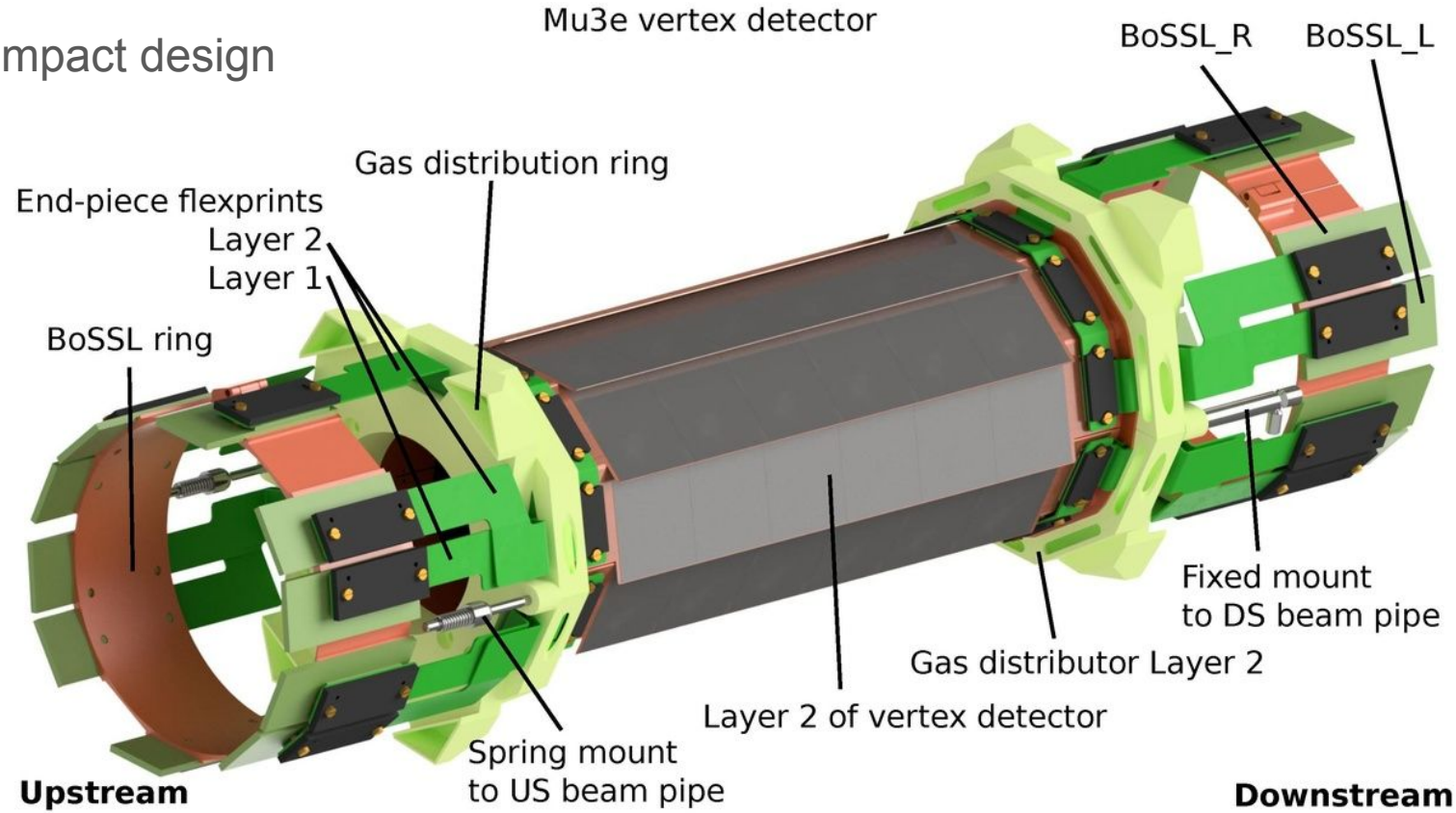




Design challenges

Very compact design



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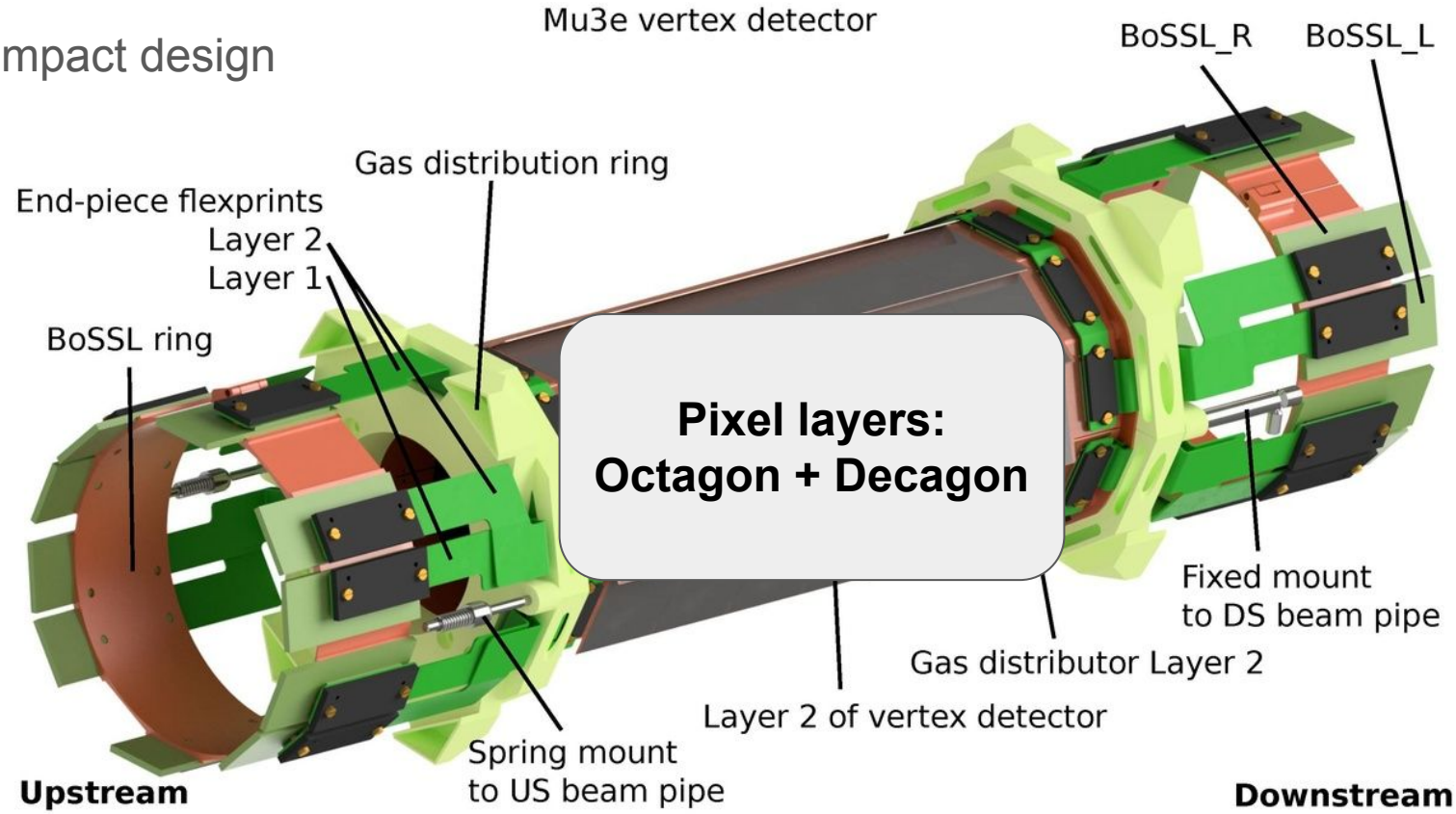

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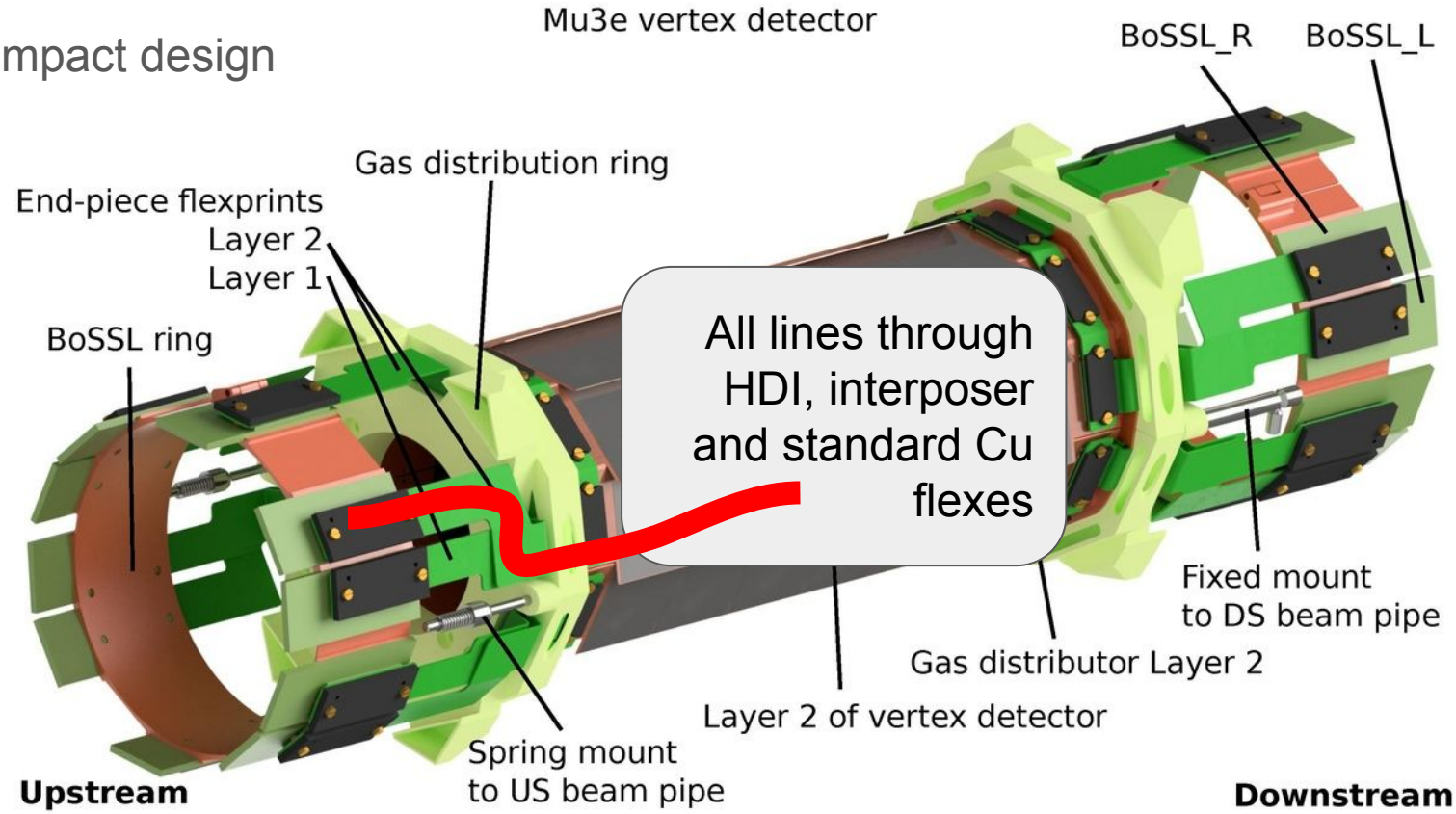

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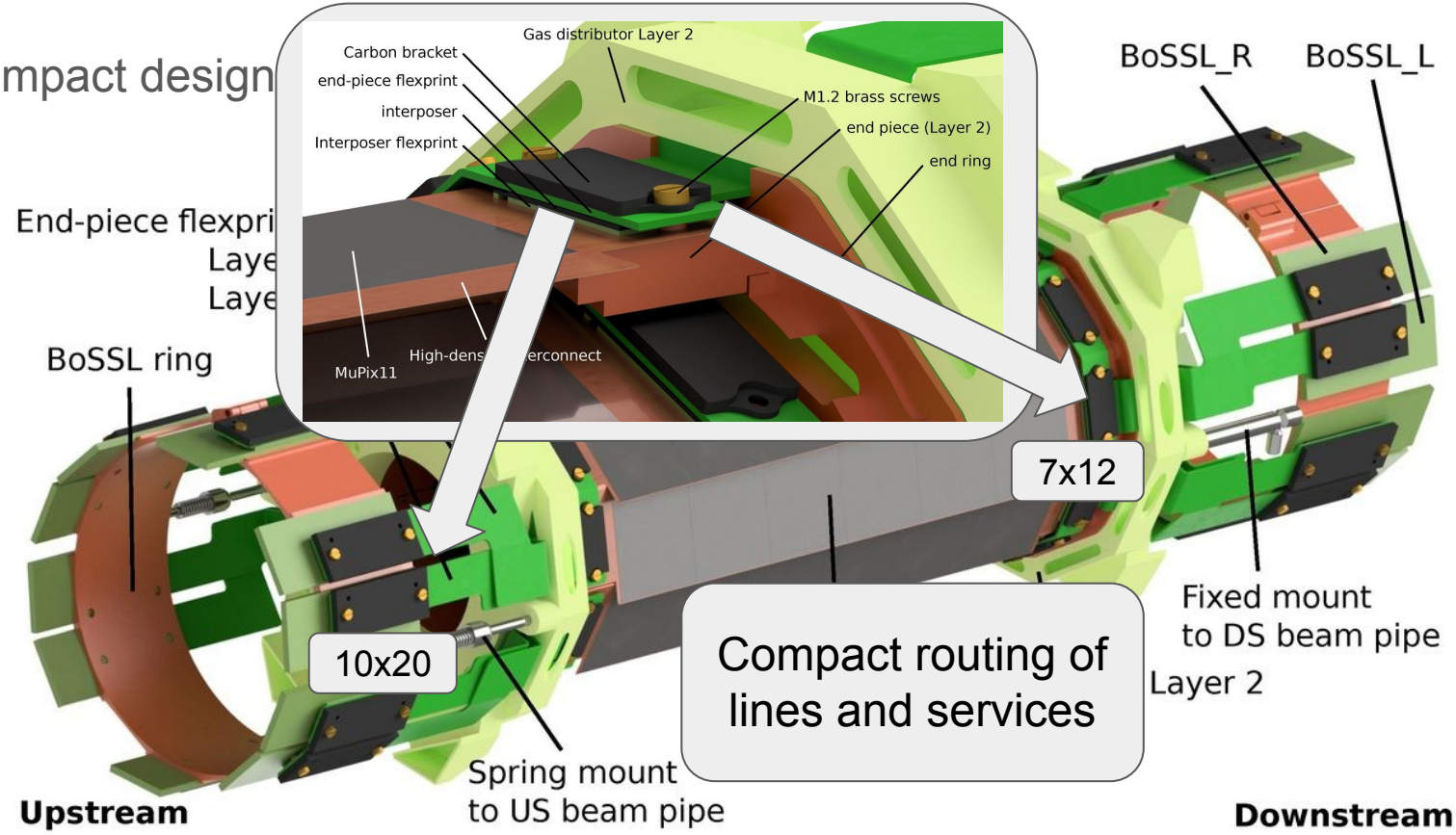

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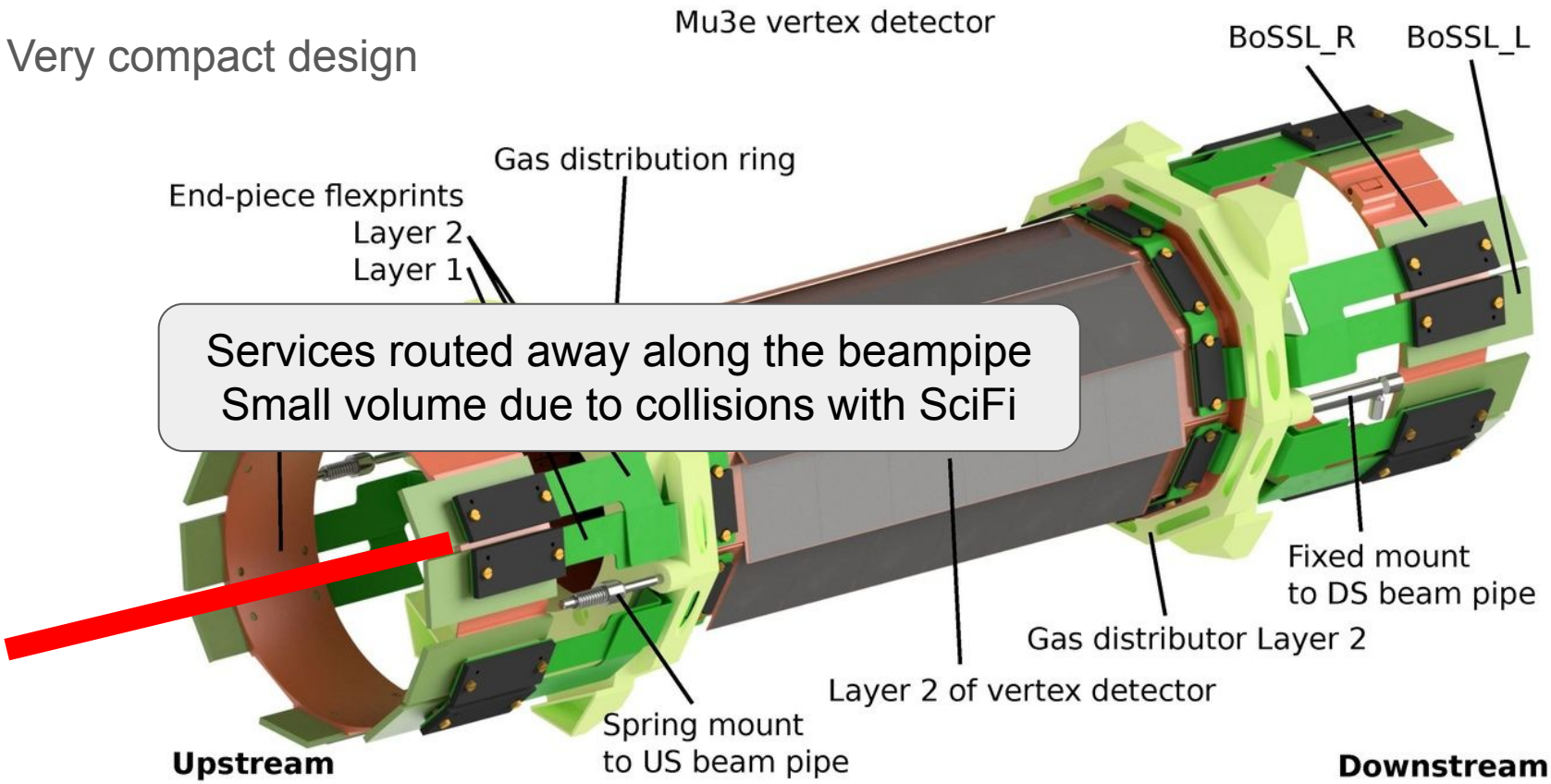

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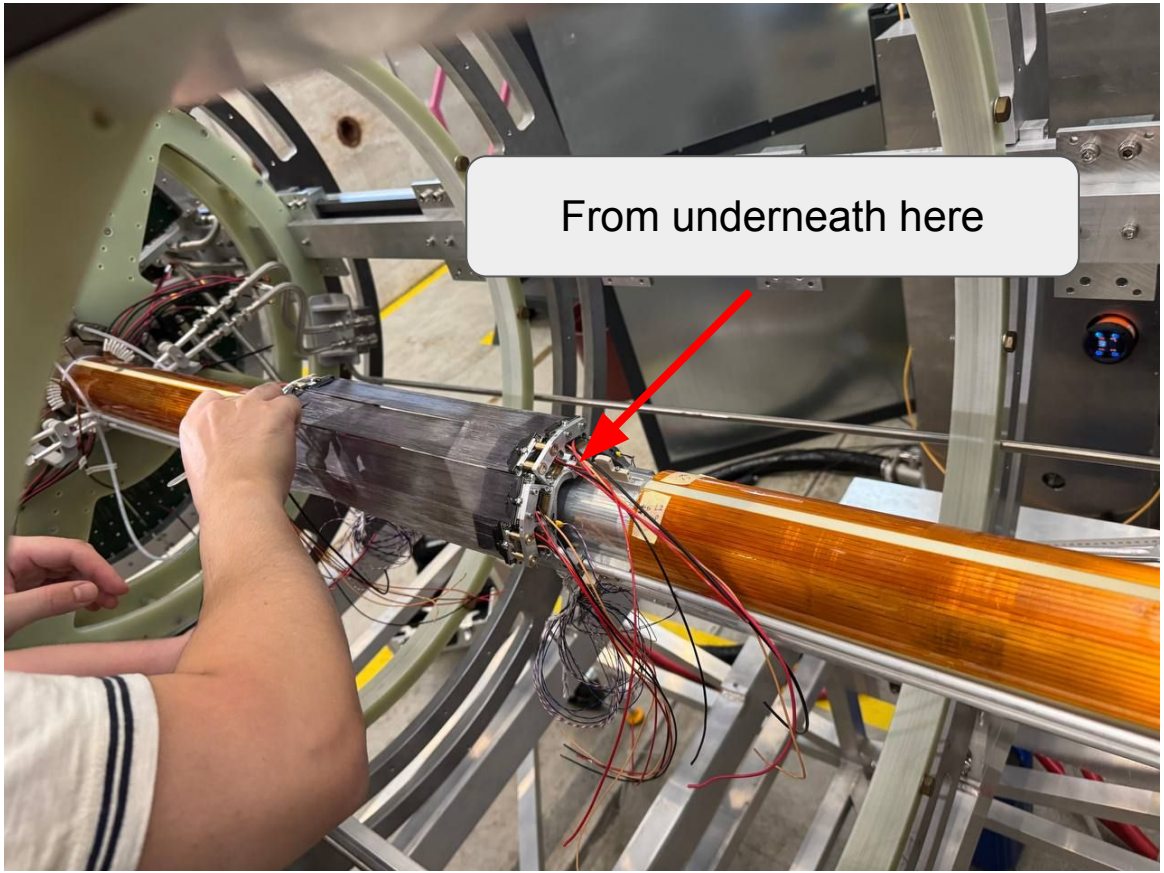
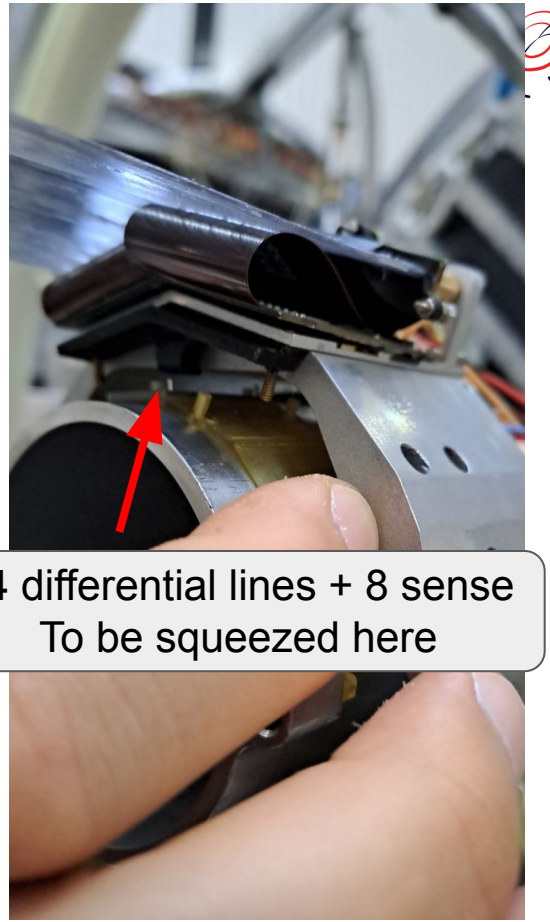


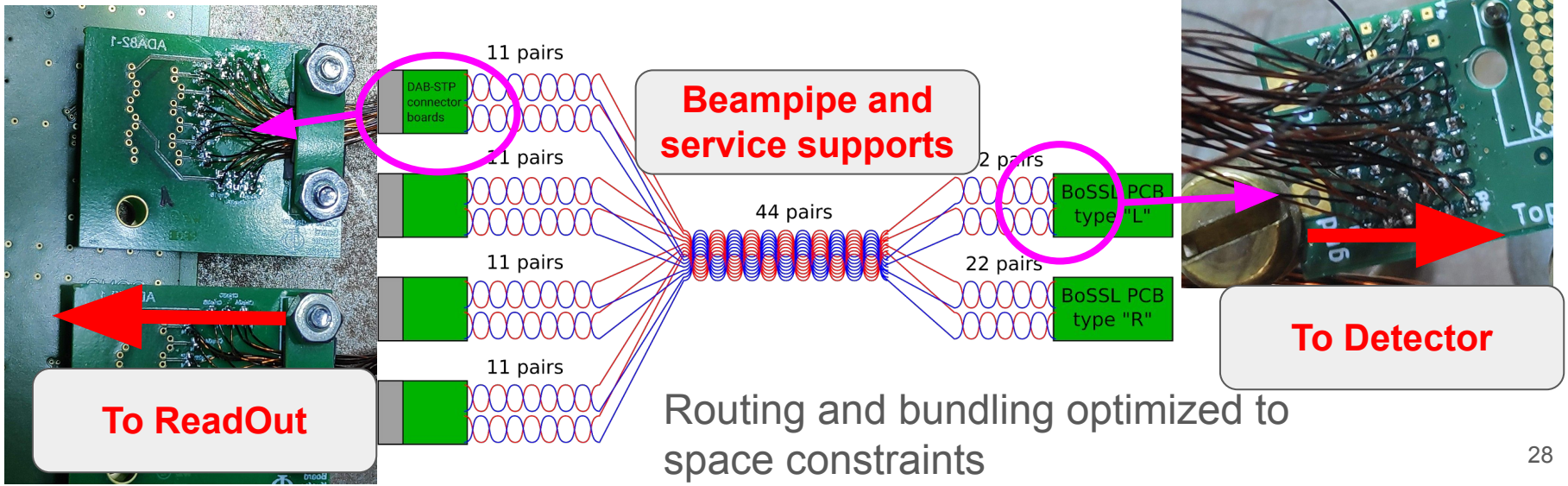


24 differential lines + 8 sense
To be squeezed here

Design challenges

Solution:

- Micro-twisted pair cable bundles
  - 127 um copper, 25 µm polyimide, 30 µm extra distance for impedance matching
- Wires stripped and soldered directly on connector boards



Routing and bundling optimized to space constraints

Vertex Status

- Production almost finished
  - All chips qualified
  - All ladders produced → to be qualified
  - Module+layer assembly to follow
- Services currently mounted on cage
  - Cables + infrastructure + DAQ + cooling pipes + …
- Vertex to be mounted by beginning of next year

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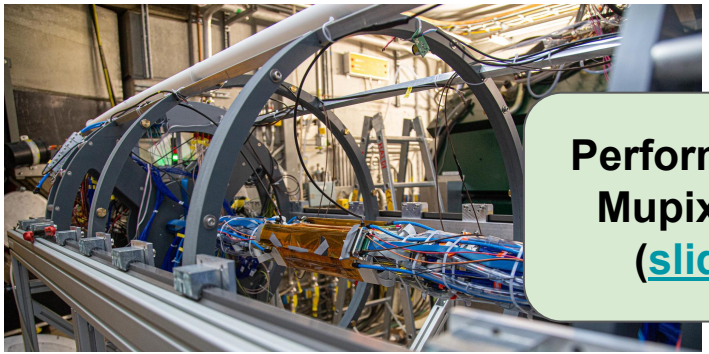
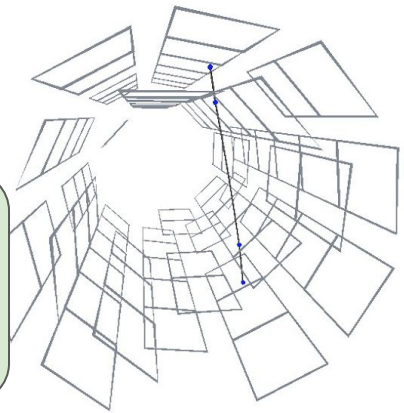
- Services currently mounted on cage
  - Cables + infrastructure + DAQ + cooling pipes + …
- Vertex to be mounted by beginning of next year
- Qualification with cosmic run to follow



Performed previously with a Mupix10 Vertex prototype (slides from Vertex22)

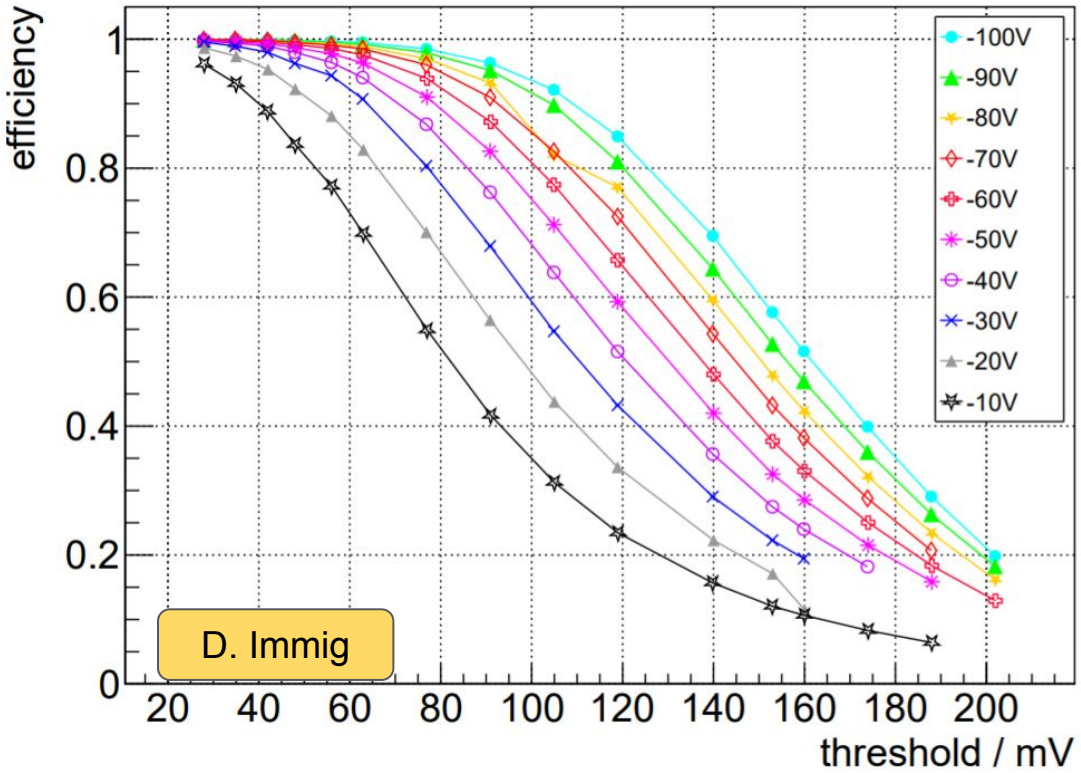


Backup

MuPix sensors: requirements

pixel size [μm^2]	80×80
sensor size [mm^2]	20×23
active area [mm^2]	20×20
active area [mm^2]	400
sensor thinned to thickness [μm]	50
LVDS links	$3 + 1$
maximum bandwidth[§] [Gbit/s]	3×1.6
timestamp clock [MHz]	≥ 50
RMS of spatial resolution [μm]	≤ 30
power consumption [mW/cm^2]	≤ 350
time resolution per pixel [ns]	≤ 20
efficiency at 20 Hz/pix noise [%]	≥ 99
noise rate at 99 % efficiency [Hz/pix]	≤ 20

MuPix10: results

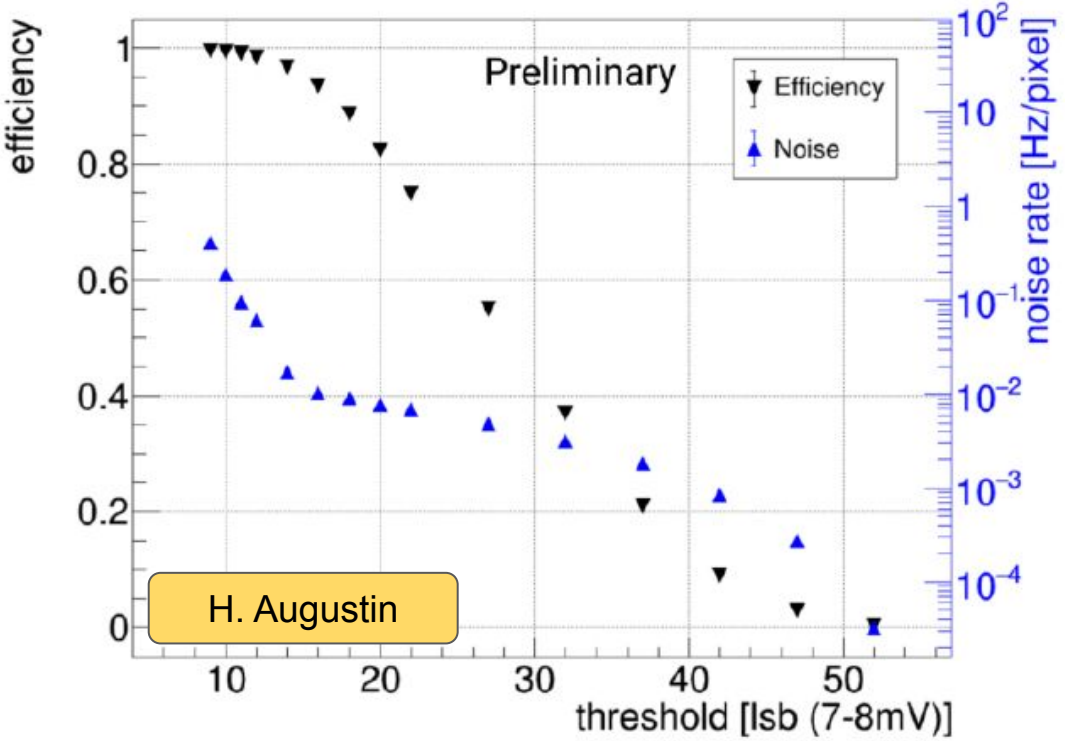


100 µm thickness

110 V breakdown

Efficiency plateau well defined above 20 V

MuPix10: results



50 µm thickness

20 V (see later why)

Efficiency and noise requirements met

Mupix10 detailed studies

Testbeam at DESY

Alpide telescope

6 layers

5 µm resolution

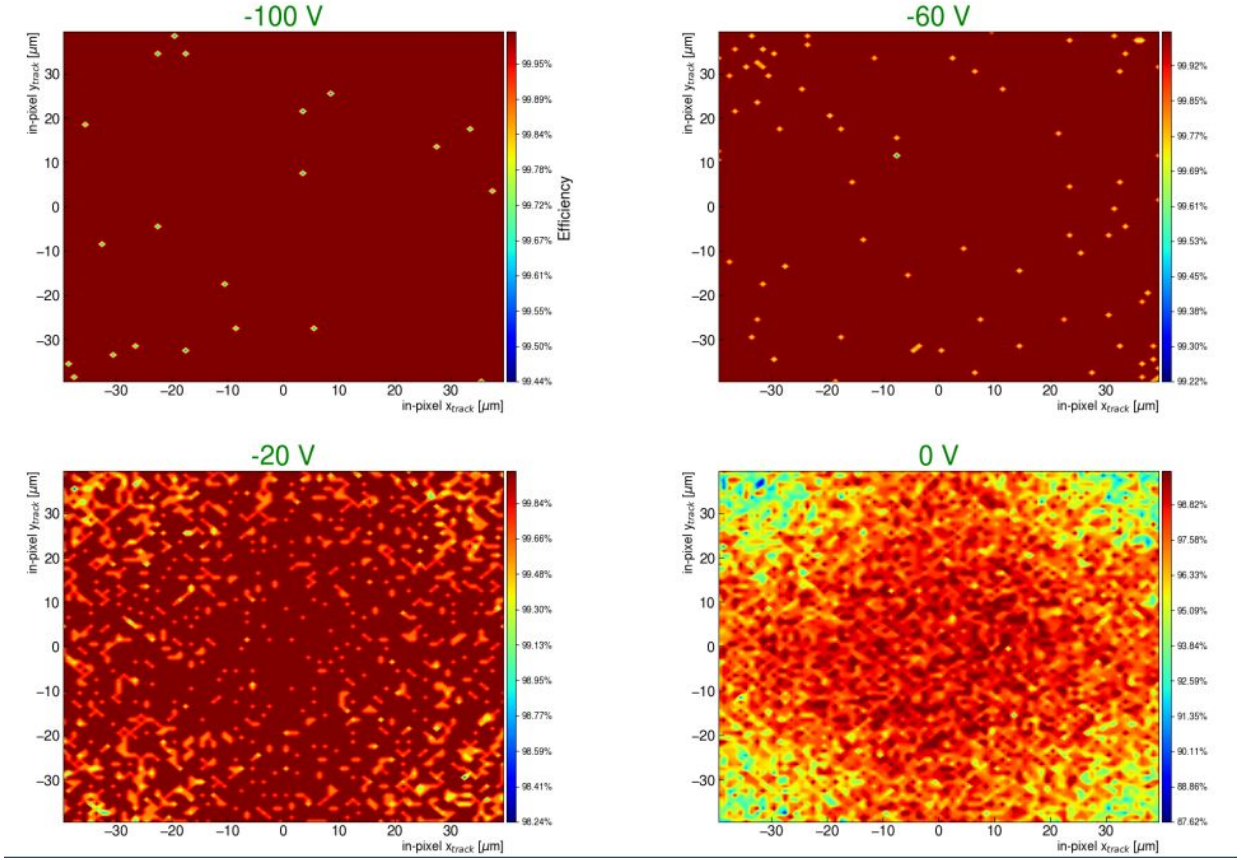
EuDAQ + Corryvreckan

Mupix10 detailed studies

In-pixel efficiency

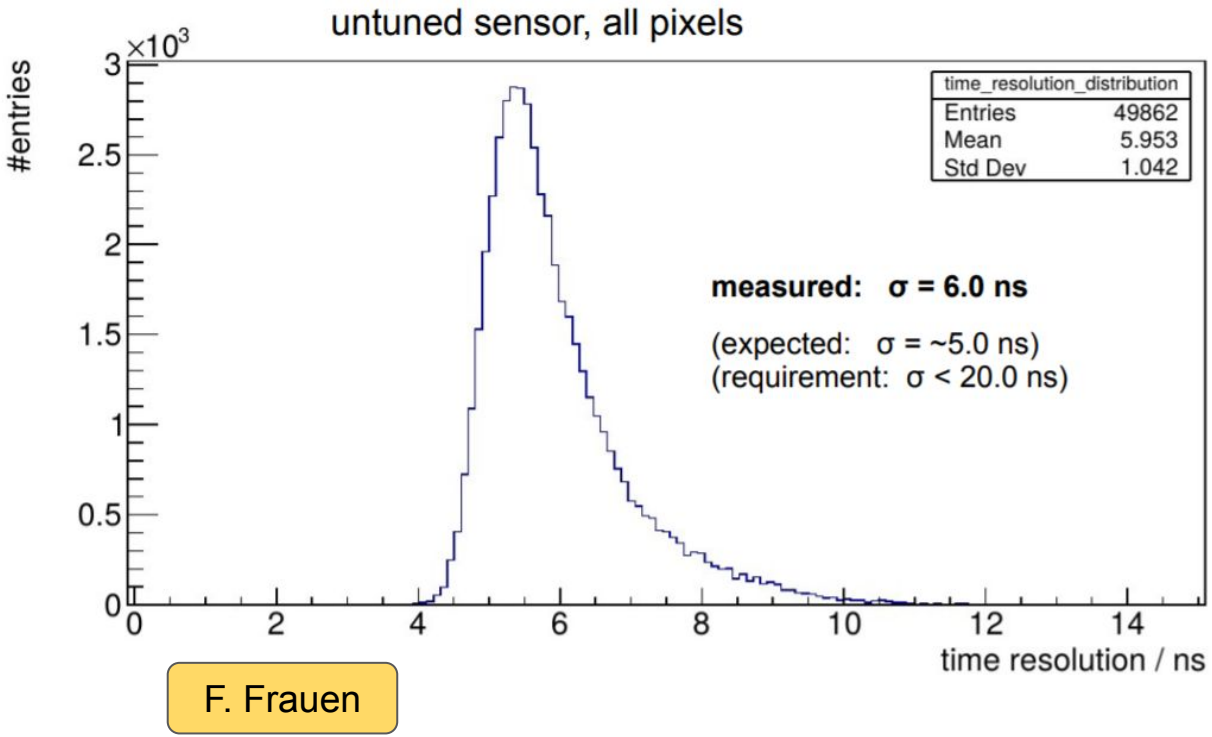
100 µm thick

43 mV threshold



A.M. Gonzales

MuPix10: results



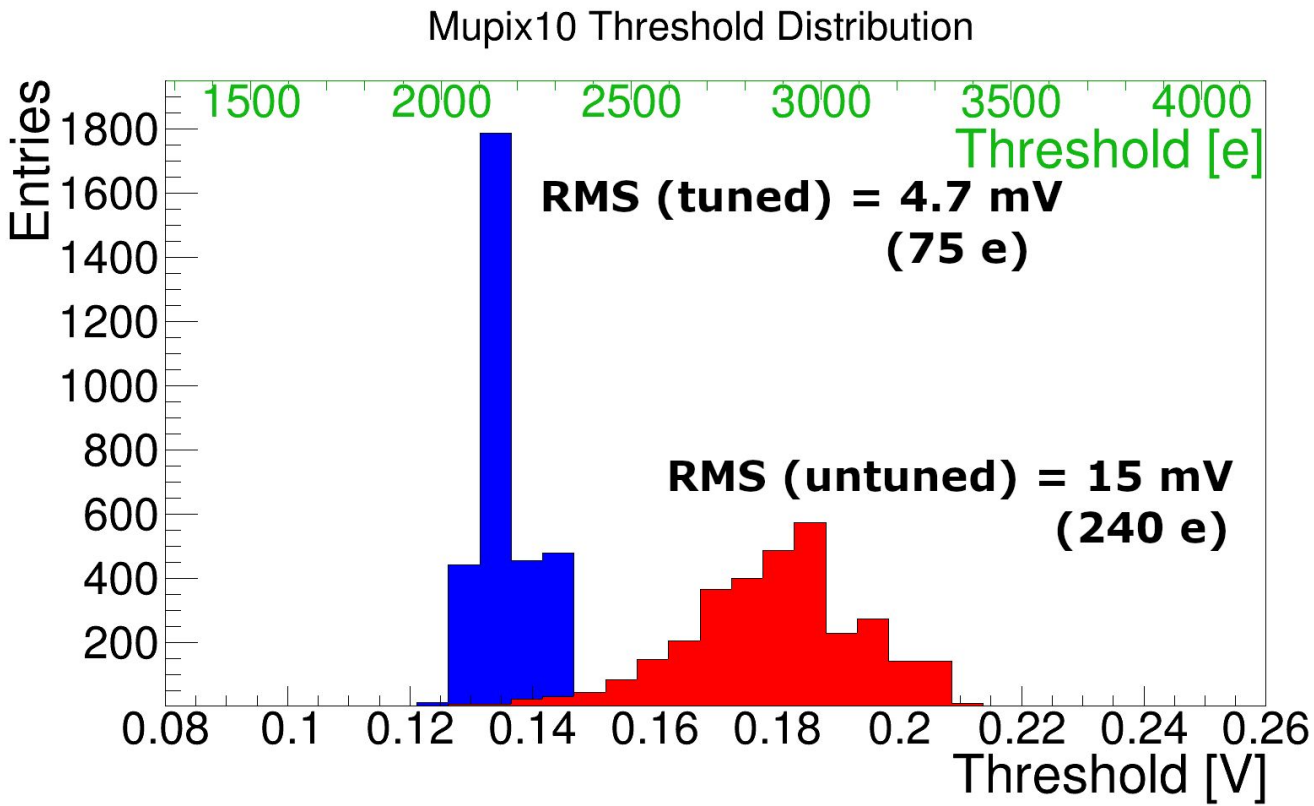
F. Frauen

Time resolution well within specifications

~15 ns without corrections

6 ns after row and time-walk corrections

MuPix10: results



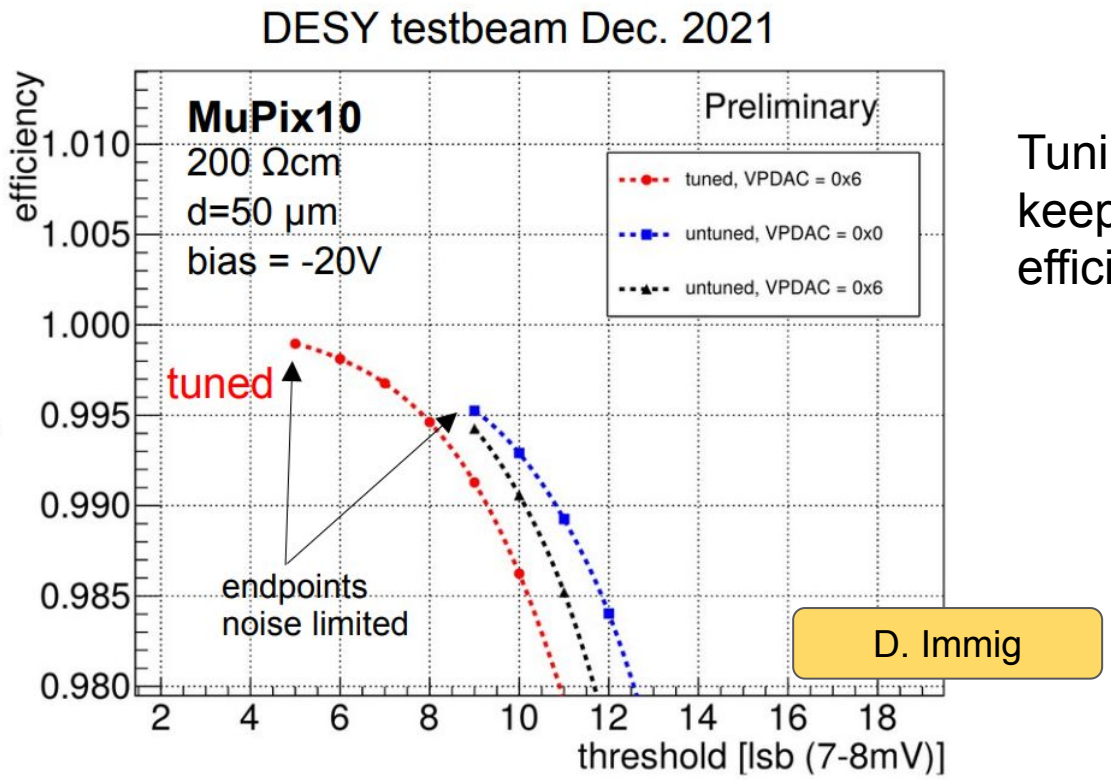
Tunable threshold for each pixel

Tuning with threshold scans:

Low threshold dispersion

M. Menzel

MuPix10: results

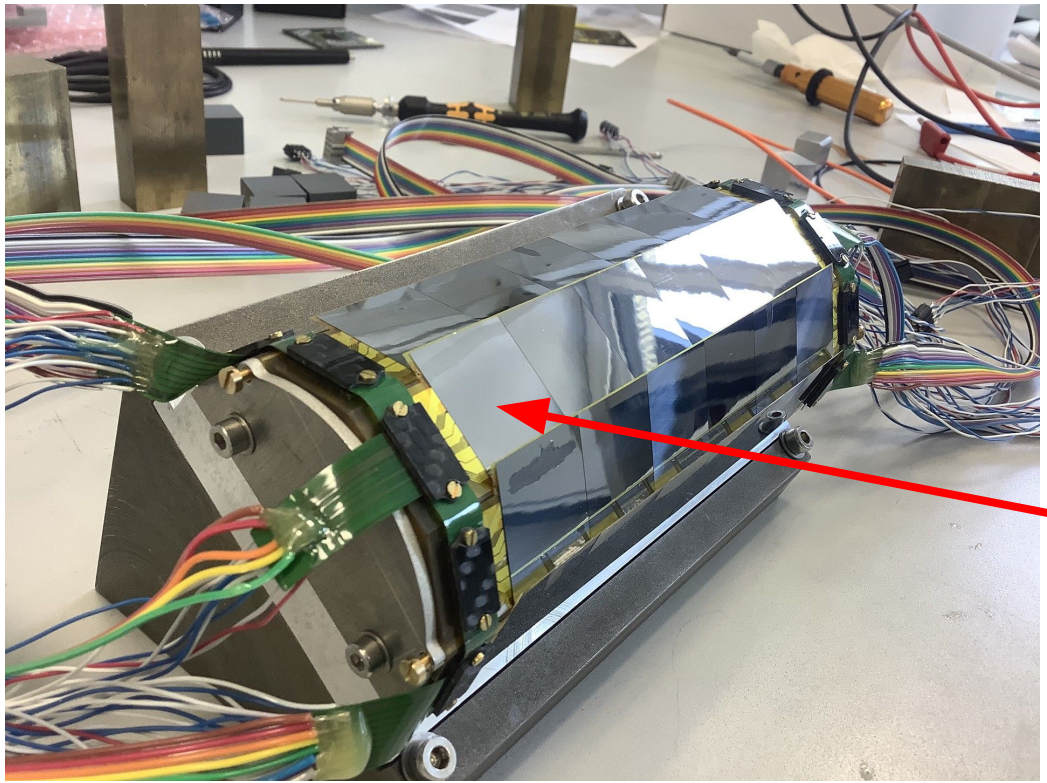


Tuning by lowering threshold while keeping noise constant: maximize efficiency!

D. Immig

Backup: Prototyping

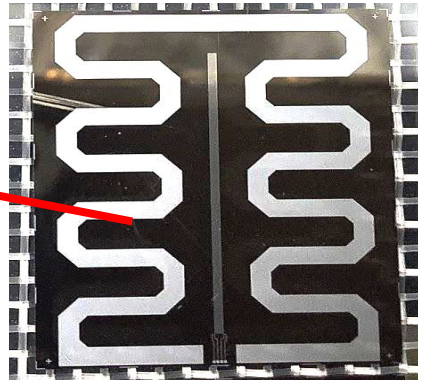
Thermo-mechanical stability



Silicon heater prototype

Reproduction of inner tracker with same materials and connections

Chips are just passive silicon heaters

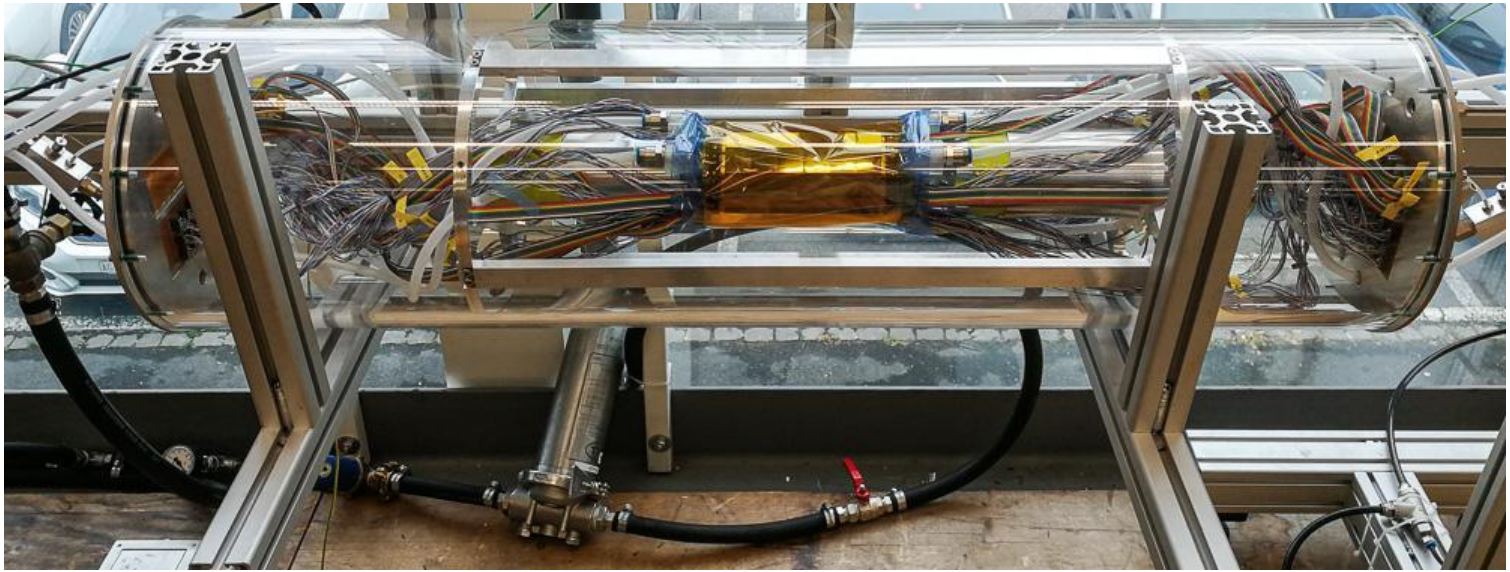


Backup: Prototyping

Thermo-mechanical stability

Silicon heater prototype

Test stand with Helium cooling system

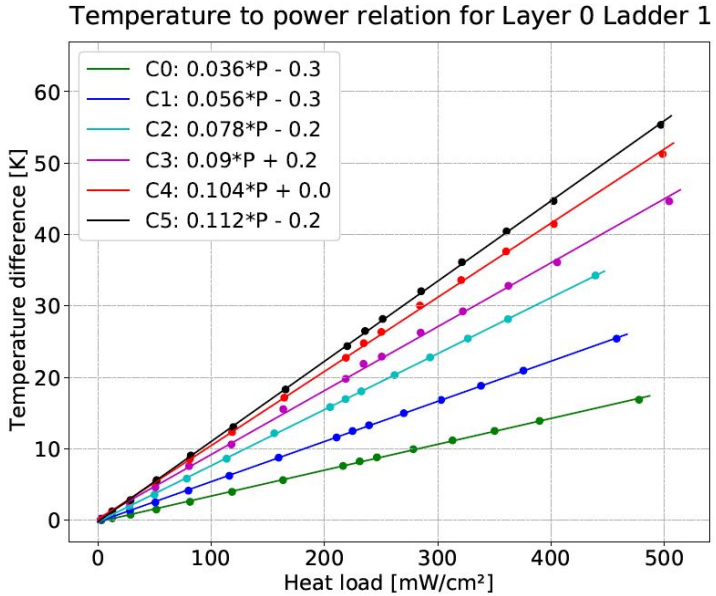


Backup: Prototyping

Thermo-mechanical stability

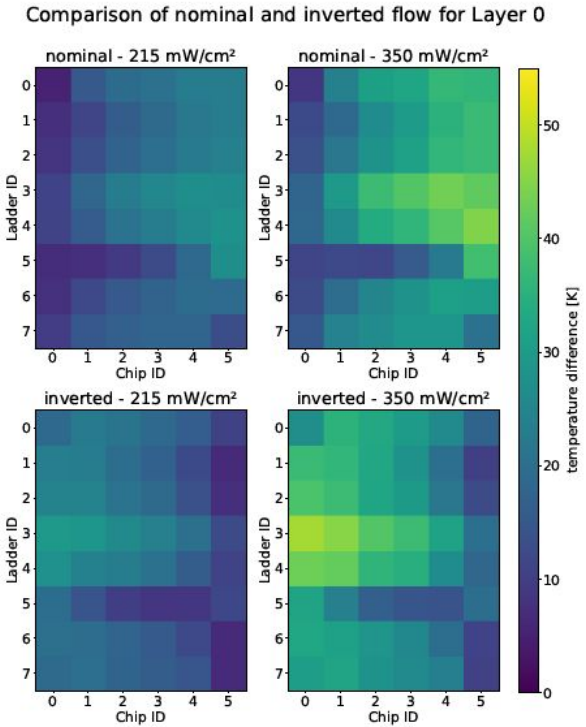
- Measurement of temperature-to-power relation
- Temperature difference linearly depending on heat dissipation
- Expected ΔT < 70 K for 350 mW/cm² (conservative limit)
- Cooling concept works ✅
- More detailed studies to come

Silicon heater prototype

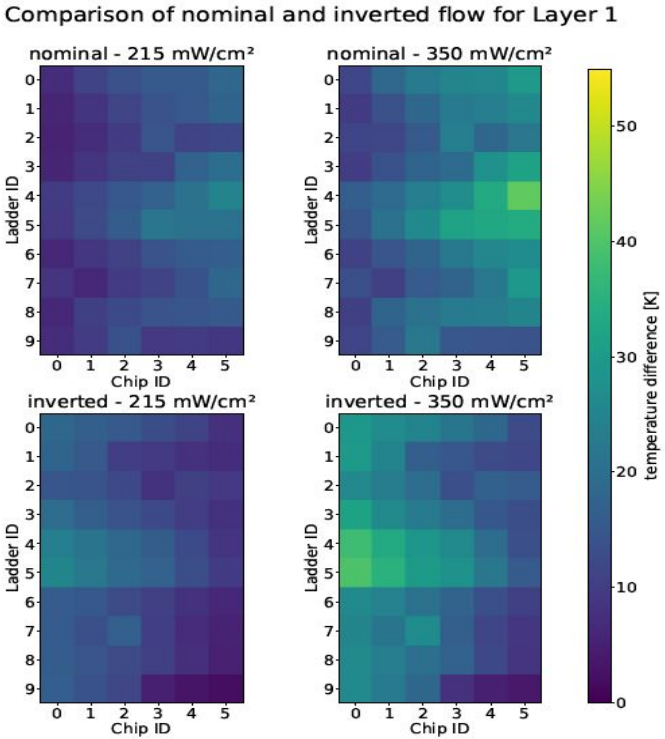


Backup: Prototyping

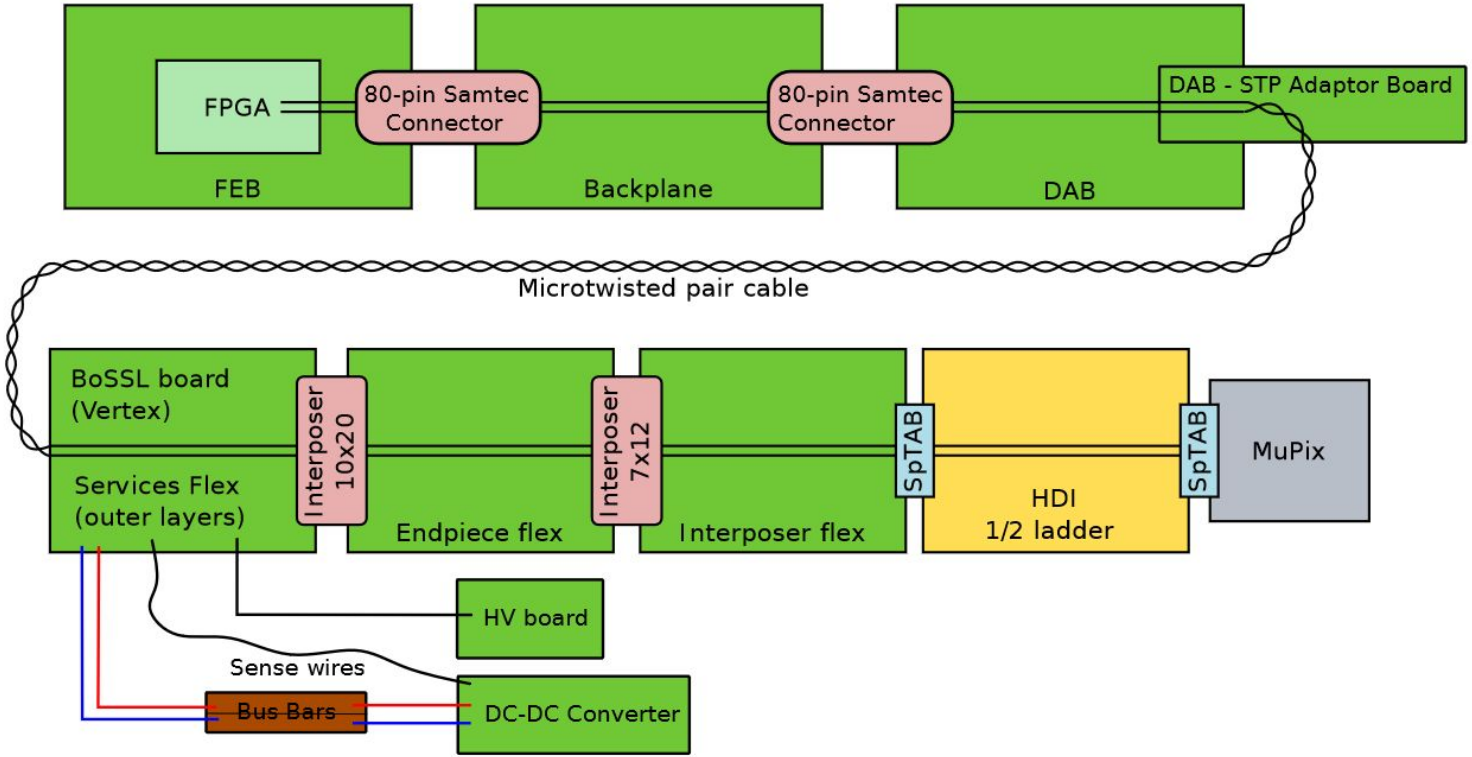
Thermo-mechanical stability



Silicon heater prototype



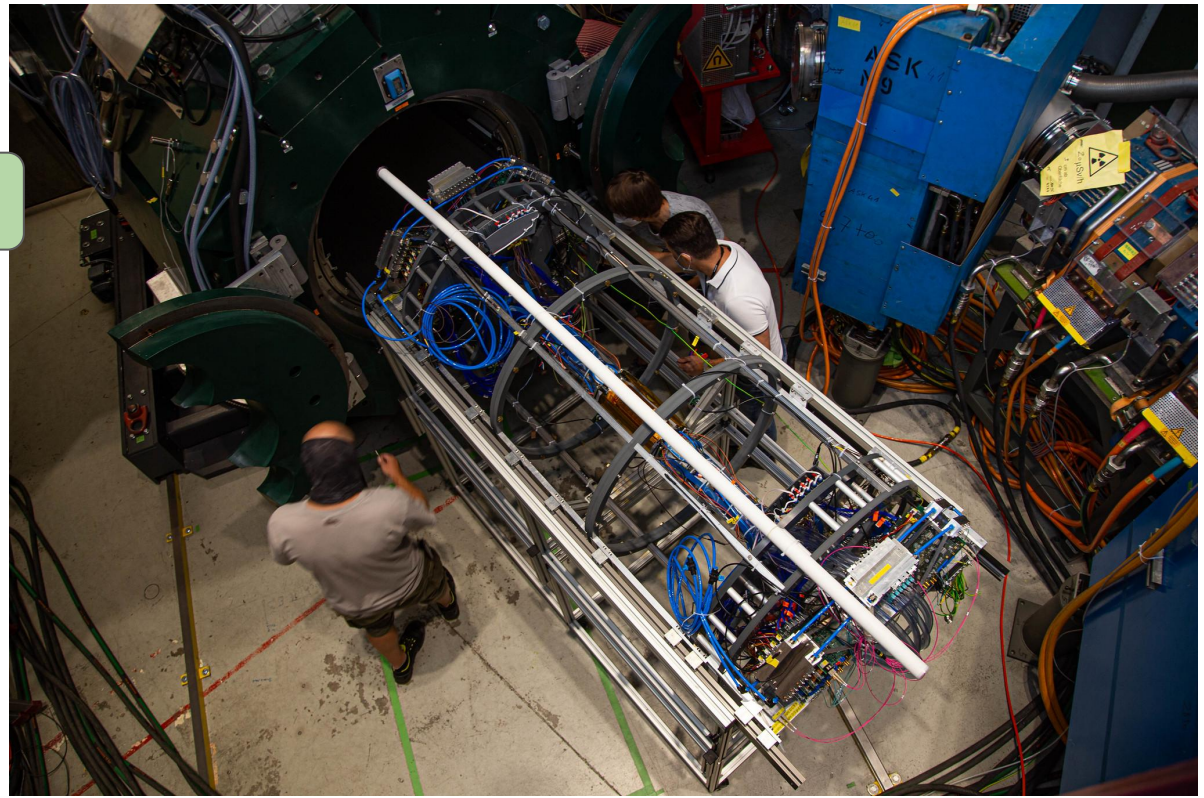
Vertical slice breakdown



Operation in experimental conditions

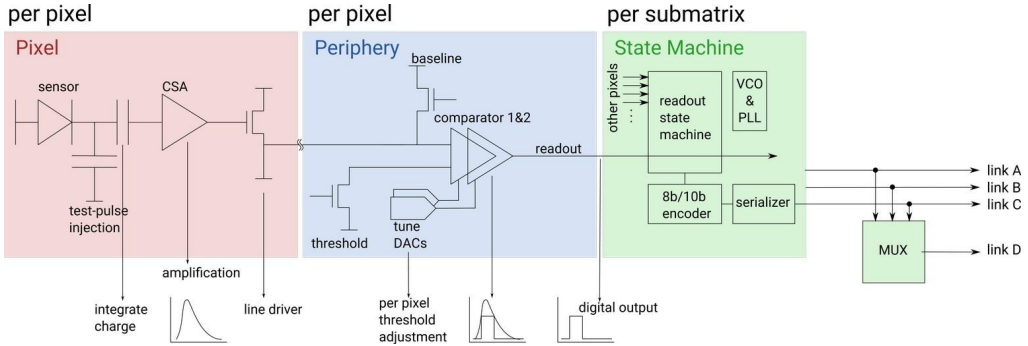
DAQ and experimental concept

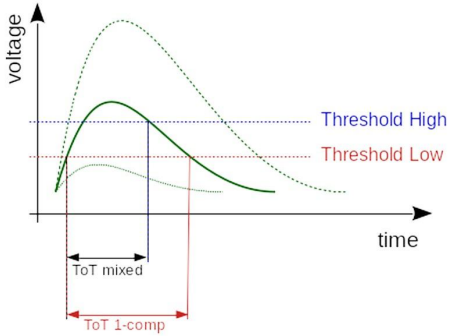
Inside Magnet



More pics at
https://www.flickr.com/photos/nberger/albums/72157719305216074/page1/

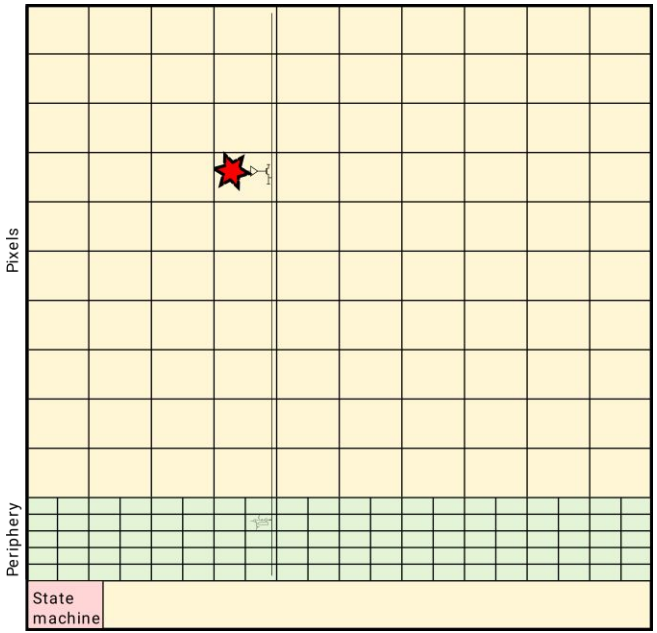
MuPix Architecture





- Clear separation of analog and digital electronics
- 2 comparator design
- Tuning/Trimming and masking available
- Priority encoder / column-drain readout
- Chip sub-divided into 3 matrices → 1 Data link each + 1 multiplexed link

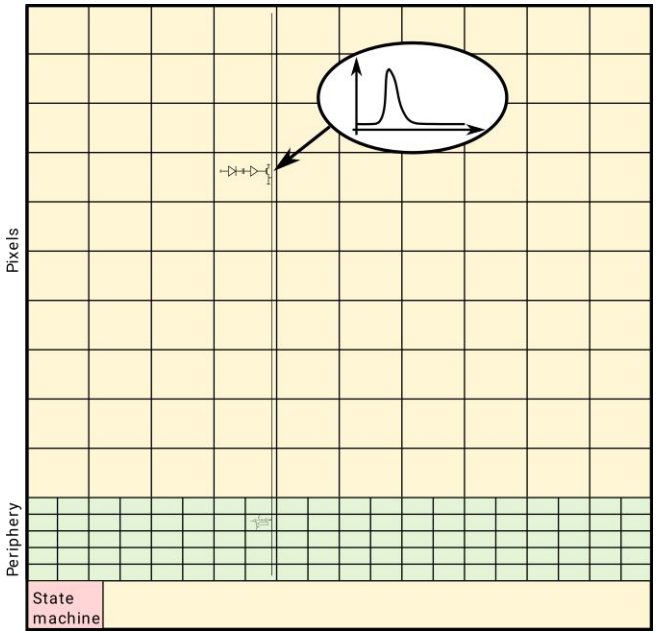
The MuPix Principle



Courtesy: Frank Meier

- Deposited charge amplified by in-pixel amplifier
- Source follower drives the signal to the periphery
- Digitisation in periphery
- Timestamp sampling
- Readout statemachine manages column-drain readout
- Data is send out via a 1.25 Gbit/s differential link

The MuPix Principle



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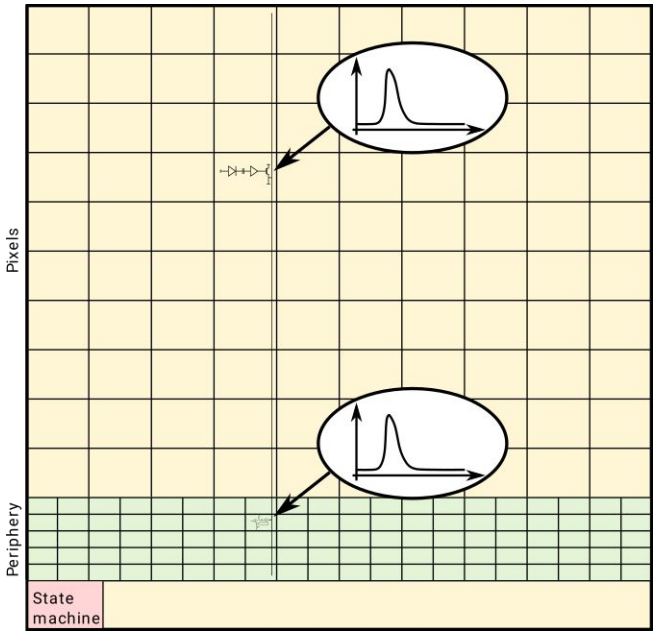
The MuPix Principle



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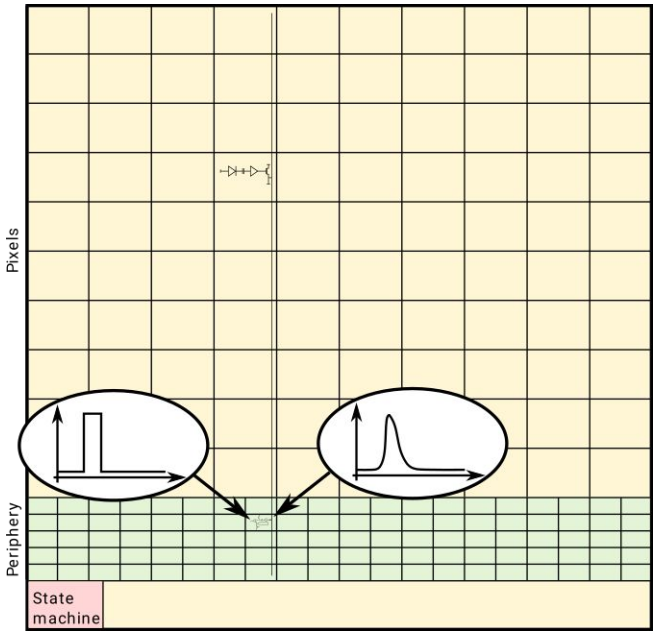

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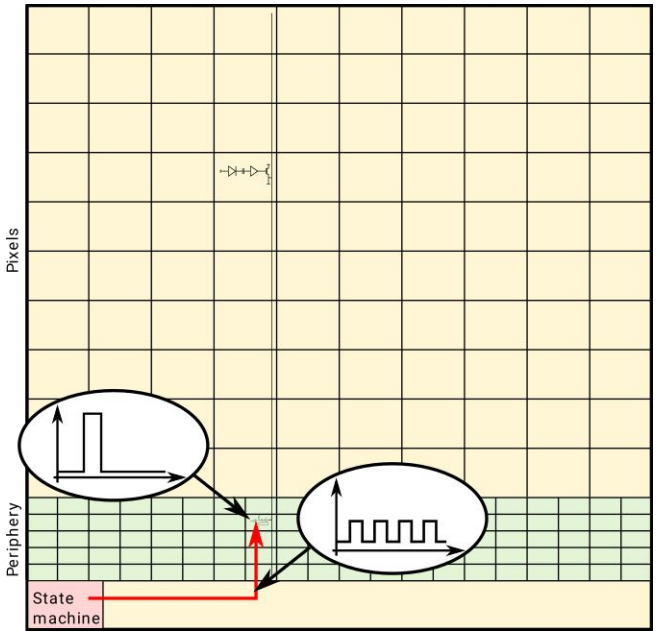

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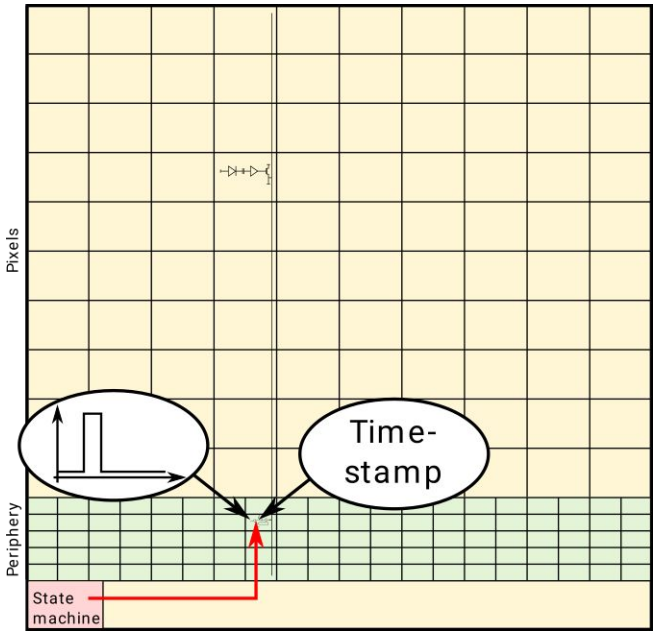
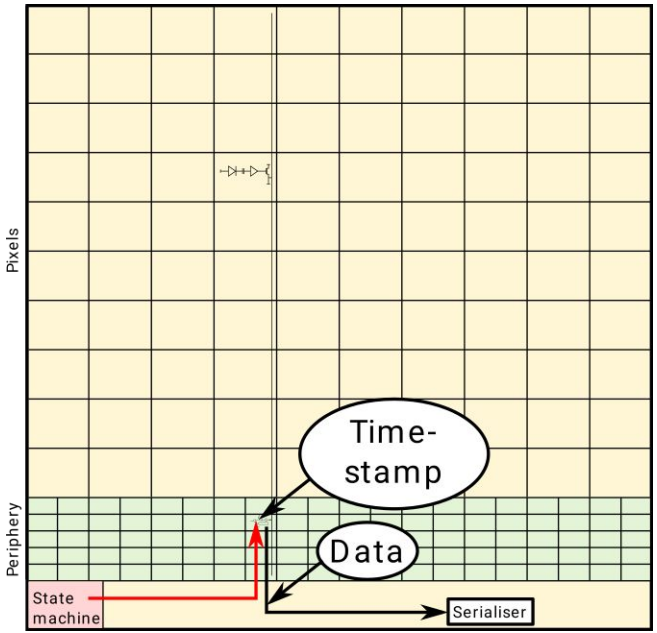


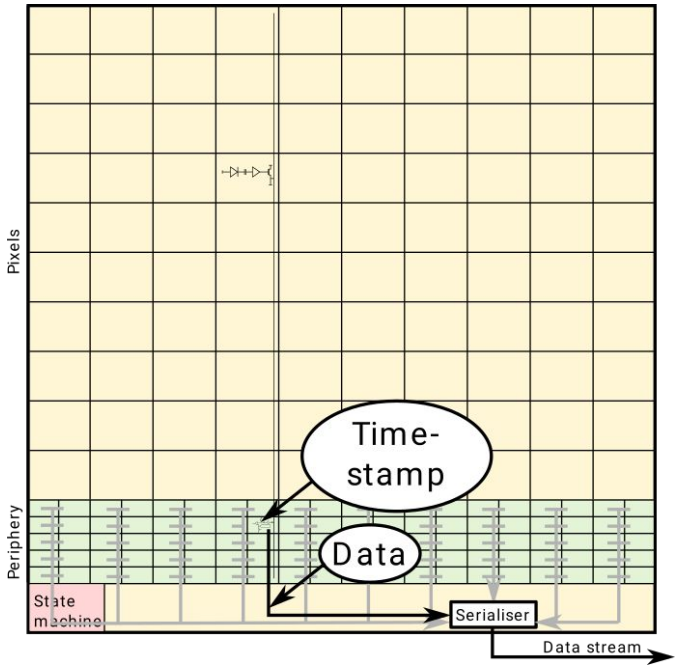
- Deposited charge amplified by in-pixel amplifier
- Source follower drives the signal to the periphery
- Digitisation in periphery
- Timestamp sampling
- Readout statemachine manages column-drain readout
- Data is send out via a 1.25 Gbit/s differential link

The MuPix Principle



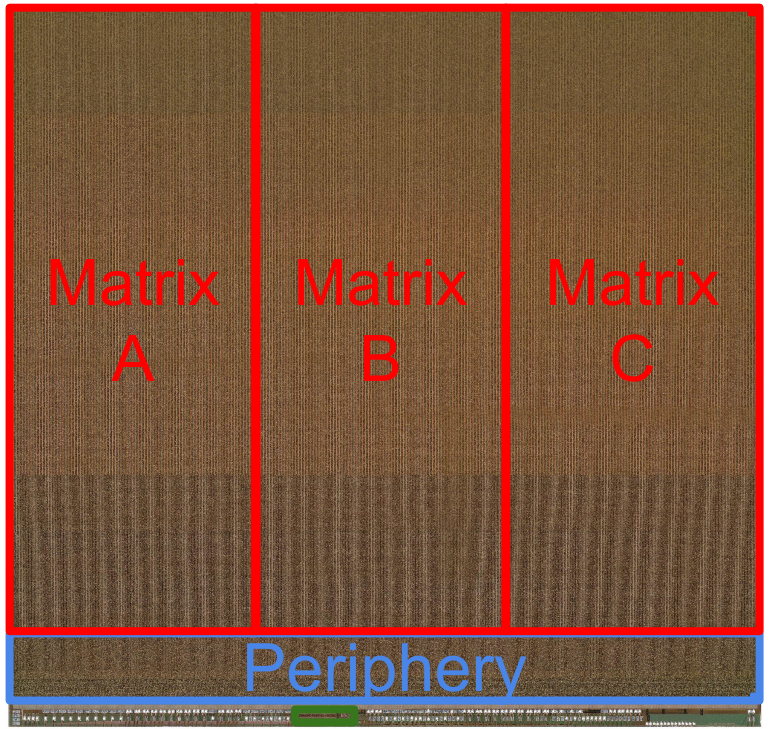
- Deposited charge amplified by in-pixel amplifier
- Source follower drives the signal to the periphery
- Digitisation in periphery
- Timestamp sampling
- Readout state machine manages column-drain readout
- Data is send out via a 1.25 Gbit/s differential link

The MuPix Principle



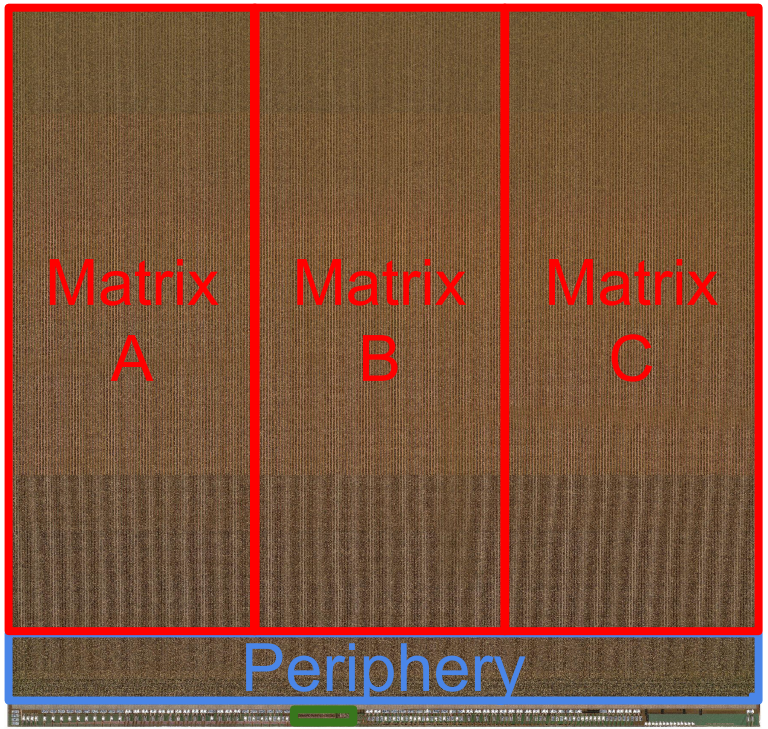
- Deposited charge amplified by in-pixel amplifier
- Source follower drives the signal to the periphery
- Digitisation in periphery
- Timestamp sampling
- Readout statemachine manages column-drain readout
- Data is send out via a 1.25 Gbit/s differential link

MuPix10 & MuPix11



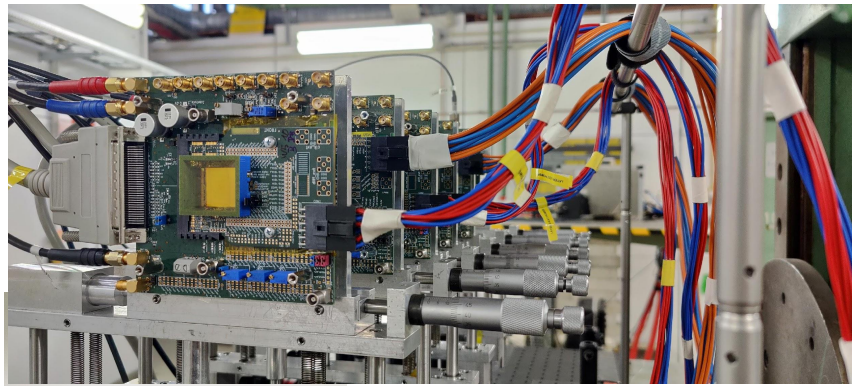
Pixel size [µm²]	80 x 80
Sensor size [mm²]	20.66 x 23.18
Active size [mm²]	20.48 x 20.0
Pixel matrix	256 x 250
Thickness [µm]	**50, 70**
Substrate [Ωcm]	80, 370
Data links	**3+1**
Data speed [Gbit/s]	1.25
Time-of-arrival [bits]	11
ToT [bits]	5
TS binning [ns]	8 (option for 1.6)

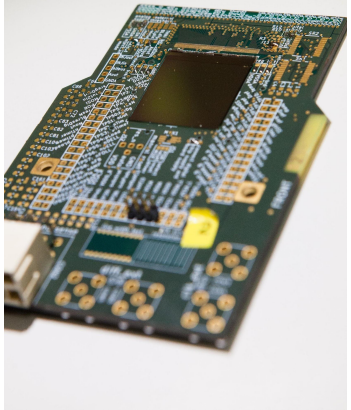
From MuPix10 to MuPix11



- Removal of R&D features
  - ➡ More pads for powering
- Improvement of powering grid
  - ➡ Less on-chip voltage drop
- Buffering of data lines
  - ➡ Full speed readout
    30 MHits/s per sub-matrix
- Re-synthesis of State machine
  - ➡ Fast configuration interface available
- Re-done pixel point-to-point connection
  - ➡ Reduced delays and parasitic couplings

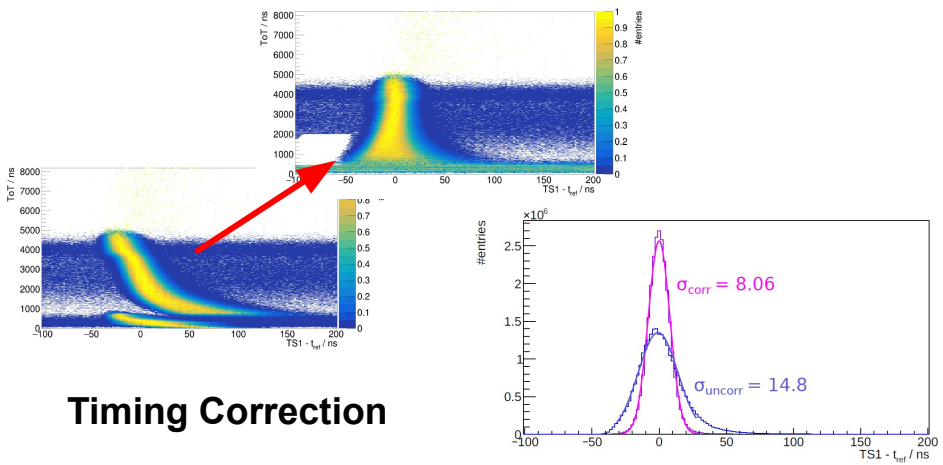
Sensor Characterisation



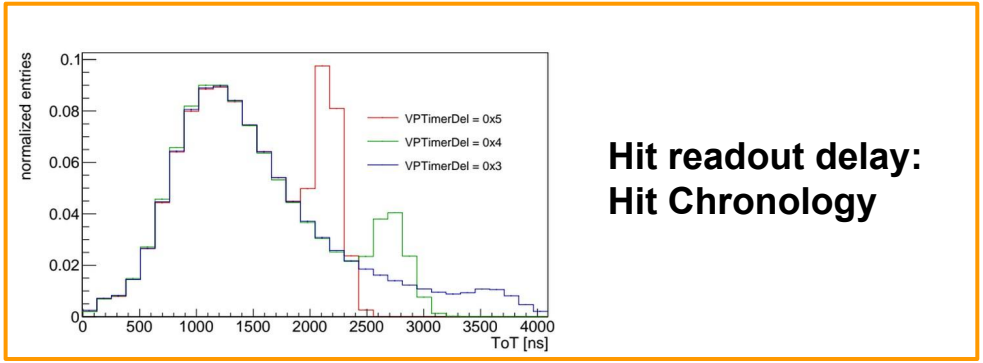


- Lab commissioning
- Lab optimisation:
  Radioactive sources: ^{55}Fe, ^{90}Sr
  Time coincidence
- Testbeam Campaigns:
  DESYII (Hamburg, GER)
  MAMI (Mainz, GER)
  PSI piM1 (Villigen, CH)
- MuPix-Telescope
- Mimosa/Alpide-Telescopes

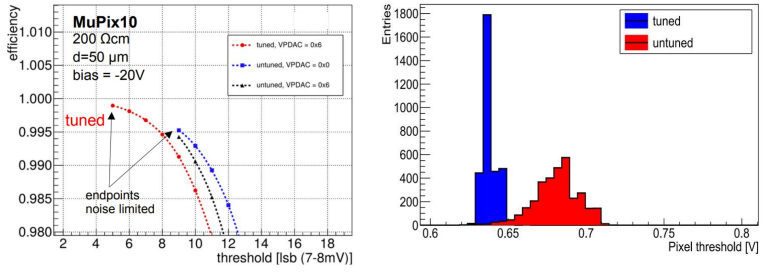
Summary - Results MuPix10



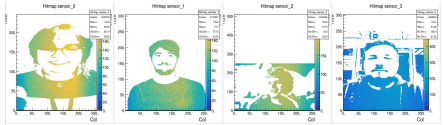
Timing Correction

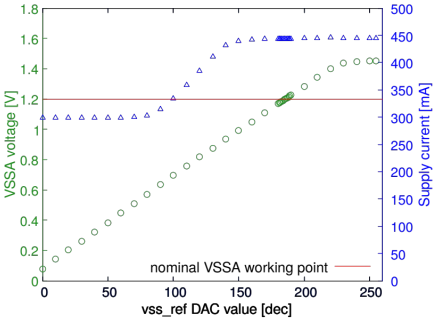


Hit readout delay:
Hit Chronology



Tuning/Trimming
Masking



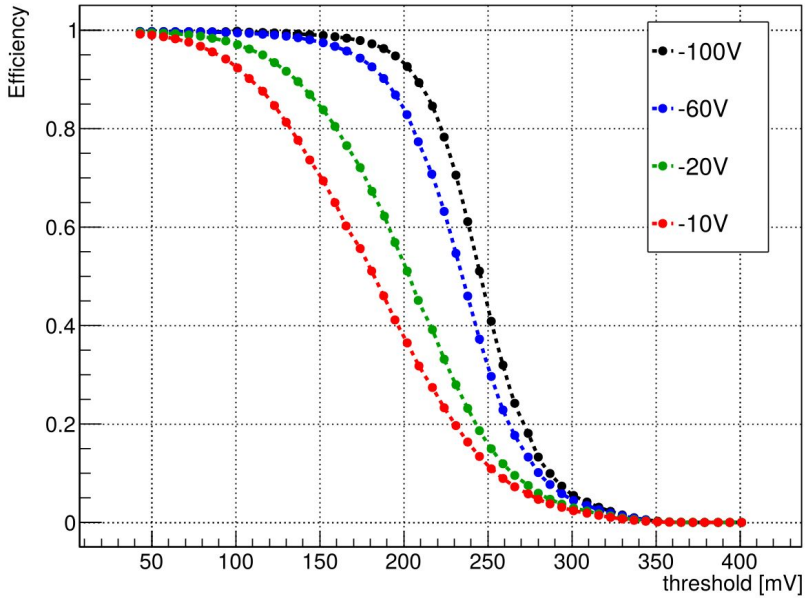


Voltage Regulator:
Single Supply

[arXiv:2012.05868] & VERTEX2022

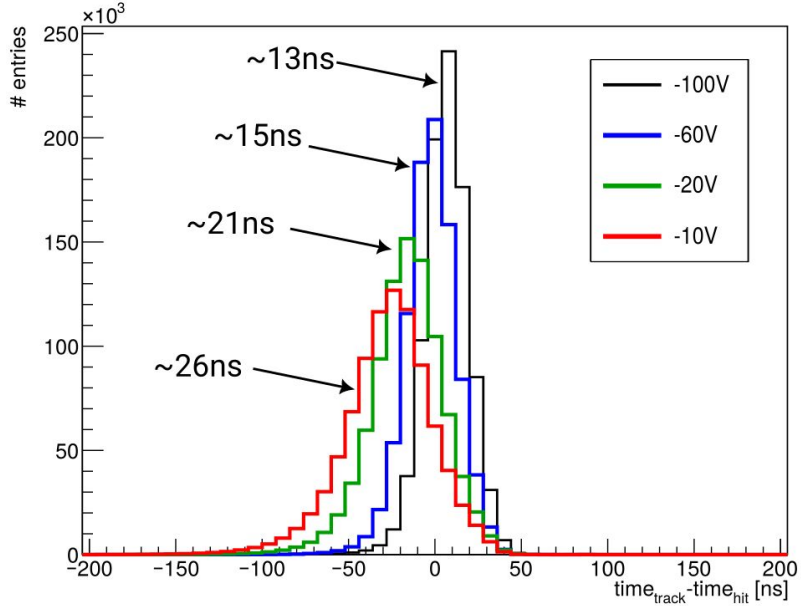
MuPix11 - First Light

Efficiency - 100µm thick sensor



Depletion depth proportional to **sqrt(HV)**

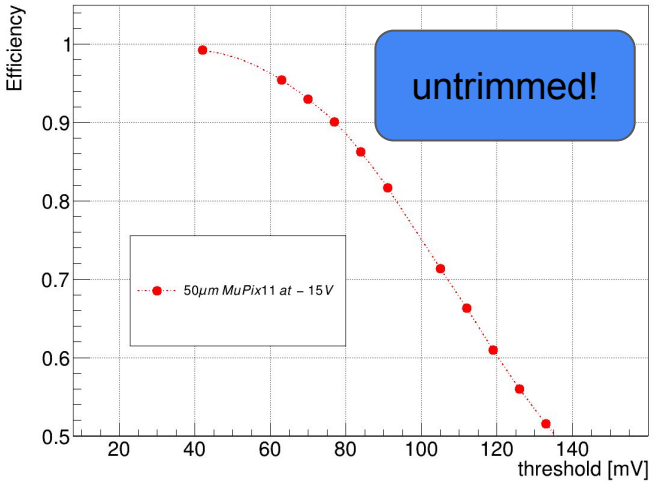
Time resolution (Gaussian estimate)



Raw time resolution,
no corrections of any kind

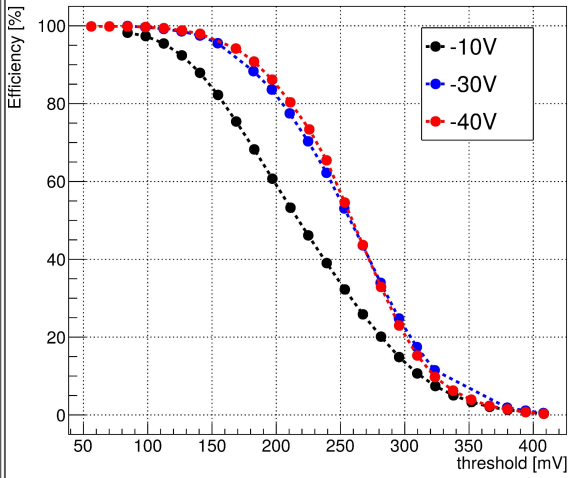
MuPix11 - Efficiency for 50 and 70 µm

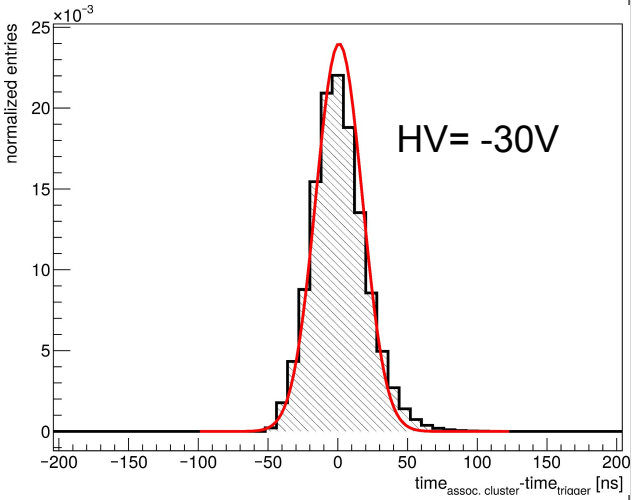
50µm thickness



➡ Needs calibration/trimming!

70µm thickness





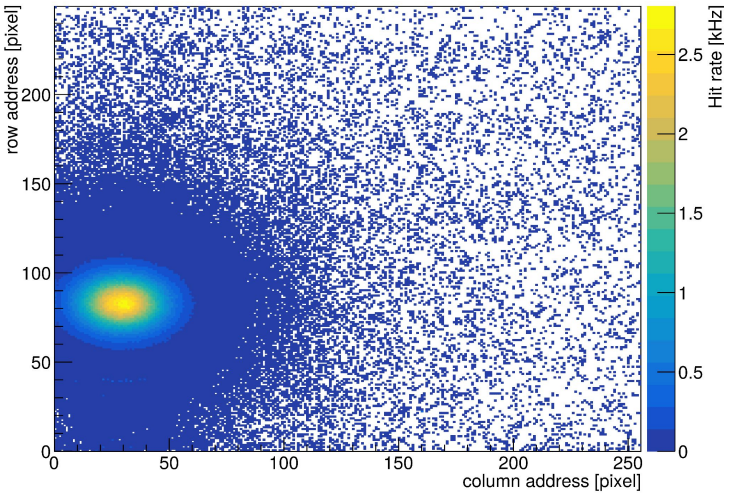
➡ Works out of the box!

$\sigma_{\text{uncorrected}} \sim 16.6\,\text{ns}$

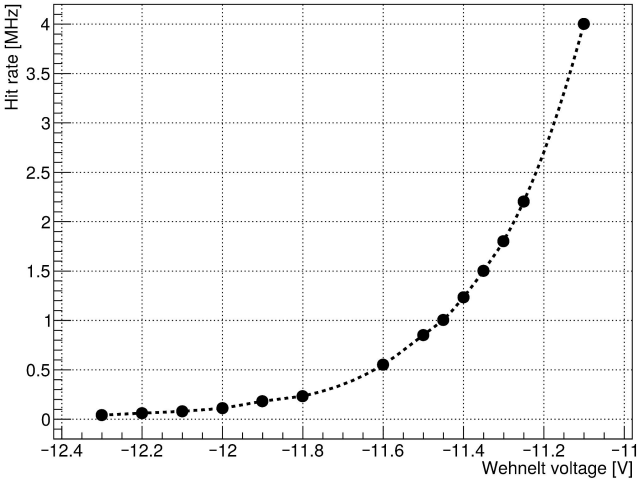
Mu3e: 50µm sensors for the vertex detector (~100 Sensors)
70µm sensors for the outer layers (~3000 Sensors)

MuPix11 - High Rate capability

MAMI - Beam spot on sub-matrix A



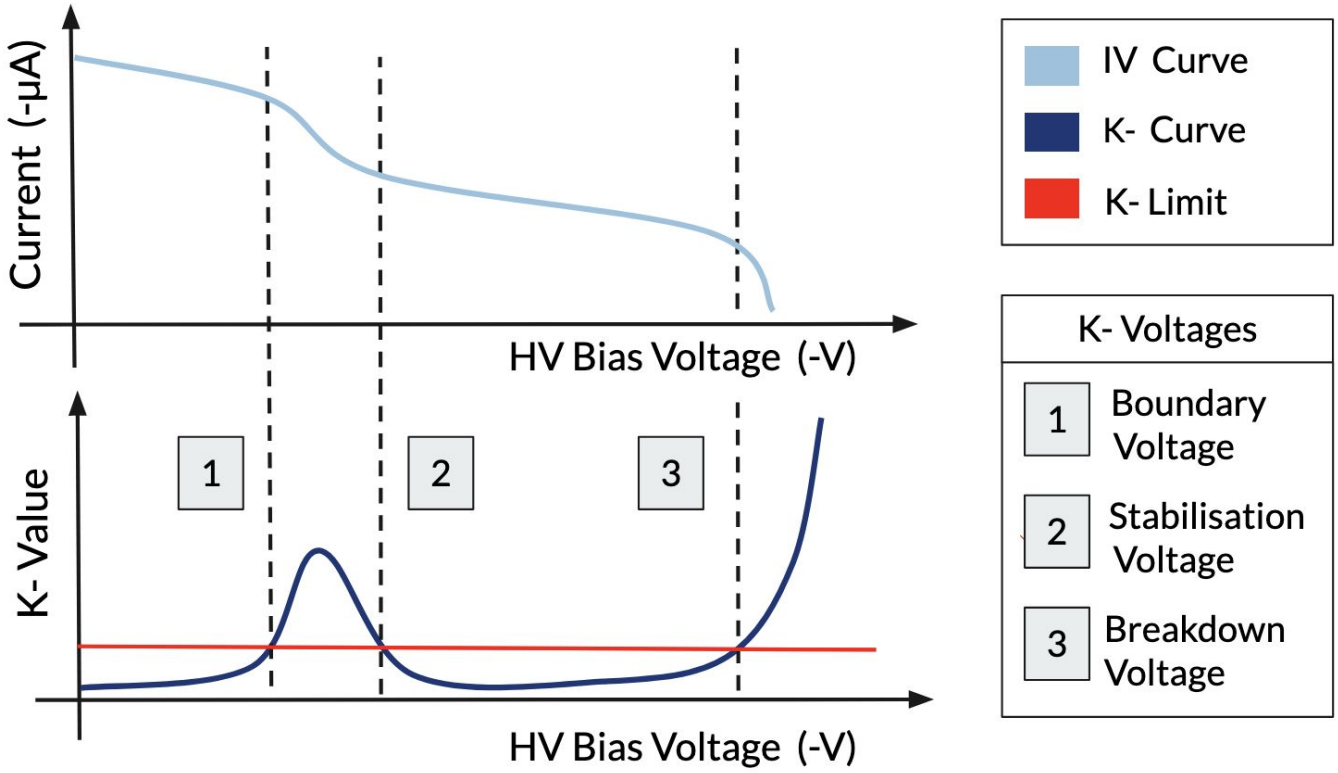
Beam rate measured with MuPix11



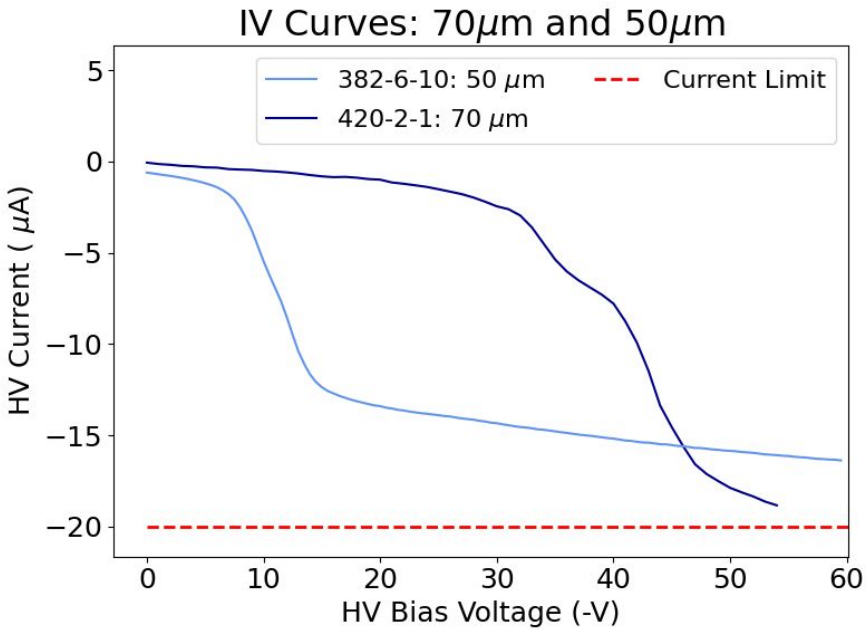
No Readout saturation visible @ 4 MHz Hitrate

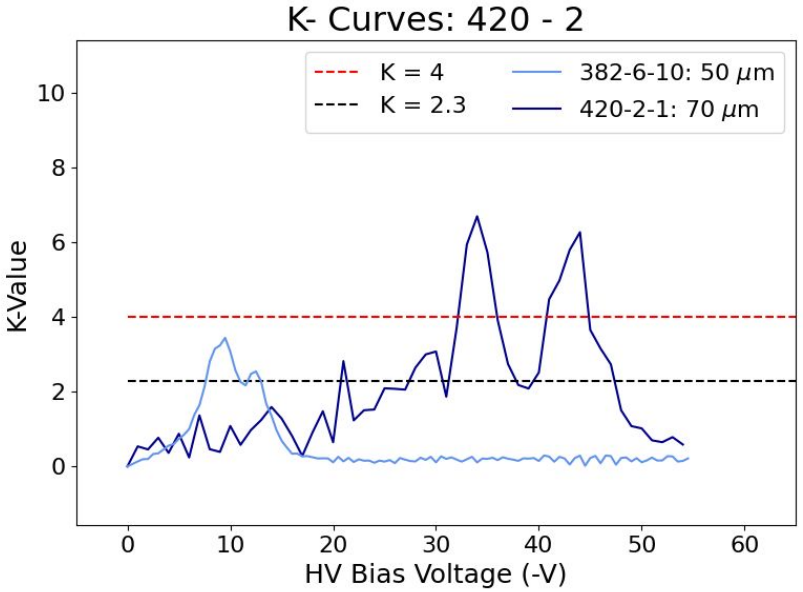
➡ Average Rate on “Hottest” Sensor 6 MHz

IV issues

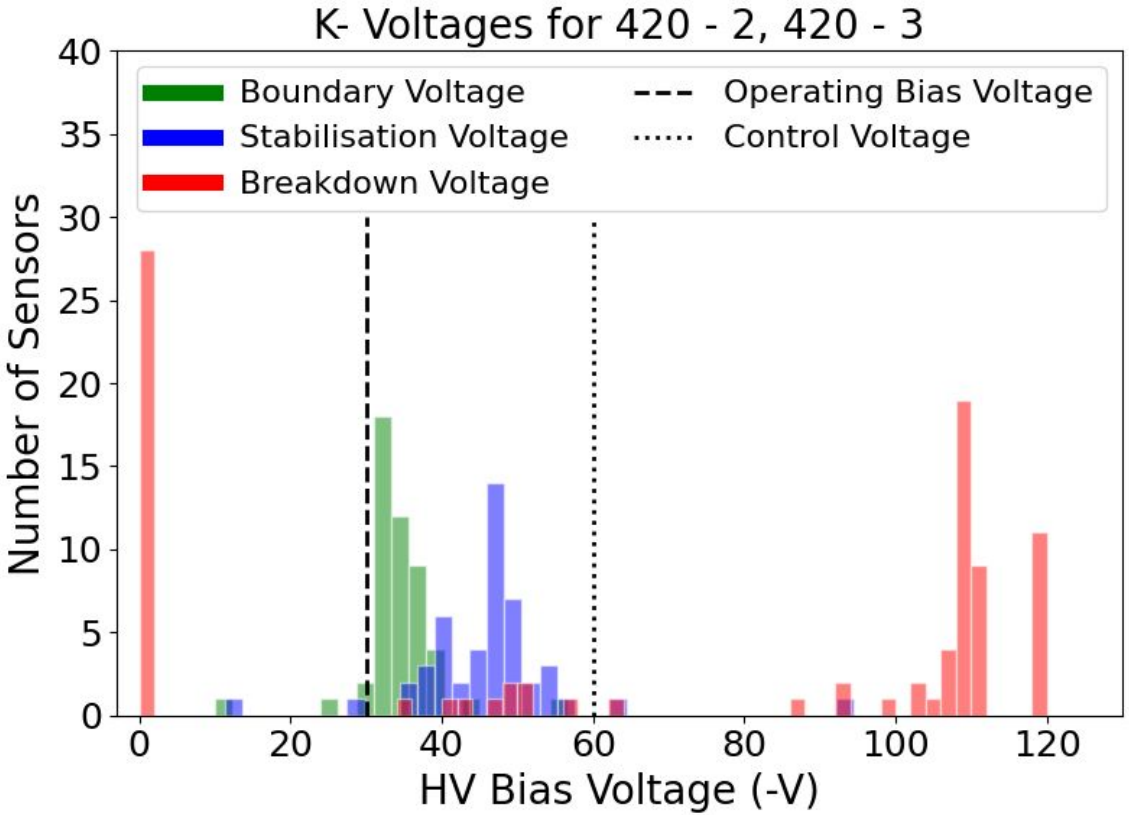

Current (-µA)
HV Bias Voltage (-V)
K- Value
1
2
3
HV Bias Voltage (-V)
IV Curve
K- Curve
K- Limit
K- Voltages
1 Boundary Voltage
2 Stabilisation Voltage
3 Breakdown Voltage

IV issue


IV Curves: 70μm and 50μm
382-6-10: 50 μm
420-2-1: 70 μm
Current Limit
HV Current (μA)
HV Bias Voltage (-V)
5
0
−5
−10
−15
−20
0
10
20
30
40
50
60


K- Curves: 420 - 2
K = 4
K = 2.3
382-6-10: 50 μm
420-2-1: 70 μm
K-Value
HV Bias Voltage (-V)
10
8
6
4
2
0
0
10
20
30
40
50
60

IV issues


K- Voltages for 420 - 2, 420 - 3
Boundary Voltage
Stabilisation Voltage
Breakdown Voltage
Operating Bias Voltage
Control Voltage
Number of Sensors
HV Bias Voltage (-V)
0
5
10
15
20
25
30
35
40
0
20
40
60
80
100
120