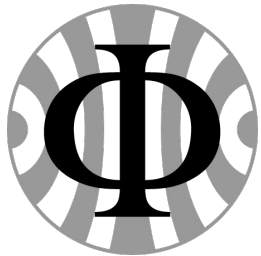


First Experience with the Mu3e Vertex Detector Construction



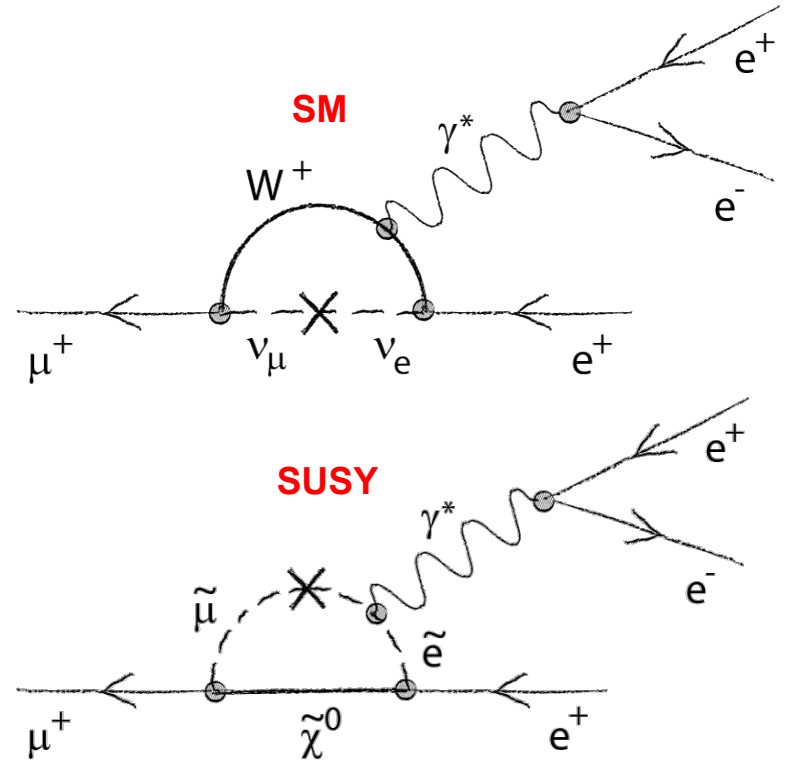
Luigi Vigani
University of Heidelberg
Pixel 2024
22/11/2024



Mu3e: Physics Motivation



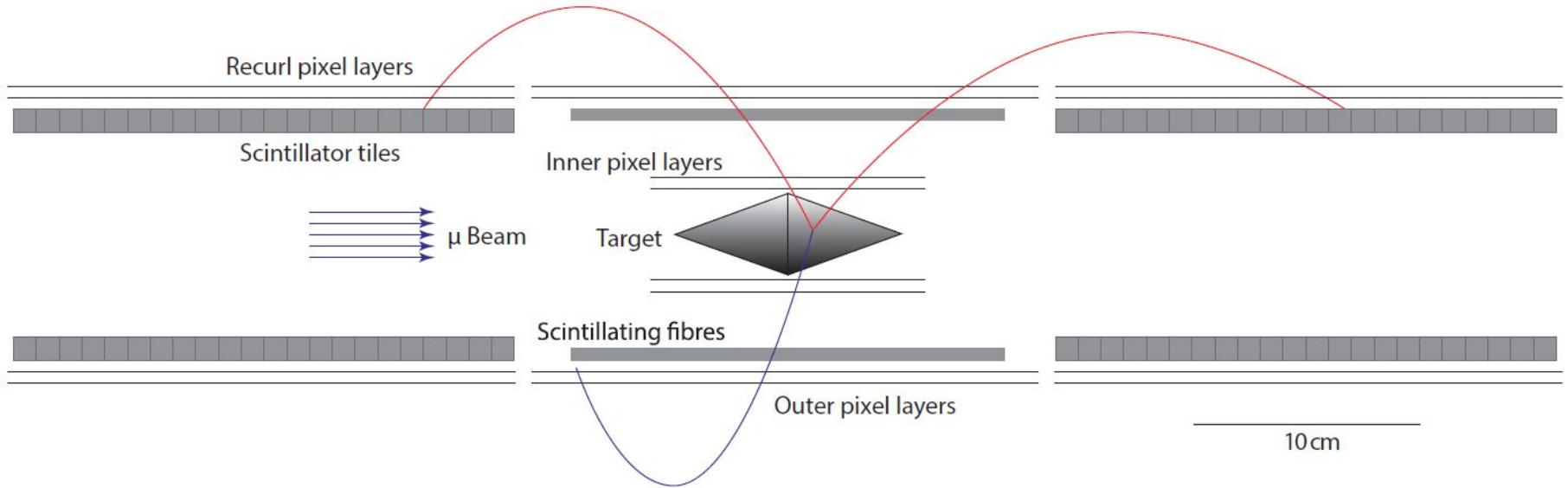
- Search for $\mu \rightarrow eee$
 - Standard Model: $\text{BR}(\mu \rightarrow eee) < 10^{-54}$
- New physics might enhance BR
- Current limit:
 - $\text{BR}(\mu \rightarrow eee) < 10^{-12}$ (SINDRUM, 1988)
- Aimed single-event sensitivity:
 - $\text{BR}(\mu \rightarrow eee) < 2 \cdot 10^{-15}$ (Phase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



Experimental concept



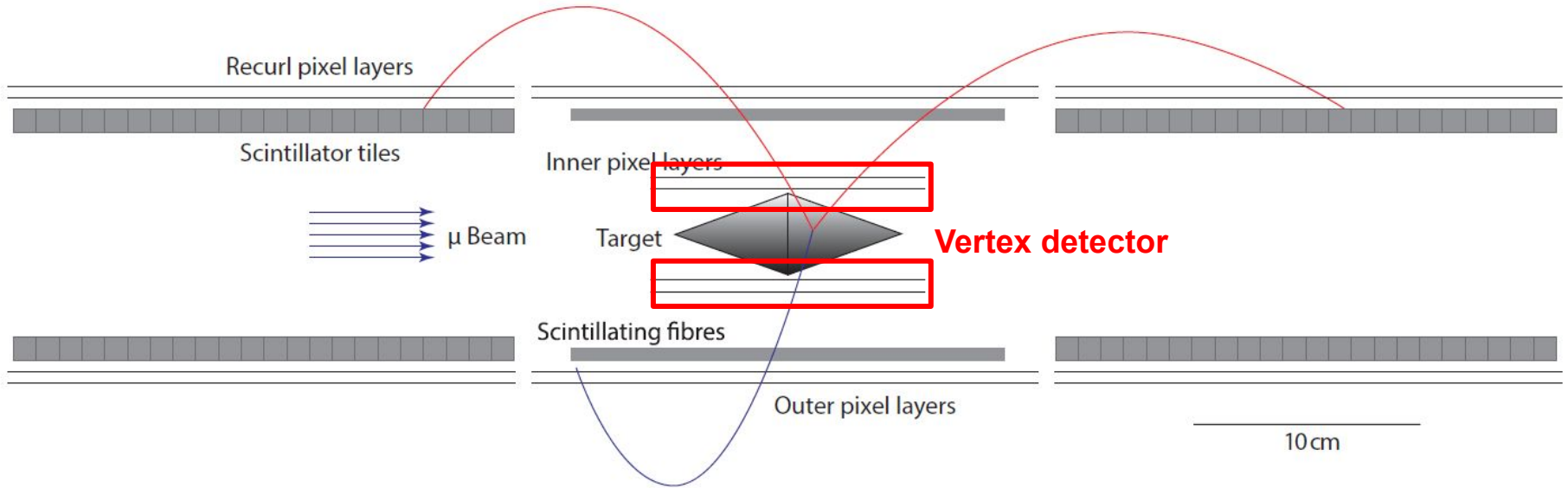
- Tracking electrons coming from muon decays ($\sim 10^8$ Hz in Phase I)
- Magnetic field (1 T)



Experimental concept



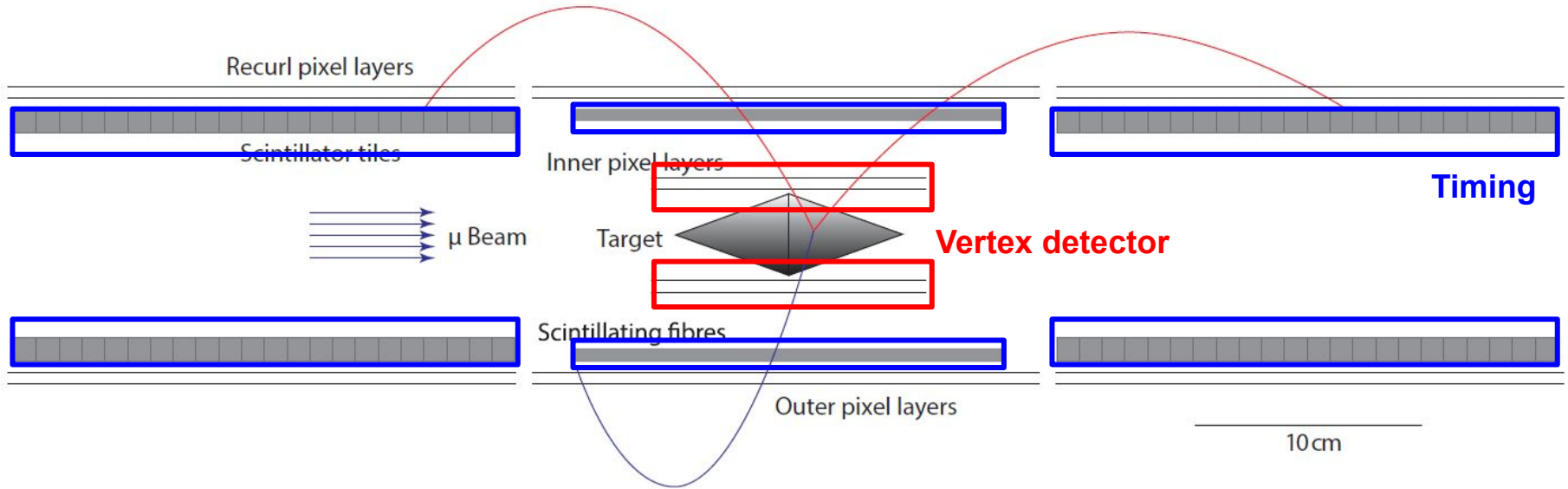
- Tracking electrons coming from muon decays ($\sim 10^8$ Hz in Phase I)
- Magnetic field (1 T)



Experimental concept



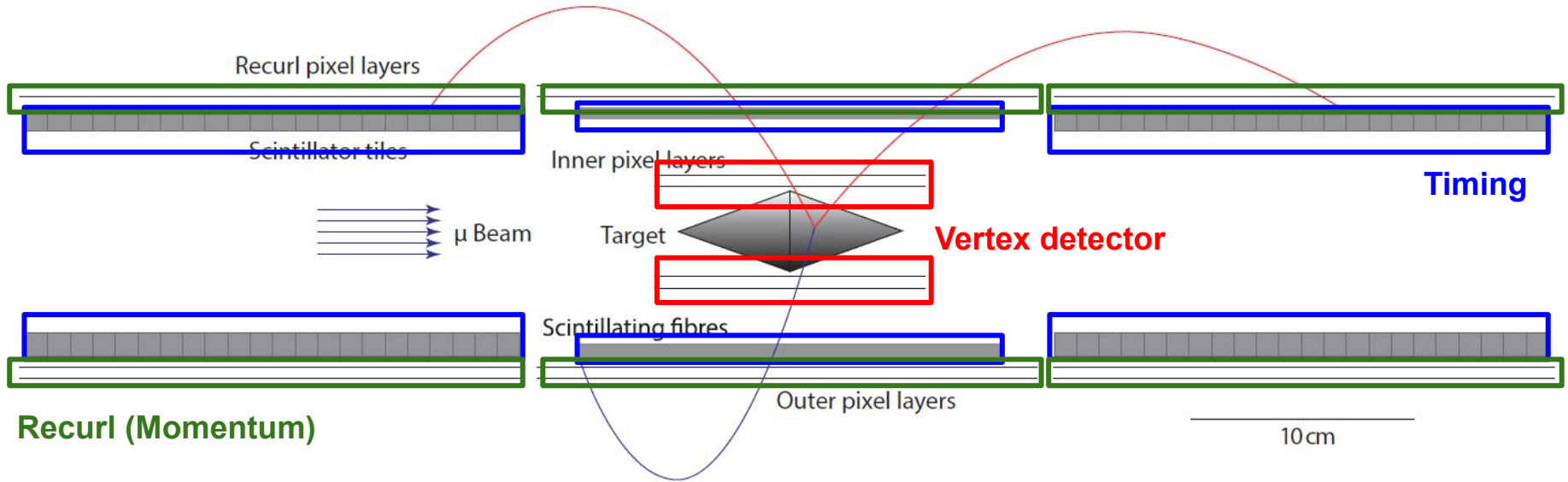
- Tracking electrons coming from muon decays ($\sim 10^8$ Hz in Phase I)
- Magnetic field (1 T)



Experimental concept



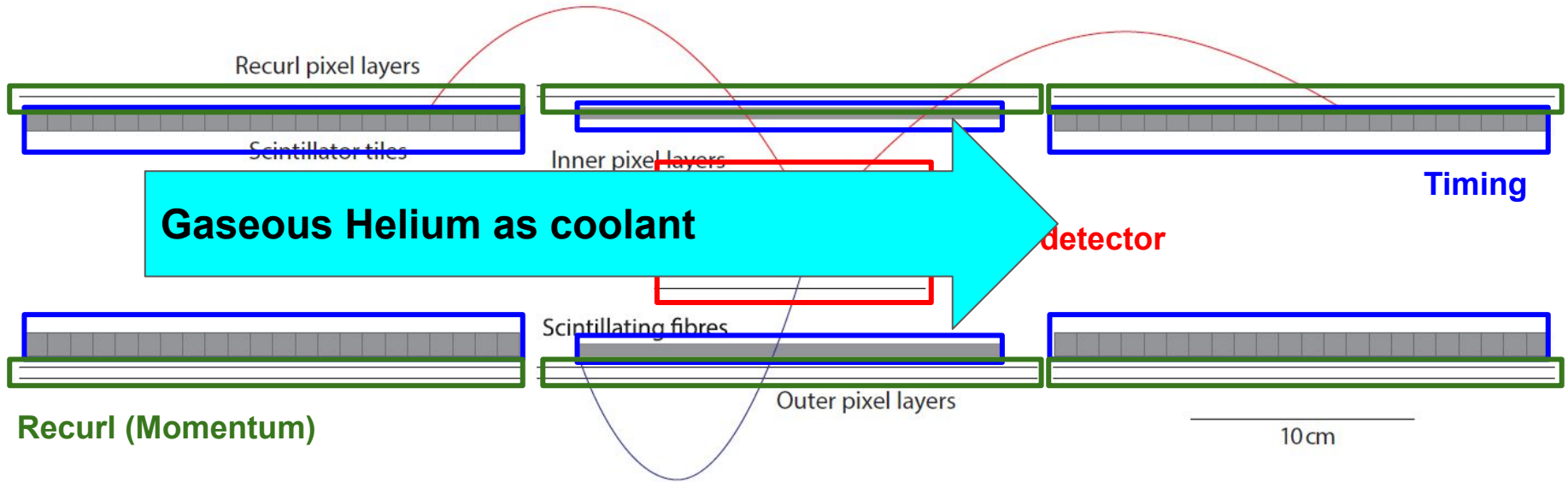
- Tracking electrons coming from muon decays ($\sim 10^8$ Hz in Phase I)
- Magnetic field (1 T)



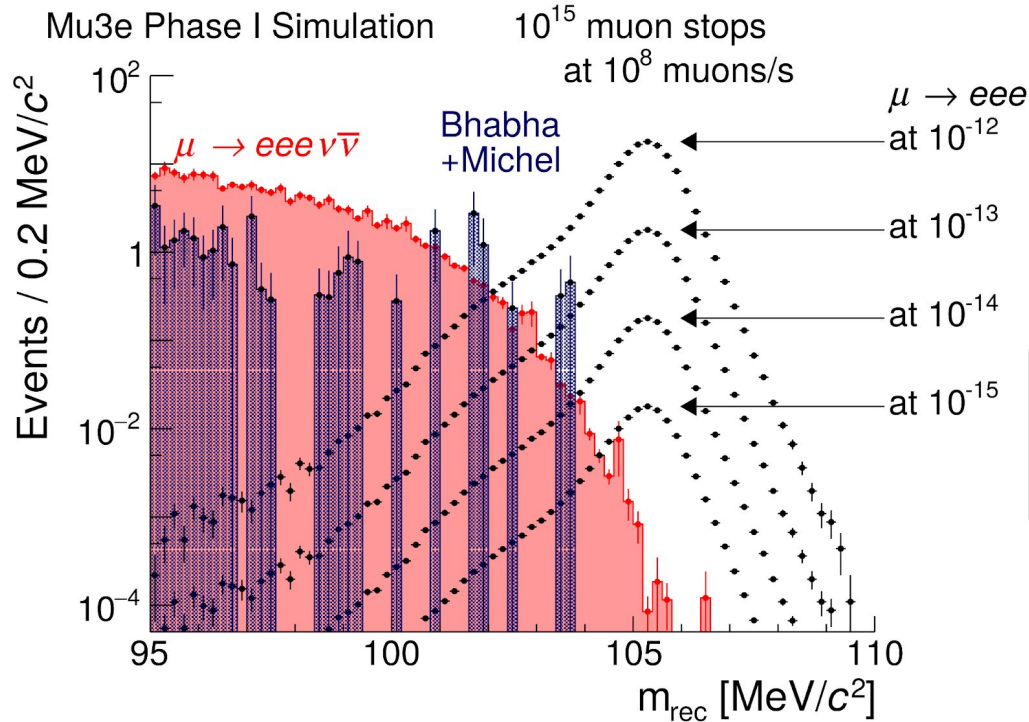
Experimental concept



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



Experimental sensitivity



Invariant mass of signal decay, radiative decay and accidental background (Bhabha+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



Mu3e Phase I Simulation

10^{15} muon stops

Events / $0.2 \text{ MeV}/c^2$

10^2
1
 10^{-2}
 10^{-4}
9



All done by a collaboration of 12 institutes in 3 countries

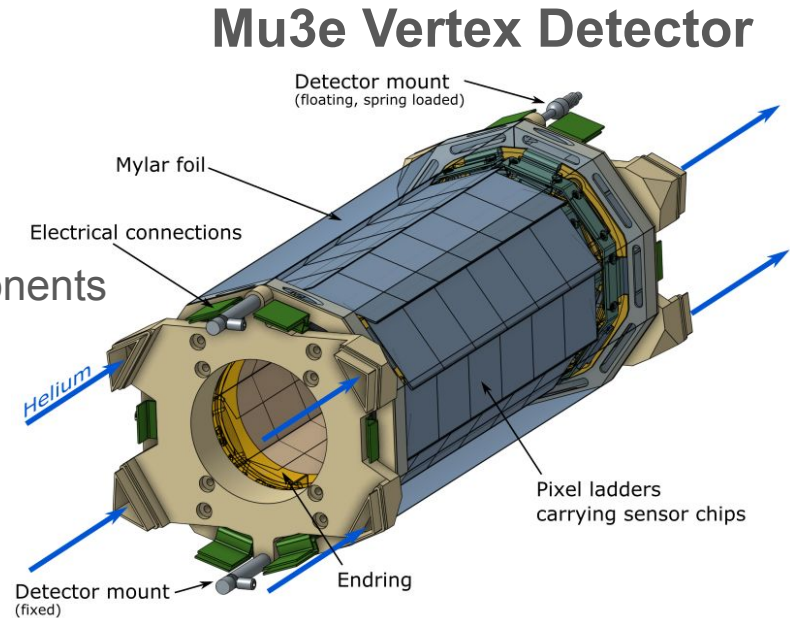
Invariant mass of signal decay, radiative decay and accidental background (Bhaba+Michel) [[Mu3e TDR](#)]

Mu3e Collaboration Meeting Wengen 2024

Construction challenges for the pixel detectors

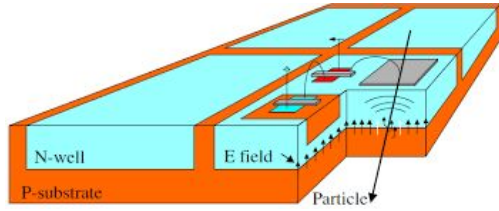


- Thin chips
 - Post-processing and qualification
 - Handling
 - QC
- Thin Aluminum-Kapton HDIs
 - Both electrical and mechanical integration
 - Reduced number of lines, no electronic components
- Compact design
 - Cabling and routing
- Helium cooling system [not in this talk]
 - $\sim 250 \text{ mW/cm}^2$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



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

Thin chips



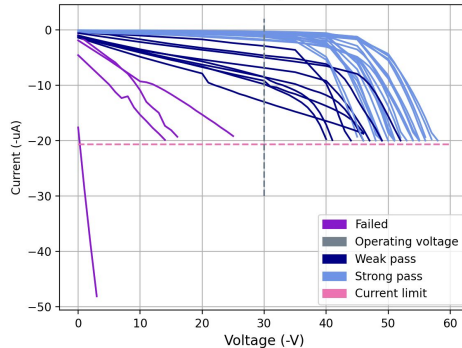
Mupix11 chips based on HV-CMOS technology
Thinned to 50 μm (Vertex)
80 Ωcm resistivity (380 Ωcm for first prototype modules)

W/O plasma etching

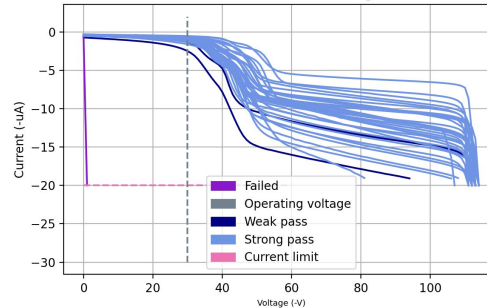
W/ plasma etching



IV curves, LV on, configured
420-1



420-3: IV curves, LV on, configured

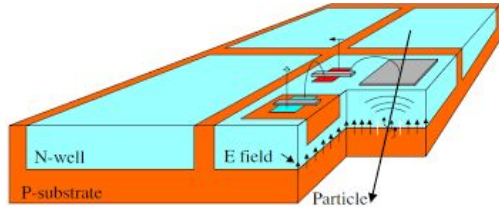


Post processing at Optim
(Marseille, France)

Small tolerance in dicing (11 μm)

Significant improvements with
plasma etching

Thin chips



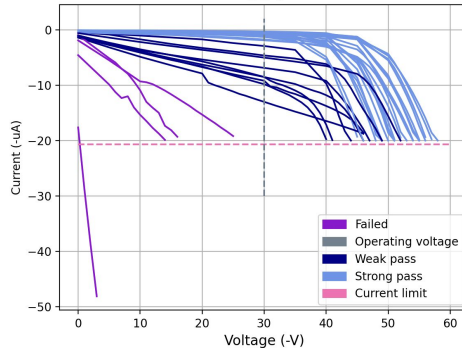
Mupix11 chips based on HV-CMOS technology
Thinned to 50 μm (Vertex)
80 Ωcm resistivity (380 Ωcm for first prototype modules)

W/O plasma etching

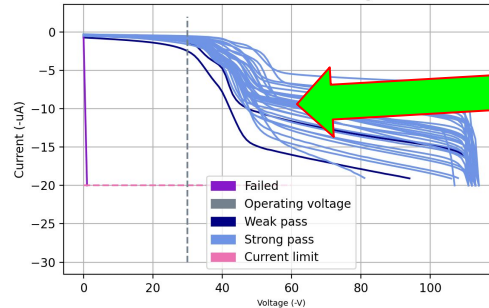
W/ plasma etching



IV curves, LV on, configured
420-1



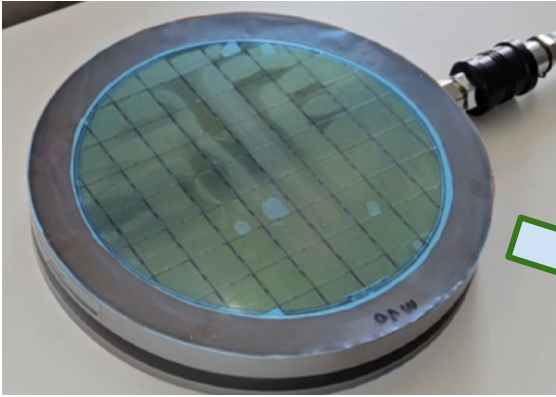
420-3: IV curves, LV on, configured



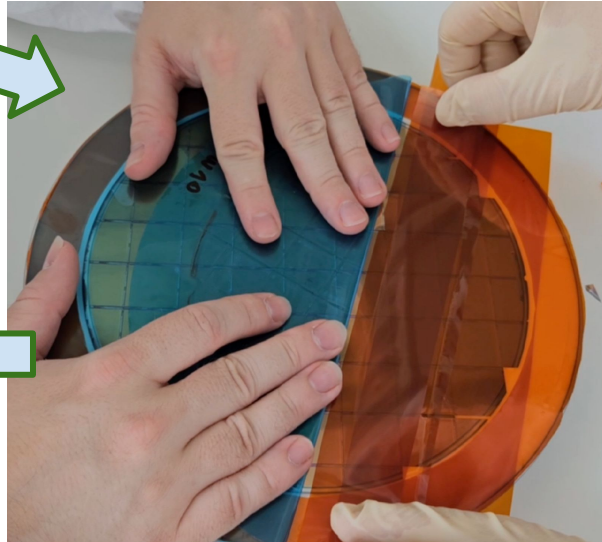
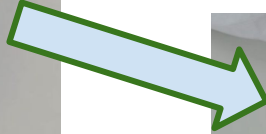
99.5 % efficiency
20 ns time resolution

After full depletion

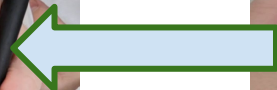
Thin chips: handling



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

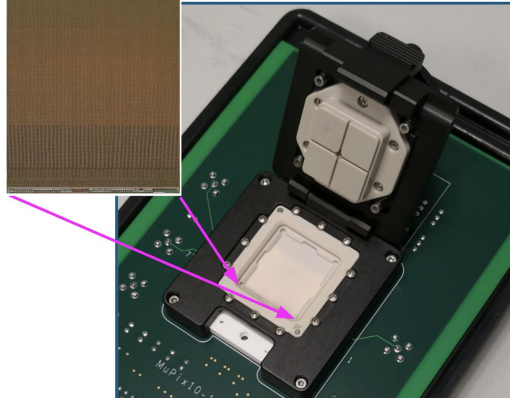


Careful peeling
while vacuum on



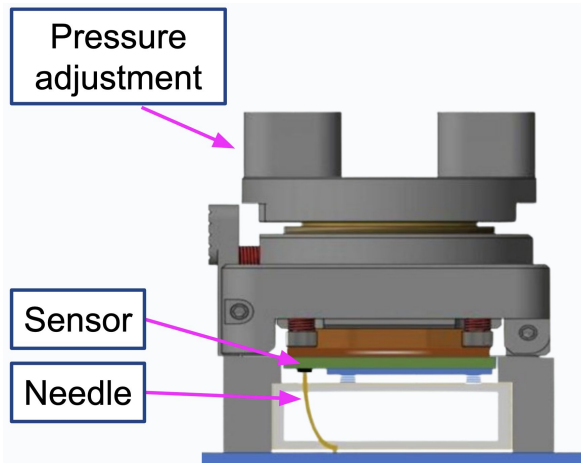
Extra care for
vacuum loss (here:
kapton foils, next:
tailor-made
aluminum chuck)

Thin chips: QC



Probe card with manual actuator developed for the task

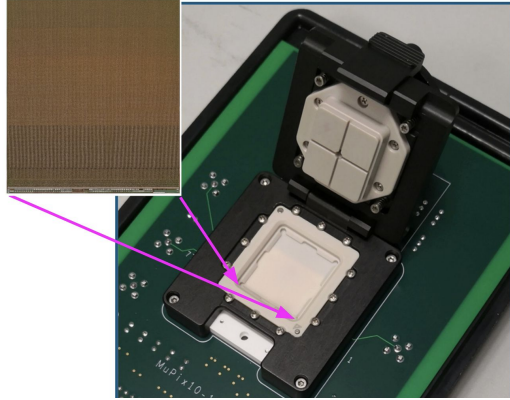
- ✓ Table-top system
- ✓ No dependency on probe stations
- ✓ Easy to transfer between institutes
- ✗ Manual procedure (training required)
- ✗ Slow throughput (2-3 minutes to replace chips)



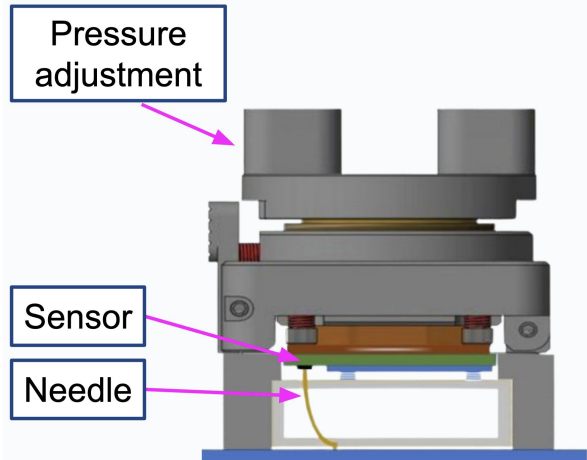
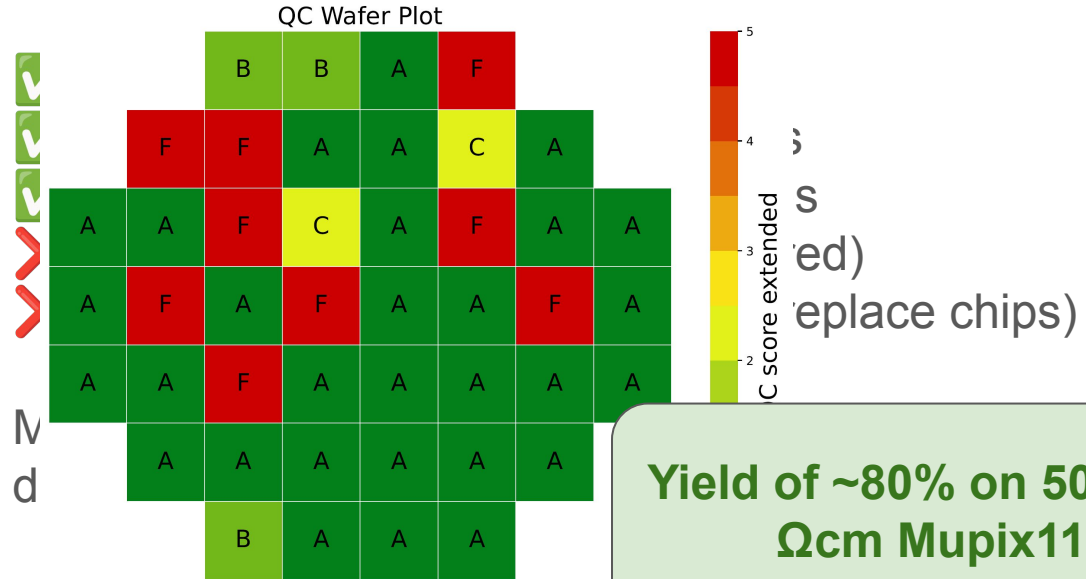
Note: Mu3e Vertex detector consists of only 108 chips and is developed between Heidelberg and PSI

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

Thin chips: QC



Probe card with manual actuator developed for the task



Yield of ~80% on 50 μ m 80 Ω cm Mupix11*

*after some optimization iteration

Thin HDIs



Katpon-Aluminum flexes produced by LTU (Kharkiv)

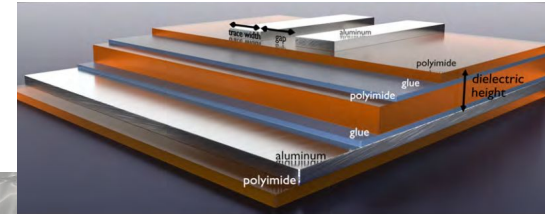
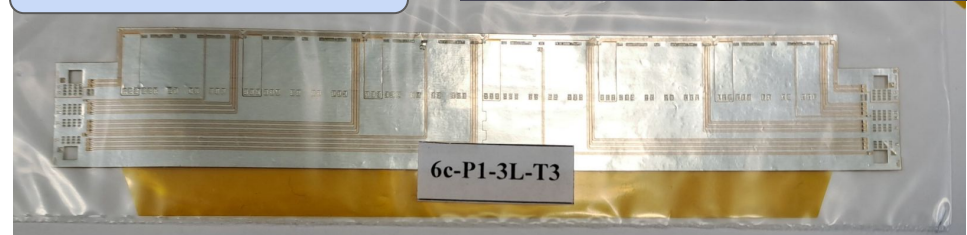
2 layers + spacer: stack and traces geometry optimized for LVDS transmission

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

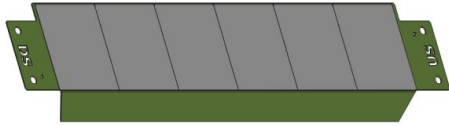
HDI + 6 chips + connecting flex = “Ladder” (see poster by T. Senger, with QC)

Long design and qualification stage needed.

6-chip “ladder”

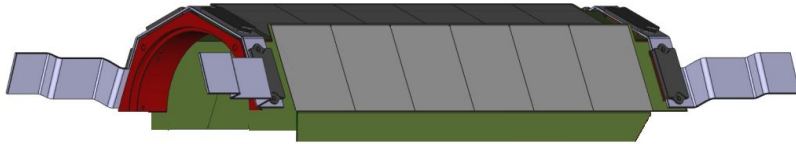


Modules



Ladder

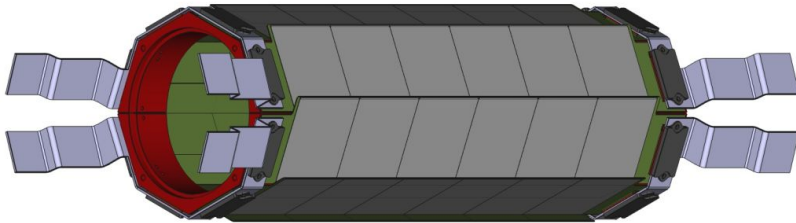
Design aims to be as modular as possible



Module

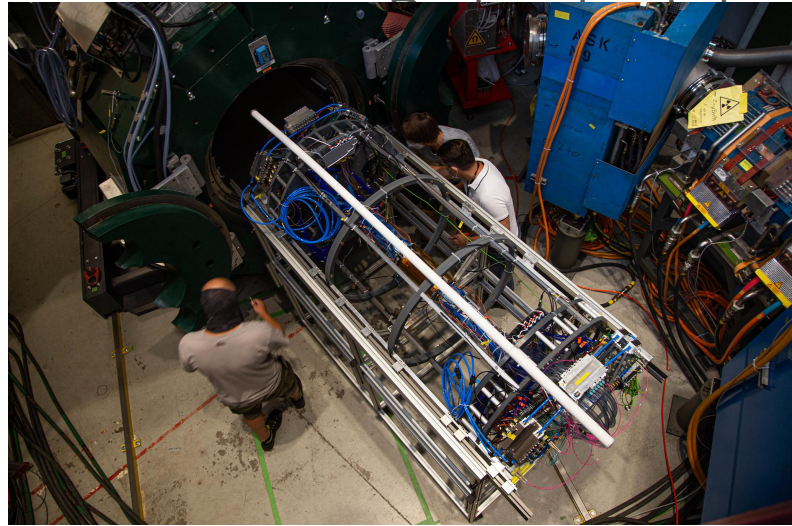
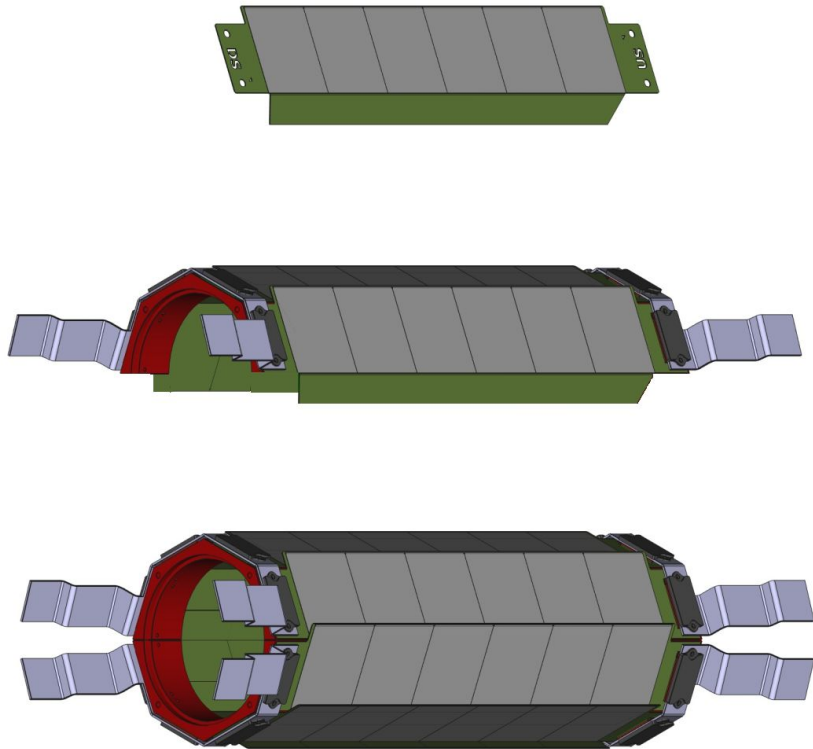
The module is the basic mechanical and electrical unit.

A module can be replaced without replacing anything else



Layer

Modules



as
e
basic
electrical
replaced
anything

Layer

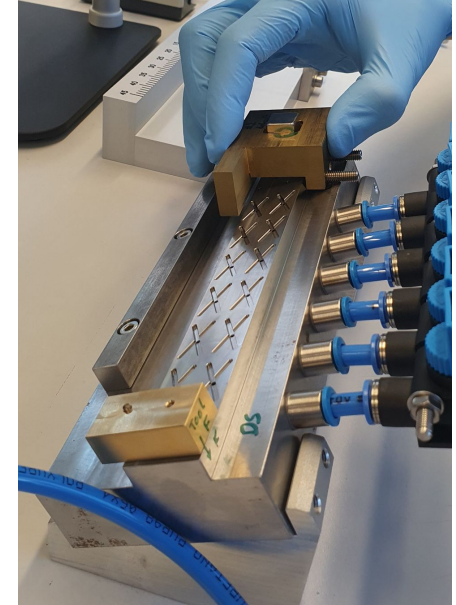
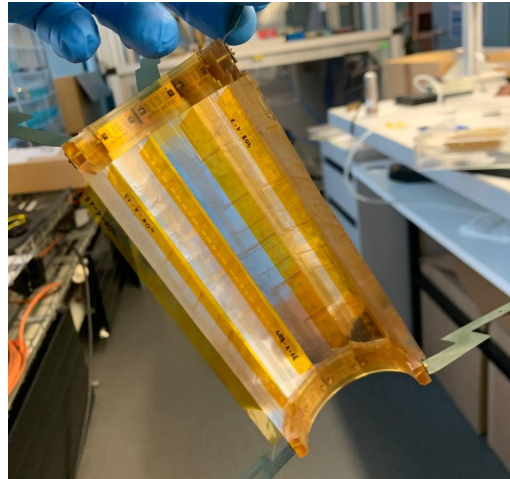
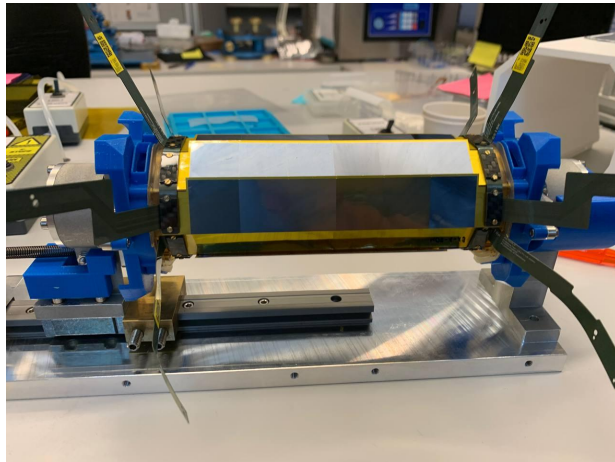
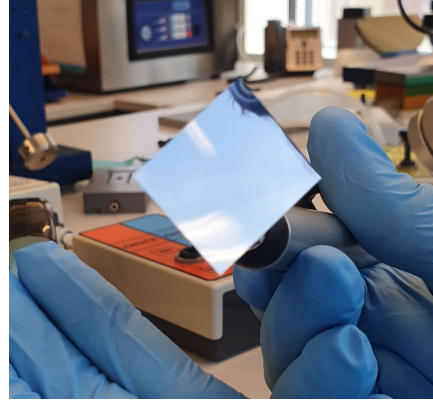
Note: Mu3e sits at ground level, relatively easy to access

Thin HDIs: mounting



Manual procedures:

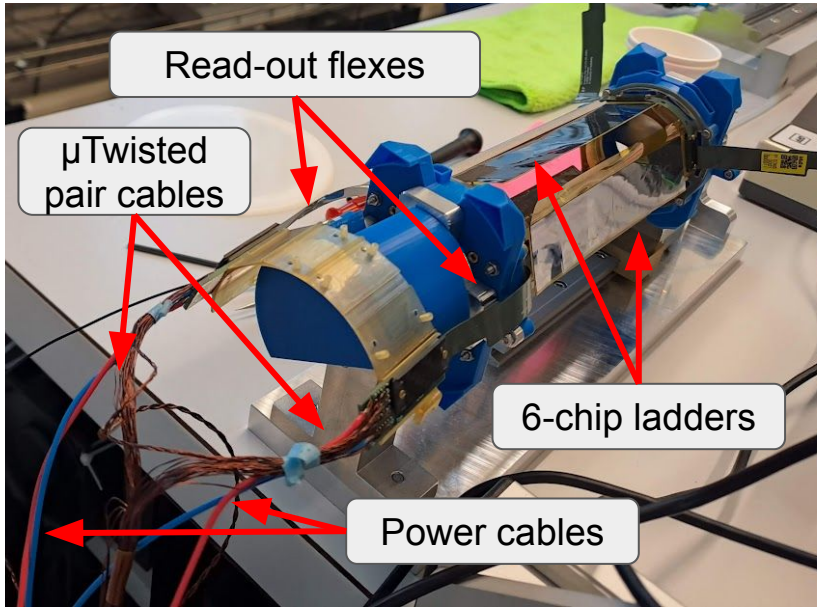
- Aligning chips
- Glueing
- HDI overlay
- TA-Bonding
- Module assembly



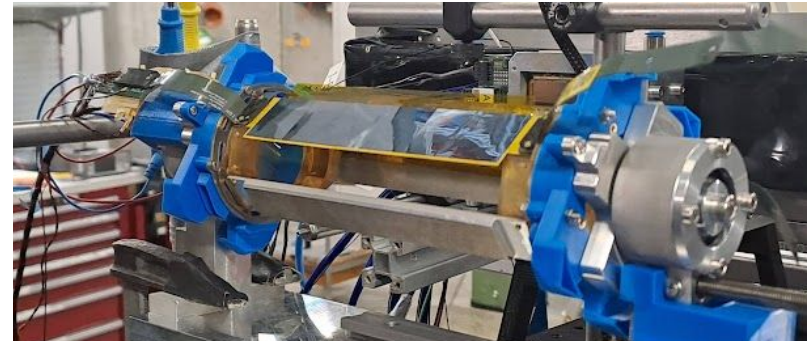
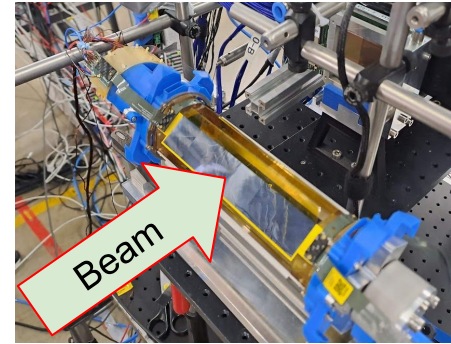
Thin HDI qualification



In the lab



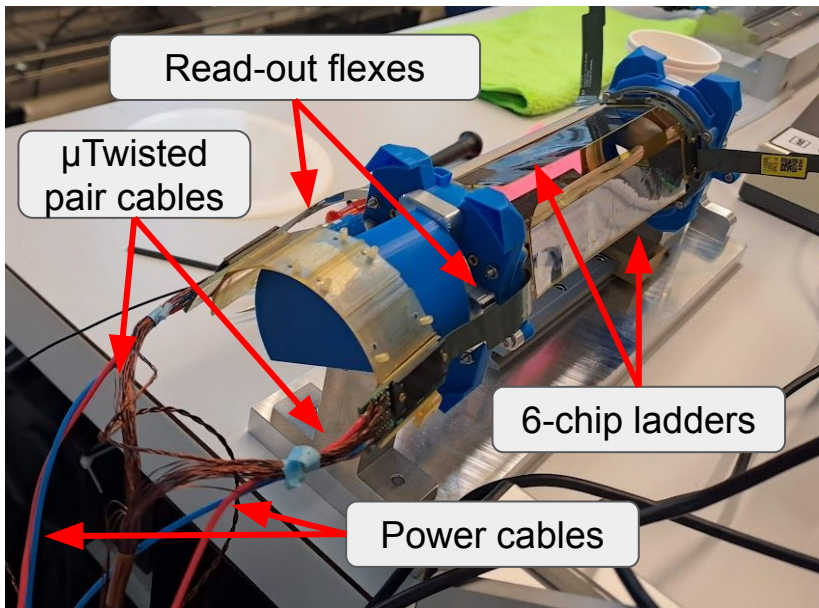
In the testbeam area



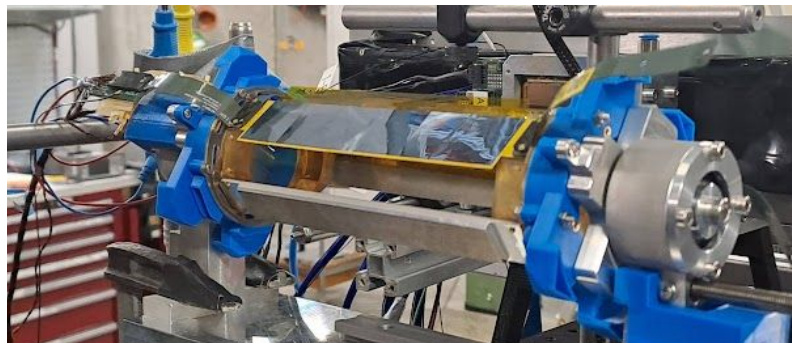
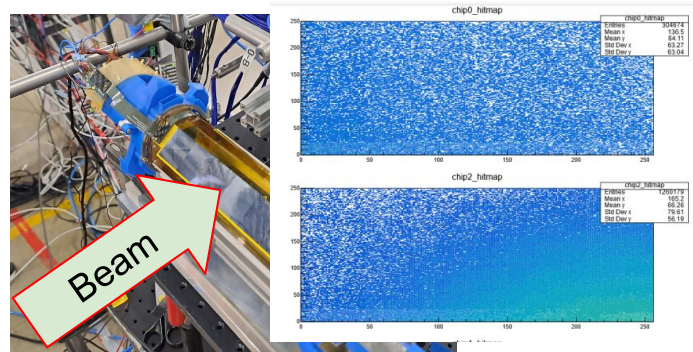
Thin HDI qualification



In the lab



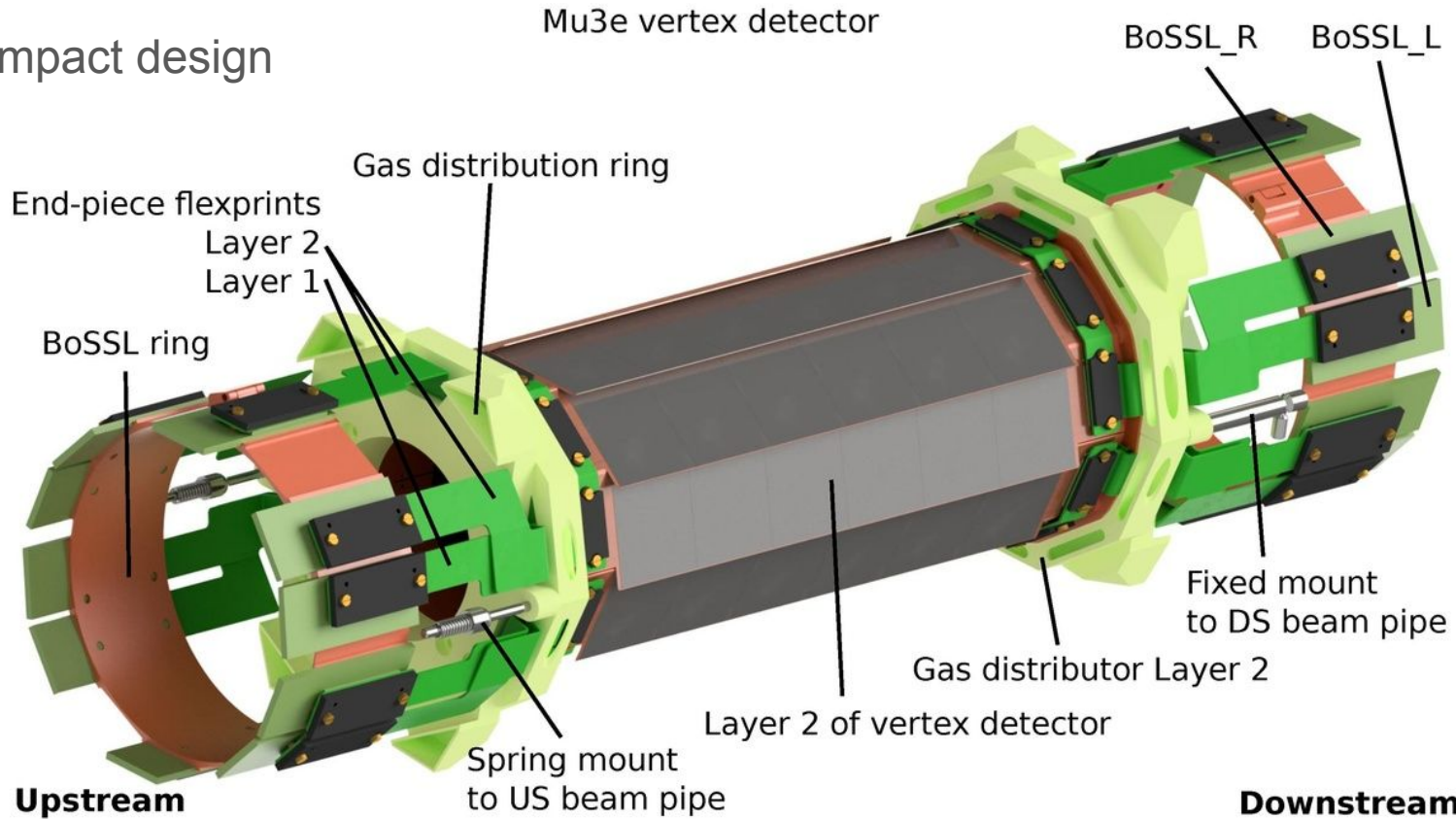
In the testbeam area



Design challenges



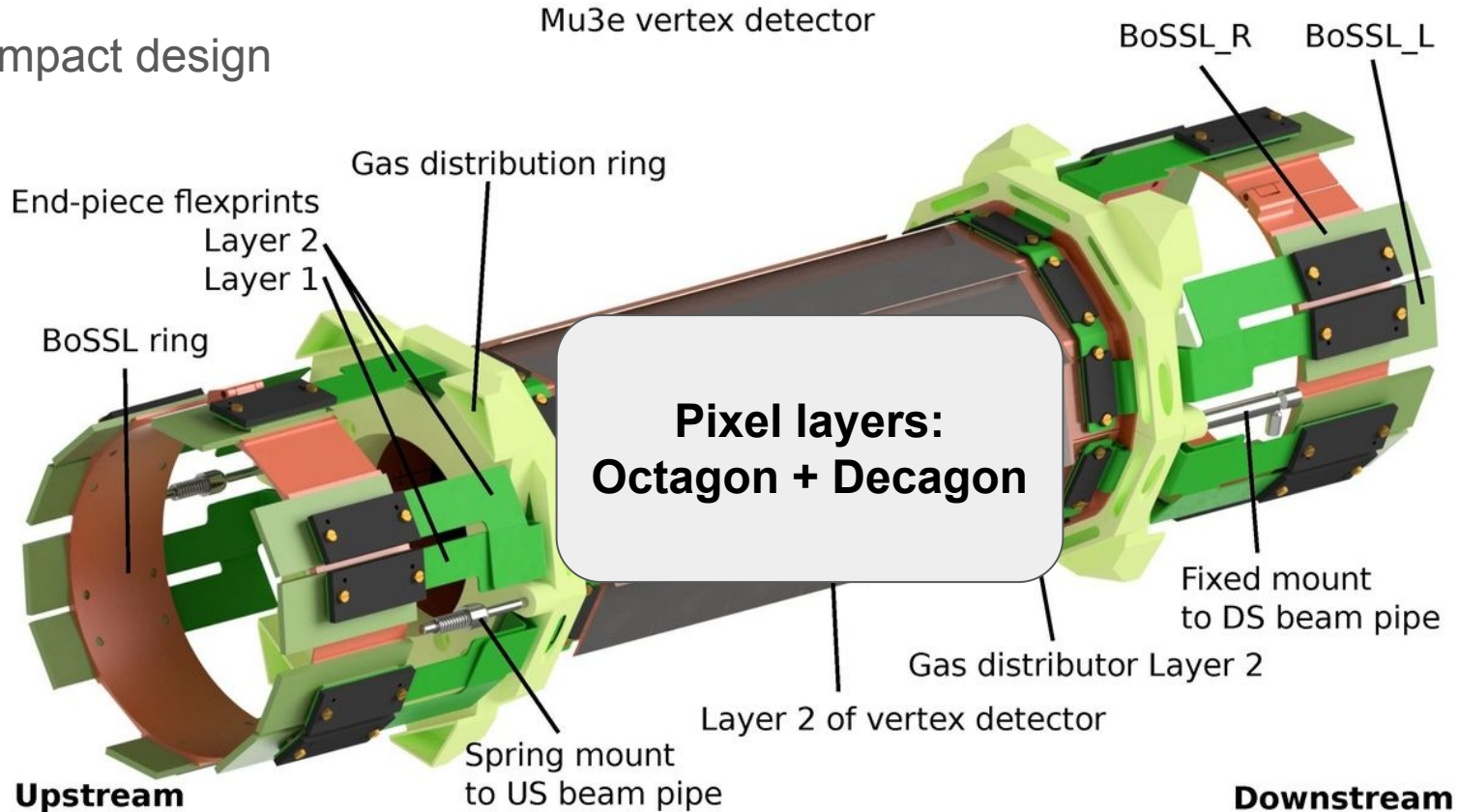
Very compact design



Design challenges



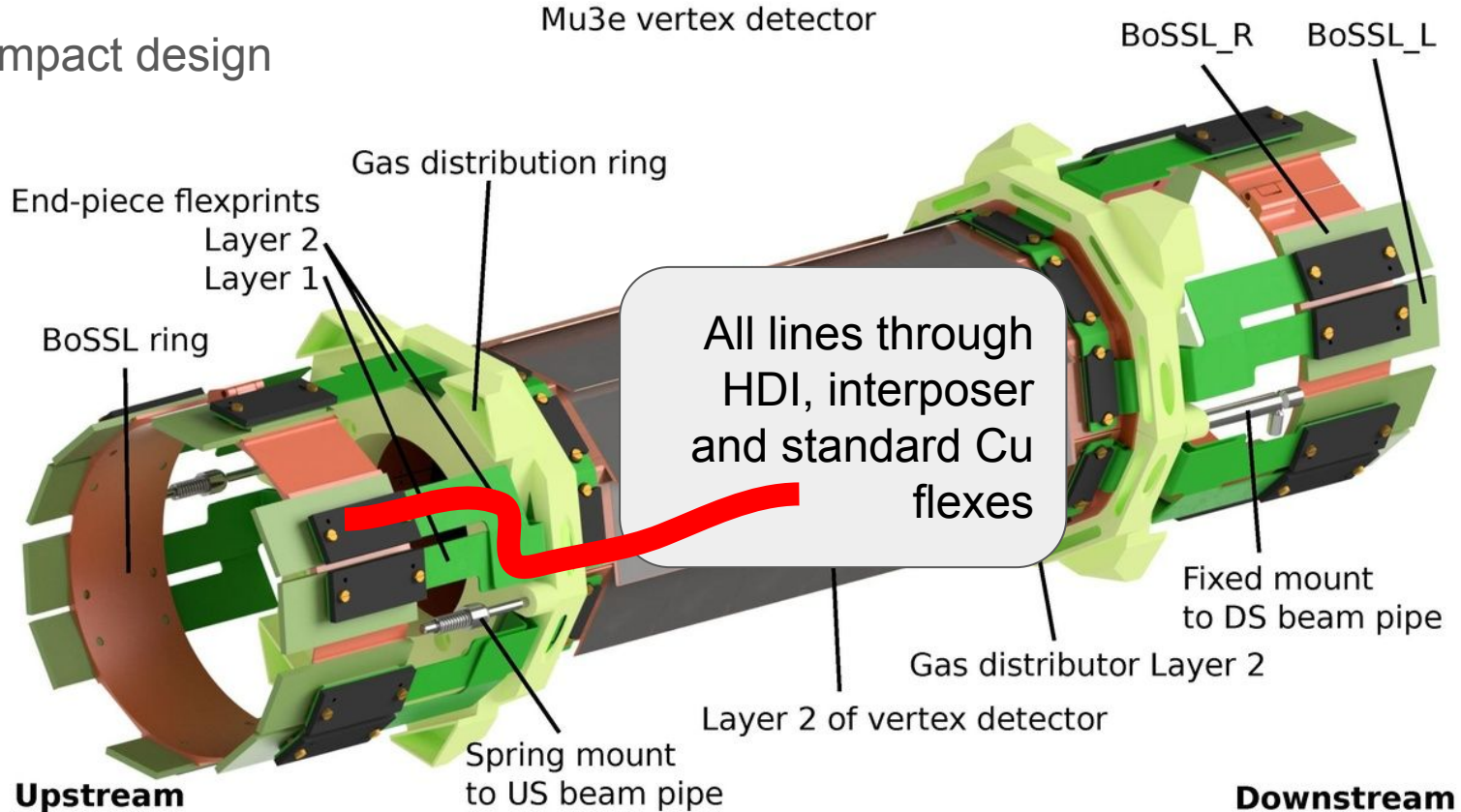
Very compact design



Design challenges



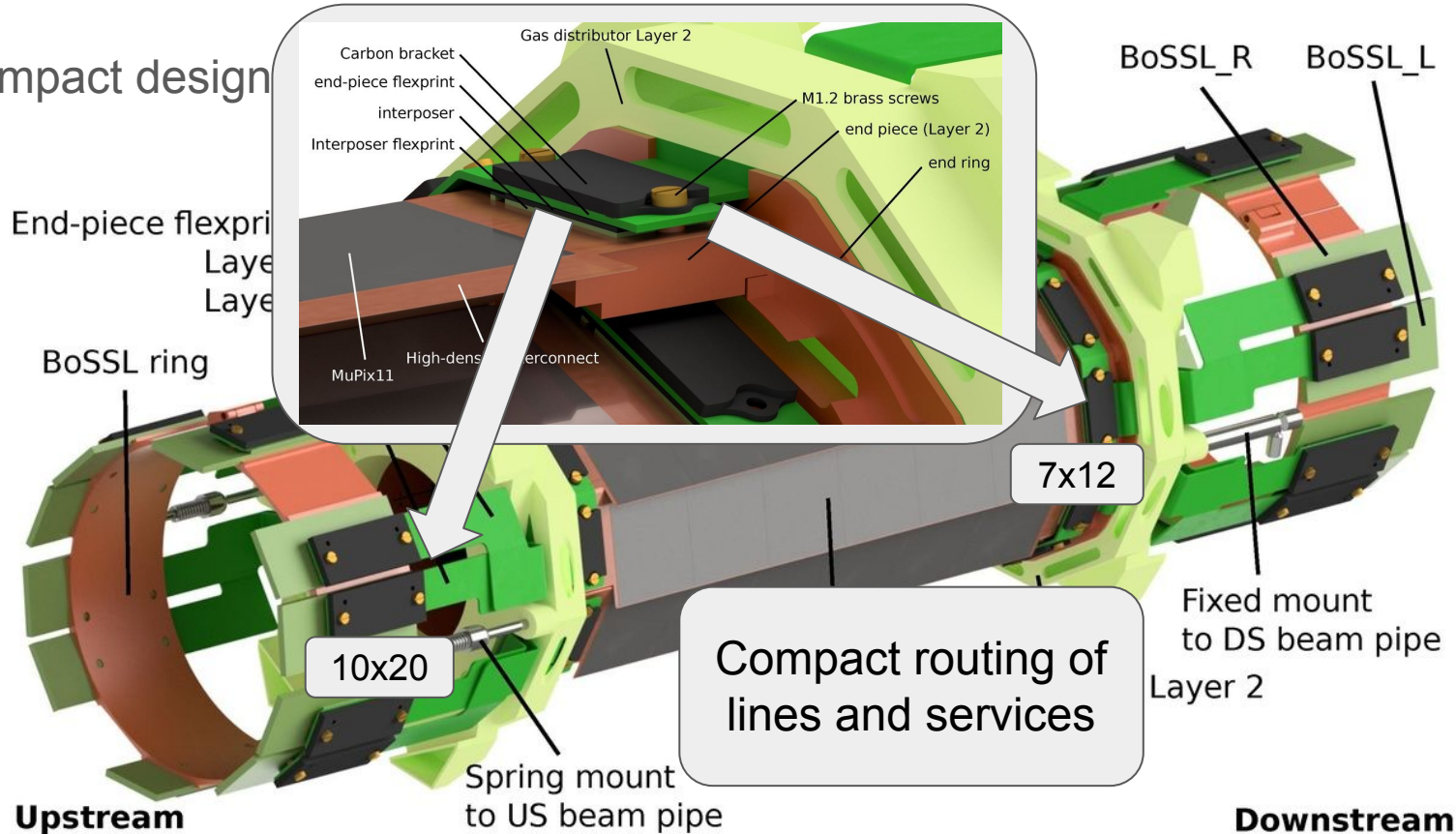
Very compact design



Design challenges



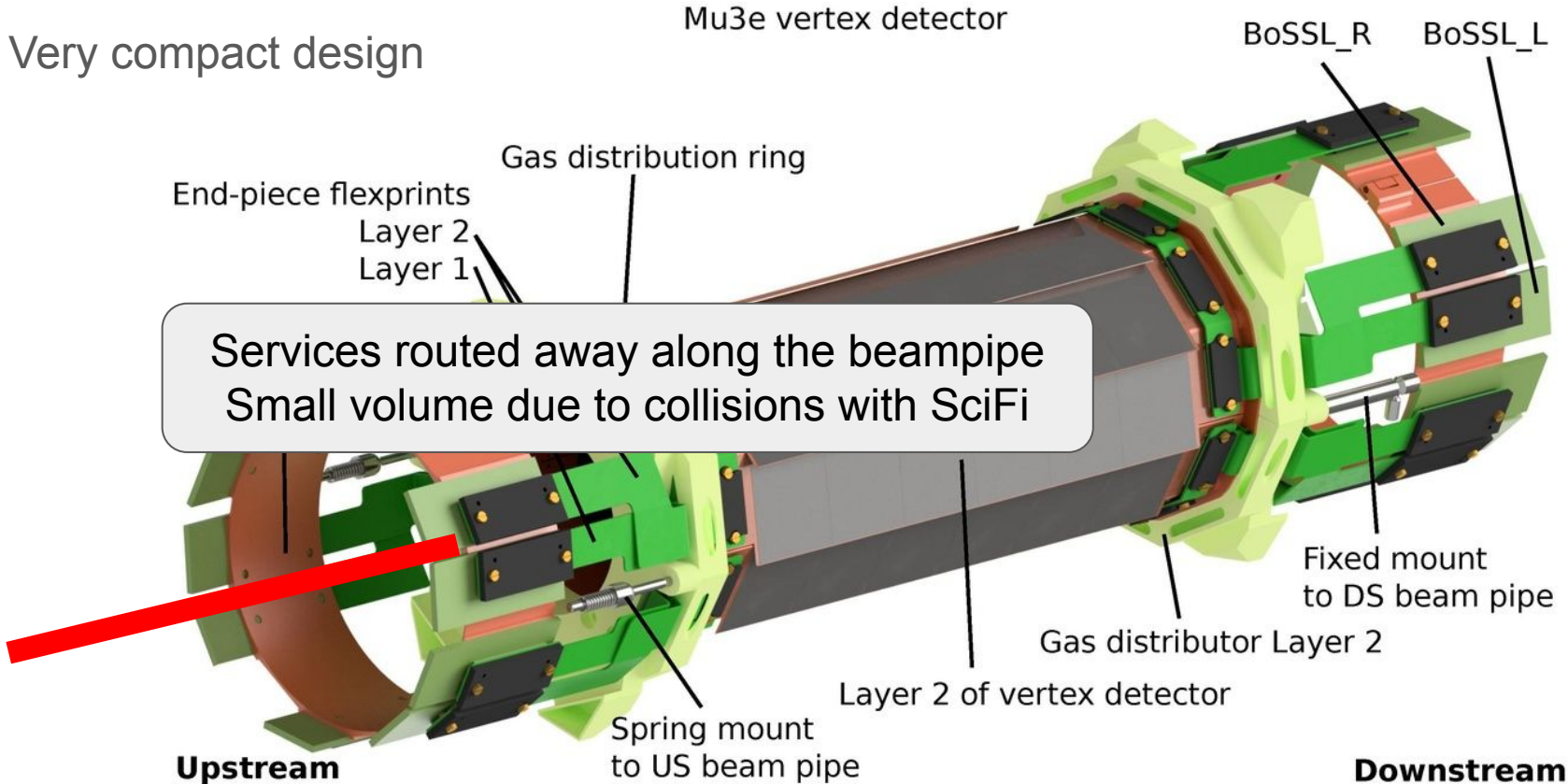
Very compact design



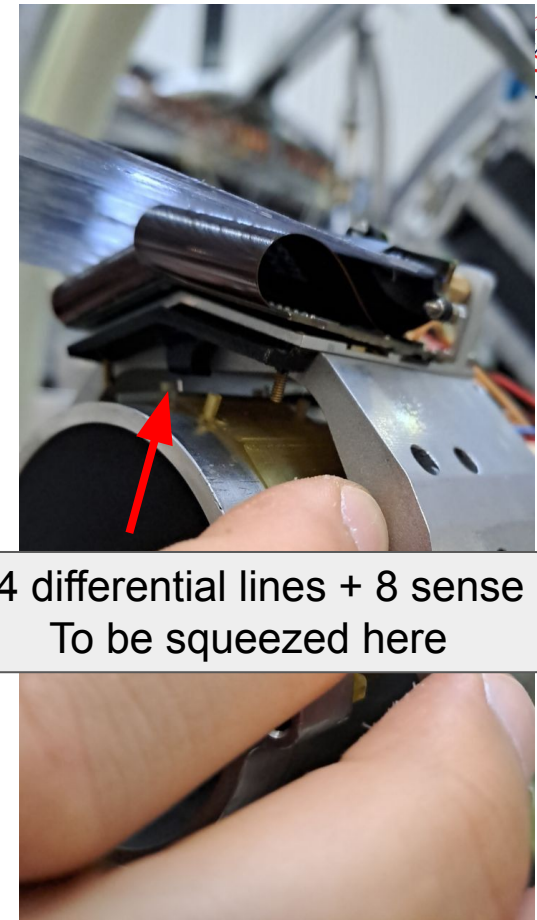
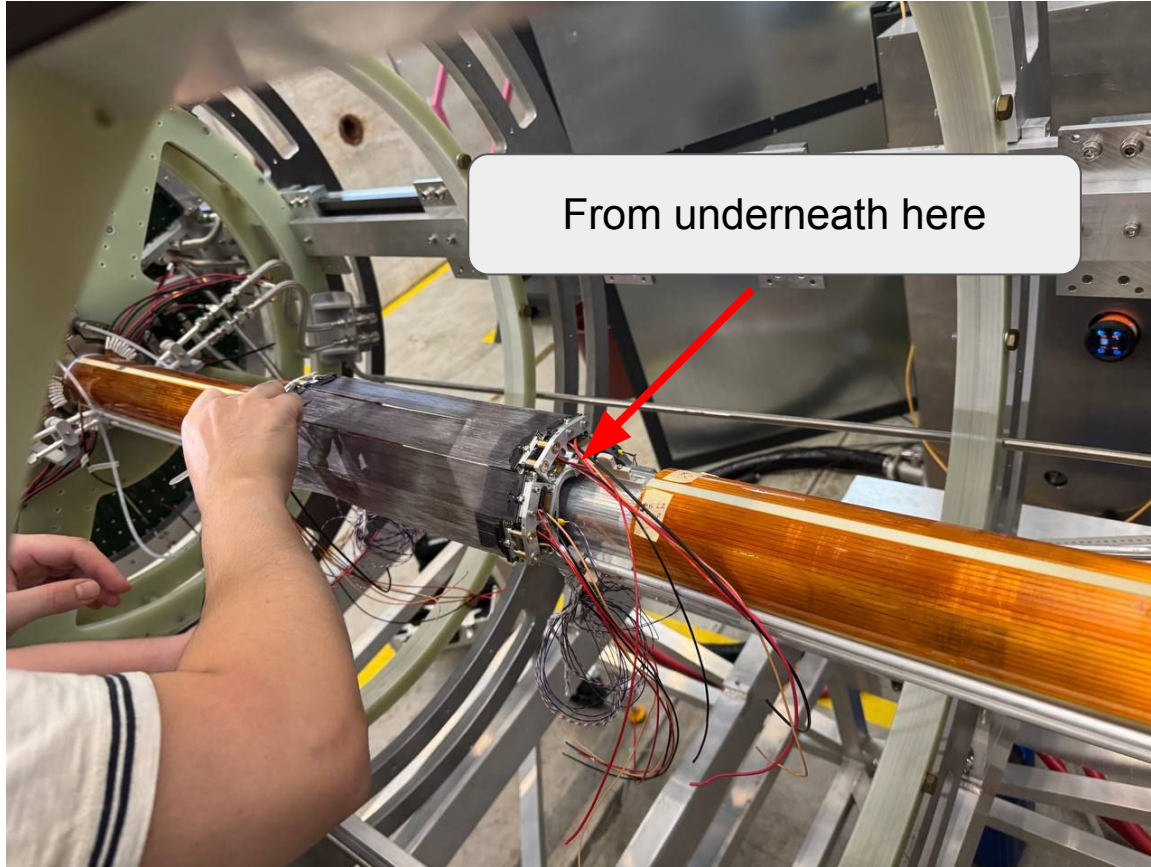
Design challenges



Very compact design



Design challenges

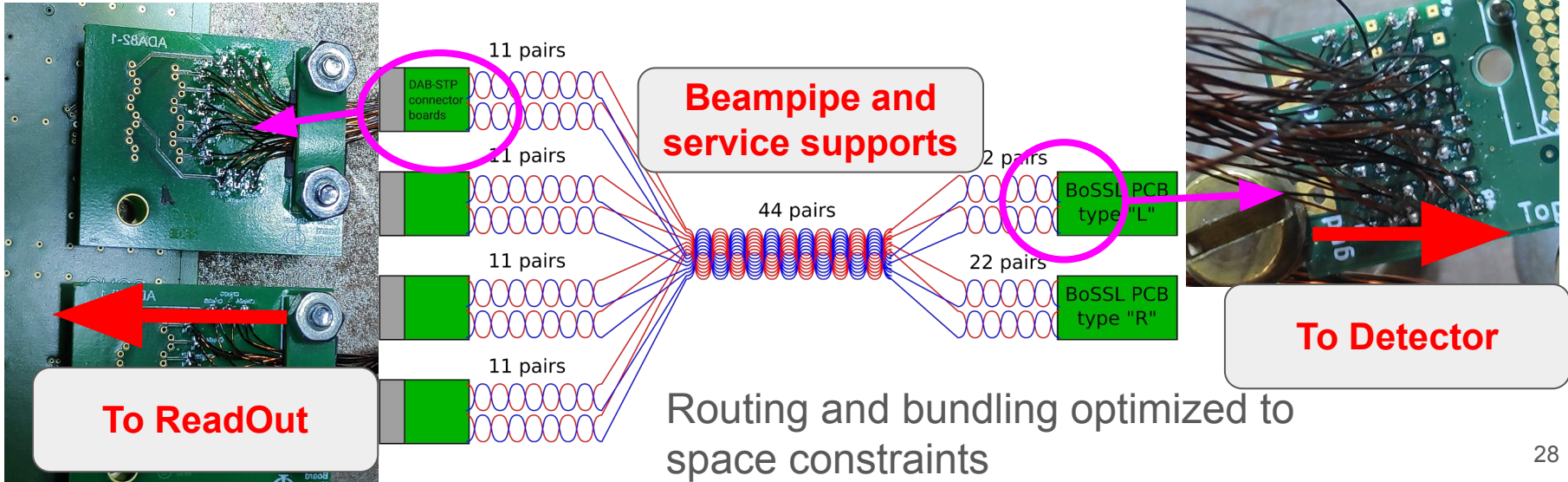


Design challenges



Solution:

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



Vertex Status

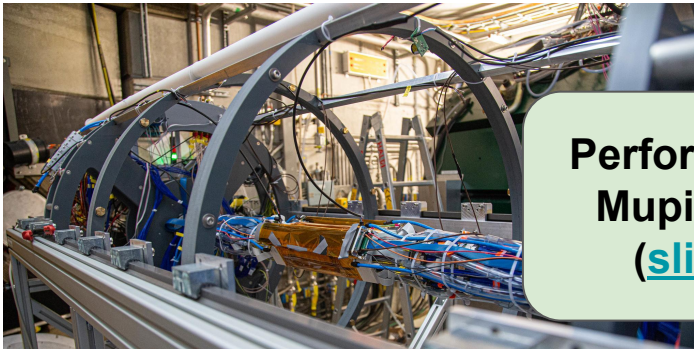


- Production almost finished
 - All chips qualified
 - All ladders produced → to be qualified
 - Module+layer assembly to follow
- Services currently mounted on cage
 - Cables + infrastructure + DAQ + cooling pipes + ...
- Vertex to be mounted by beginning of next year

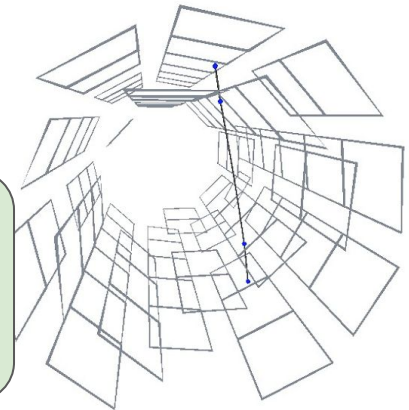
Vertex Status



- 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
- Qualification with cosmic run to follow



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





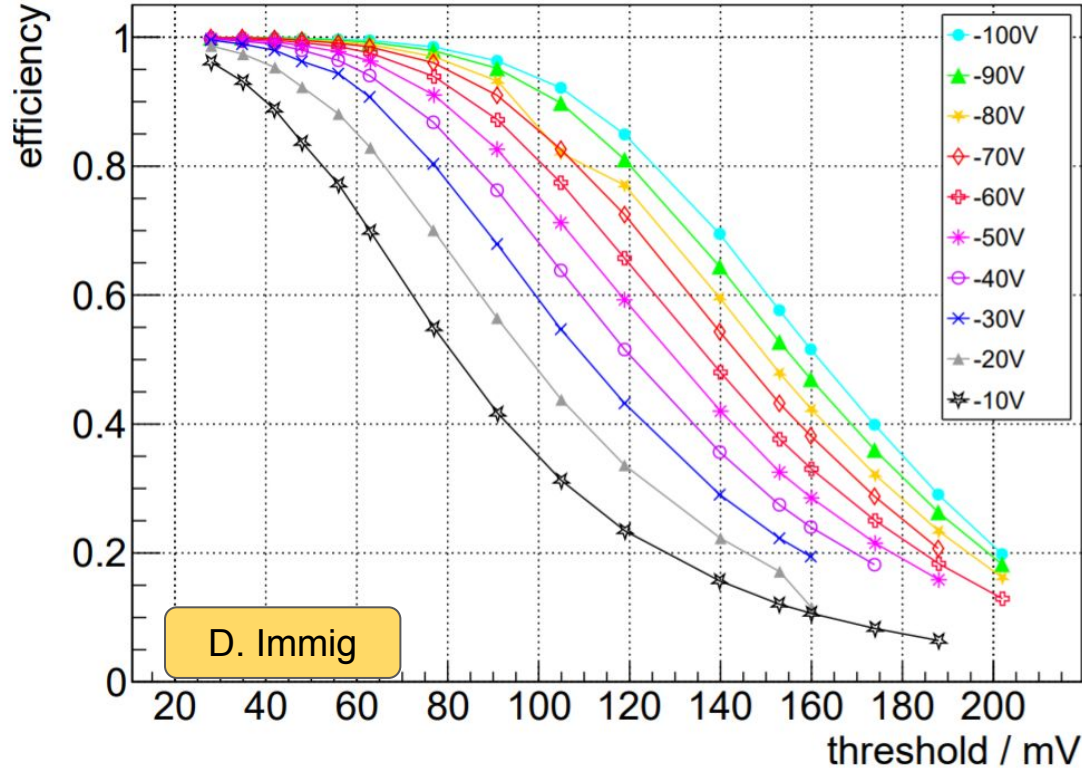
Backup

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
<hr/>	
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

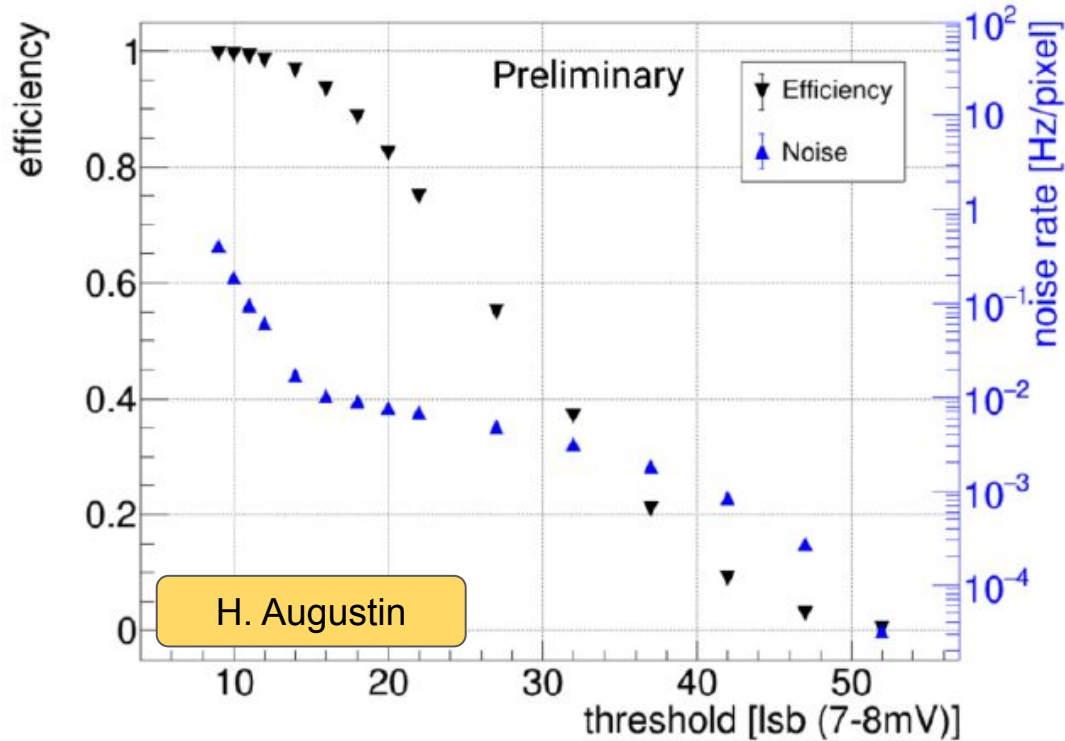


100 μm thickness

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



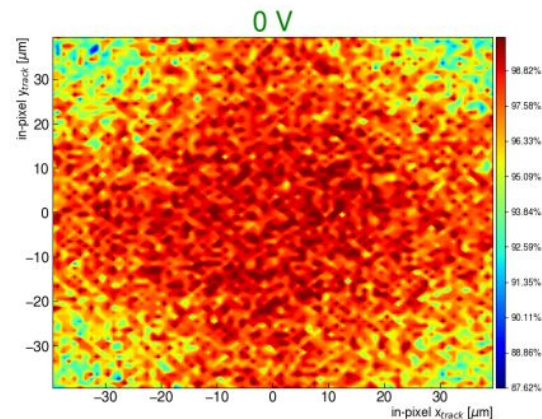
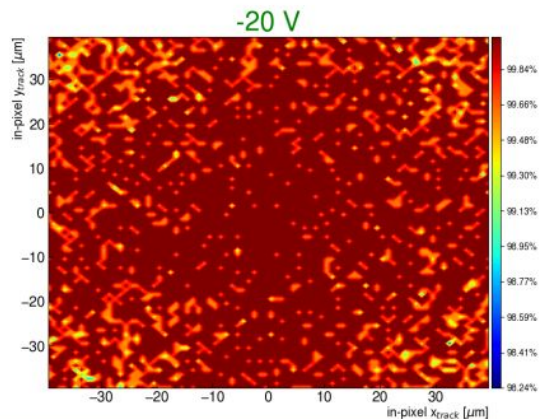
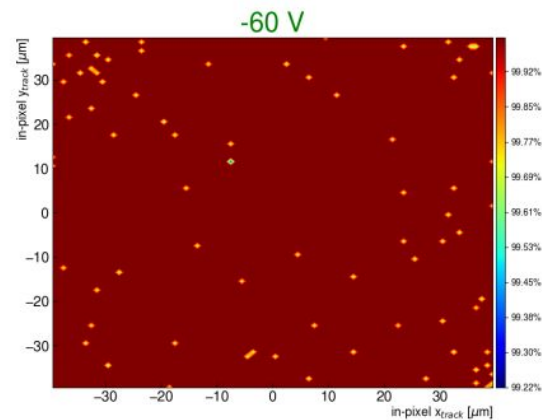
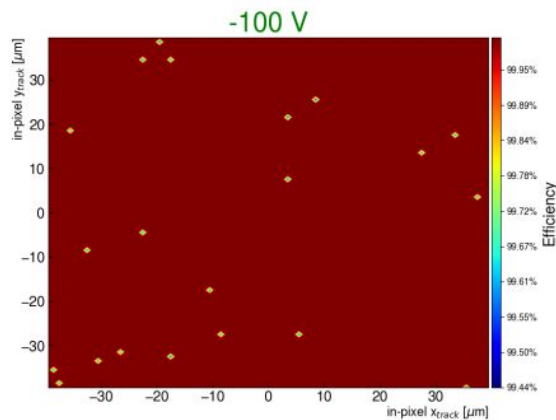
Mupix10 detailed studies



In-pixel efficiency

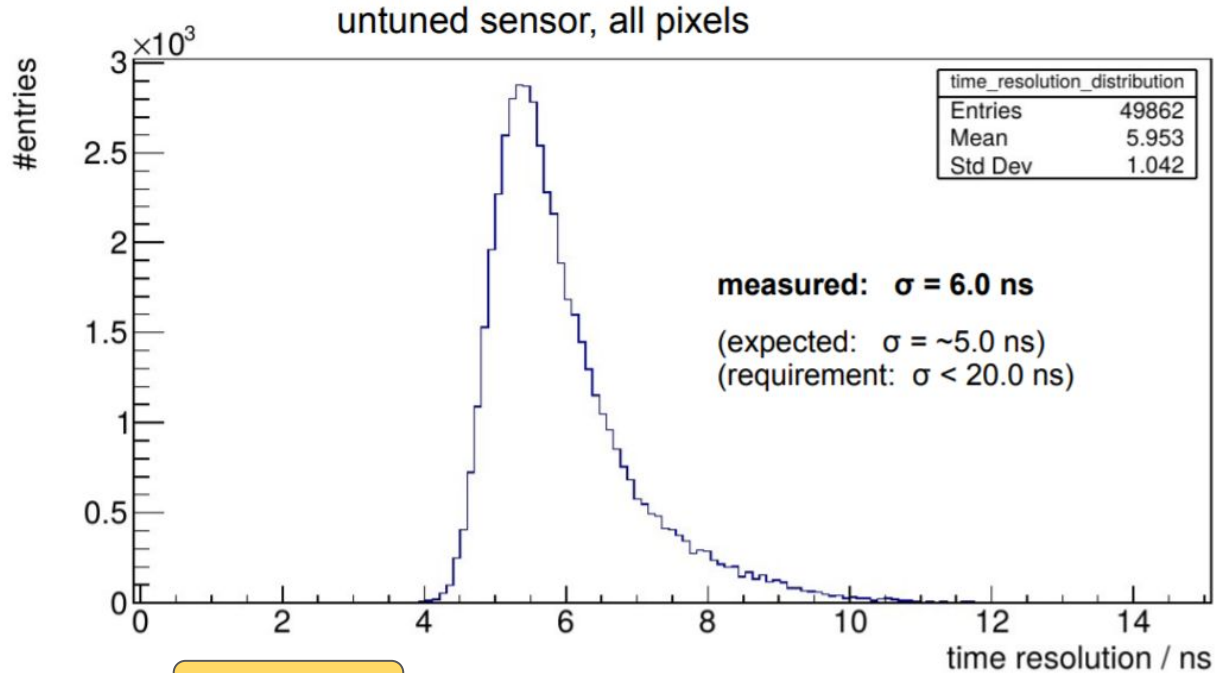
100 μm thick

43 mV threshold



A.M. Gonzales

MuPix10: results



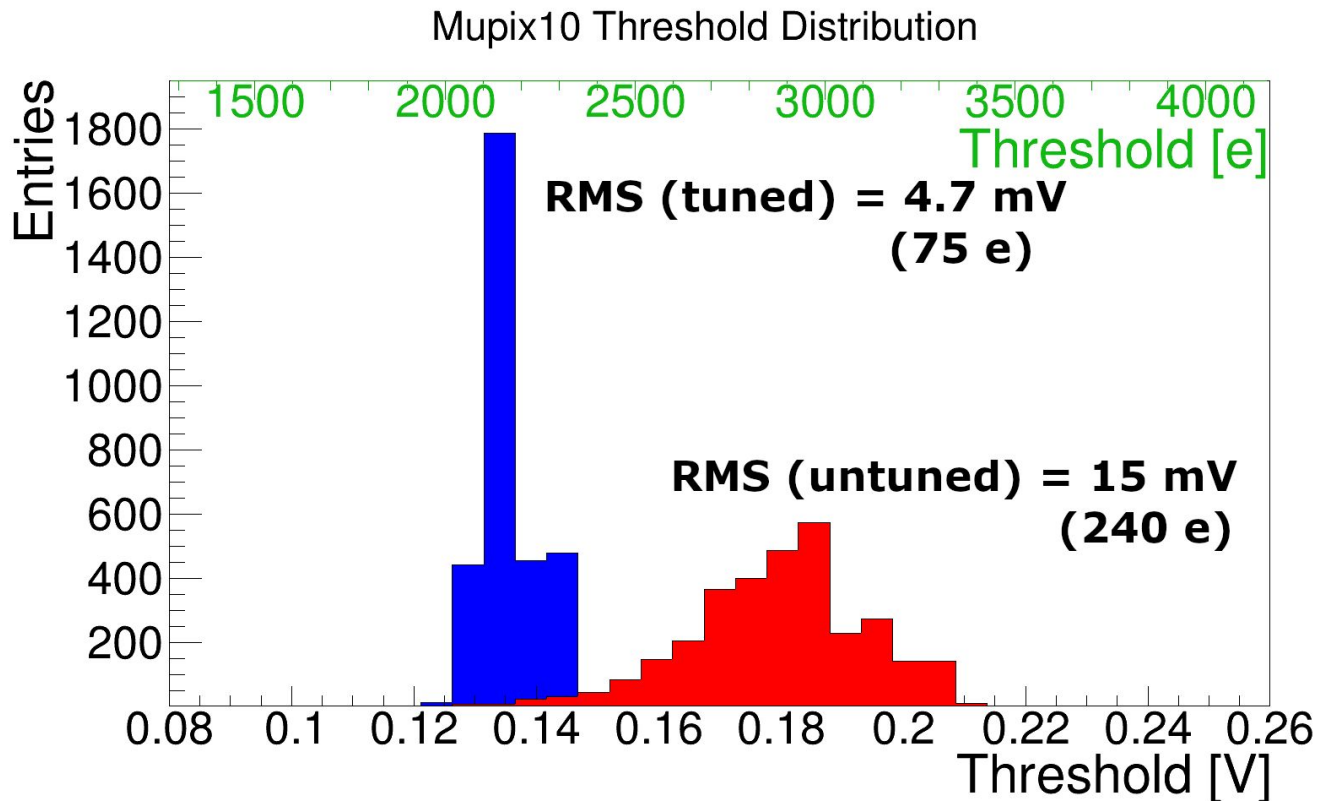
F. Frauen

Time resolution well within specifications

~ 15 ns without corrections

6 ns after row and time-walk corrections

MuPix10: results



Tunable threshold
for each pixel

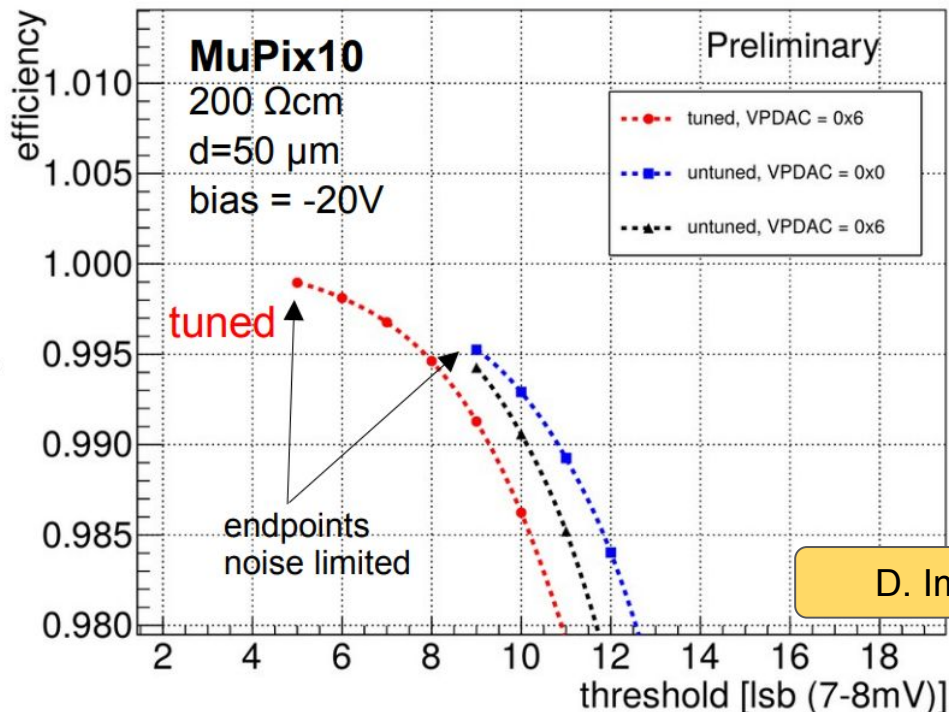
Tuning with
threshold scans:

Low threshold
dispersion

MuPix10: results



DESY testbeam Dec. 2021

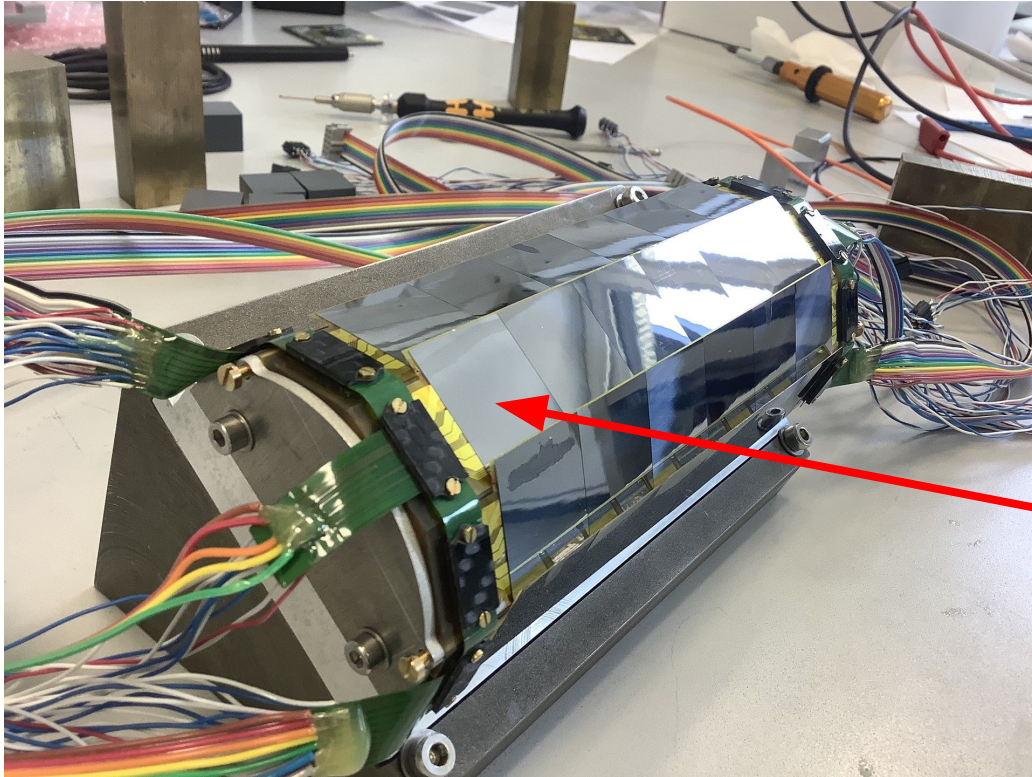


Tuning by lowering threshold while keeping noise constant: maximize efficiency!

Backup: Prototyping



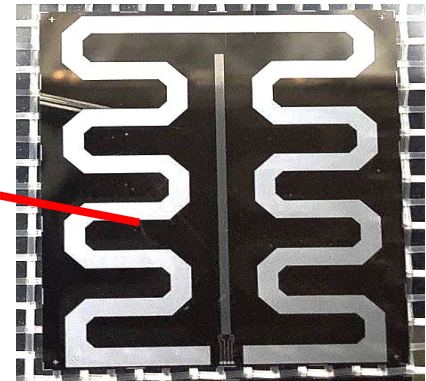
Thermo-mechanical stability



Silicon heater prototype

Reproduction of inner tracker with same materials and connections

Chips are just passive silicon heaters



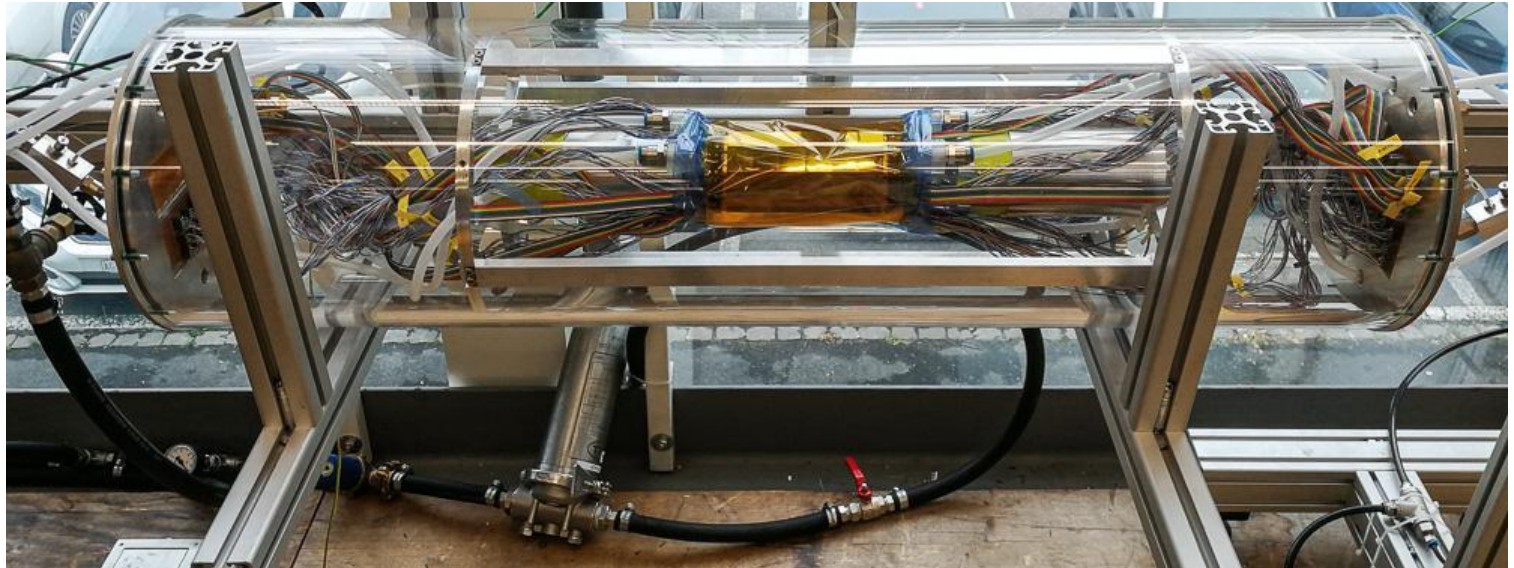
Backup: Prototyping



Thermo-mechanical stability

Silicon heater prototype


Test stand
with Helium
cooling
system



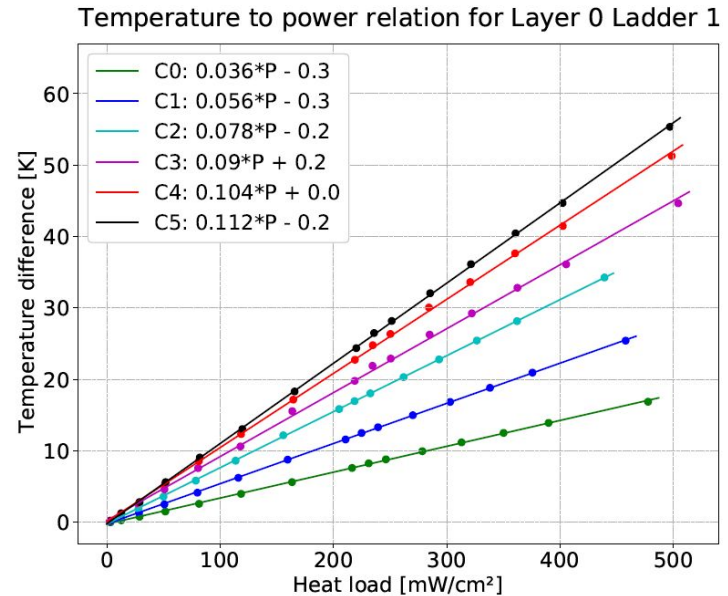
Backup: Prototyping



Thermo-mechanical stability

- Measurement of temperature-to-power relation
- Temperature difference linearly depending on heat dissipation
- Expected $\Delta T < 70$ K for 350 mW/cm^2 (conservative limit)
- Cooling concept works 
- More detailed studies to come

Silicon heater prototype

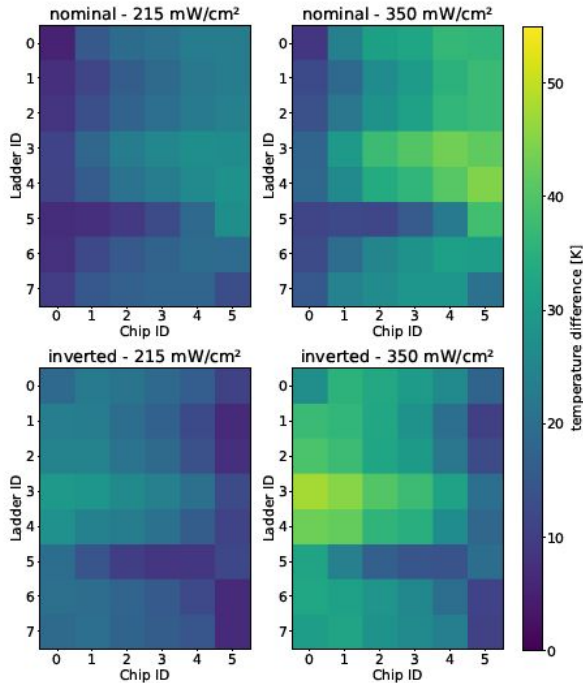


Backup: Prototyping



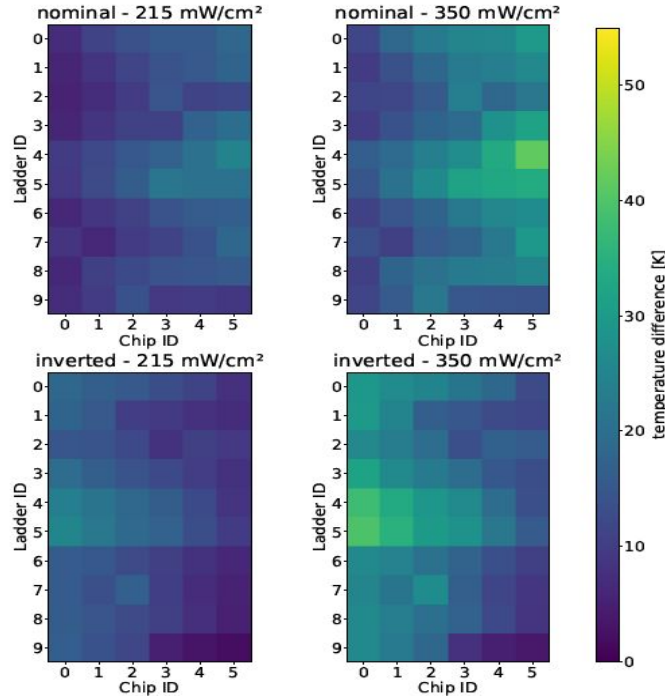
Thermo-mechanical stability

Comparison of nominal and inverted flow for Layer 0

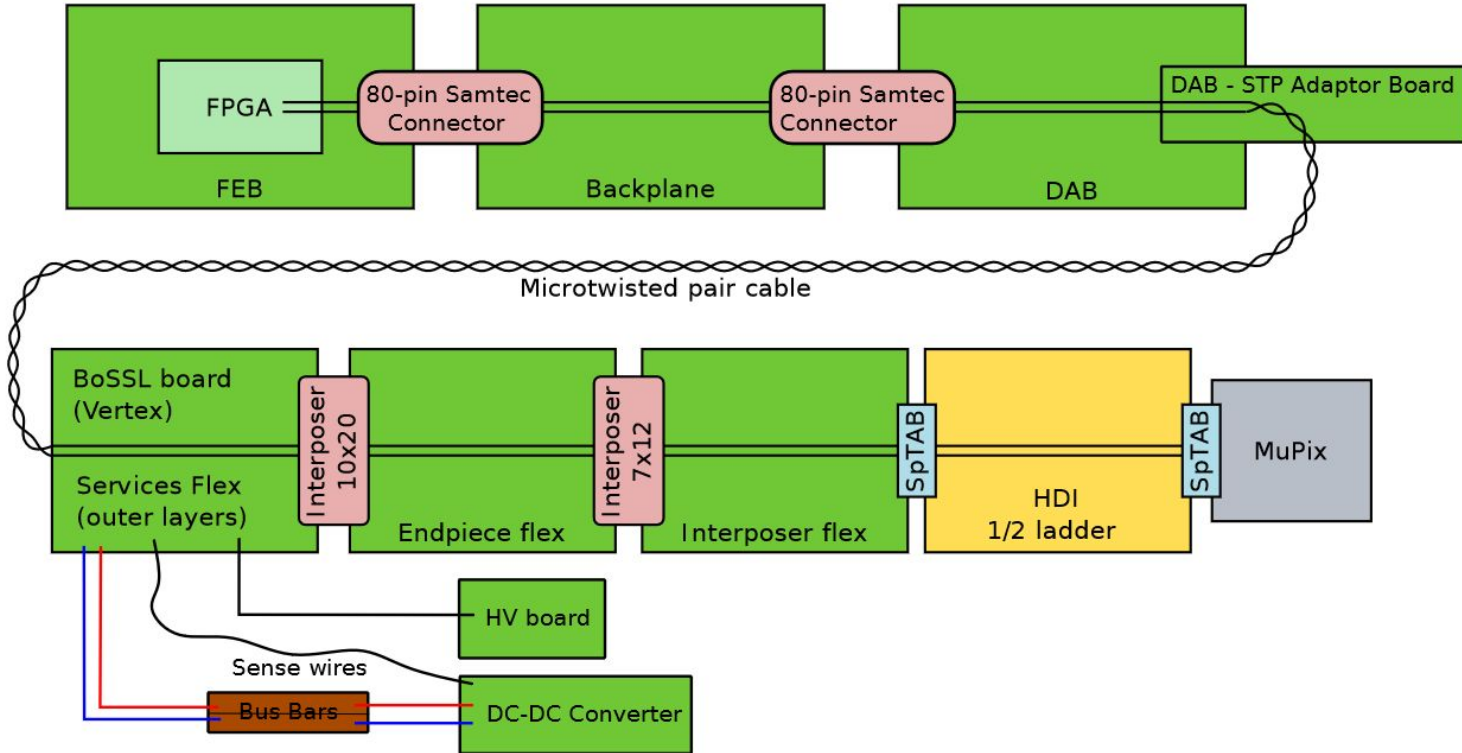


Silicon heater prototype

Comparison of nominal and inverted flow for Layer 1



Vertical slice breakdown

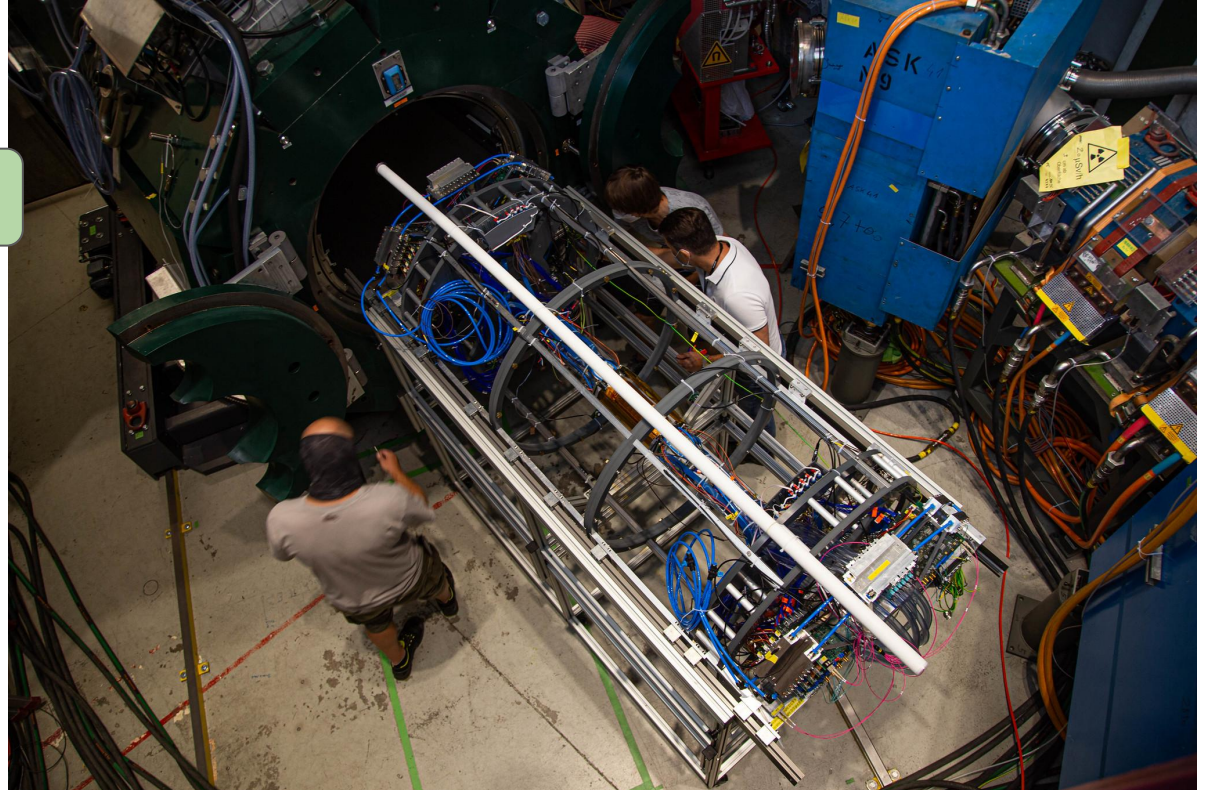


Operation in experimental conditions



DAQ and experimental concept

Inside Magnet

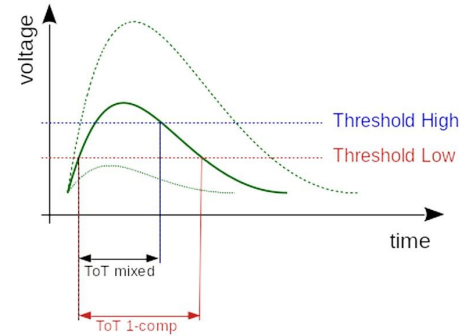
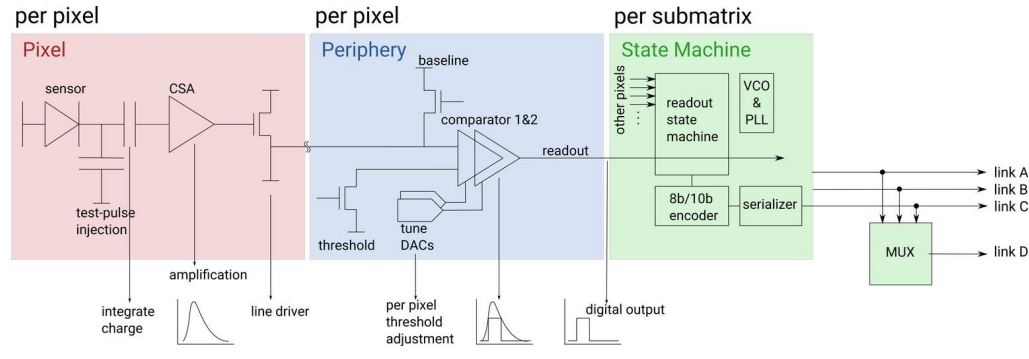


More pics at

<https://www.flickr.com/photos/nberger/albums/72157719305216074/page1/>

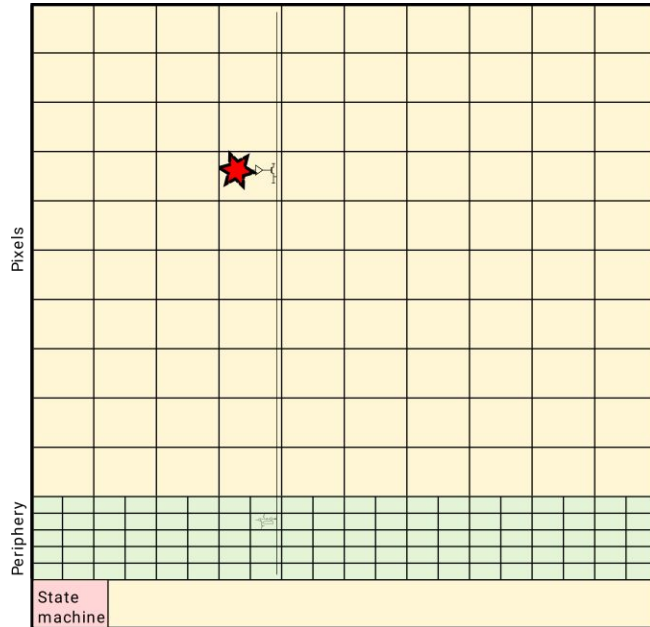


MuPix Architecture



- 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

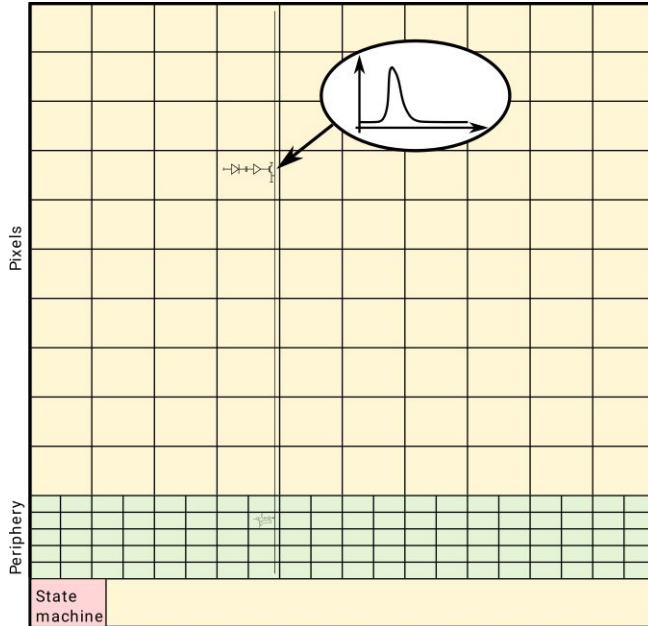
The MuPix Principle



Courtesy: Frank Meier

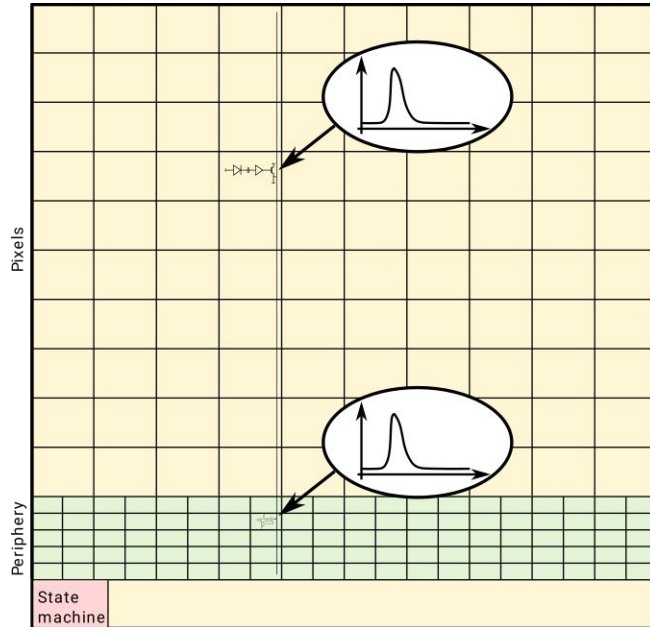
- Deposited charge amplified by in-pixel amplifier
- Source follower drives the signal to the periphery
- Digitisation in periphery
- Timestamp sampling
- Readout statemachine manages column-drain readout
- Data is send out via a 1.25 Gbit/s differential link

The MuPix Principle



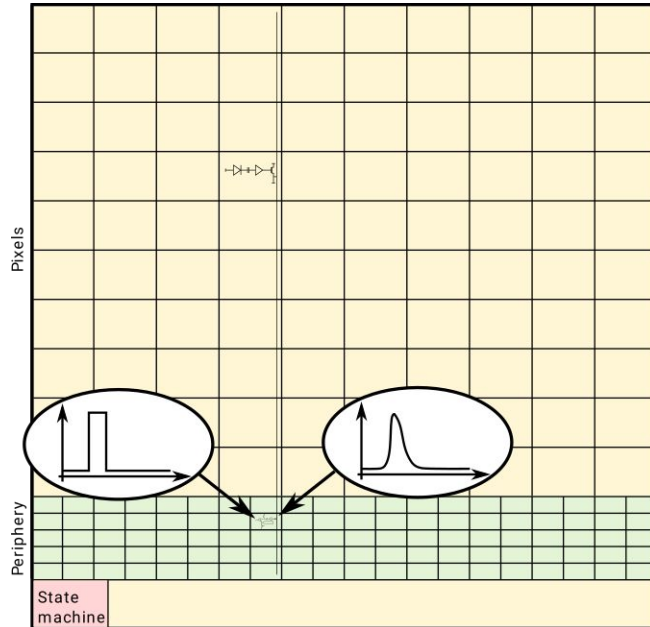
- Deposited charge amplified by in-pixel amplifier
- Source follower drives the signal to the periphery
- Digitisation in periphery
- Timestamp sampling
- Readout statemachine manages column-drain readout
- Data is send out via a 1.25 Gbit/s differential link

The MuPix Principle



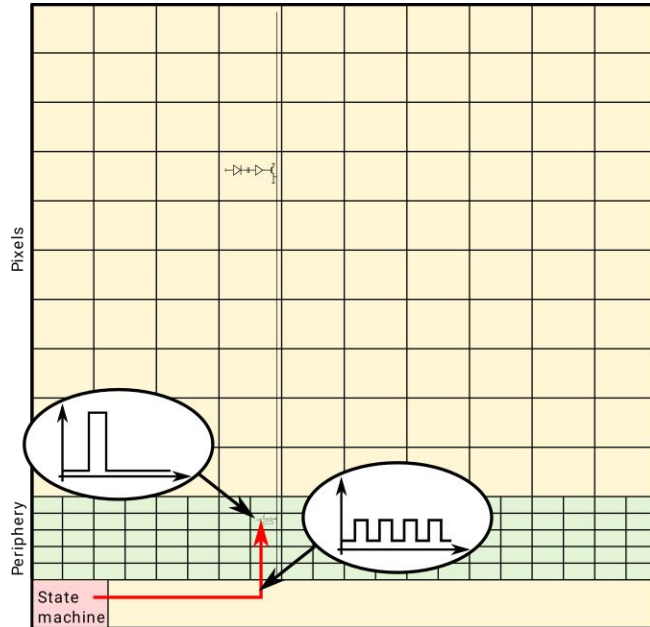
- Deposited charge amplified by in-pixel amplifier
- **Source follower drives the signal to the periphery**
- Digitisation in periphery
- Timestamp sampling
- Readout statemachine manages column-drain readout
- Data is send out via a 1.25 Gbit/s differential link

The MuPix Principle



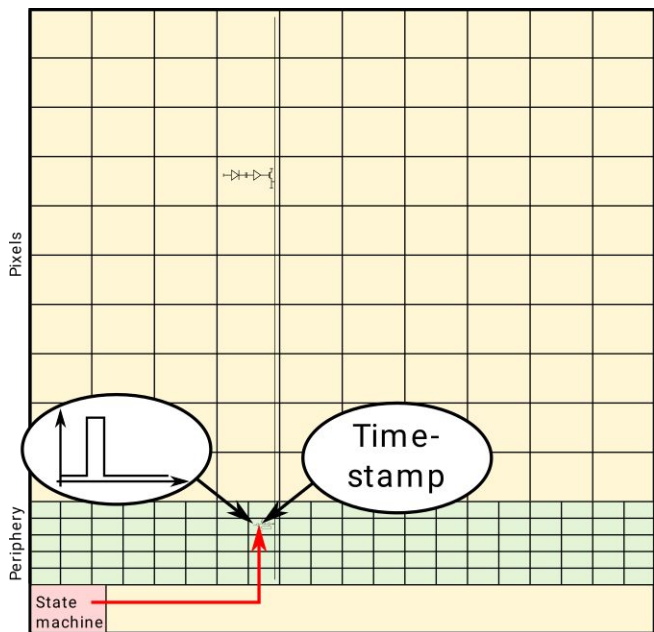
- Deposited charge amplified by in-pixel amplifier
- Source follower drives the signal to the periphery
- **Digitisation in periphery**
- Timestamp sampling
- Readout state machine manages column-drain readout
- Data is send out via a 1.25 Gbit/s differential link

The MuPix Principle



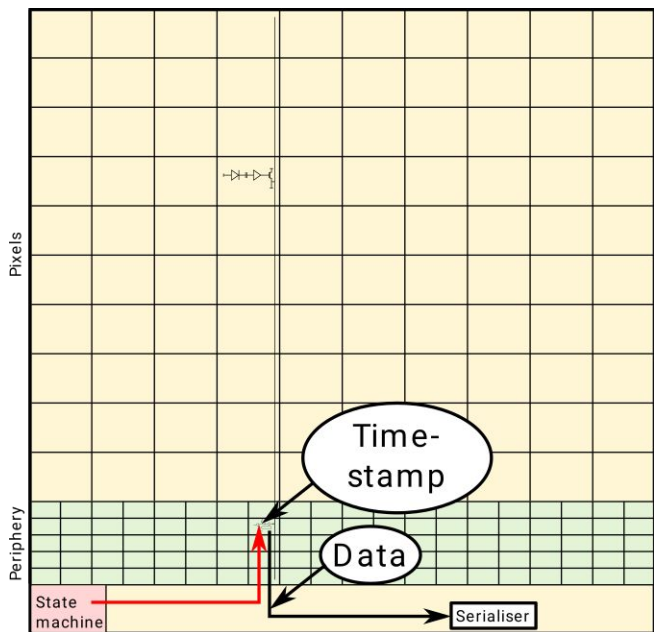
- Deposited charge amplified by in-pixel amplifier
- Source follower drives the signal to the periphery
- Digitisation in periphery
- **Timestamp sampling**
- Readout statemachine manages column-drain readout
- Data is send out via a 1.25 Gbit/s differential link

The MuPix Principle



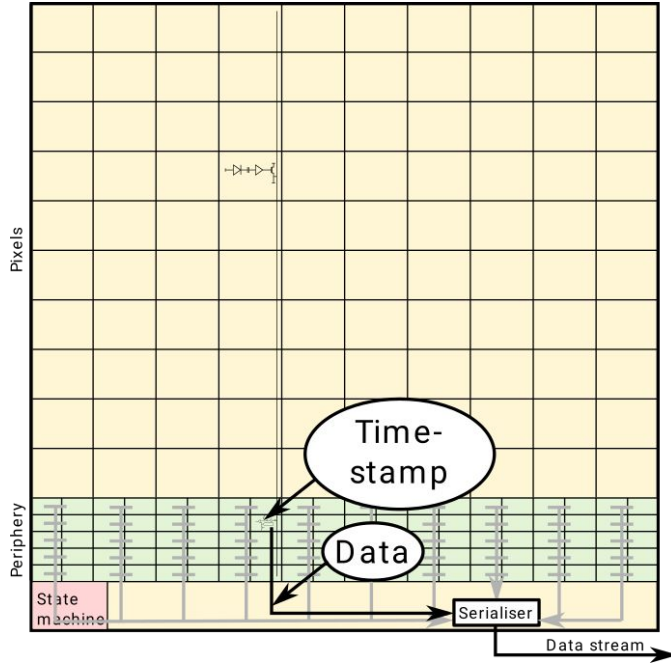
- Deposited charge amplified by in-pixel amplifier
- Source follower drives the signal to the periphery
- Digitisation in periphery
- **Timestamp sampling**
- Readout statemachine manages column-drain readout
- Data is send out via a 1.25 Gbit/s differential link

The MuPix Principle



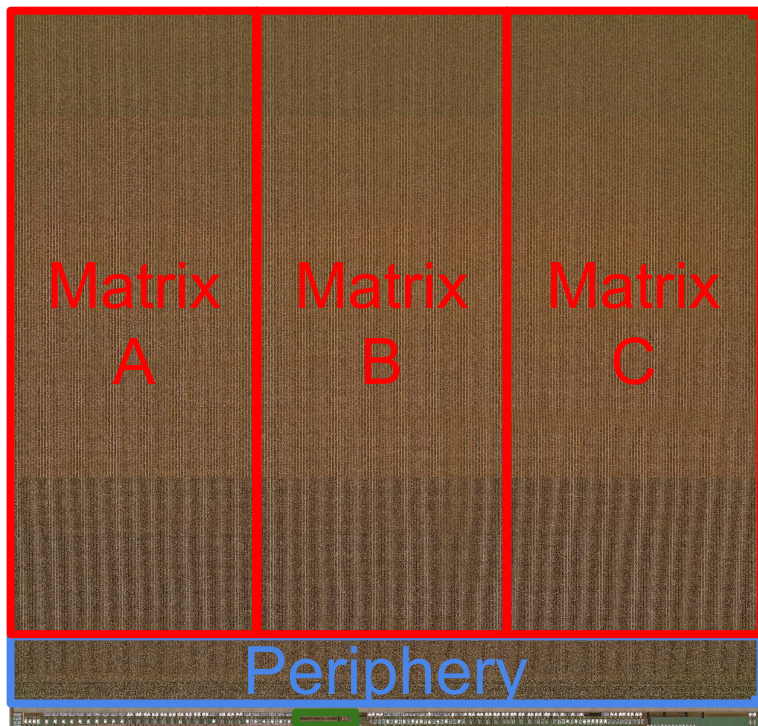
- Deposited charge amplified by in-pixel amplifier
- Source follower drives the signal to the periphery
- Digitisation in periphery
- Timestamp sampling
- **Readout state machine manages column-drain readout**
- Data is send out via a 1.25 Gbit/s differential link

The MuPix Principle



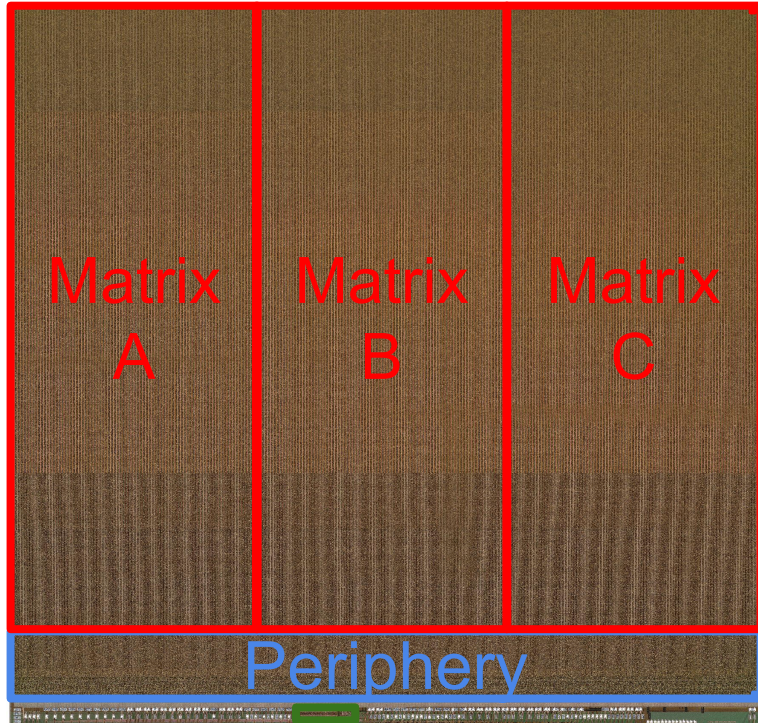
- Deposited charge amplified by in-pixel amplifier
- Source follower drives the signal to the periphery
- Digitisation in periphery
- Timestamp sampling
- Readout statemachine manages column-drain readout
- **Data is send out via a 1.25 Gbit/s differential link**

MuPix10 & MuPix11



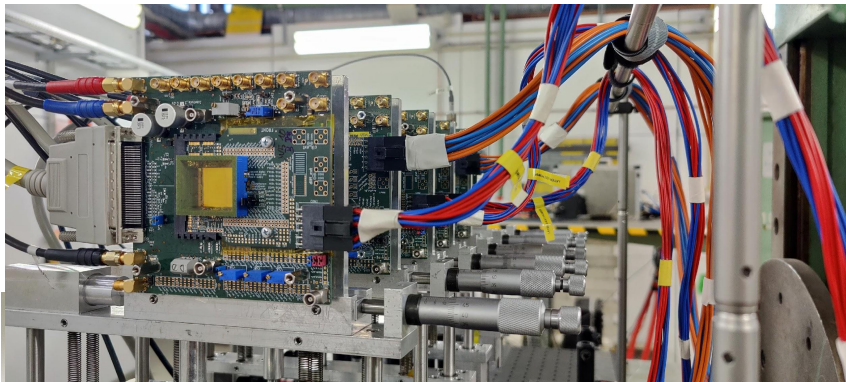
Pixel size [μm^2]	80 x 80
Sensor size [mm^2]	20.66 x 23.18
Active size [mm^2]	20.48 x 20.0
Pixel matrix	256 x 250
Thickness [μm]	50, 70
Substrate [Ωcm]	80, 370
Data links	3+1
Data speed [Gbit/s]	1.25
Time-of-arrival [bits]	11
ToT [bits]	5
TS binning [ns]	8 (option for 1.6)

From MuPix10 to MuPix11



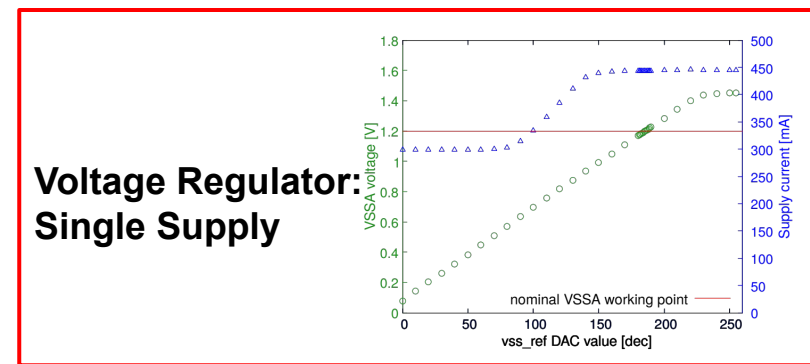
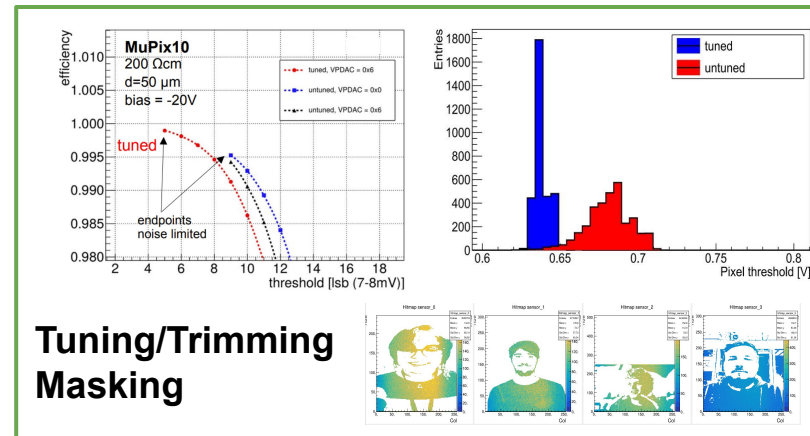
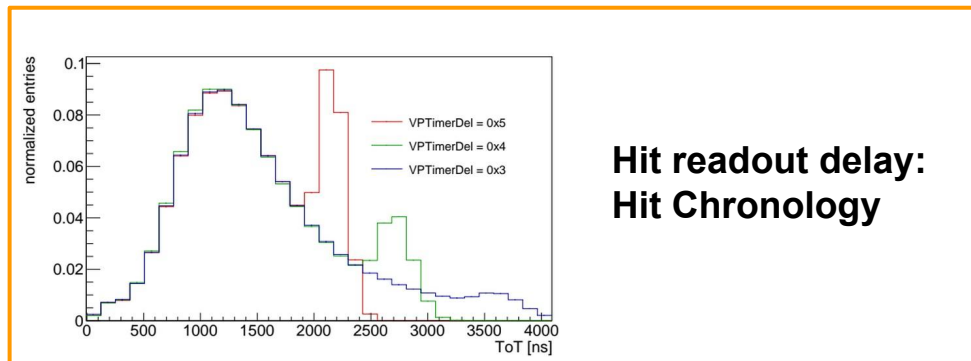
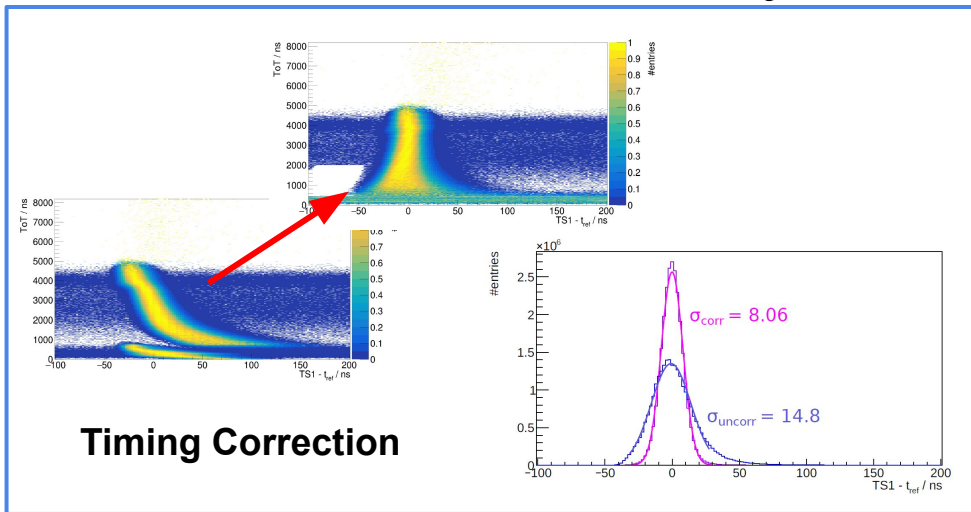
- Removal of R&D features
 - ➔ More pads for powering
- Improvement of powering grid
 - ➔ Less on-chip voltage drop
- Buffering of data lines
 - ➔ Full speed readout
30 MHits/s per sub-matrix
- Re-synthesis of State machine
 - ➔ Fast configuration interface available
- Re-done pixel point-to-point connection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

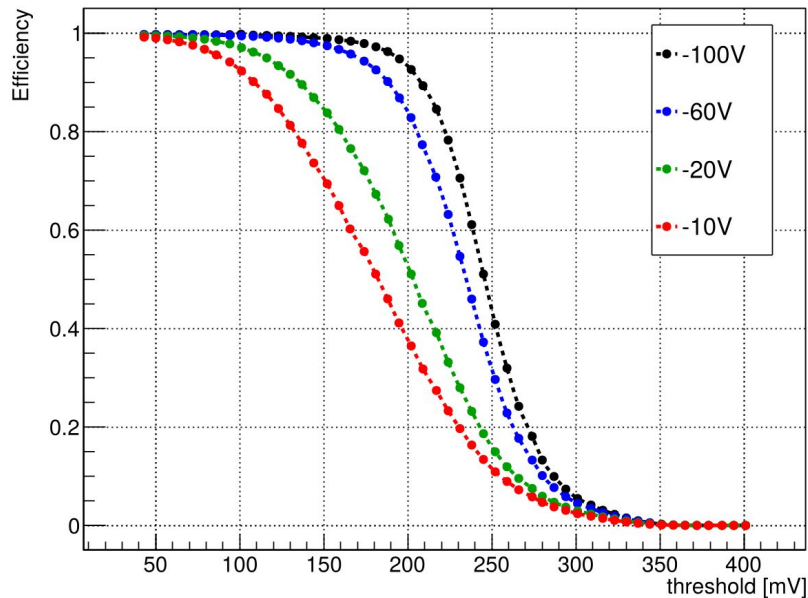
Summary - Results MuPix10



MuPix11 - First Light

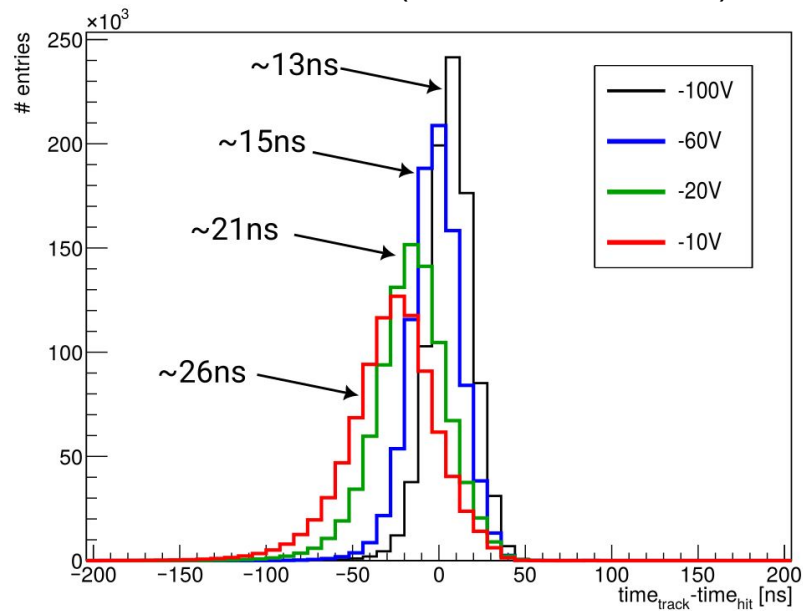


Efficiency - 100 μ m thick sensor



Depletion depth proportional to $\sqrt{\text{HV}}$

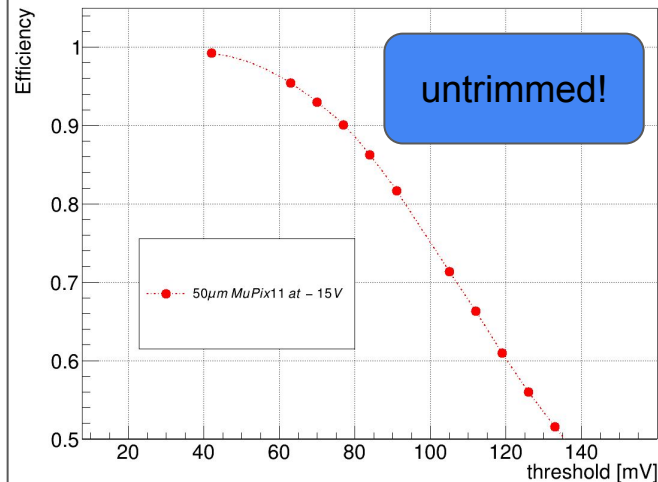
Time resolution (Gaussian estimate)



Raw time resolution,
no corrections of any kind

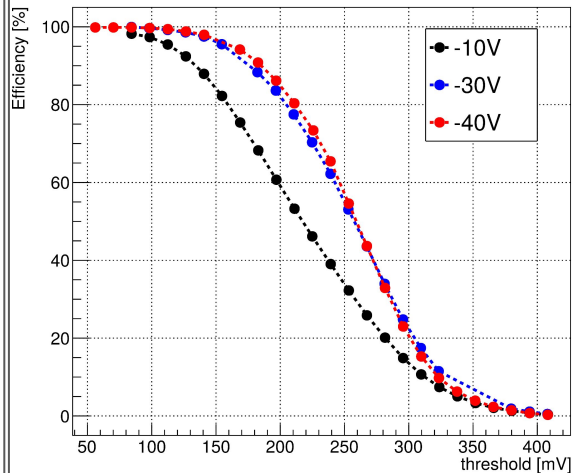
MuPix11 - Efficiency for 50 and 70 μm

50 μm thickness

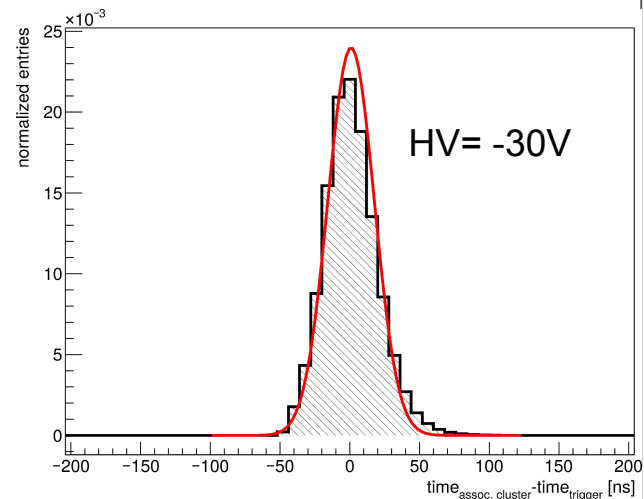


➔ Needs calibration/trimming!

70 μm thickness



➔ Works out of the box!



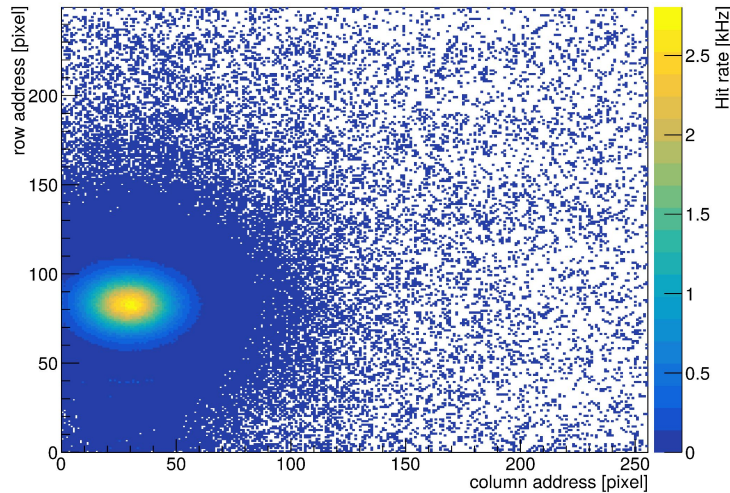
$\sigma_{\text{uncorrected}} \sim 16.6 \text{ ns}$

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

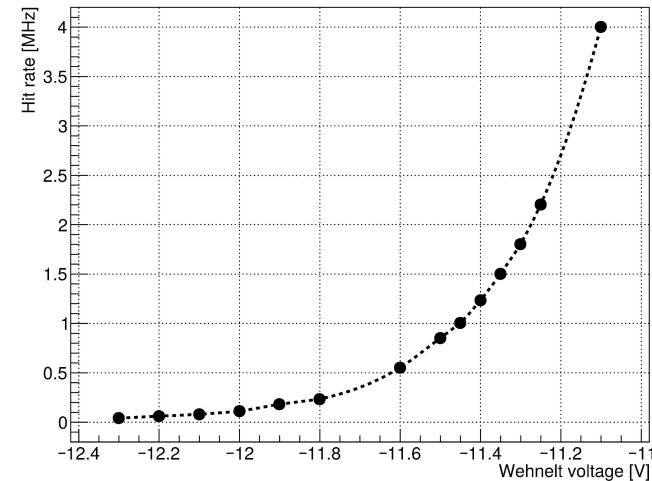
MuPix11 - High Rate capability



MAMI - Beam spot on sub-matrix A

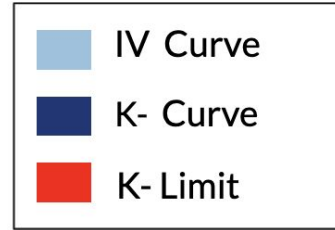
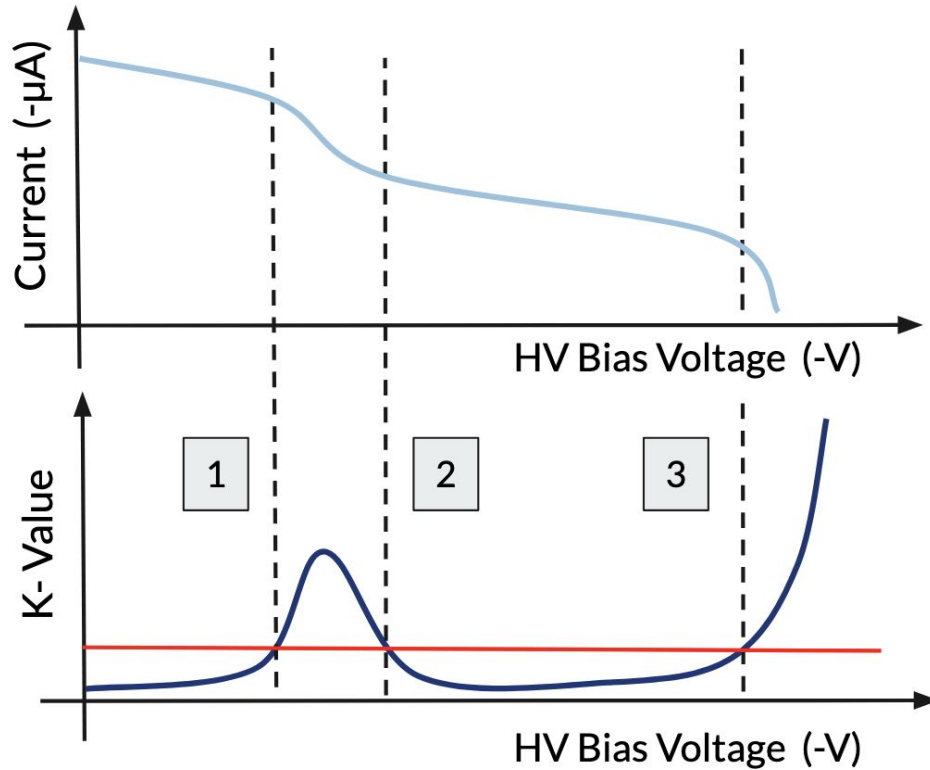


Beam rate measured with MuPix11



No Readout saturation visible @ 4 MHz Hitrate
➔ Average Rate on “Hottest” Sensor 6 MHz

IV issues

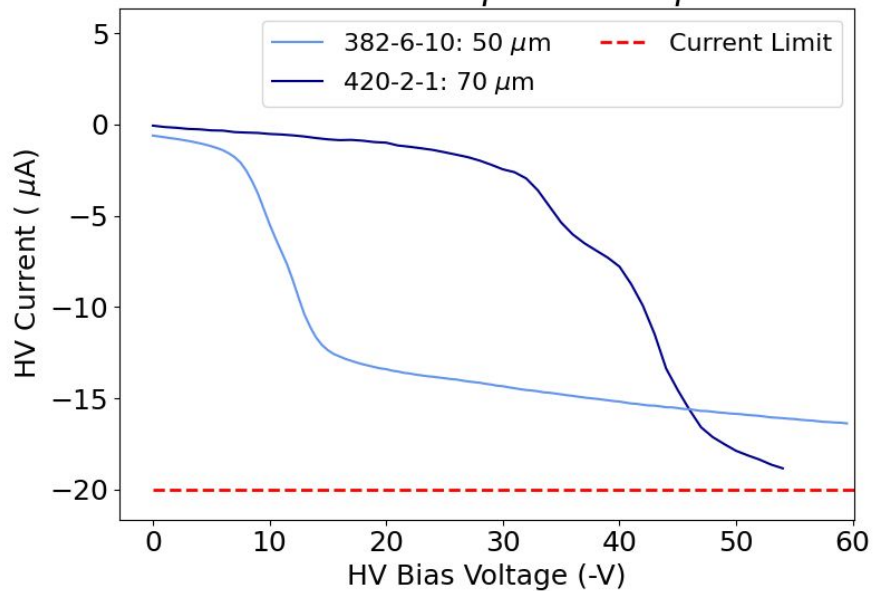


K- Voltages	
1	Boundary Voltage
2	Stabilisation Voltage
3	Breakdown Voltage

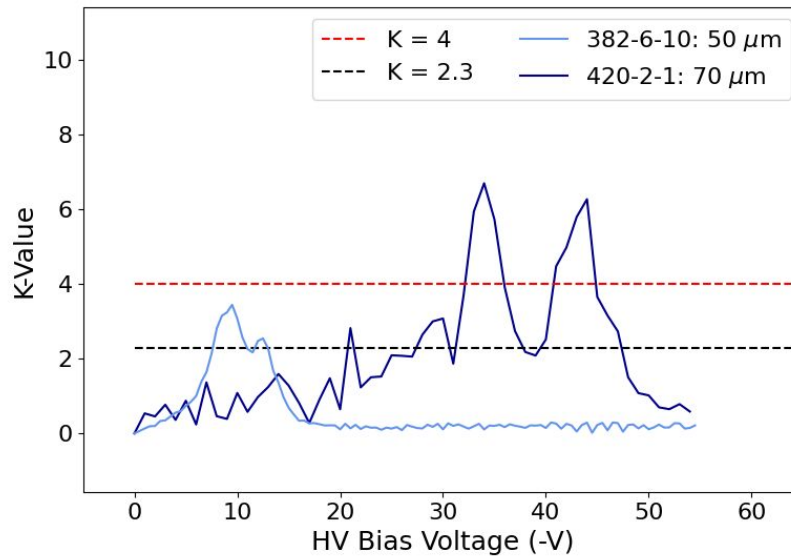
IV issue



IV Curves: 70 μm and 50 μm



K- Curves: 420 - 2



IV issues



K- Voltages for 420 - 2, 420 - 3

