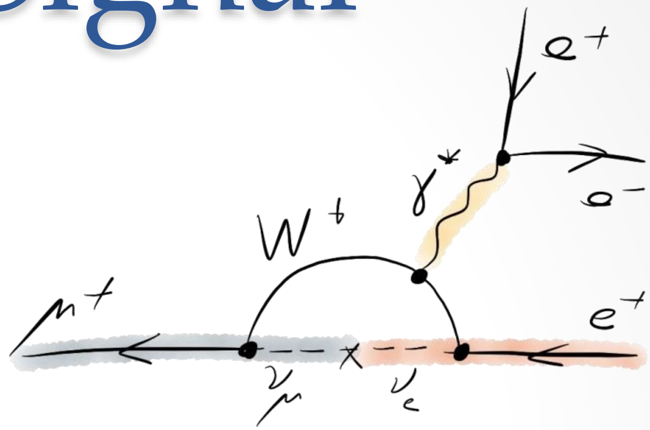
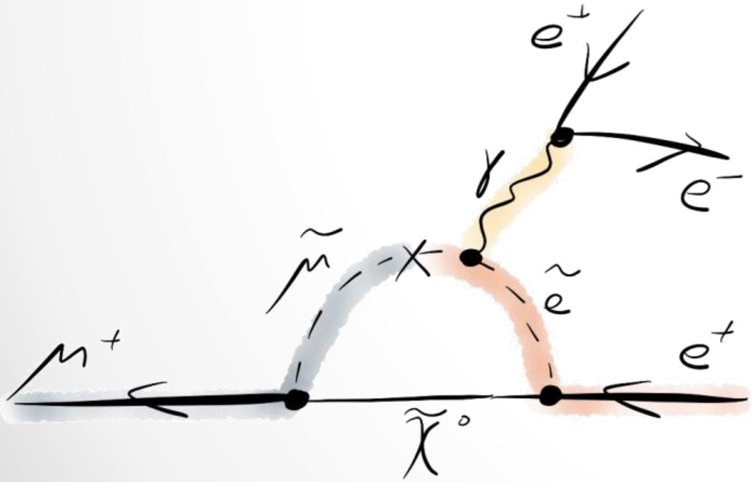
Novel thin High Voltage Monolithic Active Pixel Sensors for the Mu3e experiment

Dirk Wiedner, Heidelberg
On Behalf of the Mu3e Collaboration

The Mu3e Signal

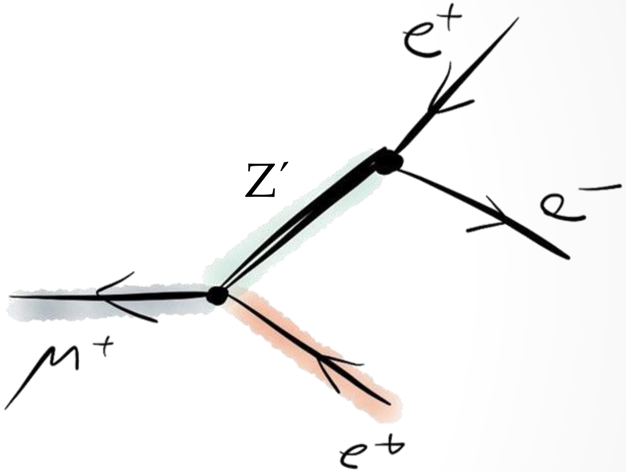
- $\mu^+ \rightarrow e^+e^-e^+$ rare in νSM
  - Branching ratio $<10^{-54}$ →unobservable
- Enhanced in BSM theories



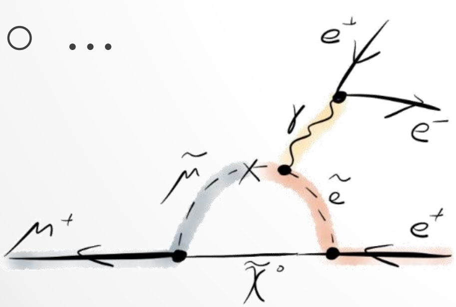


The Mu3e Signal

- $\mu^+ \rightarrow e^+e^-e^+$ rare in SM
- Enhanced in:
  - Super-symmetry
  - Grand unified models
  - Left-right symmetric models
  - Extended Higgs sector
  - Large extra dimensions
  - …



Tree level:
Z′



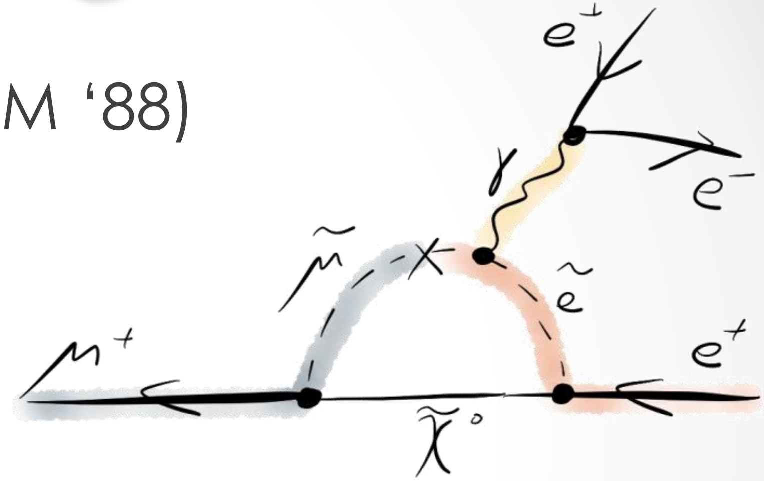
Loop level:
SUSY

The Mu3e Signal

- Rare decay (BR<10^{-12}, SINDRUM ‘88)

For BR O(10^{-15})

- >10^{15} muon decays
- High decay rates O(10^{8} μ/s)

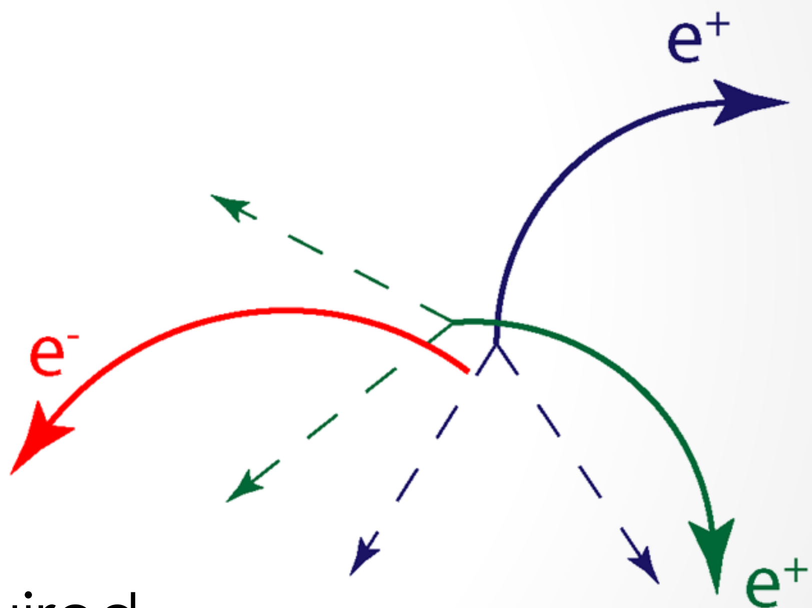


Signal properties:

- $\sum E_e = m_\mu c^2$
- $\sum \overrightarrow{p_e} = 0$
- Common vertex
- Coincident in time
- Maximum electron momentum 53 MeV/c

The Mu3e Background

- Accidental combinations
  - $\mu^+ \rightarrow e^+ \nu\nu$ & $\mu^+ \rightarrow e^+ \nu\nu$ & $e^+ e^-$
  - many possible combinations
- $\sum E_e \neq m_\mu c^2$
- $\sum \overrightarrow{p_e} \neq 0$



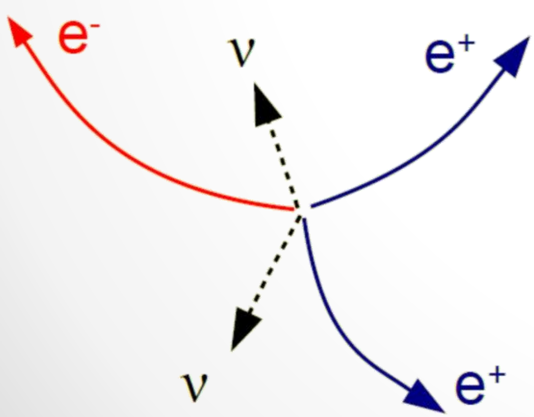
➢ **Good time** and

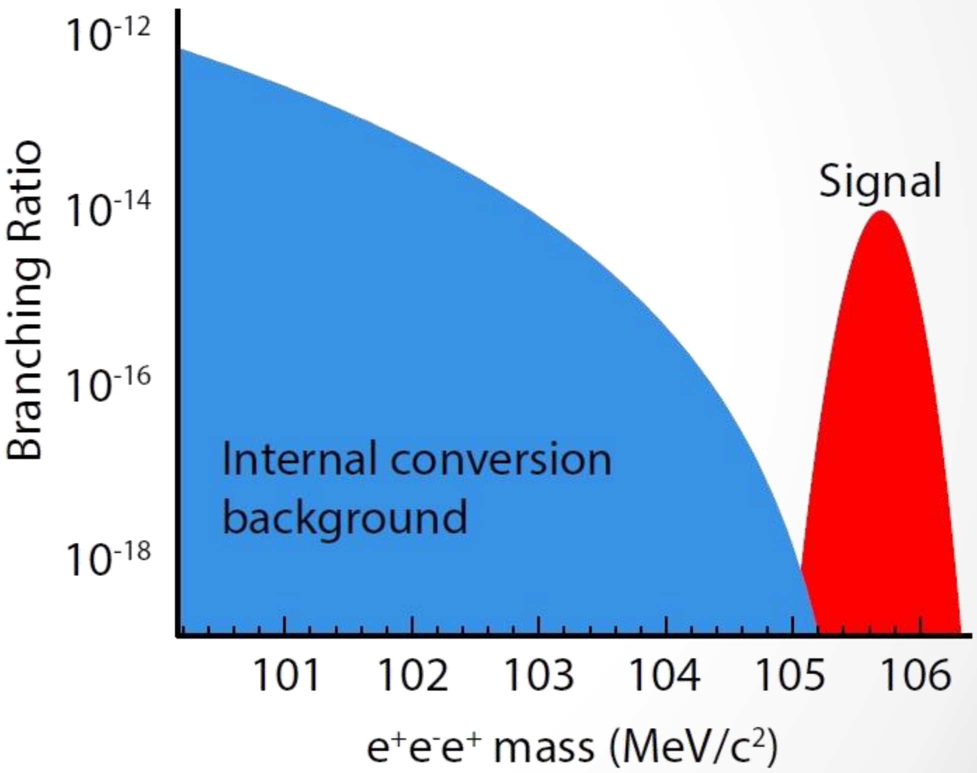
➢ **Good vertex resolution** required

The Mu3e Background

- Internal conversion background:
  - $\mu^+ \rightarrow e^+ e^- e^+ \nu\nu$
- $\sum E_e < m_\mu c^2$
- $\sum \overrightarrow{p_e} \neq 0$

➢ **Good momentum resolution**





Phased experiment

- **Phase I** uses the existing PiE5 beam line at PSI, shared with MEG II, 10^8 muons/s
- **Phase II** requires a High Intensity Muon Beamline: HiMB, > $2 \cdot 10^9$ muons/s

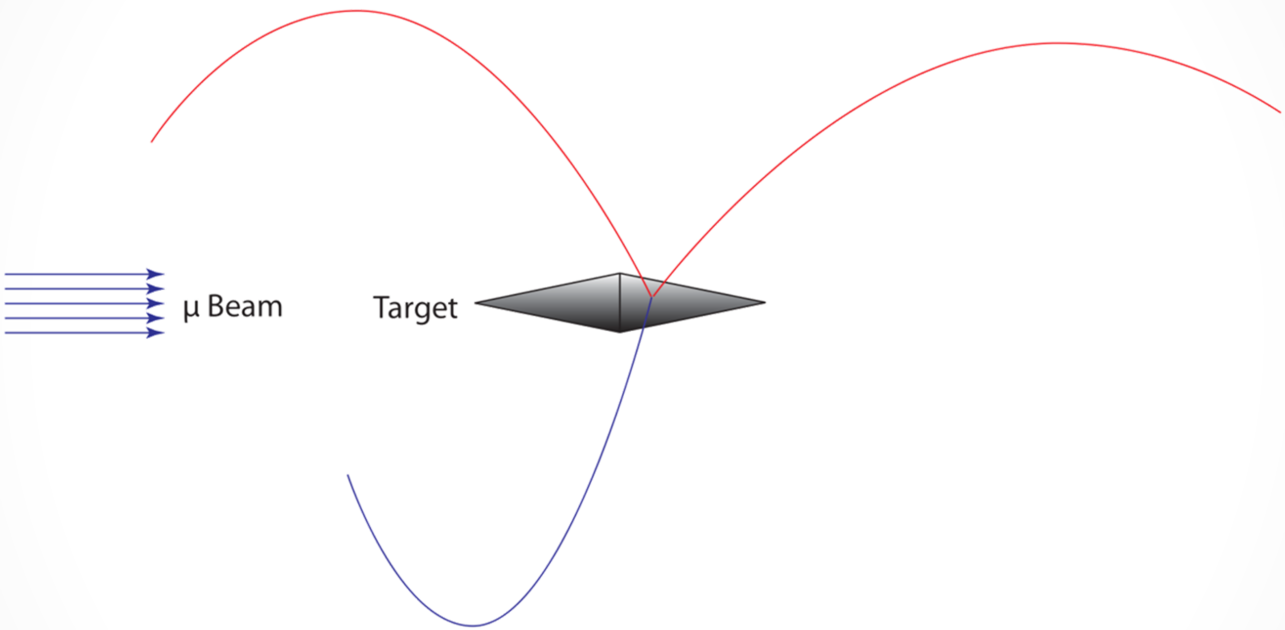
➢ In the following **phase I** will be discussed

Challenges

- High rates: up to 10^8 μ/s
- Good time resolution: 100 ps
- Good vertex resolution: ~200 μm
- Excellent momentum resolution: ~ 0.5 MeV/c
- ➢ **Extremely low material budget:** **1‰ X_0** per Si-Tracker Layer

$$\sigma_p \sim \frac{1}{p}\sqrt{\frac{x}{X_0}}$$

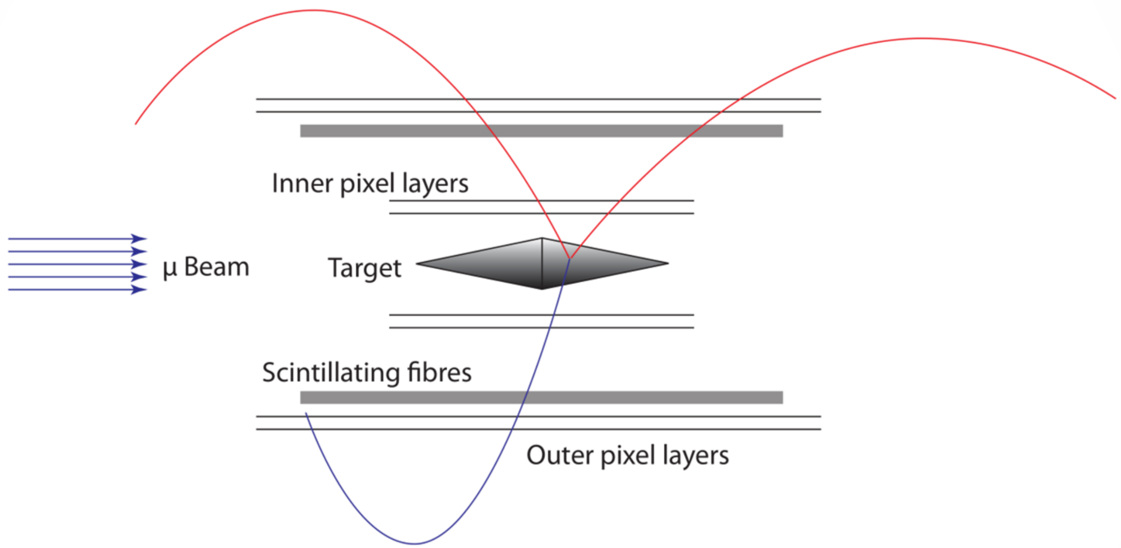
The Mu3e Experiment



- Muon beam
- Helium atmosphere
- 1 T B-field

- Target double hollow cone
- Silicon pixel tracker
- Scintillating fiber detector
- Tile detector

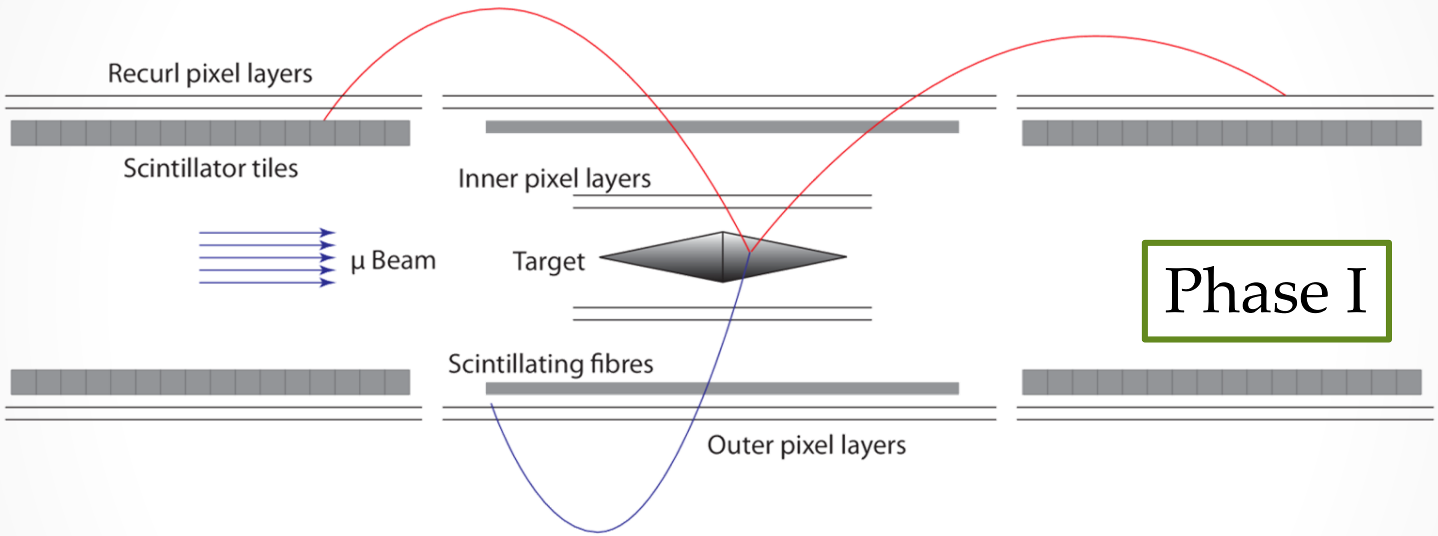
The Mu3e Experiment



- Muon beam
- Helium atmosphere
- 1 T B-field

- Target double hollow cone
- Silicon pixel tracker
- Scintillating fiber detector
- Tile detector

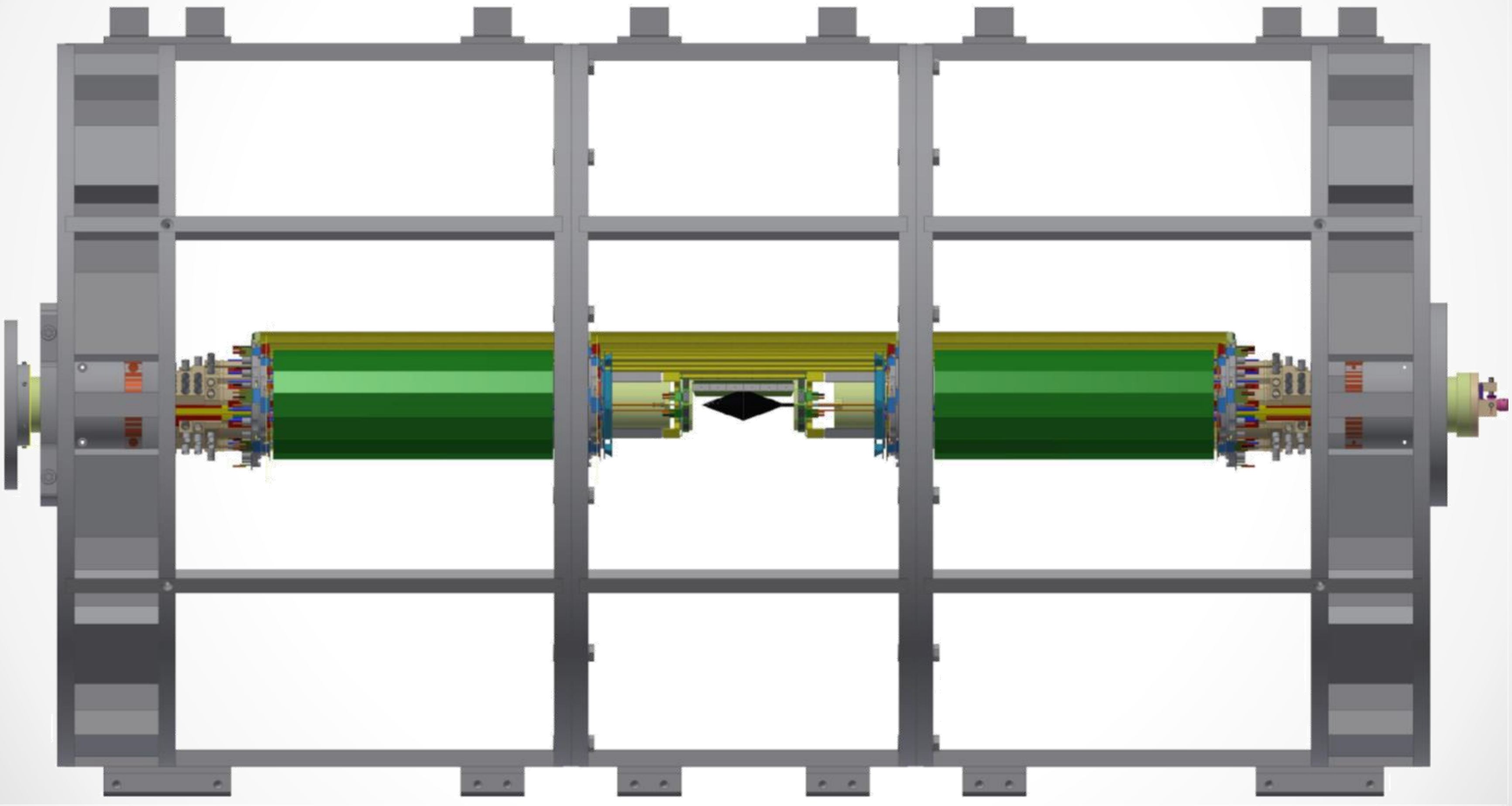
The Mu3e Experiment



- Muon beam **O(10^8/s)**
- Helium atmosphere
- 1 T B-field

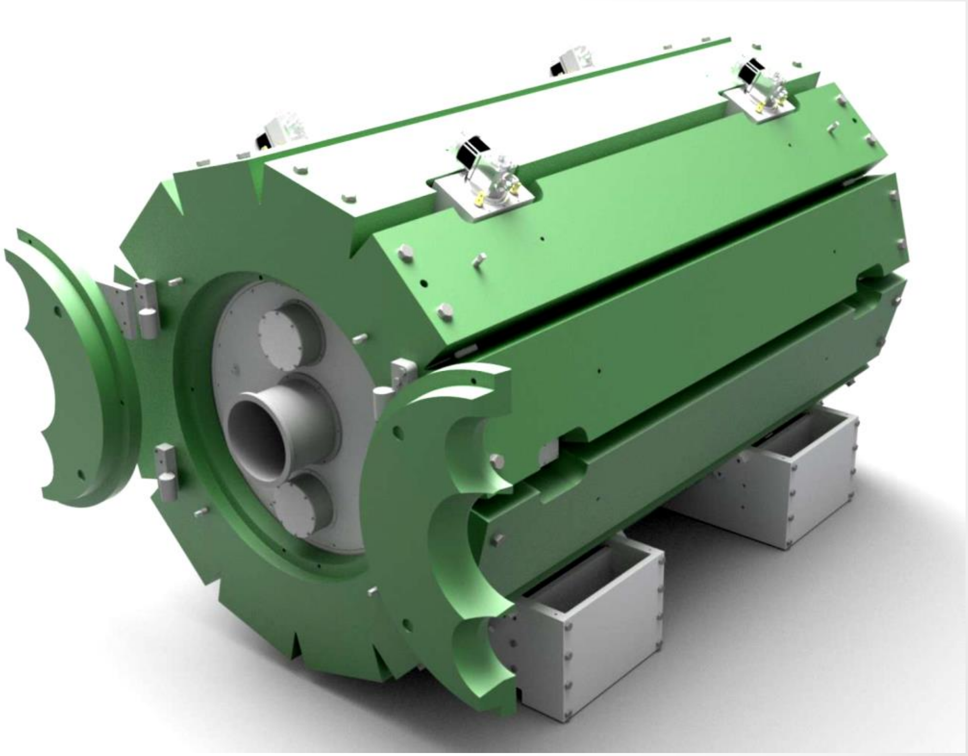
- Target double hollow cone
- Silicon pixel tracker
- Scintillating fiber detector
- Tile detector

The Mu3e Experiment

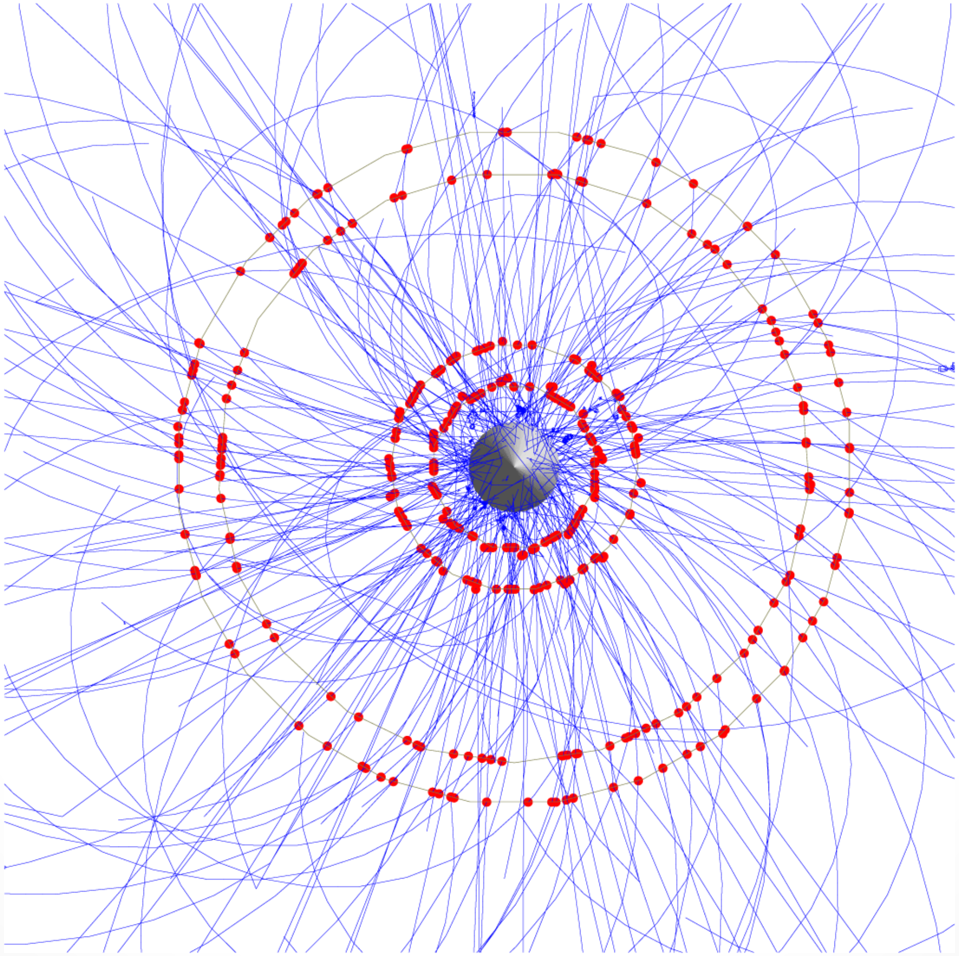


Mu3e Magnet

- 1T solenoid
- 3m long
- 1m bore diameter
- Superconducting coil
- Dry cryo system
- Magnet TDR ready
- Delivery early 2019



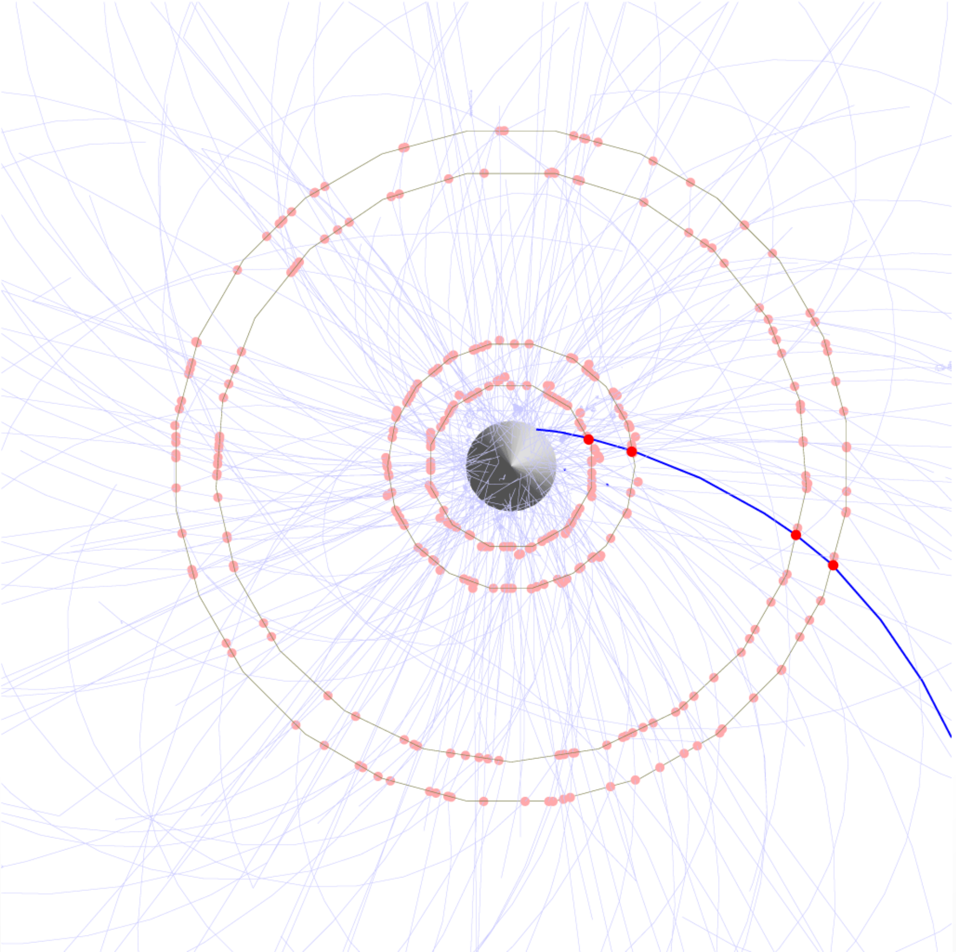
Timing Detectors



Simulated tracks for Phase II

50 ns

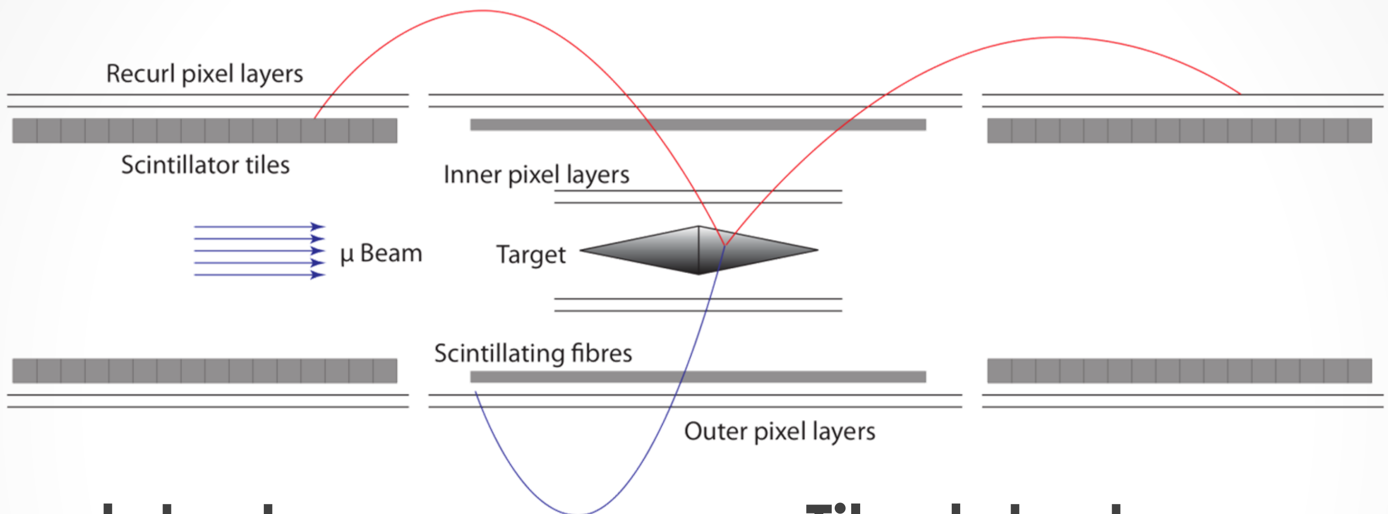
Timing Detectors



Simulated tracks for Phase II

0.1 ns

Timing Detectors



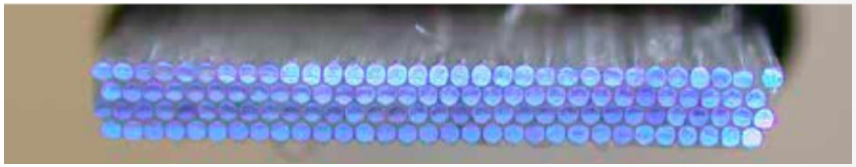
- **Fiber detector**
  - Inner detector
  - 250 μm scintillating fibers
  - ≈ 0.3% X/X_0
  - ≤ 0.5 ns resolution
- **Tile detector**
  - Recurl stations
  - 6.5 x 6.5 x 5.0 mm^3 tiles
  - ≤ 100 ps resolution

Common readout ASIC - MuTrig

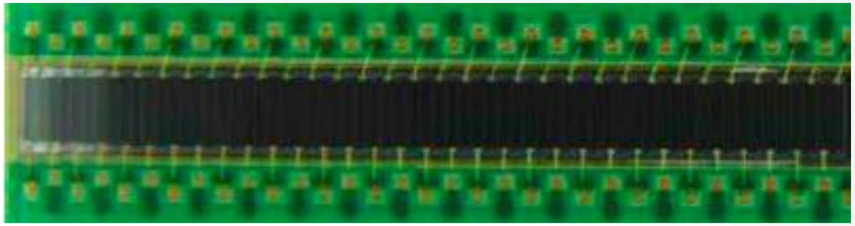
Fiber Detector

Fiber ribbon modules

- 32 mm wide
- ~290 mm long
- 4 layers fibers of ø 250 µm
- SiPM arrays (LHCb type)
- 4 MuTrig readout chips



Scintillating fiber ribbons

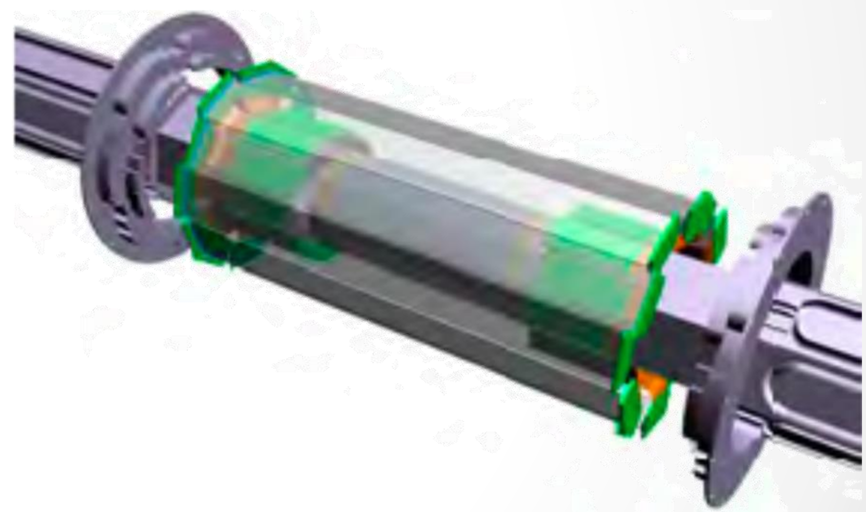


Silicon photo multiplier (SiPM) array

Fiber Detector

Fiber ribbon modules

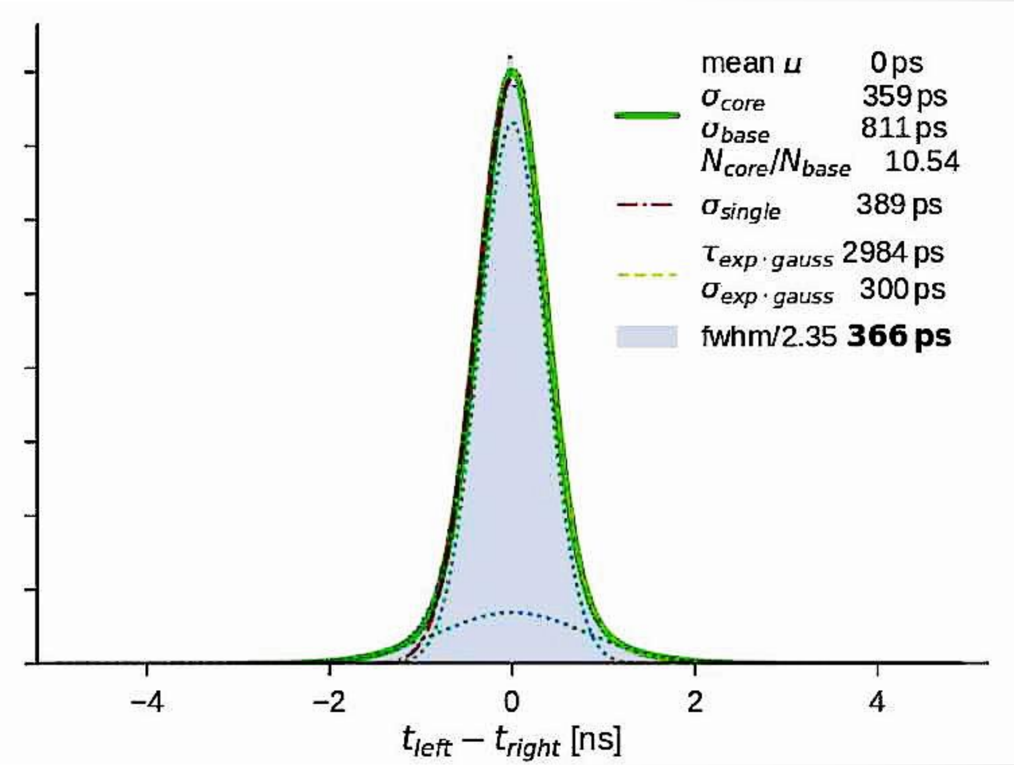
- 32 mm wide
- ~290 mm long
- 4 layers fibers of ø 250 µm
- SiPM arrays (LHCb type)
- 4 MuTRiG readout chips
- A demonstrator will be build by the end of the year



Fiber tracker mechanical design study

Fiber Time Resolution

- Fiber detector prototypes tested
- Good time resolution:
- <400ps including ASIC



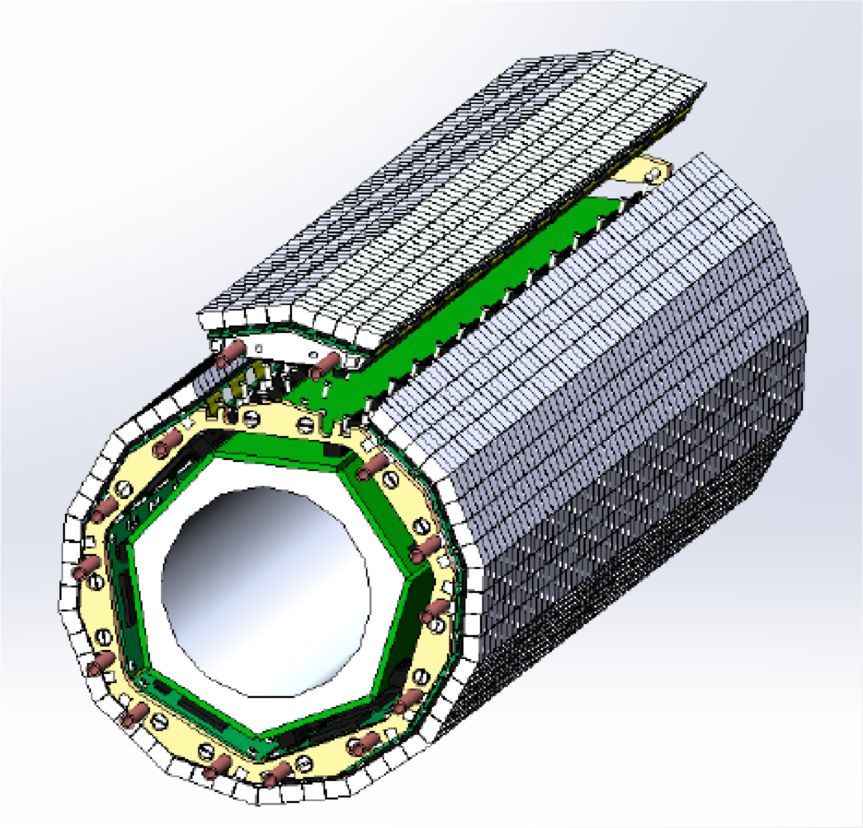
Tile Detector

Recurl station:

- 7 x 14 sub modules mounted on end rings and cooling structure
- Total length 368 mm
- 3136 channels

Full detector phase I

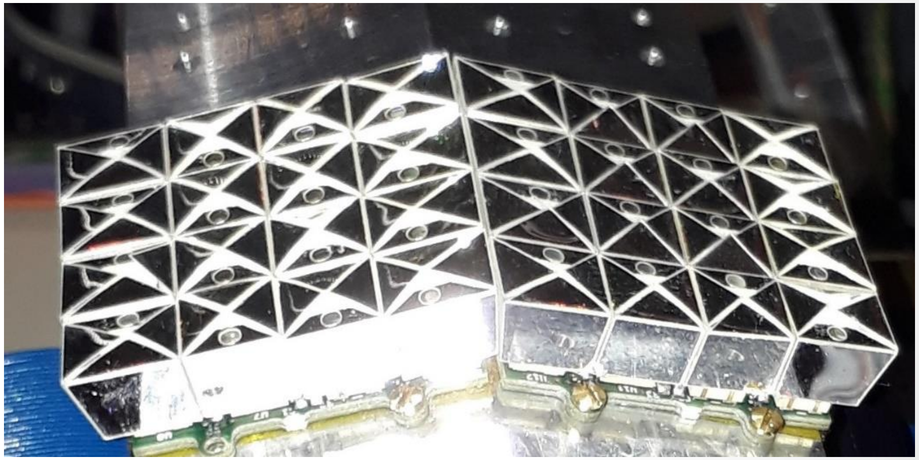
- 2 recurl stations –
- total of 6272 channels



Rendering of Tile Detector station

Tile Prototype

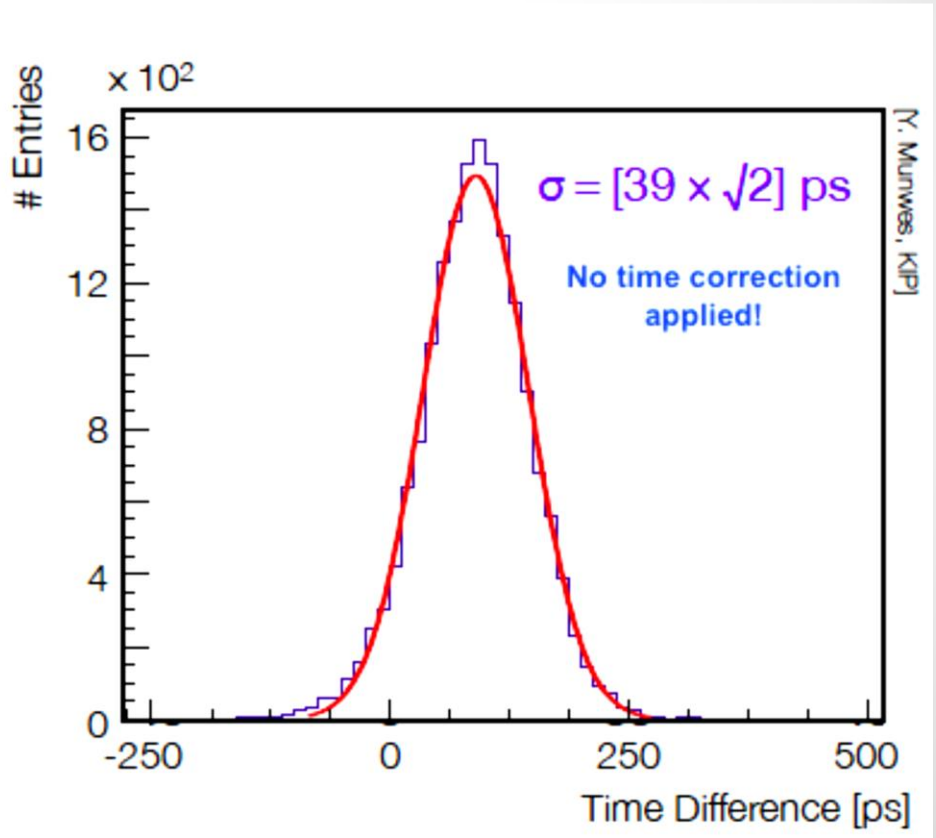
- Technical prototype build this year
- Develop assembly tools for mass production
- Tested with electron beam @ DESY (2-7 GeV)
- Excellent light yield
- Low crosstalk

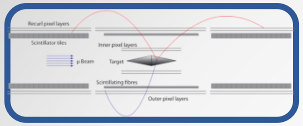


Tile sub-module prototype

Tile Prototype

- Tested with electron beam @ DESY (2-7 GeV)
- Excellent light yield
- Low crosstalk
- Excellent time resolution of 35 ps achieved
    - without time walk correction

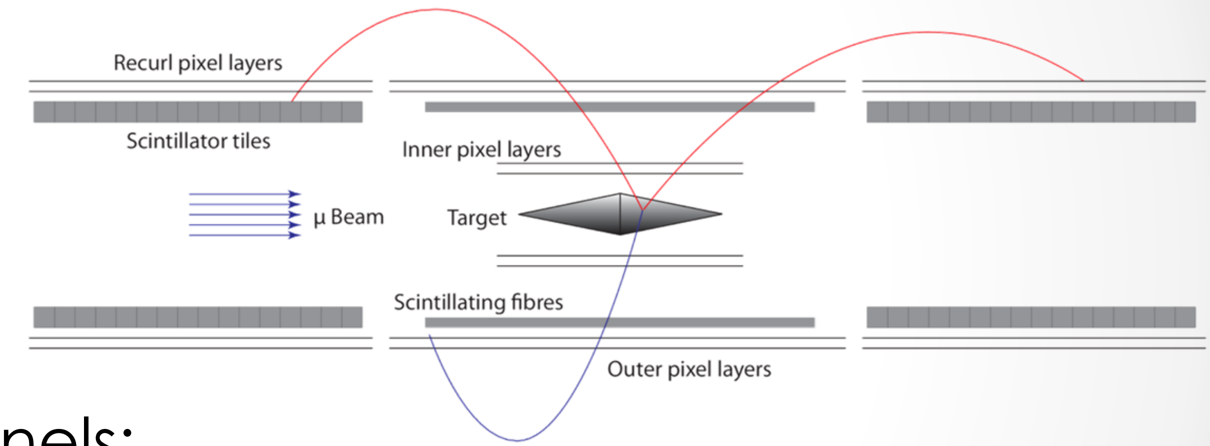




Pixel Tracker

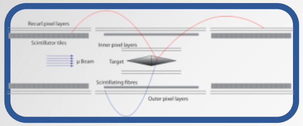
Silicon pixel tracker:

- 2 vertex layers
- 2 outer layers
  - Central station
  - 2 recurl stations



Mu3e detector scheme

- Total No of channels:
- Phase I - 178 M

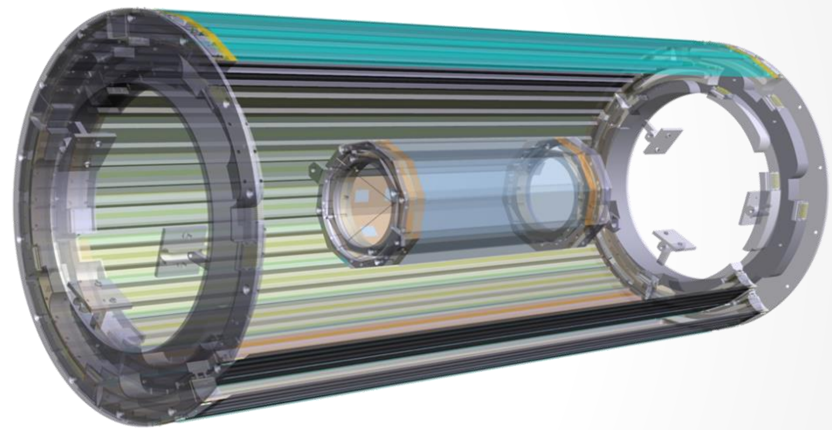


Pixel Tracker

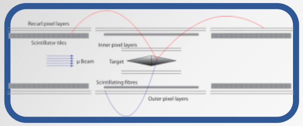
Single layer structure:

- 50 µm silicon
- 25 µm Kapton flex print with aluminum traces
- 25 µm Kapton frame as support
- Less than 1‰ of radiation length per layer
- Helium cooling

- Total No of channels:
- Phase I - 178 M

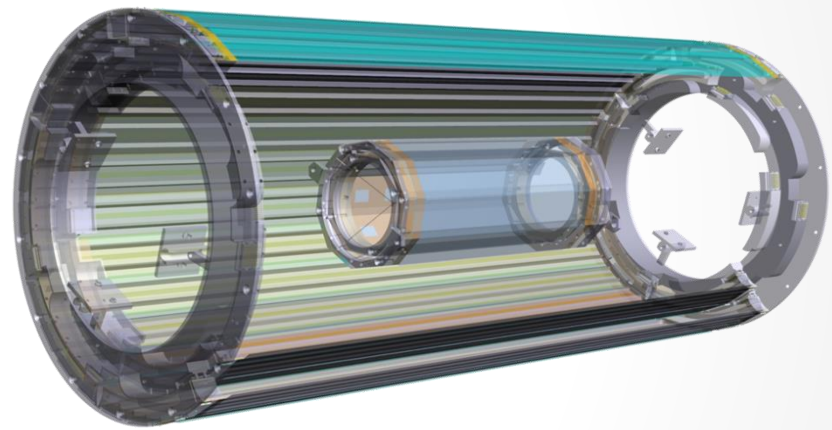


Pixel Tracker
Rendering of CAD study

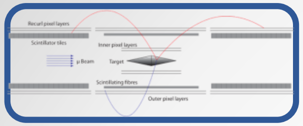


Pixel Tracker

- ✓ Successful **feasibility** studies for:
  - ✓ Module mechanics
  - ✓ He-cooling with low vibration
  - ✓ **Ultra-thin flexible circuit boards**
  - ✓ **HV-CMOS small prototypes**
  - ✓ Readout board prototype

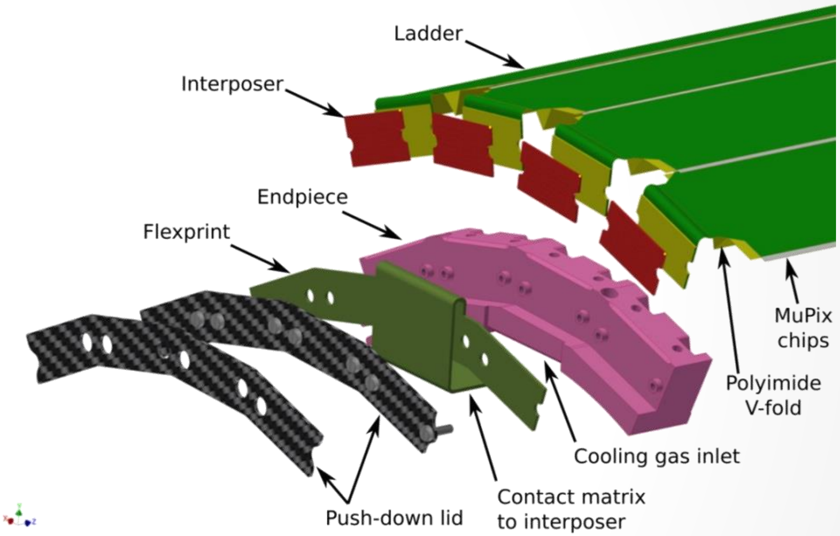


Pixel Tracker
Rendering of CAD study

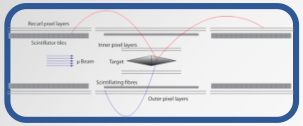


Pixel Tracker

- ✓ Detailed design for:
  - ✓ **Module mechanics**
  - ✓ He-cooling distribution
  - ✓ HV-CMOS large prototype
  - ✓ Readout board pre production prototype

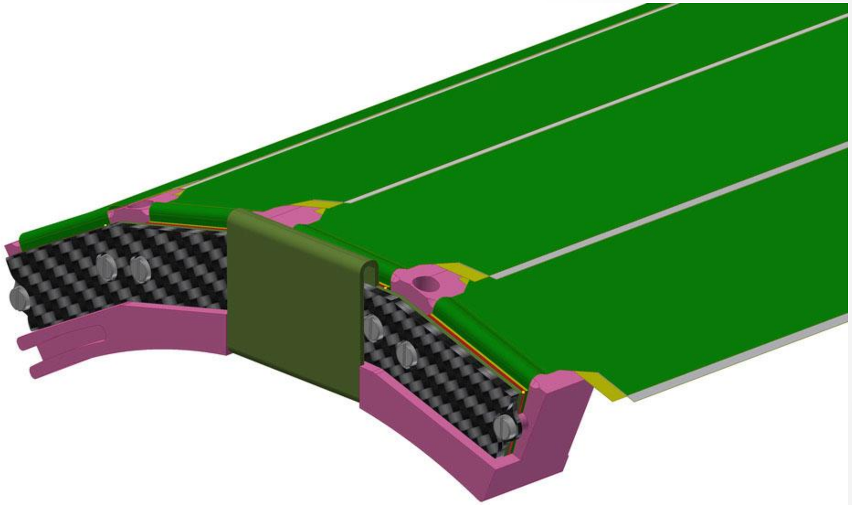


Pixel Tracker
Details of CAD

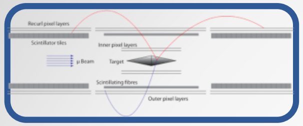


Pixel Tracker

- ✓ Detailed design for:
  - ✓ **Module mechanics**
  - ✓ He-cooling distribution
  - ✓ HV-CMOS large prototype
  - ✓ Readout board pre production prototype

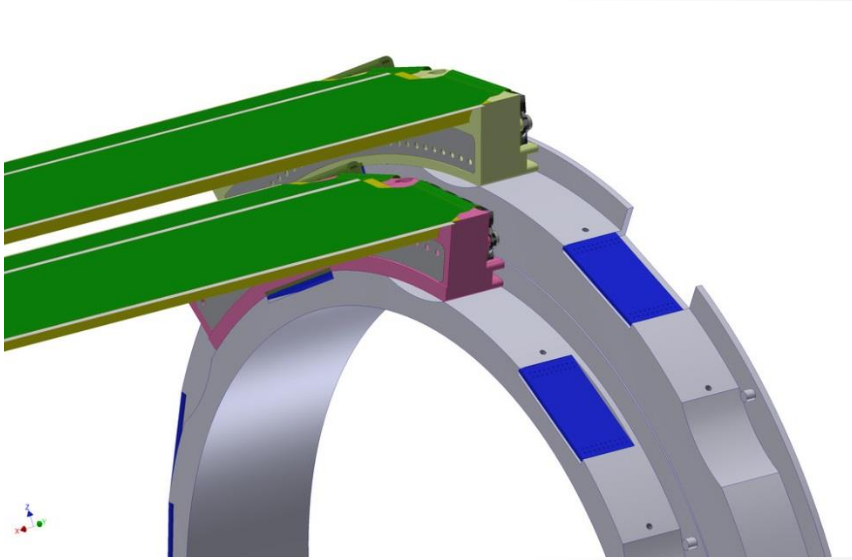


Pixel Tracker
Details of CAD

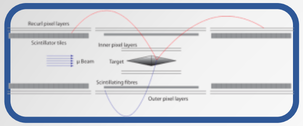


Pixel Tracker

- ✓ Detailed design for:
  - ✓ **Module mechanics**
  - ✓ He-cooling distribution
  - ✓ HV-CMOS large prototype
  - ✓ Readout board pre production prototype

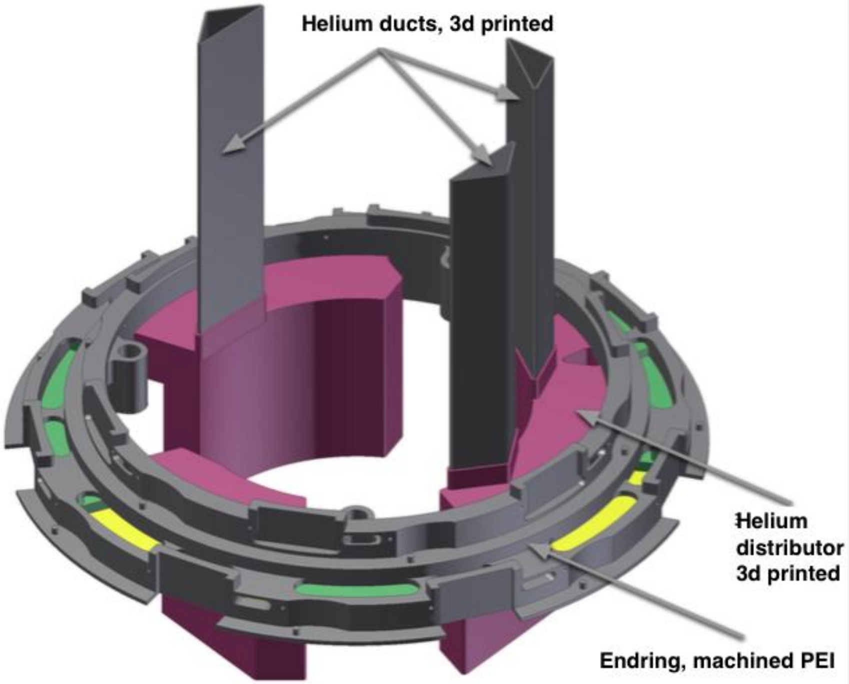


Pixel Tracker
Details of CAD

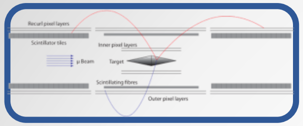


Pixel Tracker

- ✓ Detailed design for:
  - ✓ Module mechanics
  - ✓ **He-cooling distribution**
  - ✓ HV-CMOS large prototype
  - ✓ Readout board pre production prototype

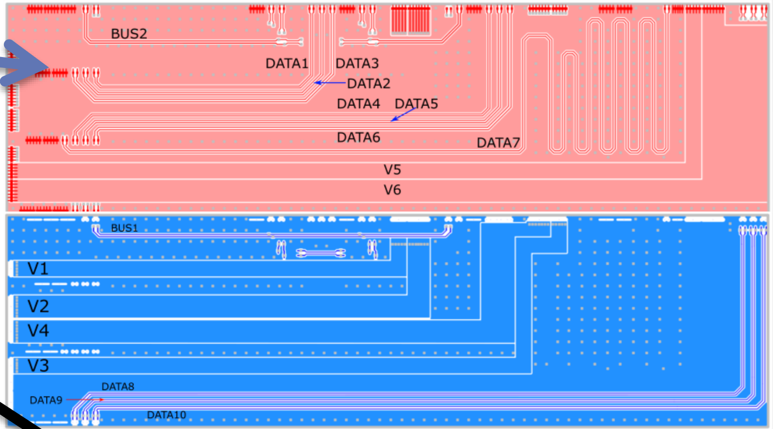


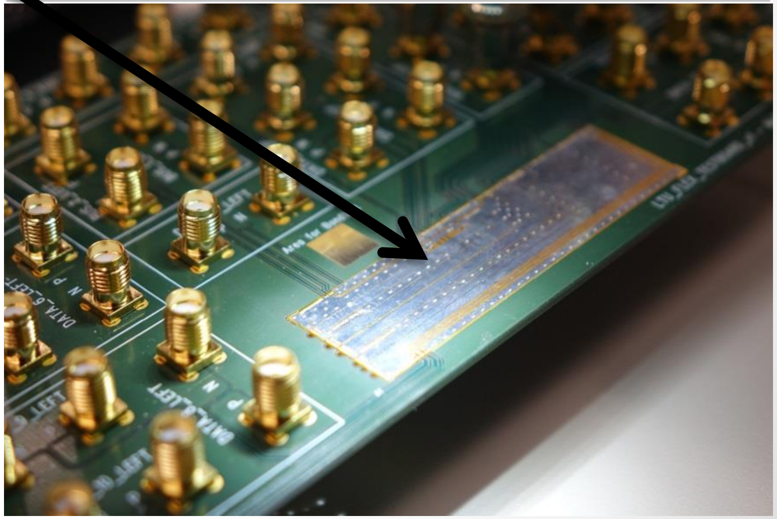
Pixel Tracker
Details of CAD

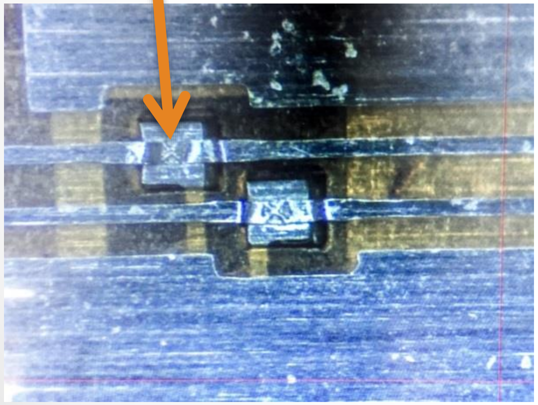


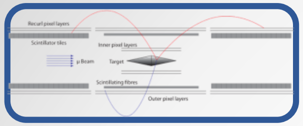
Ultra-thin HDI

- Two layer HDI test design (top)
- Prototype from LTU
- Single point tape automated bonding









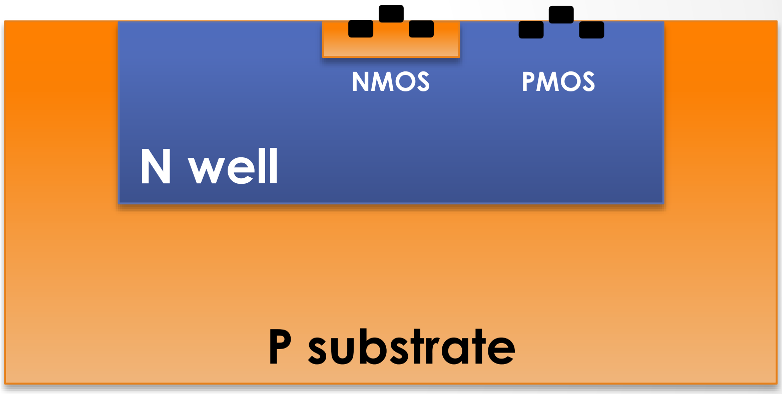
Ultra-thin HDI

- Two layer HDI test design (top)

Material	Thickness [µm]	X/X0
upper Al layer	14	$1.57 \cdot 10^{-4}$
isolator (PI)	35	$1.22 \cdot 10^{-4}$
glue	10	$0.25 \cdot 10^{-4}$
lower Al layer	14	$1.57 \cdot 10^{-4}$
lower PI shield	10	$0.35 \cdot 10^{-4}$
total	83	$\mathbf{4.96 \cdot 10^{-4}}$

HV-MAPS

- **H**igh **V**oltage **M**onolithic **A**ctive **P**ixel **S**ensors
- HV-CMOS technology
- N-well in p-substrate
- Reversely biased

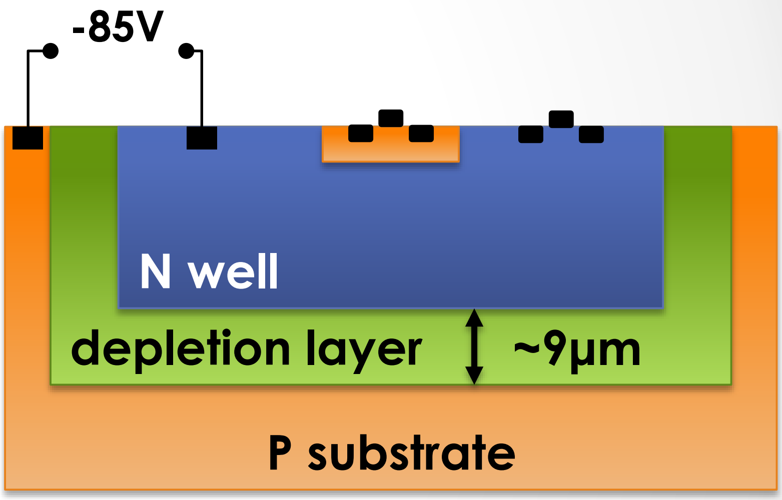


by Ivan Perić

I. Perić, A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology Nucl.Instrum.Meth., 2007, A582, 876

HV-MAPS

- **H**igh **V**oltage **M**onolithic **A**ctive **P**ixel **S**ensors
- HV-CMOS technology
- N-well in p-substrate
- Reversely biased ~85V
  - Depletion layer
  - Charge collection via drift
  - ➢ Fast <1 ns charge collection
  - Thinning to 50 µm possible
- Integrated readout electronics

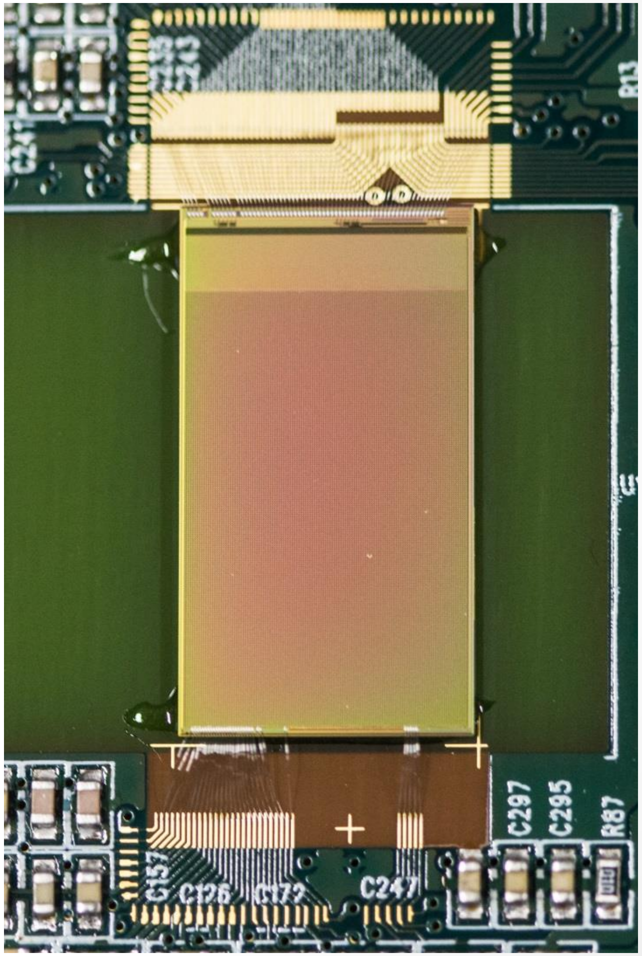


by Ivan Perić

I. Perić, A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology Nucl.Instrum.Meth., 2007, A582, 876

Full System on Chip

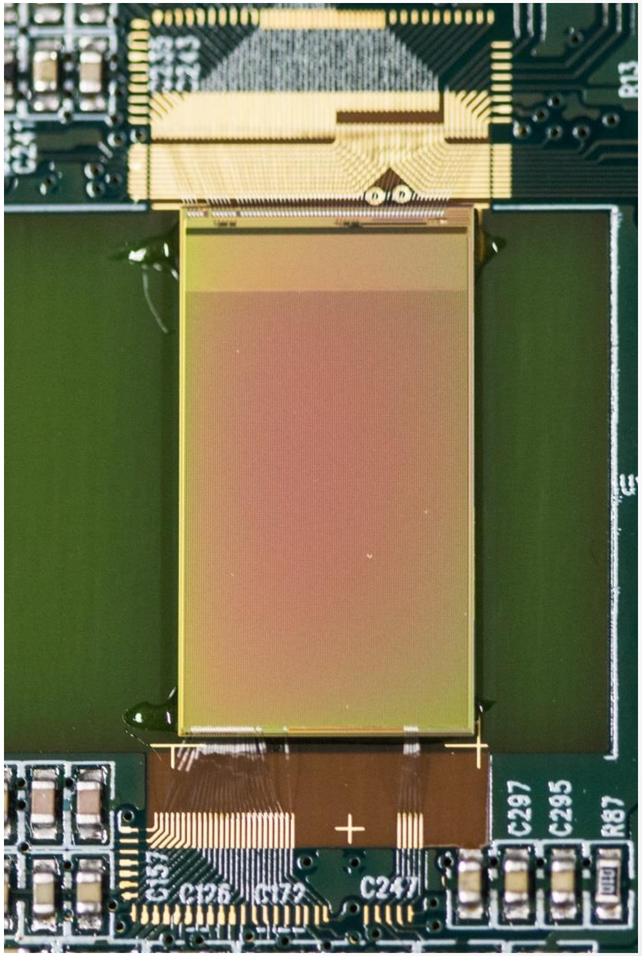
- 180 nm HV-CMOS
- Pixel matrix:
  - 128 x 200 pixels
  - 81 x 80 μm^2 each
- Analog part
  - Pixel sensor
  - Pre-amplifier
- Digital part
  - Comparator
  - Read out state machine
  - 1.25 Gbit/s serial data outputs
- Low power:
  - ~210mW/ cm^2



MuPix8

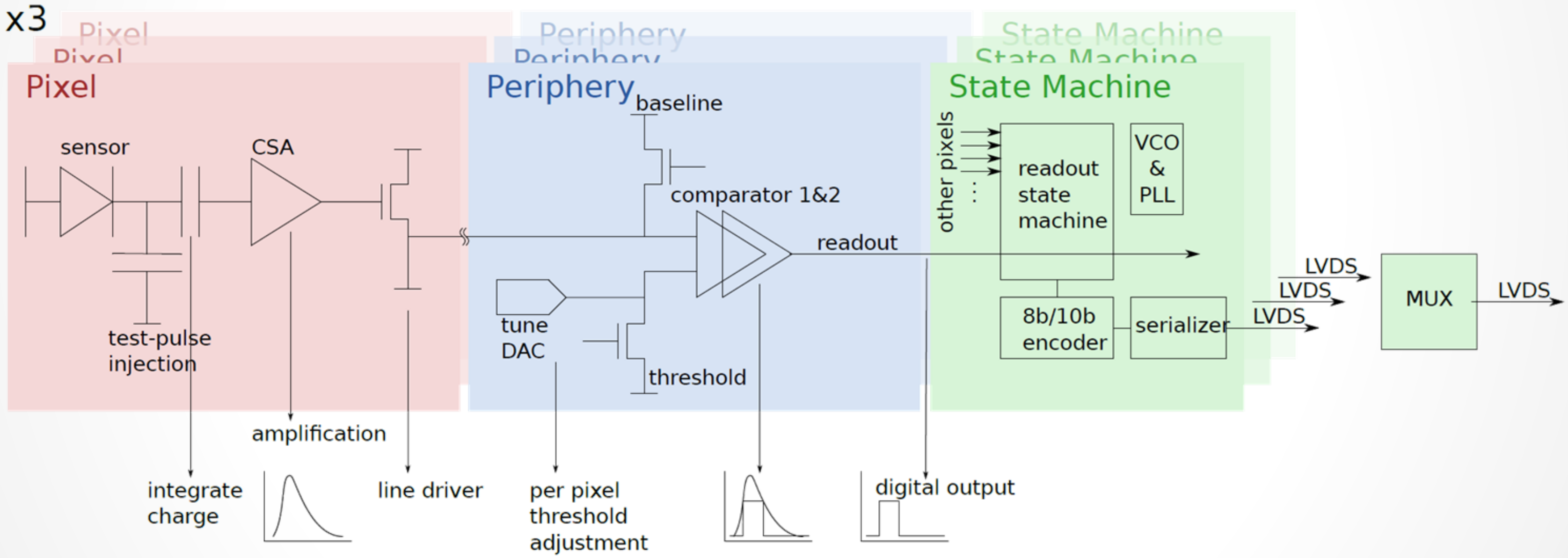
Full System on Chip

- 180 nm HV-CMOS
- Pixel matrix:
  - 128 x 200 pixels
  - 81 x 80 μm^2 each
- Analog part
  - Pixel sensor
  - Pre-amplifier
- Digital part
  - Comparator
  - Read out state machine
  - 1.25 Gbit/s serial data outputs
- Low power:
  - ~210mW/ cm^2



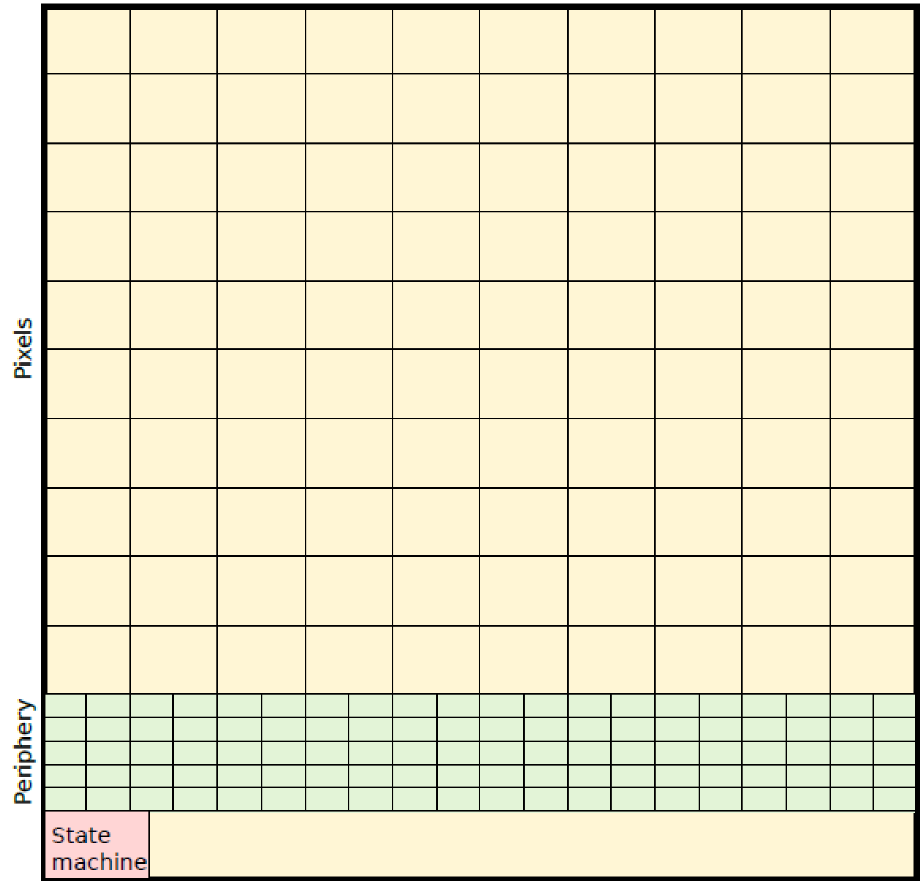
MuPix8

Sensor + Analog + Digital

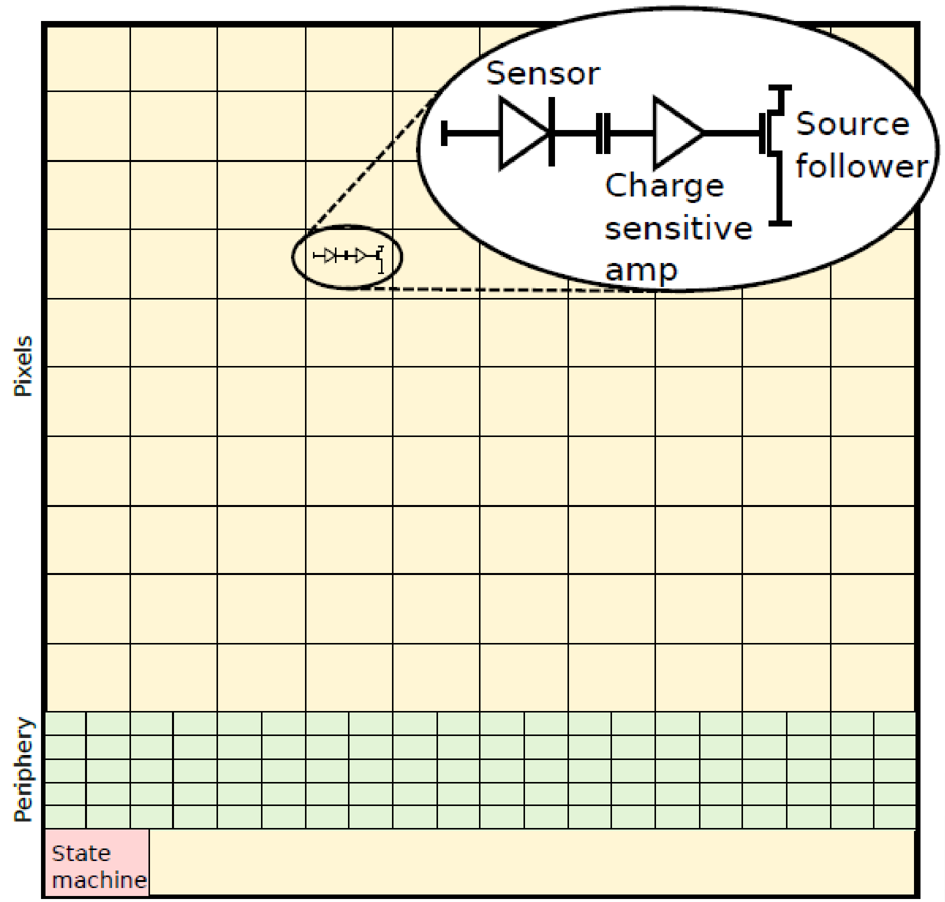


MuPix8 block diagram

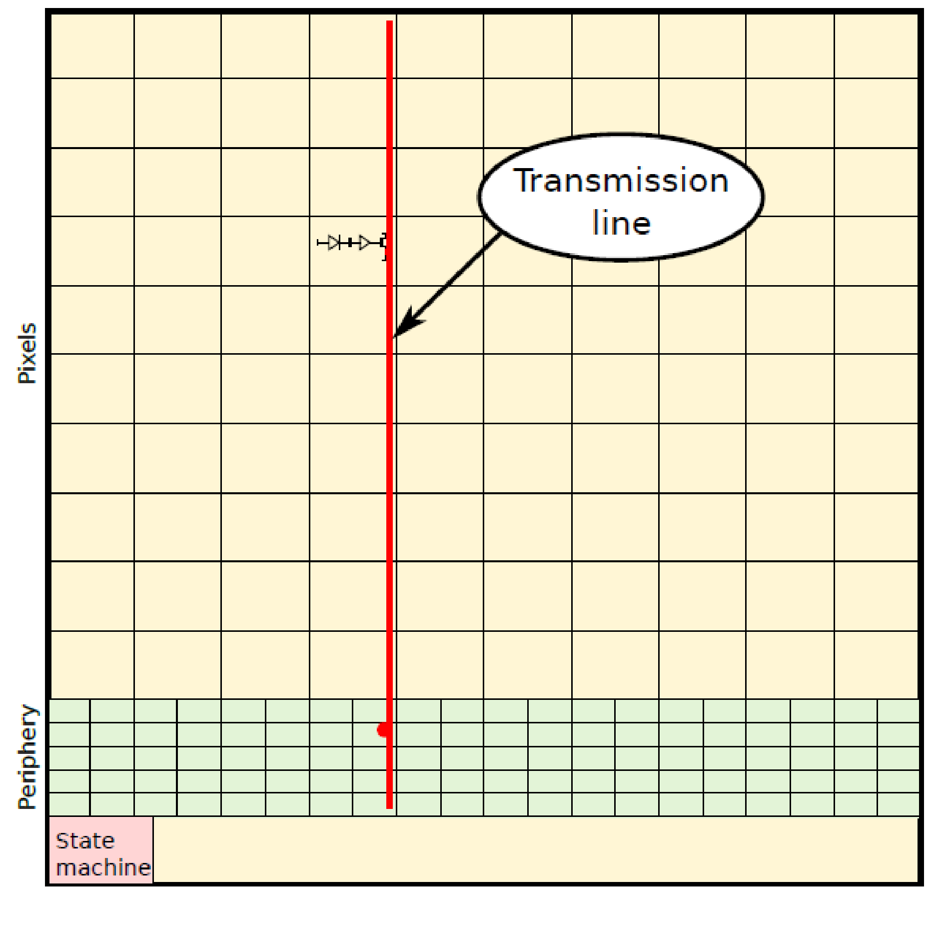
MuPix Readout



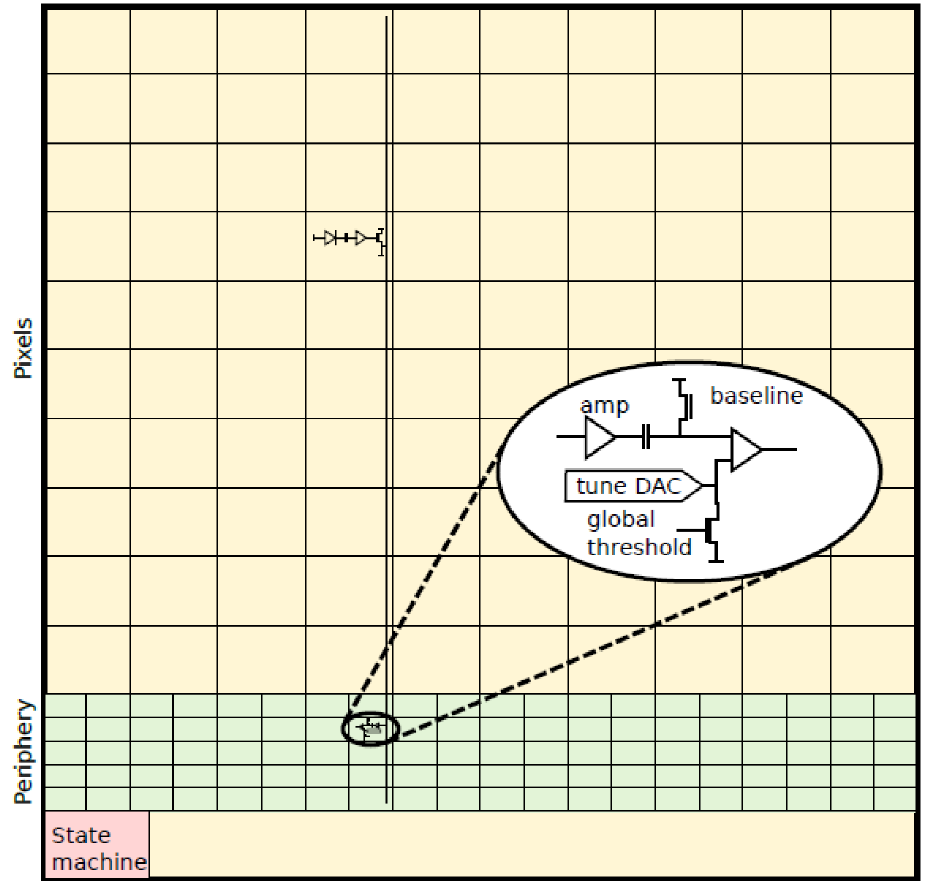
MuPix Readout



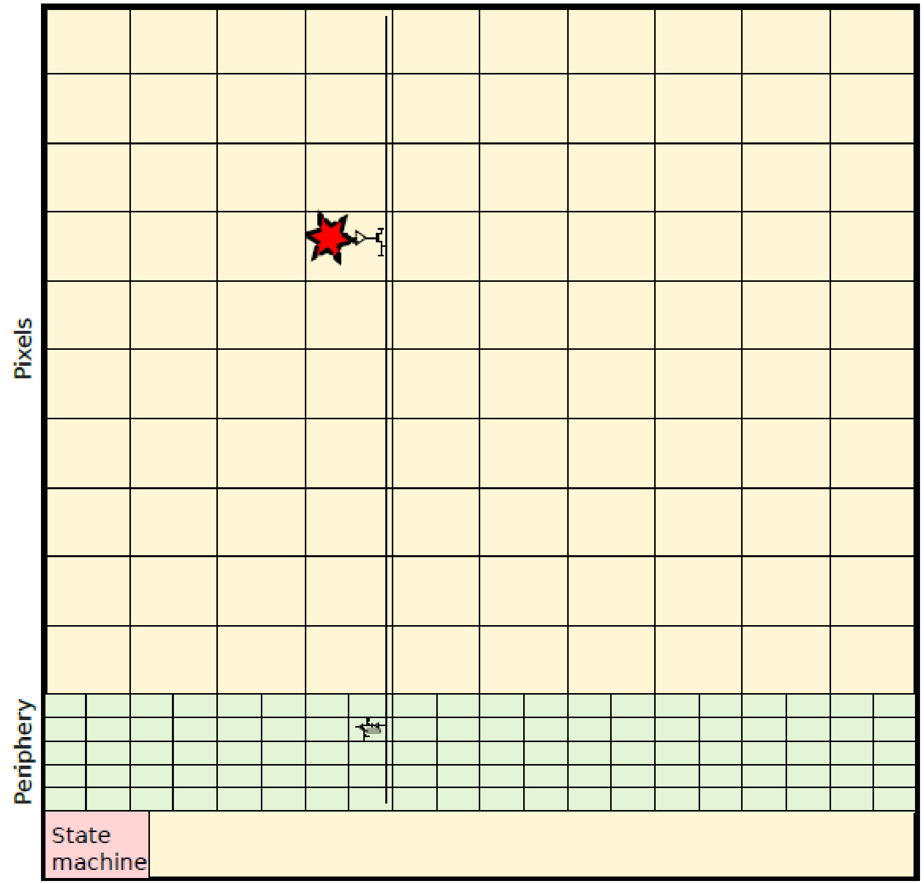
MuPix Readout



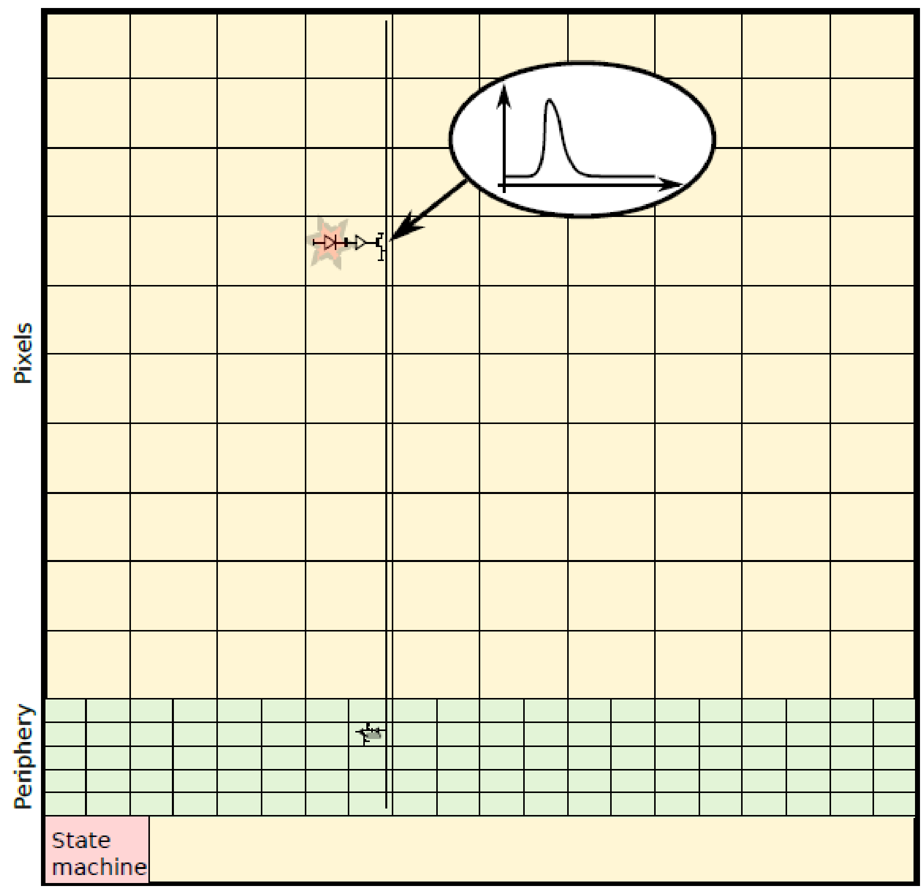
MuPix Readout



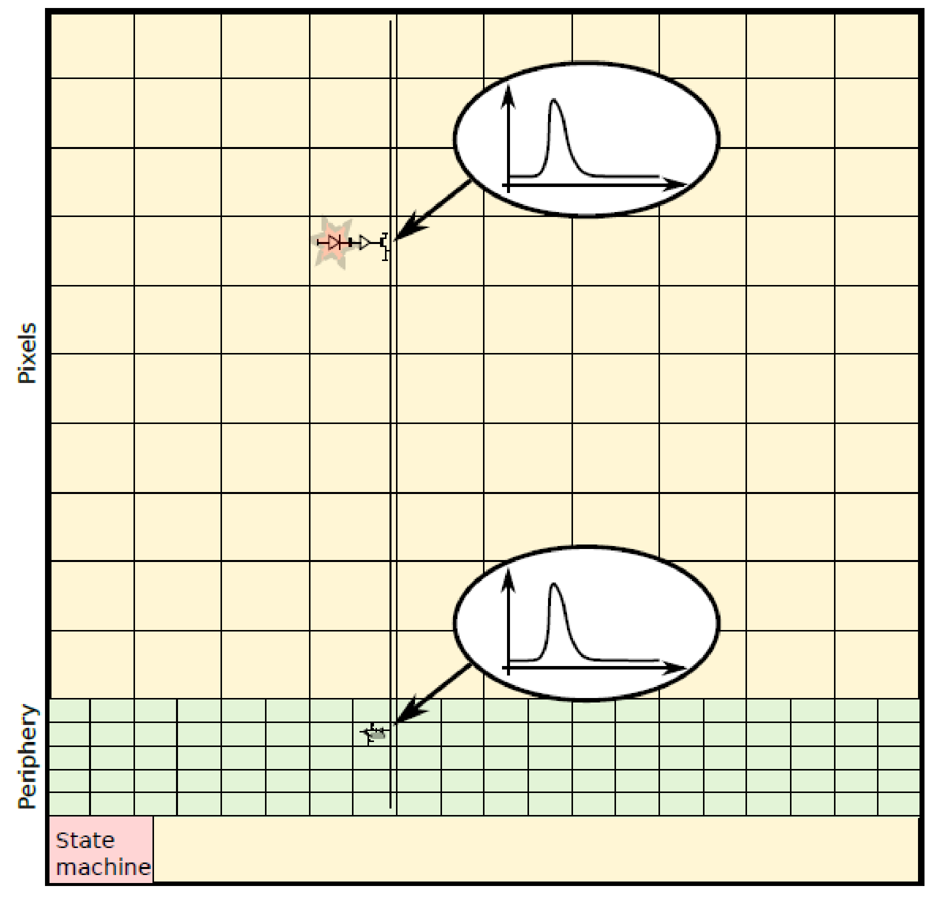
MuPix Readout



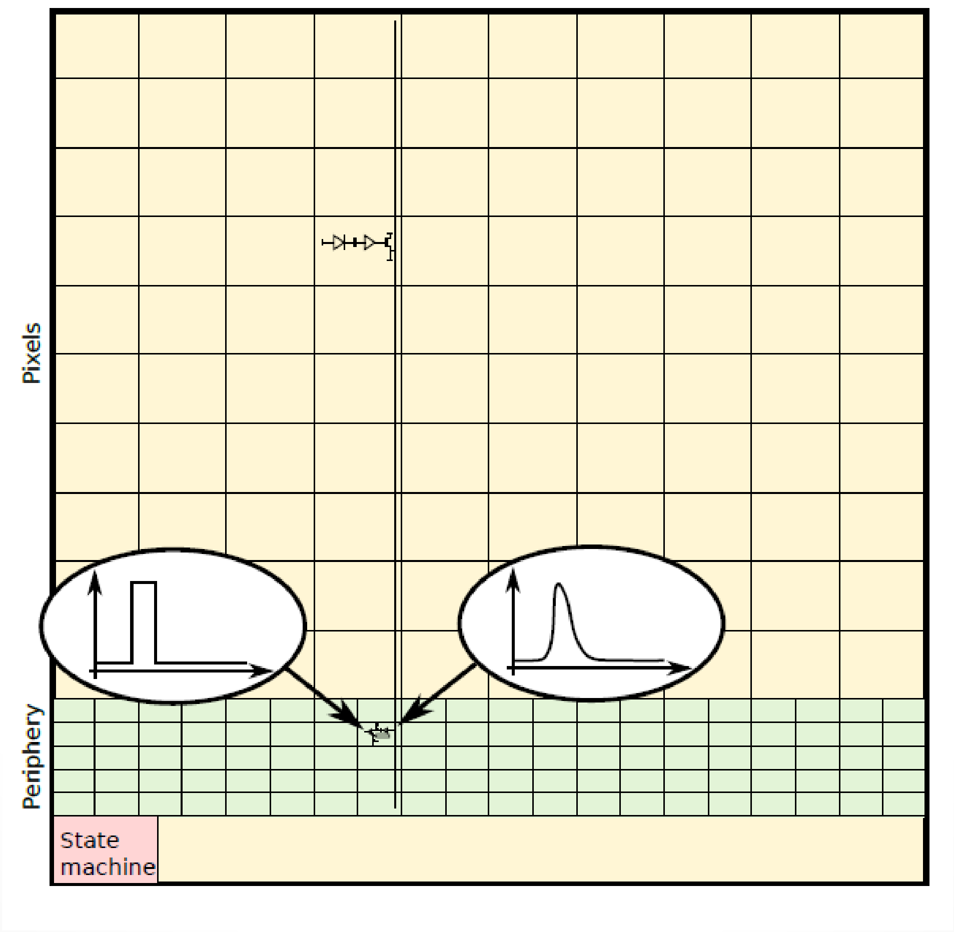
MuPix Readout



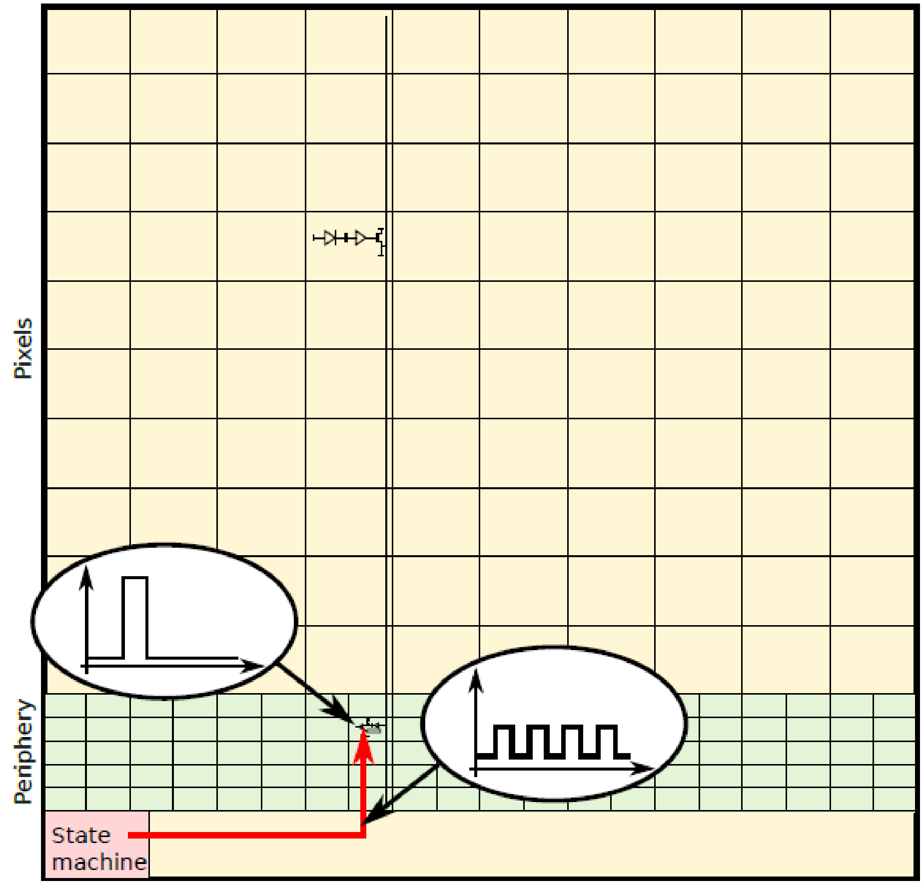
MuPix Readout



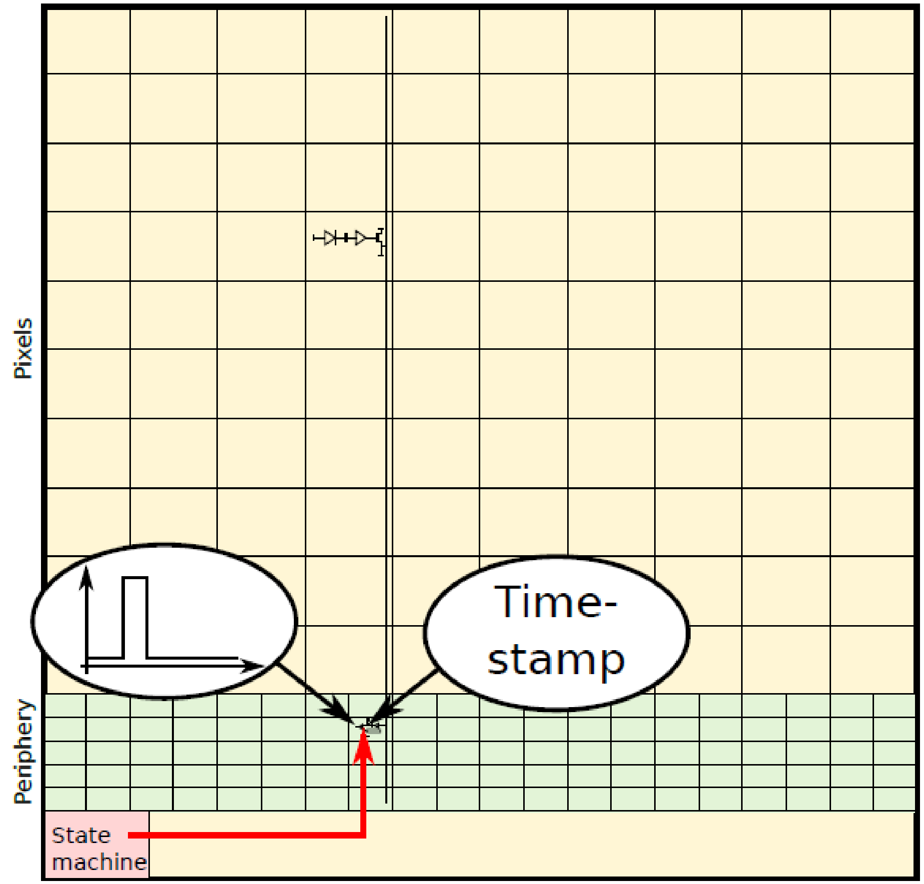
MuPix Readout



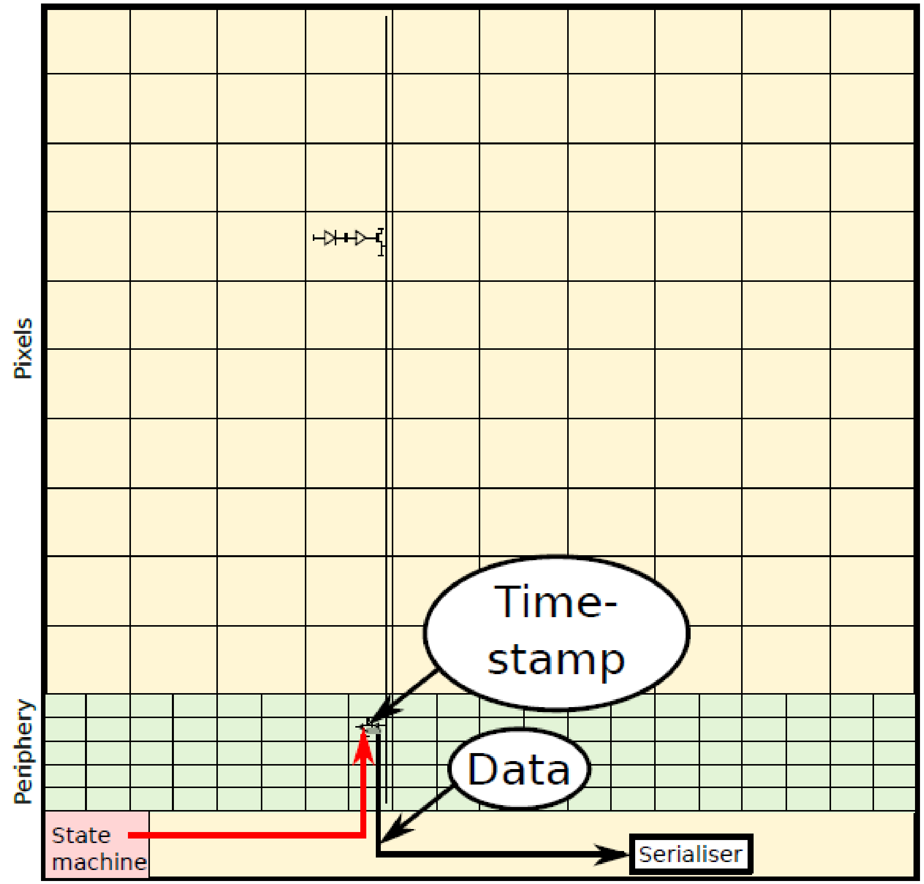
MuPix Readout



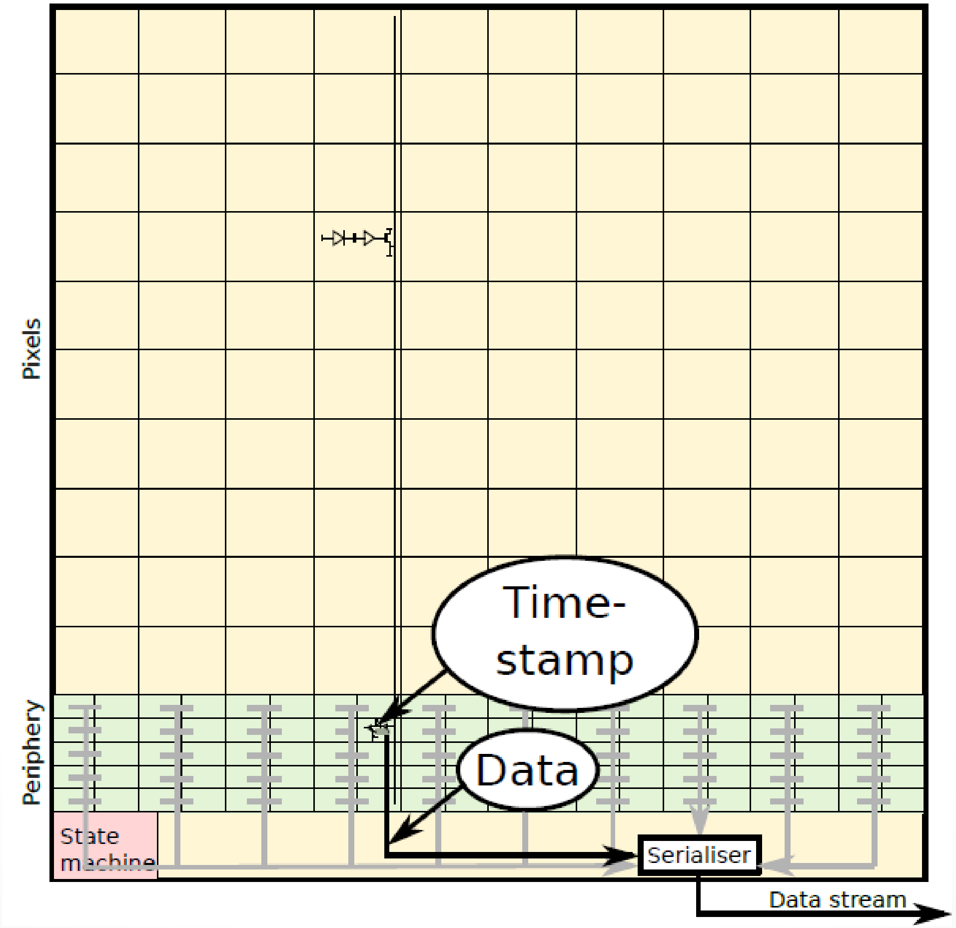
MuPix Readout



MuPix Readout



MuPix Readout

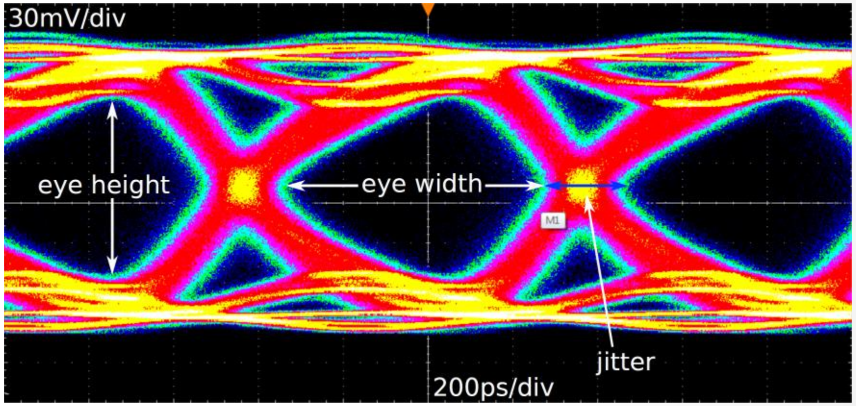


MuPix8 Readout

On Chip:

- Zero suppression
- Read-out state machine
- Voltage controlled oscillator +
- Phase locked loop
- Fast serializer

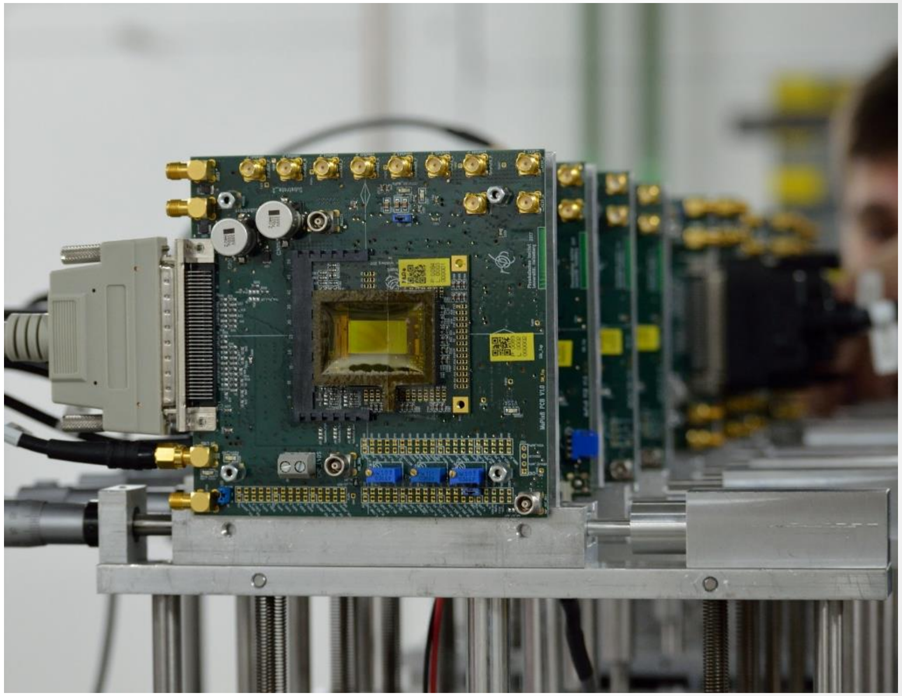
➢ 1.25 Gbit/s LVDS outputs



Eye diagram MuPix8;
eye height 199mV,
eye width > 0.65 UI

Test beam measurements

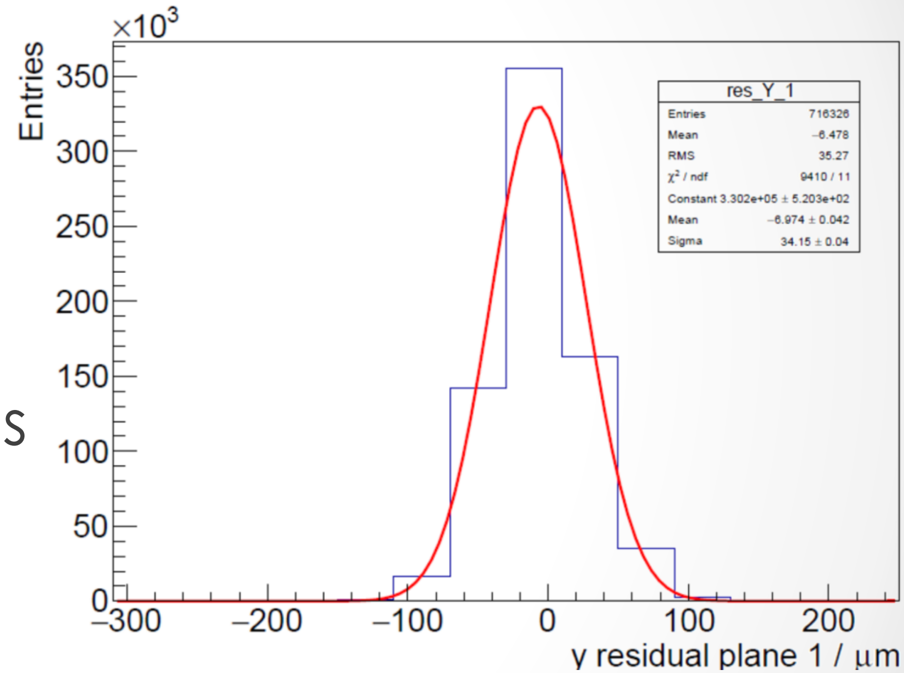
- DESY test beam
  - 4 GeV electrons
- MuPix8 telescope
  - Beam telescope
  - 4 layers of MuPix8 pixel sensors
  - Includes DUT
  - Plastic scintillators as time reference



MuPix8 beam telescope

Spatial Resolution

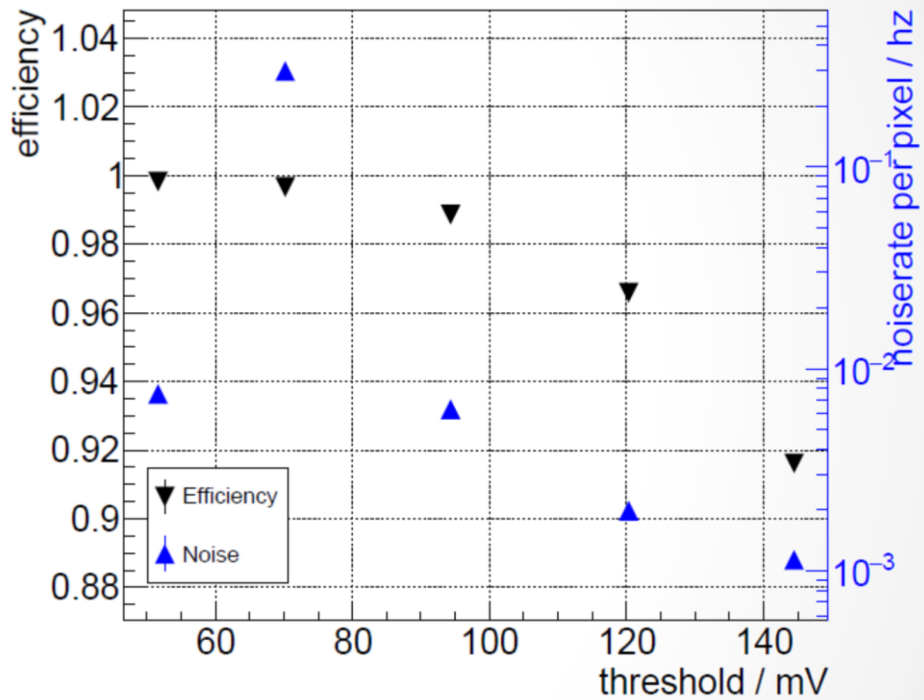
- Pixel size 80 μm x 81 μm
- Measured track residuals:
  - RMS y = 35 μm
  - 80 μm /$\sqrt{12}$ = 23 μm
- ➢ In Mu3e spatial resolution is dominated by multiple Coulomb scattering



MuPix8 spatial resolution

Efficiencies

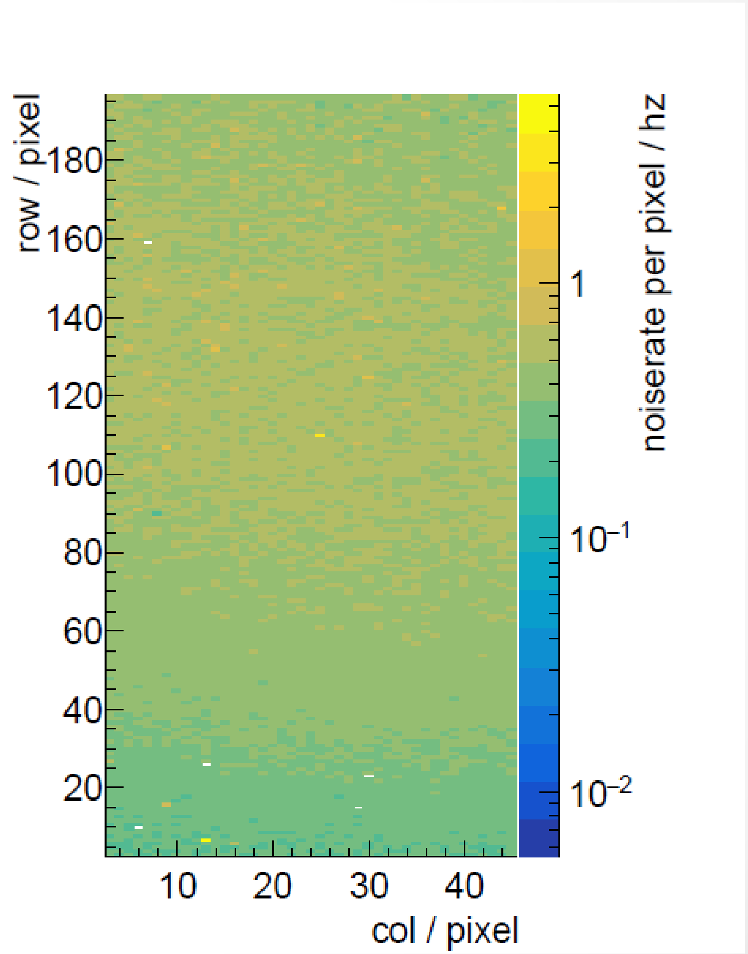
- **>99.5% efficiency**
    - 4 GeV electrons @ DESY
    - 90° impact angle
- Low pixel noise
    - Rate per pixel ~0.2Hz



MuPix8 Efficiency

and Noise

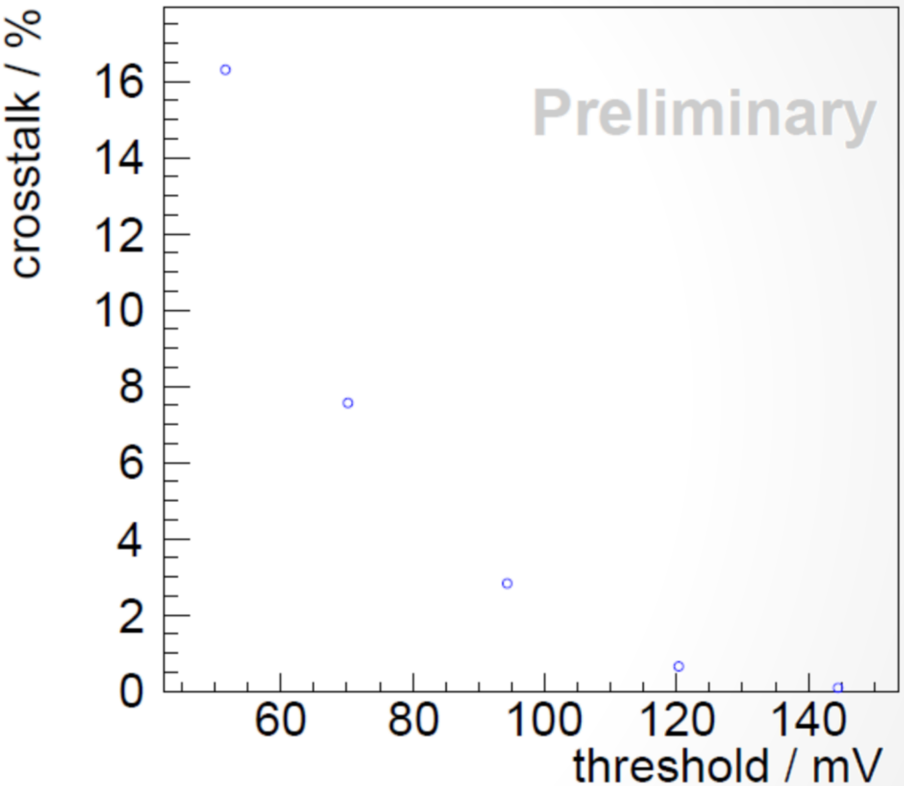
- >99.5% efficiency
  - 4 GeV electrons @ DESY
  - 90° impact angle
- **Low pixel noise**
  - Rate per pixel ~0.2Hz
  - Hot pixels masked



Noise map MuPix8

X-talk

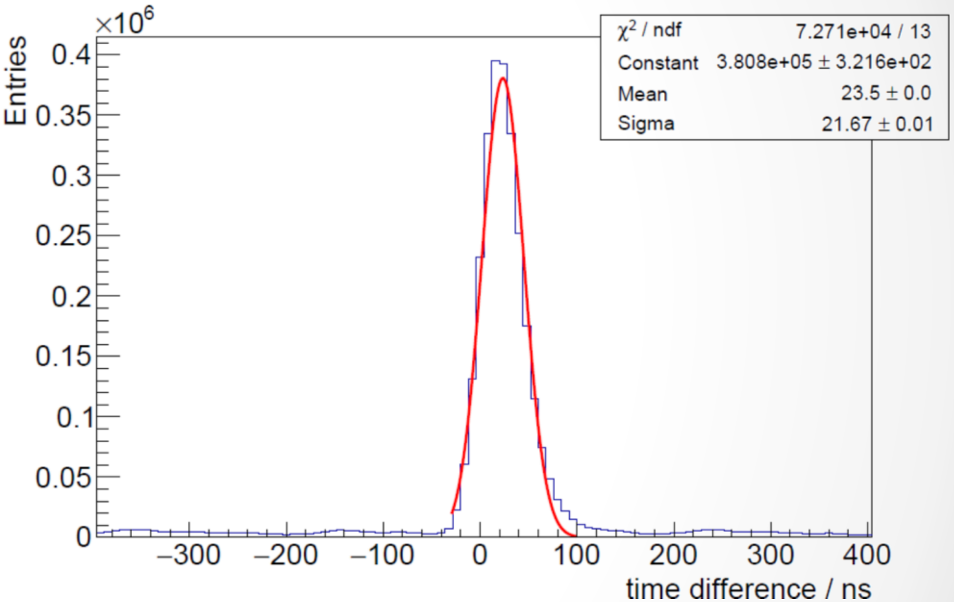
- MuPix8
- DESY November 2017
  - 4 GeV electrons@DESY
- X-talk between
  - **Rows**
  - ≤ 10% around working point



MuPix8 x-talk

Time Resolution

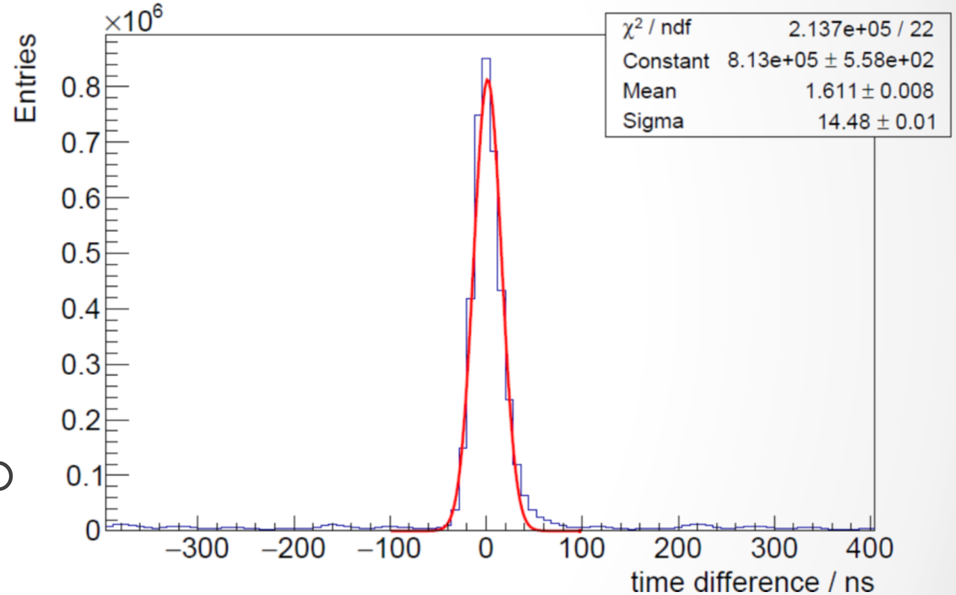
- Time difference of hits registered in MuPix8 and scintillator
- 4 GeV electrons
- Sampling rate is 125 MHz
- $\sigma = 21.67 \pm 0.01$ ns



MuPix8 time resolution

Time Resolution

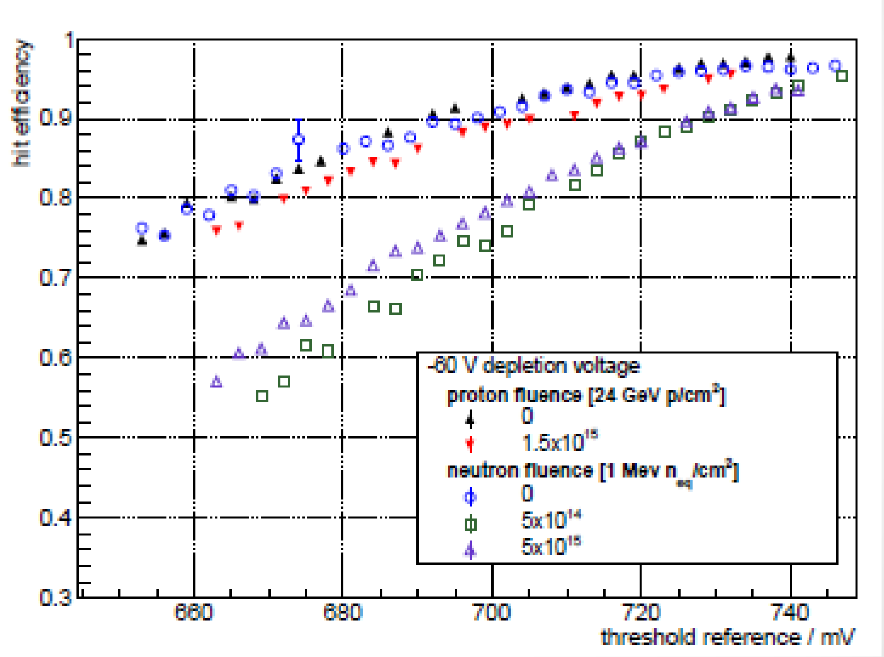
- Time difference of hits registered in MuPix8 and scintillator
- 4 GeV electrons
- Sampling rate is 125 MHz
- $\sigma = 14.48 \pm 0.01$ ns
  - After correcting for pixel to pixel delay differences



MuPix8 time resolution
pixel delay corrected

Irradiation Studies

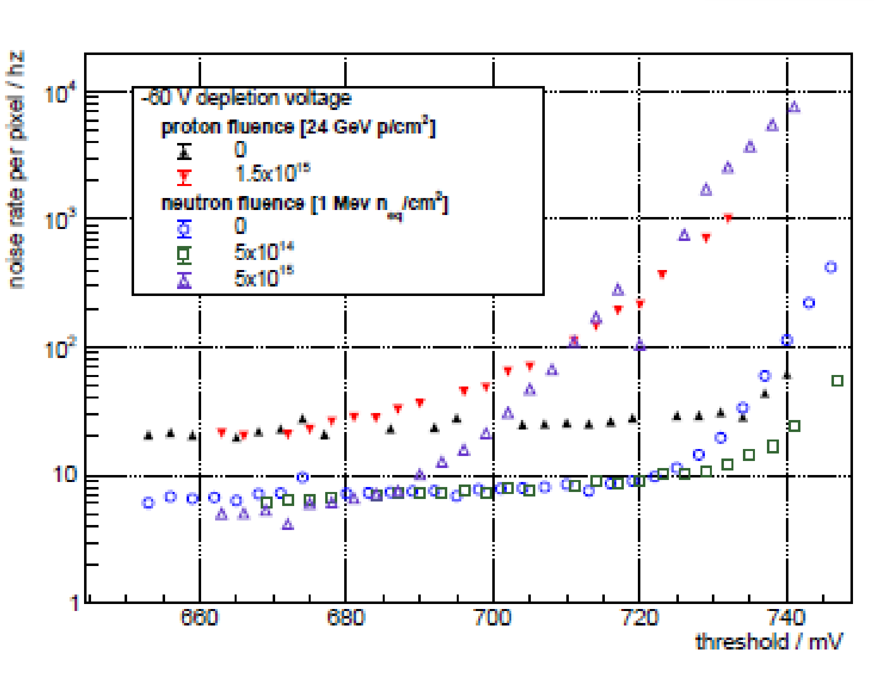
- Irradiation with neutrons and protons
- **MuPix7** irradiated with:
  - o neutrons up to
    - $5.0 \times 10^{15}\ n_{eq}/cm^2$
  - o 24 GeV protons up to
    - $7.8\ \ 10^{15}$ protons/cm^2
- Efficiencies of >90%
- Time resolution < 22ns
- Data transmission at 1.25Gbit/s



Efficiencies lower neutron irradiation

Irradiation Studies

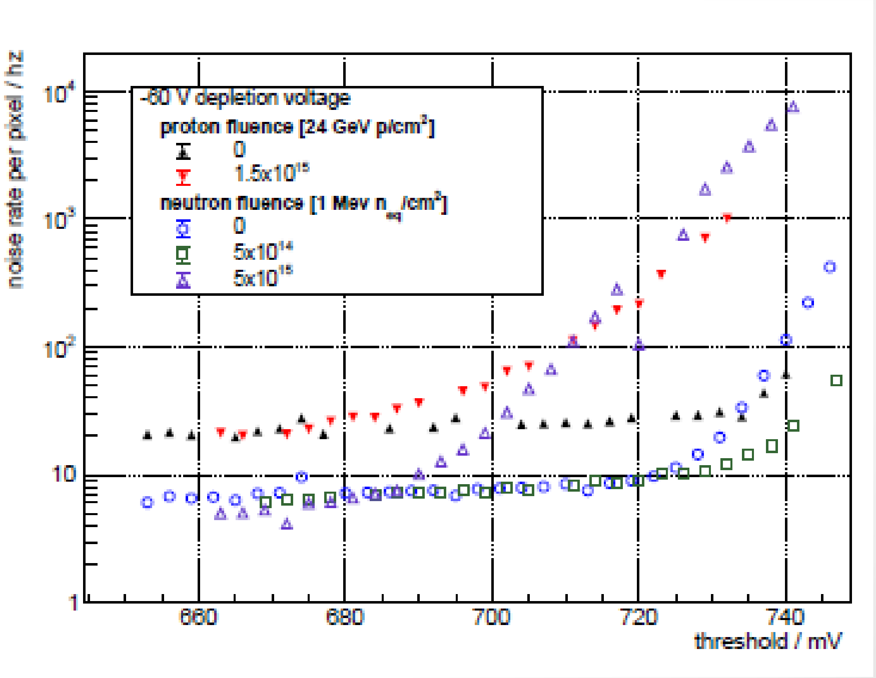
- Irradiation with neutrons and protons
- **MuPix7** irradiated with:
  - neutrons up to
    - 5.0 x 10^{15} n_{eq}/cm^2
  - 24 GeV protons up to
    - 7.8 10^{15} protons/cm^2
- Efficiencies of >90%
- Time resolution < 22ns
- Data transmission at 1.25Gbit/s



Noise increase with irradiation

Irradiation Tests

- Irradiation with neutrons and protons
- **MuPix7** irradiated
- Efficiencies of >90%
- Time resolution < 22ns
- Data transmission at 1.25Gbit/s

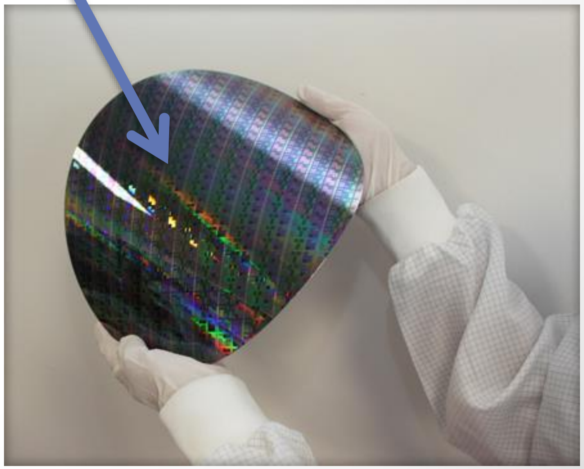


Summarized in:
H. Augustin et al.
Irradiation study of a fully monolithic HV-CMOS pixel sensor design in AMS 180 nm
https://arxiv.org/abs/1712.03921v2

Thinning

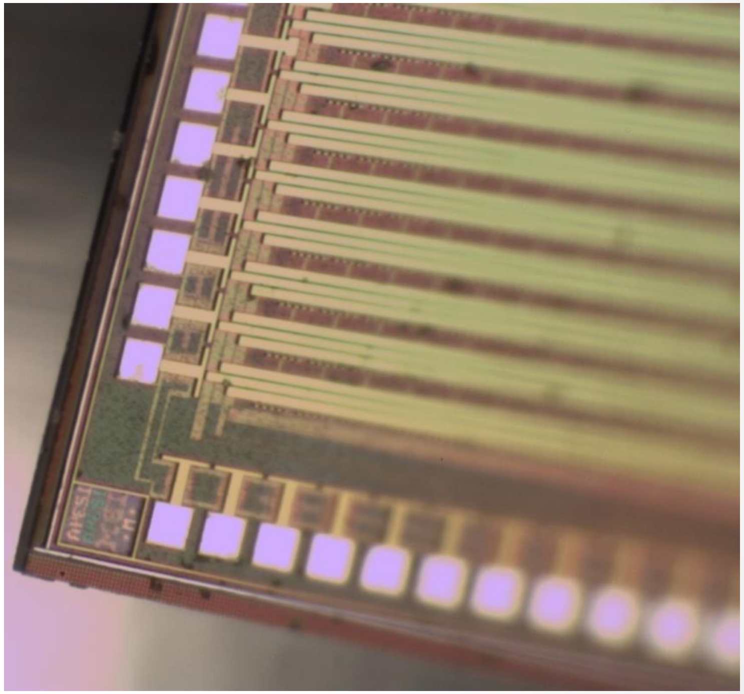
50 µm Si-wafers

- Commercially available
- HV-CMOS 50 µm (AMS)
- 50 µm for MuPix4 and MuPix7
  - 50 µm MuPix8 not tested



Thinned Sensors

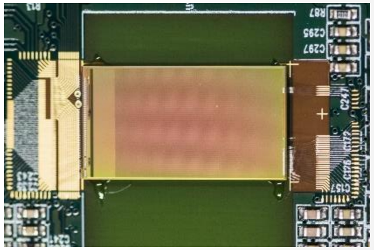
- Prototypes thinned:
  - MuPix8 thinned to 70 µm, 100 µm
- Good performance of thin chips
  - In lab
  - In particle beam
- MuPix8 50 µm just back
- MuPIx4 and MuPix7 thinned to 50 µm showed good performance

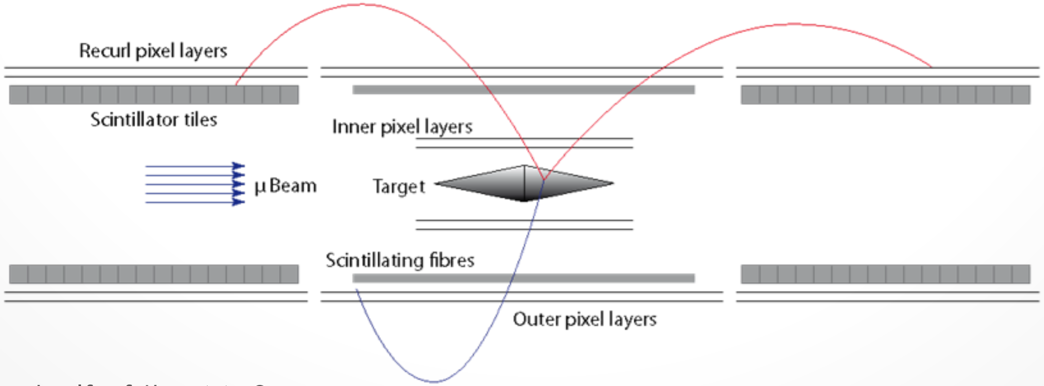


MuPix4 thinned to 50µm

Summary

- Mu3e searches for lepton flavor violation
- Ultra thin tracker with ~182M pixel
- ➢ **H**igh **V**oltage **M**onolithic **A**ctive **P**ixel **S**ensors
- Prototypes exceed requirements



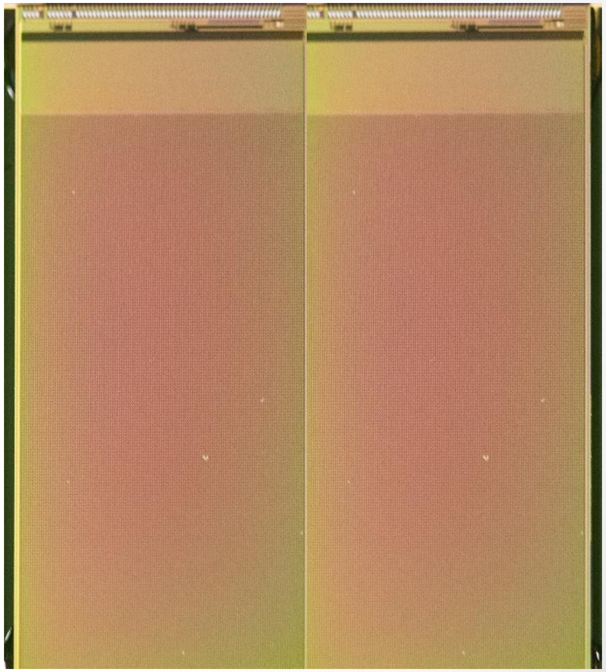


Schedule

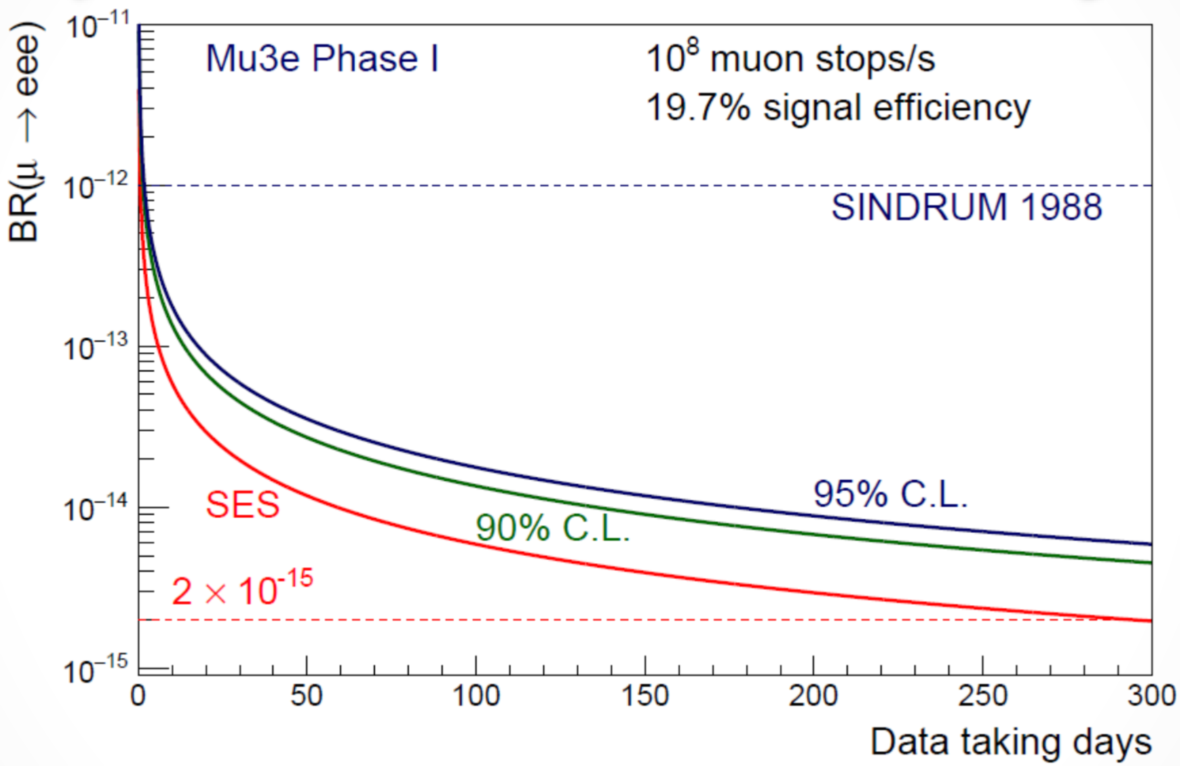
- **2018** Design of full size HV-MAPS chip
- **2019** Magnet delivery and detector **construction**
- **2020** Installation and **commissioning** at PSI
- **2021** Data taking at up to a few **10^8 μ/s**

Outlook: MuPixX

- 2x2 cm^2 pixel matrix
- Reduced number of I/O pads
- I^2C inspired slow control
- Comparator in pixel cell?
  - No analog x-talk on transmission line
- Better power distribution
  - Better timing?
- On chip ADC
  - Temperature measurement



Outlook: Projected Sensitivity



Single event sensitivity (SES) and the corresponding 90% and 95% C.L. upper limits versus data taking days for the Mu3e detector

Institutes

Mu3e-collaboration:

- ETH Zürich, Switzerland
- PSI, Switzerland
- University of Geneva, Switzerland
- Physics Institute, University of Heidelberg, Germany
- Kirchhoff Institute, University of Heidelberg, Germany
- Institute for Process Data Processing and Electronics, Karlsruhe Institute of Technology, Germany
- Institute of Nuclear Physics, University of Mainz, Germany
- University of Zürich, Switzerland
- The University of Liverpool, United Kingdom
- University of Oxford, United Kingdom
- University of Bristol, United Kingdom
- University College London, United Kingdom

Acknowledgements

- The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)
- We would like to thank PSI for valuable test beams!
- We thank the Institut für Kernphysik at the Johannes Gutenberg University Mainz for giving us the opportunity to take data at the MAMI beam.

Backup Slides
…

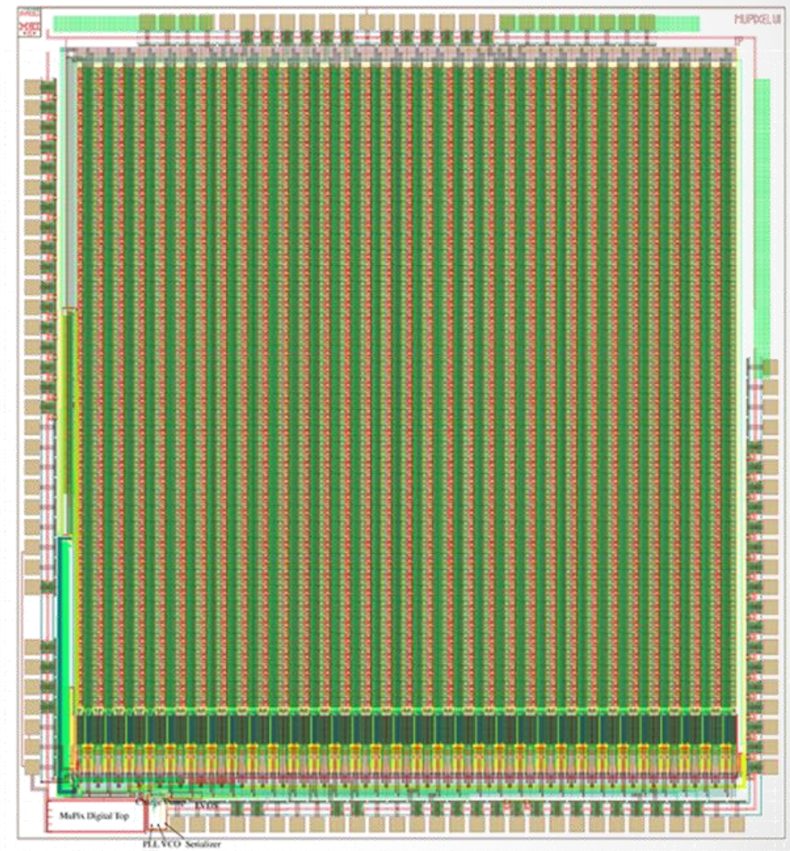
HV-MAPS Backup

Prototype Overview

Prototype	Active Area	Functionality	Bugs	Improvements
MuPix1	1.77 mm^2	Sensor + analog	Comparator **"ringing"**	First MuPix prototype
MuPix2	1.77 mm^2	Sensor + analog	**Temperature** dependence	**No ringing**
MuPix3	9.42 mm^2	Sensor, analog, dig.	bad pixel **on/off**,	**First** part of **dig.** readout
MuPix4	9,42 mm^2	Sensor, analog, dig.	Zero time-stamp and **row address** for 50% of pixels	Working digital readout, **timestamp**, temperature stable
MuPix6	10.55 mm^2	Sensor, analog, dig.	?	Removed zero time-stamp and address bug
MuPix7	10.55 mm^2	System on Chip	X-talk	Fast serial readout
MuPix8	160 mm^2	Large S.o.C.	First batch has metal 3 issues	Large, Time walk correction

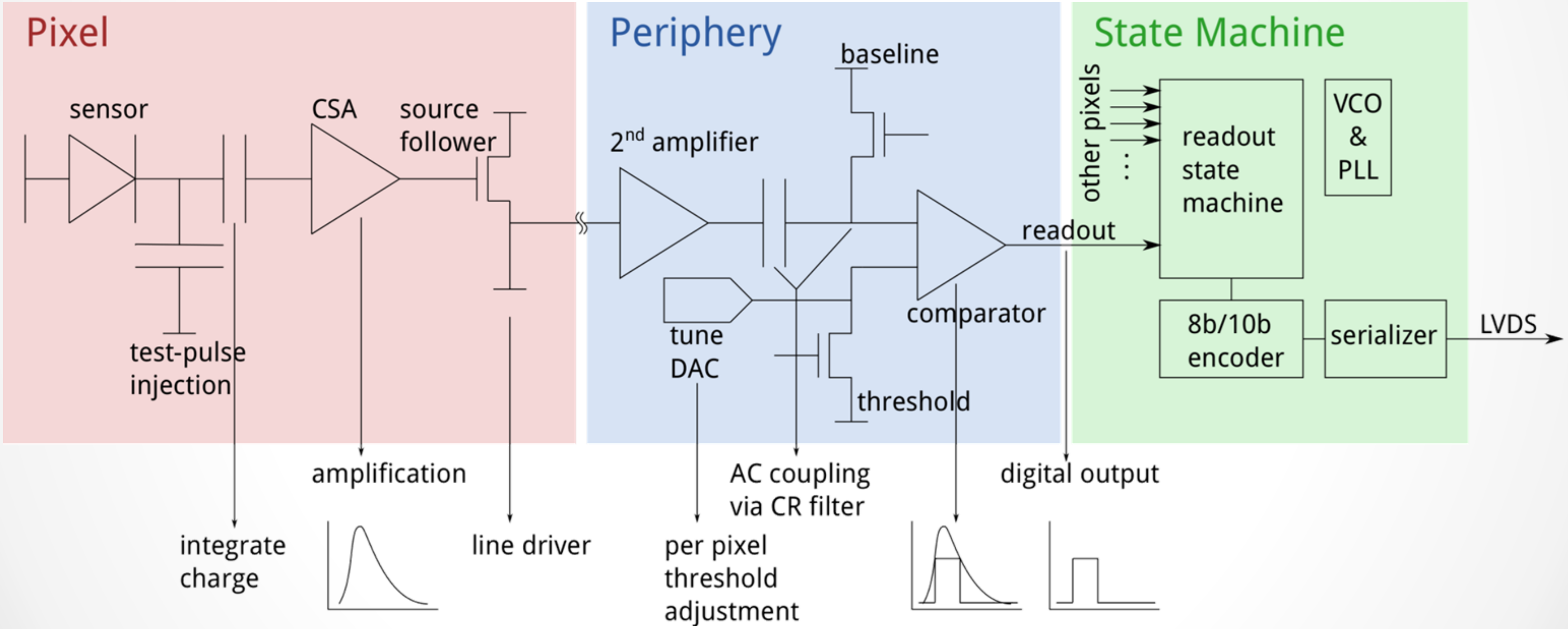
Full System on Chip

- 180 nm HV-CMOS
- Pixel matrix:
  - 40 x 32 pixels
  - 103 x 80 μm² each
- Analog part
  - Temperature tolerant
- Digital part
  - Full system on chip



MuPix7

Sensor + Analog + Digital

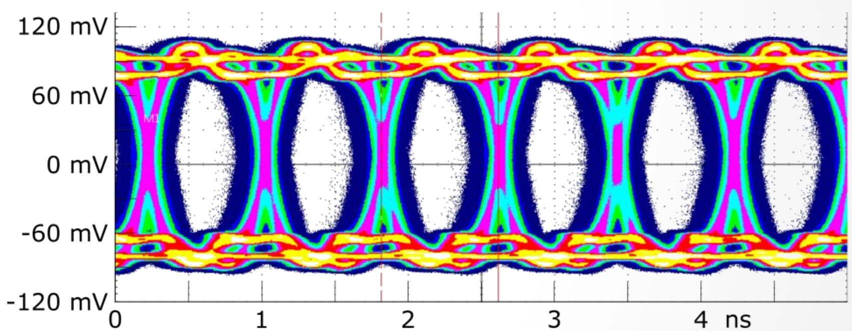


Chip Readout

On Chip:

- Zero suppression
- Read-out state machine
- PLL and VCO
- Fast serializer

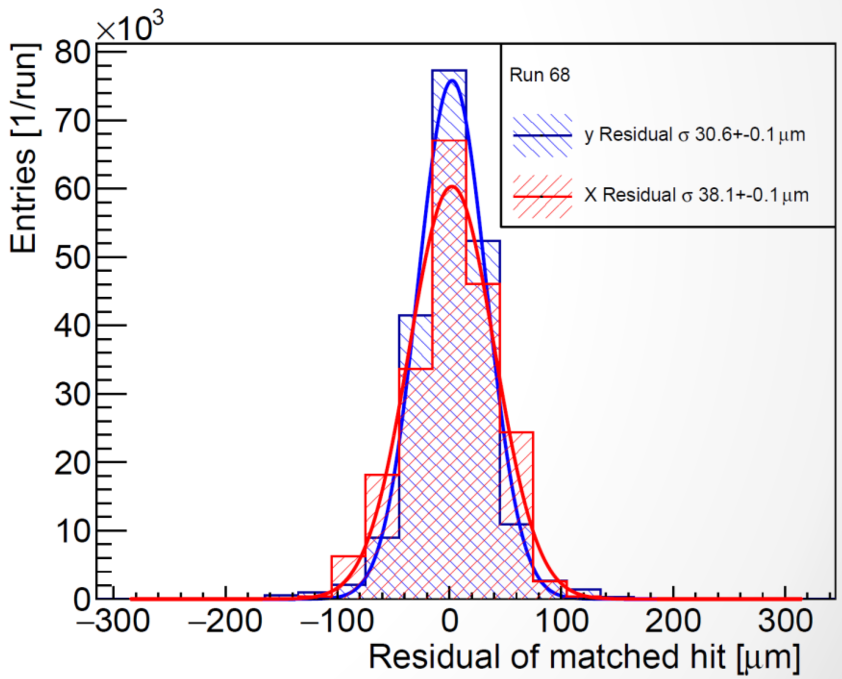
➢ 1.25 Gbit/s LVDS output



Eye diagram MuPix7;
eye height > 130mV,
eye width > 0.65 UI

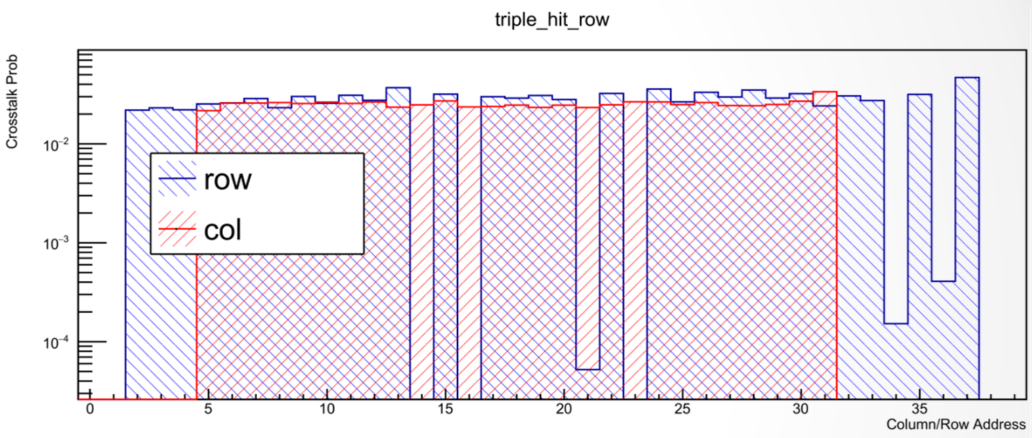
Spatial Resolution

- Pixel size 80 µm x 103 µm
- Measured track residuals:
  - RMS x = 38.1 ± 0.1 µm
  - RMS y = 30.6 ± 0.1 µm



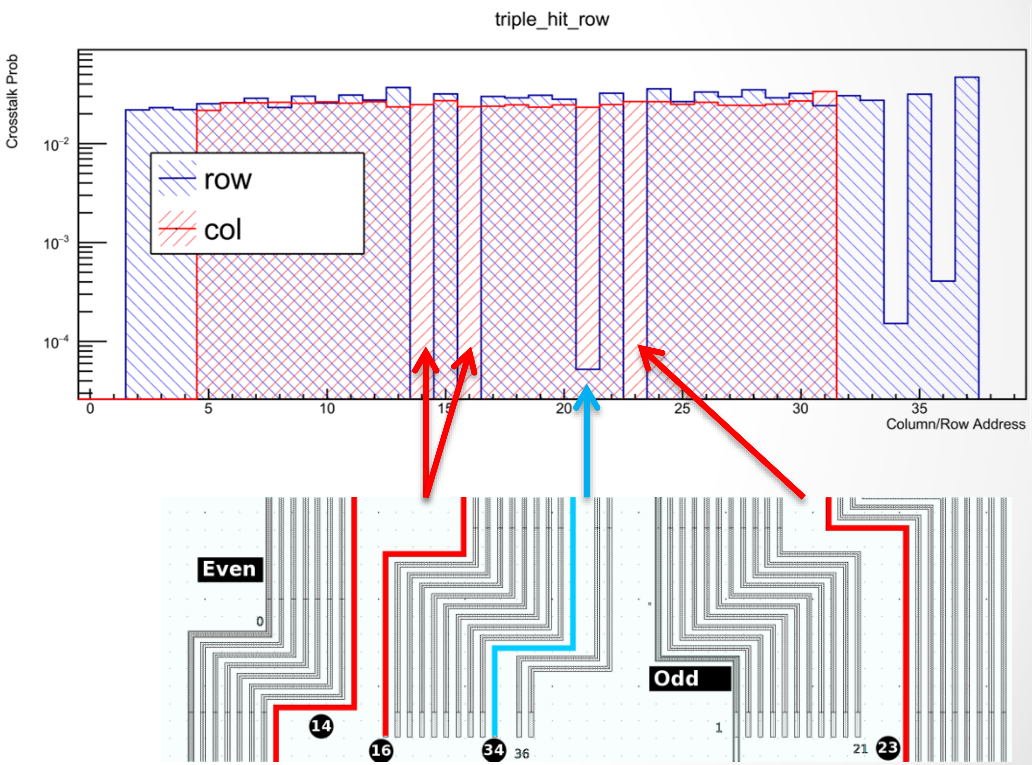
X-talk

- MuPix7
- PSI October 2015
  - 250 MeV e^+/μ^+/pion
- X-talk between
  - **Rows**
  - Around 10%



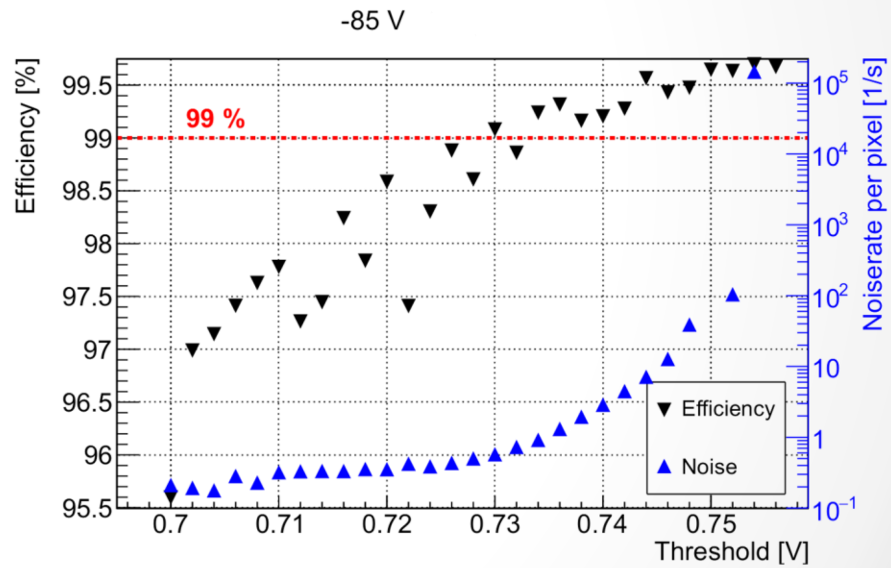
X-talk

- MUPIX7
- PSI October 2015
  - 250 MeV e^+/μ^+/pion
- X-talk between
  - **Rows**
- Capacitive coupling
  - Line from diode to comparator
  - Strongly depends on layout



Efficiencies

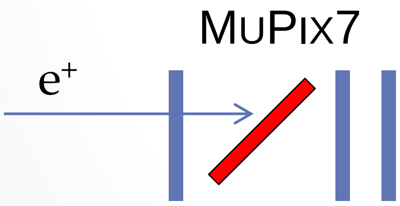
- **>99.5% efficiency**
  - 4 GeV electrons@DESY
  - 90° impact angle
  - Individual pixel thresholds



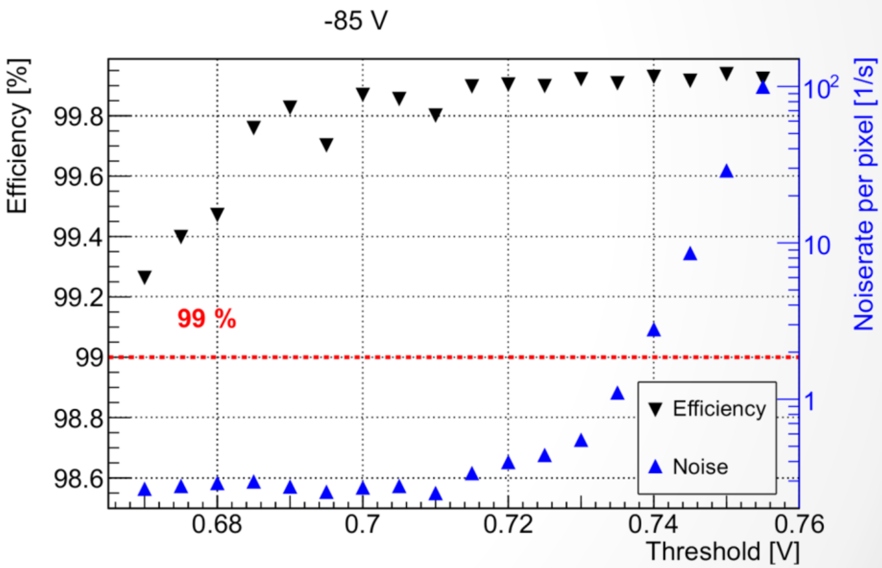
MuPix7 Efficiency

Efficiencies rotated Sensor

- **>99.8% efficiency**
  - 4 GeV electrons
  - 30° impact angle
  - Individual pixel thresholds



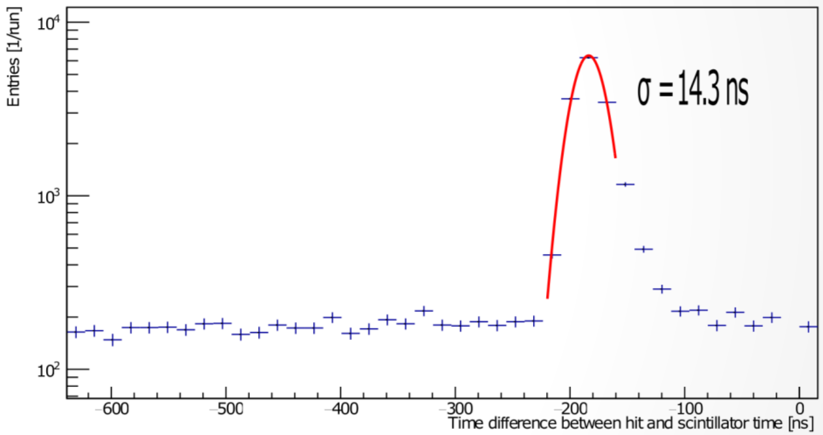
MuPix7 under angle



MuPix7 Efficiency

Time Stamps

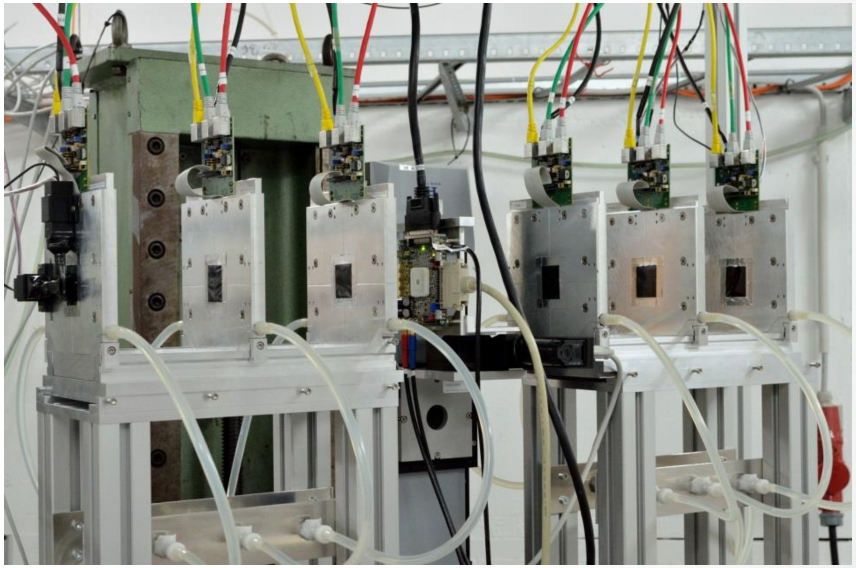
- Time difference of hits registered in MuPix 7 and scintillator
- 4 GeV electrons
- Sampling rate is 62.5 MHz



Time Resolution of Pixels

Setup March 2016 Test-Beam @ DESY

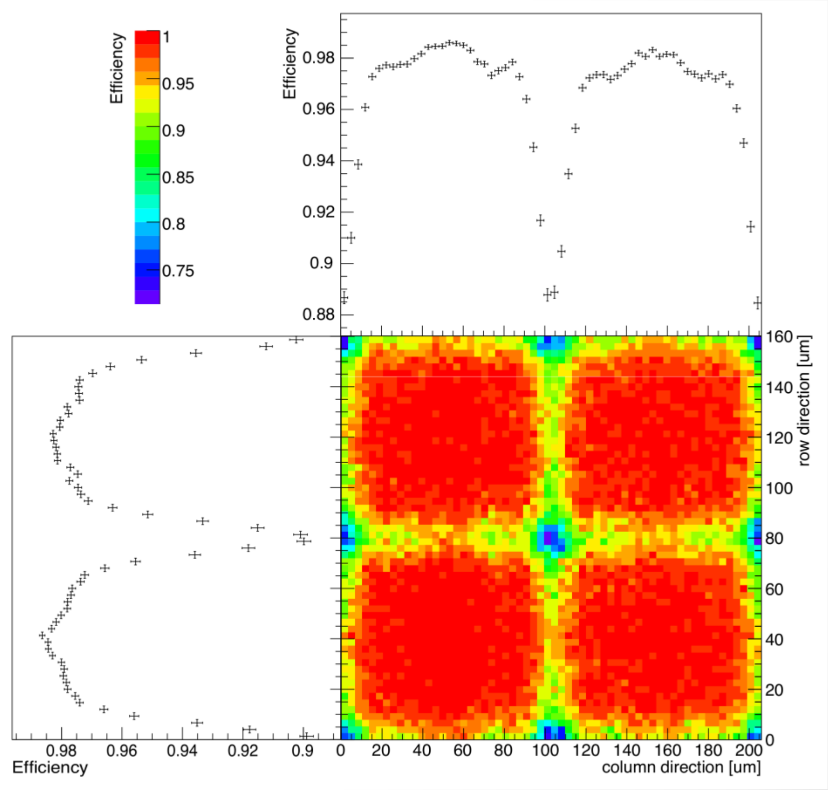
- Beam-line TB22
  - up to **5 GeV** electrons
- Aconite telescope
- MuPix7 prototype
- Readout setup from PI Heidelberg



MuPix7 @ DESY test-beam in EUDET telescope

Sub-Pixel Efficiencies

- Hit efficiency map and projections for 2×2 pixel array
- 4 GeV electrons
- Bias voltage −40V to enhance the inefficient regions
- Studies for **MuPix8** ongoing



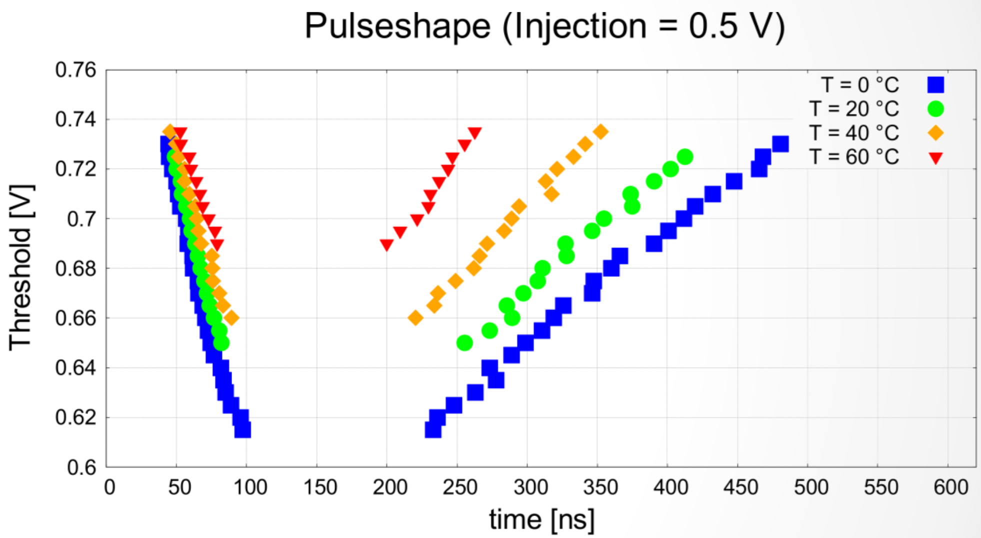
MuPix7

Temperature Dependence

- Pulse shape vs temperature
  - Injection pulse to pixel discriminator output
- Climate chamber
  - 0°C, 20°C, 40°C, 60°C

➢ Significant change to
  ➢ Pulse shape
  ➢ Signal amplitude

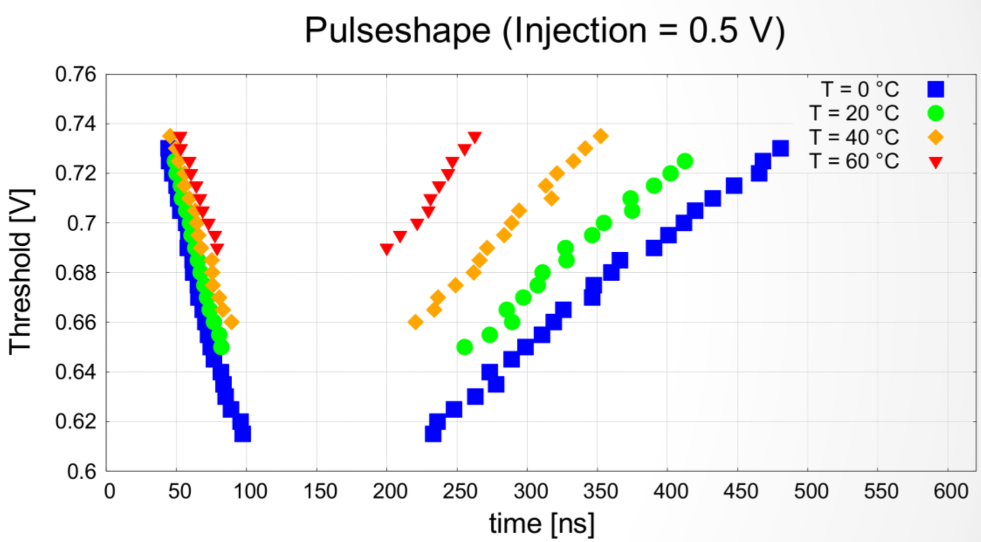
➢ Slight change to time resolution
  ➢ Re-calibration



MuPix7
High bias currents (1W/cm²)
HV -85V

Temperature Dependence

- Pulse shape vs temperature
  - Injection pulse to pixel discriminator output
- Climate chamber
  - 0°C, 20°C, 40°C, 60°C
- ➢ Significant change to
  - ➢ Pulse shape
  - ➢ Signal amplitude
- ➢ Slight change to time resolution
  - ➢ Re-calibration



MuPix8 still under investigation

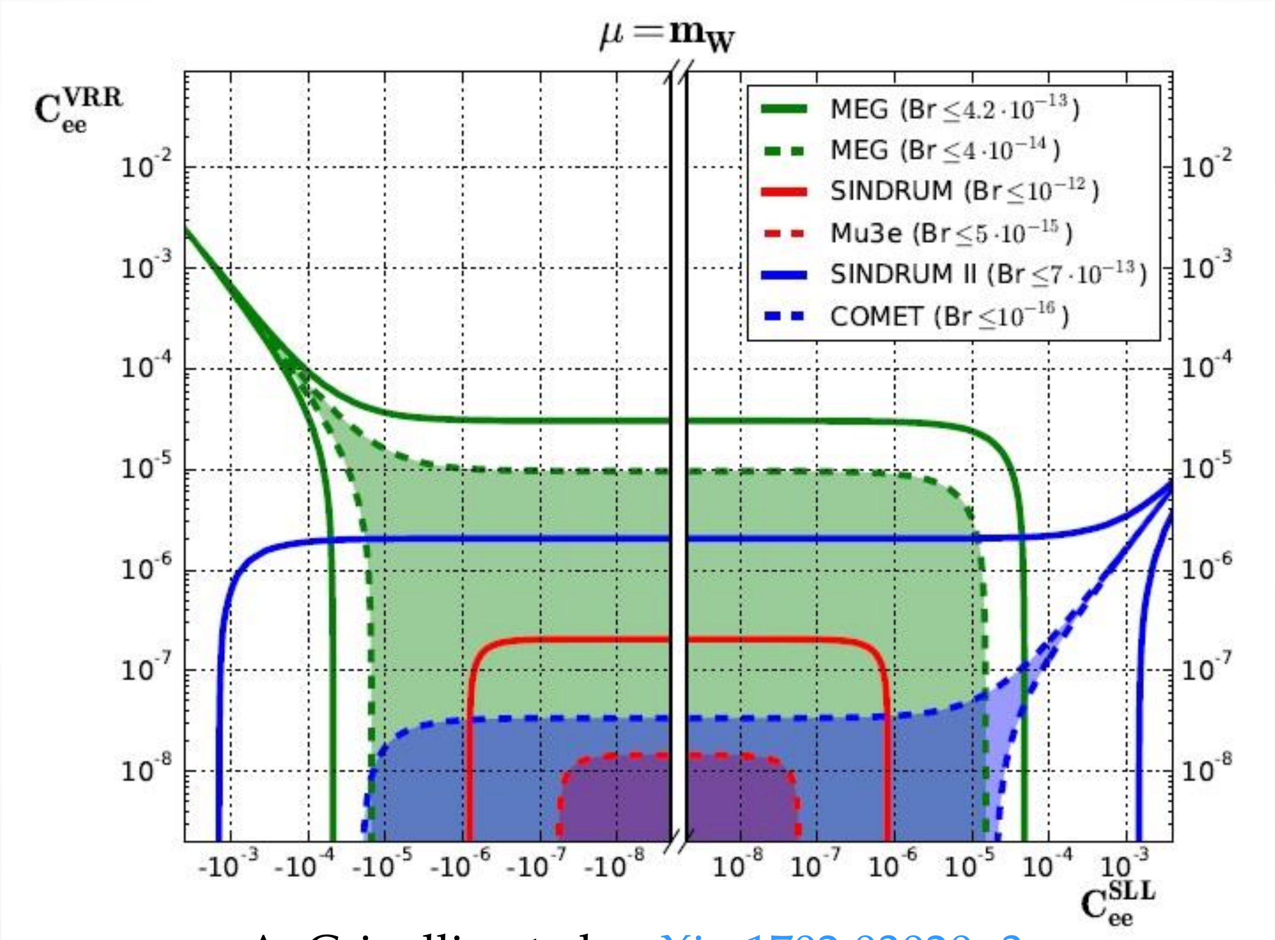
Challenges

…

Challenges

- High rates: 10^8 μ/s
- Good timing resolution: 100 ps
- Good vertex resolution: ~200 μm
- Excellent momentum resolution: ~ 0.5 MeV/c^2
- Extremely low material budget:
  - 1×10^{-3} X_0 (Si-Tracker Layer)
- HV-MAPS spectrometer
  - 50 μm thin sensors
  - B ~1 T field
- + Timing detectors

μ→eee vs. μ→eγ and μN→eN

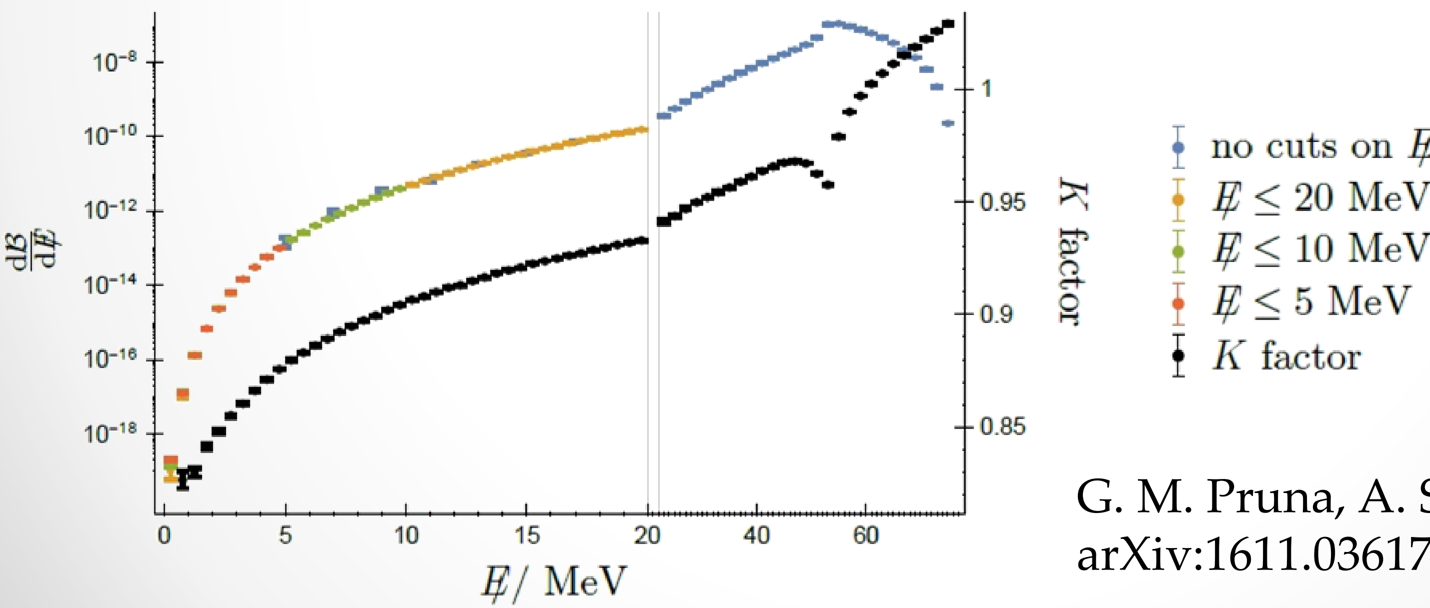


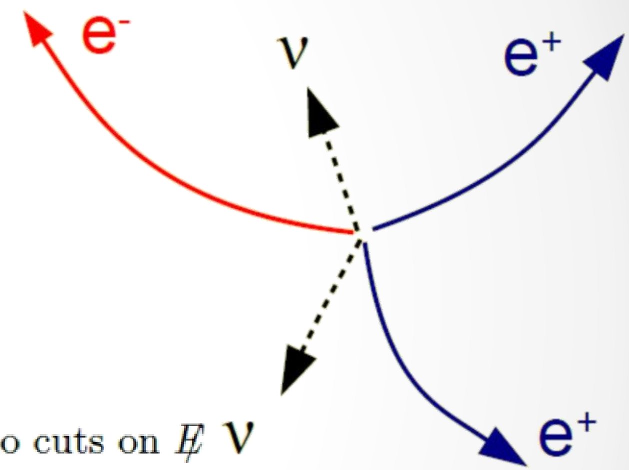
A. Crivellin et al. arXiv:1702.03020v3

The Mu3e Background

- Irreducible background: $\mu^+ \rightarrow e^+ e^- e^+ \nu\nu$
- $\sum E_e < m_\mu c^2$
- $\sum \overrightarrow{p_e} \neq 0$

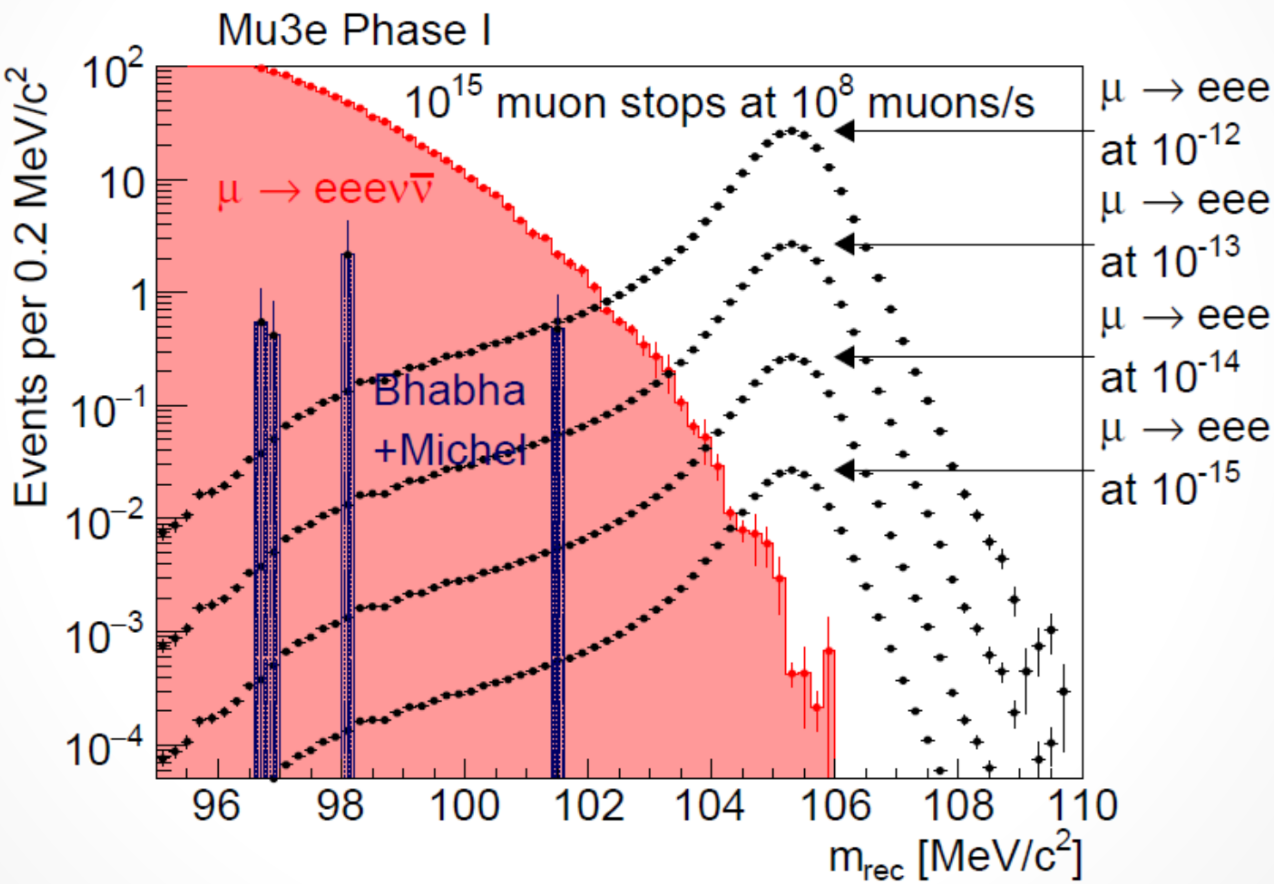
➢ **Good momentum resolution**





G. M. Pruna, A. Signer, Y. Ulrich
arXiv:1611.03617v1

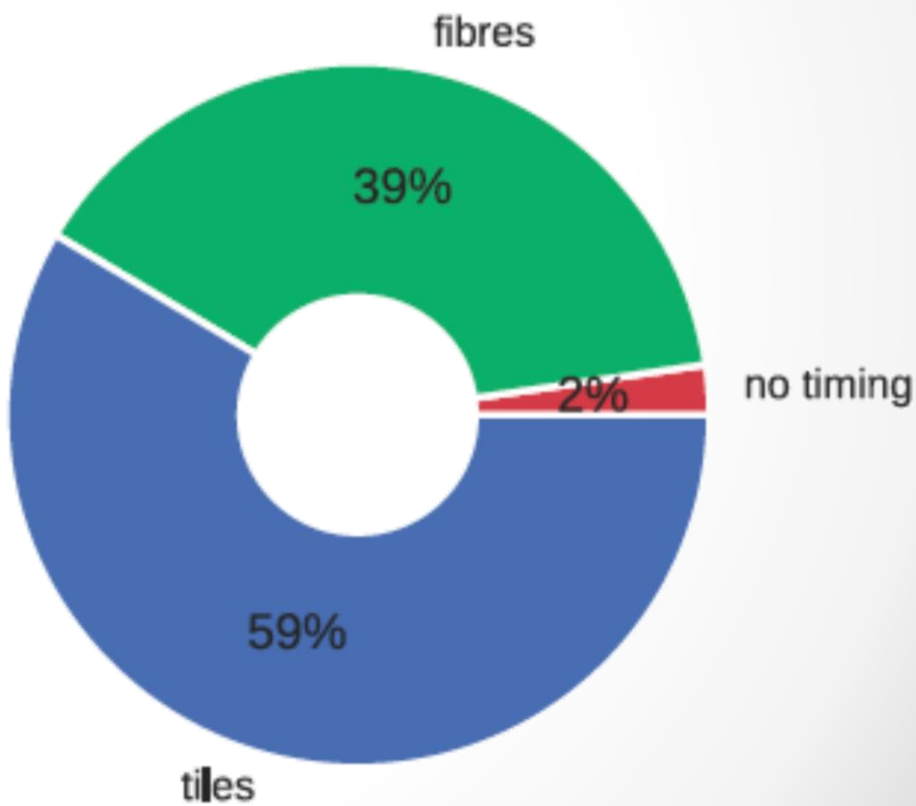
Outlook: Phase I performance Simulation



SciFi Backup

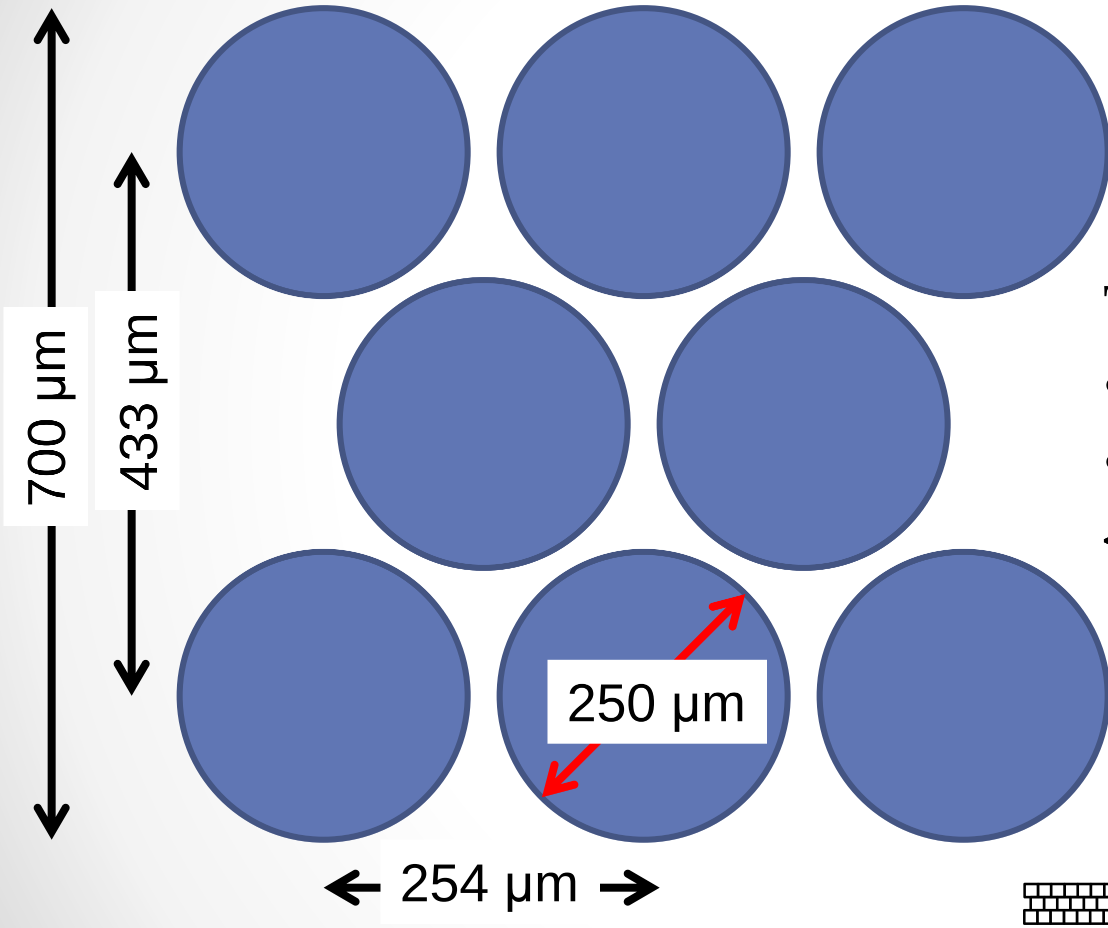
Timing Detectors

- Combinatorial background suppression by a factor of 100 needed



Details …

staggered layers

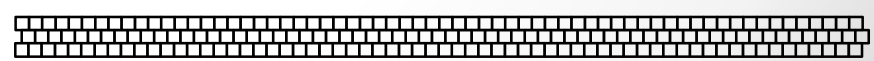


Thickness:

- theoretical ~ 683 µm
- measured ~ 750 µm

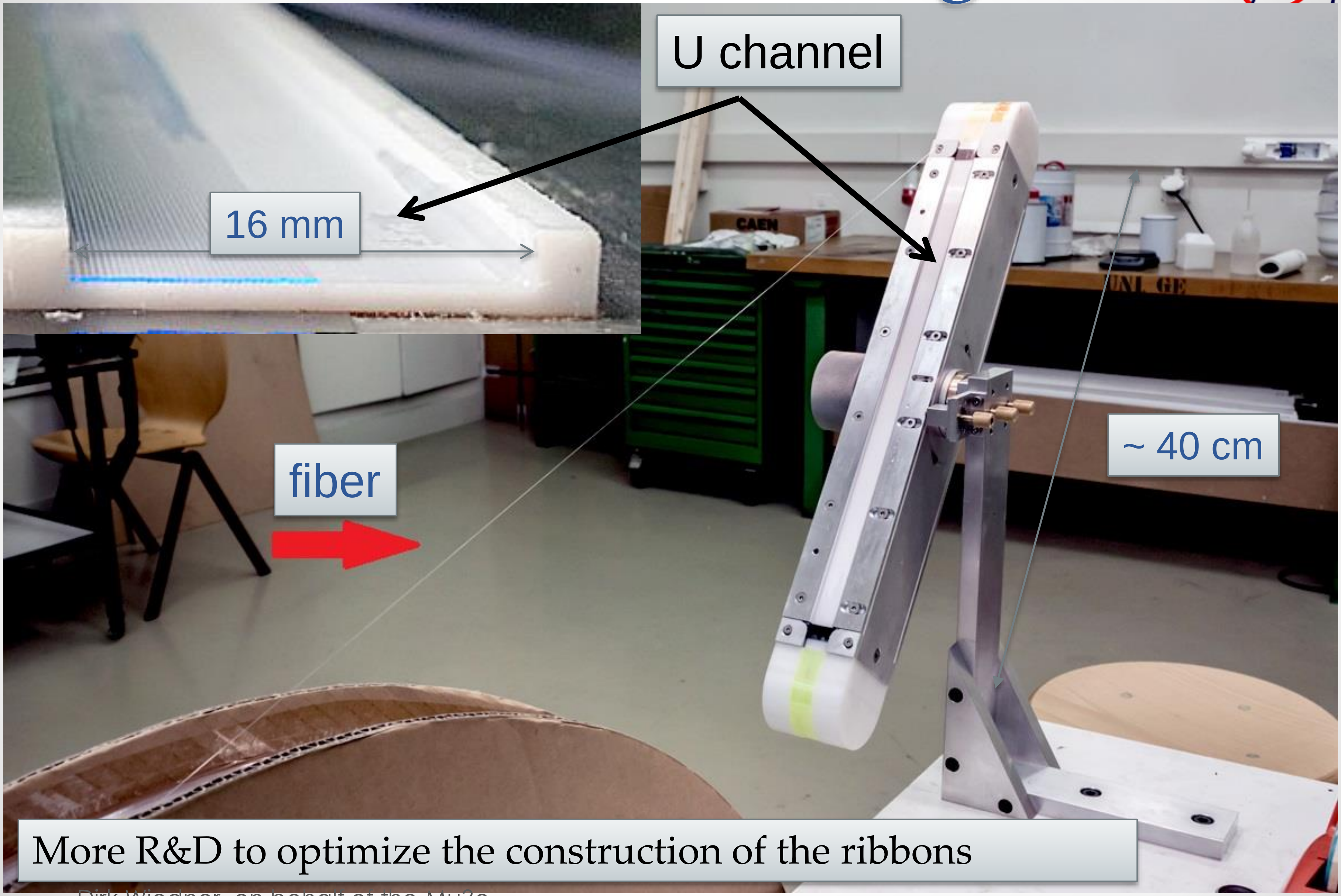
< 1 g of glue / ribbon

Alternative:
Square shape fibers



Horizontal gap between fibers ~ 4 µm

Fiber Winding Tool

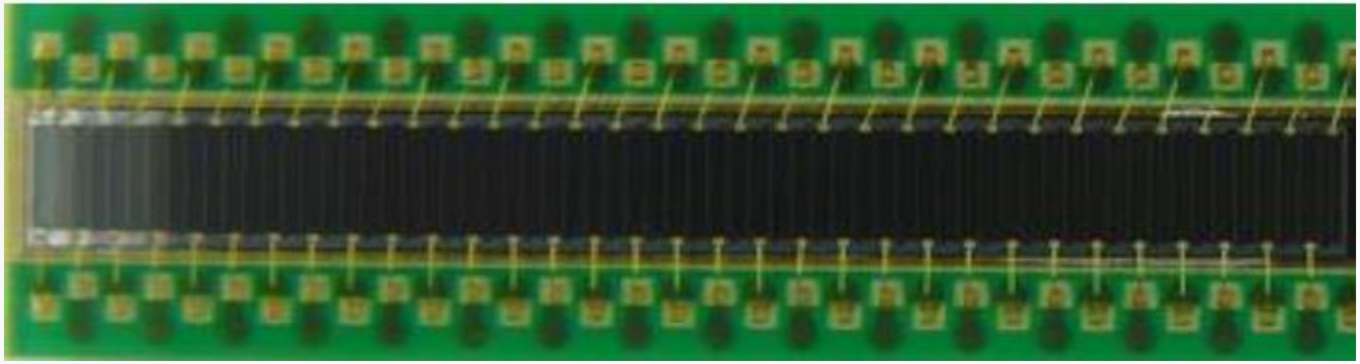


More R&D to optimize the construction of the ribbons

Readout of Fibers

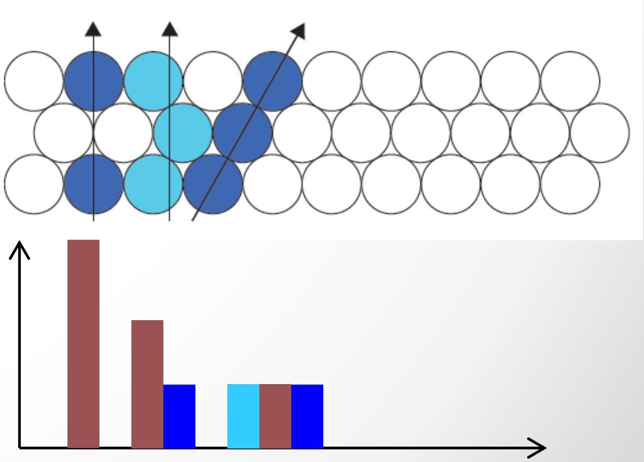
Si-PMs (MPPCs) at both fiber ends

SciFi column readout with Si-PM arrays



LHCb type detector

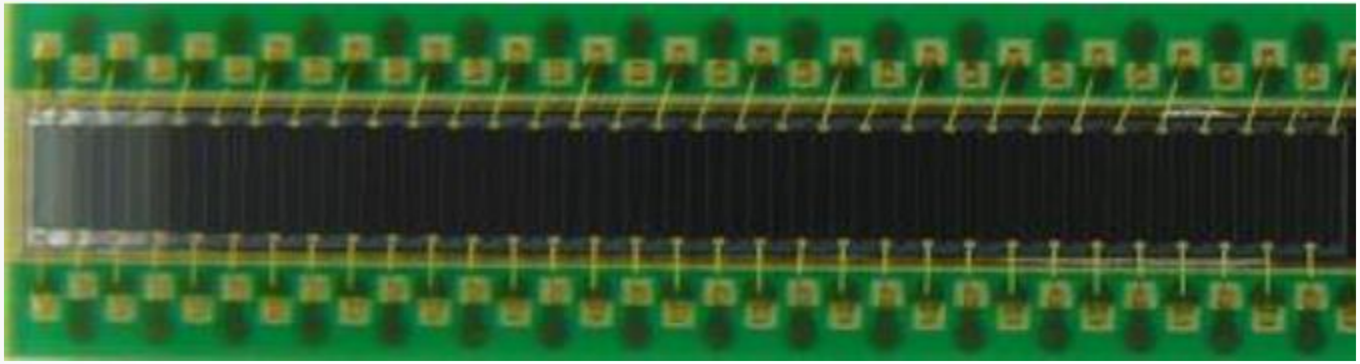
- 64 channel monolithic device (custom design)
- ~250 µm effective “pitch”
- 50 µm × 50 µm pixels
- Grouped in 0.25 mm × 1 mm vertical columns
- Common bias voltage



Readout of Fibers

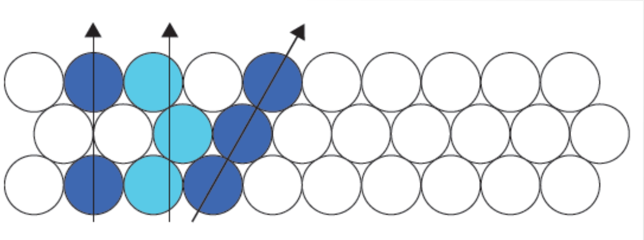
Si-PMs (MPPCs) at both fiber ends

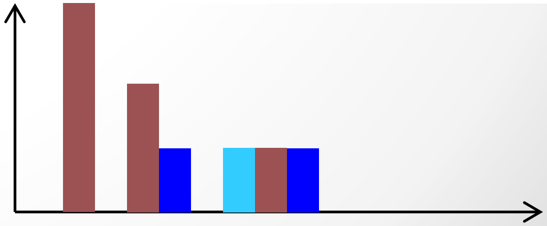
SciFi column readout with Si-PM arrays



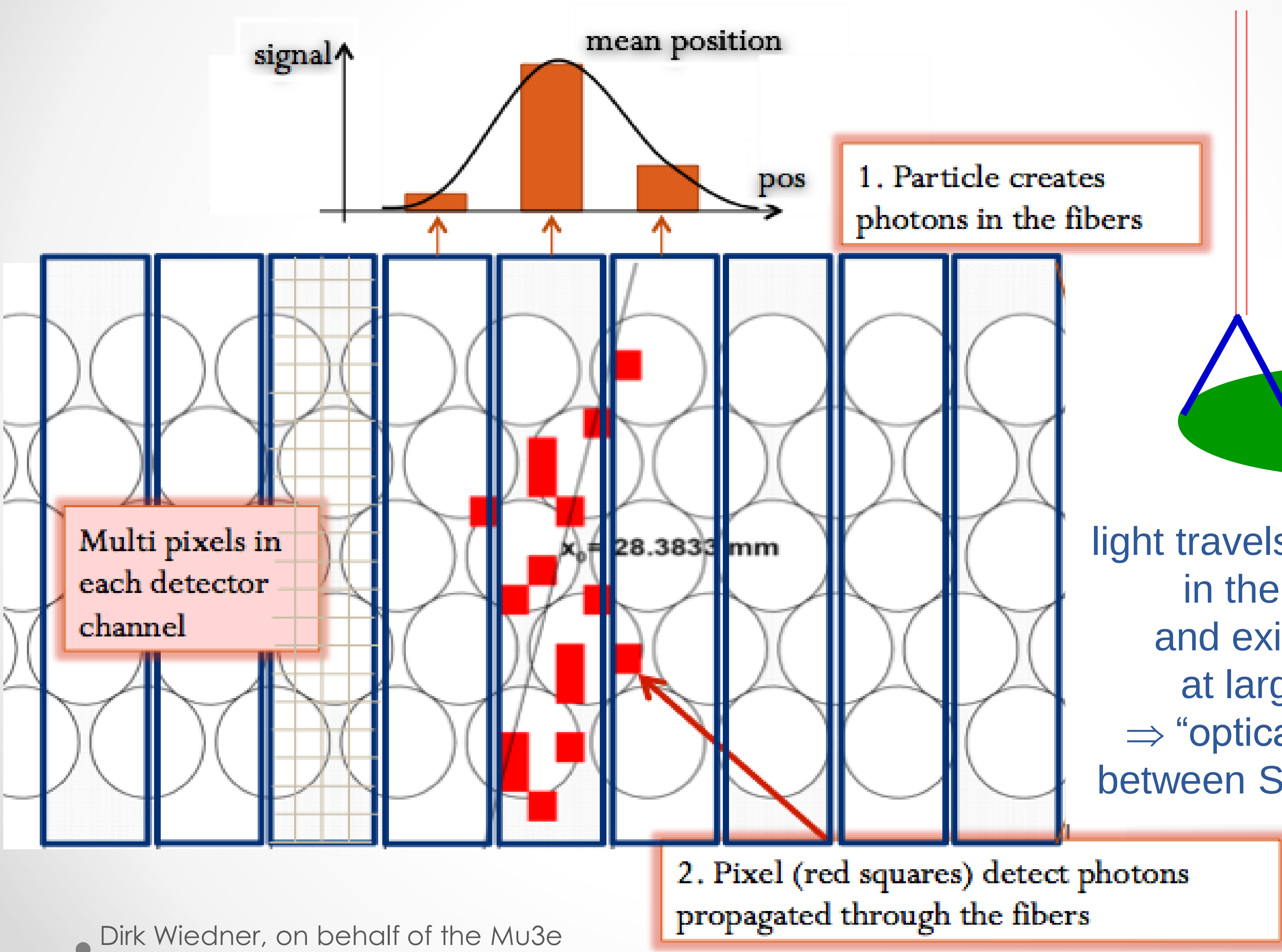
LHCb type detector

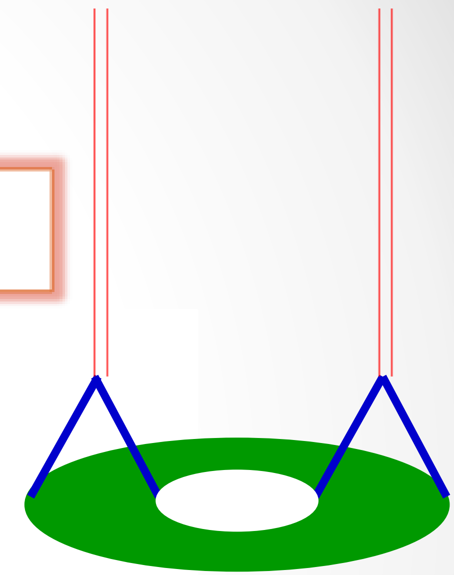
- ☺Reduced # of readout channels (2 × 64)
- ☺Easy, direct coupling
- ☹ Higher occupancy
- ☹ “Optical” cross talk





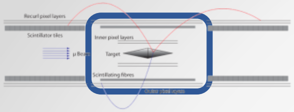
SciFi Column Readout





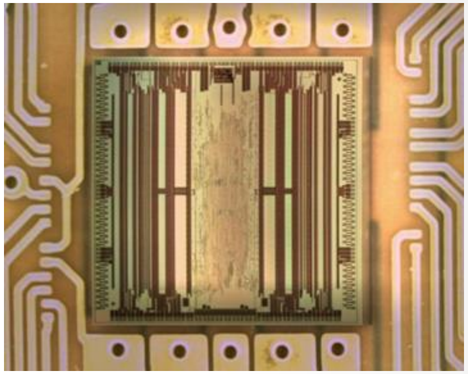
light travels preferentially in the cladding and exits the fiber at large angles

⇒ “optical” cross talk between Si-PM columns



Readout Electronics

- **MuTRiG** ASIC (KIP)
- Fulfills SciFi requirements
  - Compact design
    - Installation very close to Si-PM arrays
  - 32 channels
    - 4 chips / Si-PM array
    - Assuming MuTRiG can sustain ~10 MHz hit-rate
- Performance to be tested
  - In particular for low photon yield



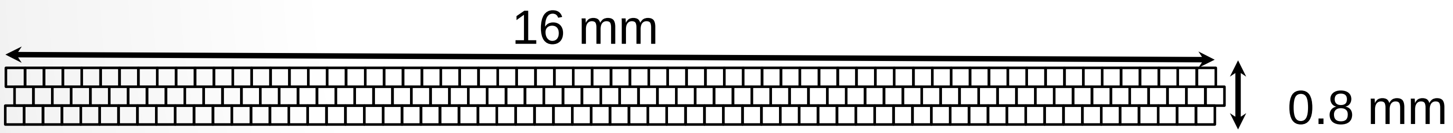
STiC

Alternative Design with Square Fibers

2-3 layers of 250 μm square double cladding scint. fibers

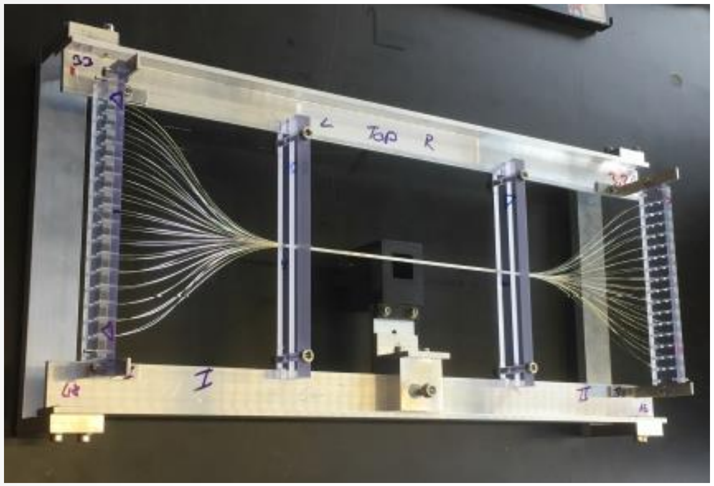
128 fibers/layer

Single fiber Al coating (minimum "optical" cross-talk)



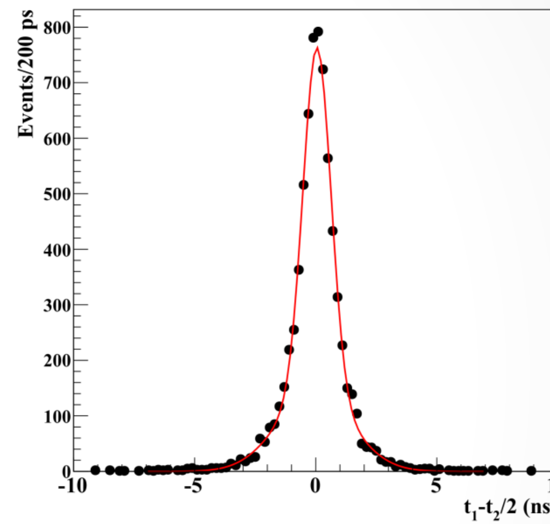
Testing Square Fibers

Fiber test setup developed at PSI



250 µm square fiber

timing performance



Cross talk:

By sputtering 30 nm Al coating on the fiber cross talk < 1% was achieved

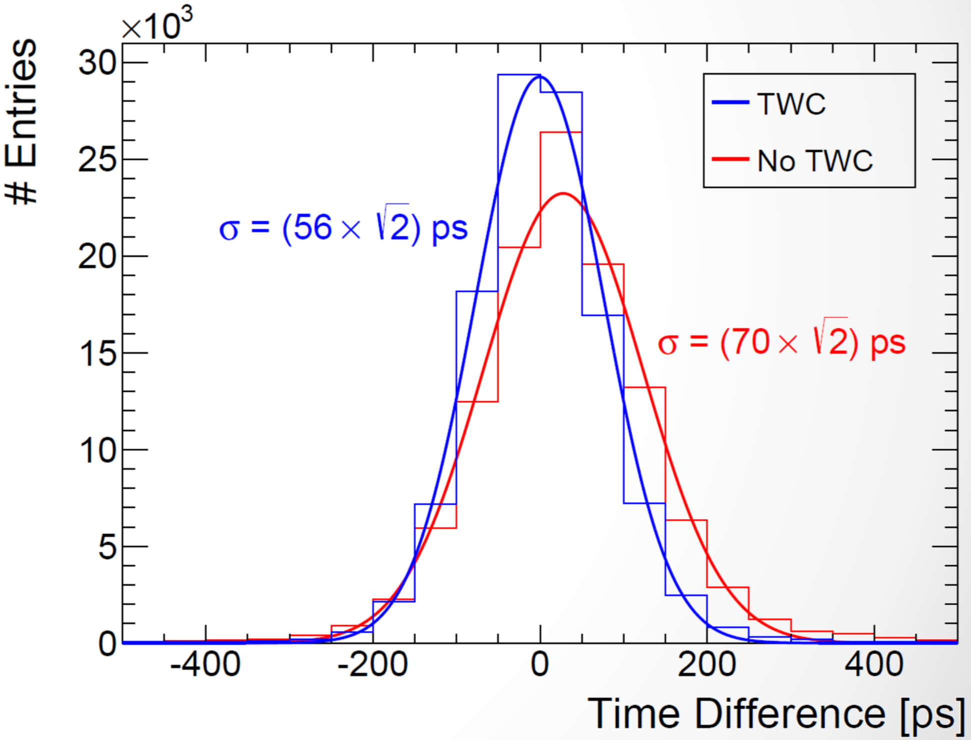
0.5 Nphe threshold

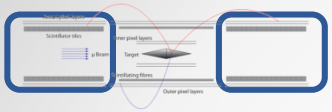
$\sigma = 750 \pm 17$ ps

Tile Detector Backup

Tile Time Resolution

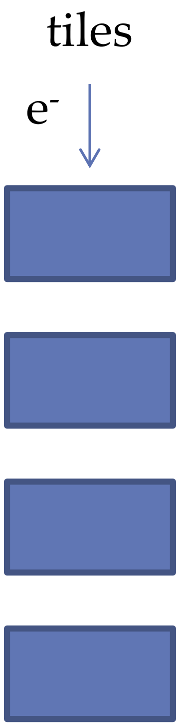
- Coincidence between 2 tiles in a row
- Time resolution ≈ 70 ps
- Time-walk effect ≈ 14 ps

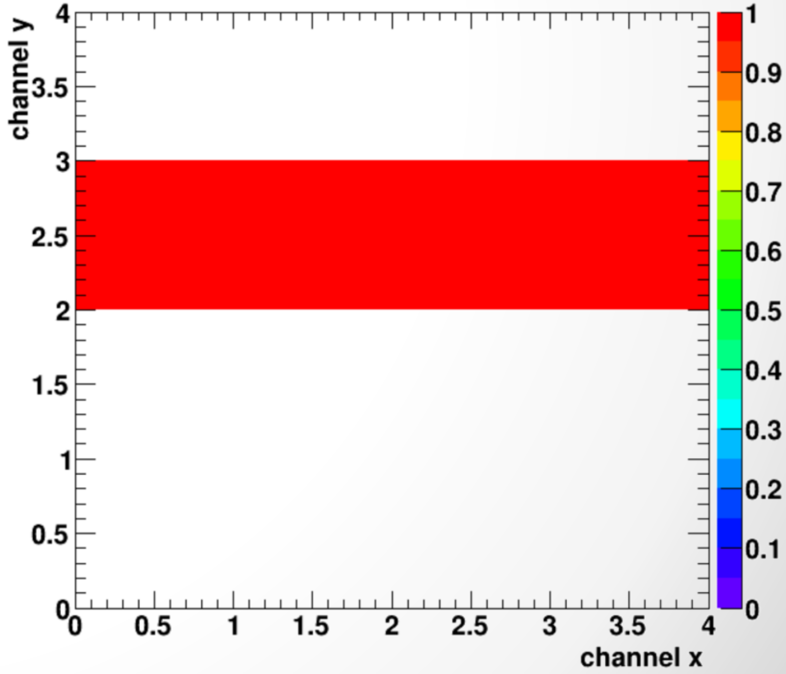


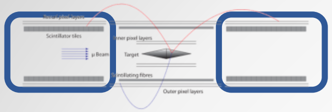


Efficiency

- Require hit in first & last column
- Look for hit in middle channel
- Efficiency > 99.5%

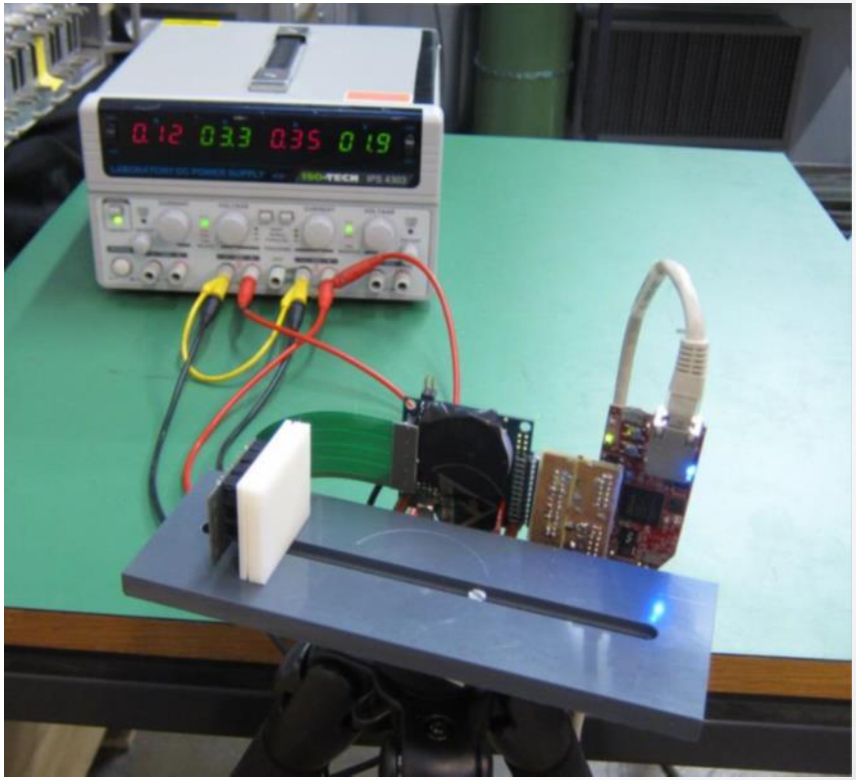




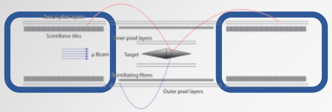


Tile Detector

- Scintillating tiles
  - 6.5 x 6.5 x 5.0 mm^3
- 7 Tile Modules per station
  - 448 tiles/module
  - Attached to end rings
- SiPMs attached to tiles
  - Distribution PCBs below
  - Readout through MuTRiG

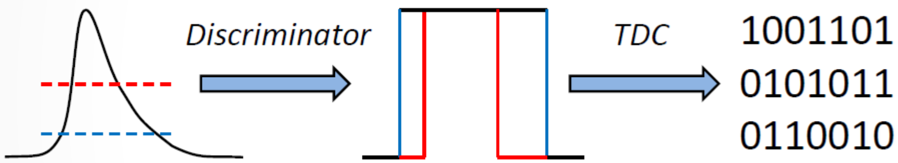


Tile detector 4 x 4 prototype



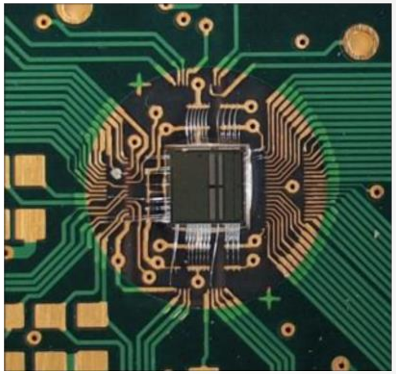
STiC Readout

- Developed at KIP for EndoTOFPET-US
  - Optimized for ToF applications
- Key features:
  - Digital timing & energy information

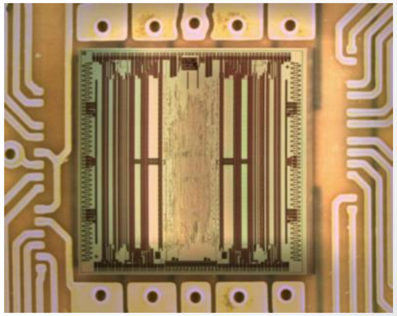


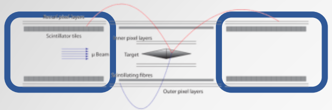
  - 64 channels (version 3.0)
  - 50 ps TDC bins
  - SiPM bias tuning
  - SiPM tail cancelation possibility (version 3.0)
  - Currently ≈ 1 MHz hit rate / chip
  - Up to ≈ 20 MHz in future version
- Version 2.0 successfully operated in test-beam

STiC 2.0



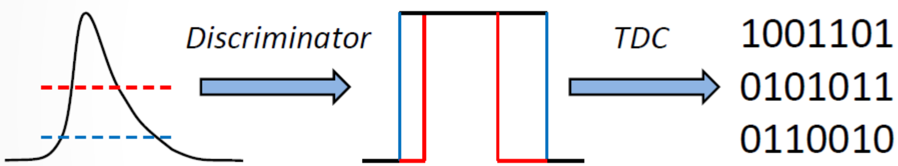
STiC 3.0





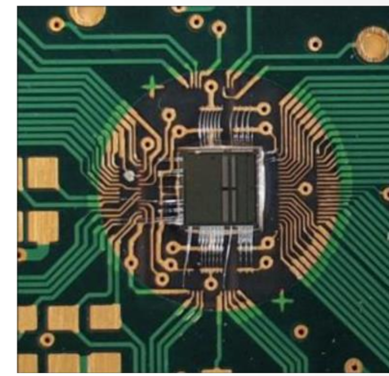
STiC Readout

- Developed at KIP for EndoTOFPET-US
  - Optimized for ToF applications
- Key features:
  - Digital timing & energy information

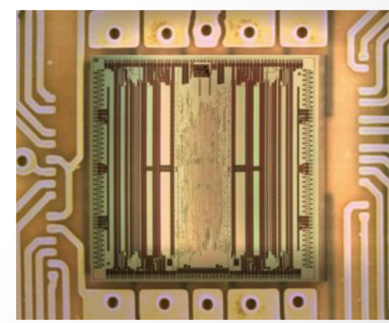


  - 64 channels (version 3.0)
  - 50 ps TDC bins
  - SiPM bias tuning
  - SiPM tail cancelation possibility (version 3.0)
  - Currently ≈ 1 MHz hit rate / chip
  - Up to ≈ 20 MHz in future version
- Version 2.0 successfully operated in test-beam

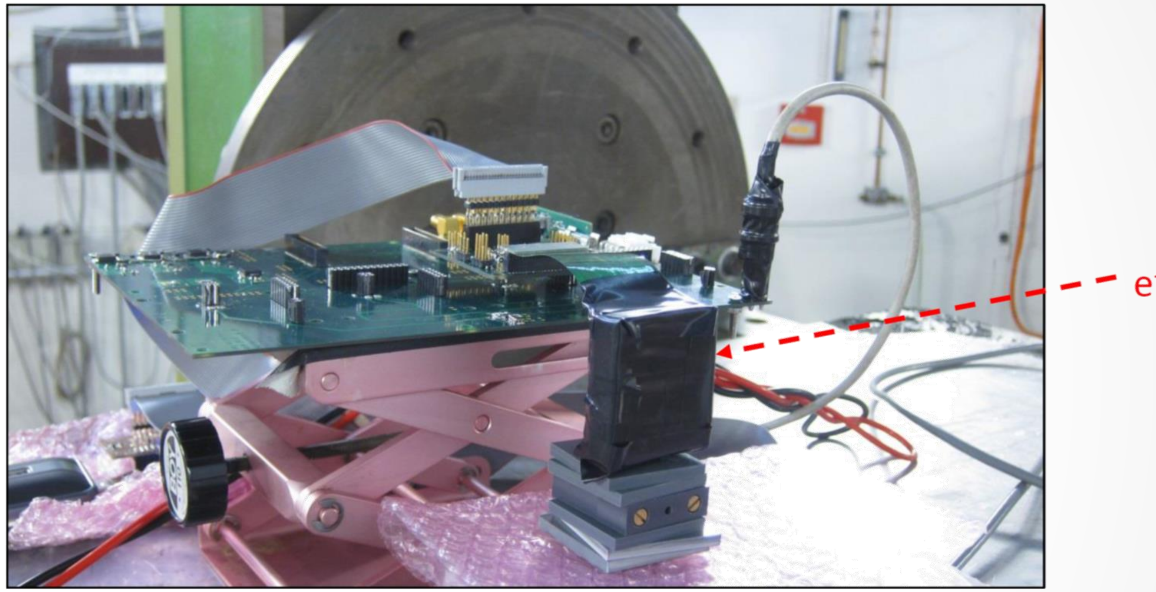
STiC 2.0

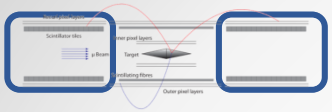


STiC 3.0

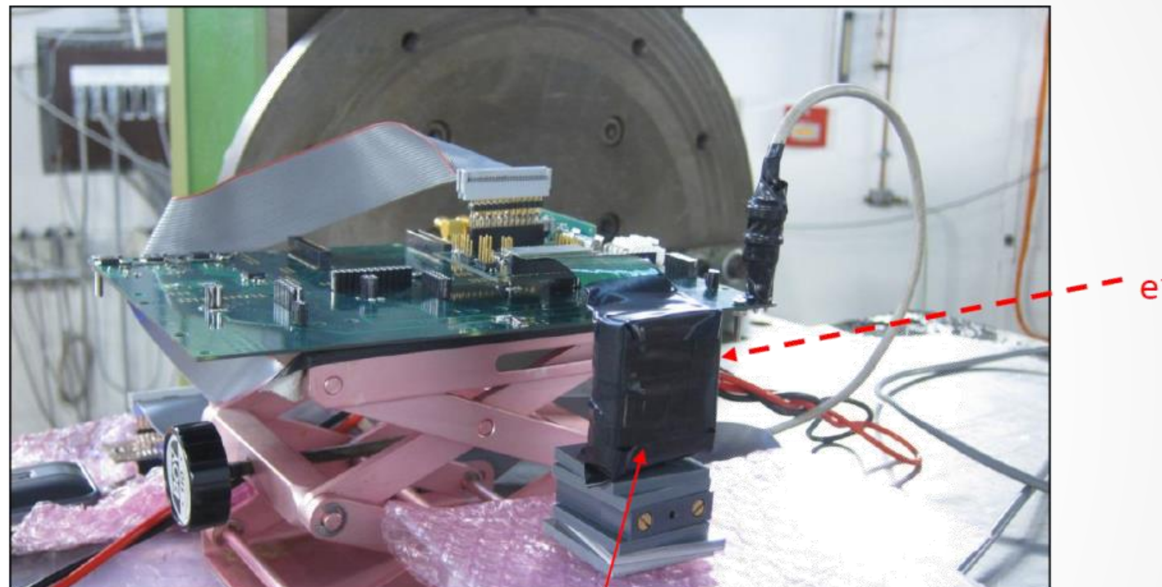


STiC Test Beam

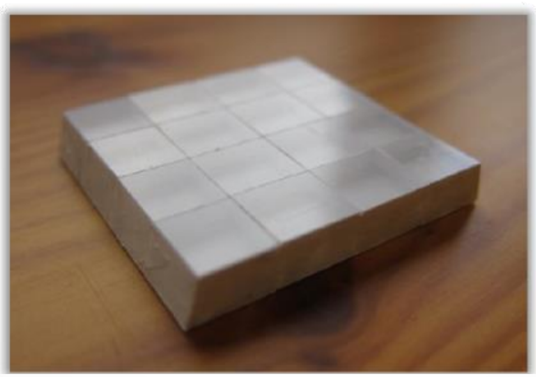


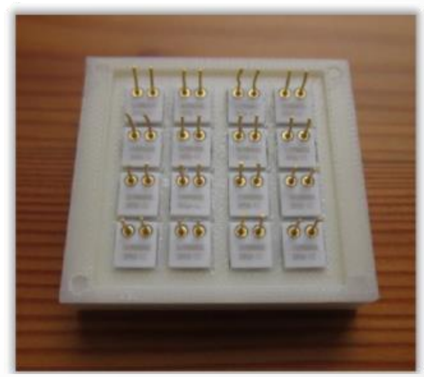


STiC Test Beam

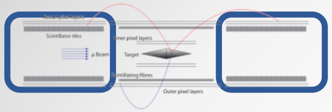


Tile Array

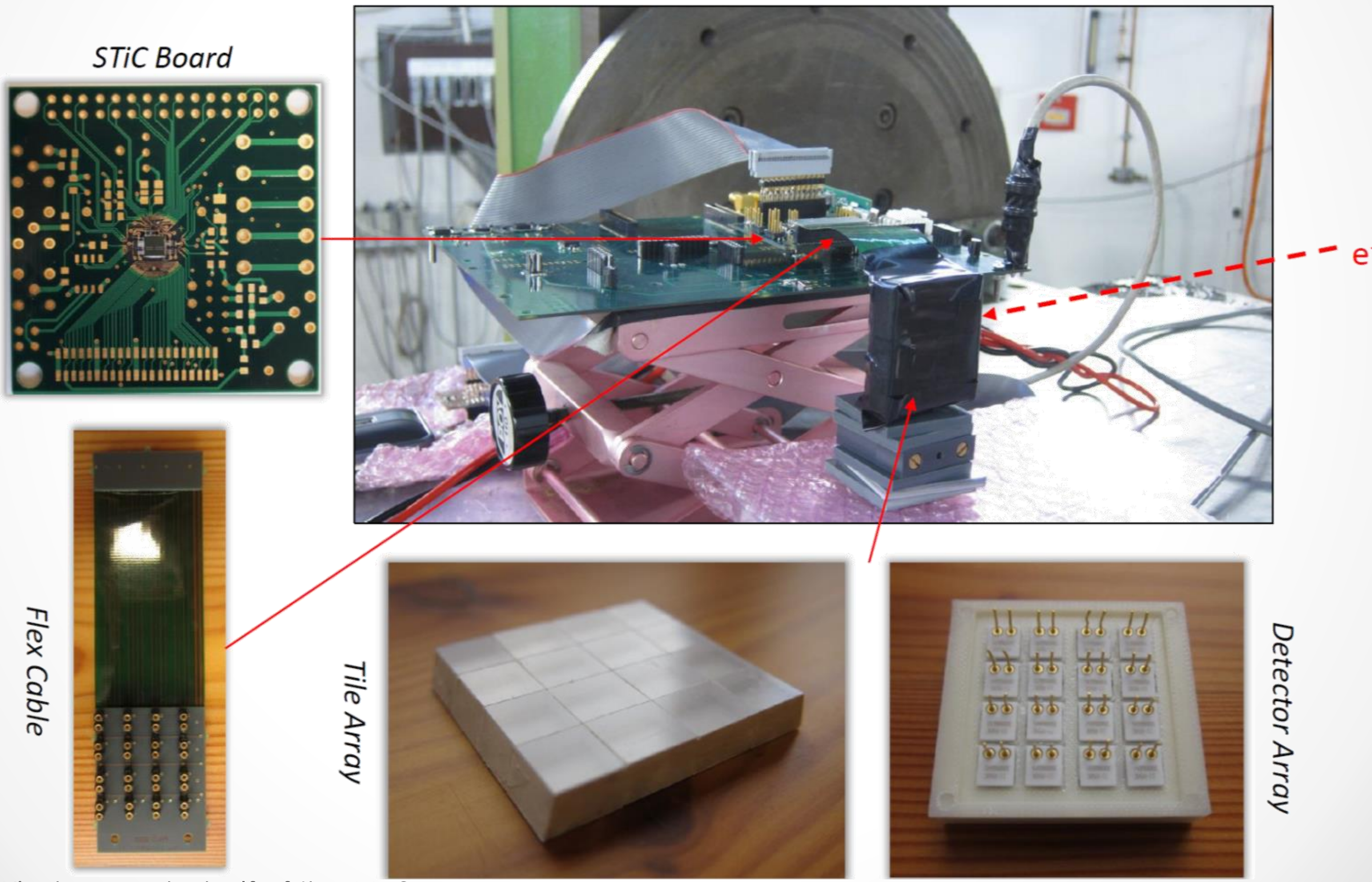




Detector Array



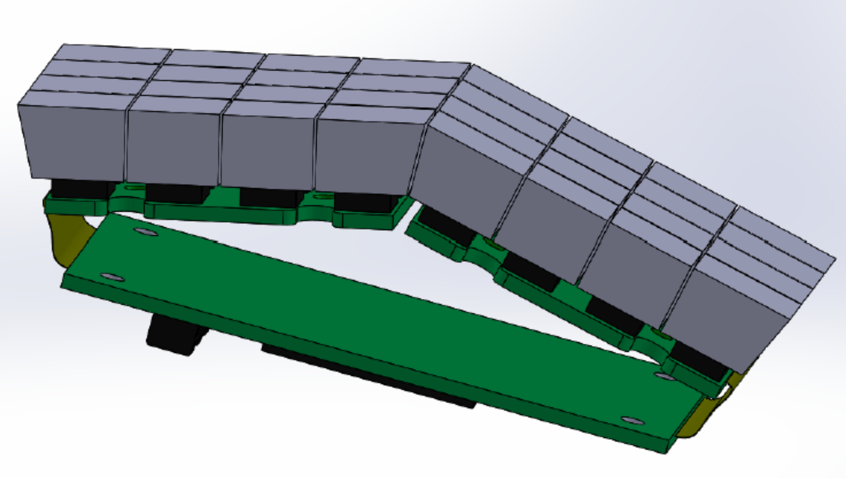
STiC Test Beam



Tile Detector

Submodule:

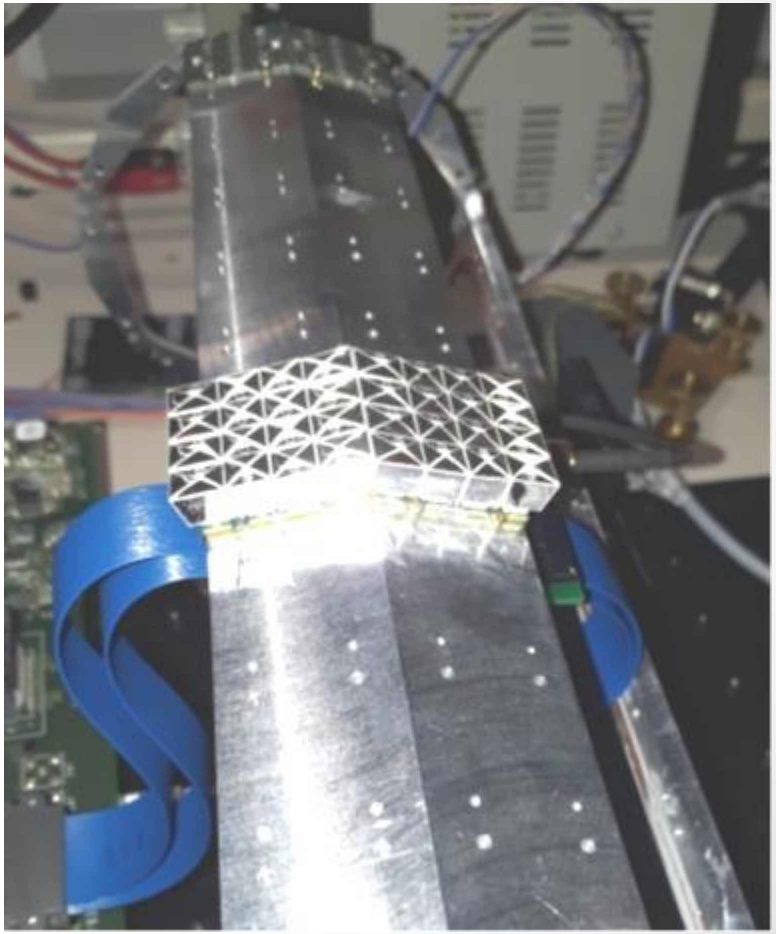
- In total 32 channel
- 3 x $3mm^2$ SiPMs
- FEBA – flex printed PCB
- MuTrig ASIC in BGA package
- Scintillator tiles Ej-228
  - 6.5 x 6.5 x $5mm^3$
  - two types: center and edge
- ESR reflected foil, individual tile wrapping



Rendering of Tile Detector sub module

Tile Prototype

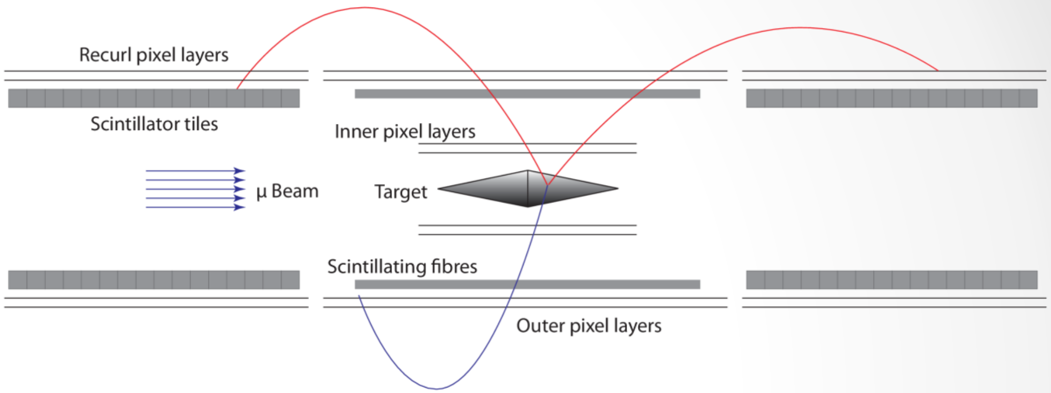
- Technical prototype build this year
- Develop assembly tools for mass production
- Tested with electron beam @ DESY (2-7 GeV)
- Excellent light yield
- Low crosstalk



Prototype on cooling structure

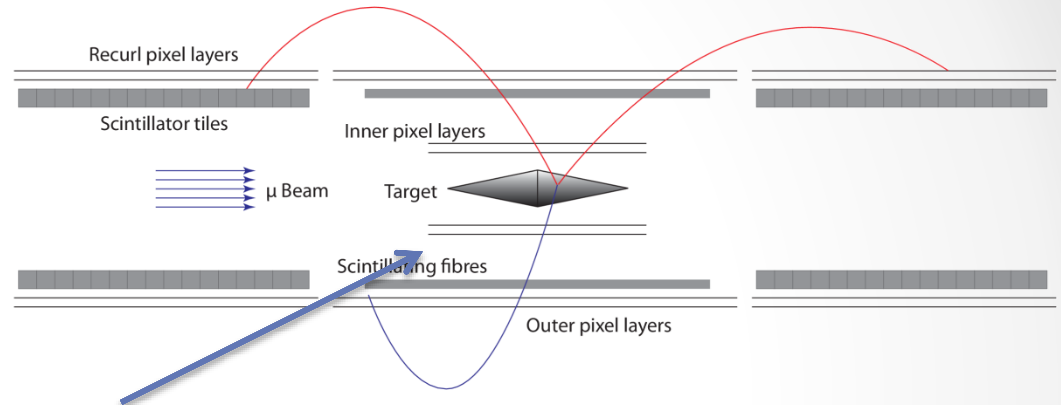
Mechanics Backup

Mu3e Silicon Detector



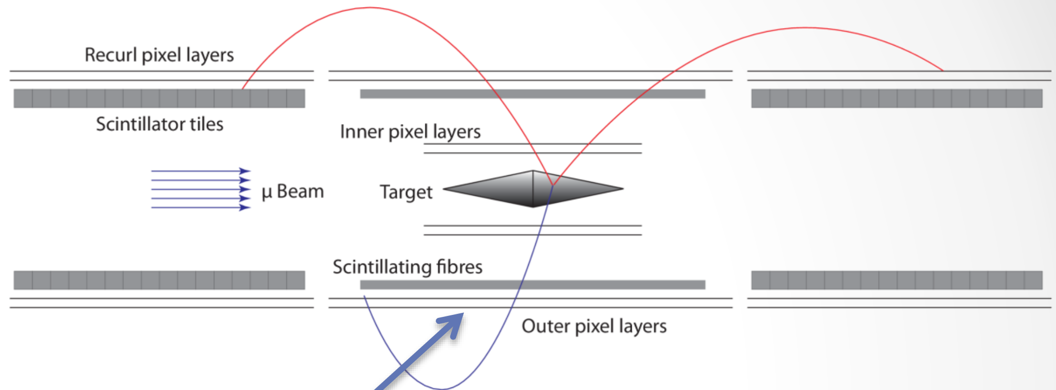
- Conical target
- Inner double layer
  - 8 and 10 sides of 2 x 12 cm^2
- Outer double layer
  - 24 and 28 sides of 2 x 36 cm^2
- Re-curl layers
  - 24 and 28 sides of 2x 36 cm^2
  - Both sides

Mu3e Silicon Detector



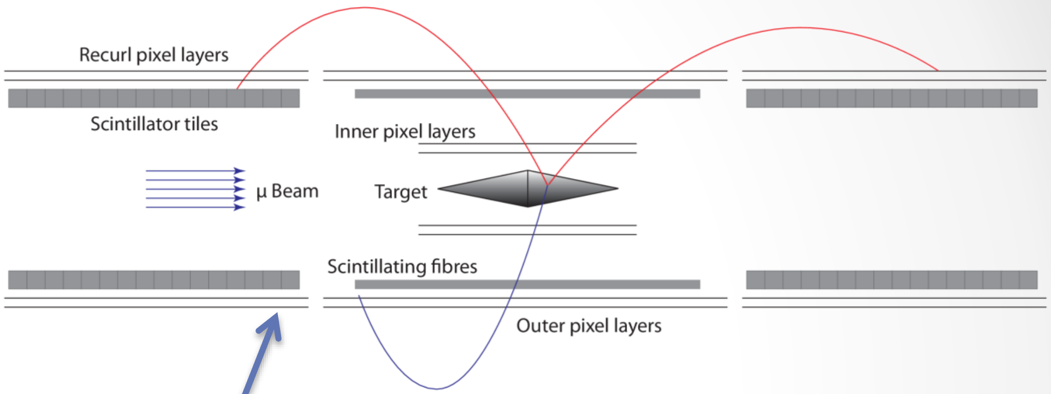
- Conical target
- Inner double layer
  - 8 and 10 sides of 2 x 12 cm^2
- Outer double layer
  - 24 and 28 sides of 2 x 36 cm^2
- Re-curl layers
  - 24 and 28 sides of 2x 36 cm^2
  - Both sides

Mu3e Silicon Detector



- Conical target
- Inner double layer
  - 8 and 10 sides of 2 x 12 cm^2
- Outer double layer
  - 24 and 28 sides of 2 x 36 cm^2
- Re-curl layers
  - 24 and 28 sides of 2x 36 cm^2
  - Both sides

Mu3e Silicon Detector

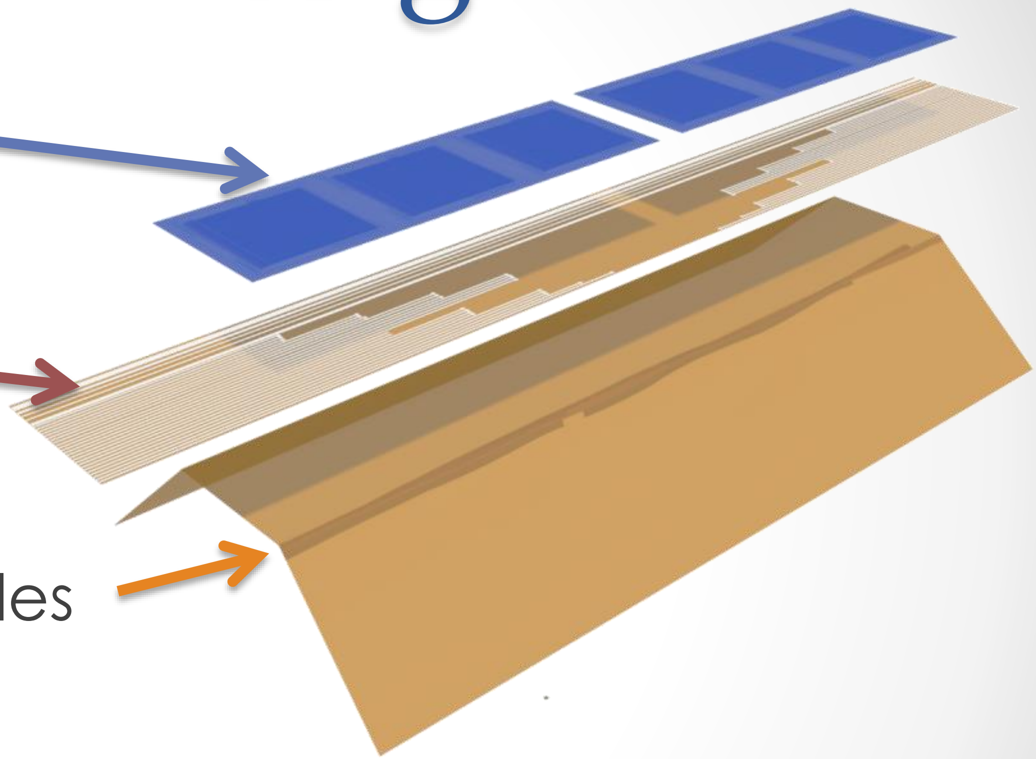


- Conical target
- Inner double layer
  - 8 and 10 sides of 2 x 12 cm^2
- Outer double layer
  - 24 and 28 sides of 2 x 36 cm^2
- Re-curl layers
  - 24 and 28 sides of 2 x 36 cm^2
  - Both sides

108 inner sensors
2736 outer sensors
~180 000 000 pixel

Sandwich Design

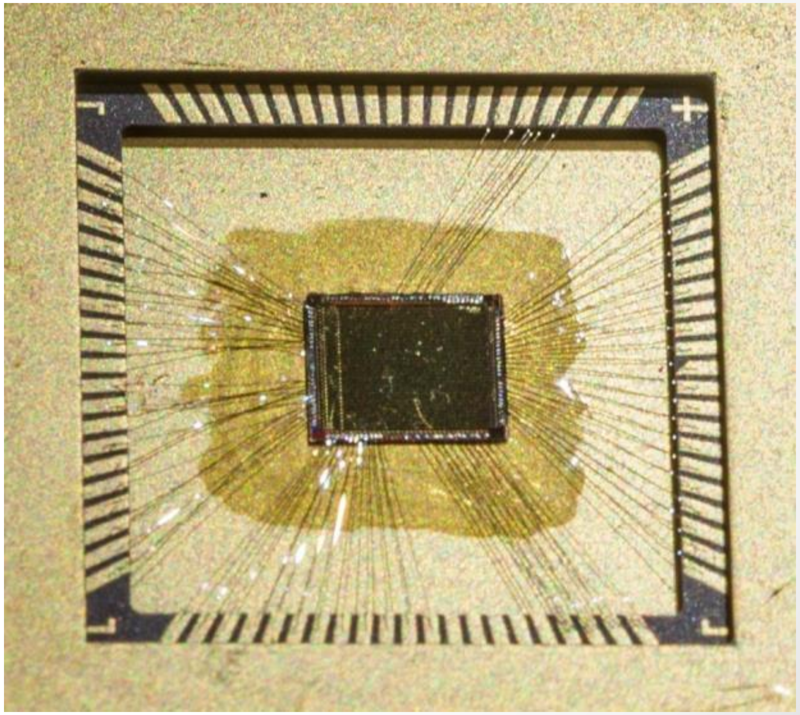
- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm²
- Kapton™ flex print
  - 25 µm Kapton™
  - 14 µm Alu traces
- Kapton™ Frame Modules
  - 25 µm foil
  - Self supporting
- Alu end wheels
  - Support for all detectors



0.11% of X_0

Thinned Pixel Sensors

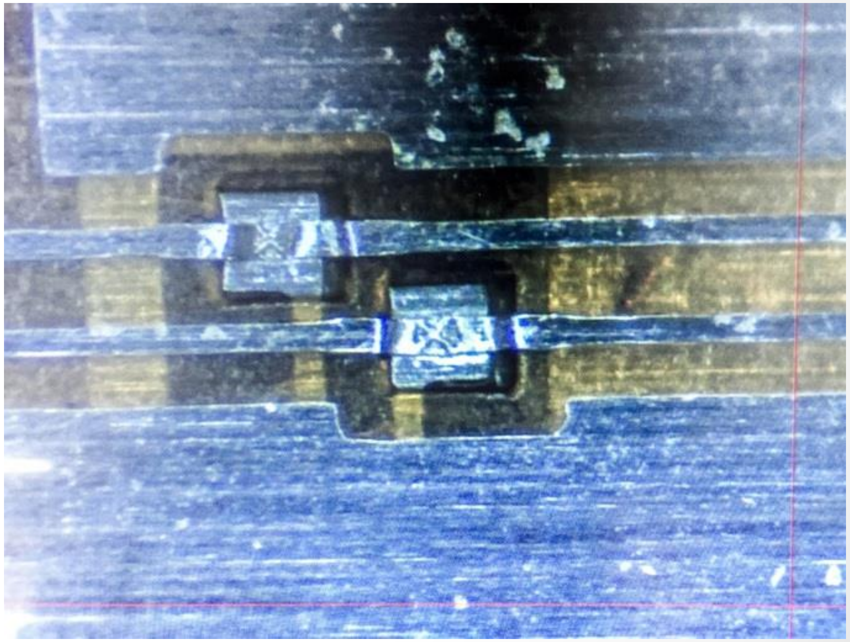
- **HV-MAPS***
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 14 µm Alu traces
- Kapton™ Frame Modules
  - 25 µm foil
  - Self supporting
- Alu end wheels
  - Support for all detectors



MuPix3 thinned to < 90µm

Kapton™ Flex Print

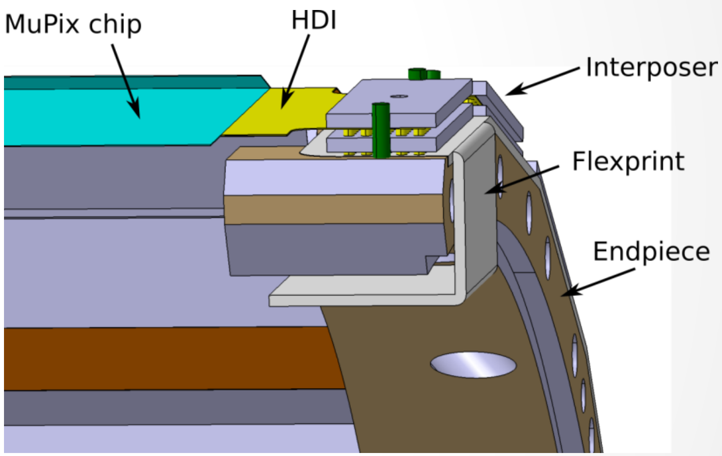
- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- **Kapton™ flex print**
  - 25 µm Kapton™
  - 14 µm Alu traces
- Kapton™ Frame Modules
  - 25 µm foil
  - Self supporting
- Alu end wheels
  - Support for all detectors



Laser-cut flex print prototype

Pixel Modules

- HV-MAPS
  - Thinned to 50 μm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 μm Kapton™
  - 14 μm Alu traces
- **Kapton™ Frame Modules**
  - 25 μm foil
  - Self supporting
- Alu end wheels
  - Support for all detectors

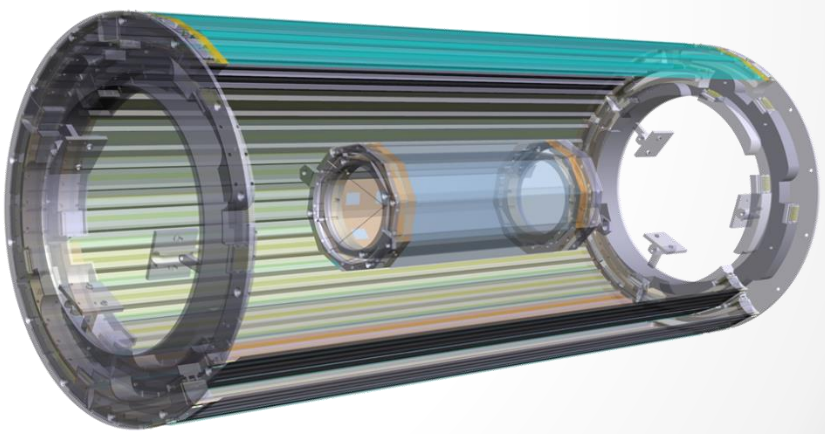


CAD of Kapton™ frames

Overall Design

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 14 µm Alu traces
- **Kapton™ Frame Modules**
  - 25 µm foil
  - Self supporting
- Alu end wheels
  - Support for all detectors

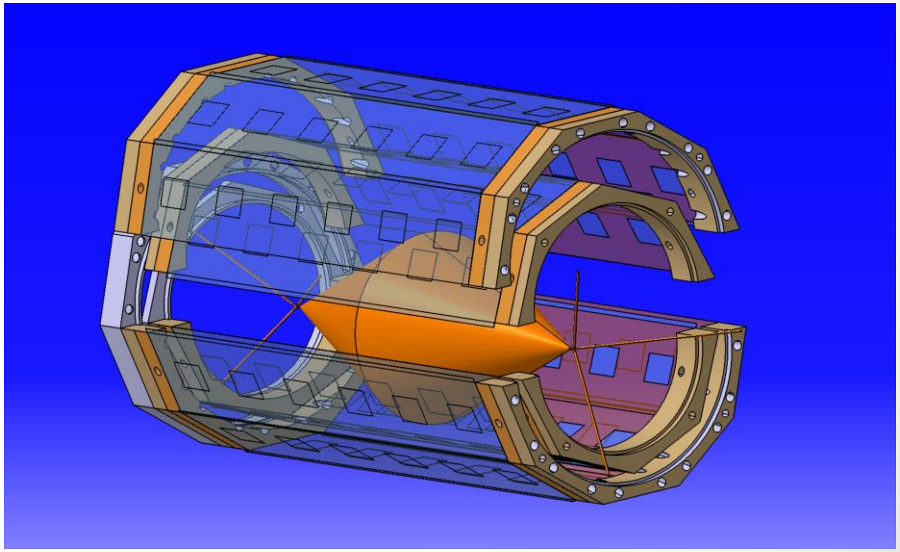
- Two halves for layers 1+2
- 6 modules in layer 3
- 7 modules in layer 4



CAD of Kapton™ frames

Inner Layers

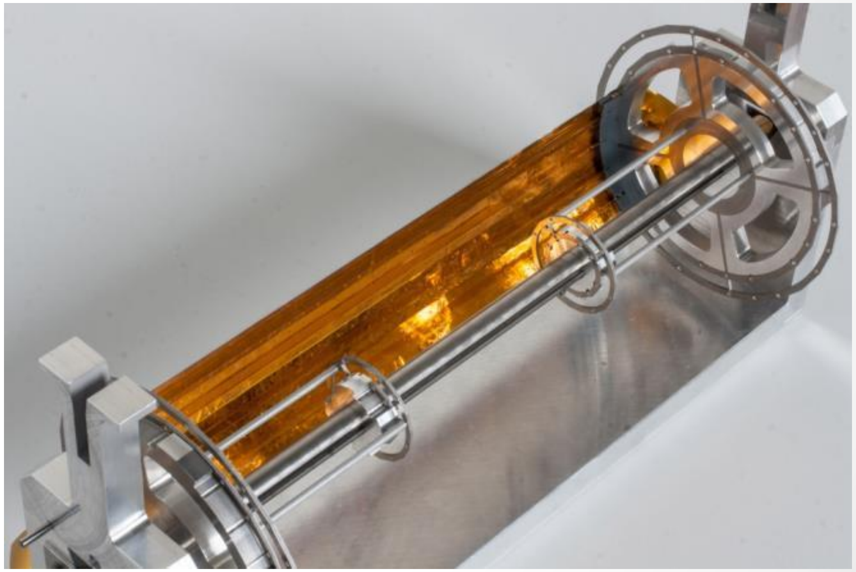
- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 14 µm Alu traces
- **Kapton™ Frame Modules**
  - 25 µm foil
  - **Self supporting**
- Alu end wheels
  - Support for all detectors



Rendering of vertex detector CAD

Outer Module

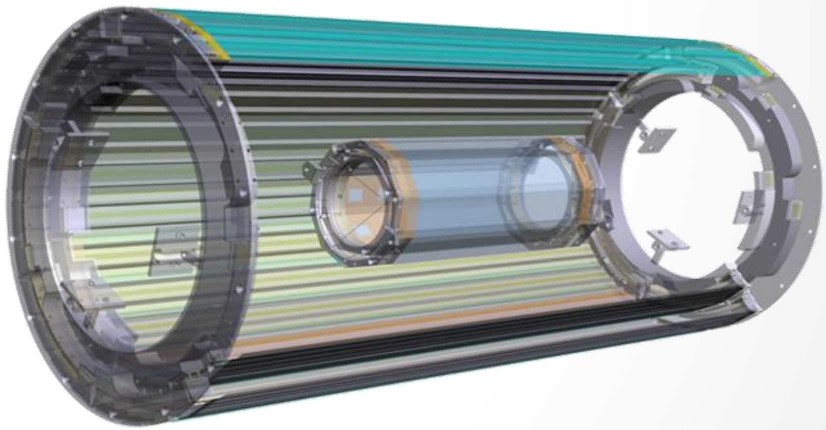
- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 14 µm Alu traces
- **Kapton™ Frame Modules**
  - 25 µm foil
  - **Self supporting**
- Alu end wheels
  - Support for all detectors



Layer 3 Prototype in Assembling Frame with 50 µm Glass

Detector Frame

- HV-MAPS
  - Thinned to 50 μm
  - Sensors 2 x 2 cm²
- Kapton™ flex print
  - 25 μm Kapton™
  - 14 μm Alu traces
- Kapton™ Frame Modules
  - 25 μm foil
  - Self supporting
- **Alu end wheels**
  - Support for all detectors



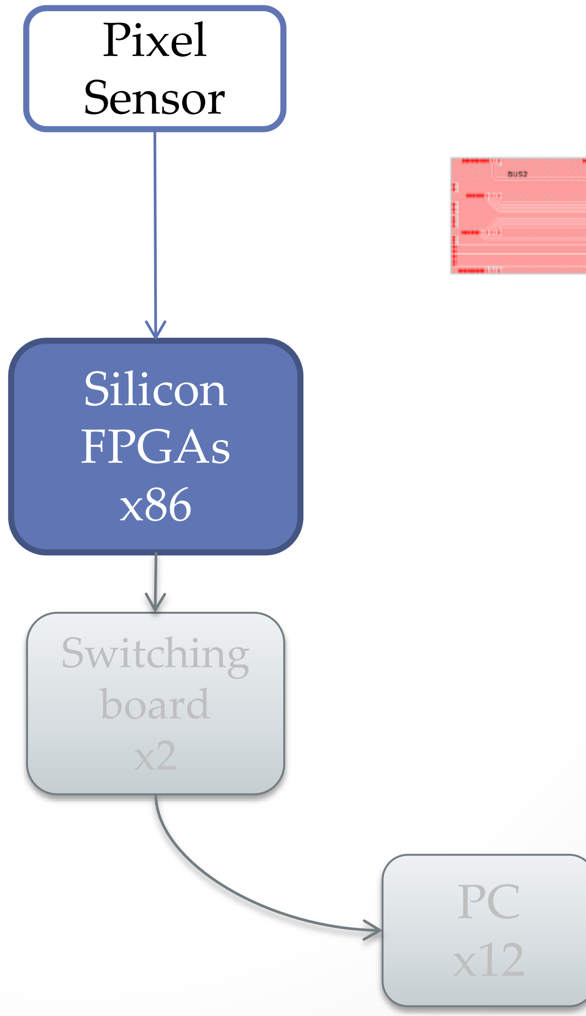
Pixel detector CAD rendering

DAQ Backup

...

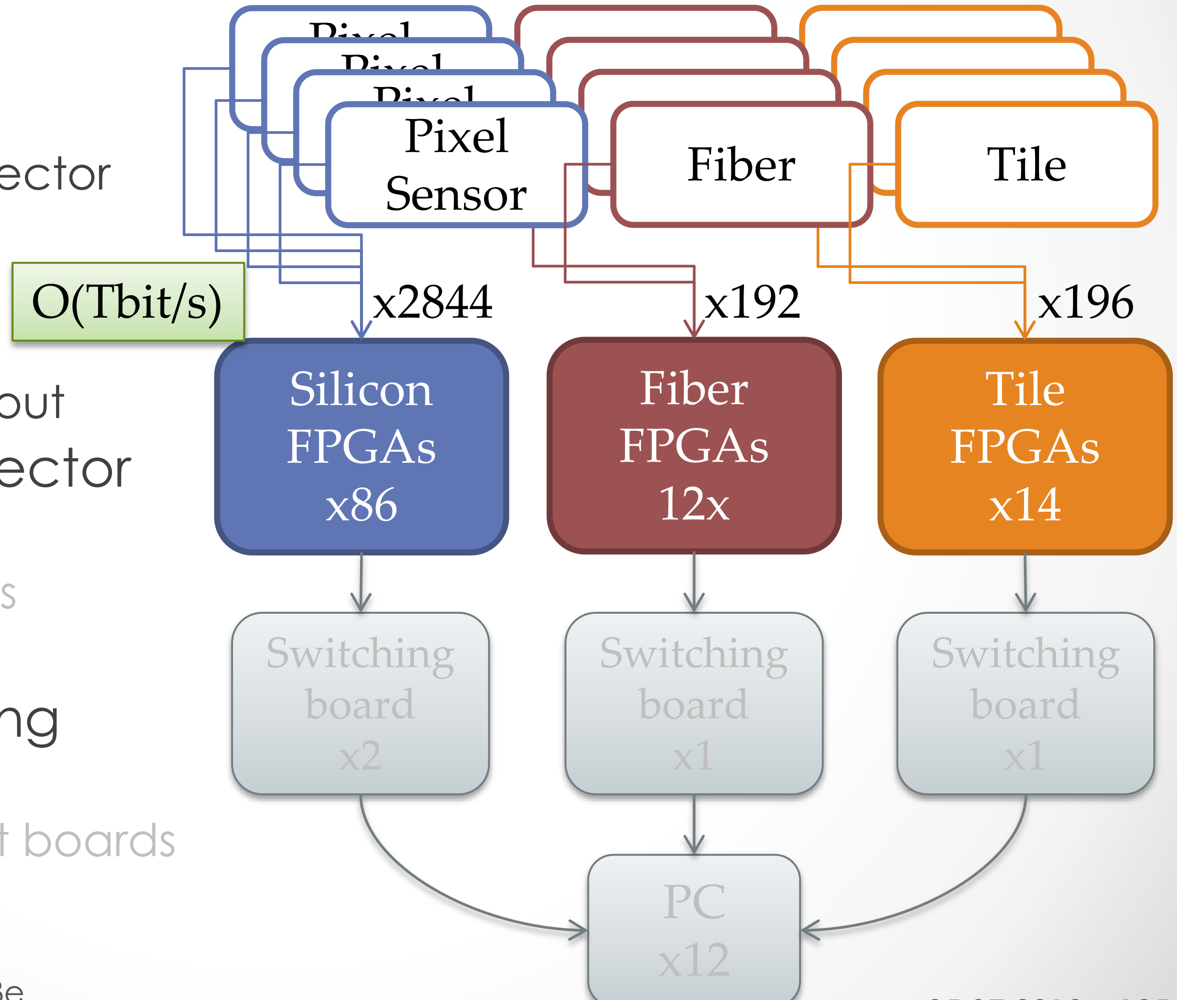
Trigger-less DAQ

- Front end links
  - Pixel sensor to on-detector FPGA
    - 1250 Mbit/s
    - LVDS
  - Timing detector readout
- Optical links from detector
  - Front end FPGAs
  - … to switching boards
  - 6.4 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - …to PC Farm



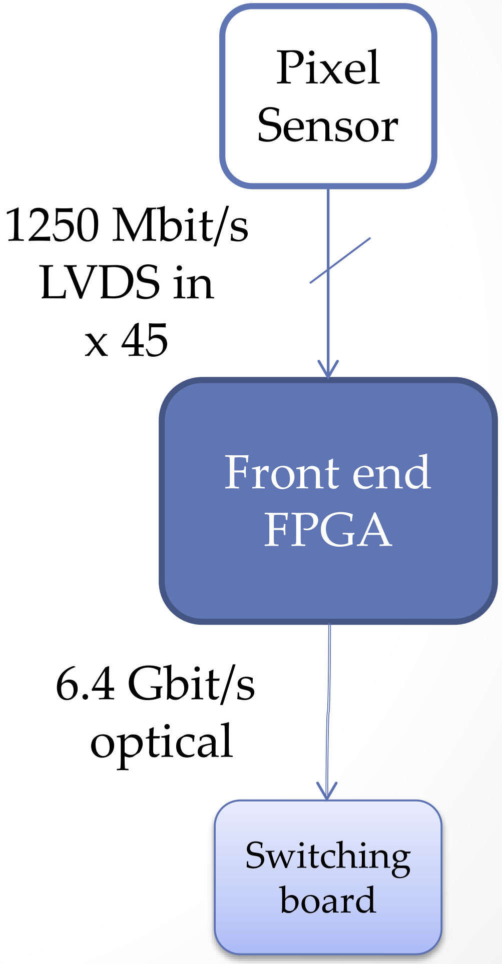
Trigger-less DAQ

- Front end links
  - Pixel sensor to on-detector FPGA
    - 1250 Mbit/s
    - LVDS
  - Timing detector readout
- Optical links from detector
  - Front end FPGAs
  - … to switching boards
  - 6.4 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - …to PC Farm



Front End FPGAs

- FPGAs in magnet volume
  - 112 pieces
- Receive sensor data
  - 36-45 LVDS inputs
- 6.4 Gbit/s outputs
  - 8 optical links
  - … to counting house

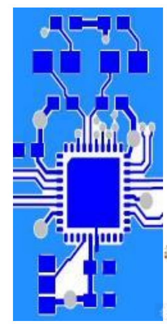


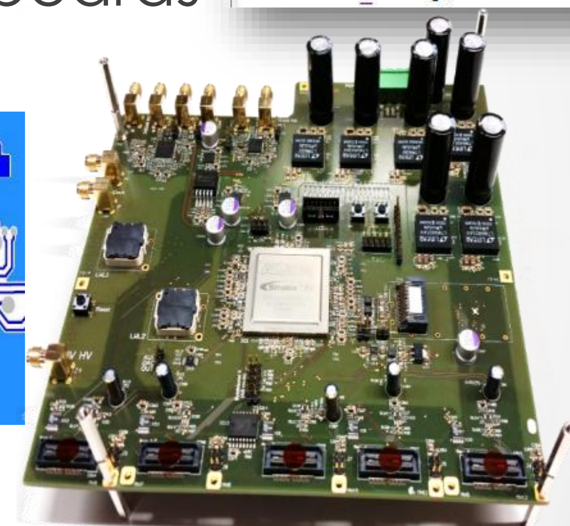
Tasks, problems, challenges

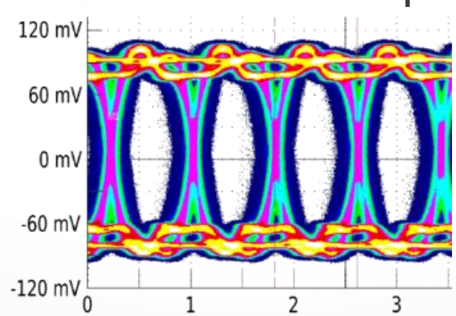
```
write_process : process(clkin, reset_n)
begin
    if(reset_n = '0')then
```

```
void MudaqDevice::zero_wrmem()
{
    uint32_t temp;
```

- Hard-, firm- and software developments
- Testing custom designed front-end boards and bringing them to operation
- Data transmission studies
  - Electrical links
  - Optical links
- Data reduction at front-end:
  Up to 45 × 1.25 Gbps → 1 × 6 Gbps
  with as little logic utilization as possible

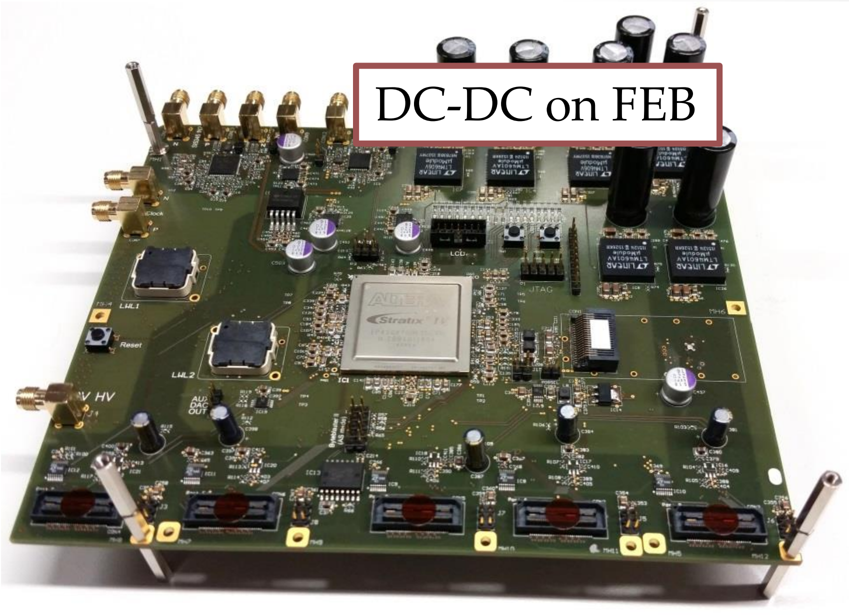






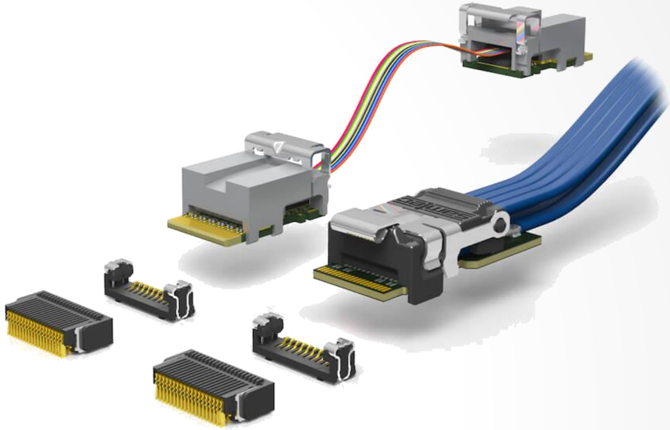
Front End Board V1.02

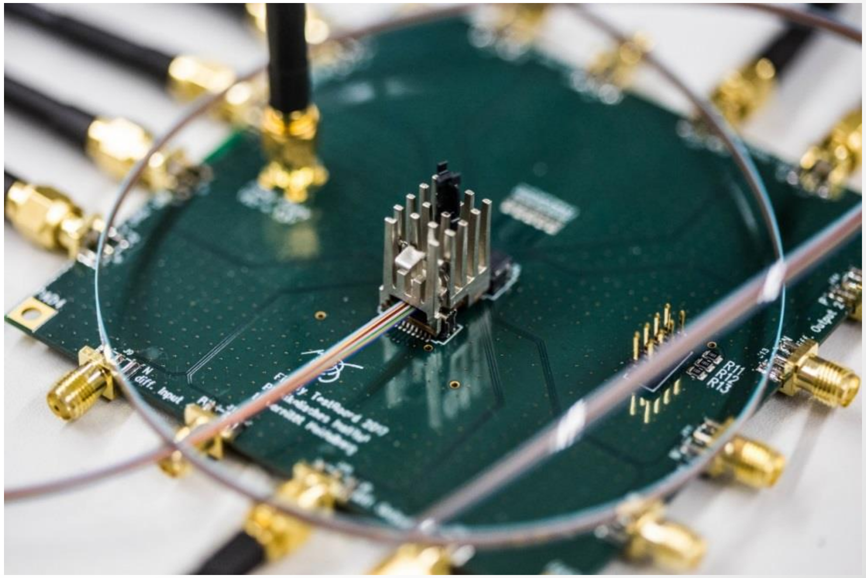
- Bug-fix of Front End Board V1.0
  - Extra resistors
  - Extra voltage regulator
- DC-DC for entire partition
- Eight PCBs produced
  - Tested and ok



Front End Board V2.0

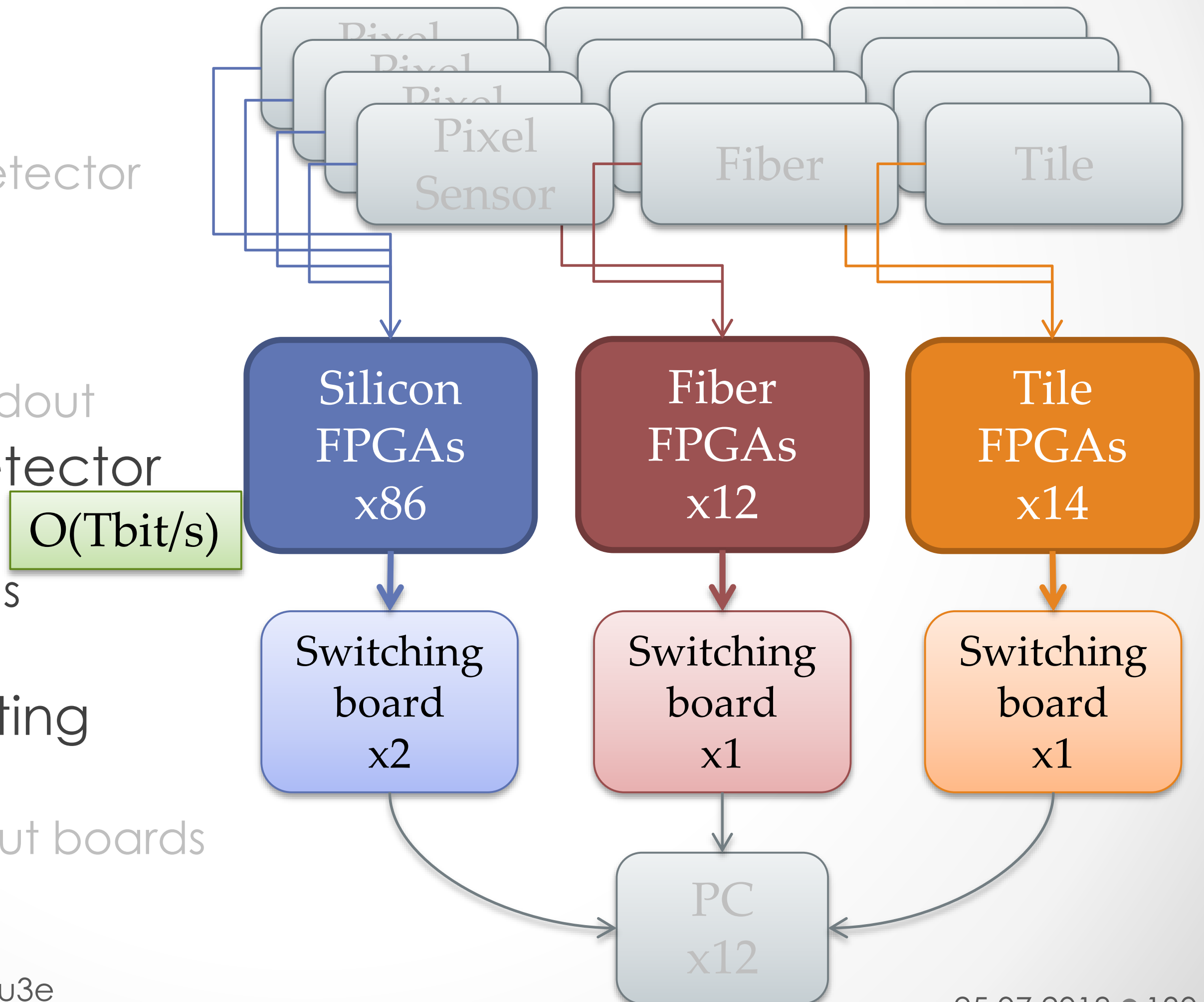
- Better FPGA
- FireFly optical transceivers
  - o Replace
    - MiniPods and
    - QSFP with
    - 2x Samtec FireFly 4-fold optical transceiver
  - o Smaller, cheaper,…
  - o Performance currently under evaluation
    (B.Sc. Thesis Benjamin Weinlaeder)





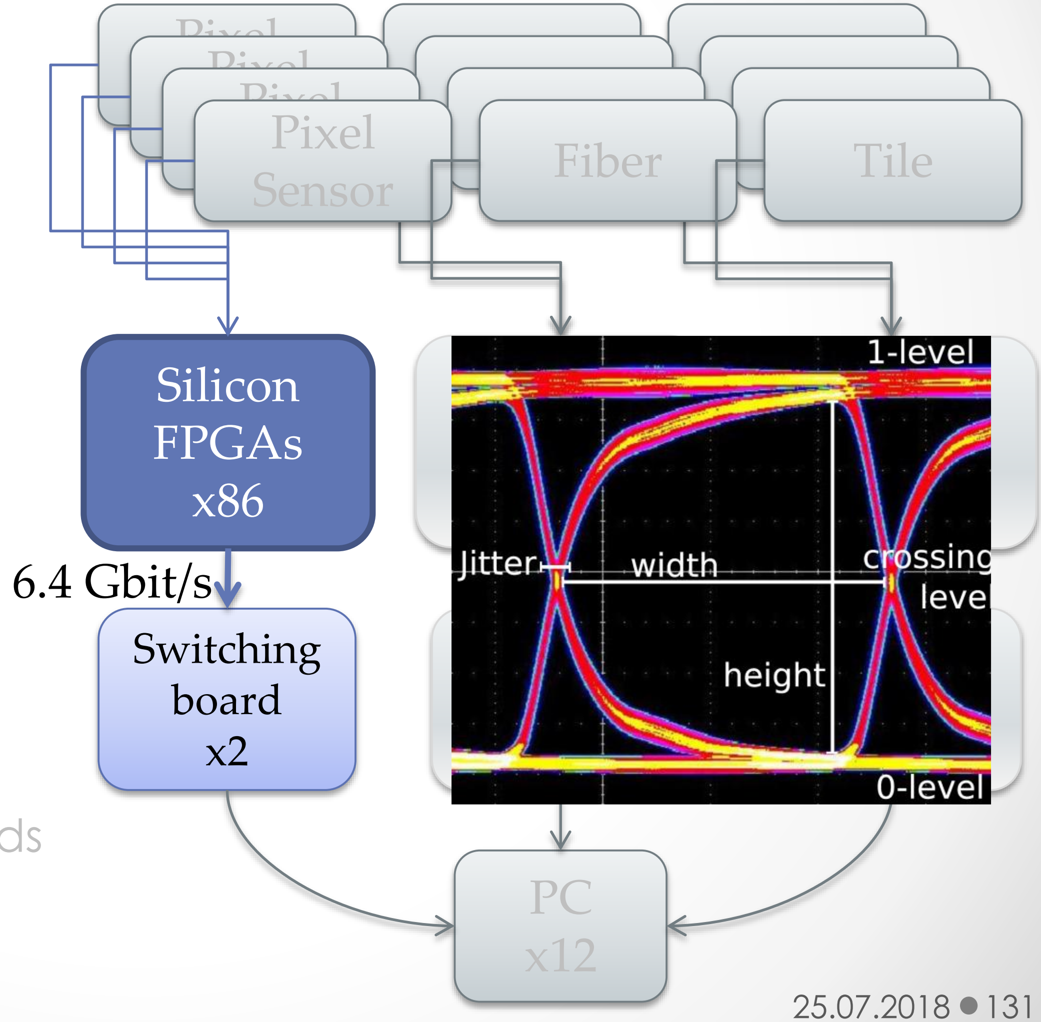
Trigger-less DAQ

- Front end links
  - Pixel sensor to on-detector FPGA
    - 1250 Mbit/s
    - LVDS
  - Timing detector readout
- Optical links from detector
  - Front end FPGAs
  - … to readout boards
  - 6.4 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - …to PC Farm



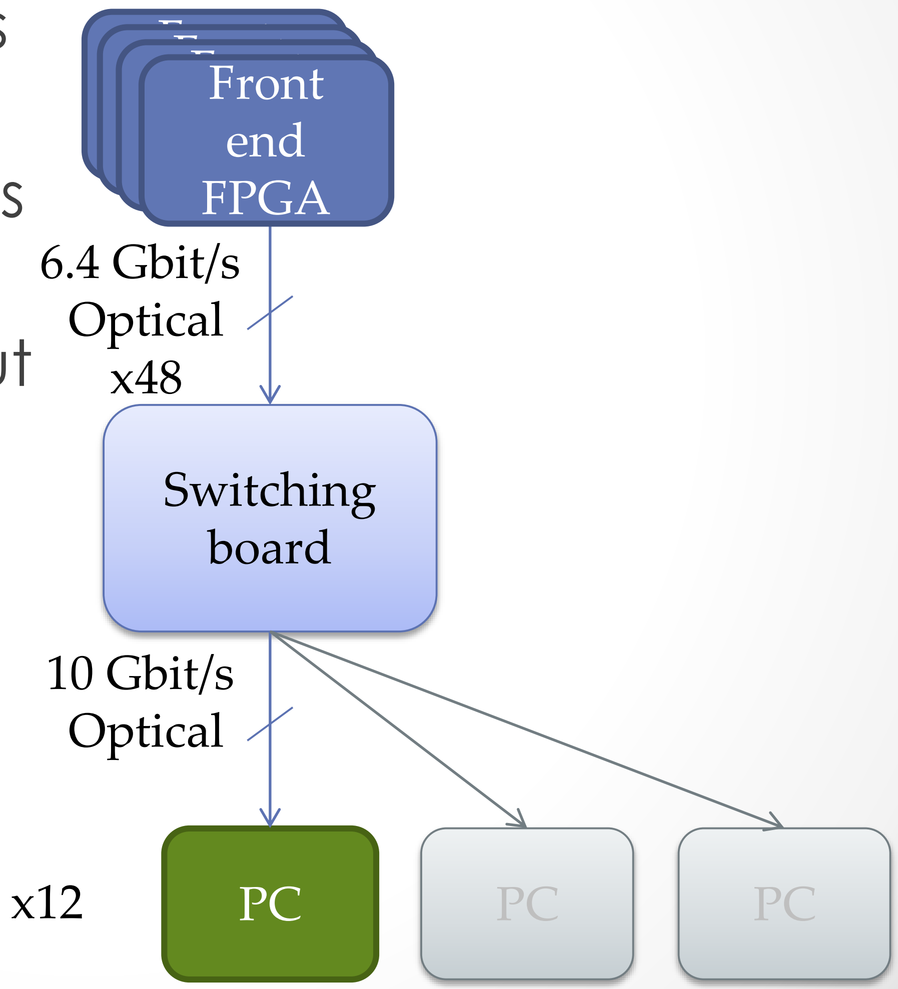
Trigger-less DAQ

- Front end links
  - Pixel sensor to on-detector FPGA
    - 1250 Mbit/s
    - LVDS
  - Timing detector readout
- Optical links from detector
  - Front end FPGAs
  - … to switching boards
  - 6.4 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - …to PC Farm



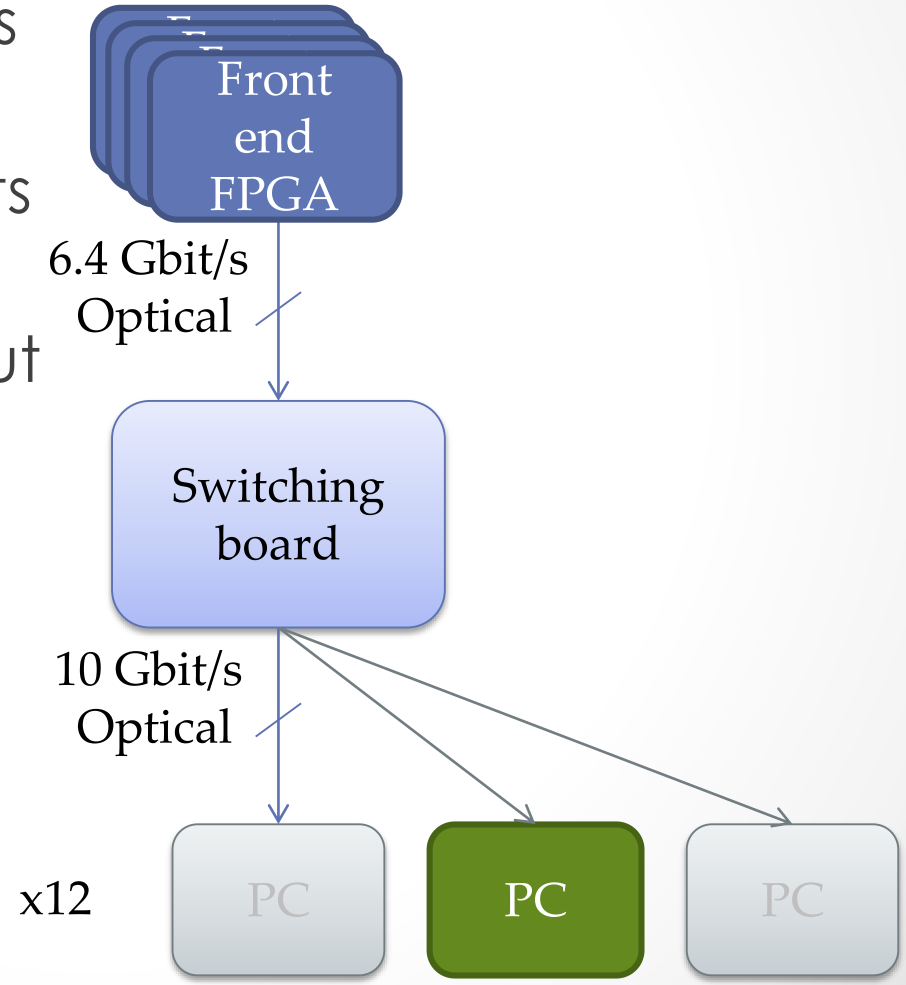
Switching Board

- FPGA switching boards
  - per sub-detector
- 6.4 Gbit/s optical inputs
  - 16-48 inputs
- 10 Gbit/s optical output
  - 12 outputs to PCs
- Switching network
  - One output per PC



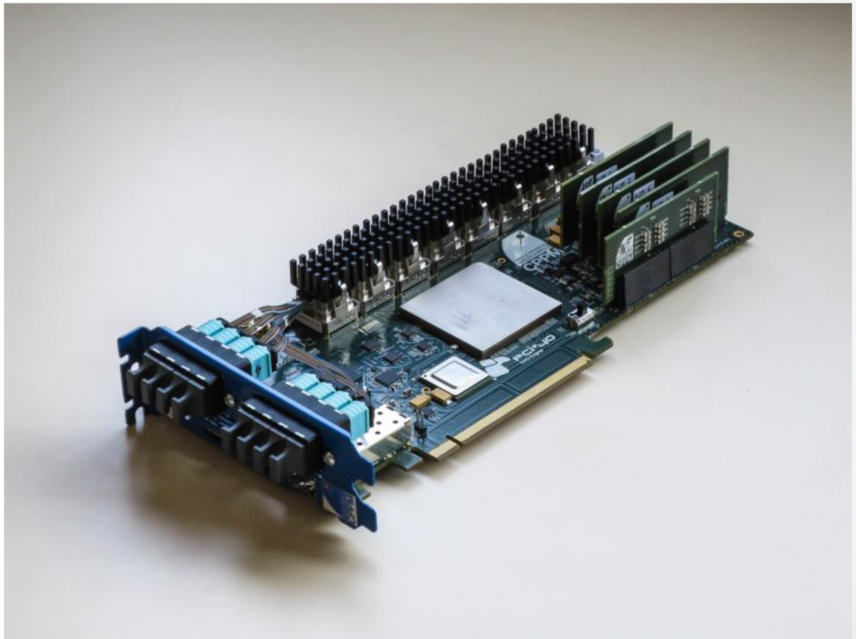
Switching Board

- FPGA switching boards
  - 4 per sub-detector
- 6.4 Gbit/s optical inputs
  - 16-48 inputs
- 10 Gbit/s optical output
  - 12 outputs to PCs
- Switching network
  - One output per PC



Switching Board

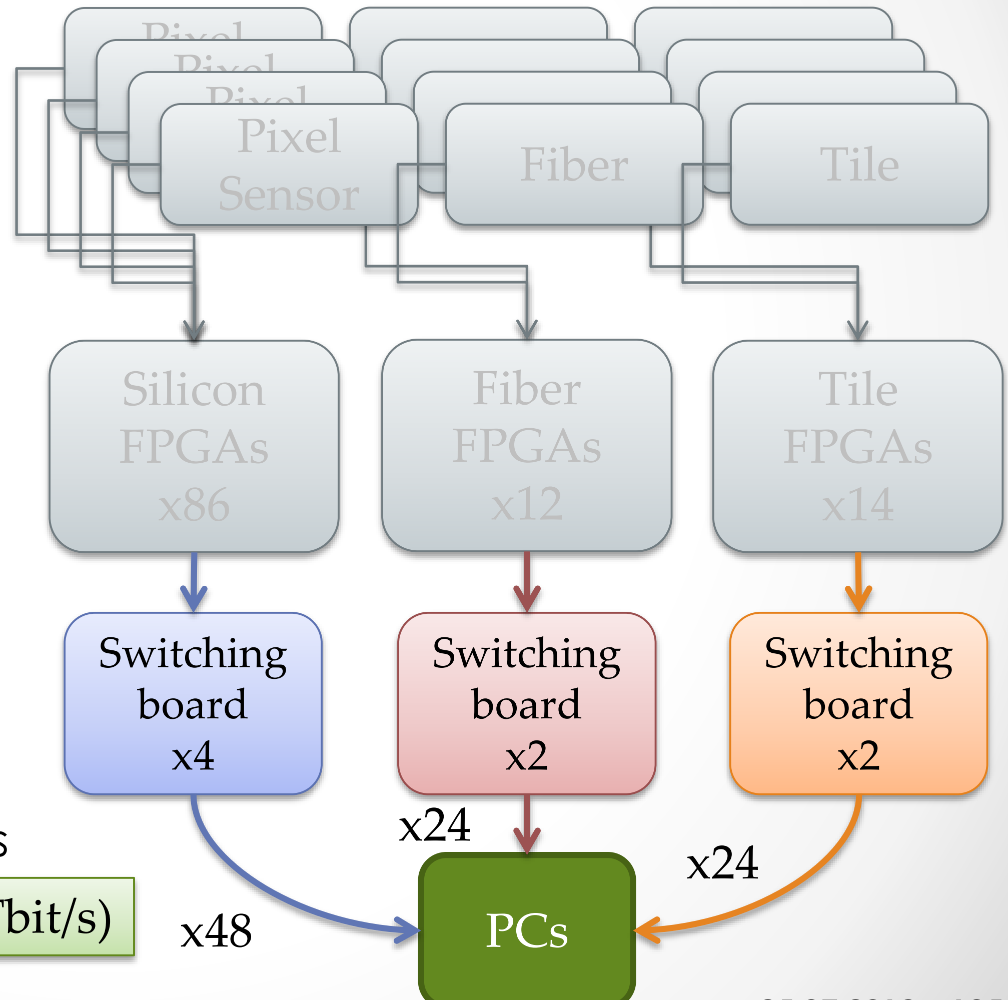
- PCIe40
- Developed for LHCb and ALICE upgrade by CPPM (Marseille)
- 48 optical I/Os
- Optcial network switch fro Mu3e filter farm
- Mu3e will receive samples from the current production



Trigger-less DAQ

- Front end links
  - Pixel sensor to on-detector FPGA
    - 1250 Mbit/s
    - LVDS
  - Timing detector readout
- Optical links from detector
  - Front end FPGAs
  - … to readout boards
  - 6.4 Gbit/s
- Optical links in counting room
  - Off-detector read out boards
  - …to PC Farm

O(Tbit/s)



GPU-PC

- PC with GPU
- 10 Gbit/s Fiber input
  - 8 inputs from sub-detectors
- Data filtering
  - Timing Filter on FPGA
  - Track filter on GPU
  - Data to tape < 100 MB/s

GPU computer

GPU-PC

- PC with GPU
- 10 Gbit/s Fiber input
  - 8 inputs from sub-detectors
- Data filtering
  - Timing Filter on FPGA
  - Track filter on GPU
  - Data to tape < 100 MB/s

FPGA PCIe board

GPU computer

Receiving FPGA board PC side

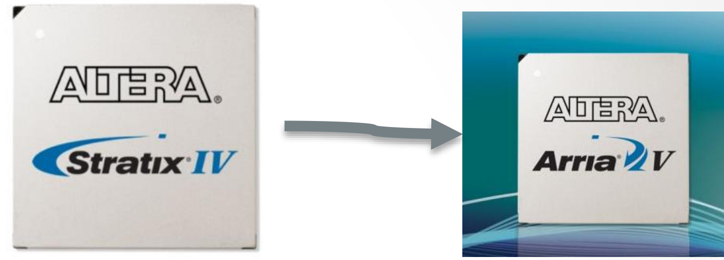
- De5a-NET boards from Terasic
- Successfully tested at Mainz
- 8 out of 12 boards already acquired

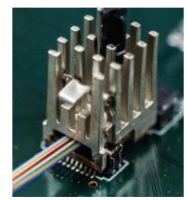
DAQ tests
Backup

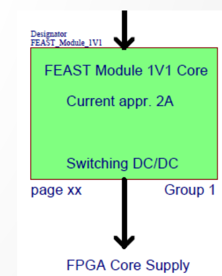
• • •

Front End Board V2.0

- Better FPGA
  - ArriaV instead of StratixIV
  - Lower power consumption
    - 6.6W → 3.3W (<10W)
- FireFly optical transceivers
  - 2 x 1W
- Clock distribution chips
  - SI5345 2 x 1W
- DC-DC only for FEB
  - FEAST2MD compatible
  - Or based on TI chip set i.e. LM27403

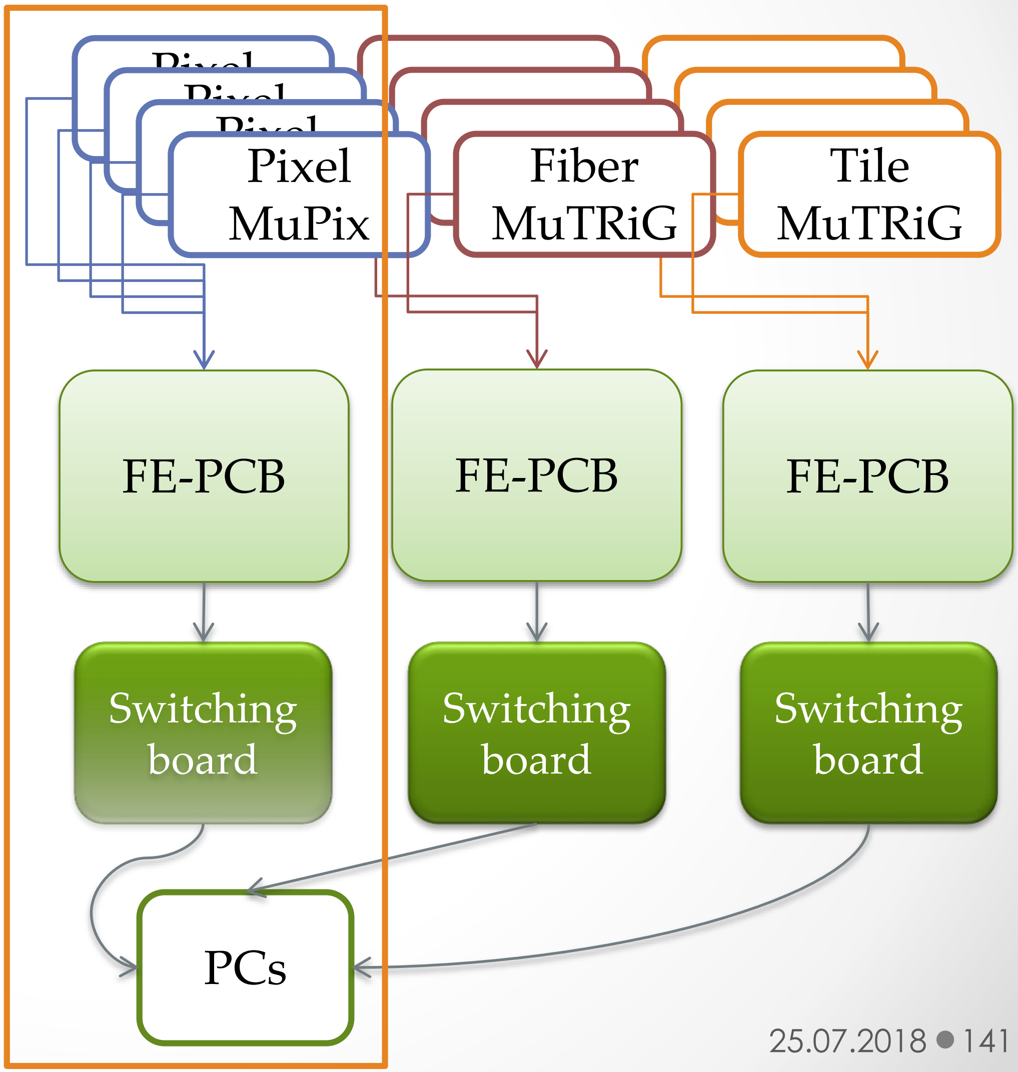






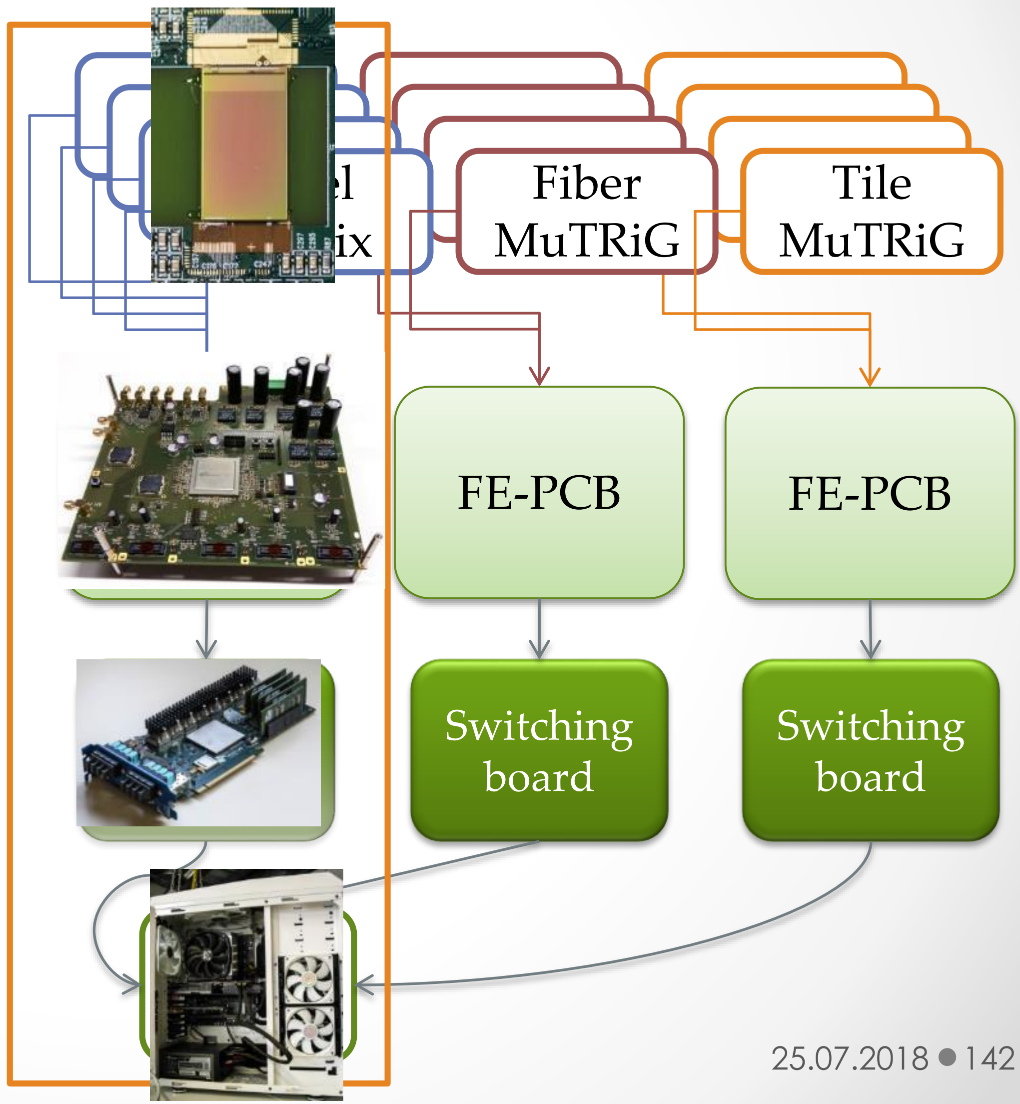
Readout Vertical Slice Test

- Pixel detector
  - HV-MAPS (MuPix8)
    - ✓ Large prototype
- Front end board
- Switching board
  - PCIe40
  - Delivery 2018
- PC

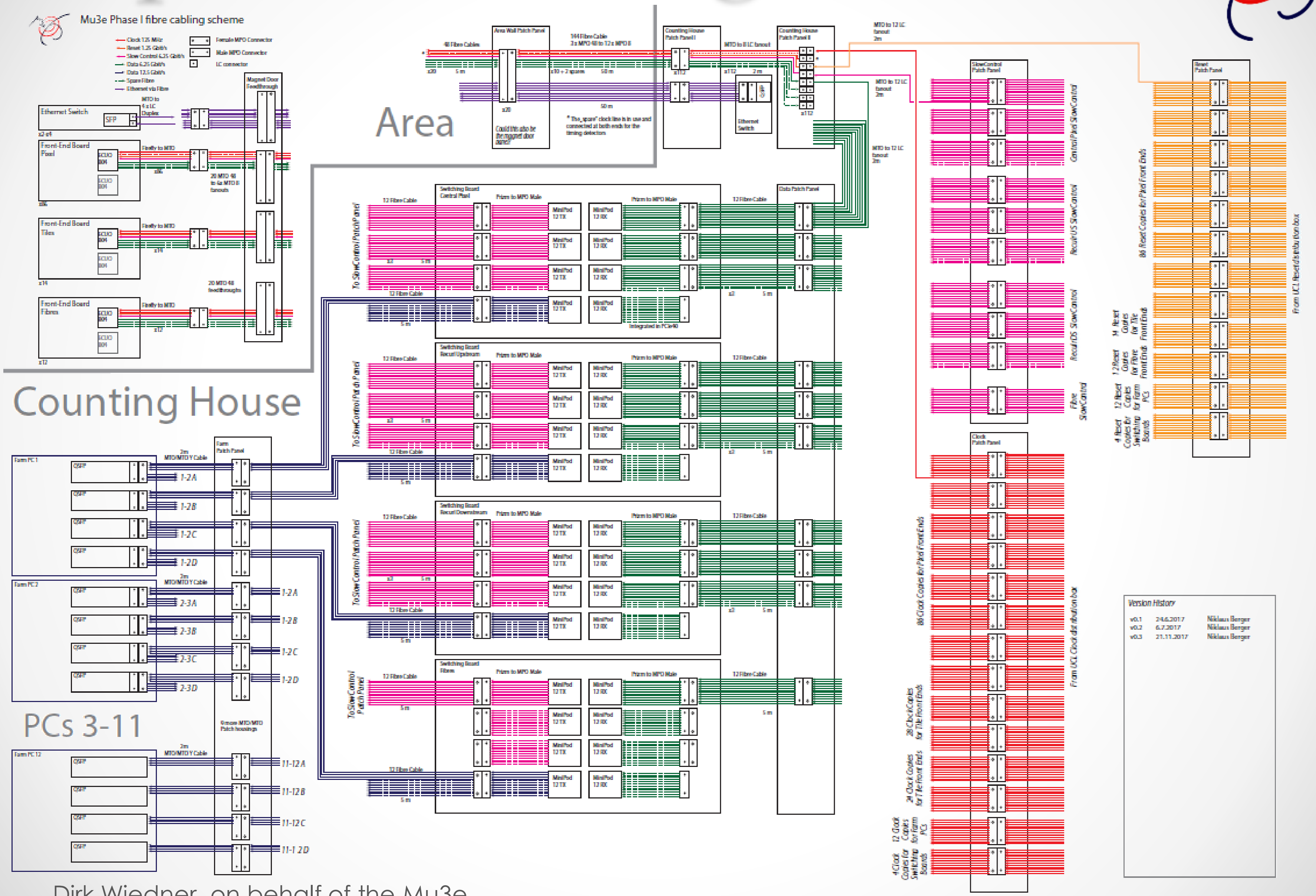


Readout Vertical Slice Test

- Pixel detector
  - HV-MAPS (MuPix8)
    - ✓ Large prototype
- Front end board
- Switching board
  - PCIe40
  - Delivery 2018
- PC



Optical cabling scheme

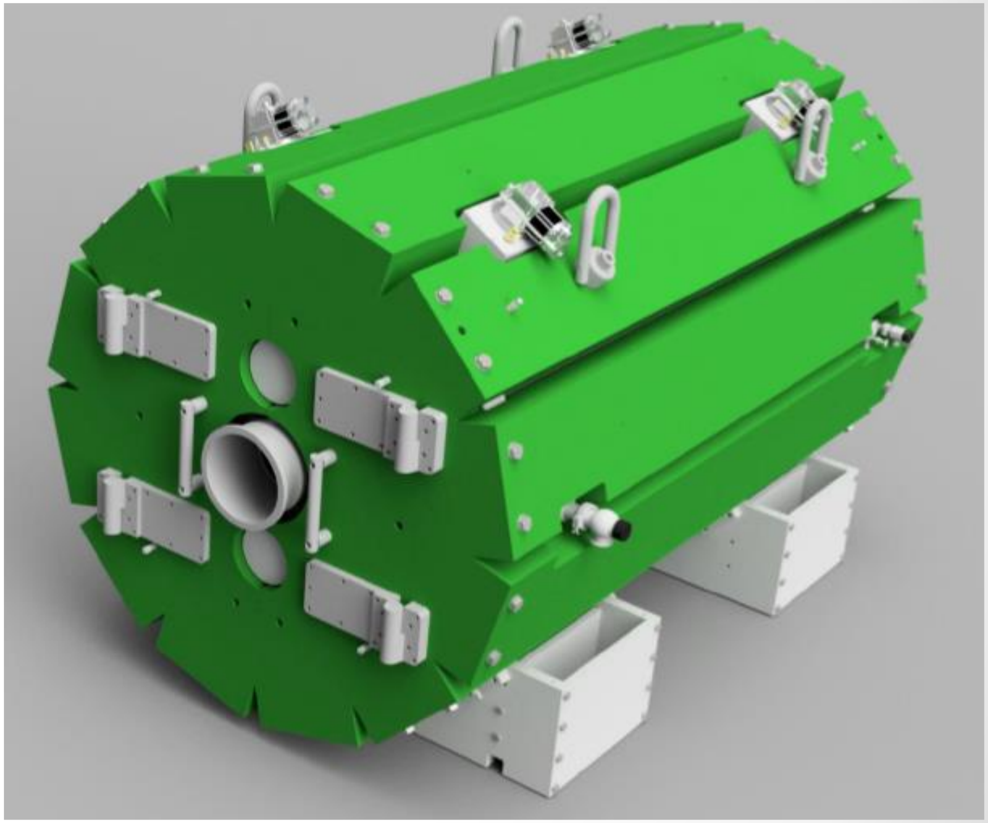


Backup Area Planning

…

Mu3e Magnet

- 1T solenoid
- 3m long
- 1m bore diameter
- Superconducting coil
- Dry cryo system
- Magnet TDR ready
- Delivery early 2019

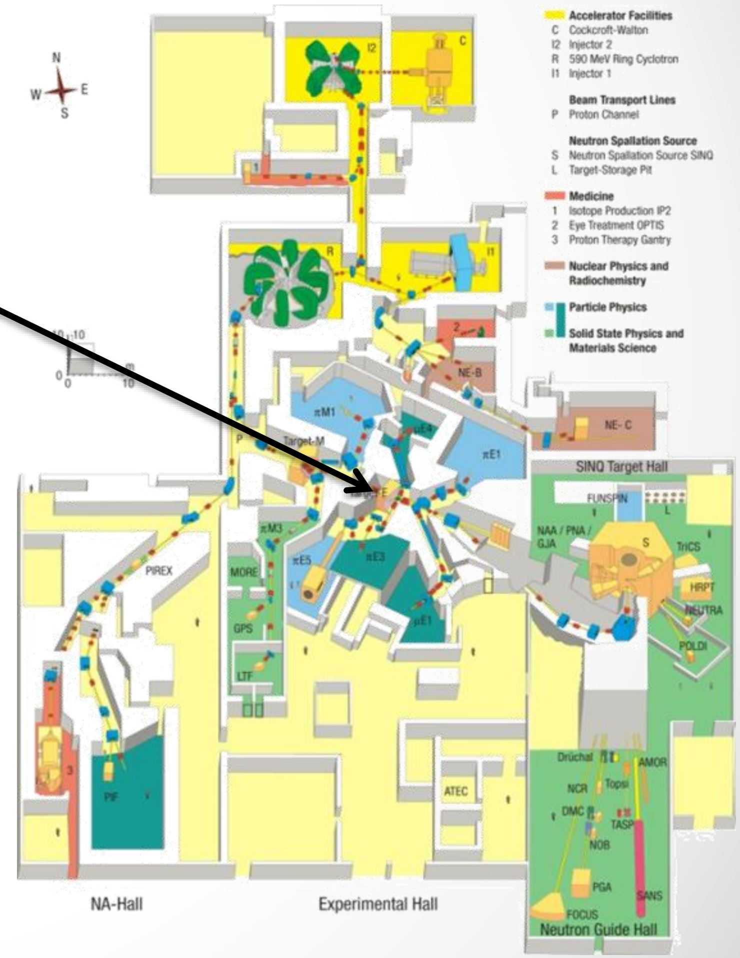


PSI μ-Beam

Paul Scherrer Institute Switzerland:

- 2.2 mA of 590 MeV/c protons
- Surface muons from target E
- Up to ~10^8 μ/s

➢ >10^{15} muon decays per year



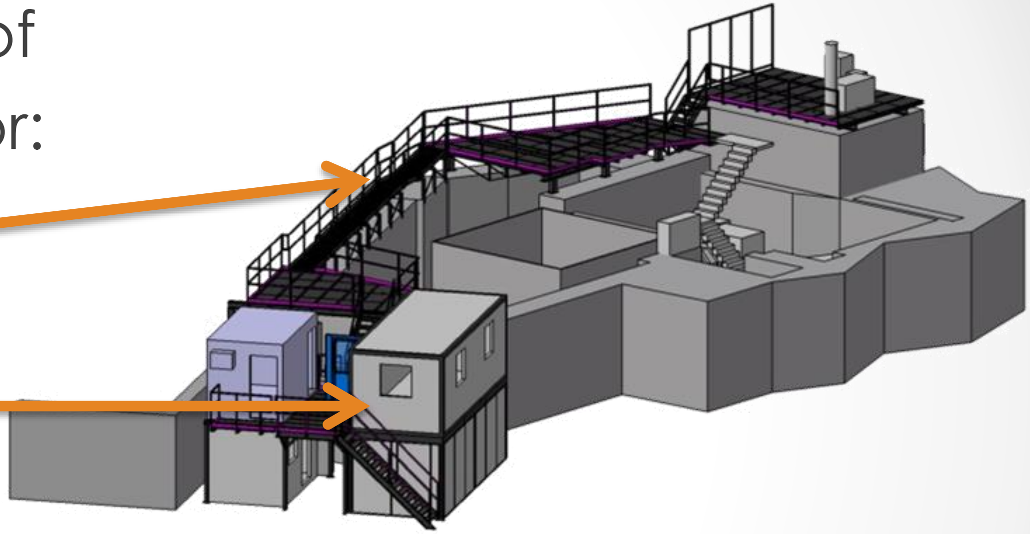
Area Planning

Good progress in terms of CAD, civil engineering for:

- ✓ Platforms
- ✓ Access ways
- ✓ Counting containers
- ✓ Power
- ➢ Cooling

Remark:

- Space in area **extremely** limited



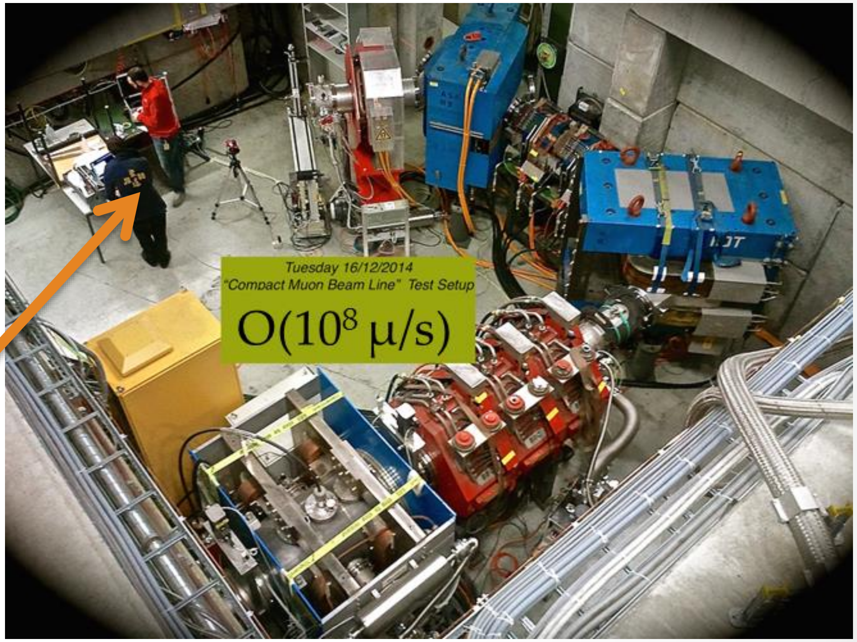
Area Planning

Good progress in terms of CAD, civil engineering for:

- ✓ Platforms
- ✓ Access ways
- ✓ Counting containers
- ✓ Power
- ➢ Cooling

Remark:

- Space in area **extremely** limited



Area Planning

Good progress in terms of CAD, civil engineering for:

- ✓ Platforms
- ✓ Access ways
- ✓ Counting containers
- ✓ Power
- ➢ Cooling

Remark:

- Space in area **extremely** limited

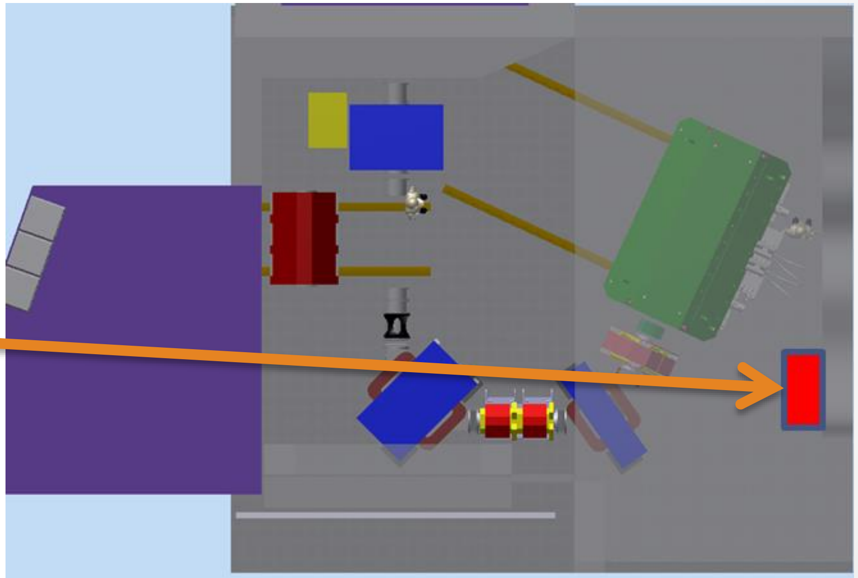
Area Planning

Good progress in terms of CAD, civil engineering for:

- ✓ Platforms
- ✓ Access ways
- ✓ Counting containers
- ✓ Power
- ➢ Cooling

Remark:

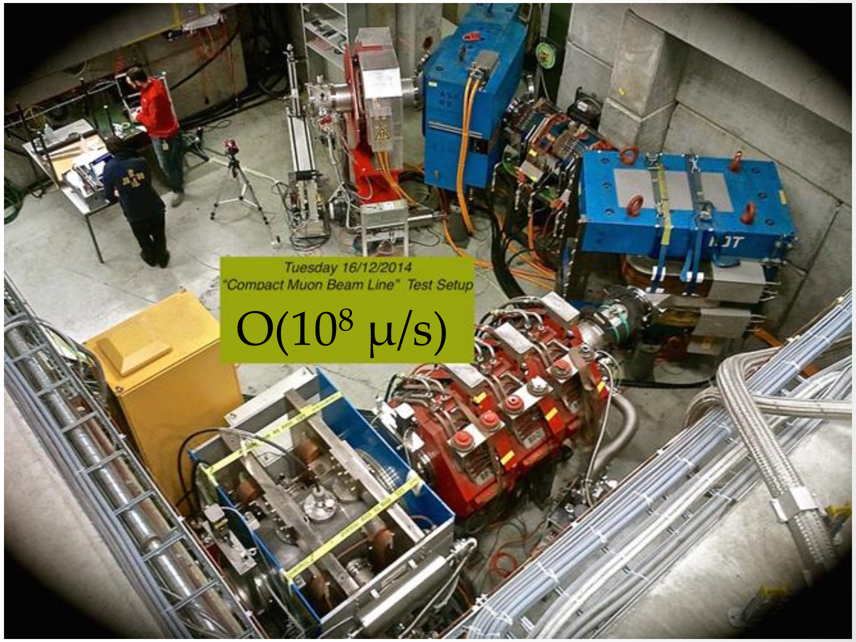
- Space in area **extremely** limited



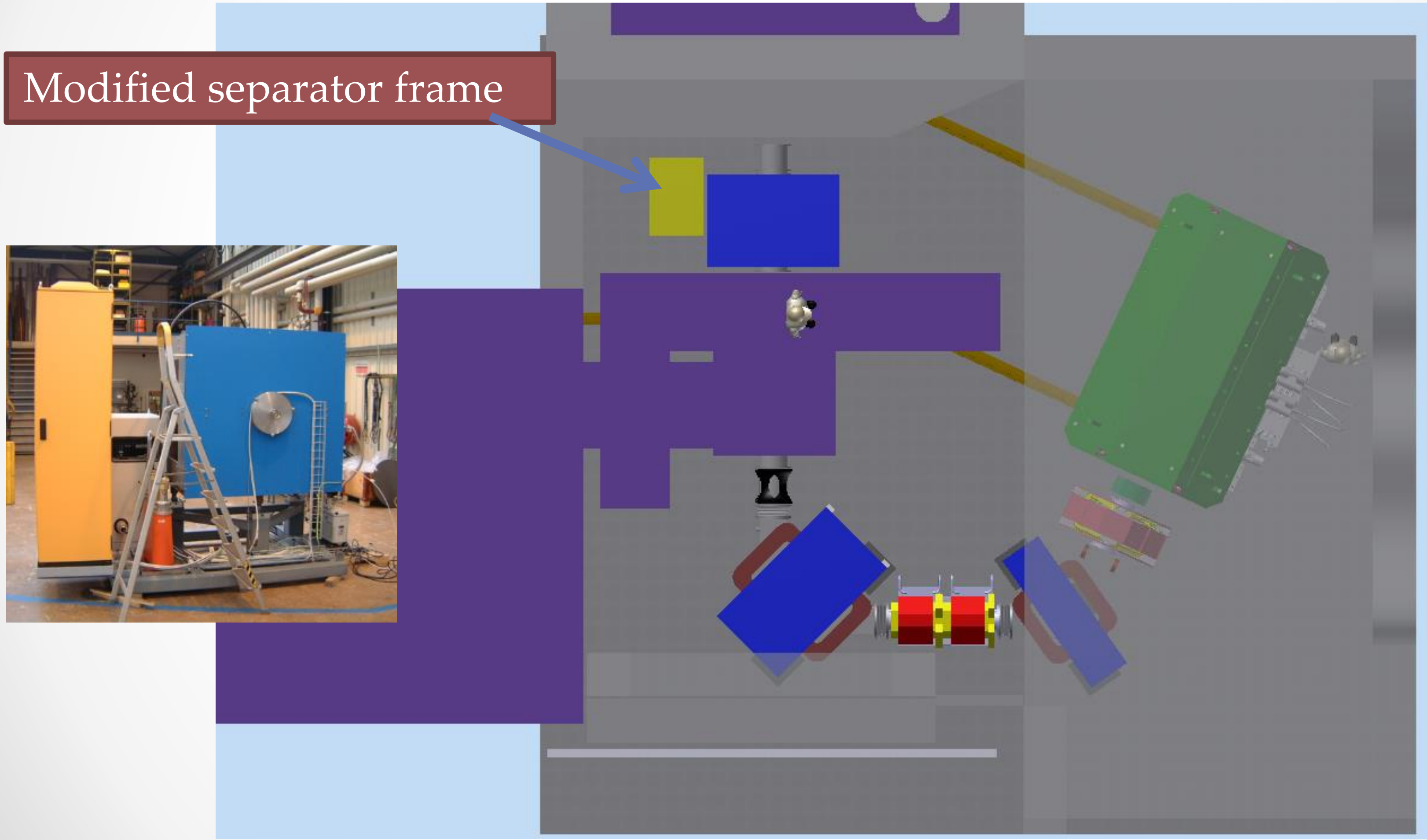
PSI μ-Beam

Paul Scherrer Institute Switzerland:

- 2.2 mA of 590 MeV/c protons
- Surface muons from target E
- Up to $\sim 10^8$ μ/s
- ➢ $>10^{15}$ muon decays per year

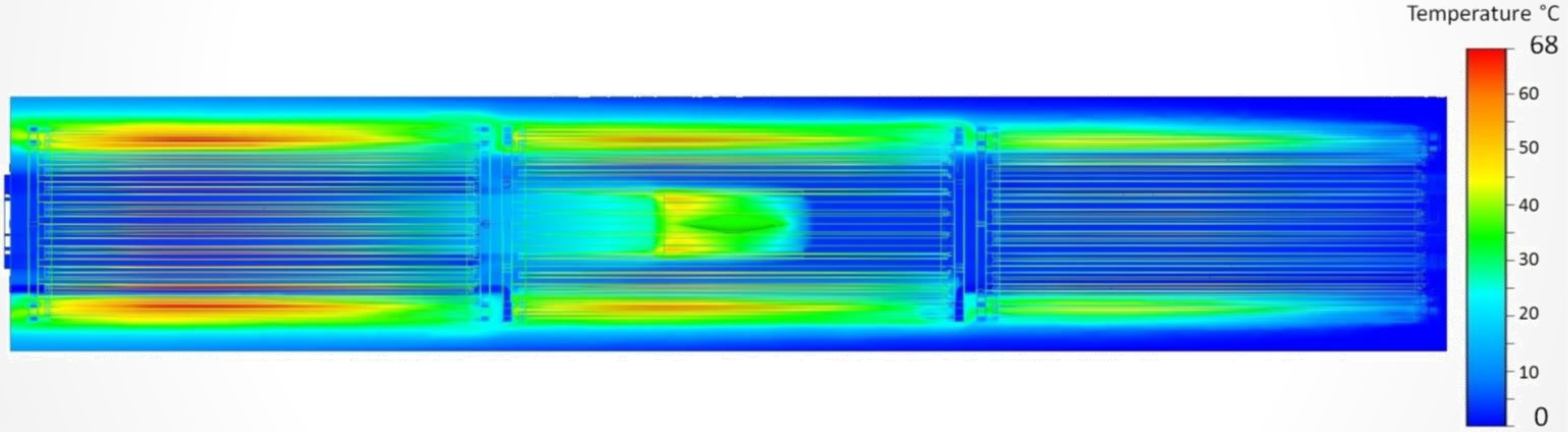


Area Layout



Cooling Backup

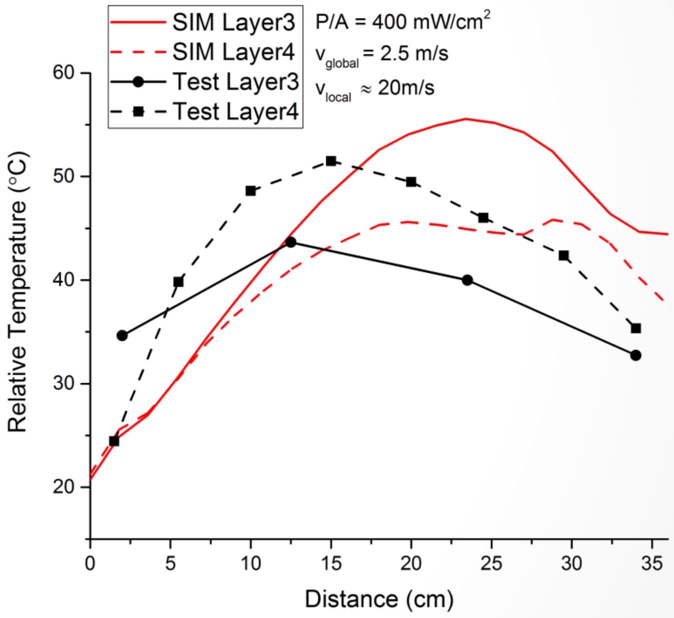
Simulation



He cooling
400mW/cm^2

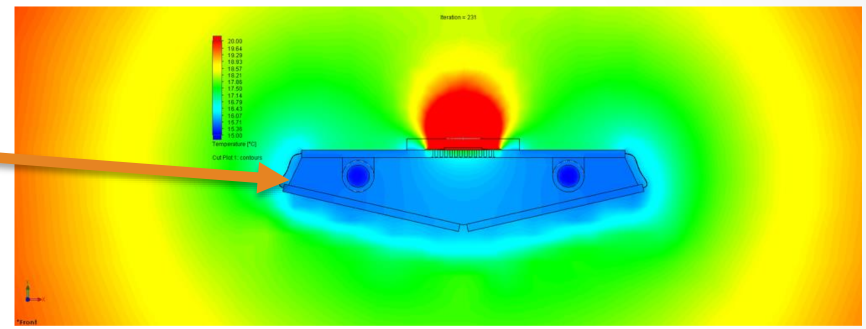
Test Results

- 1:1 Prototype
  - Layer 3+4 of silicon tracker
  - Ohmic heating 400mW/cm^2
- Cooling He
  - at several m/s
- Temperature sensors attached to foil
  - LabVIEW readout
- **Results promising**
  - **ΔT < 60°K**
  - ➢ **No sign of vibration in air**

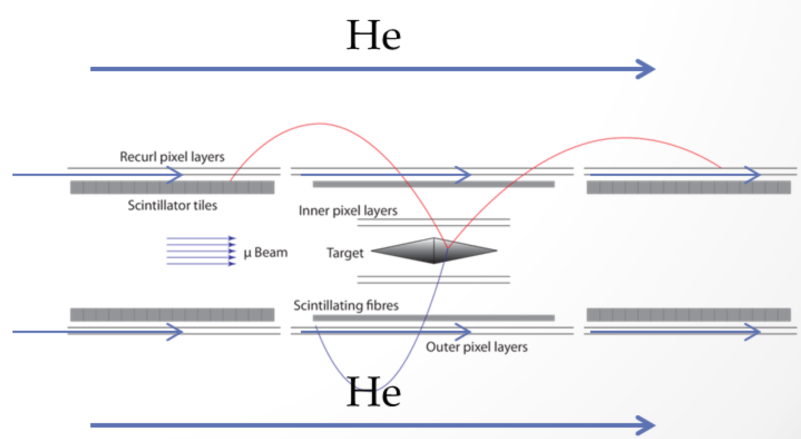


Cooling Concept

- Liquid cooling
  - Timing detectors
  - Front end boards
  - DC-DC boards
  - Wiener LV crates
  - Filter farm racks
- Gaseous He cooling
  - For Silicon tracker
  - General cooling inside magnet

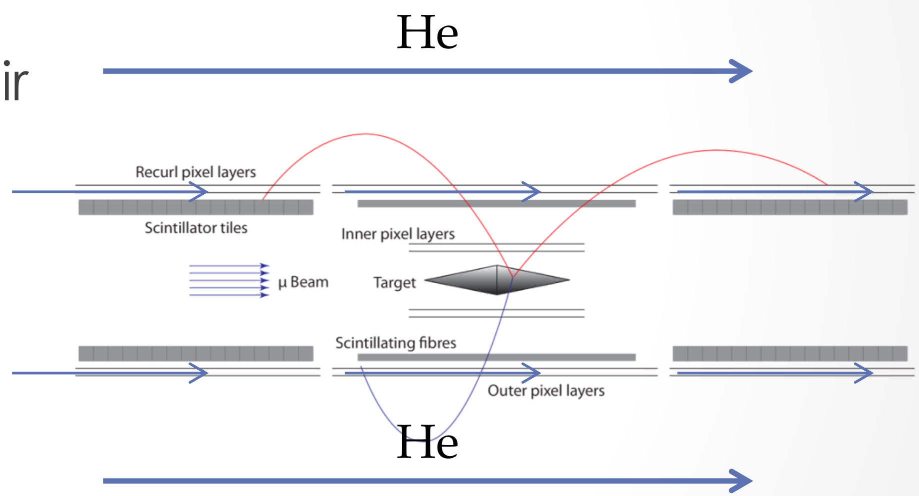


Tile cooling simulation



He Cooling

- Gaseous He cooling
  - Low multiple Coulomb scattering
  - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker
  - V-shapes
  - Outer surface
    - In between layers
    - Between SciFi and layers



$400 mW/cm^2 \times 11376 cm^2$
$= 4.5504\ KW$

Pixel helium cooling BVR49

Design status – Supplies

Required target flows per helium circuit:

Volume	He flow speed m/s	Cross-section cm^2	Volume cm^3	Occurence times	Volumetric flow m^3/min
Gap L1/L2	10	12	148	1	0.72
Gap SciFi/L3	10	39	1320	1	2.3
Gap Tile/L3	10	34	1150	2	4.2
V-folds L3	20	3.3	114	3	1.2
Gap L3/L4	10	60	2185	3	10.8
V-folds L4	20	3.9	141	3	1.4
Global flow	0.5	7600	912000	1	23
Total		7750			43

$\Rightarrow$ Volumes differ up to factor ≈ 20

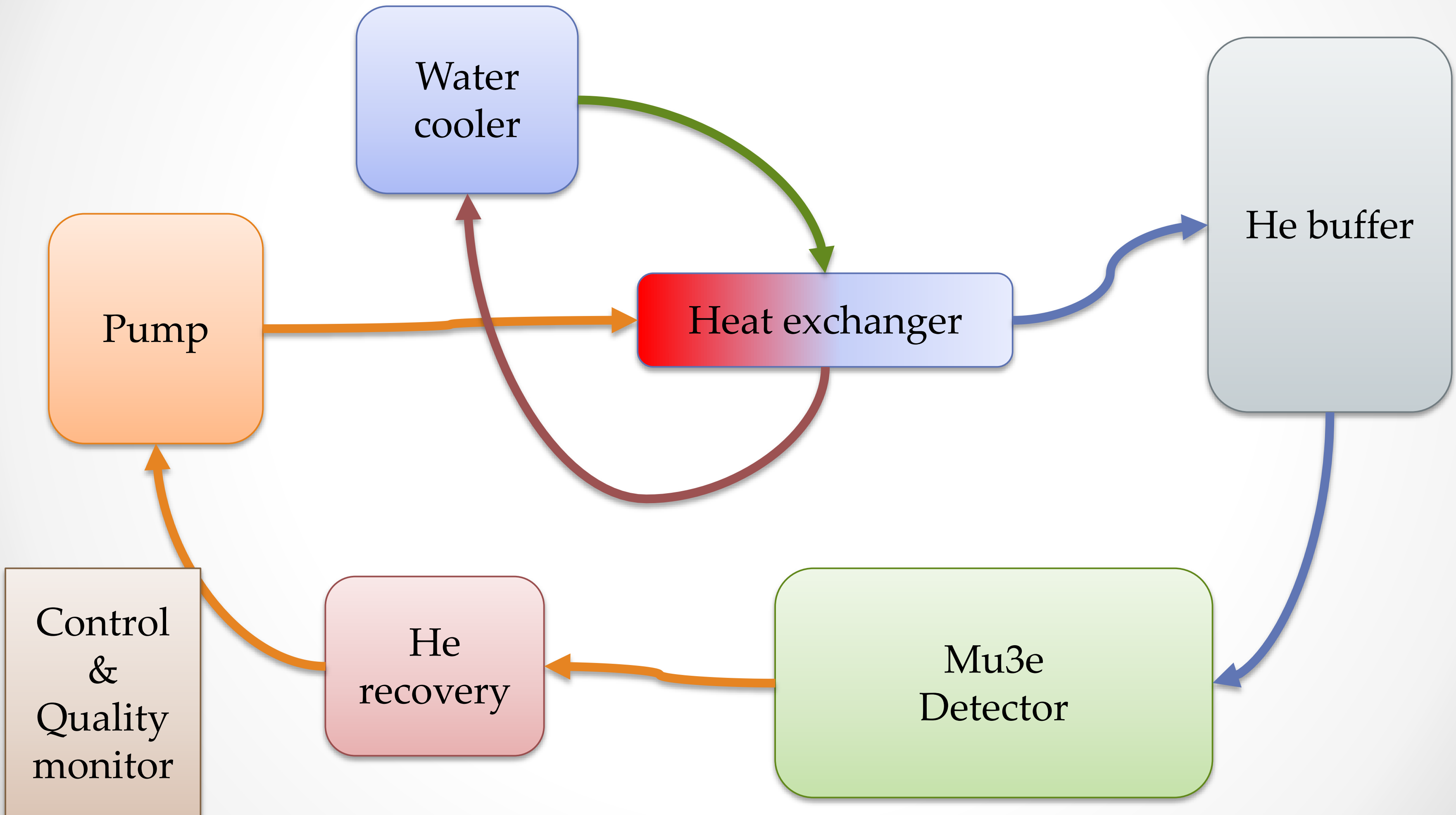
Pixel helium cooling BVR49

- Multiple He cooling circuits
- Volumetric flow between
  - 0.72 m^3/min. and
  - 23 m^3/min.
- Separately fine adjustable
- Segment overall He system?
  - Introduce redundancy

He cooling requirements

- Cooling power
  - Pixel power dissipation 4.55kW
  - Enough reserve
- Up to 50 m^3/min.
- Reliable start up procedure
- Reliable emergency reaction
- Good temperature stability
- Dry and clean
- He recovery system

He cooling system



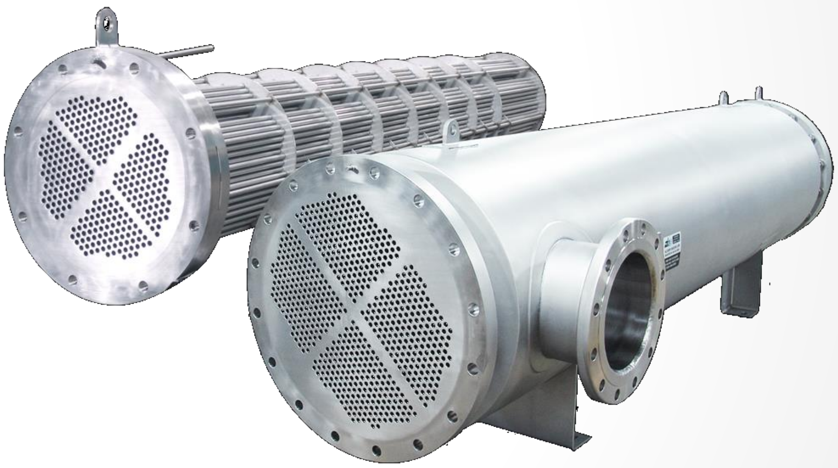
Water cooler

- 10kW chiller in HD
  - Commissioned 2016
  - Massive
- 2.25kW chiller in HD
  - Borrowed from H1
  - Commissioned in 2016
  - Intermediate size
- Extra chiller required?

Copyright Parker

Heat exchanger

- 10kW heat exchanger in HD
- Water to He
- Industry standard

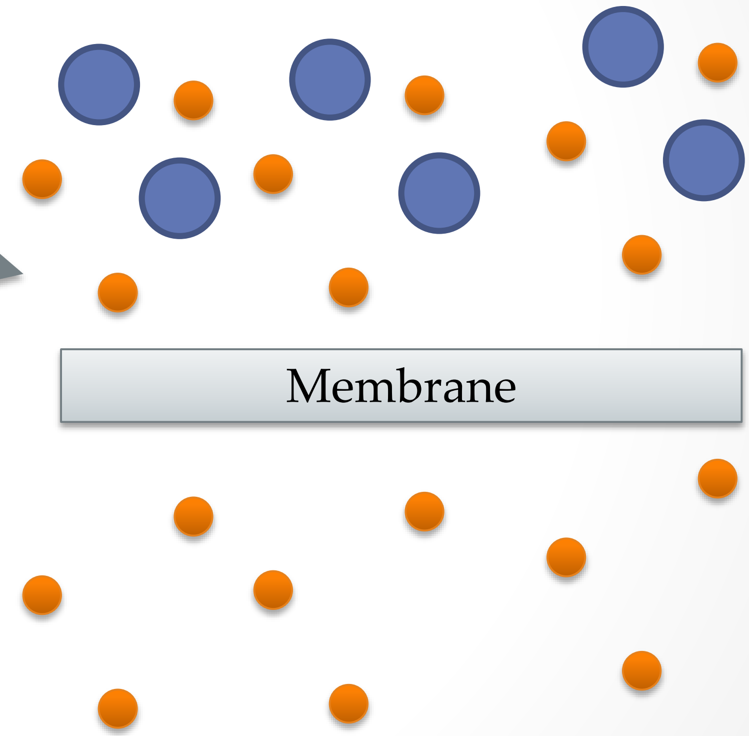


Helium buffer

- Large He buffer
- Over pressurized
- Store cold He
- Eliminate vibrations from pumps
- Delivers He in case pump stops

He recovery

- He in closed system
- Drying system
- Remove other gases
  - Membrane filter
  - Very efficient for air/He separation



Control and quality monitor

- Slow control system for
  - Pumps
  - Chillers
  - Valves
- Safety system
  - Shutdown
  - Humidity
- Monitoring
  - Temperatures
  - Pressures
  - Flows
  - Humidity
  - Contaminations

Piping

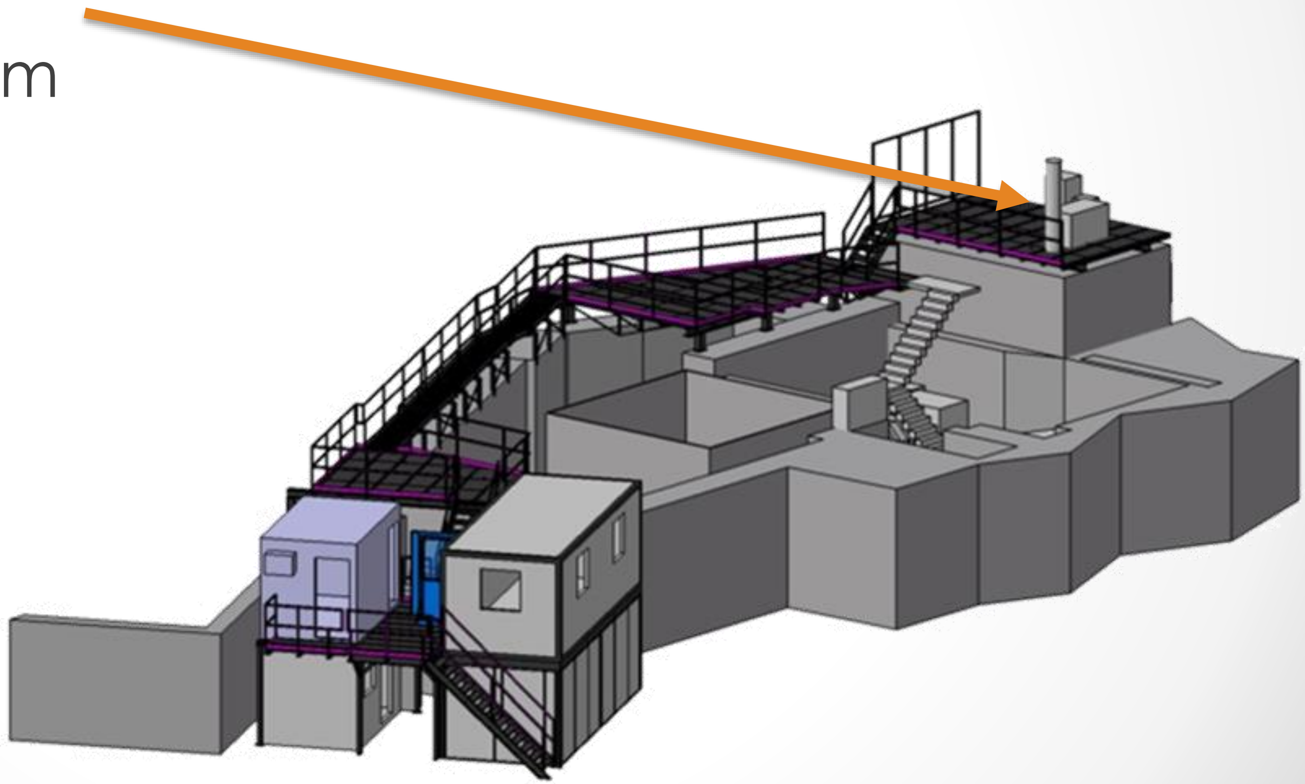
- Volumetric flow high
  - 50m^3/min.
- ≥20cm diameter pipes
- Insulated
- Flexible (?)

Pump(s)

- Large throughput
  - Up to 50m^3/min.
- Little overpressure
  - 500 mbar ok
- Must run constantly
- Must not contaminate the He
- Contact air conditioning experts?

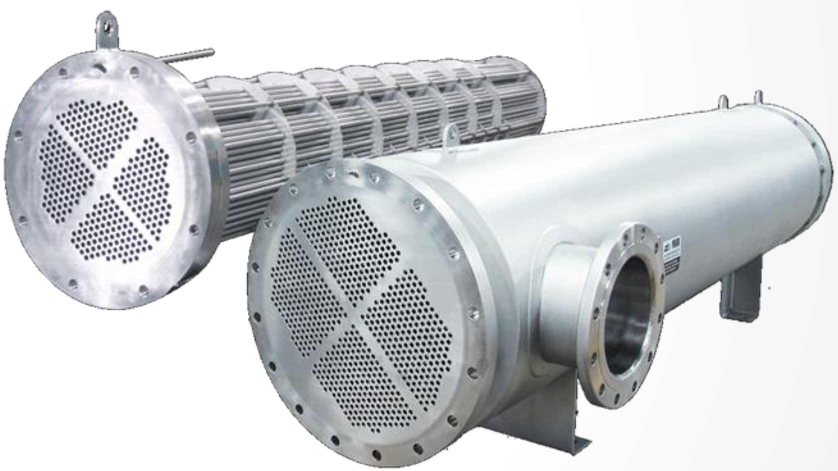
Installation space

- System of very large devices
- Vibrations from
  - Pumps
  - Chillers
- Large pipes



Summary

- He cooling system is:
  - Large
  - Complex
  - Safety relevant
- Chillers and He heat exchanger in HD
- Pumps, pipes, valves, recovery system and control system to be acquired/designed



He Properties

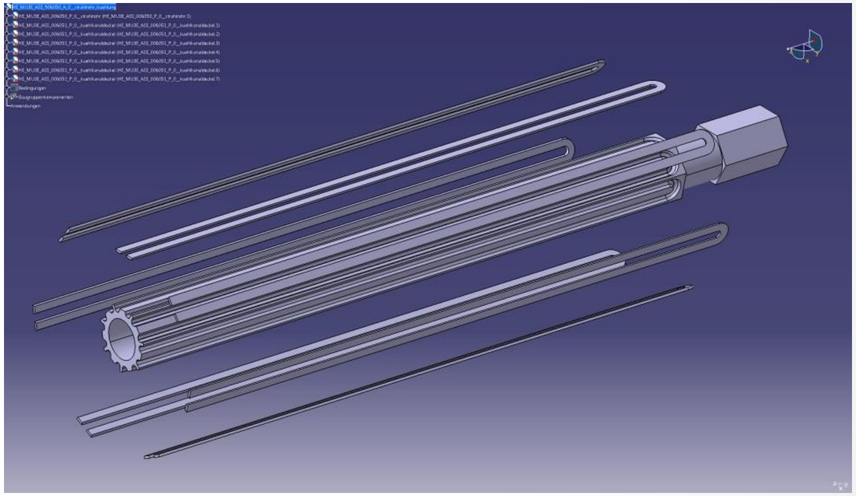
- Molecular weight : 4.0026 g/mol
- Gaseous phase
- Gas density (1.013 bar at boiling point) : 16.752 kg/m^3
- Gas density (1.013 bar and 15 °C (59 °F)) : 0.1692 kg/m^3
- Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)) : 1.0005
- Specific gravity : 0.138
- Specific volume (1.013 bar and 25 °C (77 °F)) : 6.1166 m^3/kg
- Heat capacity at constant pressure (Cp) (1.013 bar and 25 °C (77 °F)) : 0.0208 kJ/(mol.K)
- Heat capacity at constant volume (Cv) (1.013 bar and 25 °C (77 °F)) : 0.0125 kJ/(mol.K)
- Ratio of specific heats (Gamma:Cp/Cv) (1.013 bar and 25 °C (77 °F)) : 1.6665
- Viscosity (1.013 bar and 0 °C (32 °F)) : 1.8695E^{-04} Poise
- Thermal conductivity (1.013 bar and 0 °C (32 °F)) : 146.2 mW/(m.K)

Air Properties

- Molecular weight : 28.96 g/mol
- Gaseous phase
- Gas density (1.013 bar at boiling point) : 3.2 kg/m^3
- Gas density (1.013 bar and 15 °C (59 °F)) : 1.225 kg/m^3
- Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)) : 0.9996
- Specific gravity : 1
- Specific volume (1.013 bar and 25 °C (77 °F)) : 0.8448 m^3/kg
- Heat capacity at constant pressure (Cp) (1.013 bar and 25 °C (77 °F)) : 0.0291 kJ/(mol.K)
- Heat capacity at constant volume (Cv) (1.013 bar and 25 °C (77 °F)) : 0.0208 kJ/(mol.K)
- Ratio of specific heats (Gamma:Cp/Cv) (1.013 bar and 25 °C (77 °F)) : 1.4018
- Viscosity (1 bar and 0 °C (32 °F)) : 1.721E^{-04} Poise
- Thermal conductivity (1.013 bar and 0 °C (32 °F)) : 24.36 mW/(m.K)

Liquid Cooling

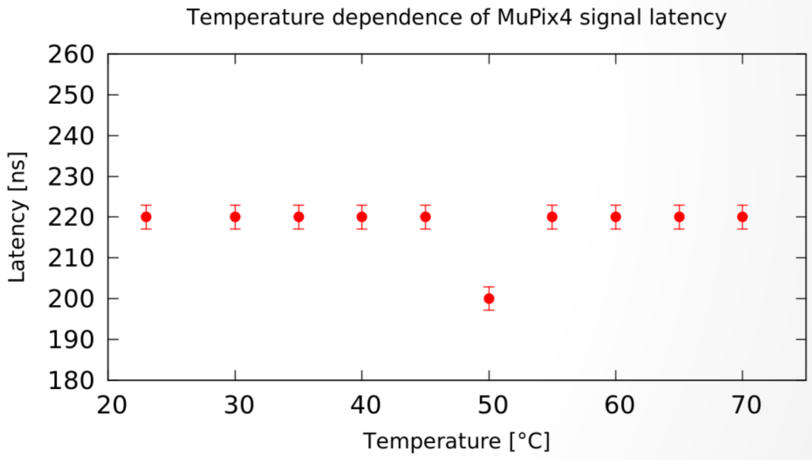
- Beam pipe cooling
  - With cooling liquid
  - 5°C temperature
  - Significant flow possible
  - … using grooves in pipe
- For electronics
  - FPGAs and
  - Power regulators
  - Mounted to cooling plates
- Total power several kW



Old design study

He Cooling

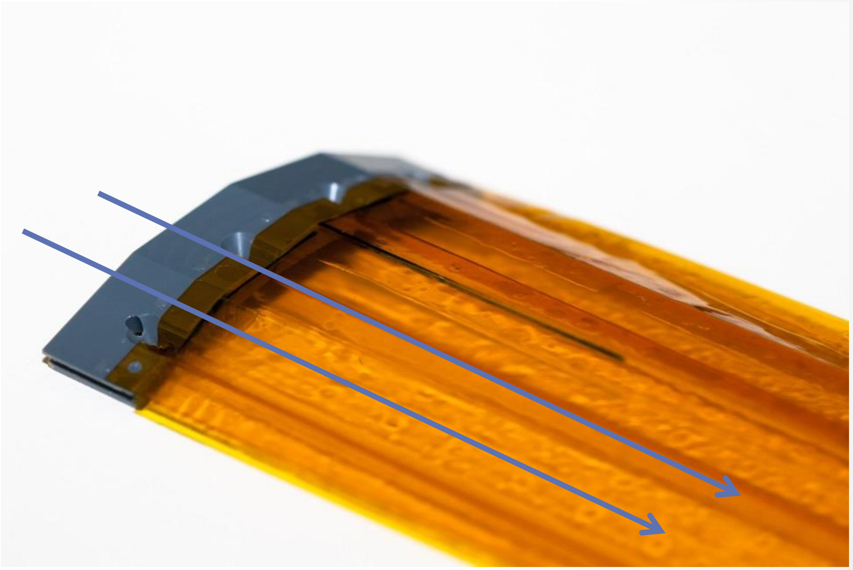
- Gaseous He cooling
  - Low multiple Coulomb scattering
  - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker
  - Distribution to Frame
    - V-shapes
    - Outer surface



Temperatures between 20°C to 70°C ok.

He Cooling

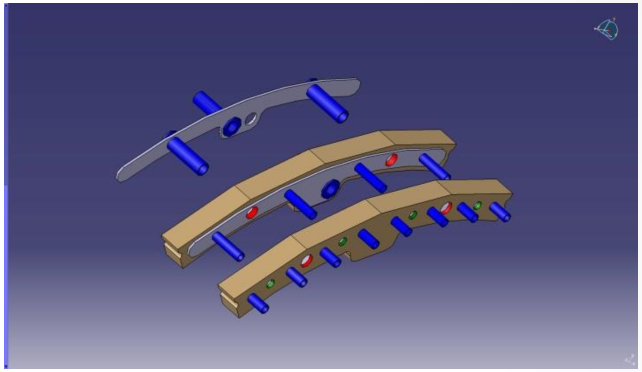
- Gaseous He cooling
  - Low multiple Coulomb scattering
  - He more effective than air
- Global flow inside Magnet volume
- **Local flow for Tracker**
  - Distribution to Frame
    - V-shapes
    - Outer surface

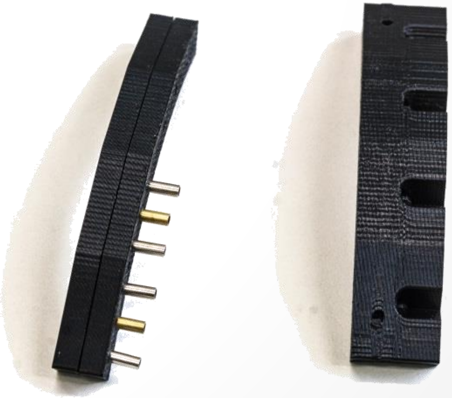


Old design study

He Cooling

- Gaseous He cooling
  - Low multiple Coulomb scattering
  - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker
  - **Distribution to Frame**
    - V-shapes
    - Outer surface

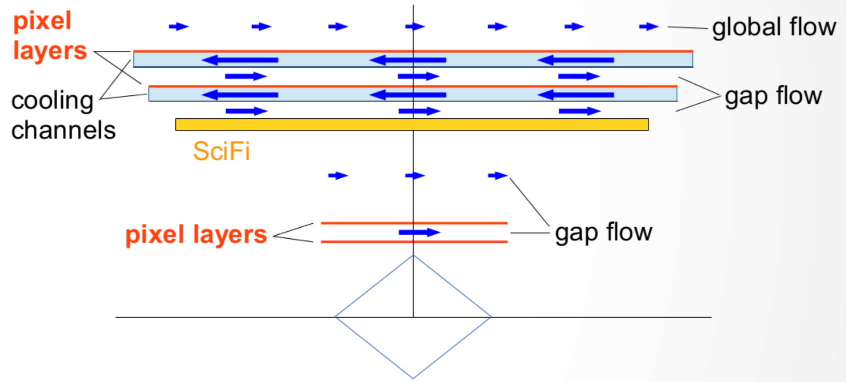




Old design study

He Cooling

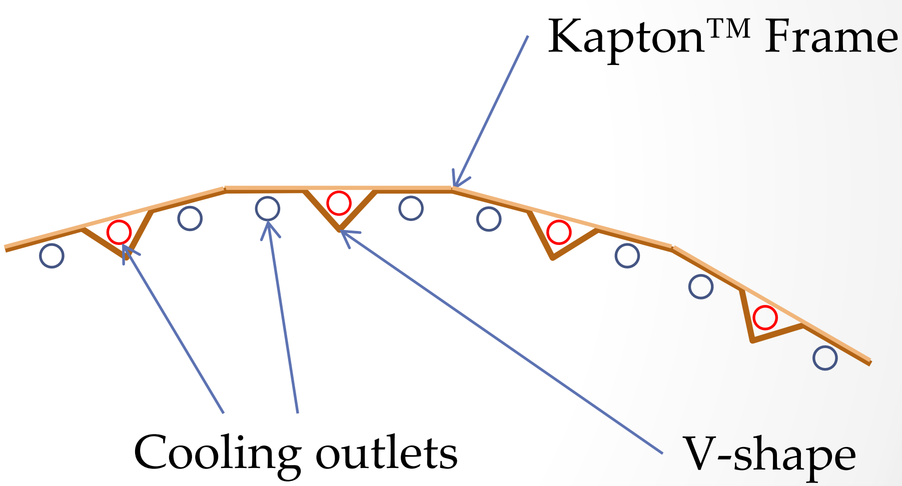
- Gaseous He cooling
  - o Low multiple Coulomb scattering
  - o He more effective than air
- Global flow inside Magnet volume
- Distribution in Frame
    - Local flow: V-shapes
    - Gap flow: Outer surface



$400 mW/cm^2 \times 11664 cm^2$
$\approx$ 4.7 KW

He Cooling

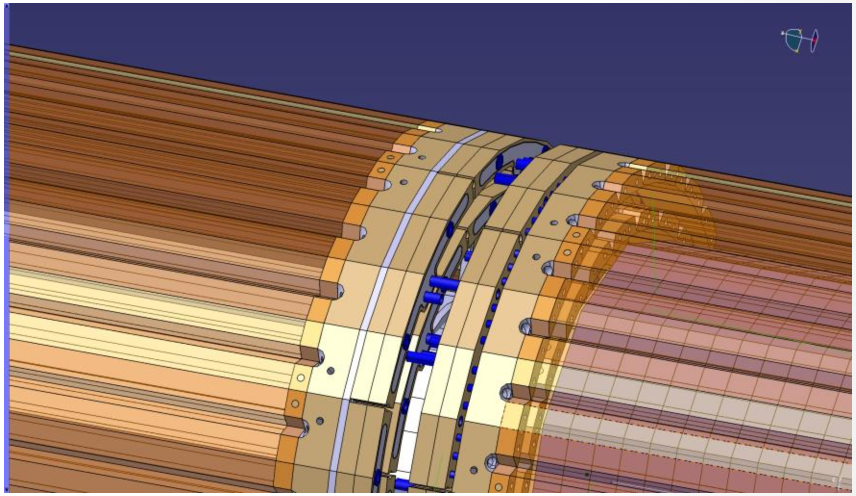
- Gaseous He cooling
  - Low multiple Coulomb scattering
  - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker
  - Distribution to Frame
    - **V-shapes**
    - **Outer surface**



Old design study

He Cooling

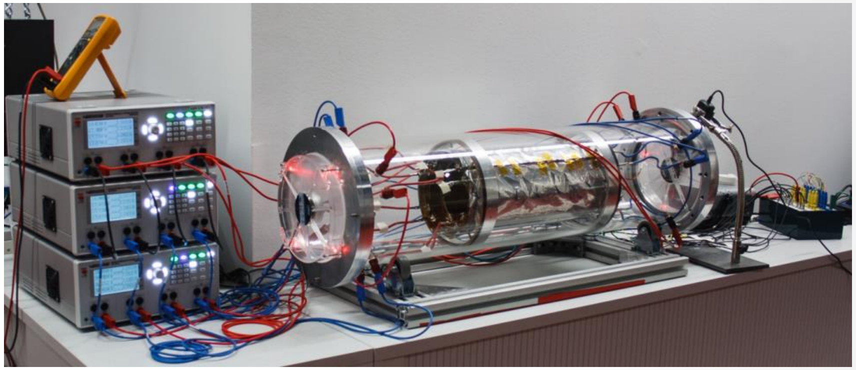
- Gaseous He cooling
  - Low multiple Coulomb scattering
  - He more effective than air
- Global flow inside Magnet volume
- Local flow for Tracker
  - Distribution to Frame
    - V-shapes
    - Outer surface

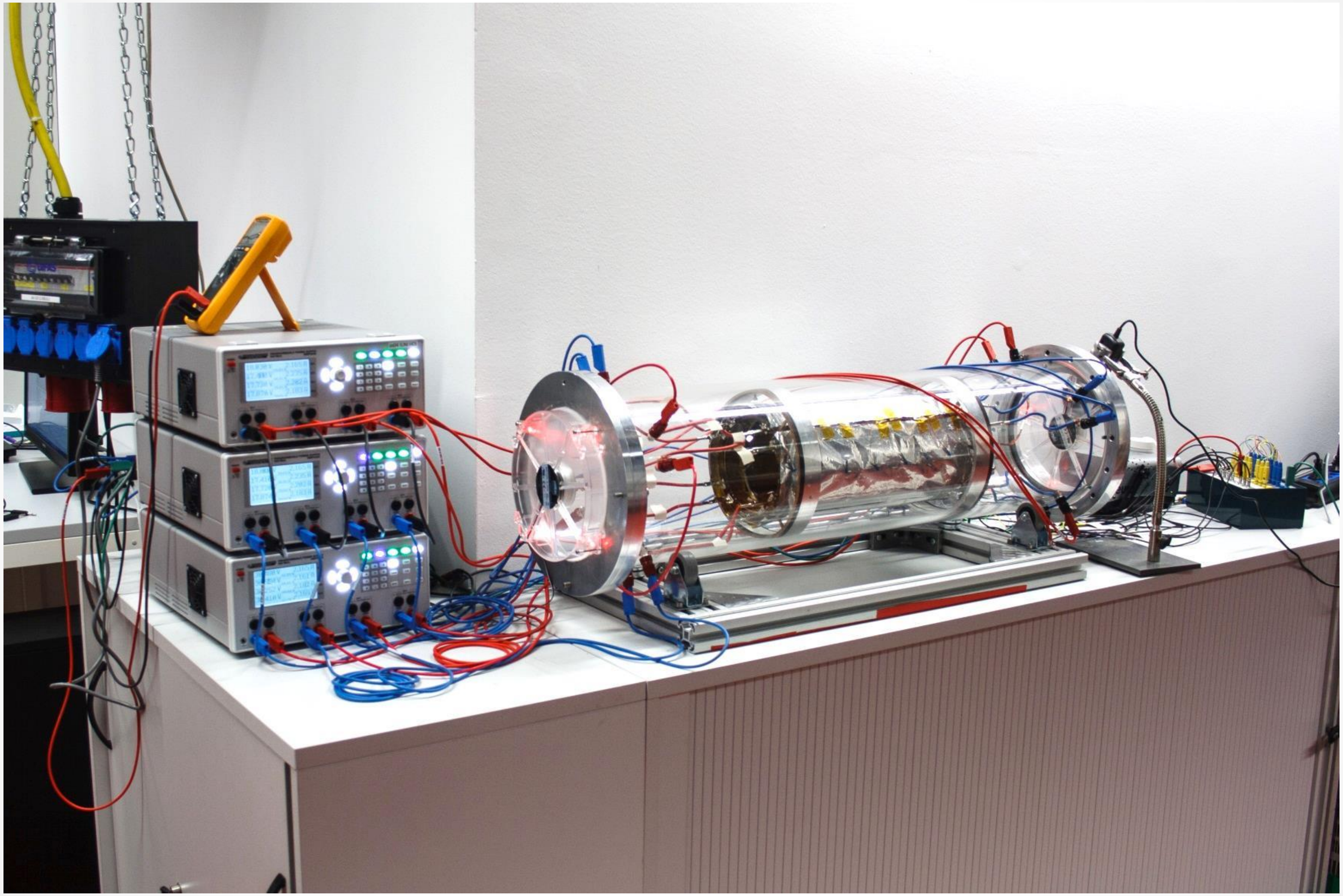


Old design study

Tests

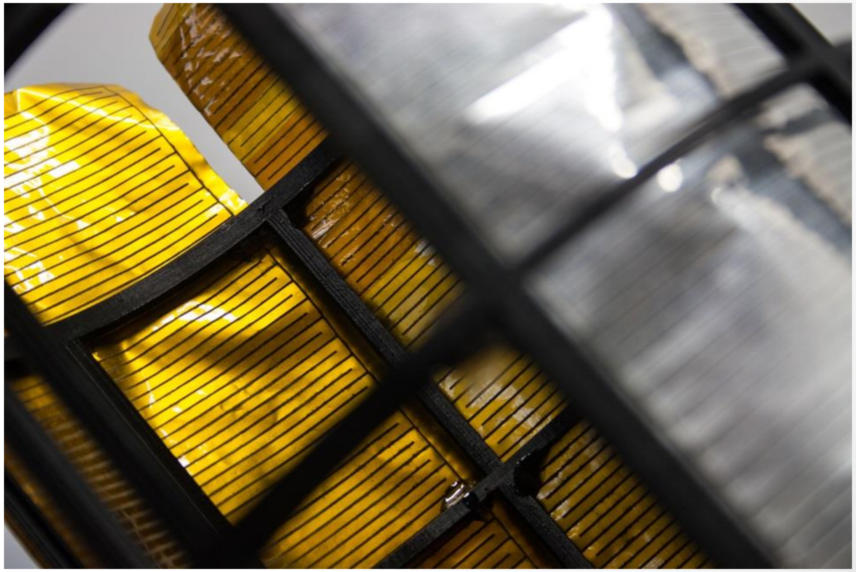
- **Full scale prototype**
  - Layer 3+4 of silicon tracker
  - Ohmic heating (150mW/cm^2)
  - 561.6 W for layer 3 +4
  - … of Aluminum-Kapton™
- Cooling with external fan
  - **Air** at several m/s
- Temperature sensors attached to foil
  - LabView readout
- First results promising
  - $\Delta T < 60°K$





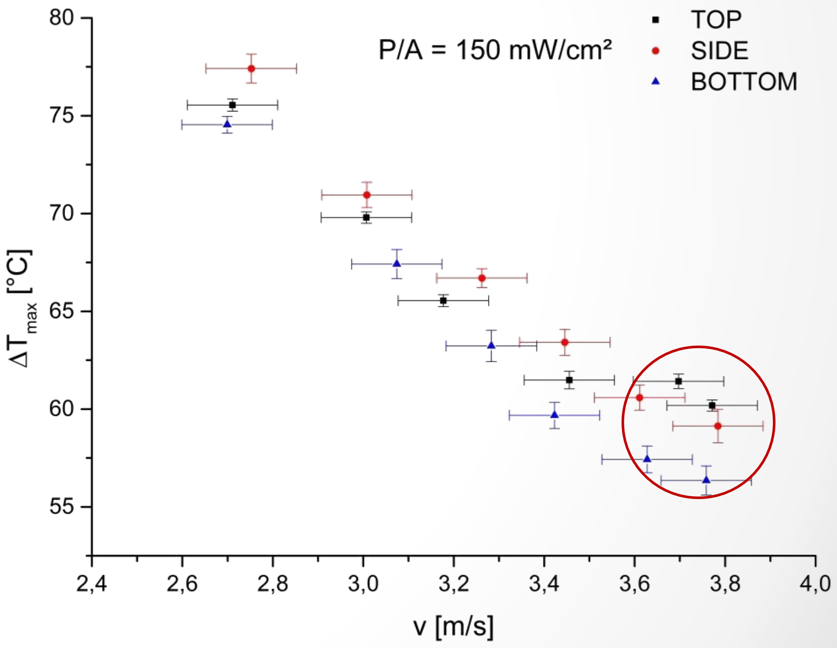
Tests

- Full scale prototype
  - Layer 3+4 of silicon tracker
  - Ohmic heating (150mW/cm^2)
  - 561.6 W for layer 3 +4
  - … of **Aluminum-Kapton™**
- Cooling with external fan
  - Air at several m/s
- Temperature sensors attached to foil
  - LabView readout
- First results promising
  - $\Delta T < 60°K$

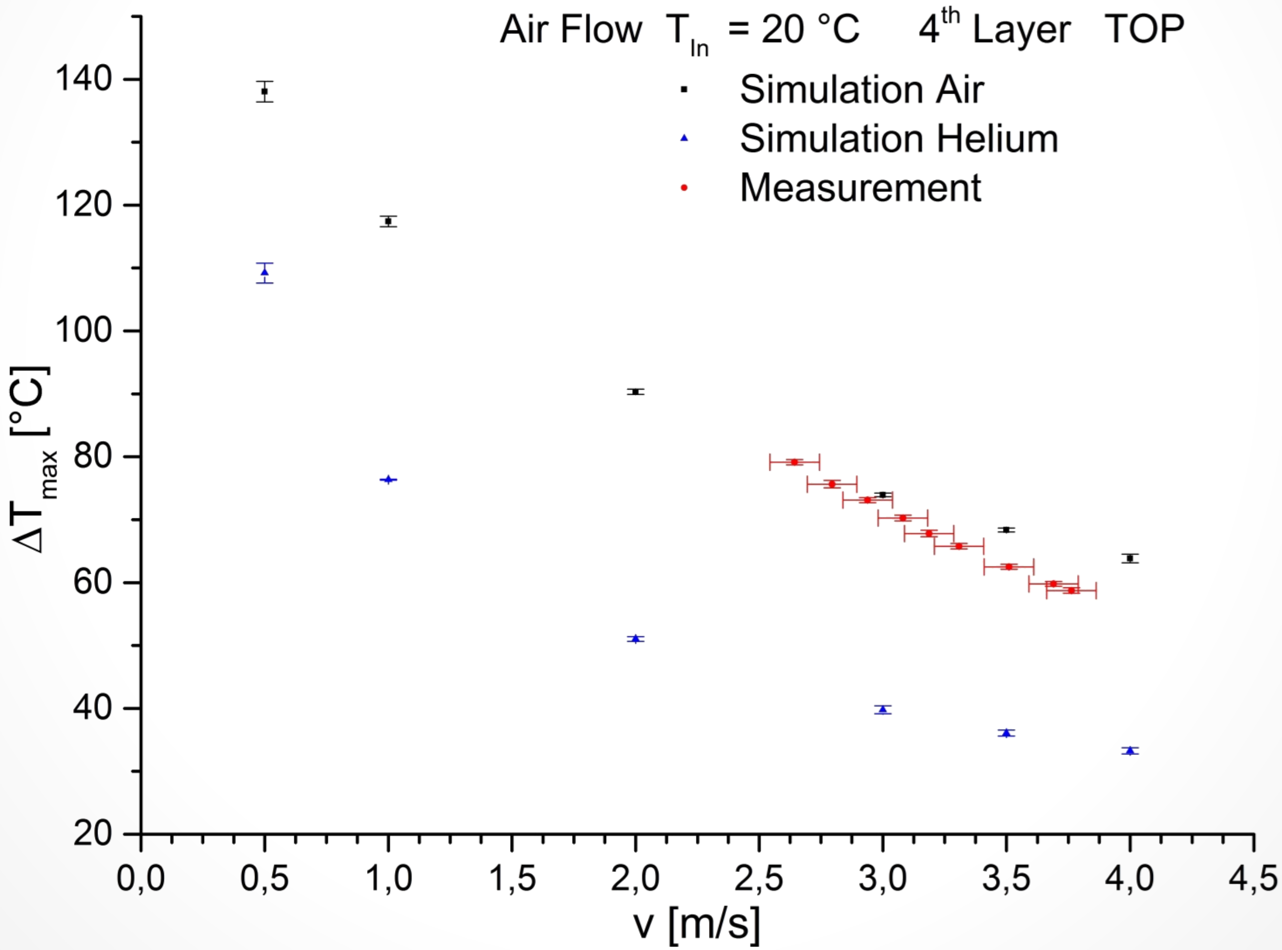


Test Results

- Full scale prototype
  - Layer 3+4 of silicon tracker
  - Ohmic heating (150mW/cm^2)
  - 561.6 W for layer 3 +4
  - … of Aluminum-Kapton™
- Cooling with external fan
  - Air at several m/s
- Temperature sensors attached to foil
  - LabView readout
- **First results promising**
  - **ΔT < 60°K**
  - ➢ **No sign of vibration in air**

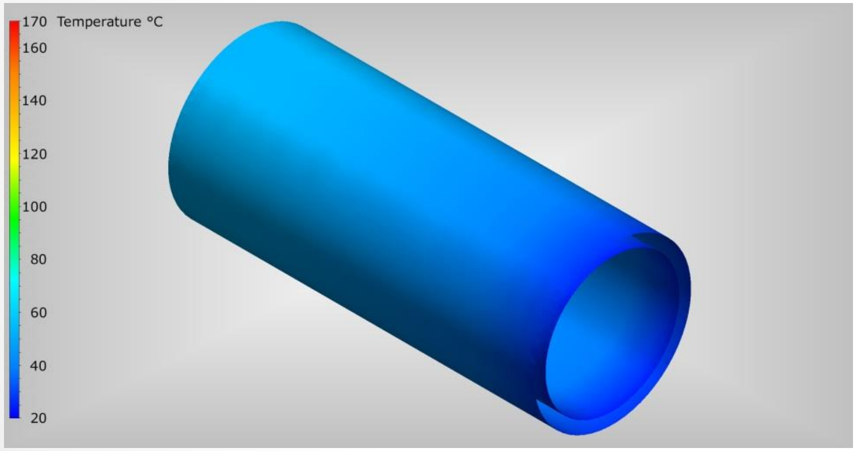


Comparison Simulation and Tests

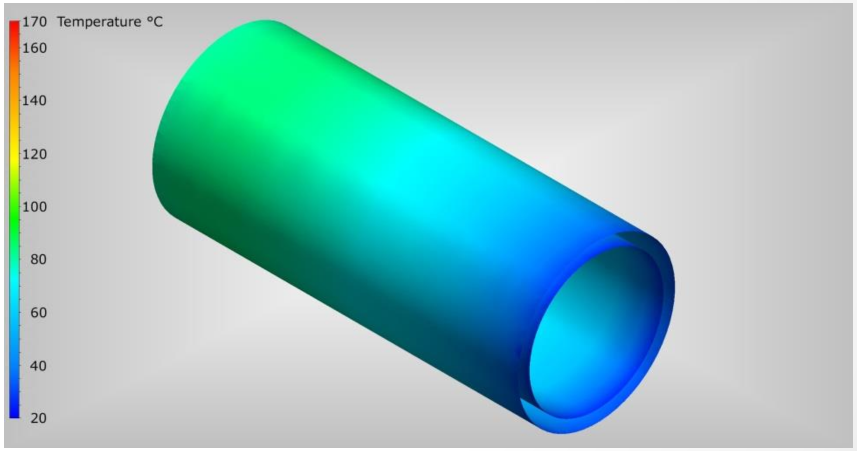


Comparison Simulation He and Air

He



Air



$$v = 4.0\ ^{m}/_{s}$$

He Cooling
750 mW/cm^2