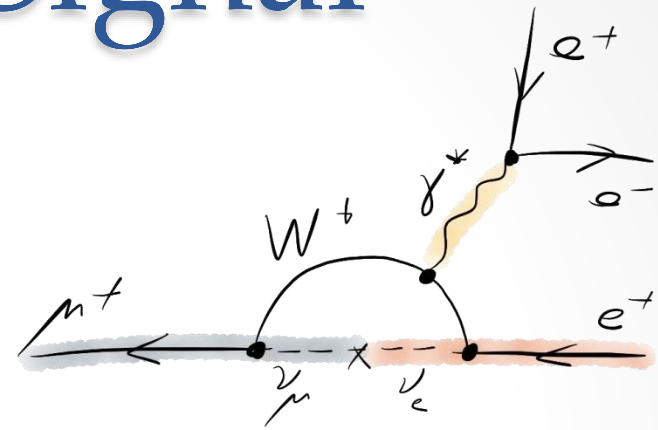
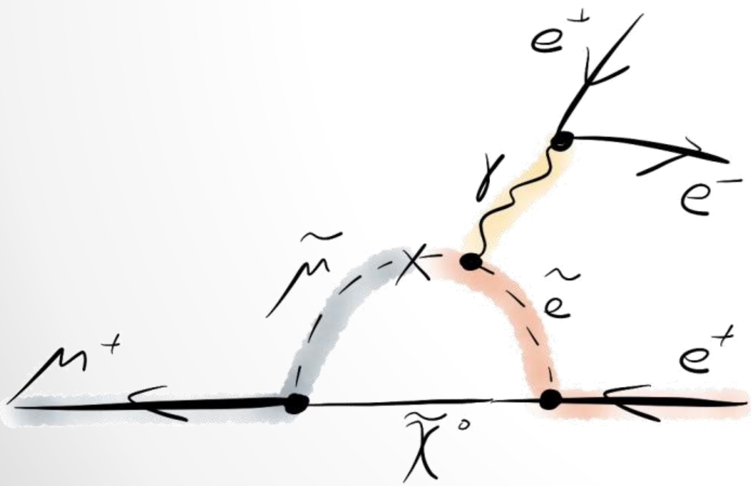
Status of the Mu3e Detector

Dirk Wiedner, Heidelberg
On Behalf of the Mu3e Collaboration

The Mu3e Signal

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





- Rare decay (BR<10^{-12}, SINDRUM '88)
- For BR O(10^{-15})
    - >10^{15} muon decays
    - High decay rates O(10^8 μ/s)

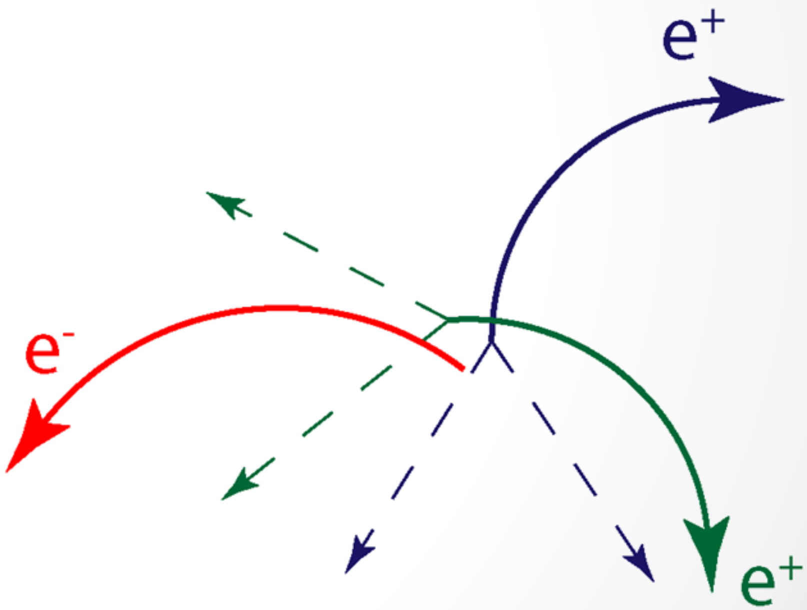
Signal properties:

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

The Mu3e Background

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

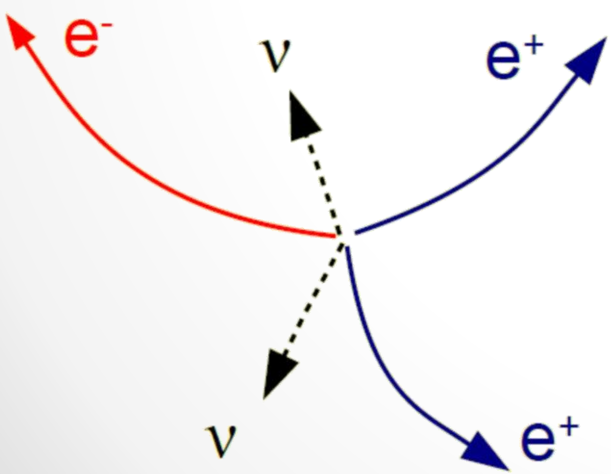
➢ **Good time** and
➢ **Good vertex resolution** required

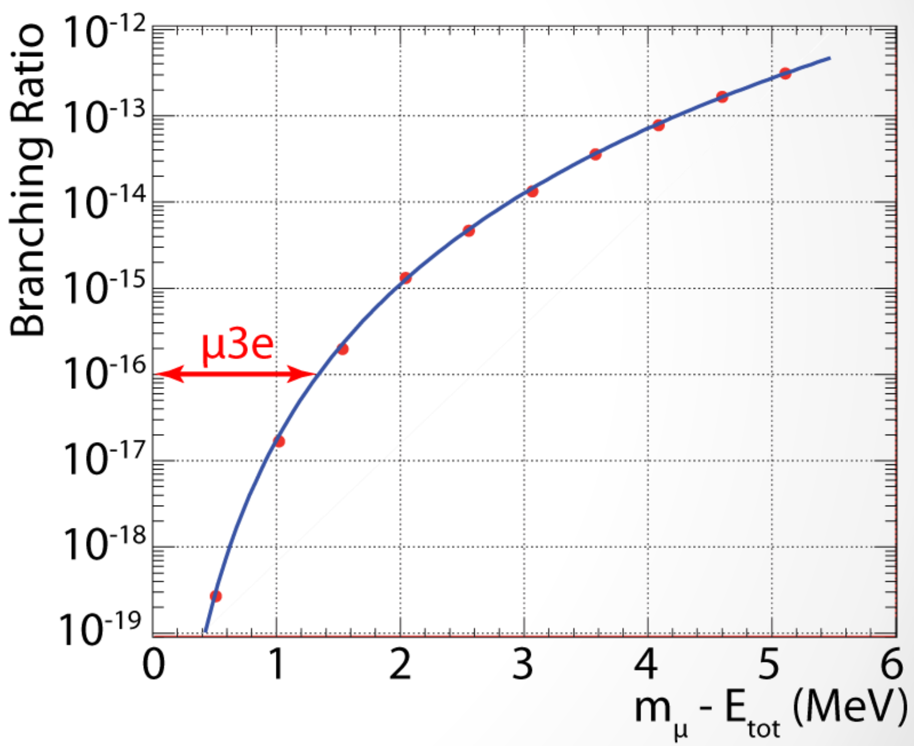


The Mu3e Background

- 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**





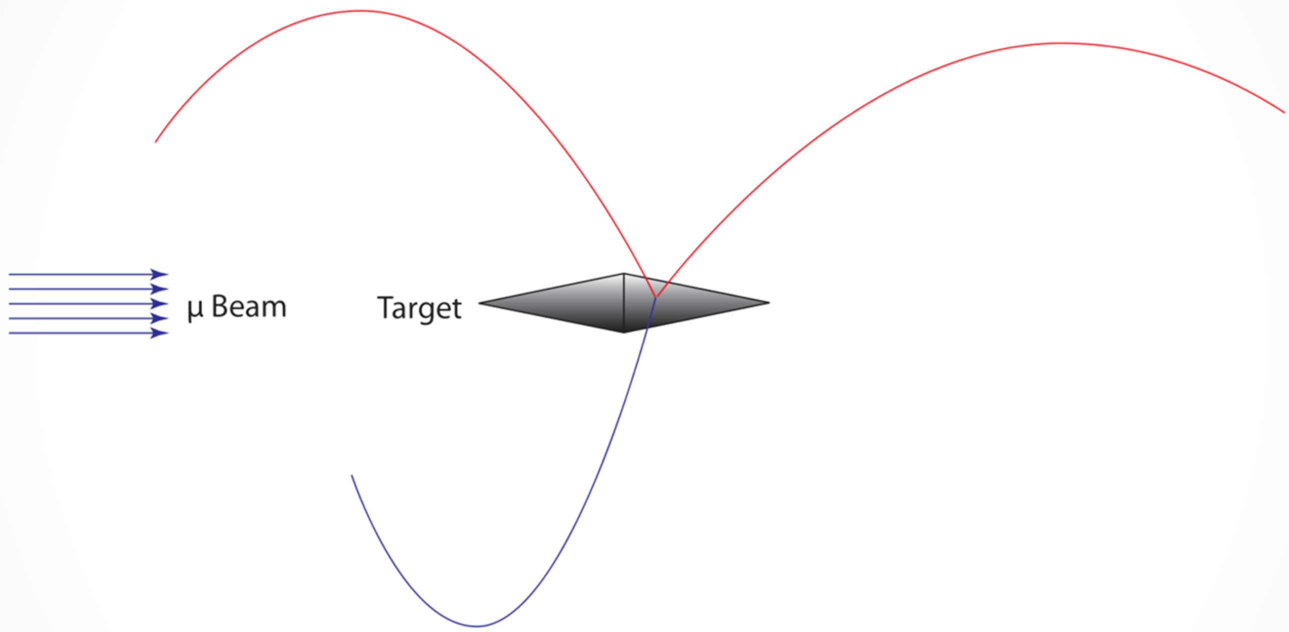
(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)

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

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

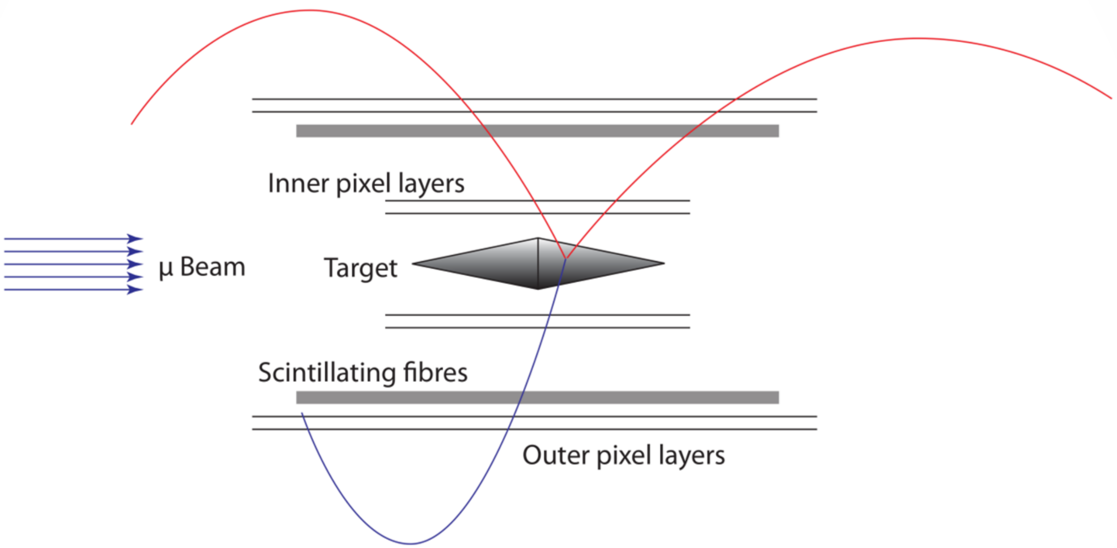
The Mu3e Experiment



- 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
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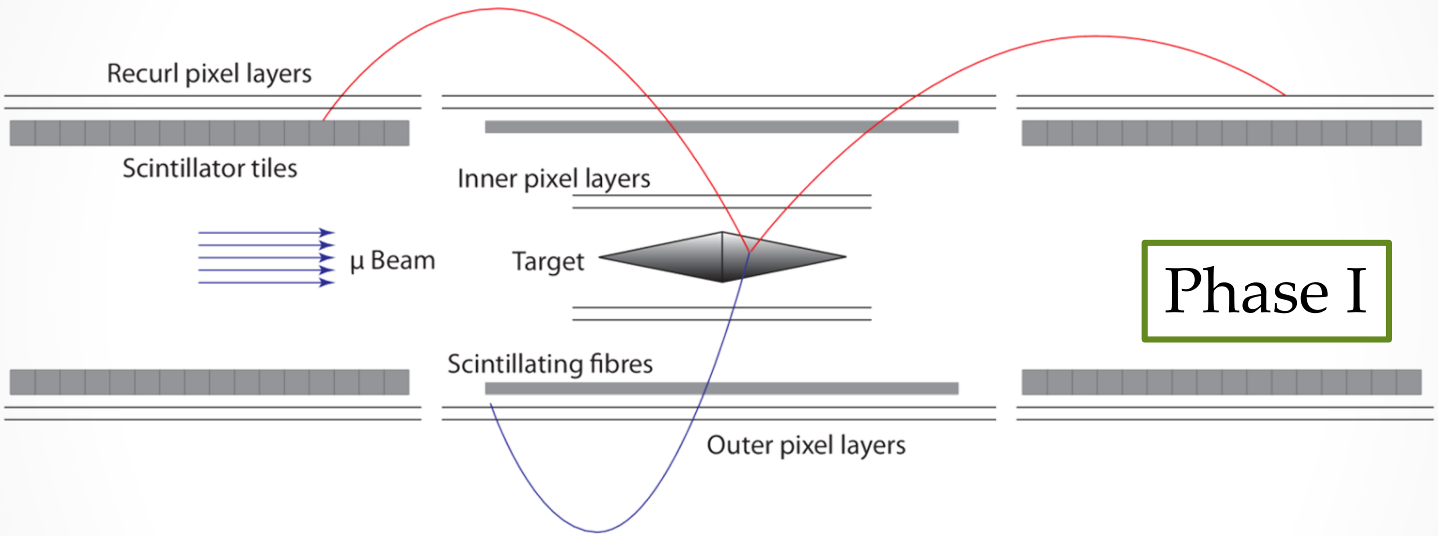
The Mu3e Experiment



Phase I

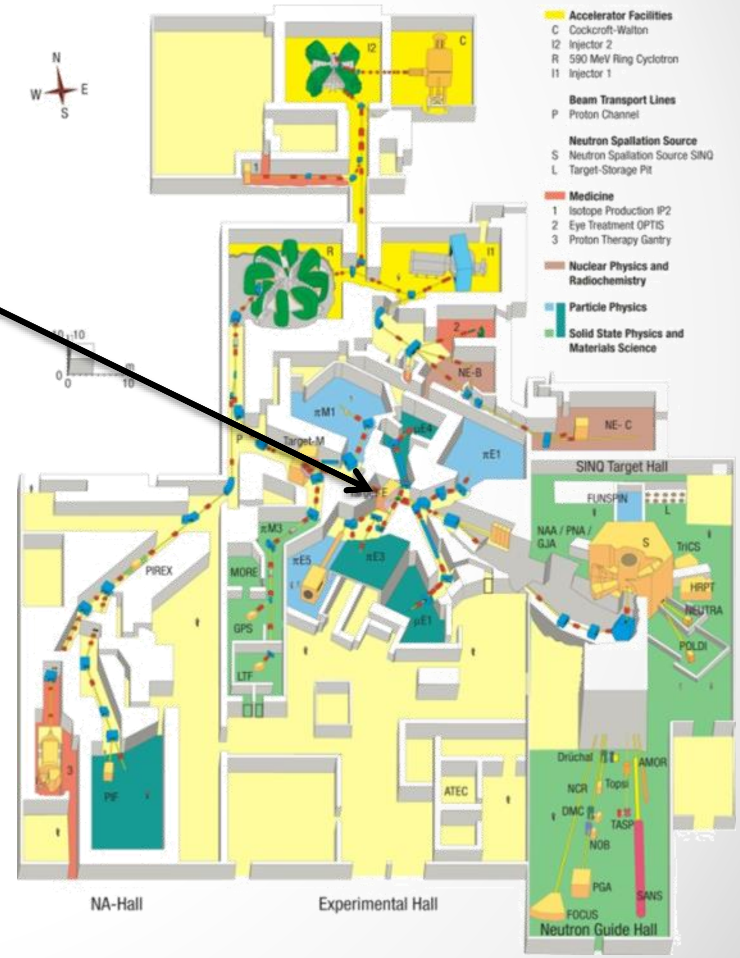
- Muon beam **O(10^8/s)**
- Helium atmosphere
- 1 T B-field

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

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



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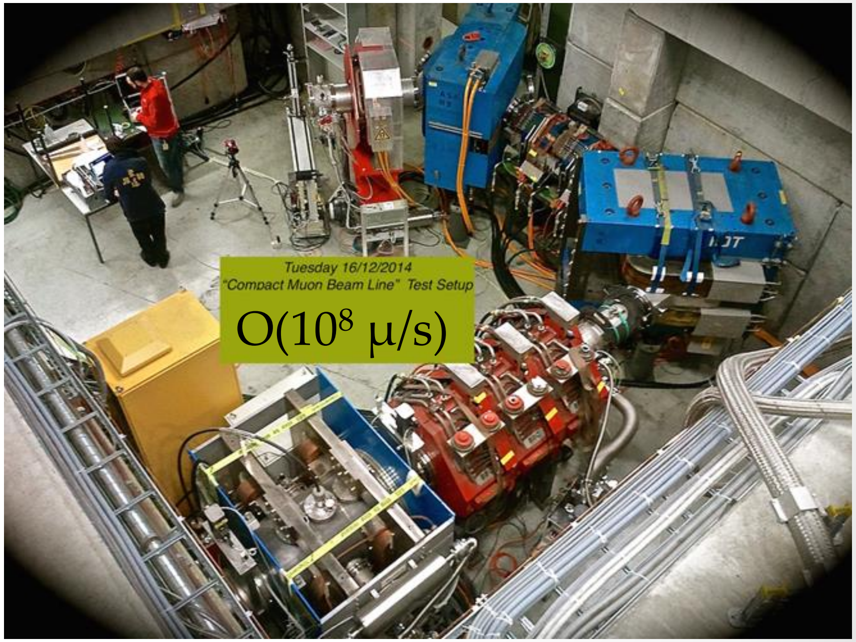
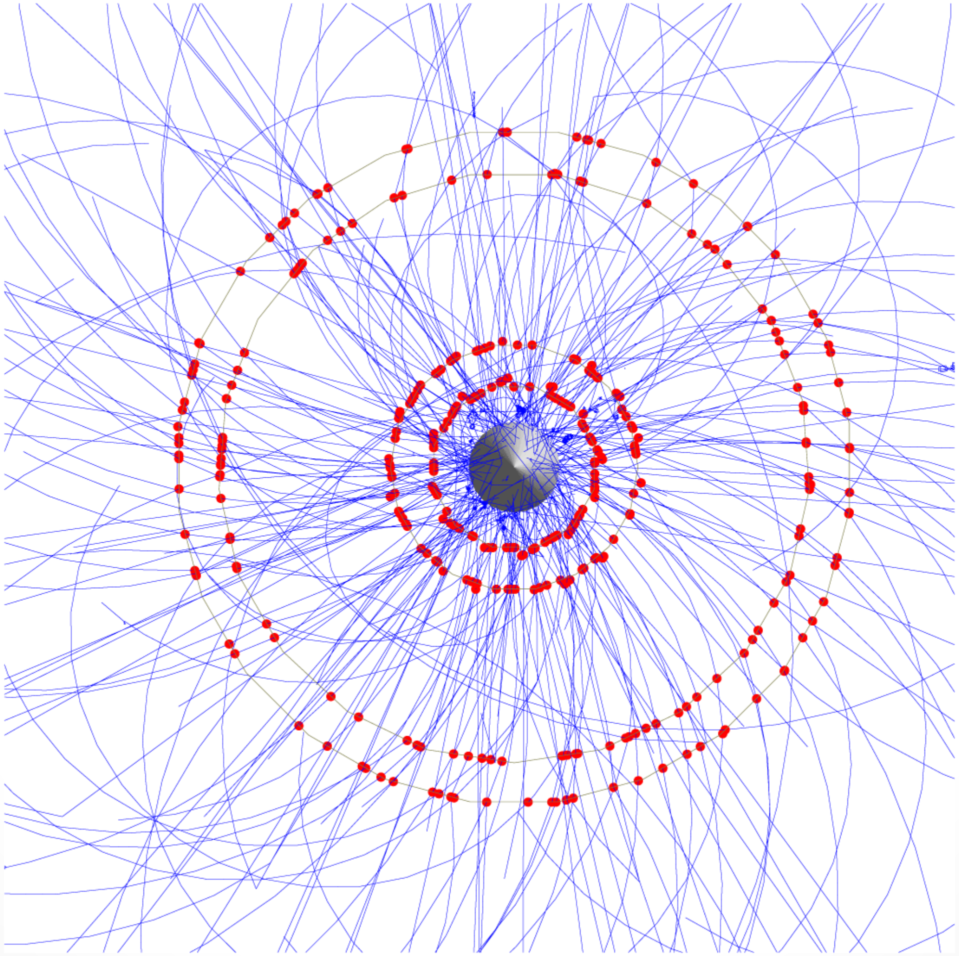
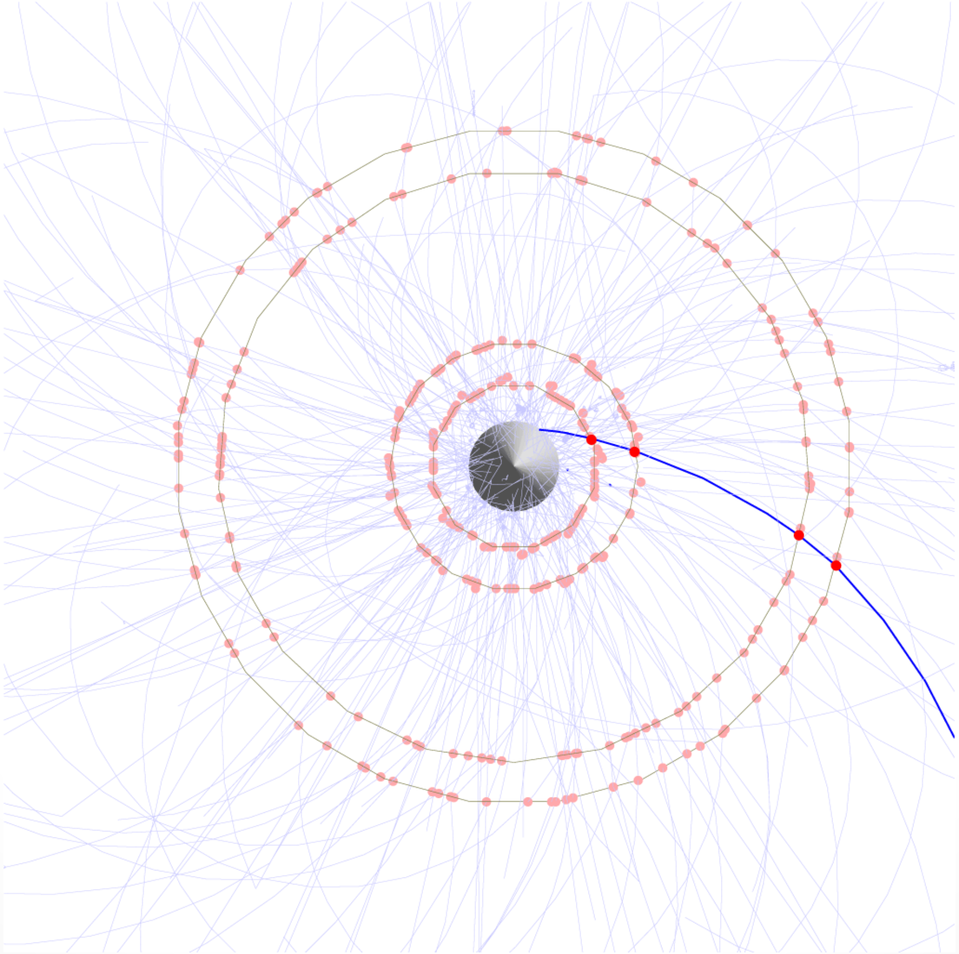


Timing Detectors



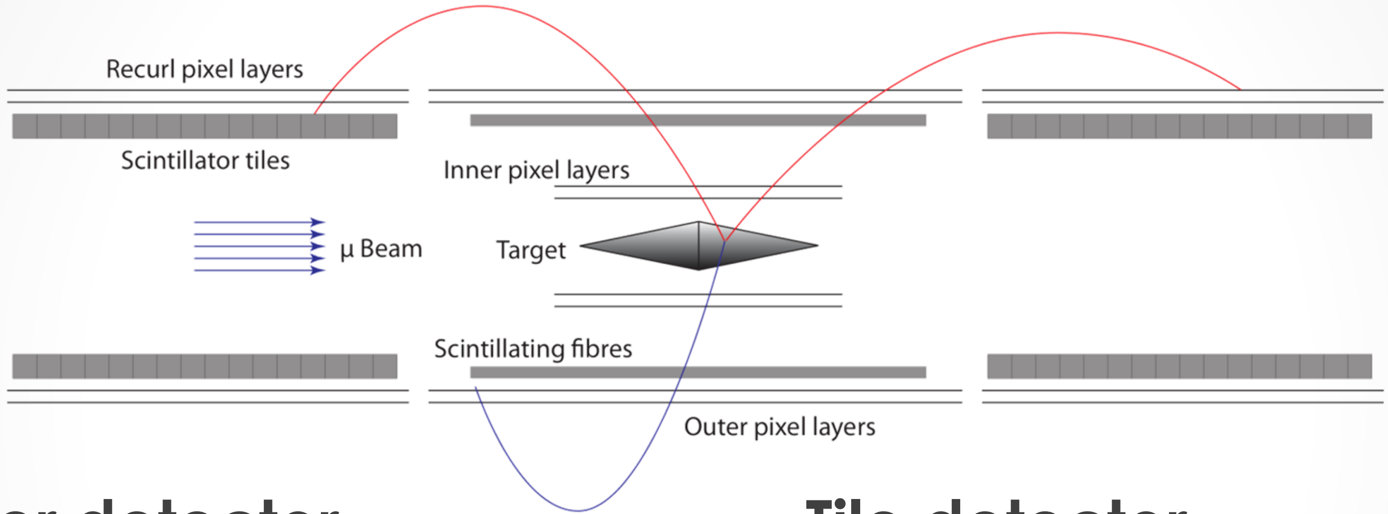
50 ns

Timing Detectors



0.1 ns

Timing Detectors

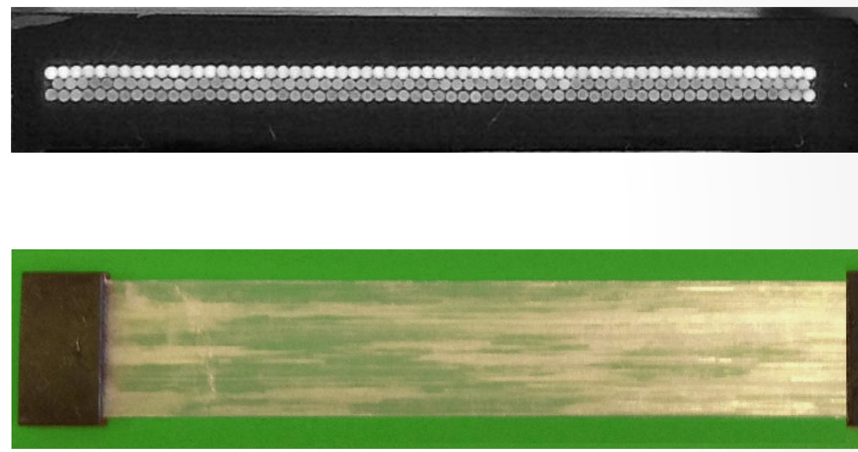


- **Fiber detector**
  - Before outer pixel layers
  - 250 μm scintillating fibers
  - 0.3% X/X_0
  - SiPMs
  - ≤ 1 ns resolution
- **Tile detector**
  - After recurl pixel layers
  - 6.5 x 6.5 x 5.0 mm^3
  - SiPMs
  - ≤ 100 ps resolution

Fiber Detector

Fiber ribbon modules

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

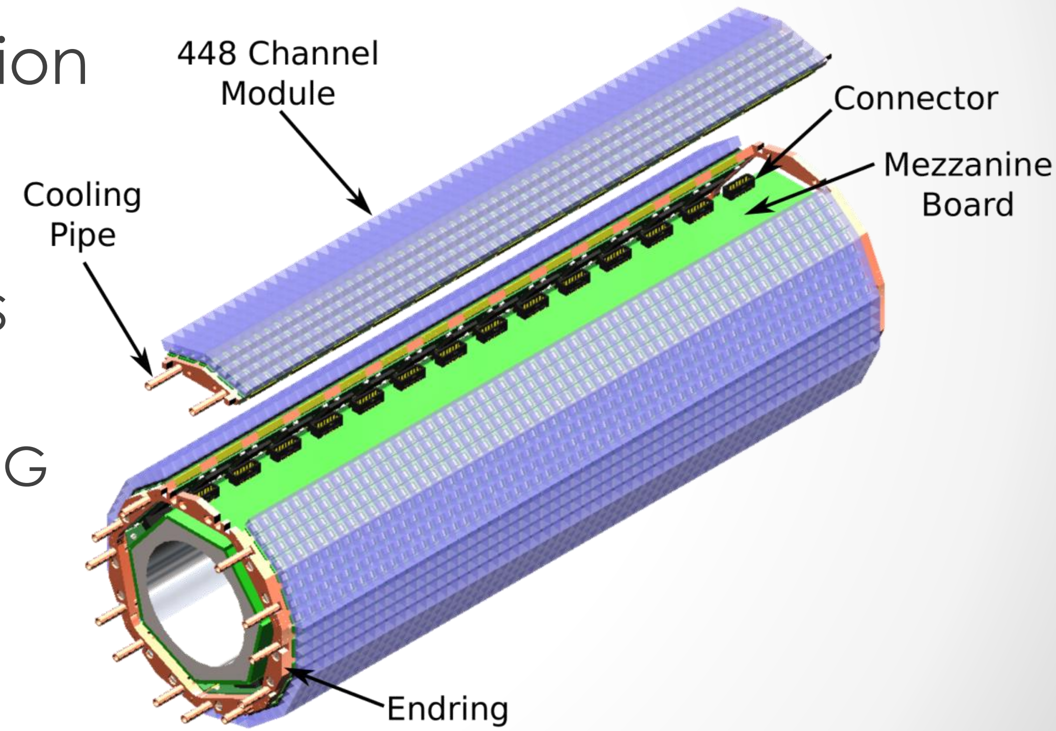


Scintillating fiber ribbons

Talk: “Scintillating Fibre Detector for the Mu3e Experiment”, Simon Corrodi on Monday

Tile Detector

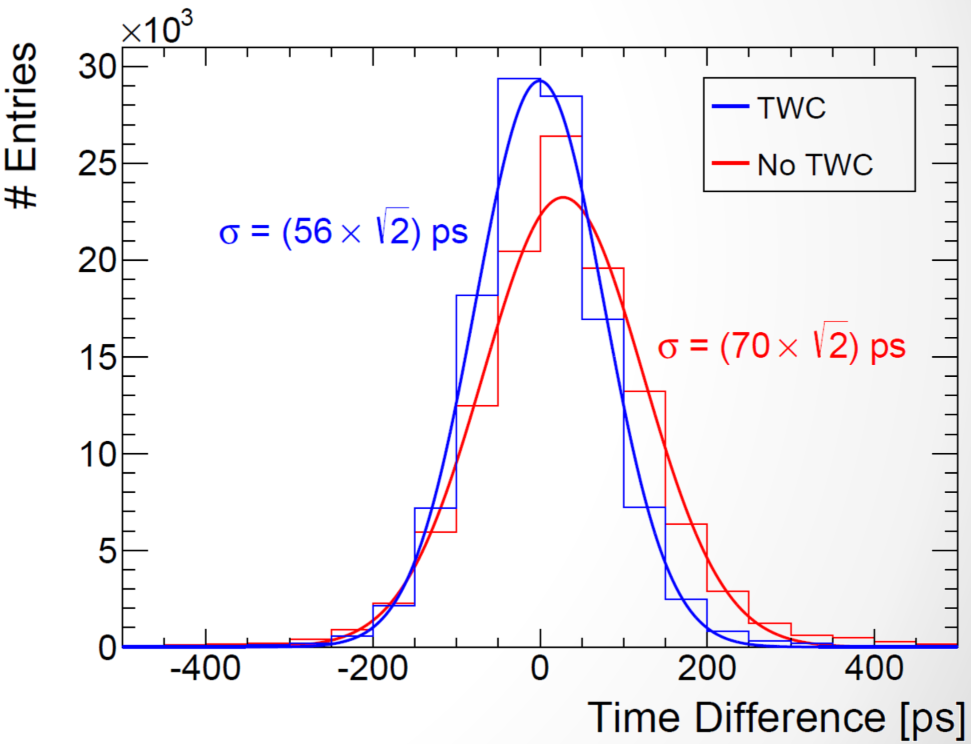
- Scintillating tiles
  - 6.5 x 6.5 x 5.0 mm^3
- 7 Tile modules per station
  - 448 tiles/module
  - Attached to end rings
- SiPMs attached to tiles
  - Front end PCBs below
  - Readout through MuTRiG

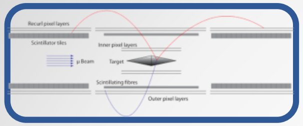


Rendering of Tile Detector station

Time Resolution

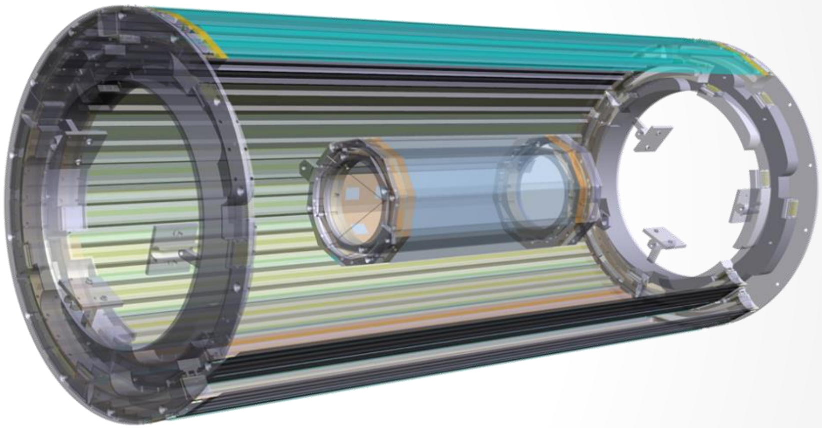
- Coincidence between 2 tiles in a row
- Time resolution ≈ 70 ps
- Time-walk effect ≈ 14 ps



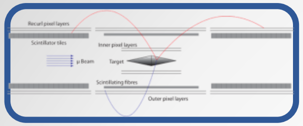


Pixel Tracker

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

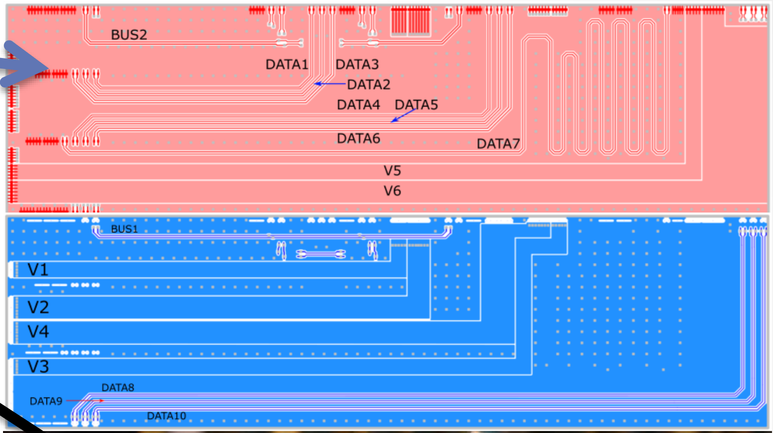


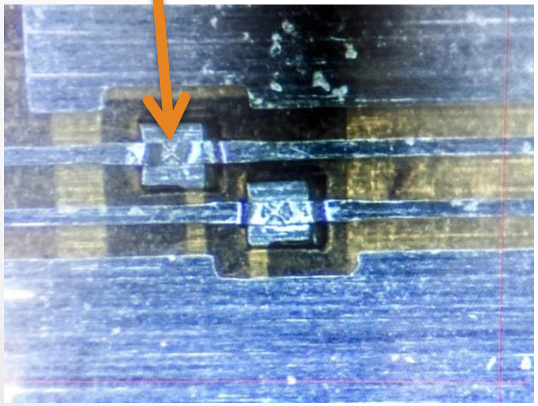
Pixel Tracker
Rendering of CAD study

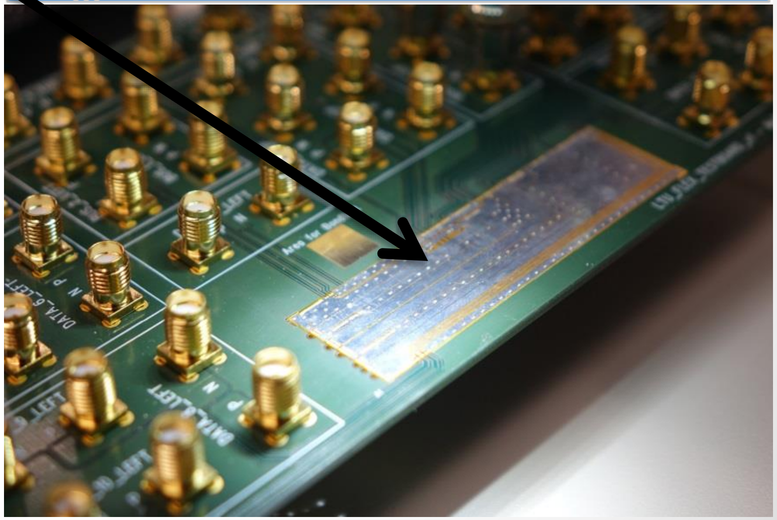


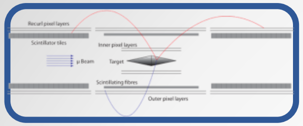
Ultra-thin HDI

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









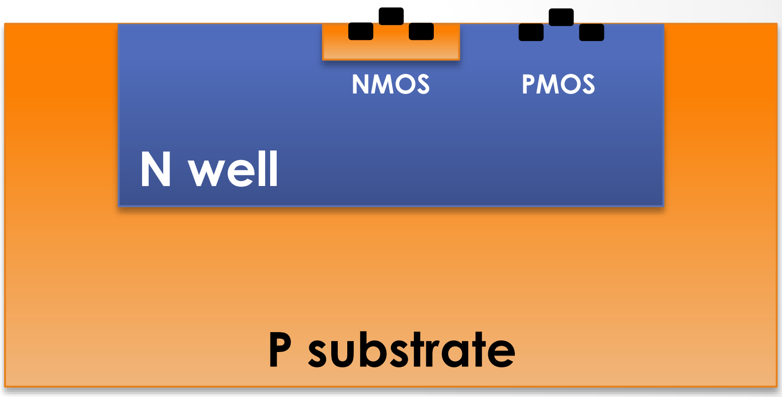
Ultra-thin HDI

- 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	**$< 5 \cdot 10^{-4}$**

HV-MAPS

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



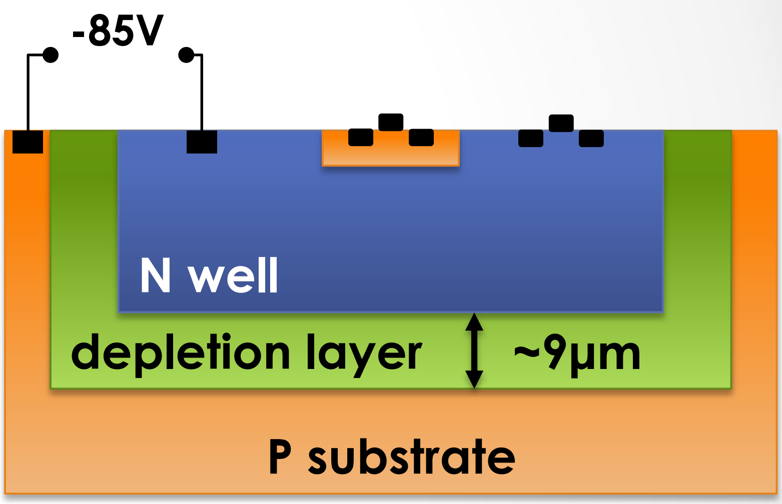
by Ivan Perić

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

See talk: "Characterisation of novel prototypes of monolithic HV-CMOS pixel detectors for high energy physics experiments", Dr. Stefano Terzo on Friday

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

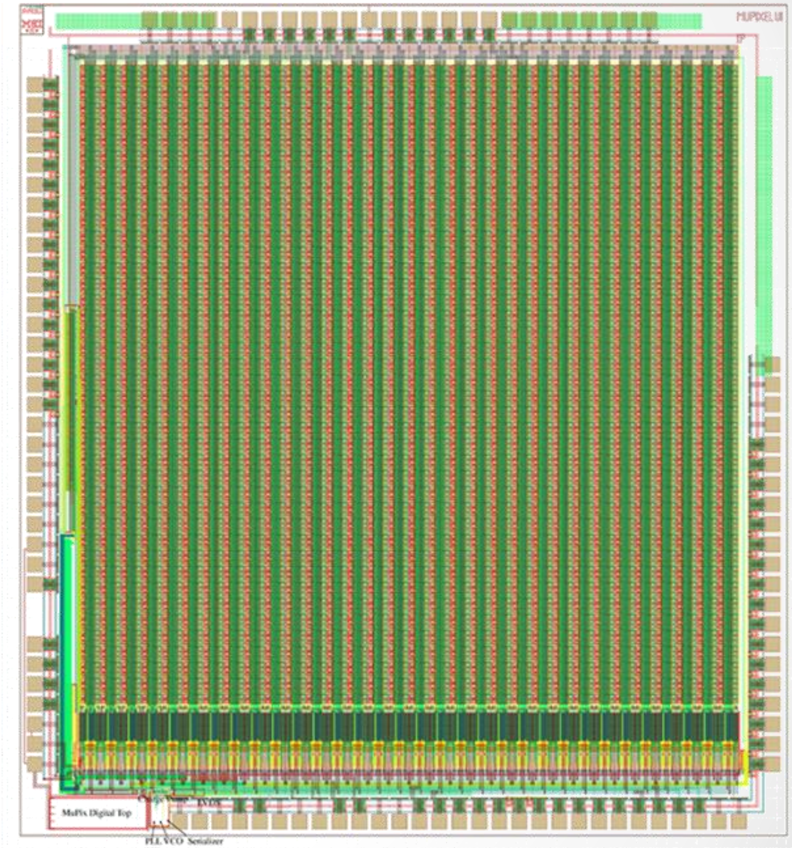


by Ivan Perić

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:
  - 40 x 32 pixels
  - 103 x 80 µm^2 each
- Analog part
  - Temperature tolerant
- Digital part
  - Full system on chip



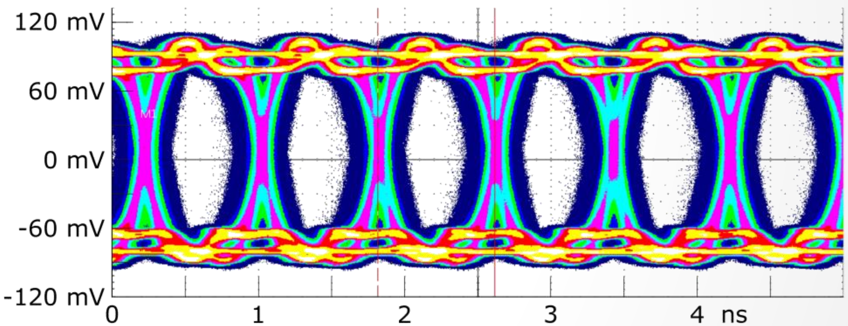
MuPix7

Chip Readout

On Chip:

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

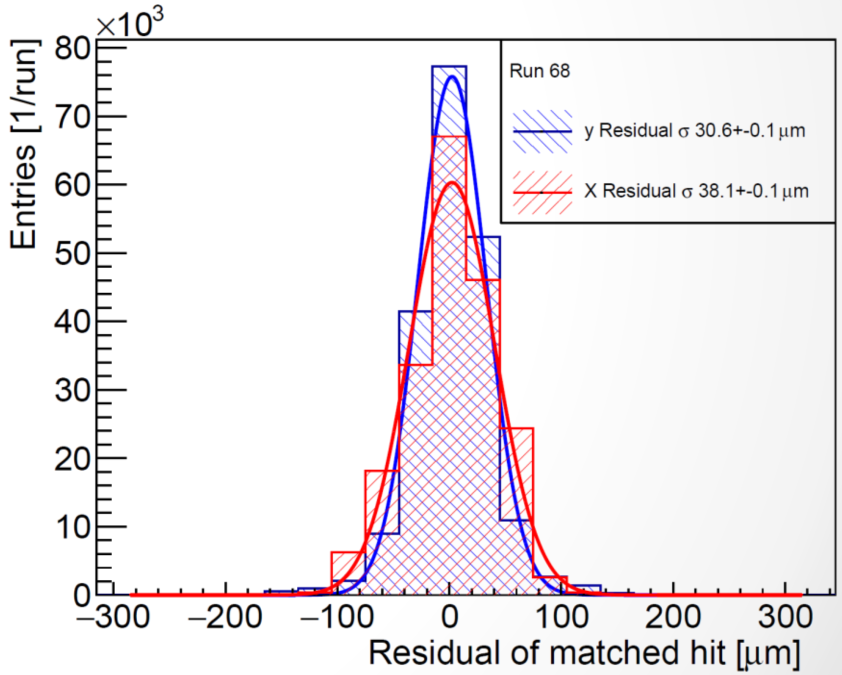
➢ 1.25 Gbit/s LVDS output



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

Spatial Resolution

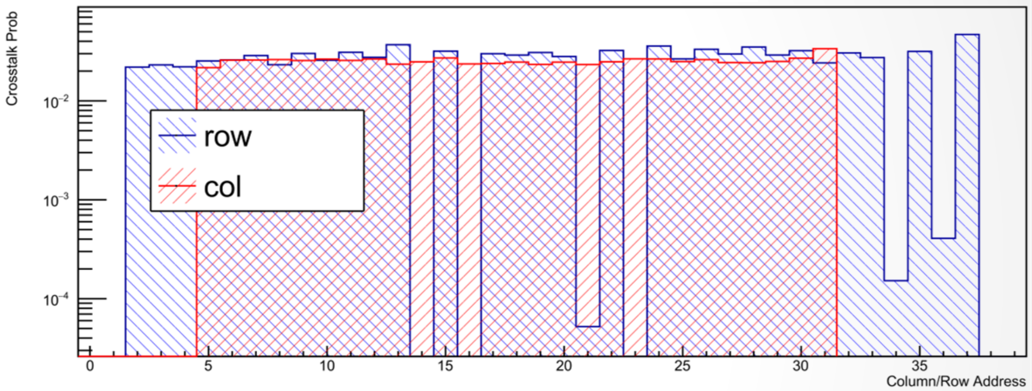
- Pixel size 80 µm x 103 µm
- Measured track residuals:
  - RMS x = 38.1 ± 0.1 µm
  - RMS y = 30.6 ± 0.1 µm



X-talk

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

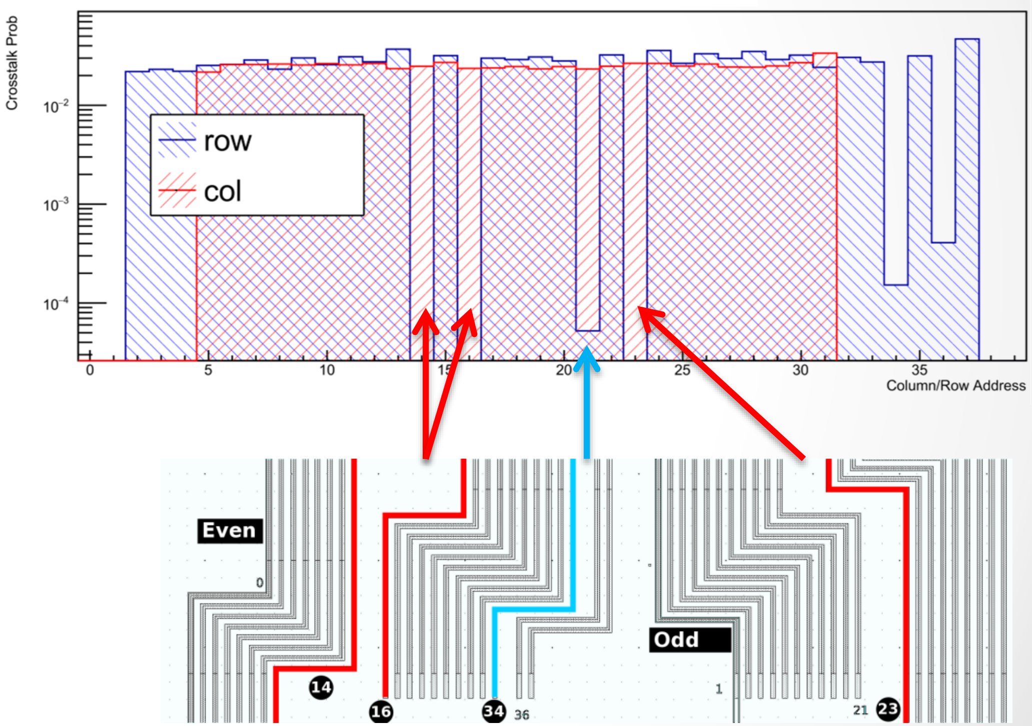
X-talk to both sides



X-talk

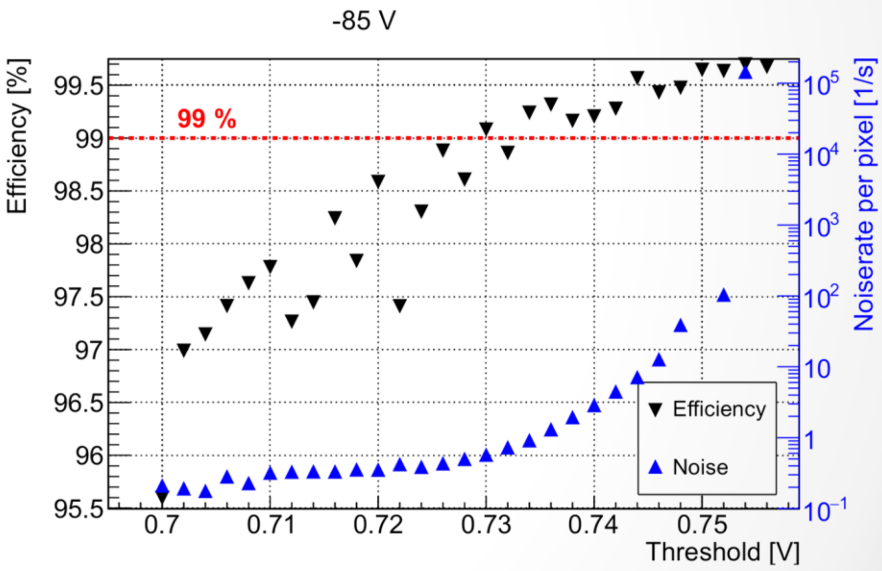
- MuPix7
- PSI October 2015
  - 250 MeV e^+/μ^+/pion
- X-talk between
  - **Rows**
- Capacitive coupling
  - Line from diode to comparator
  - Strongly depends on layout

X-talk to both sides



Efficiencies

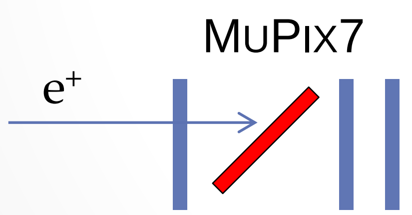
- **>99.5% efficiency**
  - 4 GeV electrons@DESY
  - 90° impact angle
  - Individual pixel thresholds



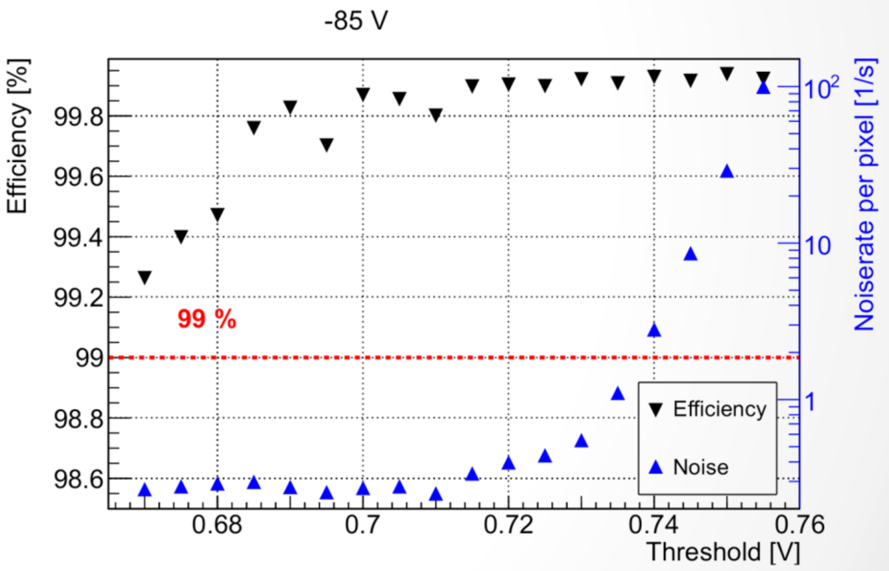
MuPix7 Efficiency

Efficiencies rotated Sensor

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



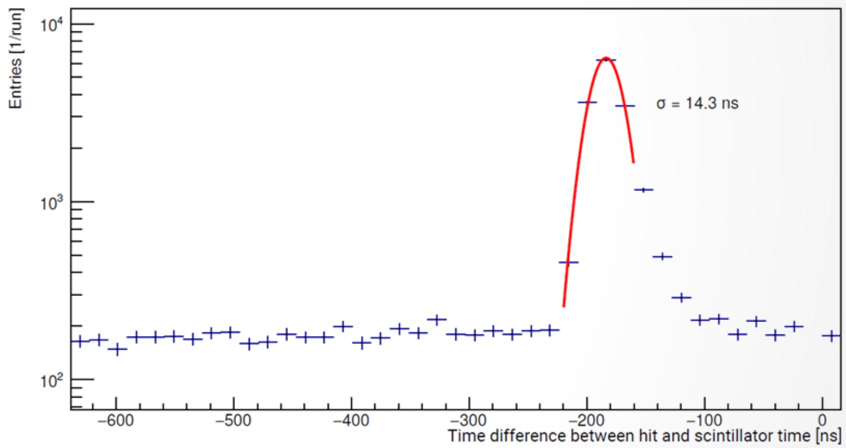
MuPix7 under angle



MuPix7 Efficiency

Time Stamps

- Time difference of hits registered in MuPix 7 and scintillator
- 4 GeV electrons
- Sampling rate is 62.5 MHz
- σ = 14.3 ns



Time Resolution of Pixels

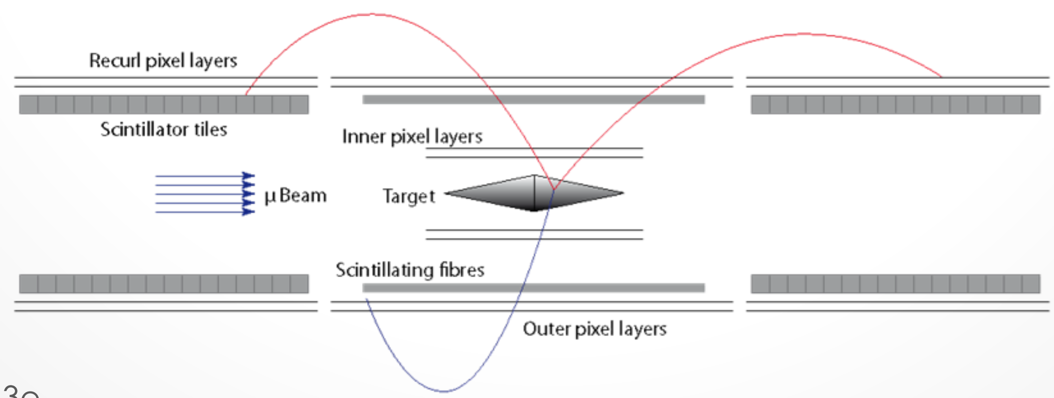
Large Pixel Prototype

- 10.8 x 20 mm^2
- Time walk correction
- 3+1 LVDS outputs
- In production

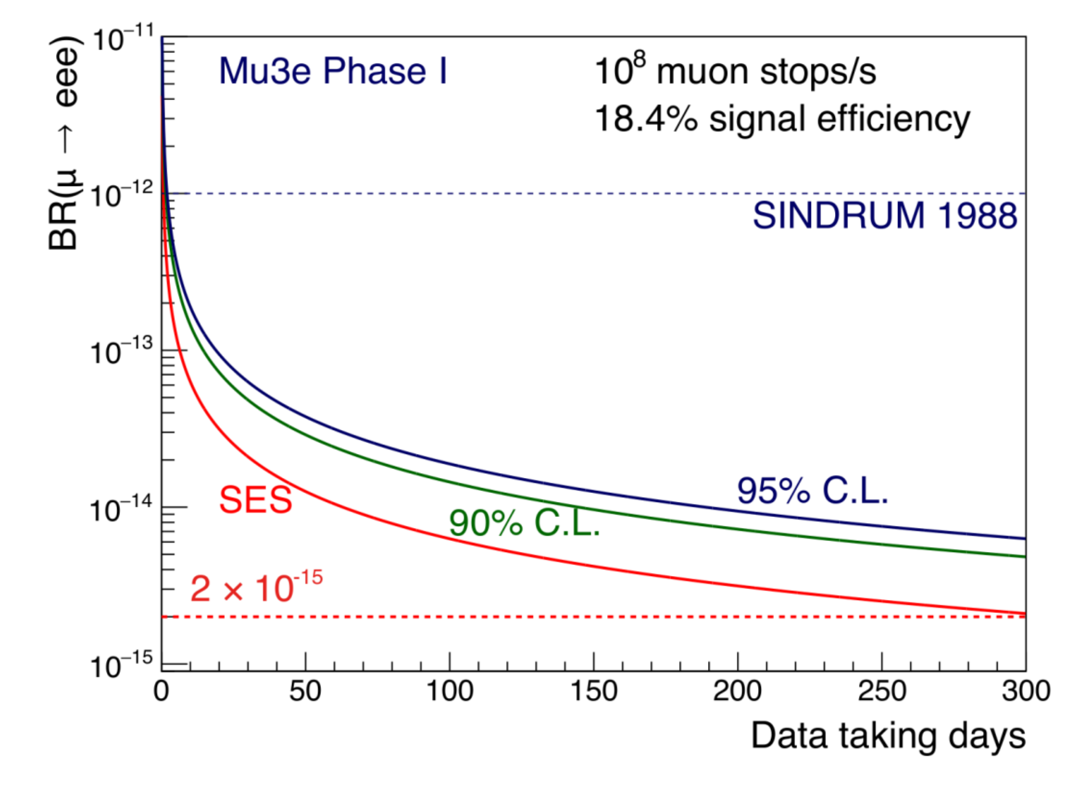
➢ Module studies

Summary

- Mu3e searches for lepton flavor violation
  - > 10^{15} μ-decays → BR O(10^{-15}) (90% CL)
- Two SiPM based timing systems
- Silicon tracker with ~182M pixel
  - HV-MAPS 50 μm thin
- Prototypes exceed requirements



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:
  - DPNC Geneva University
  - Paul Scherrer Institute
  - Particle Physics ETH Zürich
  - Physics Institute Heidelberg University
  - Institute for Nuclear Physics Mainz University
  - IPE Karlsruhe
  - KIP Heidelberg

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 owe our SPS test-beam time to the SPS team and our LHCb colleagues, especially Heinrich, Kazu and Martin.
- 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

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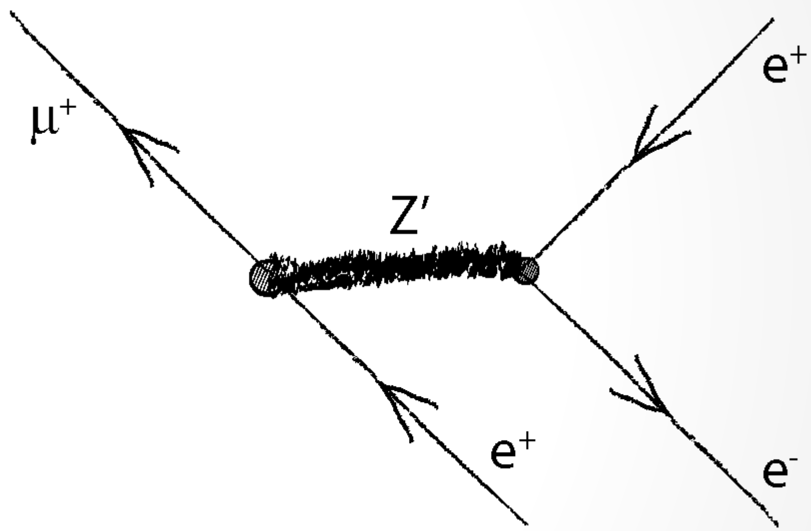
Motivation Backup

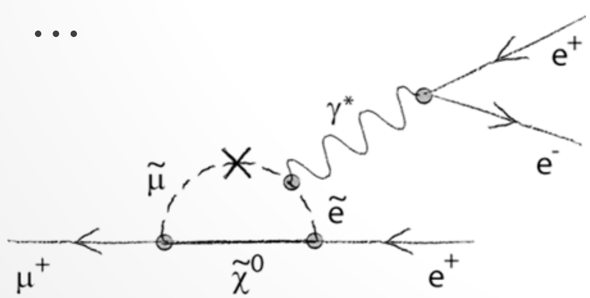
…

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
  - …

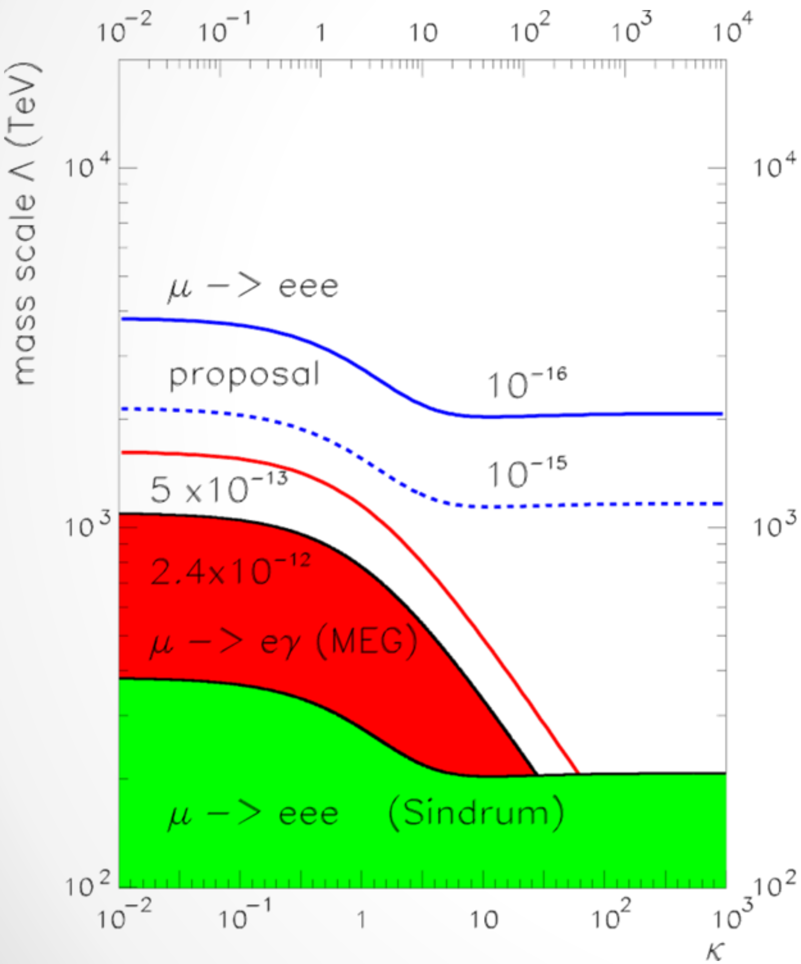


Tree level



SUSY

μ→eee vs. μ→eγ



$$
\begin{aligned}
L_{LFV} &= \left[\frac{m_\mu}{(\kappa+1)\Lambda^2}\,\overline{\mu_R}\sigma^{\mu\nu}e_L F_{\mu\nu}\right]_{\gamma-\text{penguin}} \\
&+ \left[\frac{\kappa}{(\kappa+1)\Lambda^2}\,(\overline{\mu_L}\gamma^\mu e_L)\,(\overline{e_L}\gamma_\mu e_L)\right]_{\text{tree}}
\end{aligned}
$$

A. de Gouvêa,
"(Charged) Lepton Flavor Violation",
Nucl. Phys B. (Proc. Suppl.),
188 303–308, 2009.

Challenges

…

Challenges

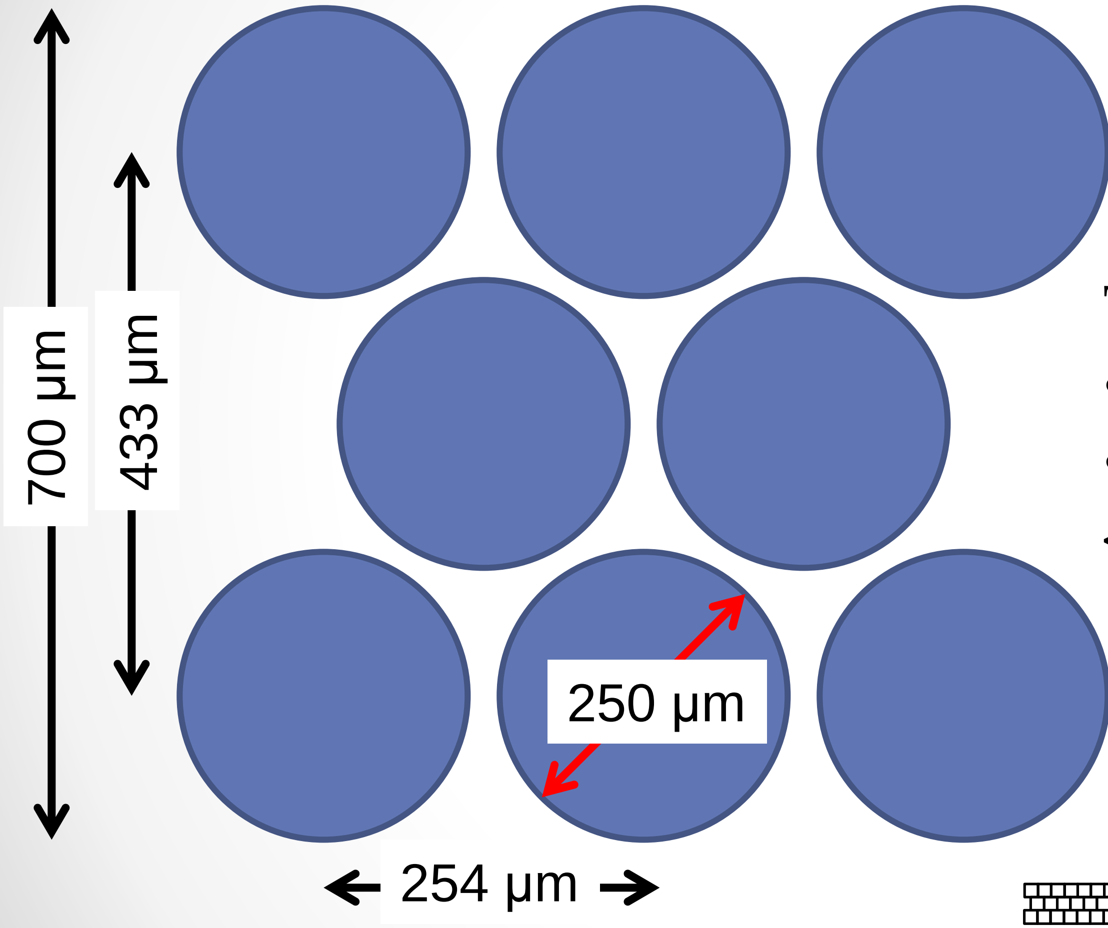
- High rates: 10^8 μ/s
- Good timing resolution: 100 ps
- Good vertex resolution: ~200 μm
- Excellent momentum resolution: ~ 0.5 MeV/c^2
- ➢ Extremely low material budget:
  - ➢ 1×10^{-3} X_0 (Si-Tracker Layer)
- ➢ HV-MAPS spectrometer
  - ➢ 50 μm thin sensors
  - ➢ B ~1 T field
- ➢ + Timing detectors

SciFi Backup

…

Details …

staggered layers

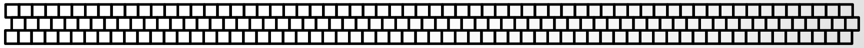


Thickness:

- theoretical ~ 683 µm
- measured ~ 750 µm

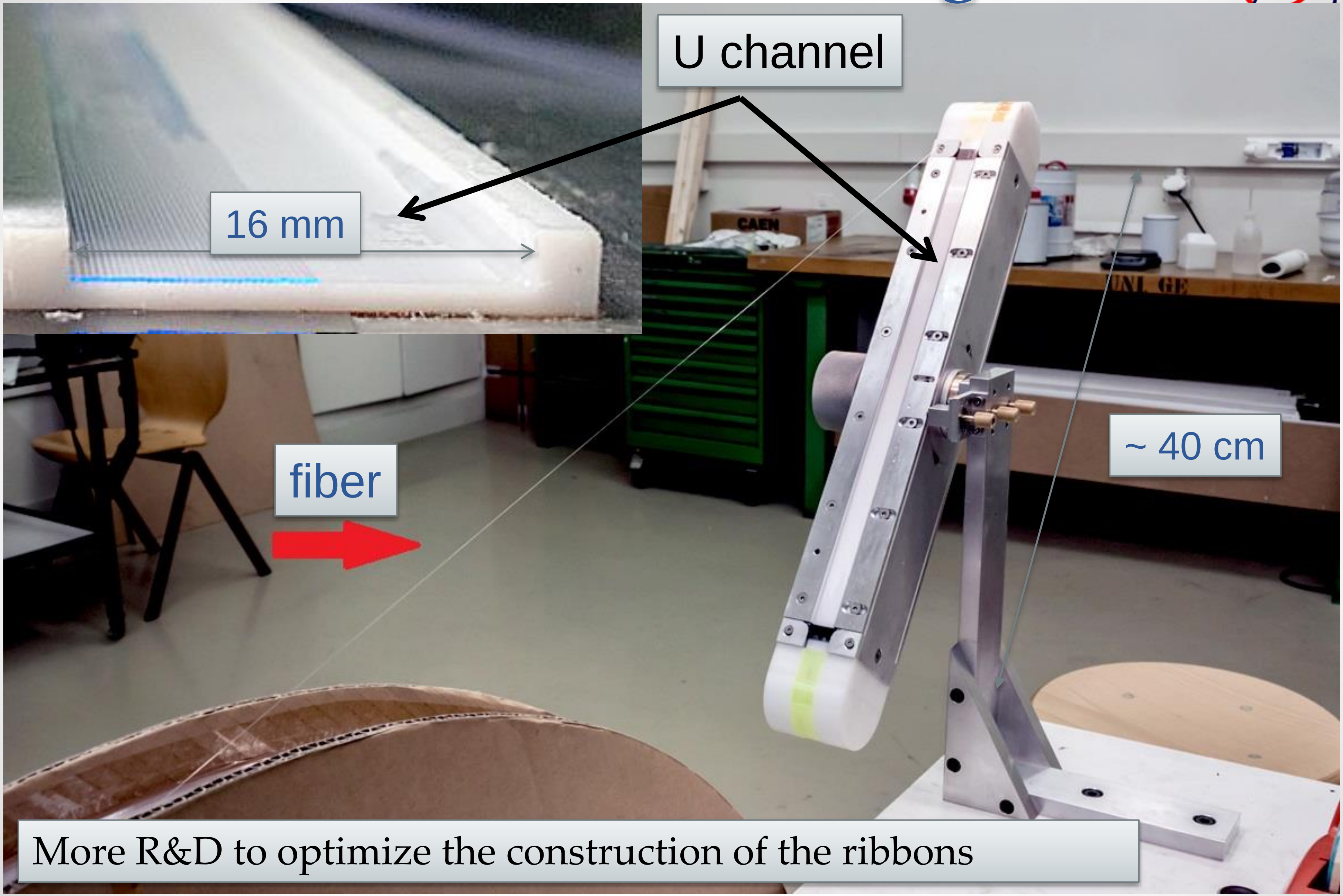
< 1 g of glue / ribbon

Alternative:
Square shape fibers



Horizontal gap between fibers ~ 4 µm

Fiber Winding Tool

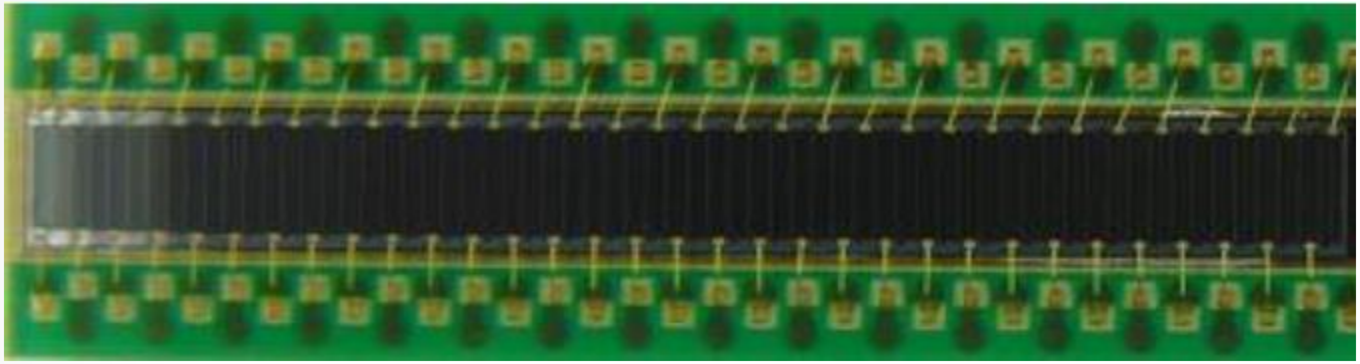


More R&D to optimize the construction of the ribbons

Readout of Fibers

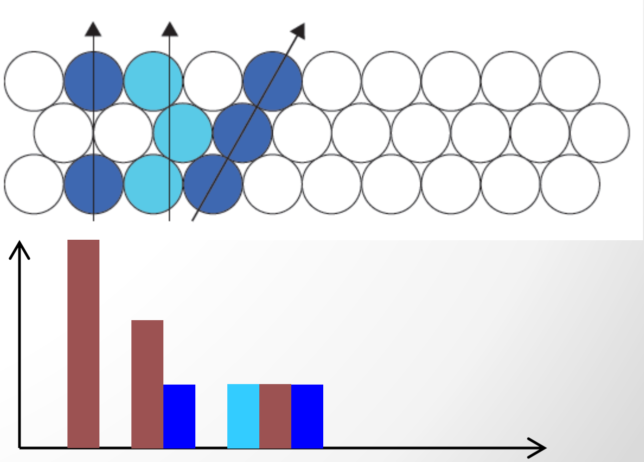
Si-PMs (MPPCs) at both fiber ends

SciFi column readout with Si-PM arrays



LHCb type detector

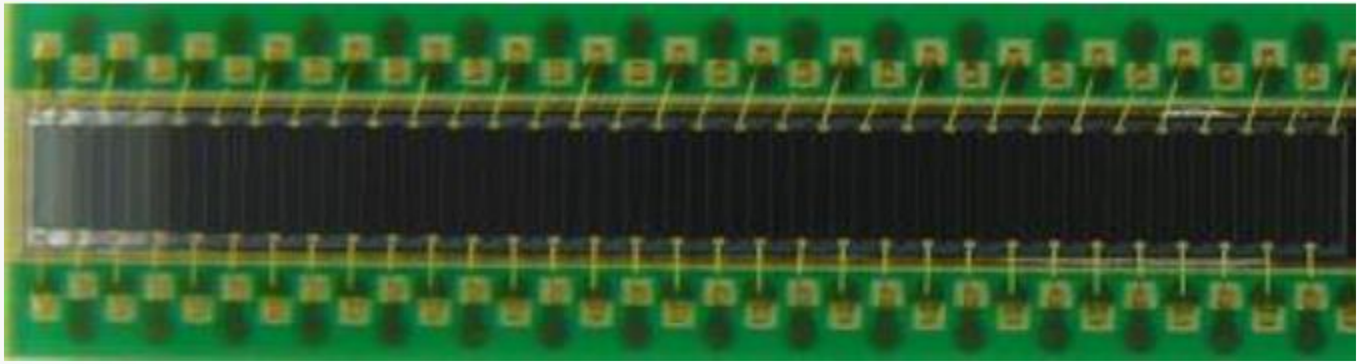
- 64 channel monolithic device (custom design)
- ~250 µm effective “pitch”
- 50 µm × 50 µm pixels
- Grouped in 0.25 mm × 1 mm vertical columns
- Common bias voltage



Readout of Fibers

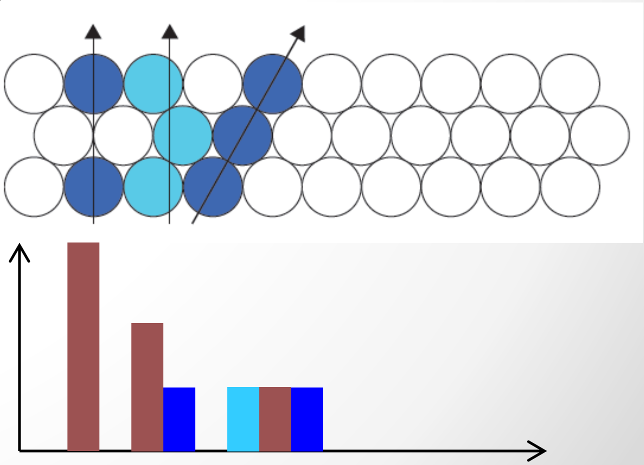
Si-PMs (MPPCs) at both fiber ends

SciFi column readout with Si-PM arrays

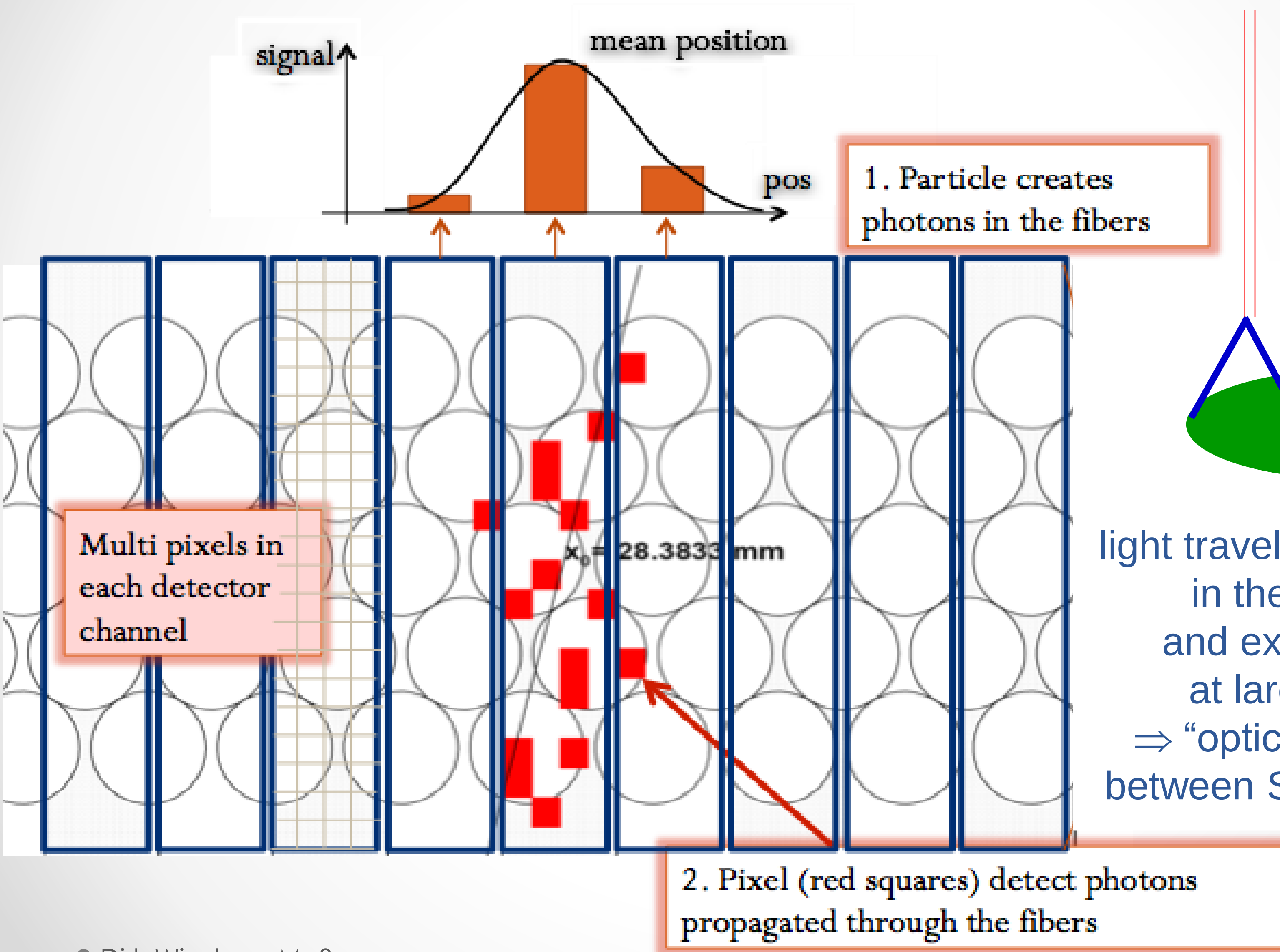


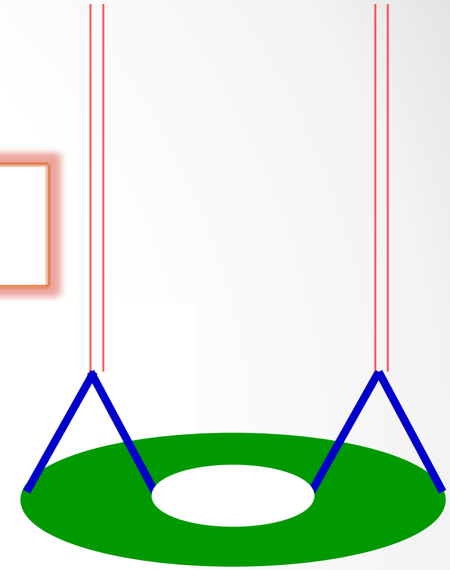
LHCb type detector

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



SciFi Column Readout

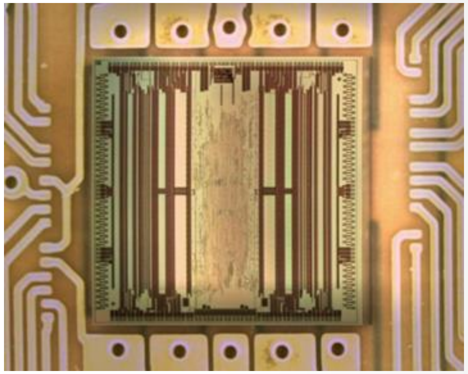




light travels preferentially in the cladding and exits the fiber at large angles
⇒ “optical” cross talk between Si-PM columns

Readout Electronics

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



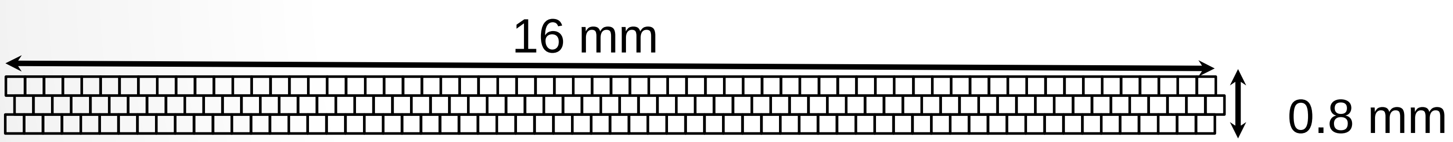
STiC

Alternative Design with Square Fibers

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

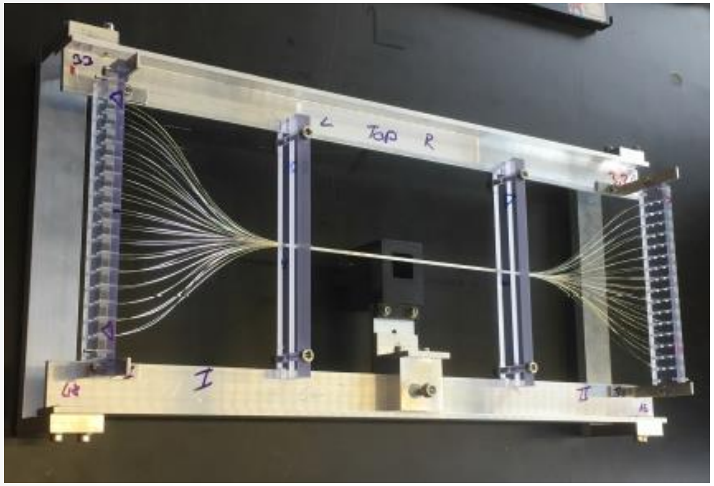
128 fibers/layer

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



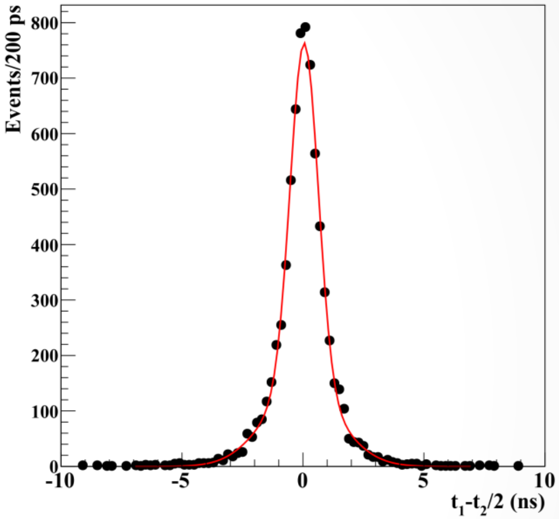
Testing Square Fibers

Fiber test setup developed at PSI



250 µm square fiber

timing performance



Cross talk:

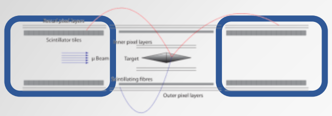
By sputtering 30 nm Al coating on the fiber cross talk < 1% was achieved

0.5 Nphe threshold

$\sigma = 750 \pm 17$ ps

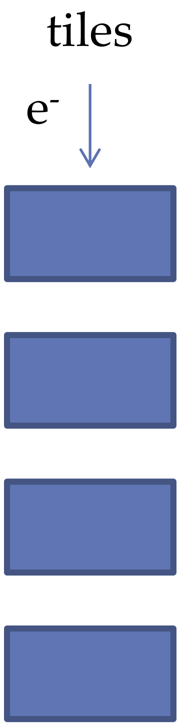
Tile Detector Backup

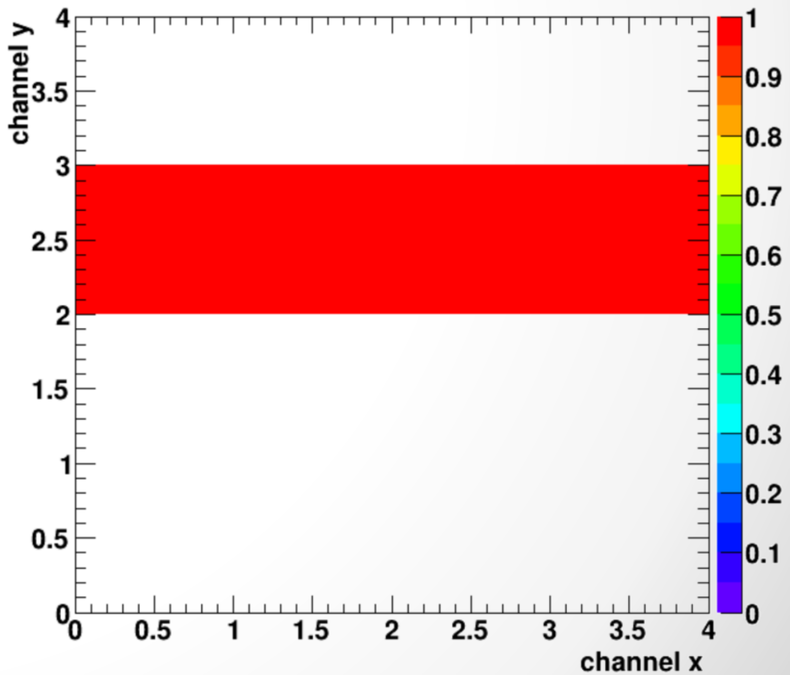
• • •

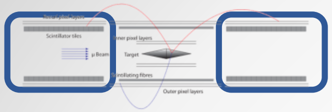


Efficiency

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

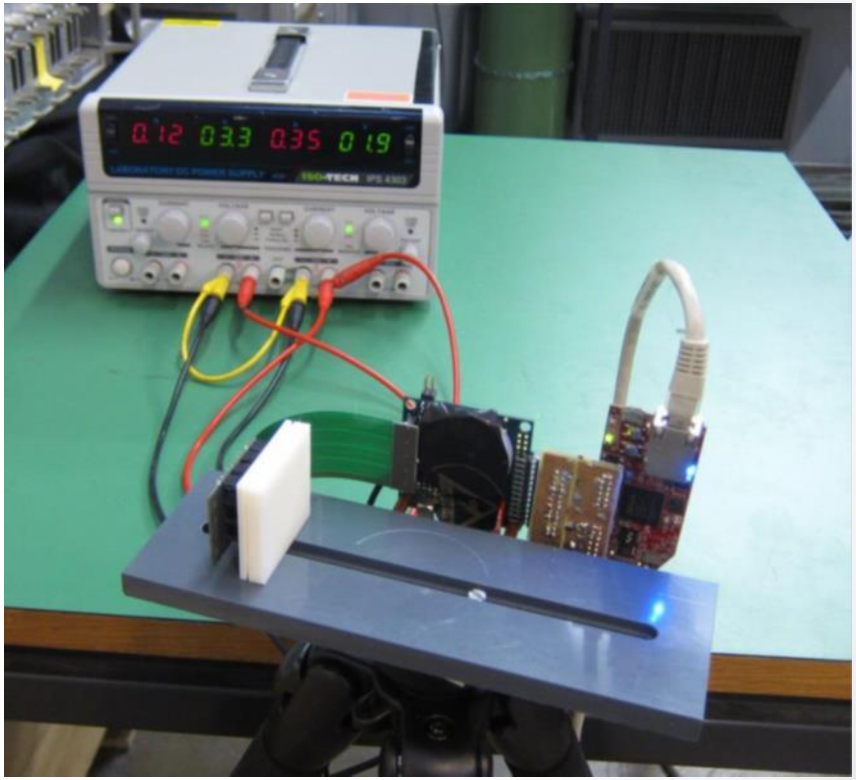




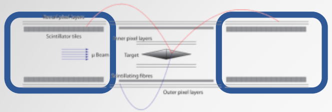


Tile Detector

- 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

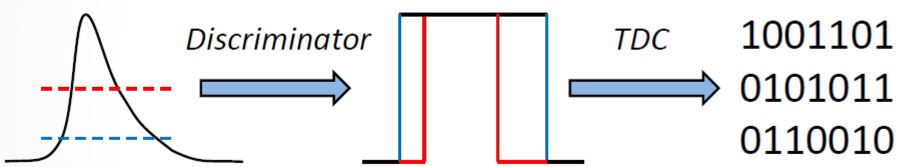


Tile detector 4 x 4 prototype



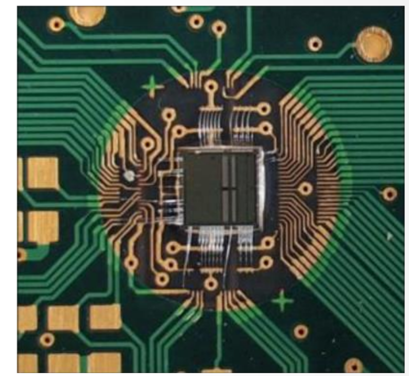
STiC Readout

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

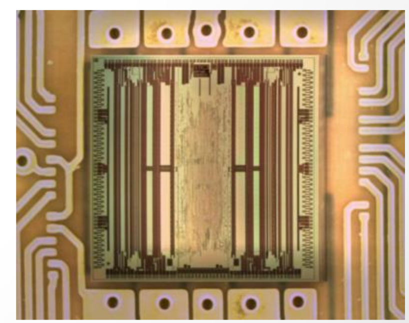


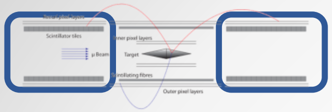
  - 64 channels (version 3.0)
  - 50 ps TDC bins
  - SiPM bias tuning
  - SiPM tail cancelation possibility (version 3.0)
  - Currently ≈ 1 MHz hit rate / chip
  - Up to ≈ 20 MHz in future version
- Version 2.0 successfully operated in test-beam

STiC 2.0



STiC 3.0





STiC Readout

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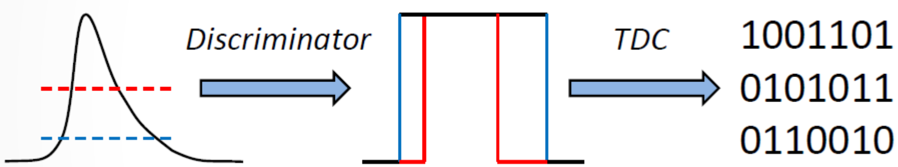

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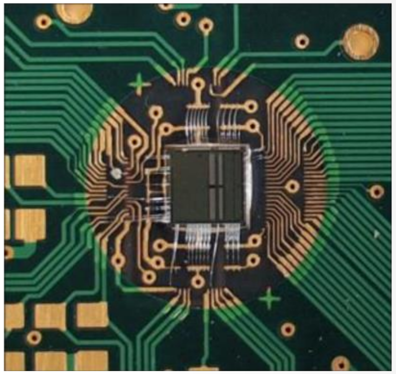
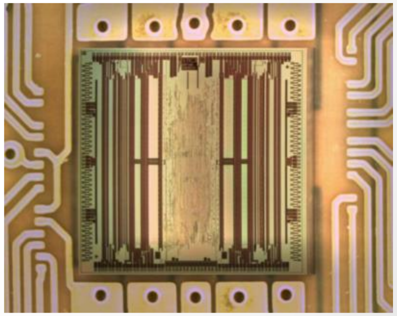
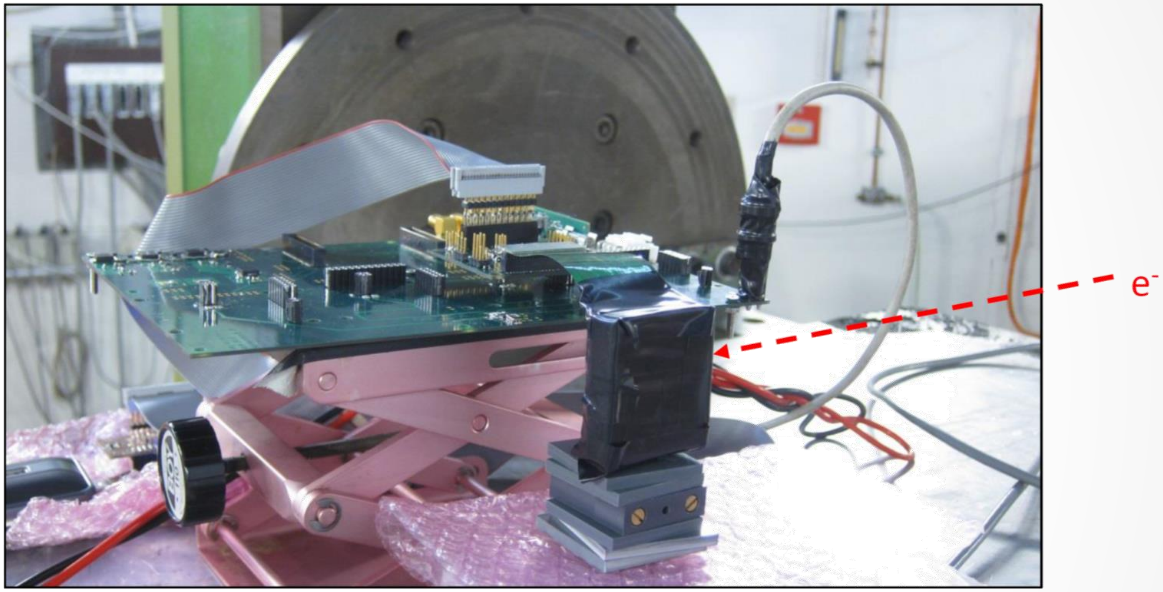
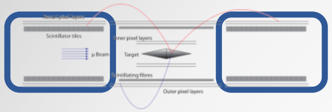


STiC 3.0

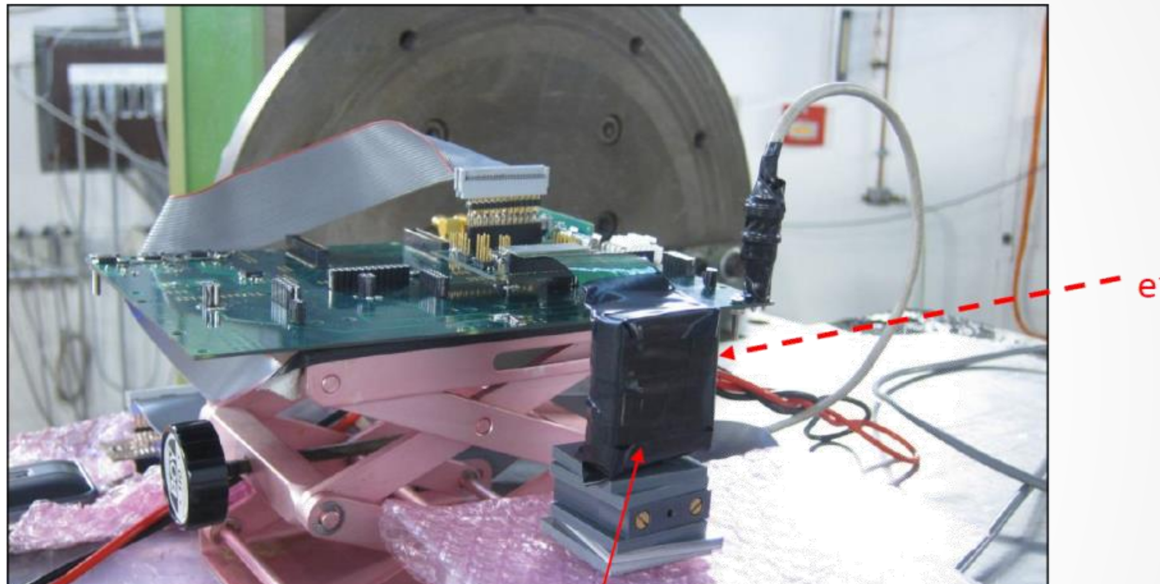


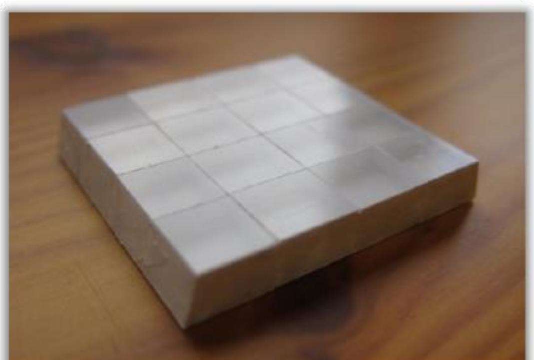
STiC Test Beam





STiC Test Beam

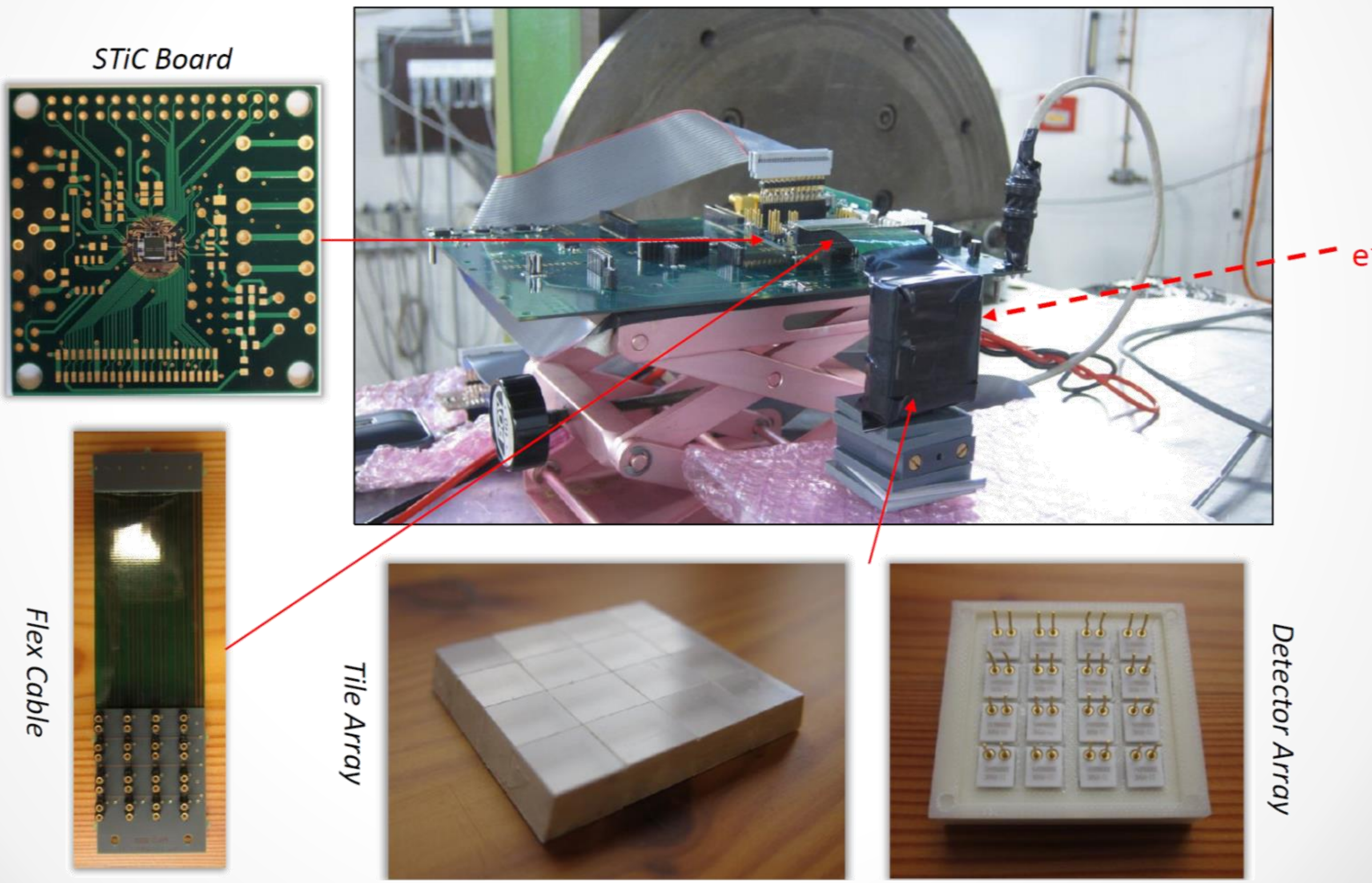




Tile Array

Detector Array

STiC Test Beam



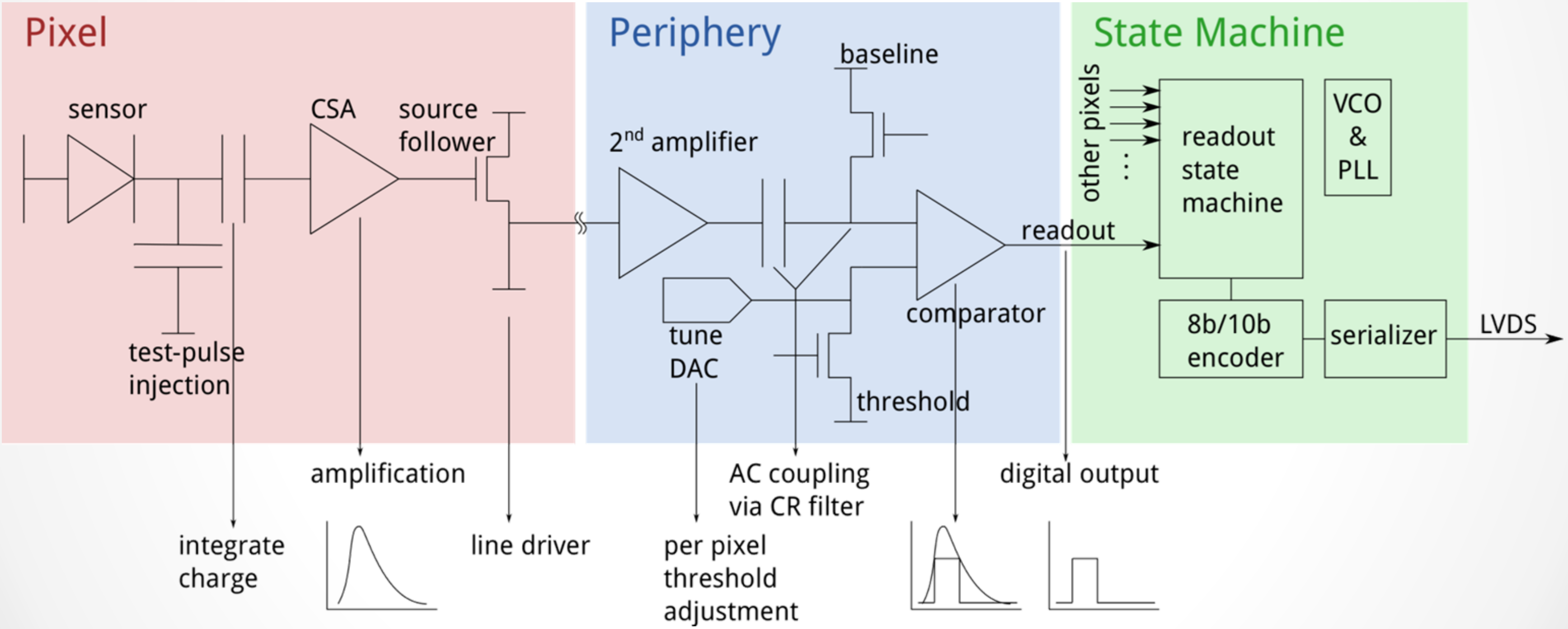
HV-MAPS Backup

...

Prototype Overview

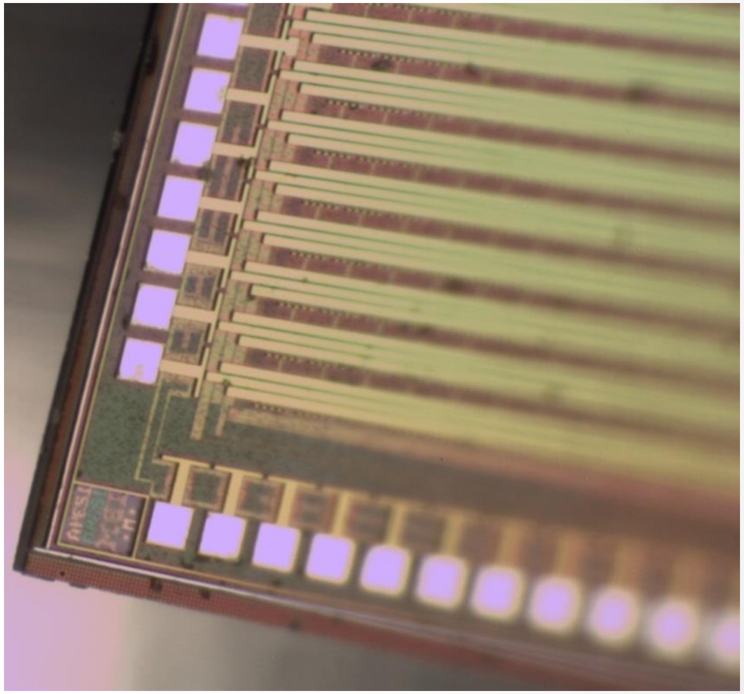
Prototype	Active Area	Functionality	Bugs	Improvements
MuPix1	1.77 mm^2	Sensor + analog	Comparator **“ringing”**	First MuPix prototype
MuPix2	1.77 mm^2	Sensor + analog	**Temperature** dependence	**No ringing**
MuPix3	9.42 mm^2	Sensor, analog, dig.	bad pixel **on/off**,	**First** part of **dig.** readout
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

Sensor + Analog + Digital



Thinned Sensors

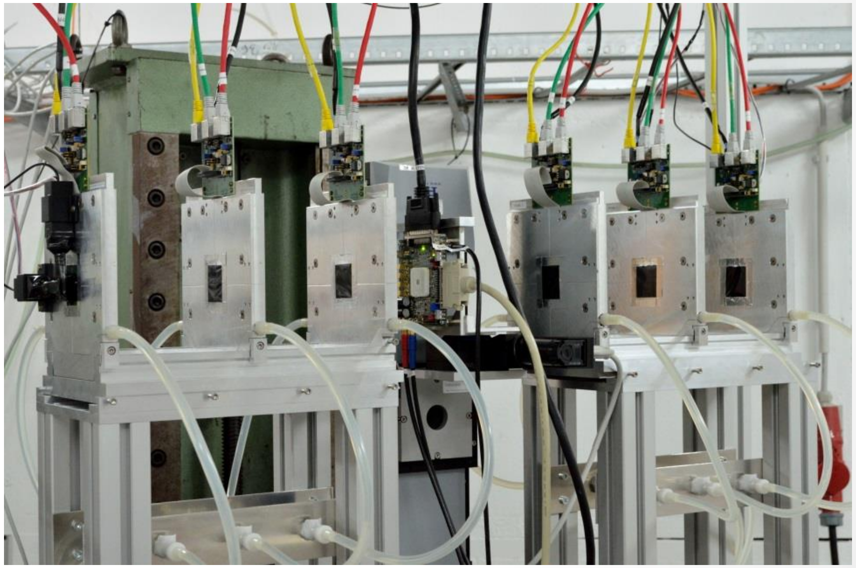
- Prototypes thinned:
  - MuPix7 thinned to **50**, 62, 75µm
- Good performance of thin chips
  - In lab
  - In particle beam



MuPix4 thinned to 50µm

Setup March 2016 Test-Beam @ DESY

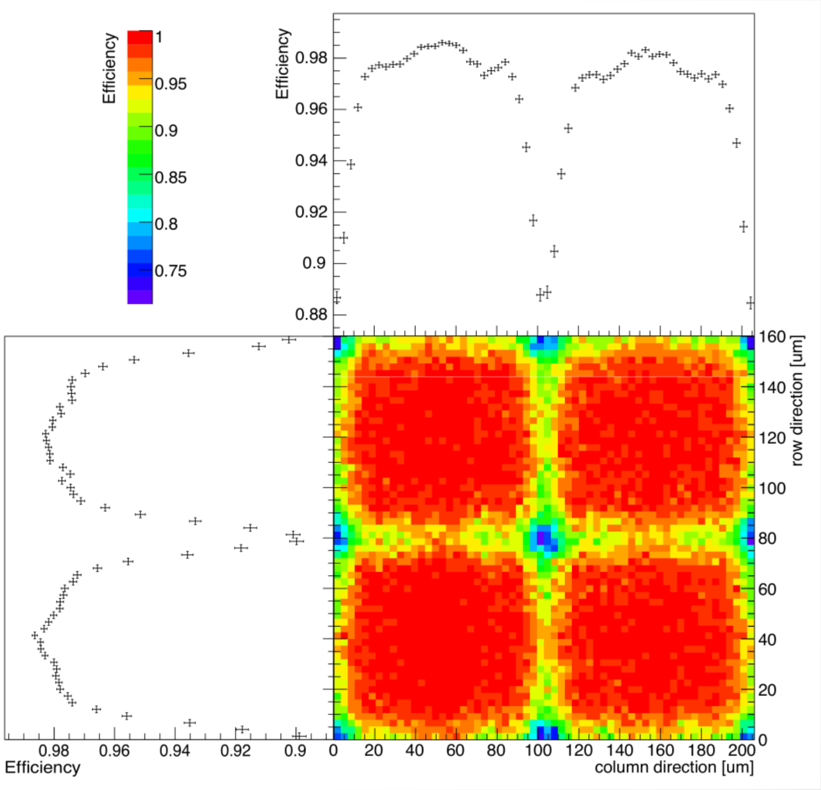
- Beam-line TB22
  - up to **5 GeV** electrons
- Aconite telescope
- MuPix7 prototype
- Readout setup from PI Heidelberg



MuPix7 @ DESY test-beam in EUDET telescope

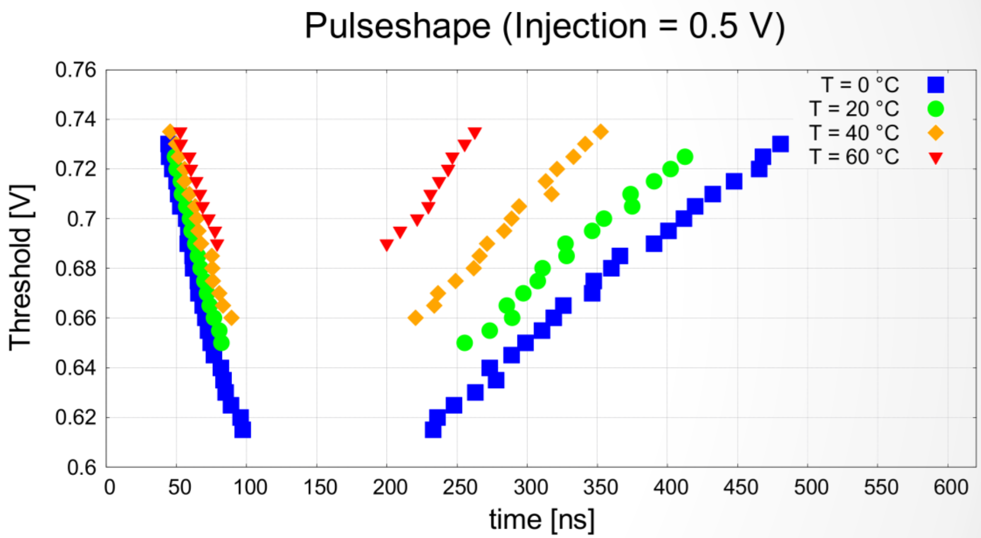
Sub-Pixel Efficiencies

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



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/cm^2)
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
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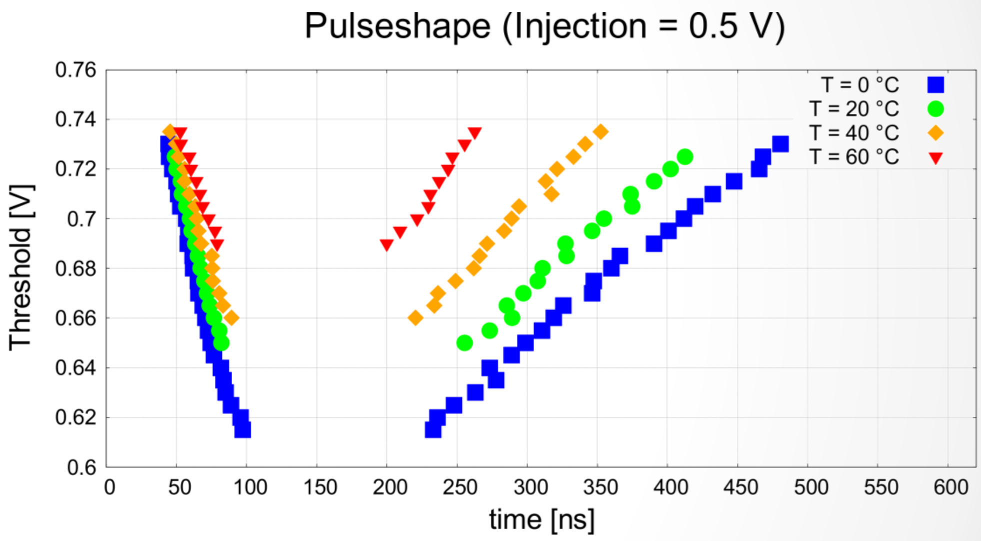
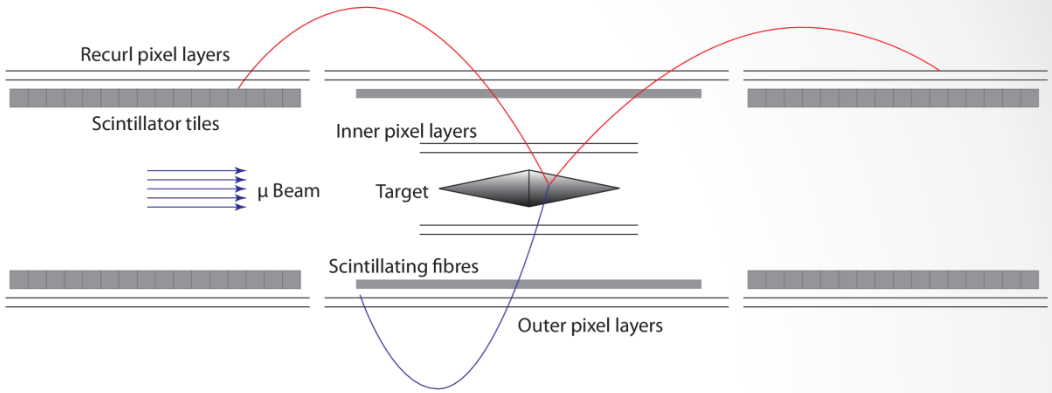


Mechanics Backup

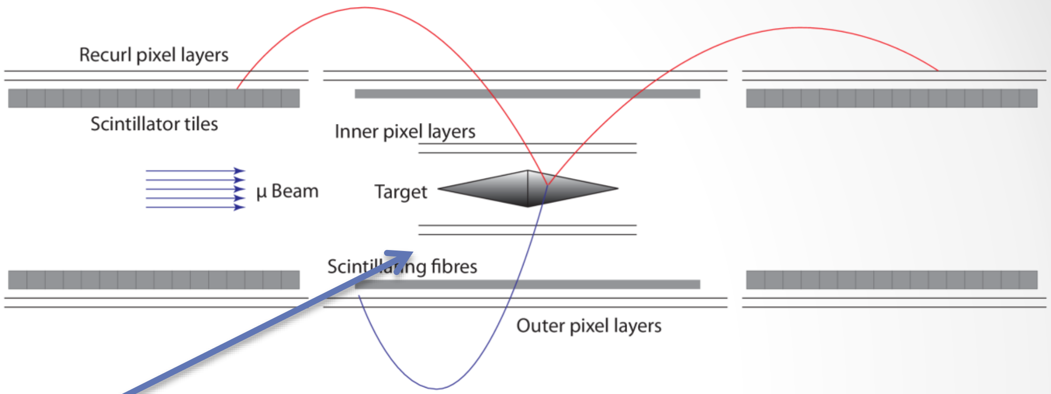
…

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



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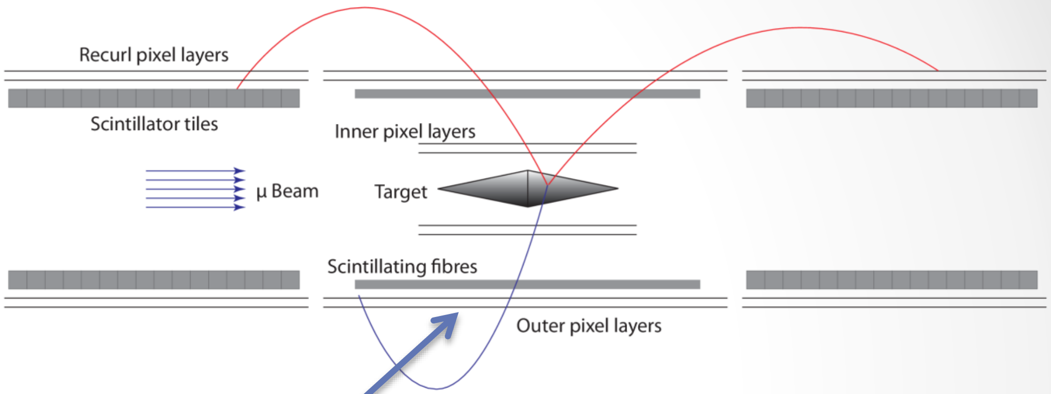
Mu3e Silicon Detector



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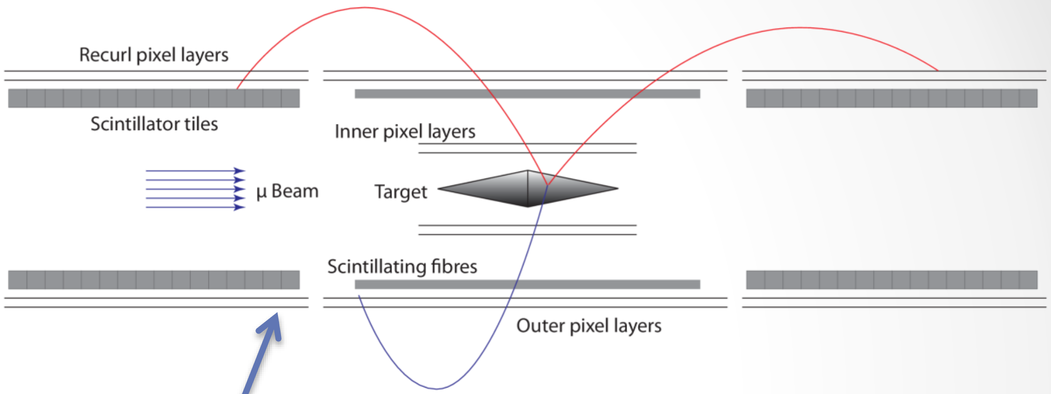
Mu3e Silicon Detector

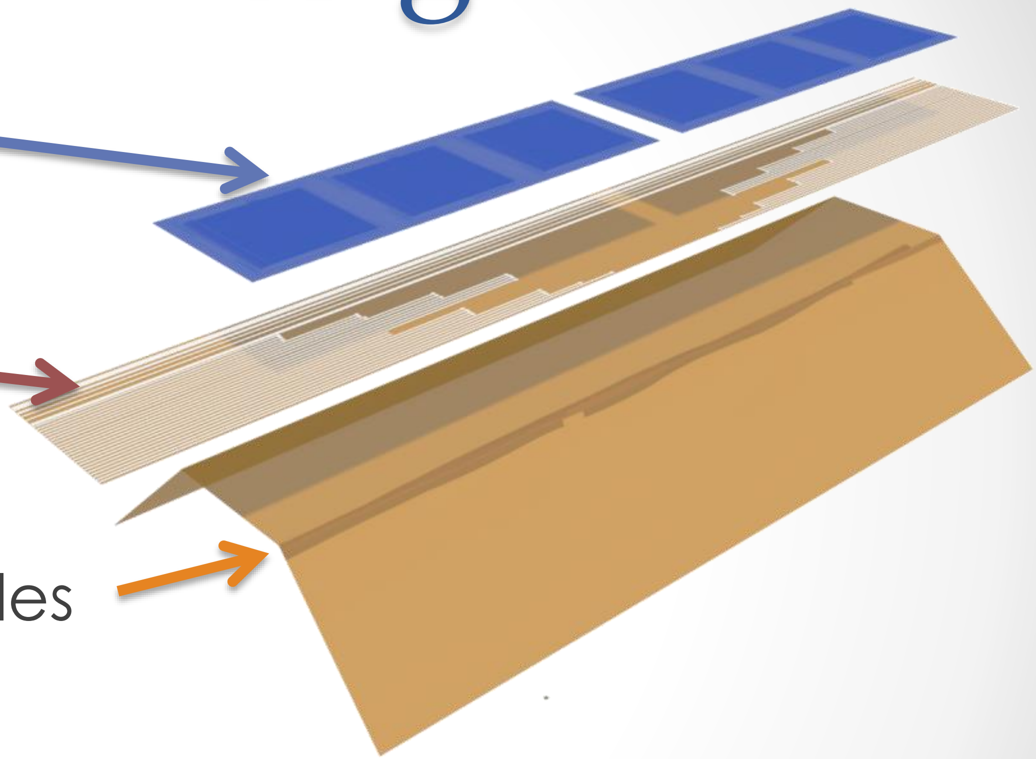


- Conical target
- Inner double layer
  - 8 and 10 sides of 2 x 12 cm^2
- Outer double layer
  - 24 and 28 sides of 2 x 36 cm^2
- Re-curl layers
  - 24 and 28 sides of 2 x 36 cm^2
  - Both sides

108 inner sensors
2736 outer sensors
~180 000 000 pixel

Sandwich Design

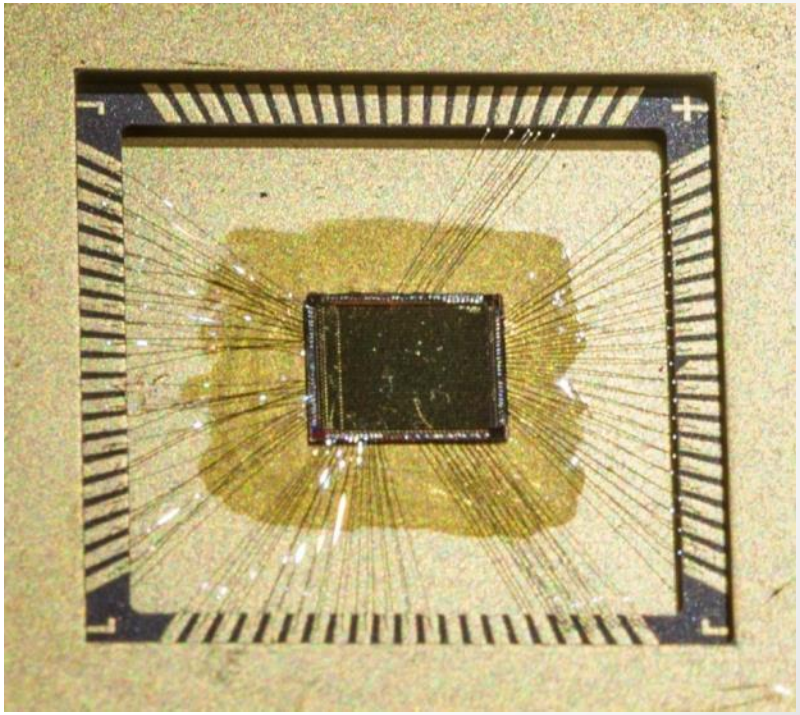
- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 14 µm Alu traces
- Kapton™ Frame Modules
  - 25 µm foil
  - Self supporting
- Alu end wheels
  - Support for all detectors



0.11% of X_0

Thinned Pixel Sensors

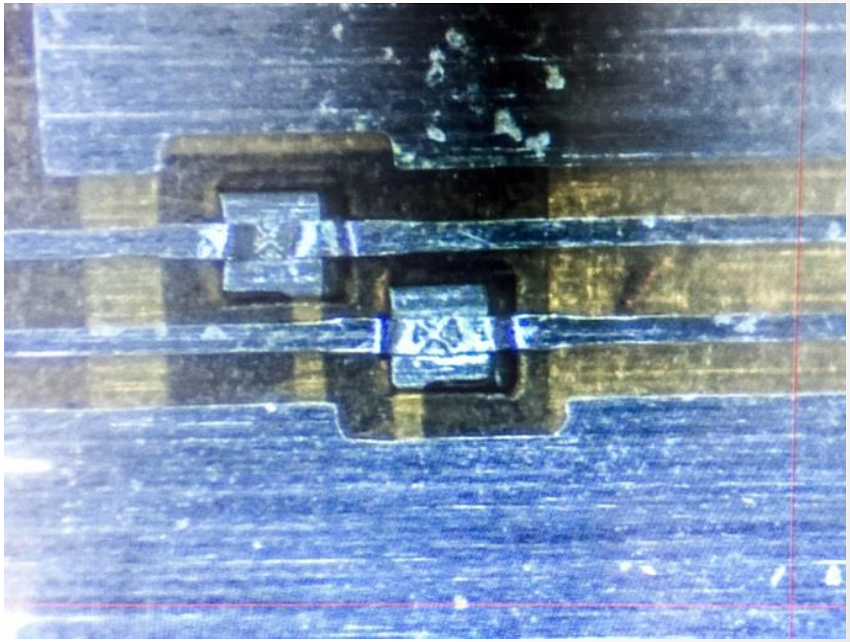
- **HV-MAPS***
  - Thinned to 50 μm
  - Sensors 2 x 2 cm²
- Kapton™ flex print
  - 25 μm Kapton™
  - 14 μm Alu traces
- Kapton™ Frame Modules
  - 25 μm foil
  - Self supporting
- Alu end wheels
  - Support for all detectors



MuPix3 thinned to < 90μm

Kapton™ Flex Print

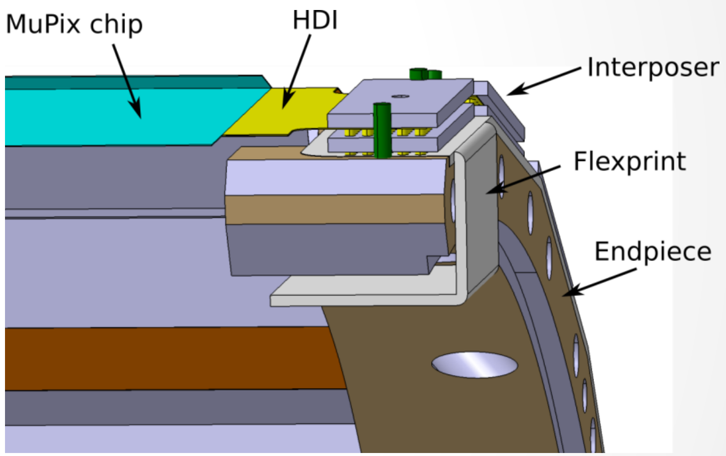
- HV-MAPS
  - Thinned to 50 μm
  - Sensors 2 x 2 cm^2
- **Kapton™ flex print**
  - 25 μm Kapton™
  - 14 μm Alu traces
- Kapton™ Frame Modules
  - 25 μm foil
  - Self supporting
- Alu end wheels
  - Support for all detectors



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

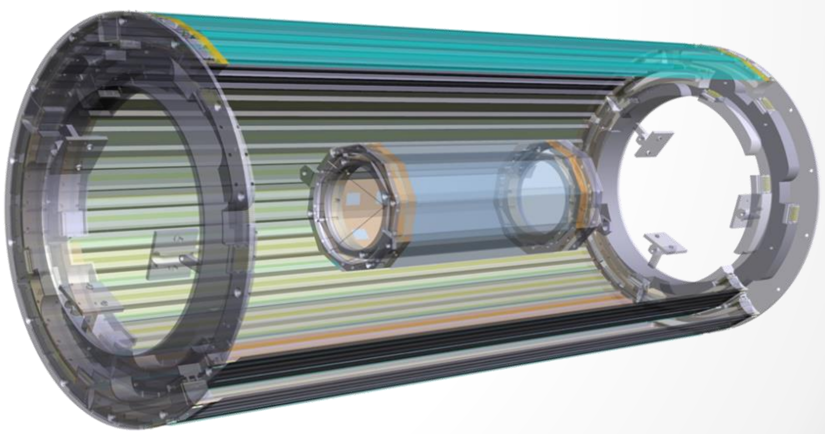


CAD of Kapton™ frames

Overall Design

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 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

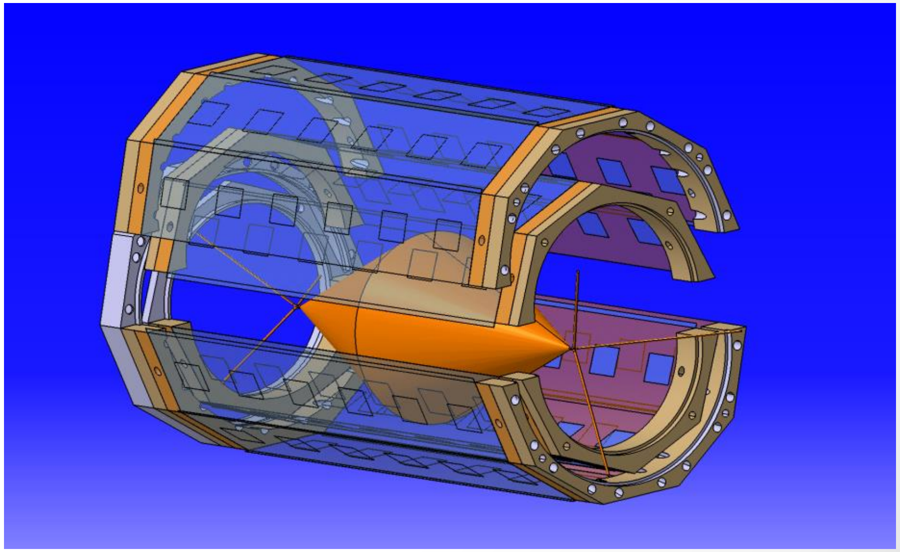
- Two halves for layers 1+2
- 6 modules in layer 3
- 7 modules in layer 4



CAD of Kapton™ frames

Inner Layers

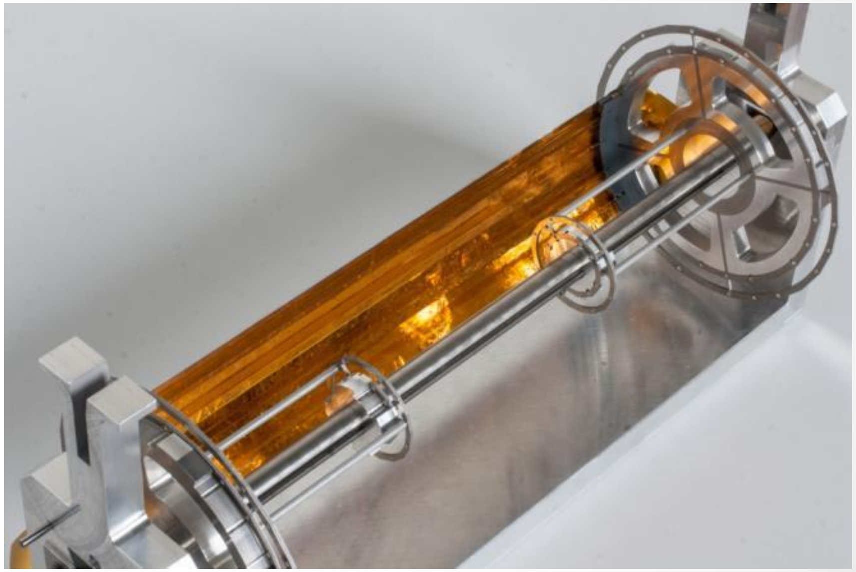
- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 14 µm Alu traces
- **Kapton™ Frame Modules**
  - 25 µm foil
  - **Self supporting**
- Alu end wheels
  - Support for all detectors



Rendering of vertex detector CAD

Outer Module

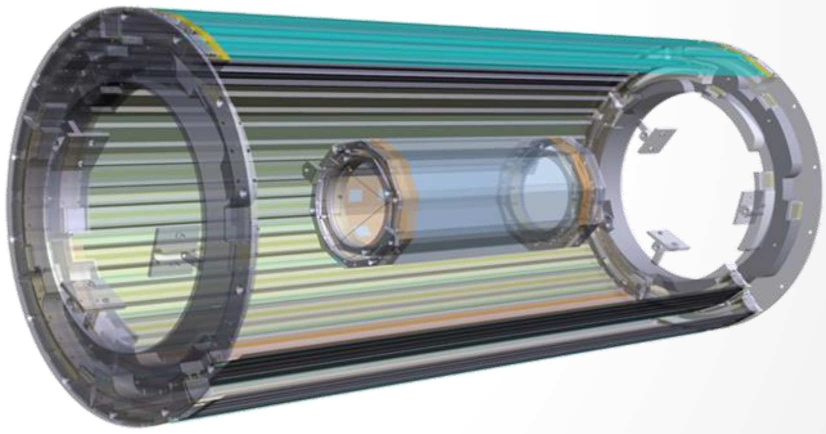
- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 14 µm Alu traces
- **Kapton™ Frame Modules**
  - 25 µm foil
  - **Self supporting**
- Alu end wheels
  - Support for all detectors



Layer 3 Prototype in Assembling Frame with 50 µm Glass

Detector Frame

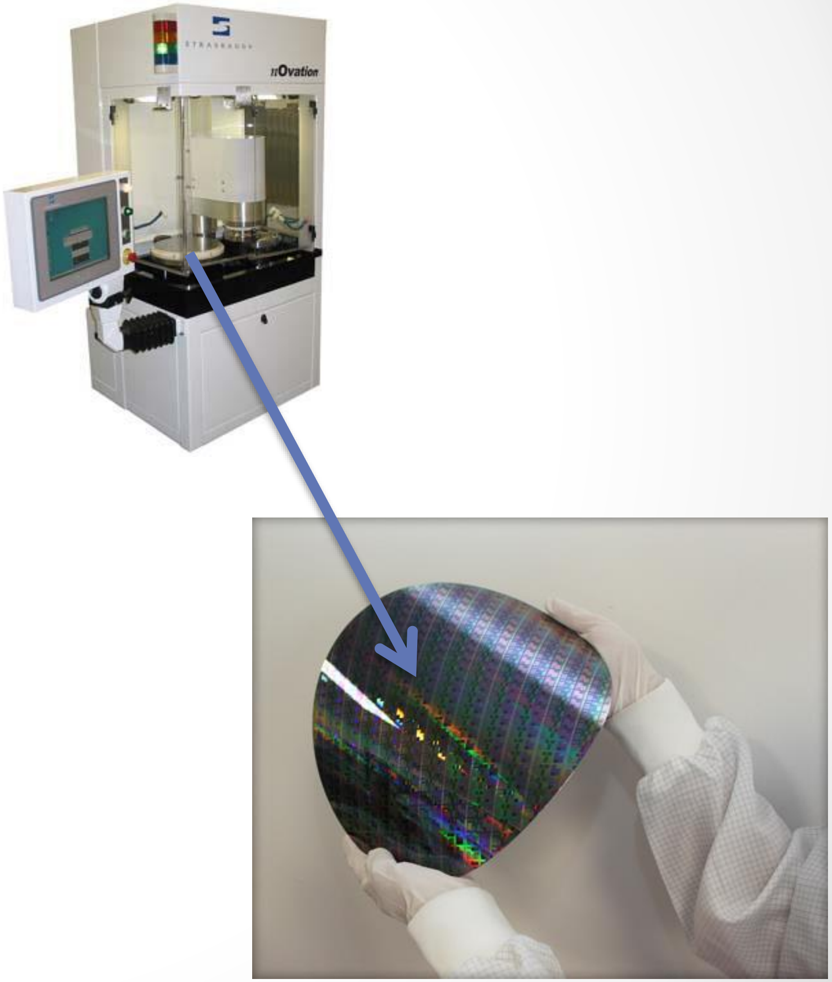
- HV-MAPS
  - Thinned to 50 μm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 μm Kapton™
  - 14 μm Alu traces
- Kapton™ Frame Modules
  - 25 μm foil
  - Self supporting
- **Alu end wheels**
  - Support for all detectors



Pixel detector CAD rendering

Thinning

- 50 µm Si-wafers
  - Commercially available
  - HV-CMOS 50 µm (AMS)
  - 50 µm for MuPix4 and MuPix7

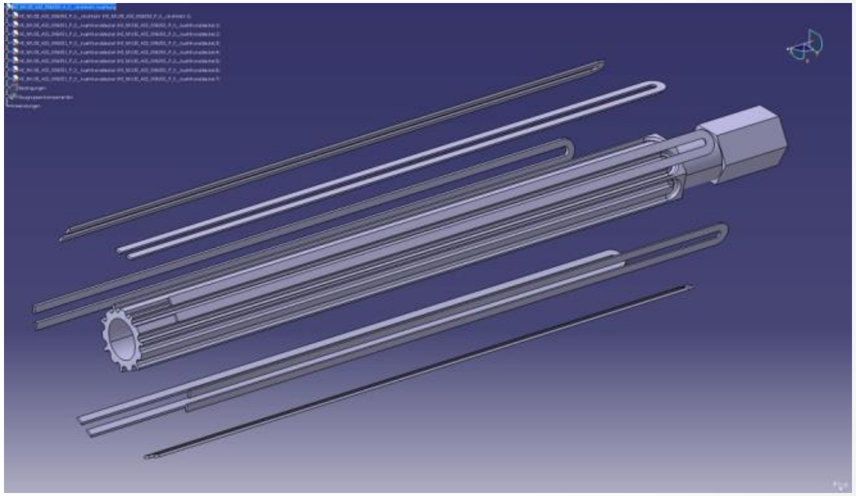


Cooling Backup

…

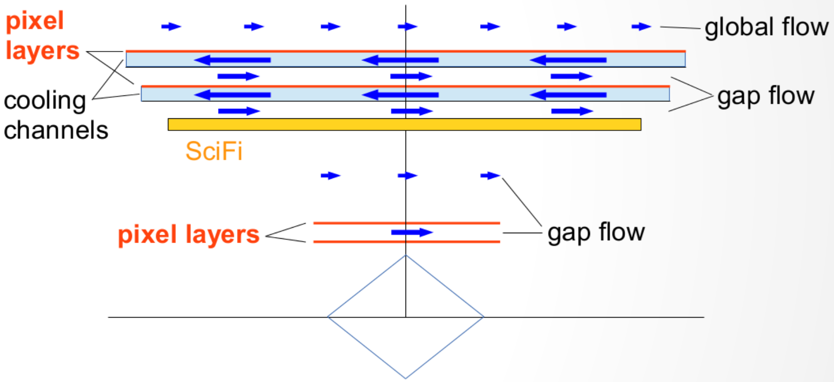
Liquid Cooling

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



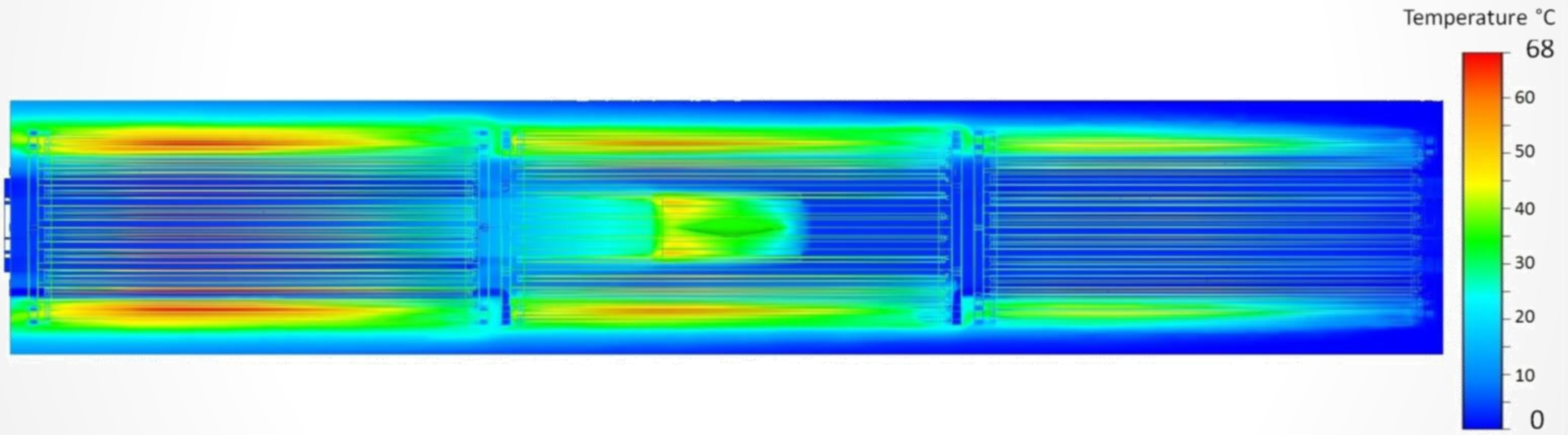
He Cooling

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



$$400\text{mW/cm}^2 \text{ x } 11664\text{cm}^2 \approx 4.7 \text{ KW}$$

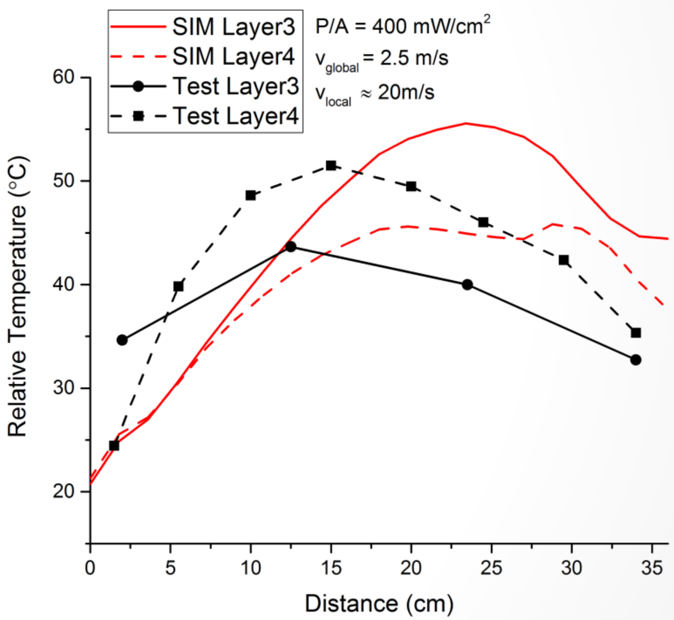
Simulation



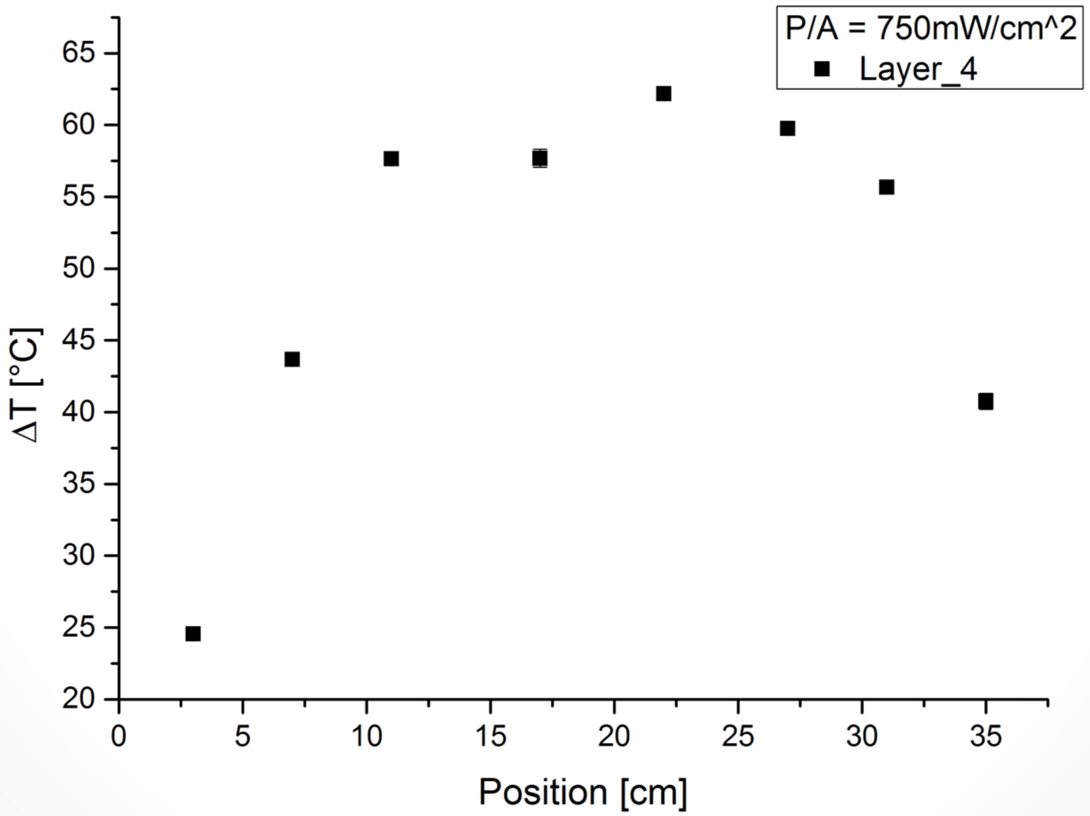
He cooling
400mW/cm^2

Test Results

- 1:1 Prototype
  - Layer 3+4 of silicon tracker
  - Ohmic heating 400mW/cm²
- Cooling He
  - at several m/s
- Temperature sensors attached to foil
  - LabVIEW readout
- **Results promising**
  - **ΔT < 60°K**
  - **No sign of vibration in air**



He Cooling 750 mW/cm^2

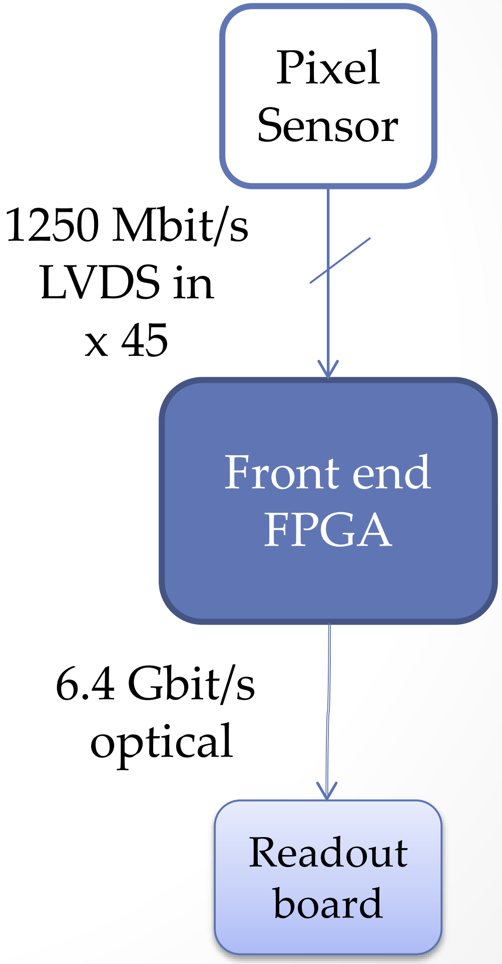


DAQ Backup

...

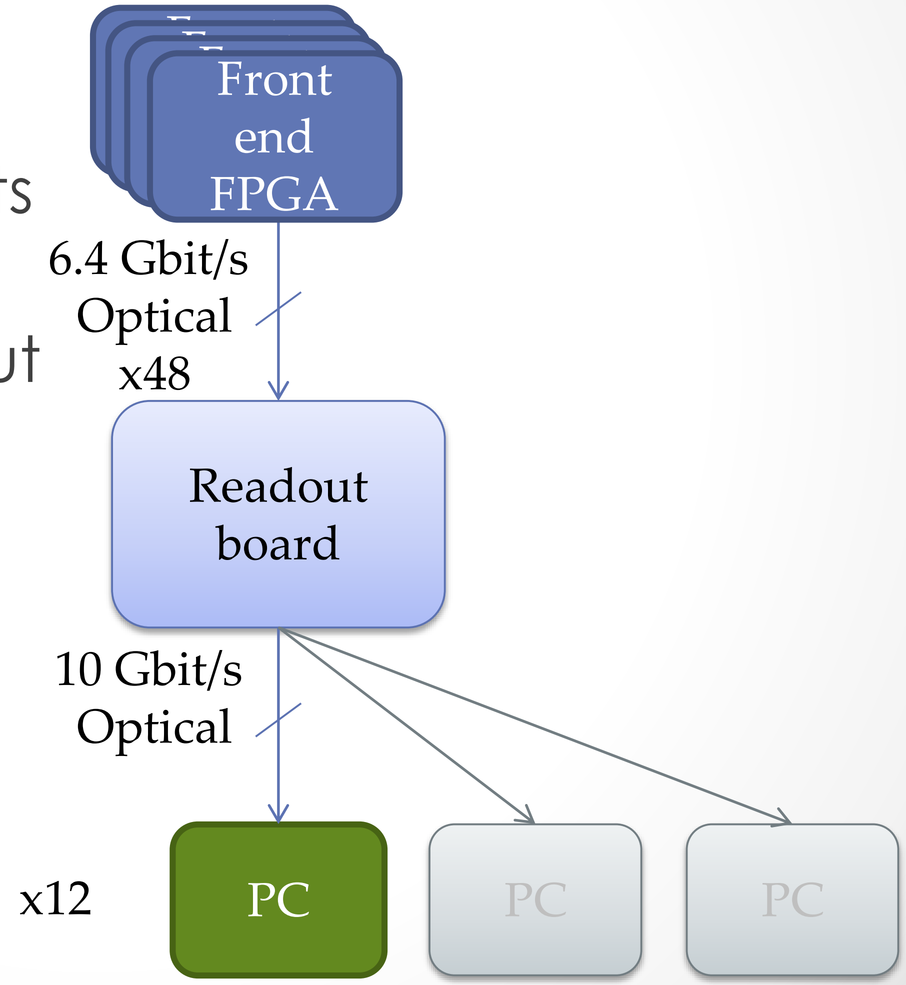
Front End FPGAs

- FPGAs on detector (?)
  - 112 pieces
- Receive sensor data
  - 36-45 LVDS inputs
- 6.4 Gbit/s outputs
  - 8 optical links
  - … to counting house



Readout Board

- FPGA readout 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



Readout Board

- FPGA readout boards
  - 4 per sub-detector
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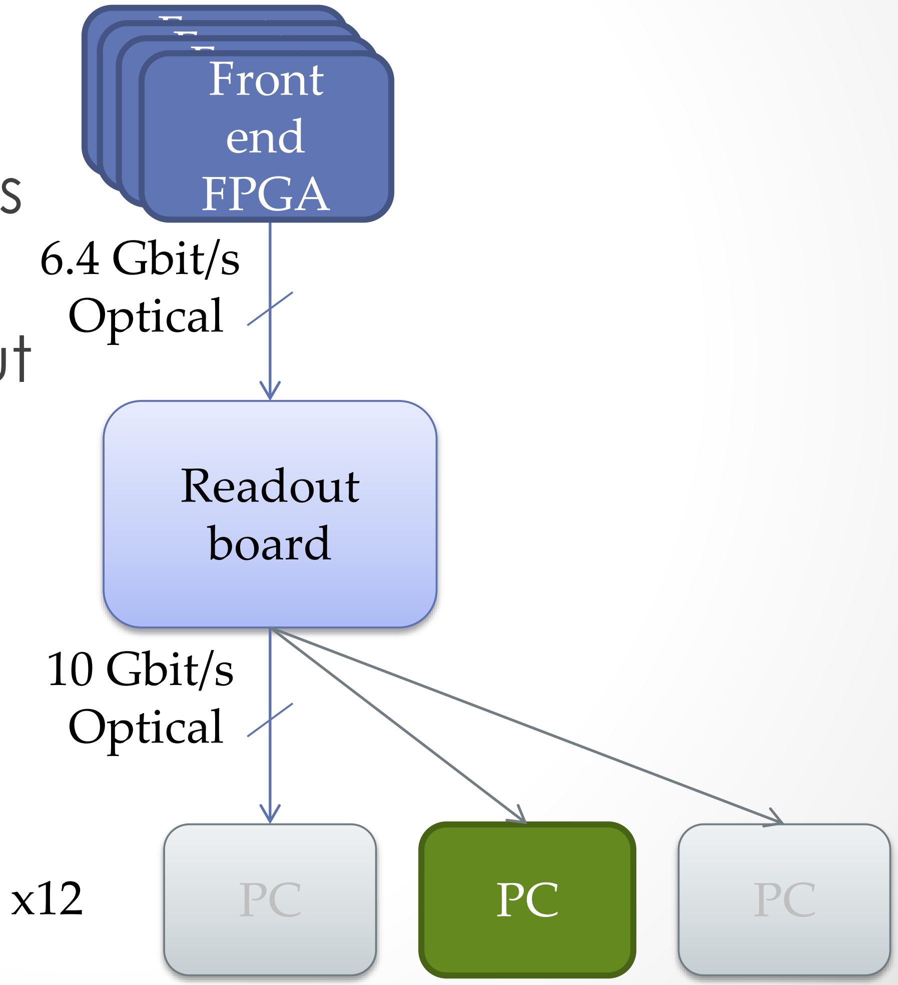
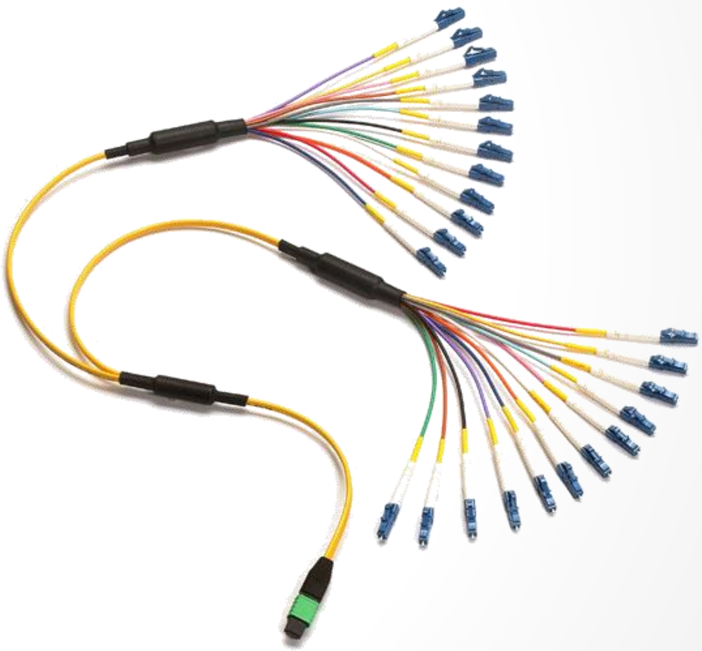


Trigger-less DAQ

- 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



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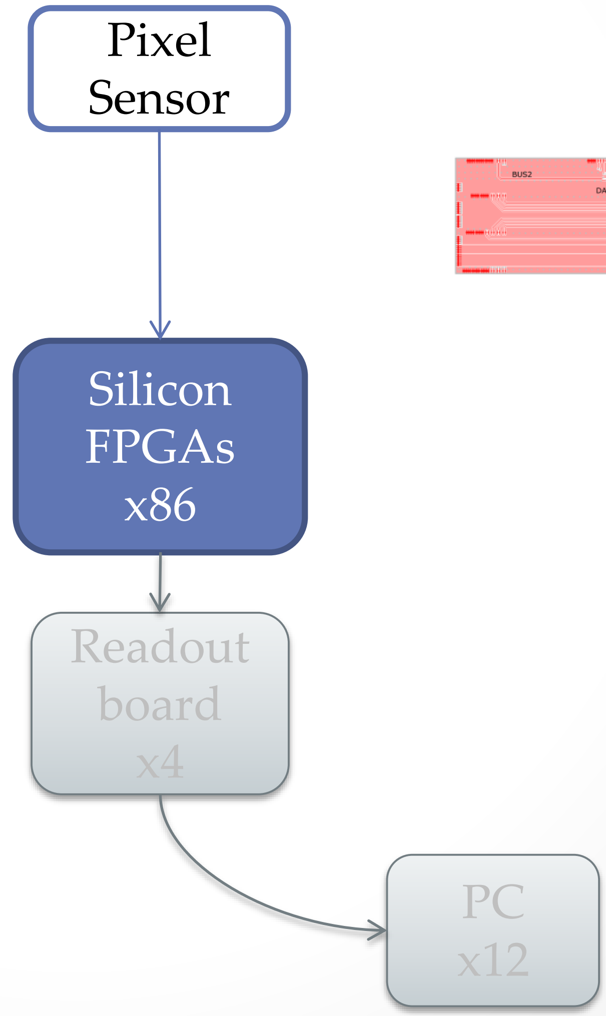

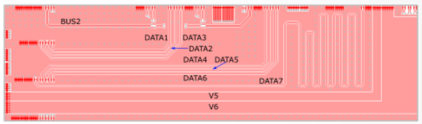

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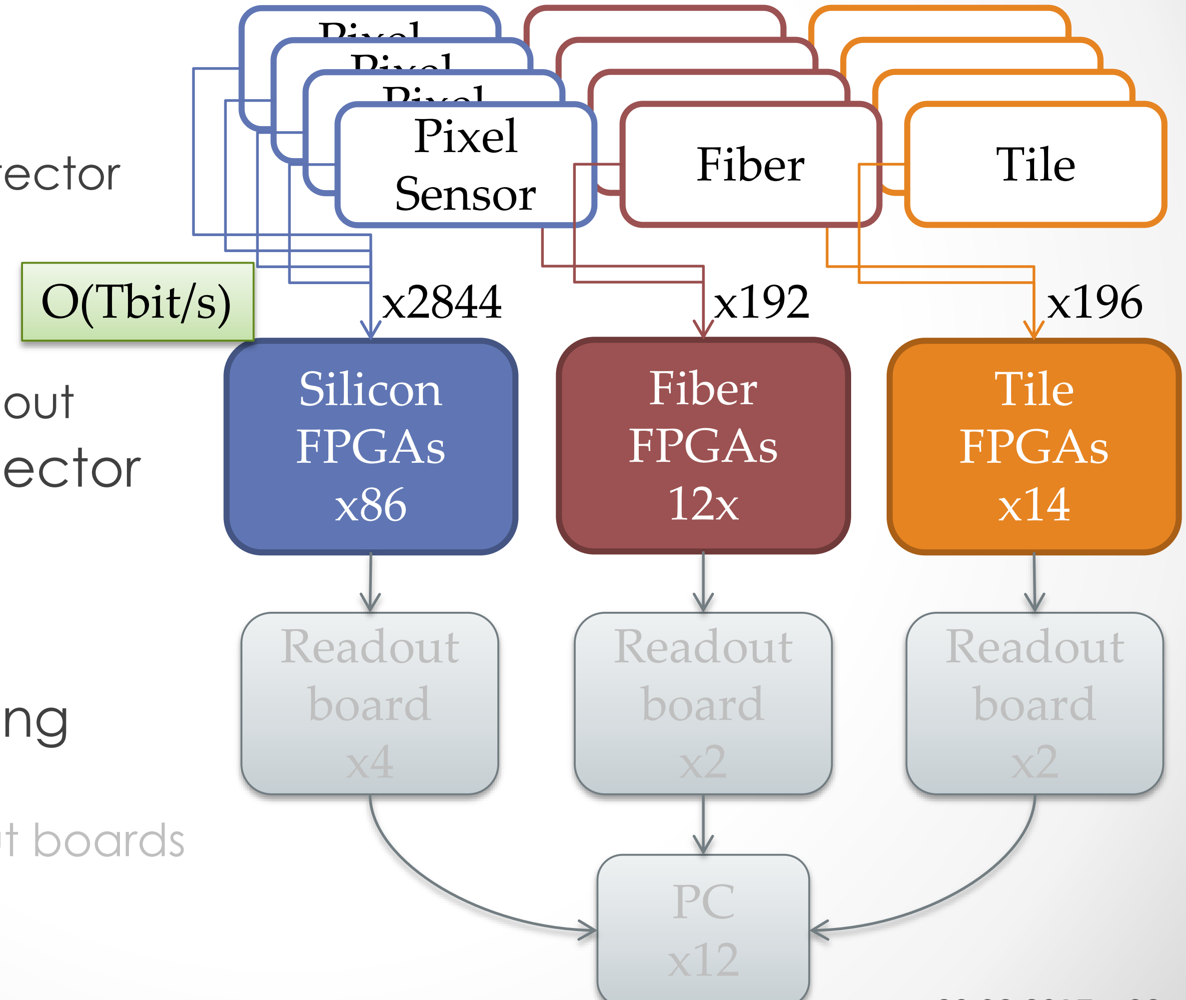

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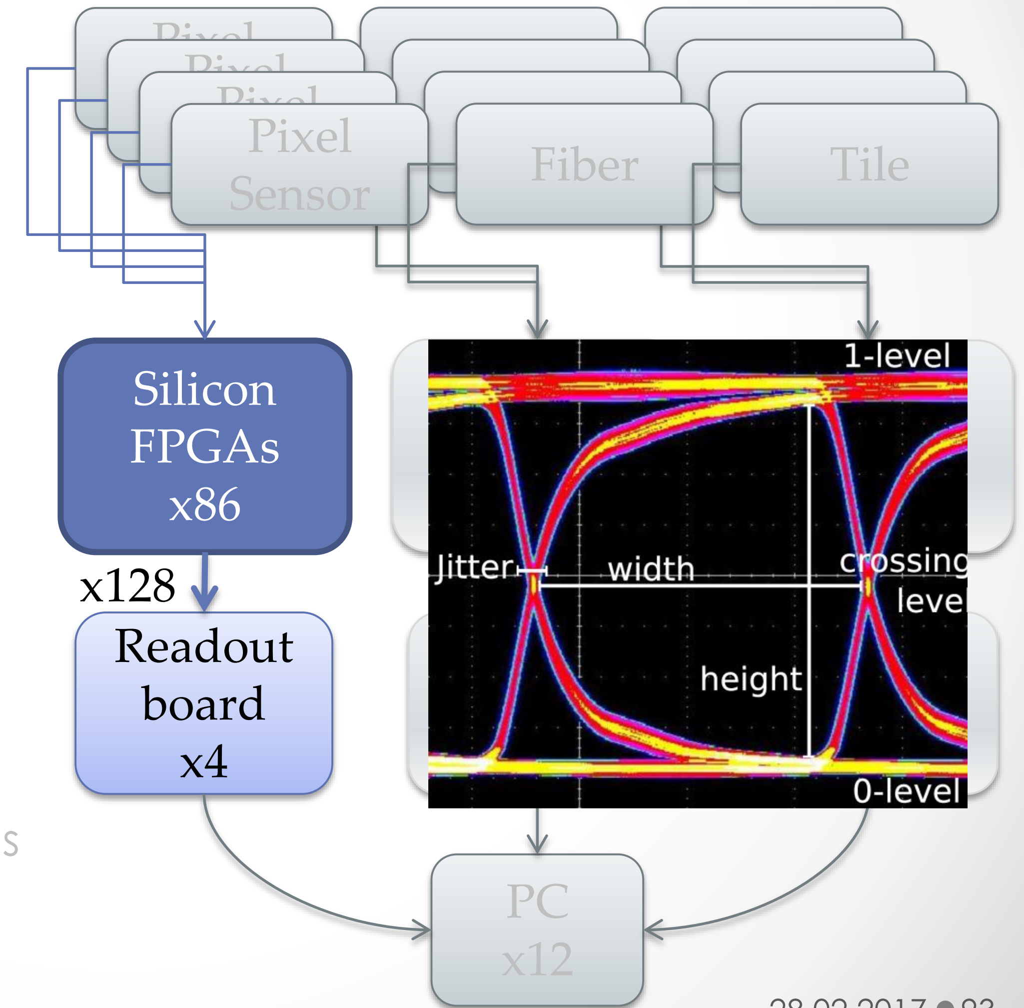

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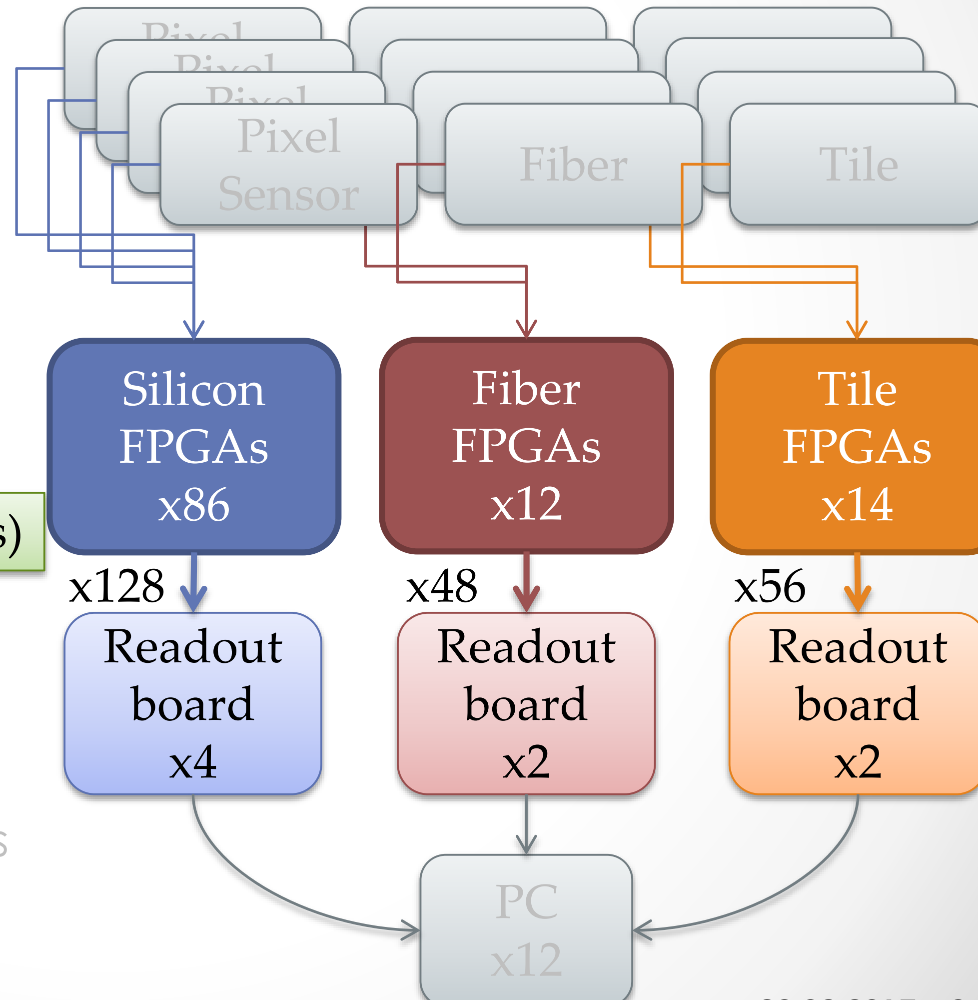

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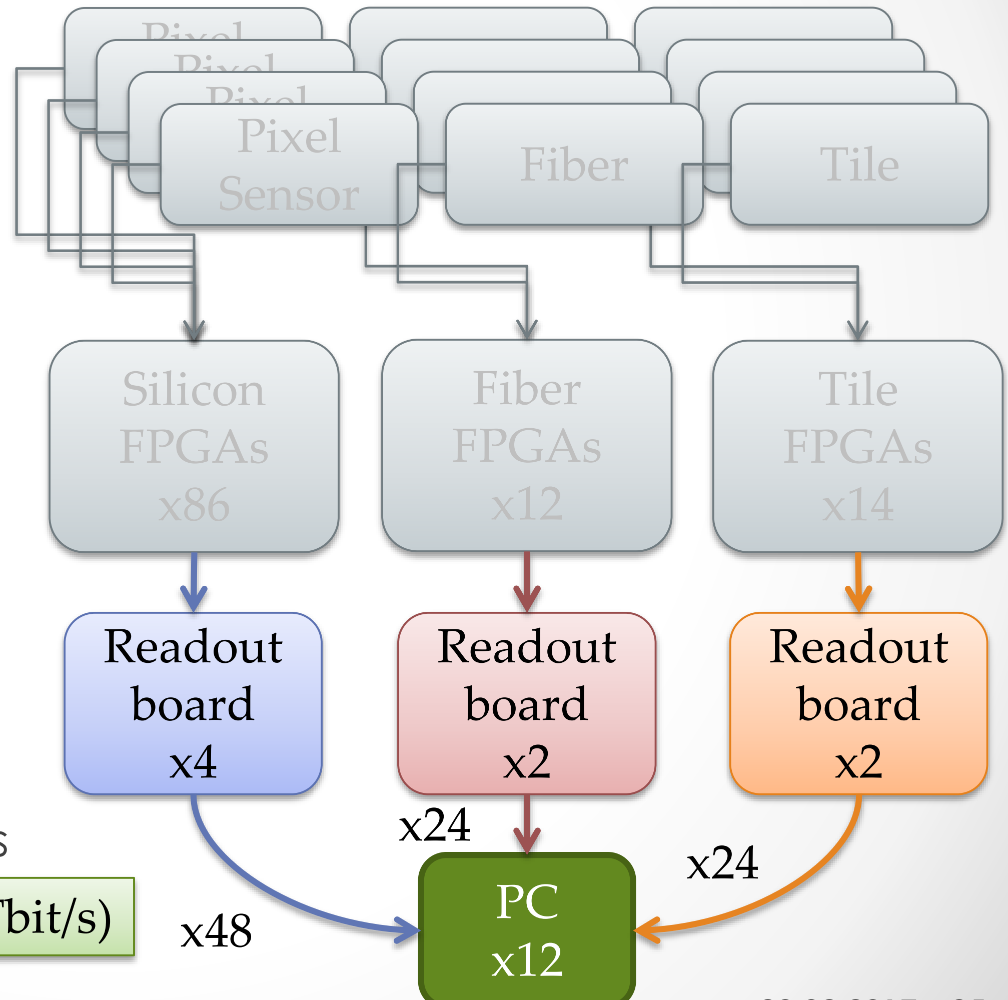

GPU-PC

- 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

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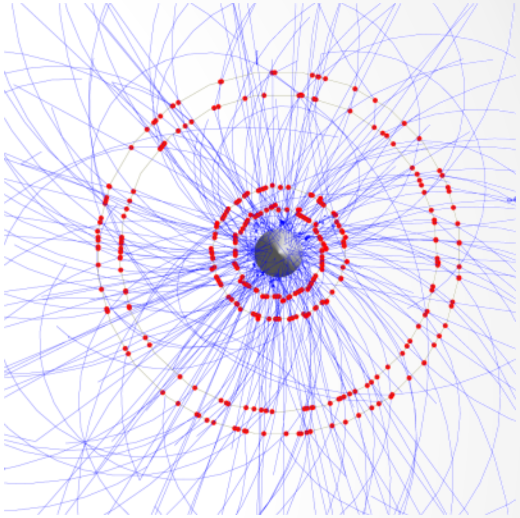
Optical mezzanine connectors

FPGA PCIe board

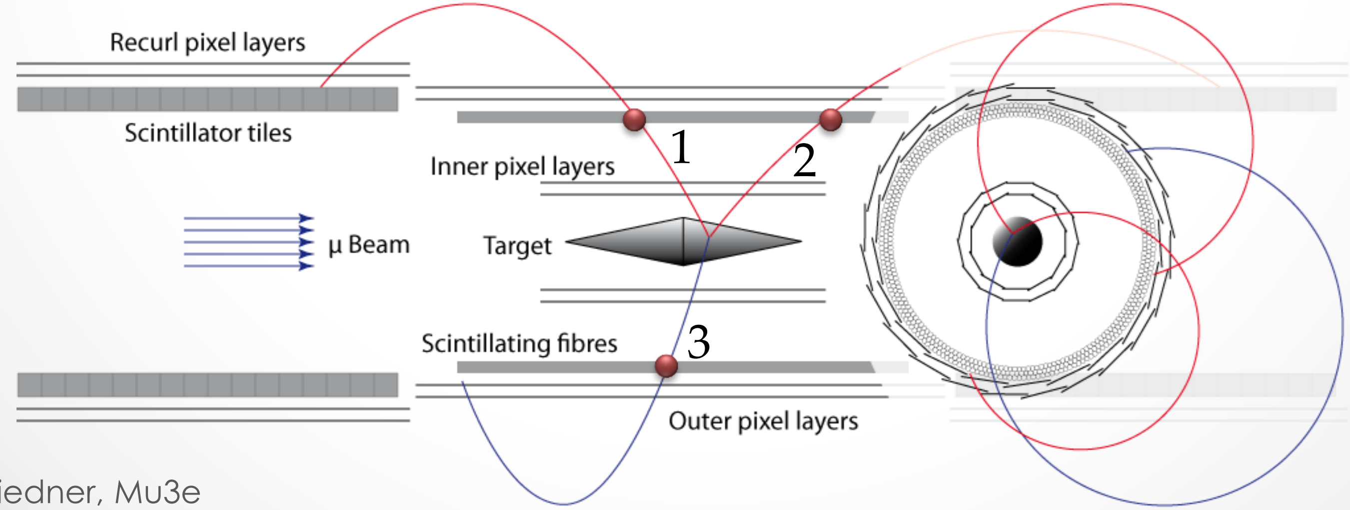
GPU computer

Timing Filter

Under discussion



- Entire event on PCIe FPGA
- Tile and Fiber data
  - Easy to match
  - Look for three tracks
- Reject data without three hits
  - … inside time interval



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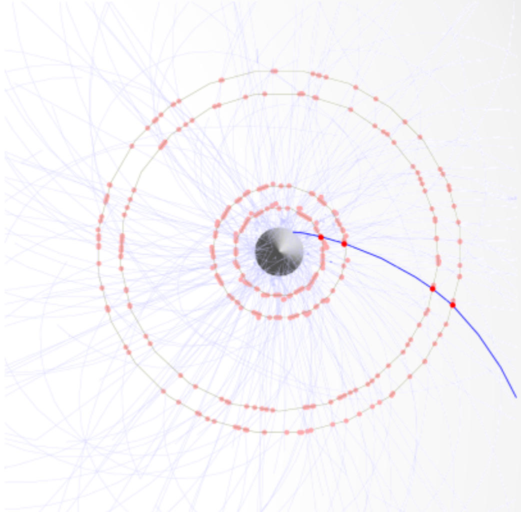
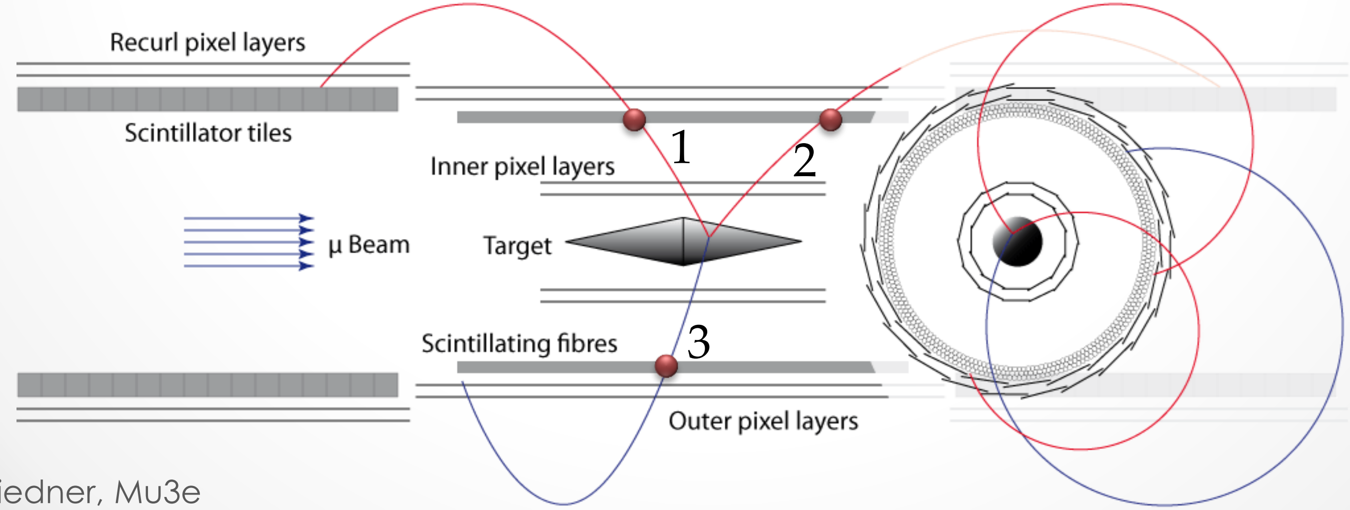
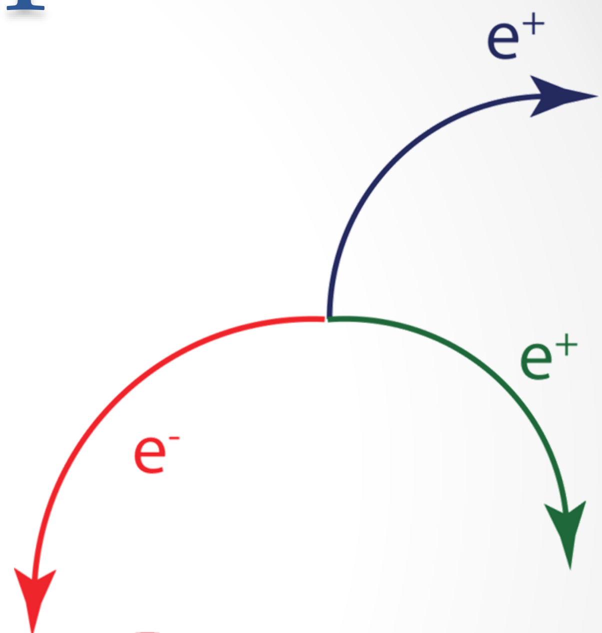
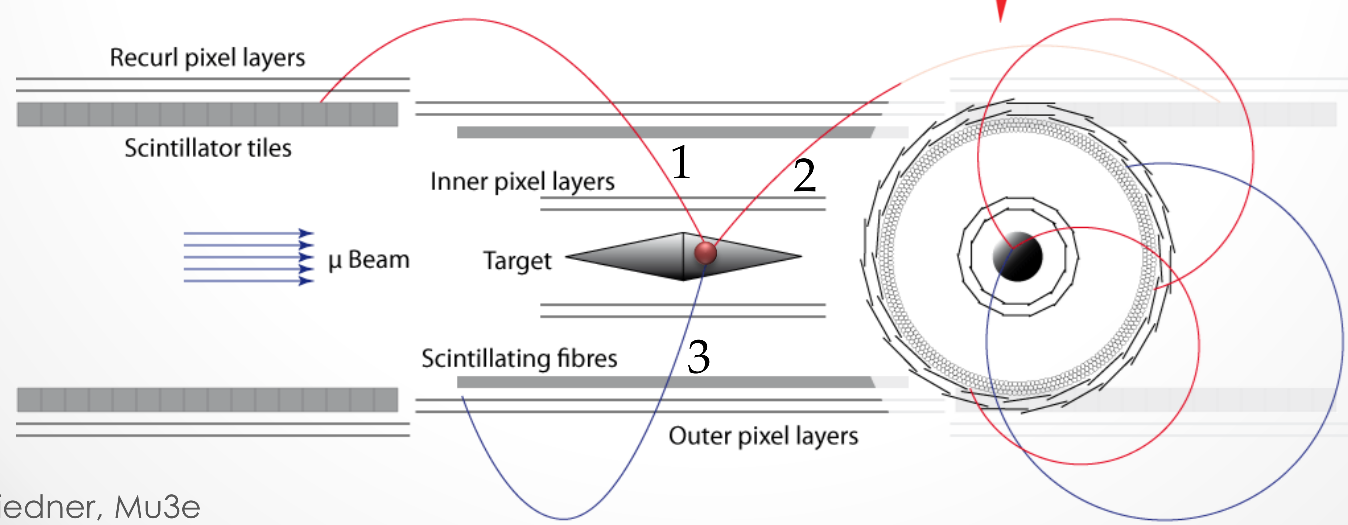




Vertex Filter

- Entire event on GPU
- Large target
  - Large spread of muons
  - Easy vertex separation
- Reject data without three tracks
  - … inside area interval on target





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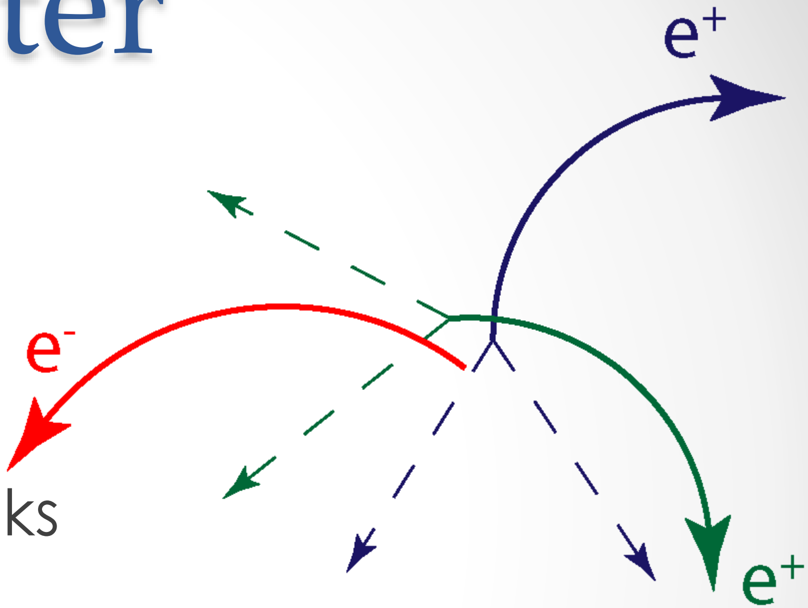
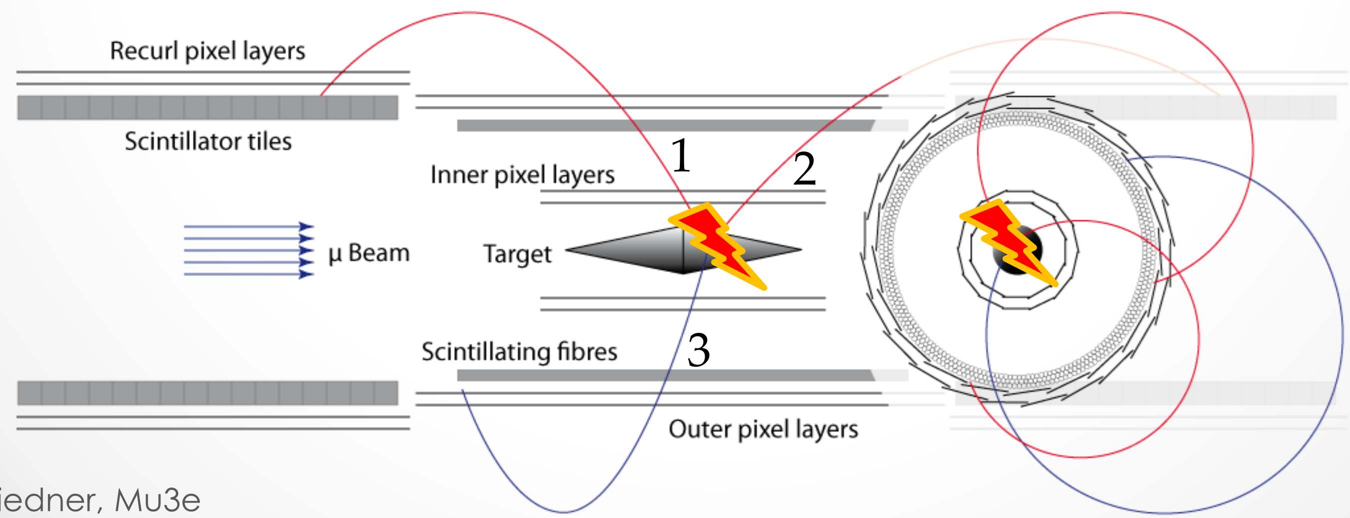
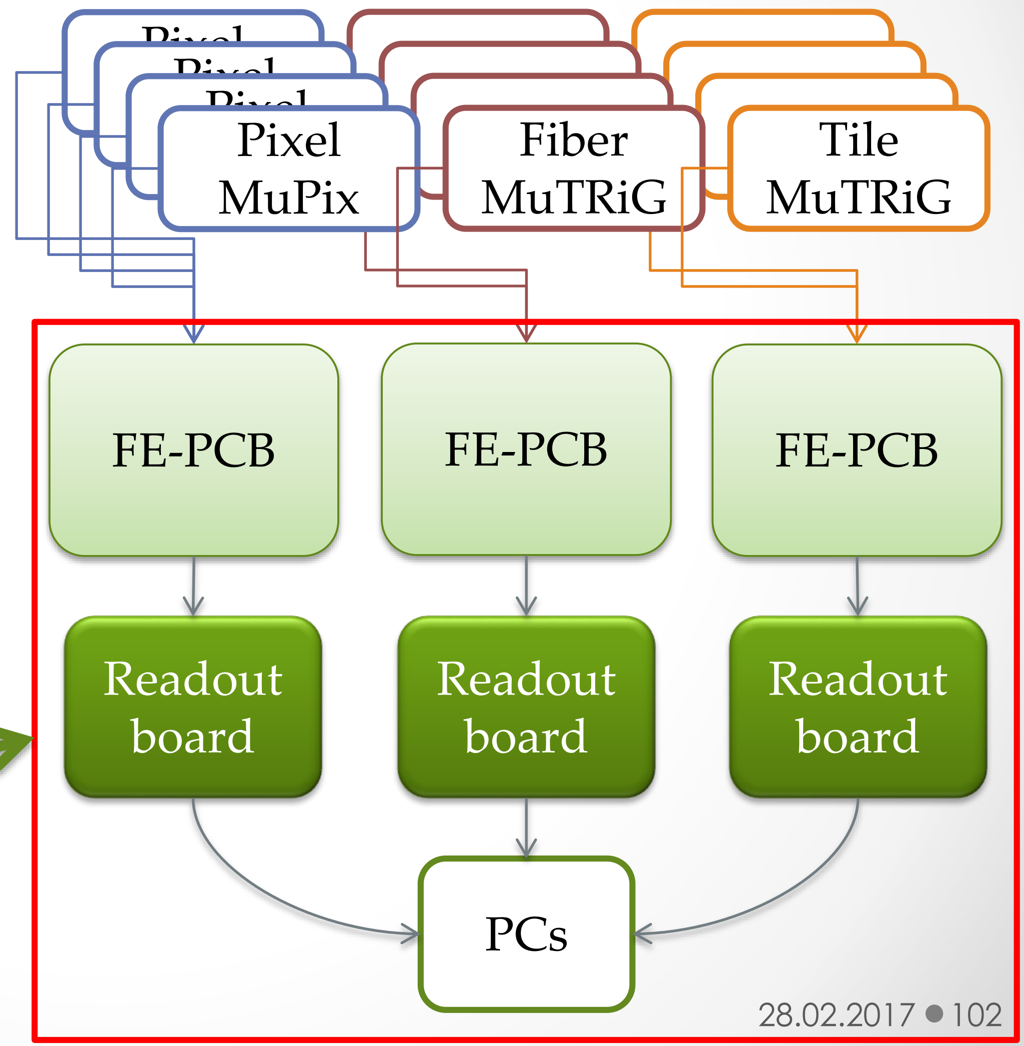




Readout system

- Pixel detector
  - o HV-MAPS (MuPix)
    - ✓ Sensor and read-out chip in one
    - ✓ Deliver zero-suppressed serialized data
- Timing detectors
  - o SiPMs plus MuTRiG TDC
    - o Deliver zero-suppressed serialized data
- **Common read-out system**



Common read-out PCB

- ✓ **Front-end PCB**
  - o Common for pixel, fibre and tile detector
  - ✓ Data acquisition
  - ✓ Clock distribution
  - ✓ Slow control distribution
- ✓ Prototype **functional**
  - o Improved version for Q3/2017
- Next: Vertical slice test:
  - o All electronics from (pixel) module to PC