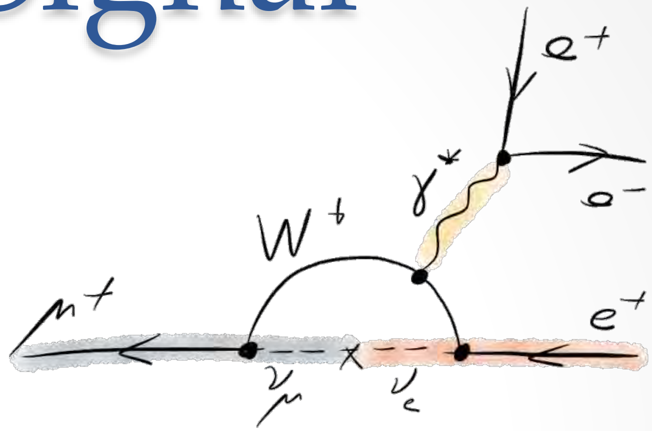
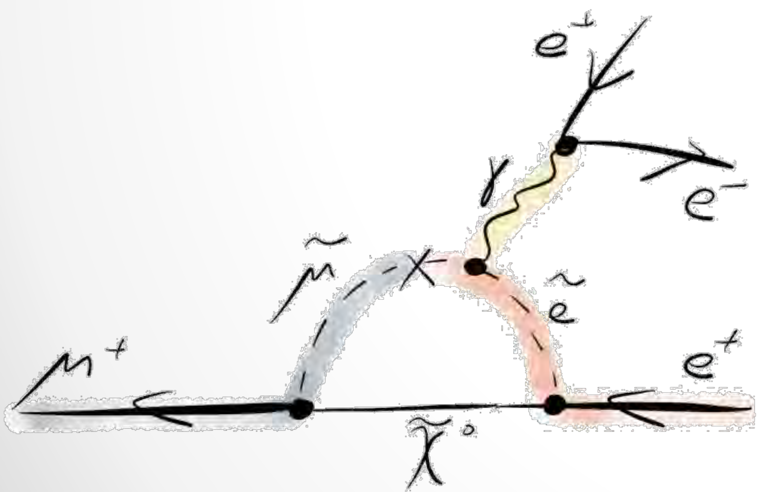
High Voltage Monolithic Active Pixel Sensors for the Mu3e experiment

Dirk Wiedner, Heidelberg
On Behalf of the Mu3e Collaboration

The Mu3e Signal

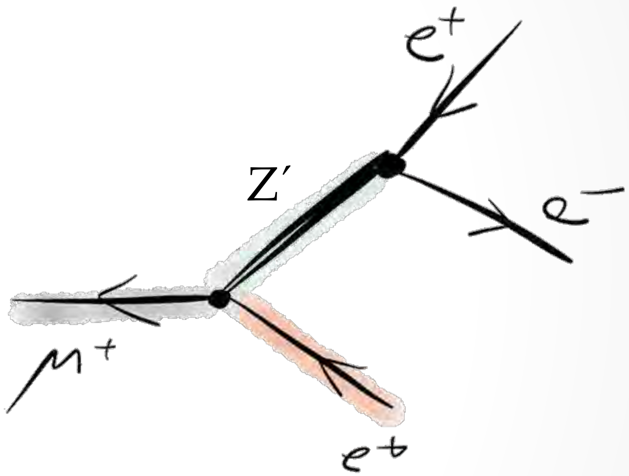
- $\mu^+ \rightarrow e^+e^-e^+$ rare in νSM
  - Branching ratio $<10^{-54}$ $\rightarrow$unobservable
- Enhanced in BSM theories



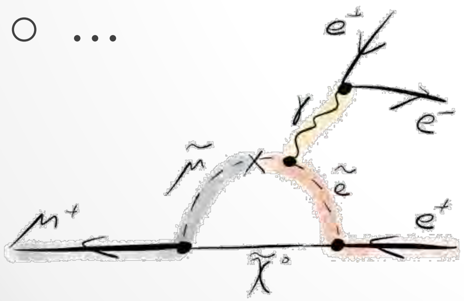


The Mu3e Signal

- $\mu^+ \rightarrow e^+e^-e^+$ 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

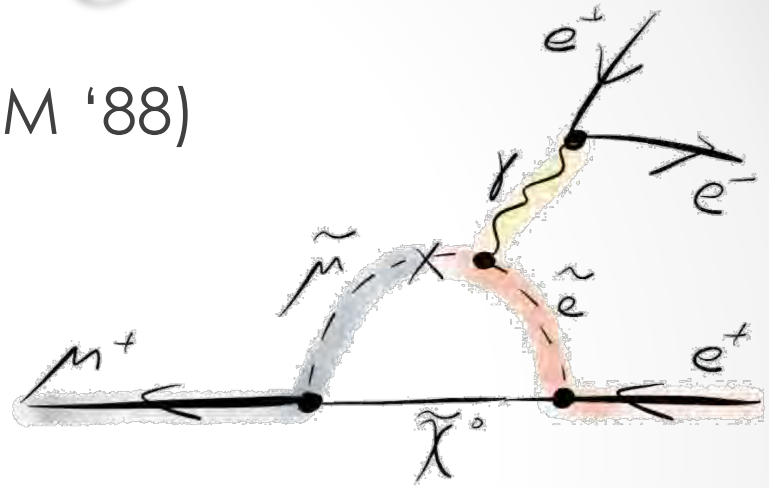
- Rare decay (BR<10^{-12}, SINDRUM ‘88)

For BR O(10^{-15})

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

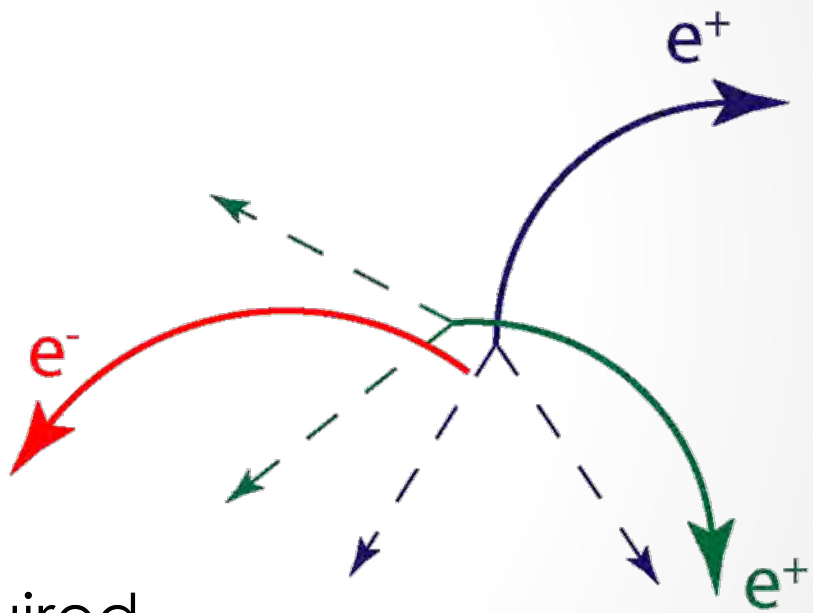
Signal properties:

- $\sum E_e = m_\mu c^2$
- $\sum \overrightarrow{p_e} = 0$
- 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
- $\sum E_e \neq m_\mu c^2$
- $\sum \overrightarrow{p_e} \neq 0$

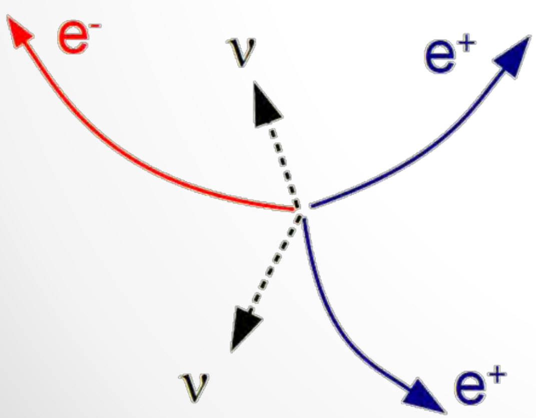


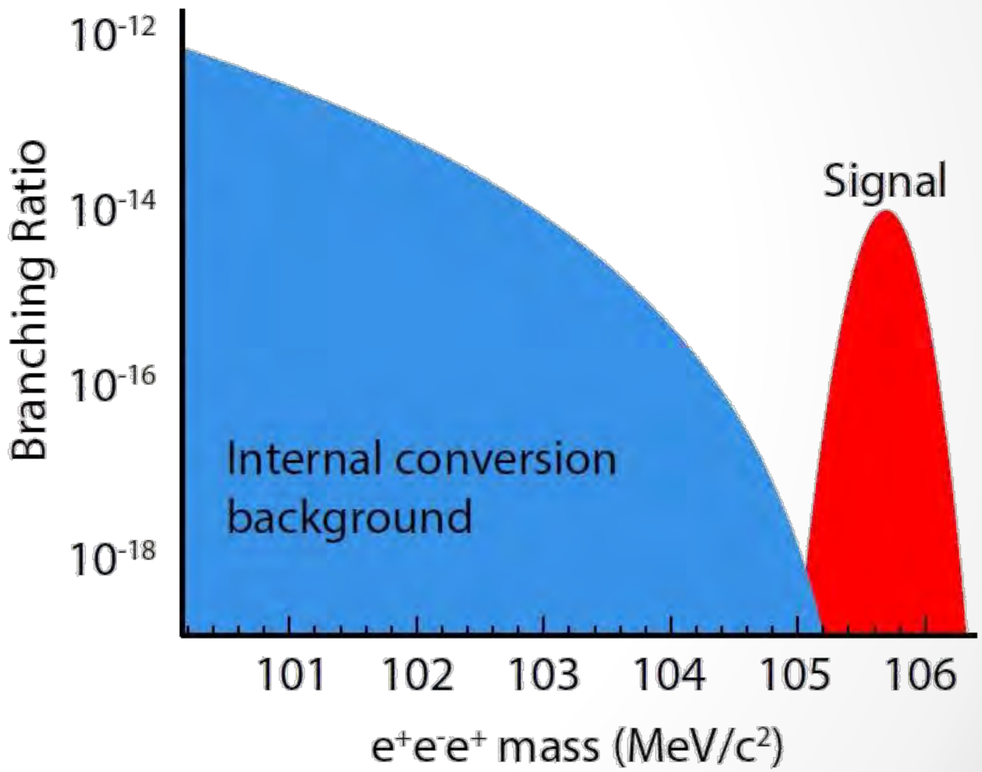
➢ **Good time** and
➢ **Good vertex resolution** required

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

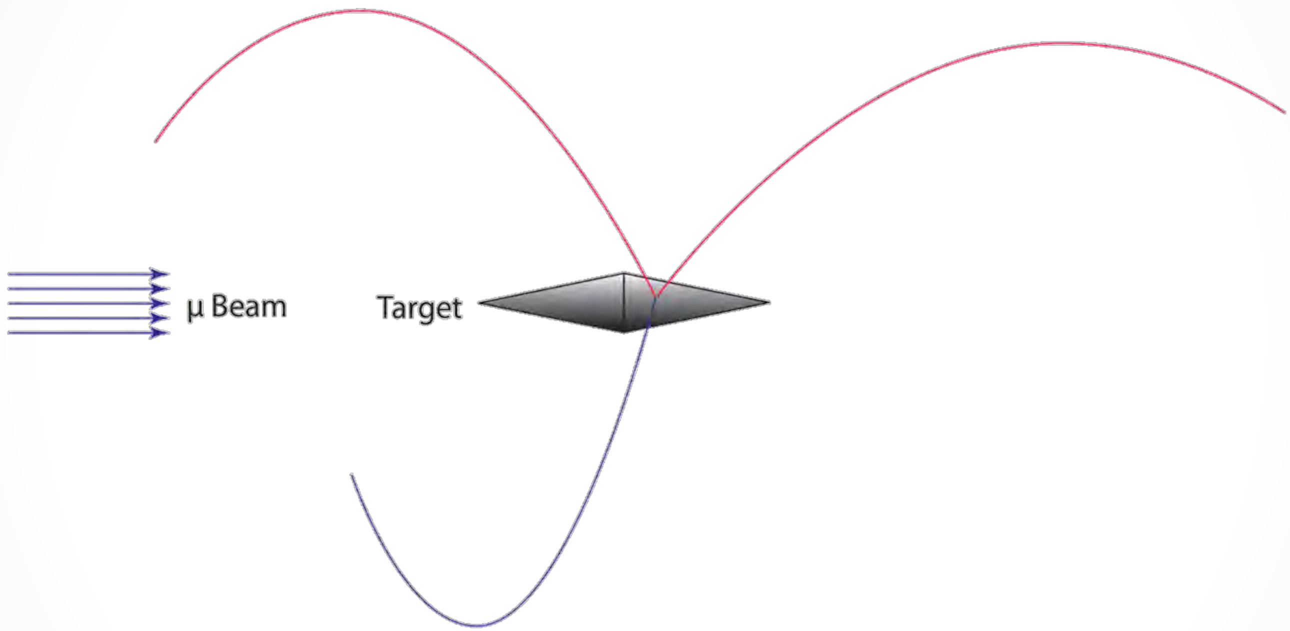
➢ In the following **phase I** will be discussed

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

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

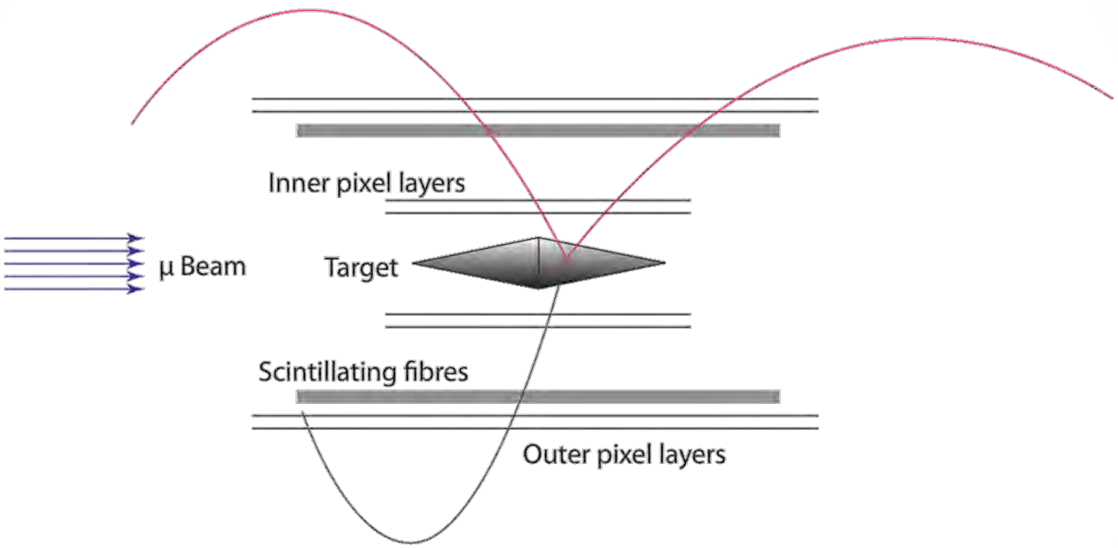
The Mu3e Experiment



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

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

The Mu3e Experiment



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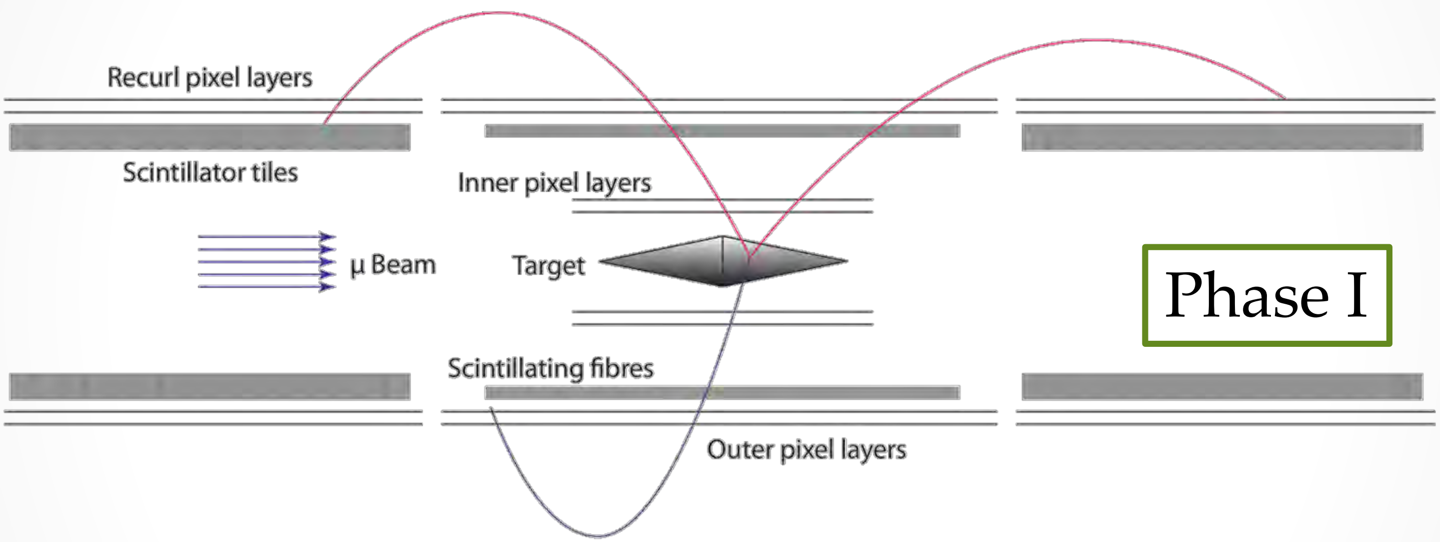
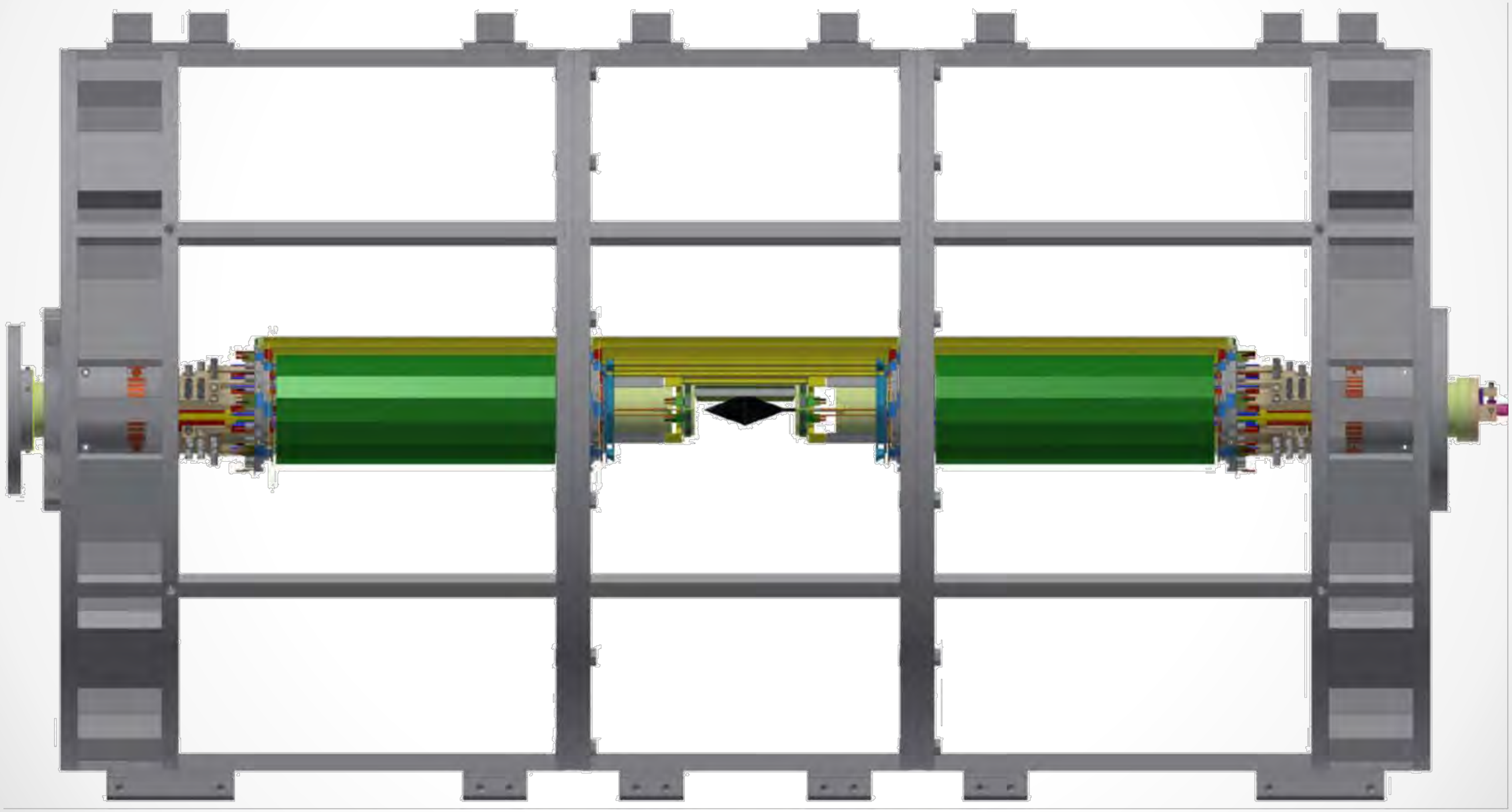


Phase I

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

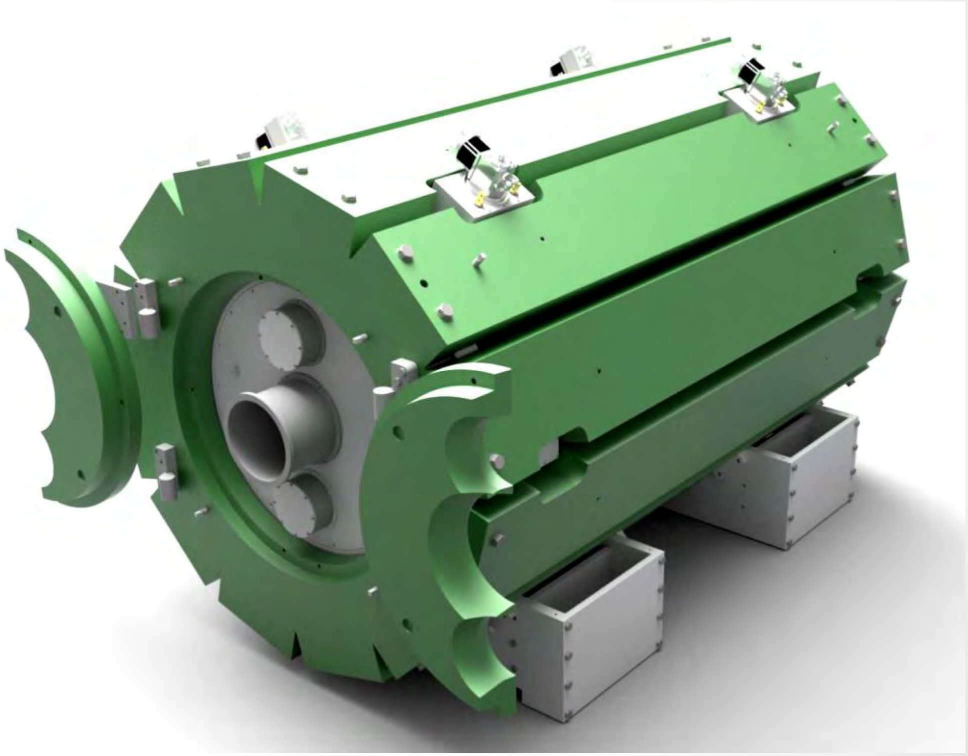
- Target double hollow cone
- Silicon pixel tracker
- Scintillating fiber detector
- Tile detector

The Mu3e Experiment

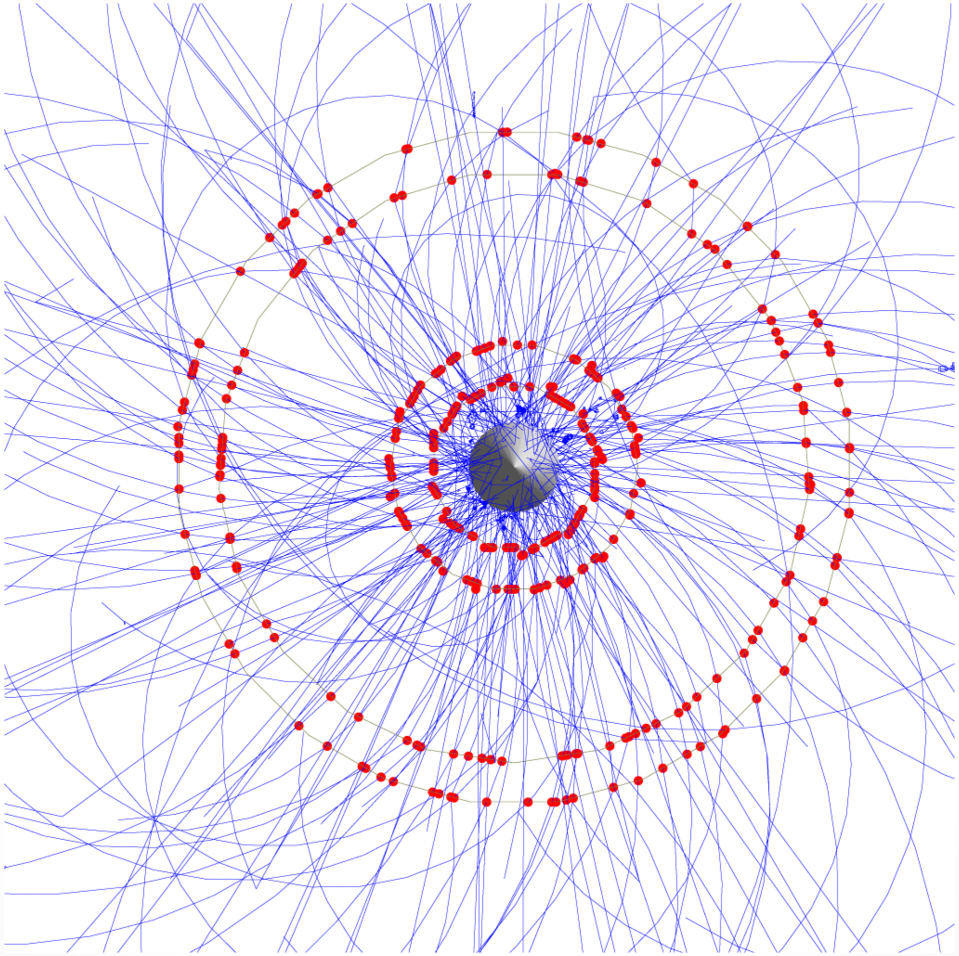


Mu3e Magnet

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



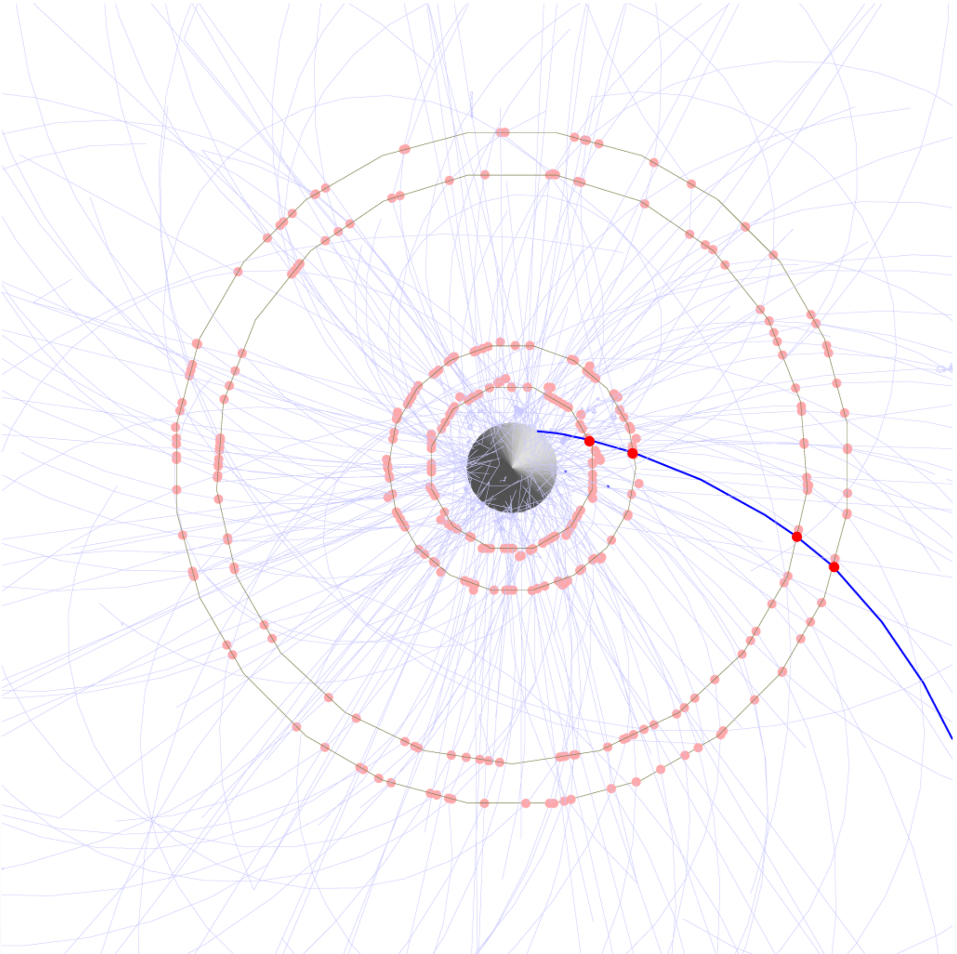
Timing Detectors



Simulated tracks for Phase II

50 ns

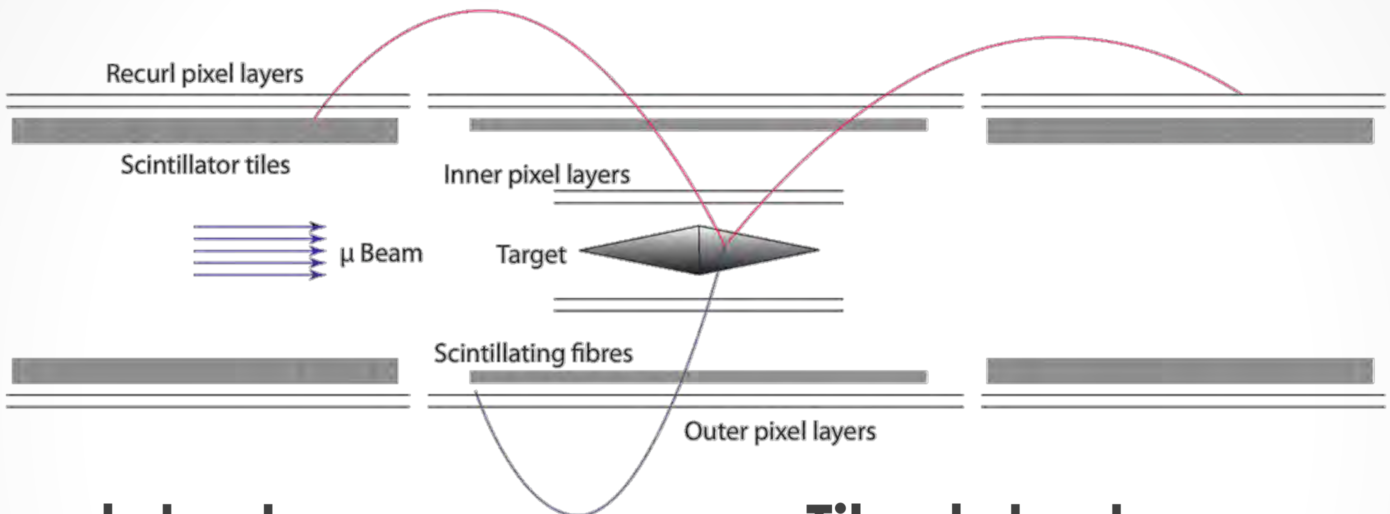
Timing Detectors



Simulated tracks for Phase II

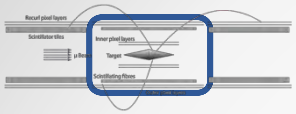
0.1 ns

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

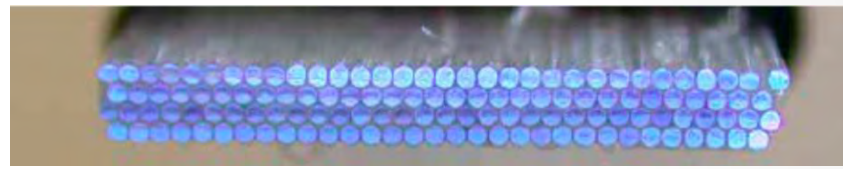
Common readout ASIC - MuTrig



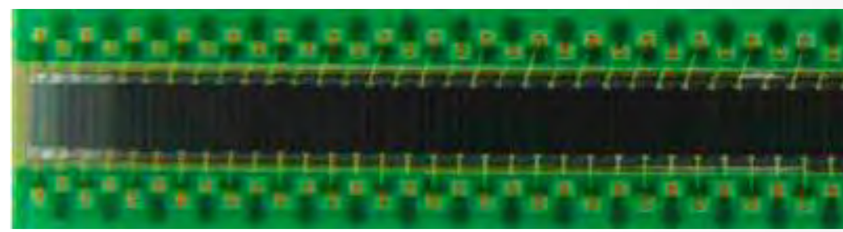
Fiber Detector

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

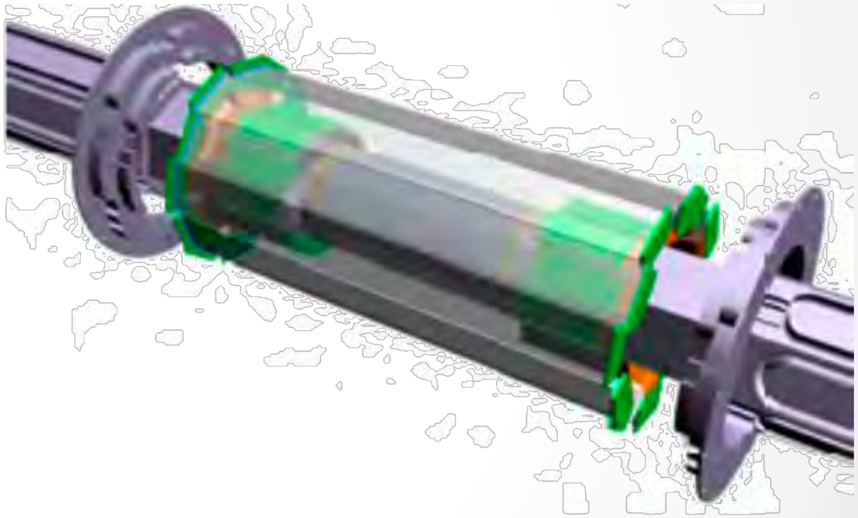


Silicon photo multiplier (SiPM) array

Fiber Detector

Fiber ribbon modules

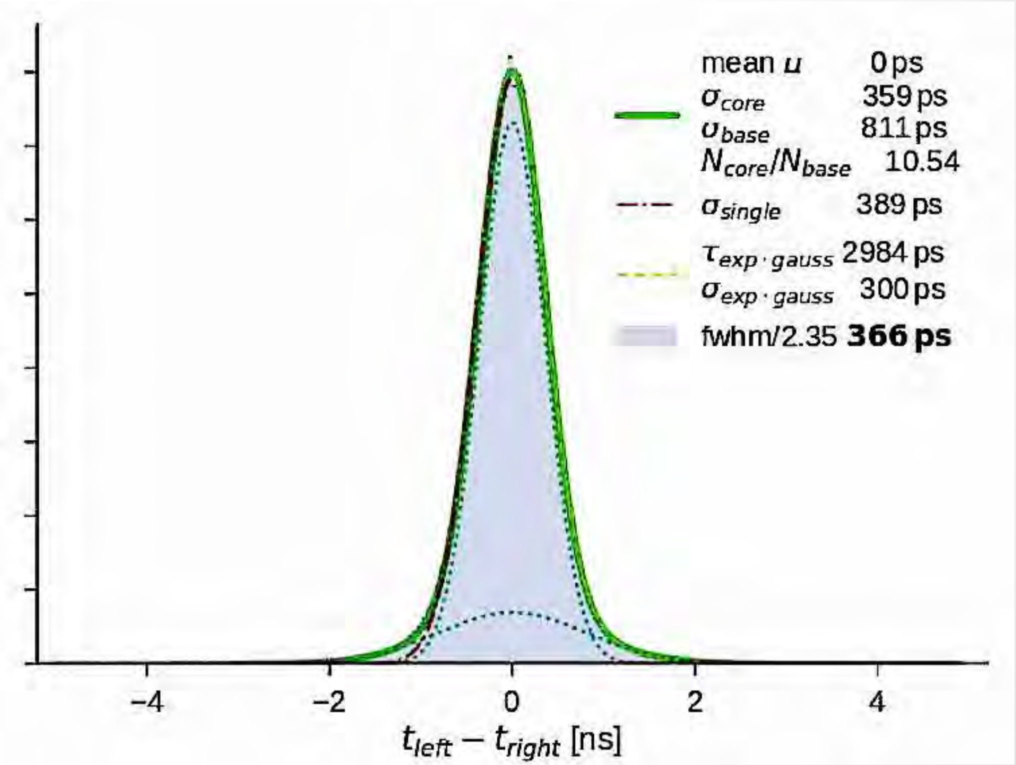
- 32 mm wide
- ~290 mm long
- 4 layers fibers of ø 250 µm
- SiPM arrays (LHCb type)
- 4 MuTRiG readout chips
- A demonstrator will be build by the end of the year



Fiber tracker mechanical design study

Fiber Time Resolution

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



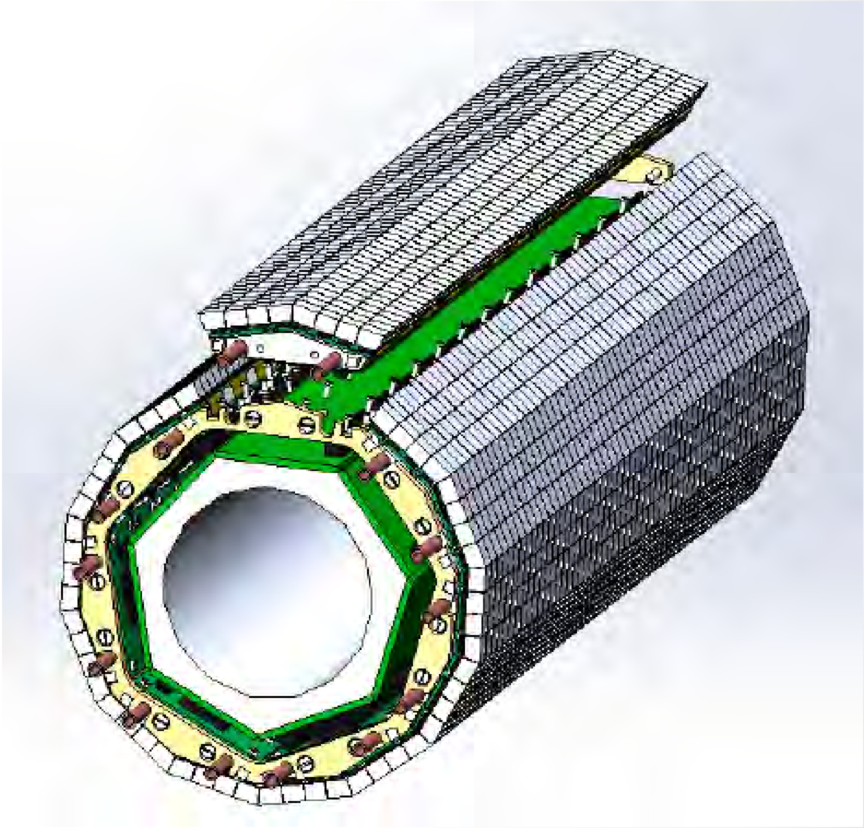
Tile Detector

Recurl station:

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

Full detector phase I

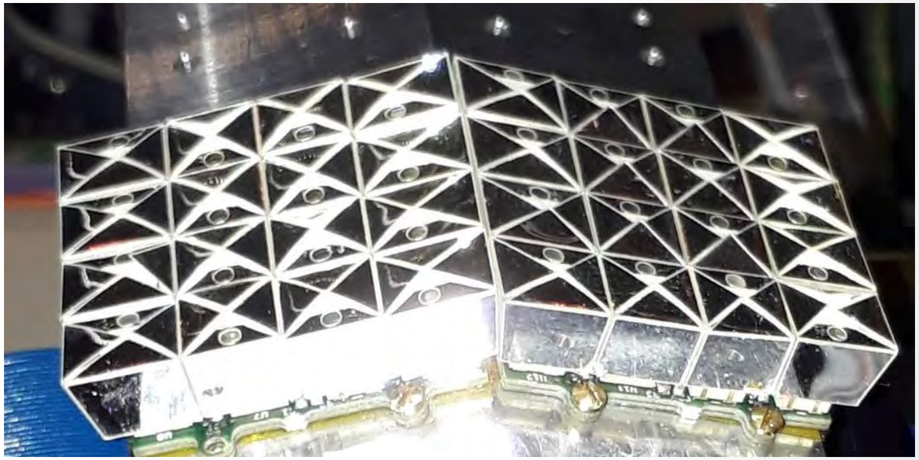
- 2 recurl stations –
- total of 6272 channels



Old Rendering of Tile Detector station

Tile Prototype

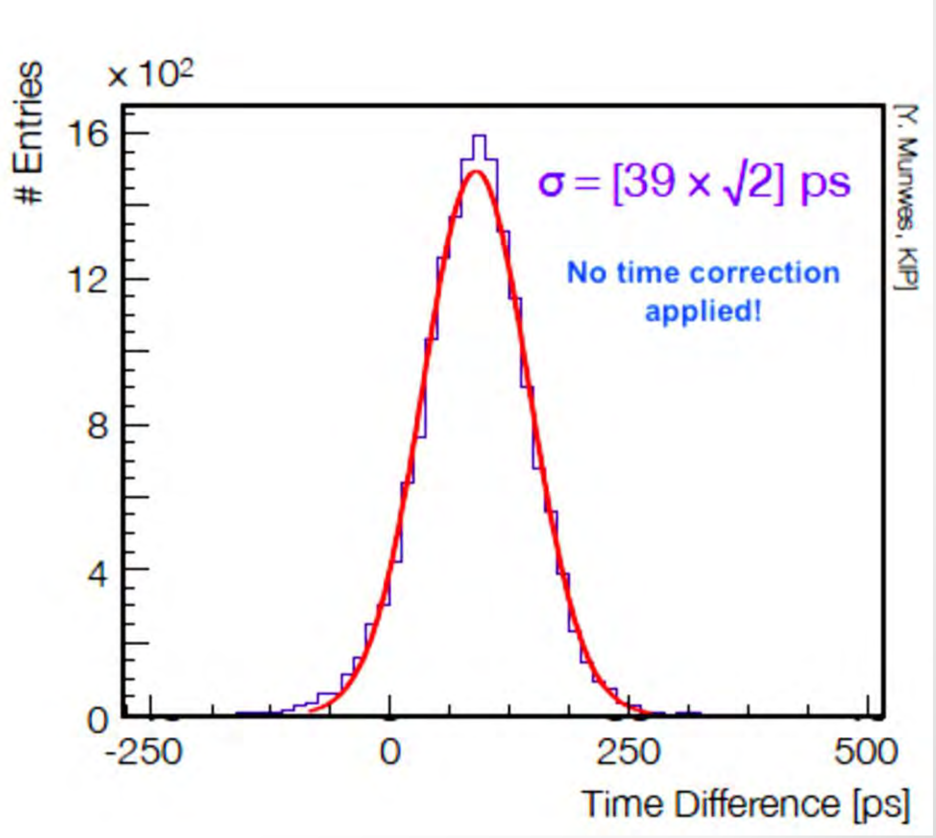
- Technical prototype build this year
- Develop assembly tools for mass production
- Tested with electron beam @ DESY (2-7 GeV)
- Excellent light yield
- Low crosstalk

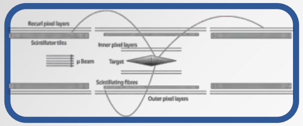


Tile sub-module prototype

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

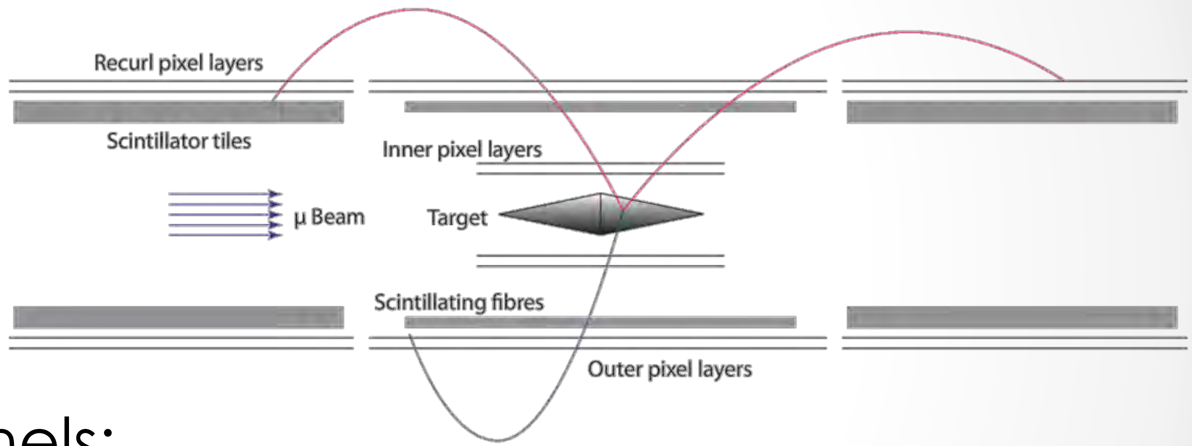




Pixel Tracker

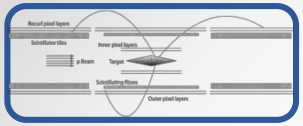
Silicon pixel tracker:

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



Mu3e detector scheme

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

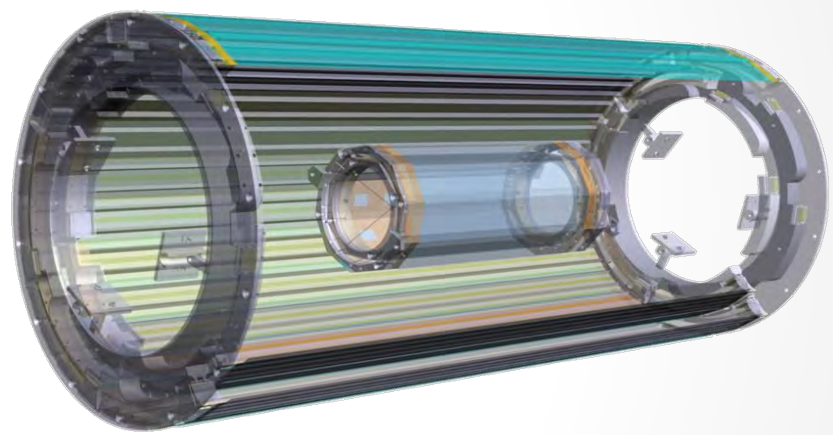


Pixel Tracker

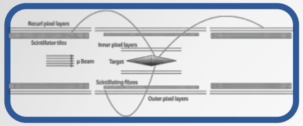
Single layer structure:

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

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

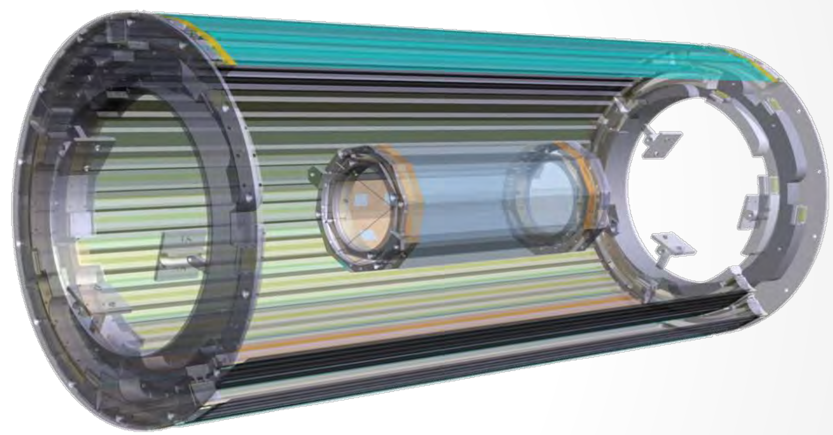


Pixel Tracker
Rendering of old CAD study



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



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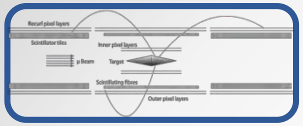
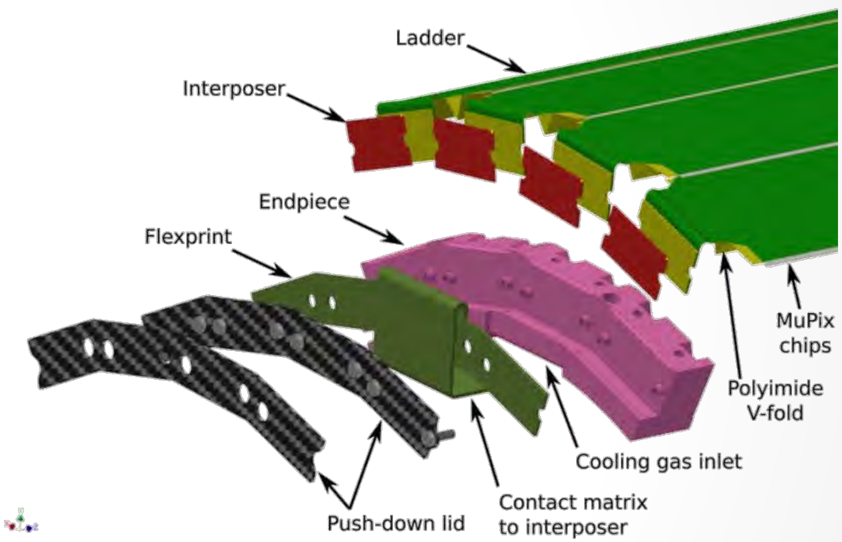
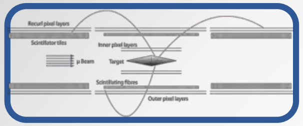


Pixel Tracker

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



Pixel Tracker
Details of CAD



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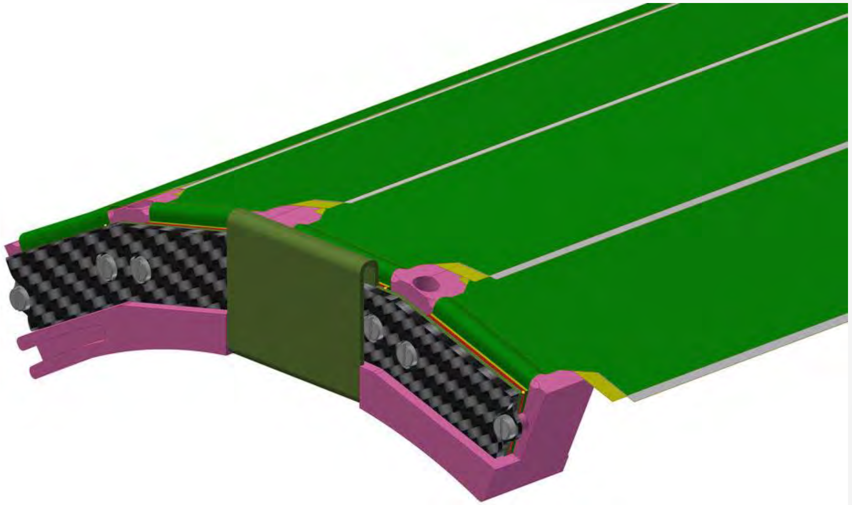

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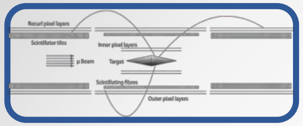

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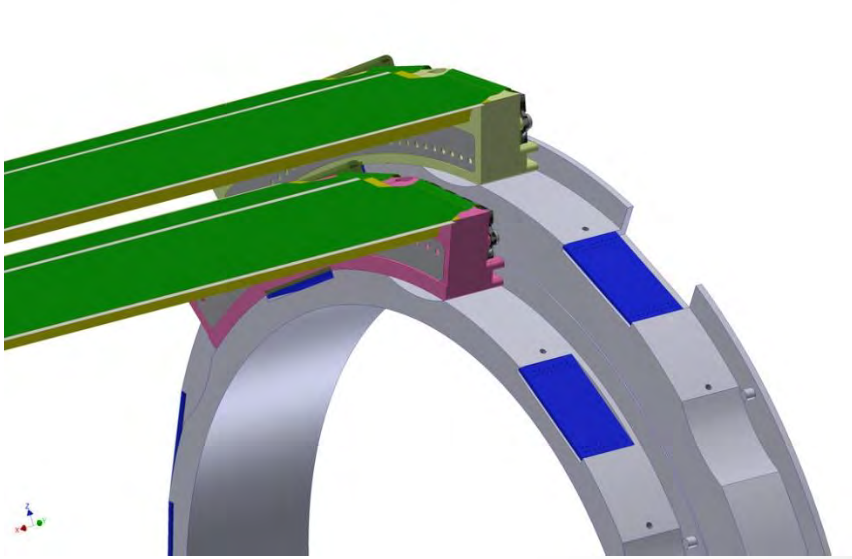

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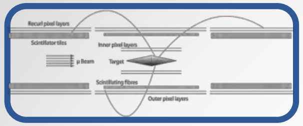

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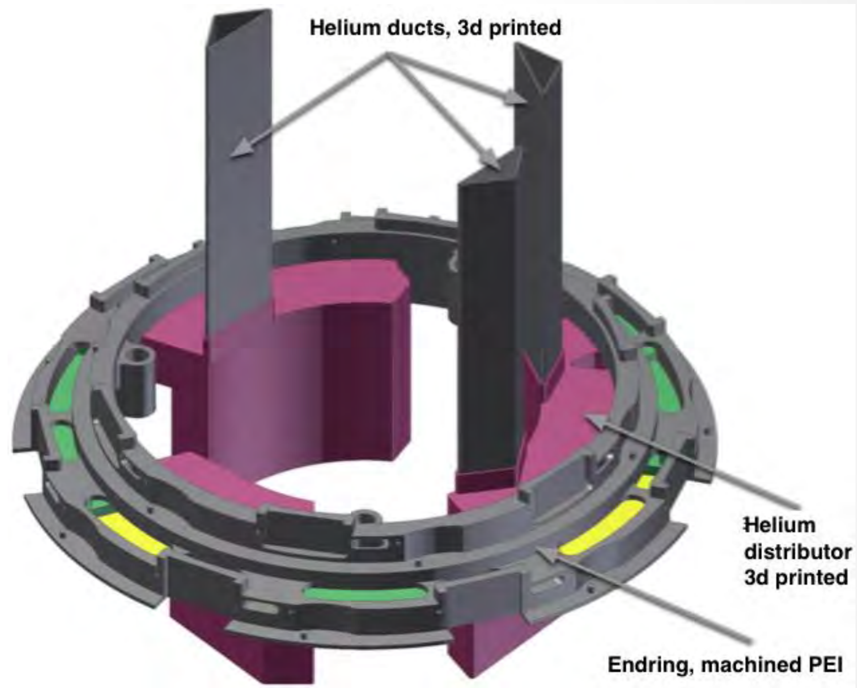

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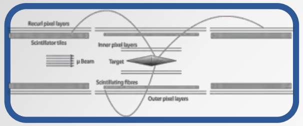
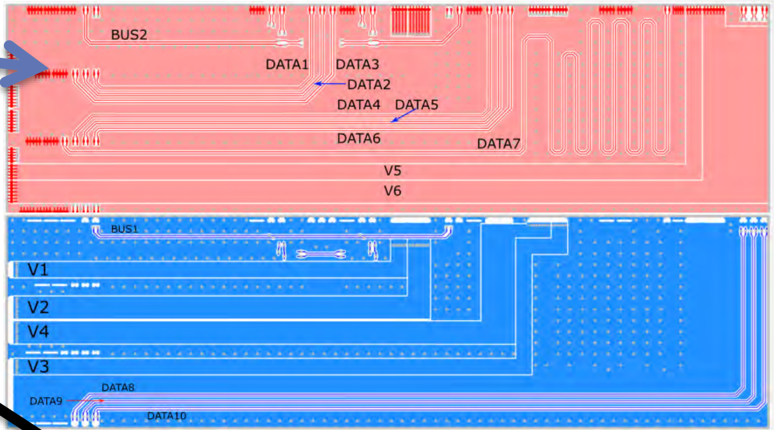
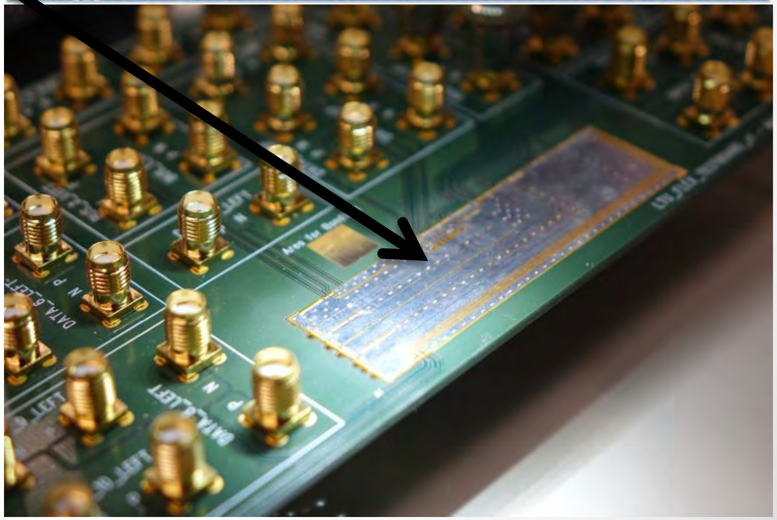
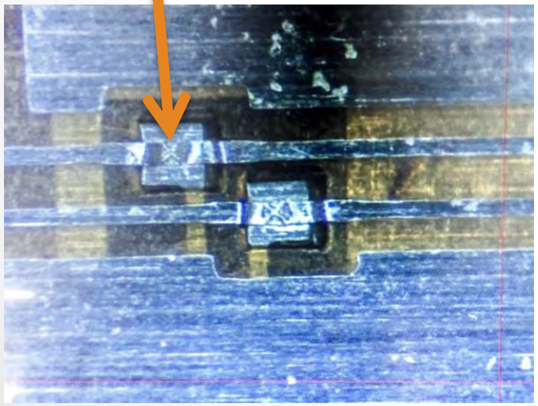


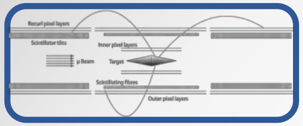
Ultra-thin HDI

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









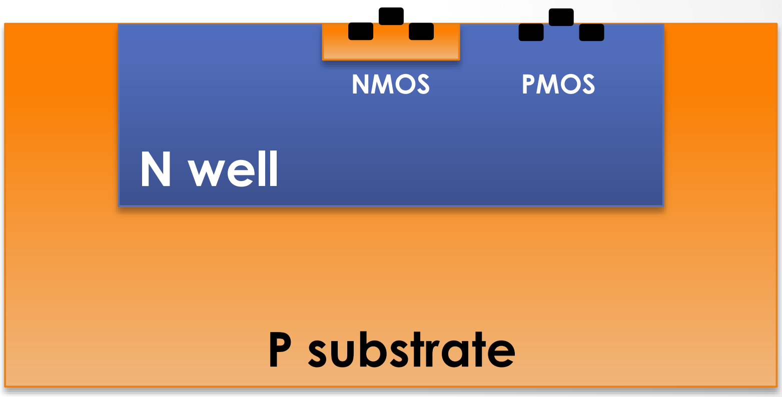
Ultra-thin HDI

- Two layer HDI test design

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

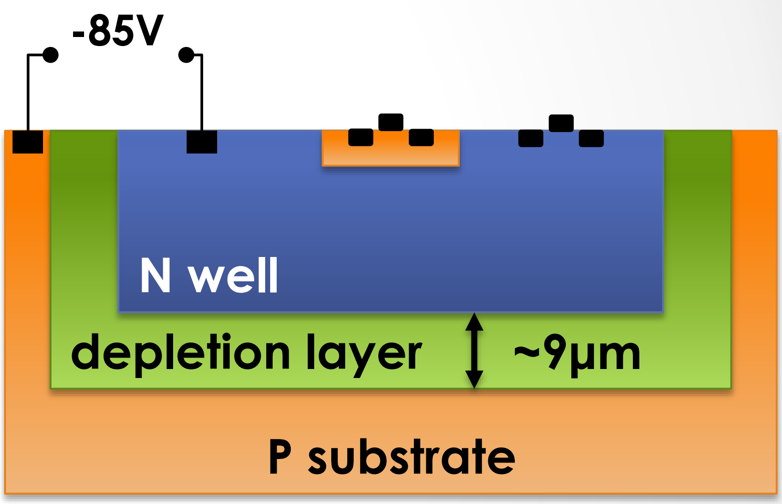


by Ivan Perić

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
  - o Depletion layer
  - o Charge collection via drift
  - ➢ Fast <1 ns charge collection
  - o Thinning to 50 μm possible
- Integrated readout electronics



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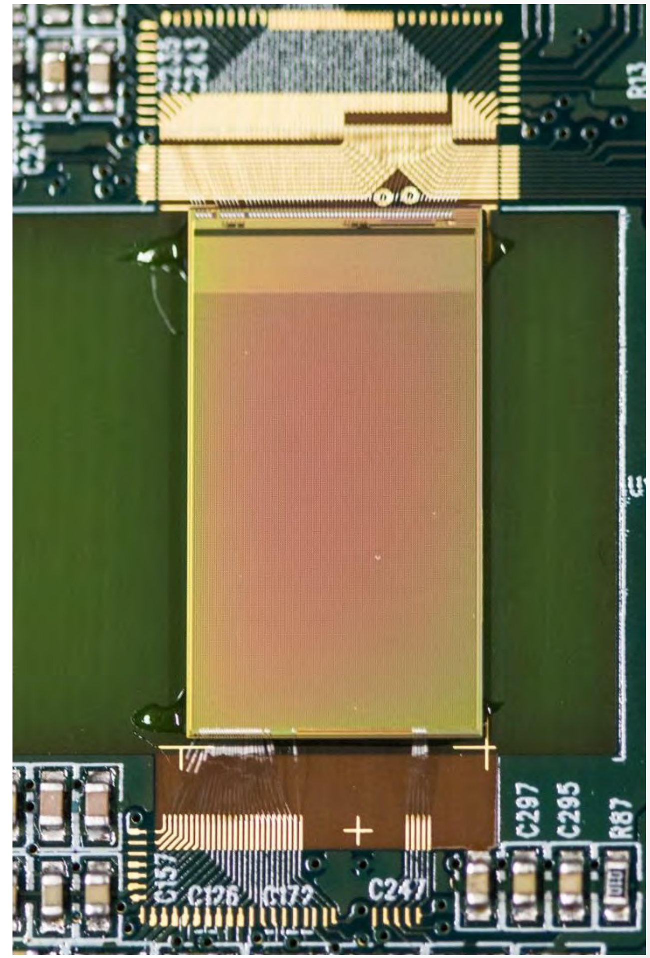
Full System on Chip

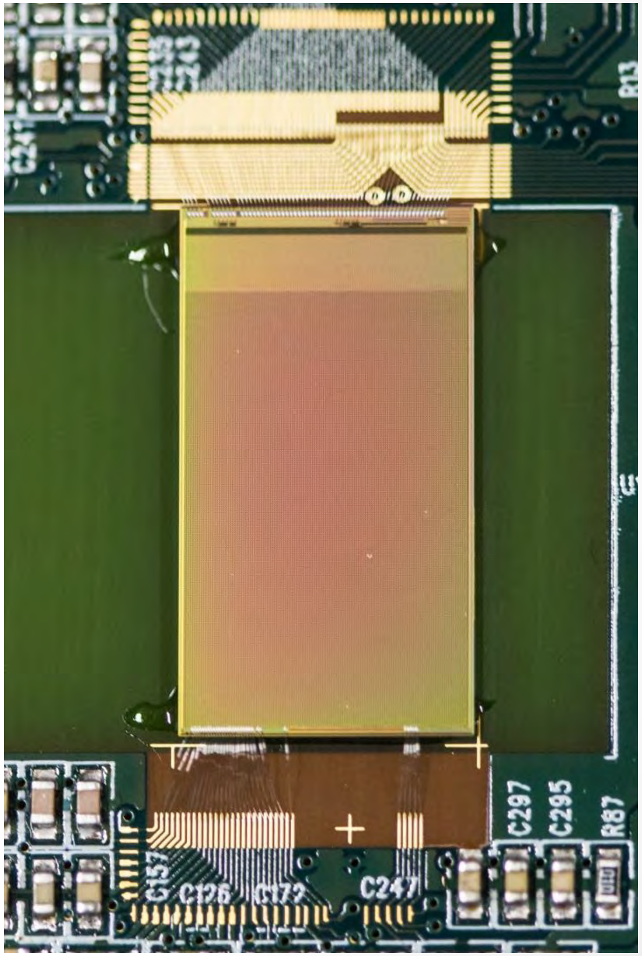
- 180 nm HV-CMOS
- Pixel matrix:
  - 128 x 200 pixels
  - 81 x 80 μm^2 each
- Analog part
  - Pixel sensor
  - Pre-amplifier
- Digital part
  - Comparator
  - Read out state machine
  - 1.25 Gbit/s serial data outputs
- Low power:
  - ~210mW/ cm^2



MuPix8

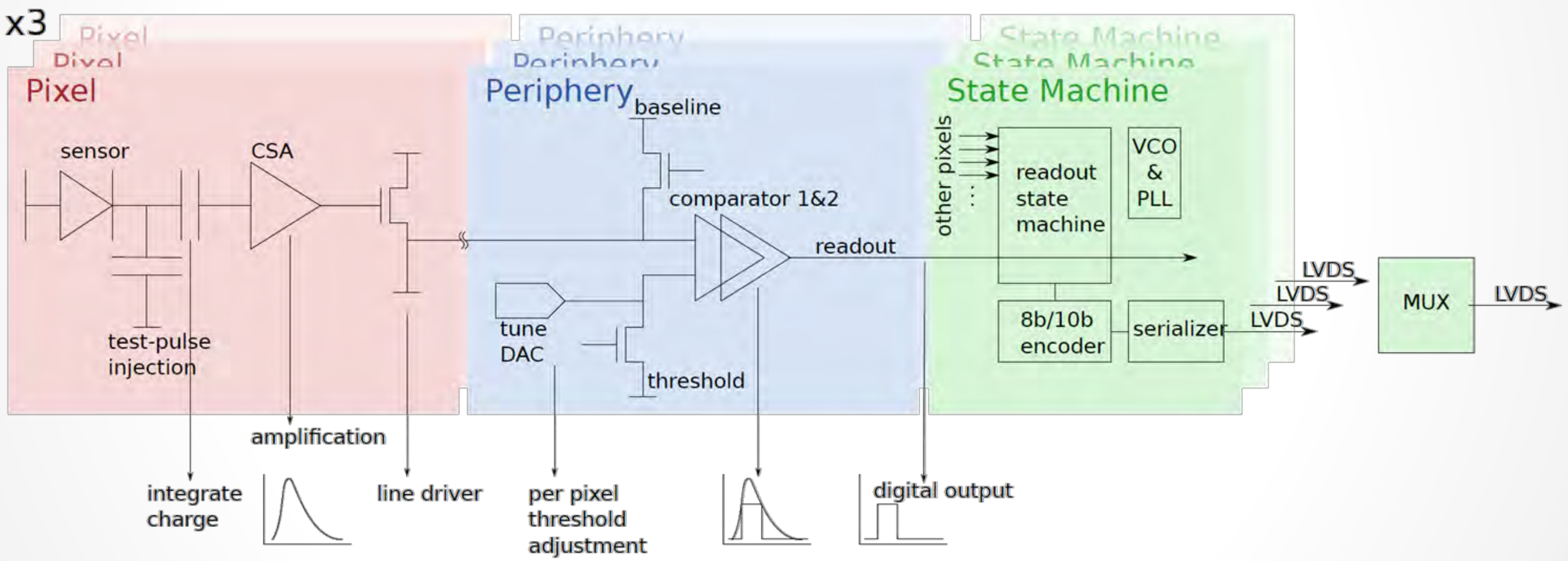
Full System on Chip

- 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:
  - ~200mW/ cm^2



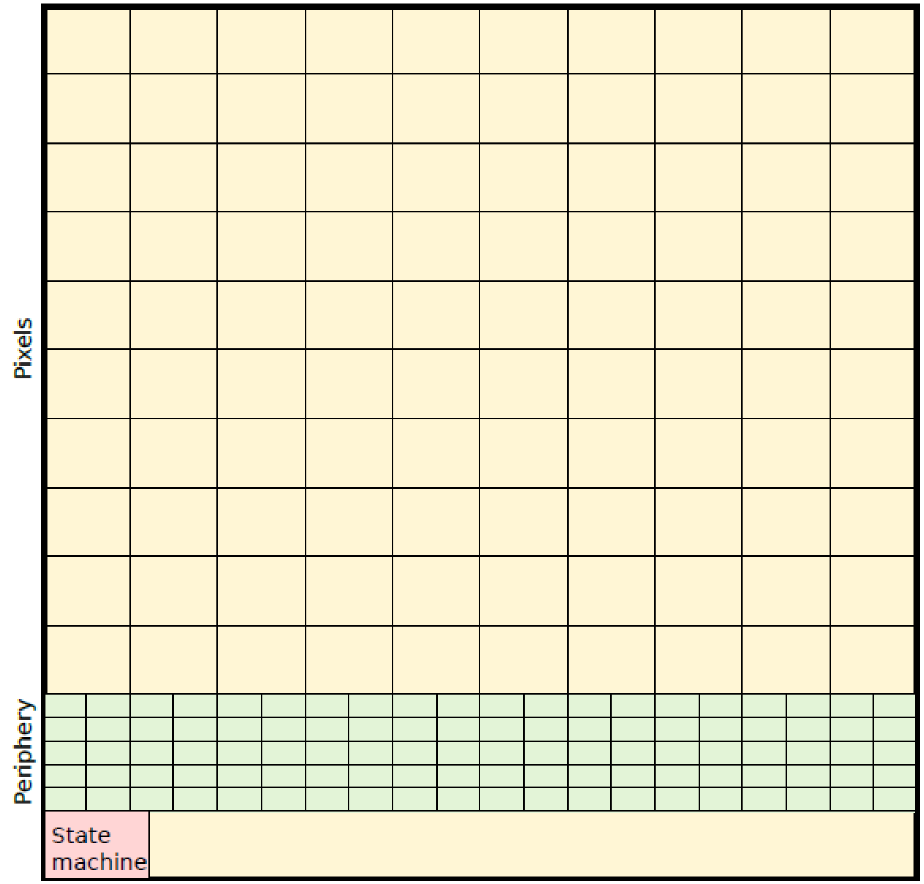
MuPix8

Sensor + Analog + Digital

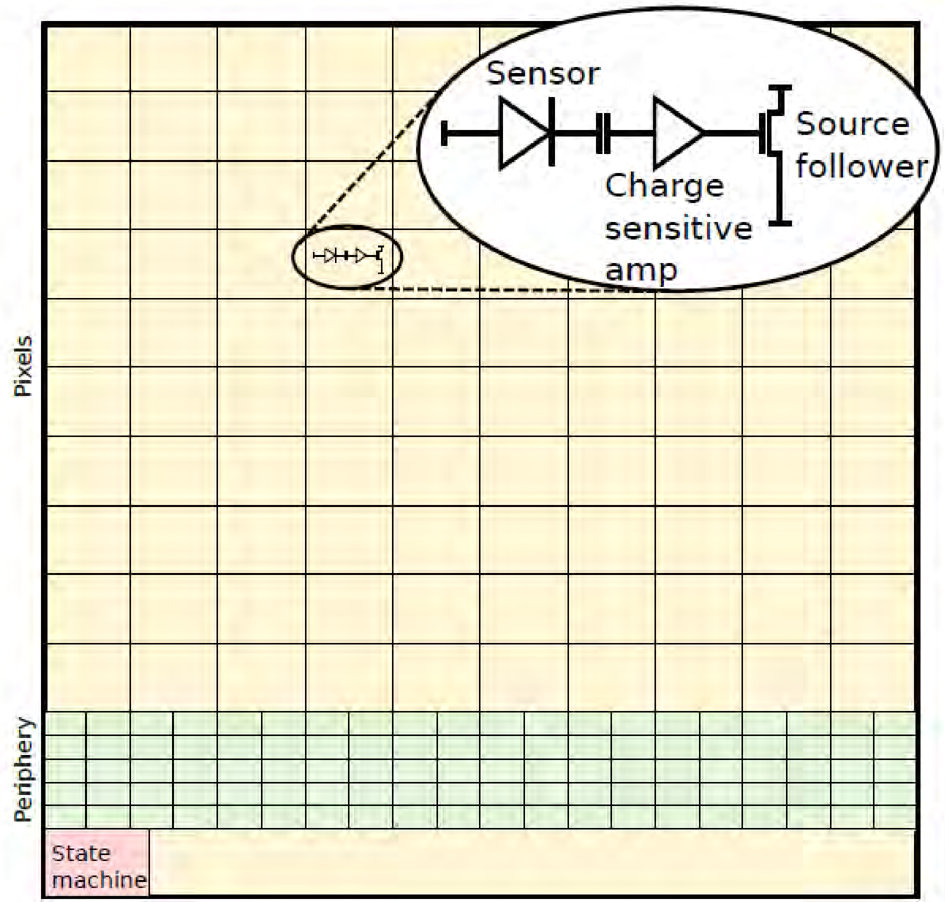


MuPix8 block diagram

MuPix Readout



MuPix Readout



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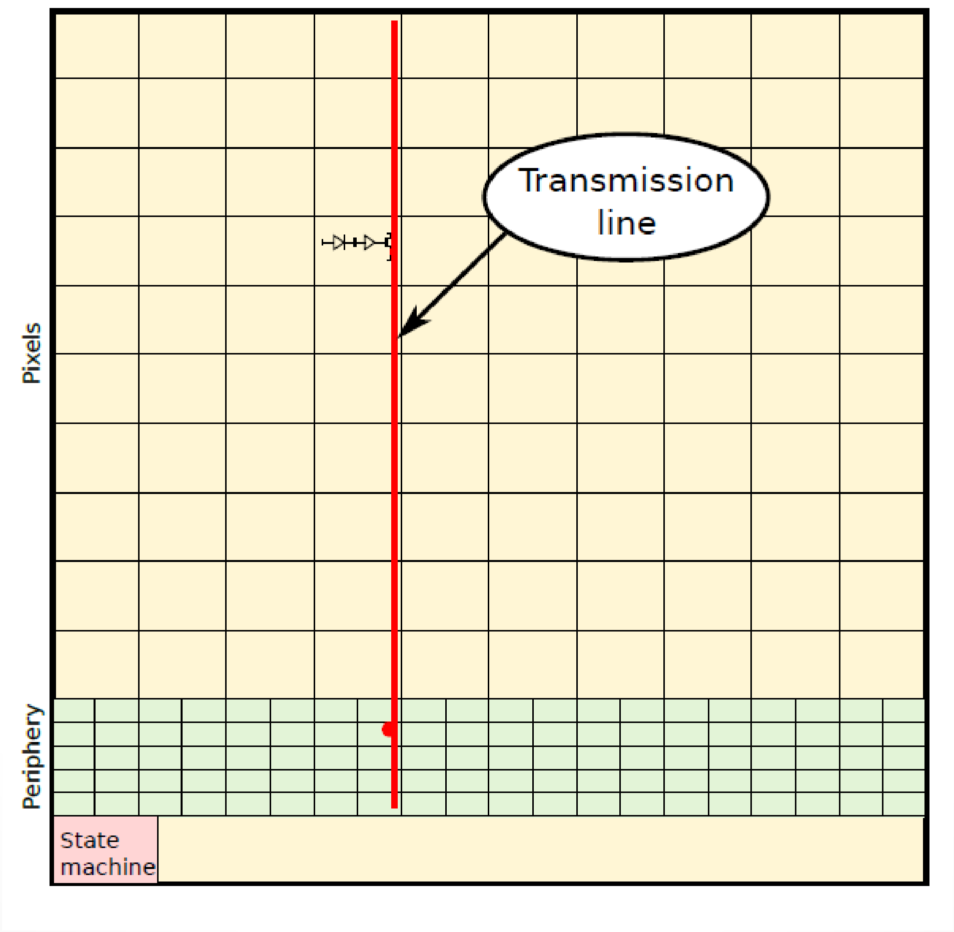

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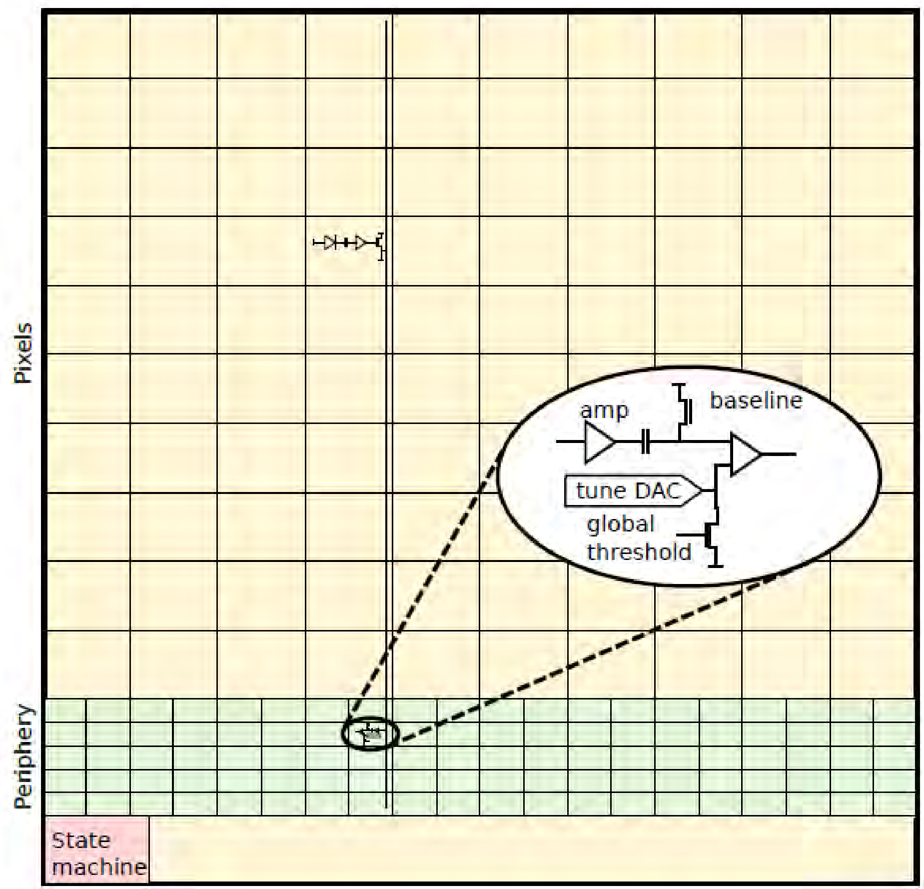

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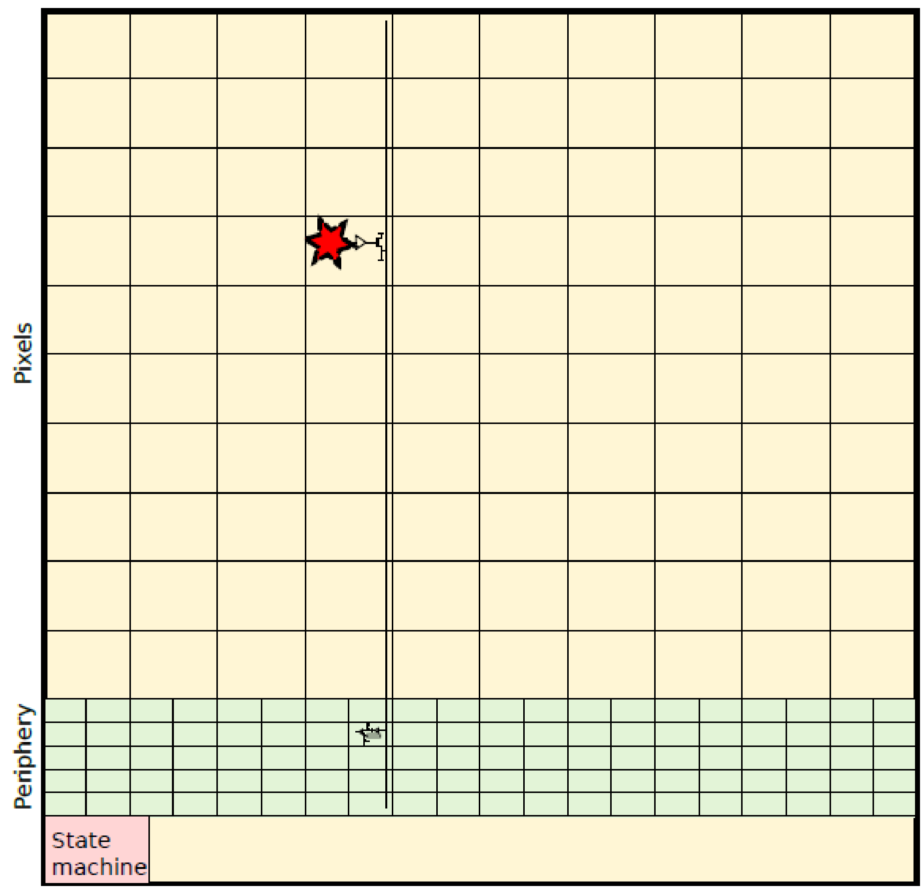
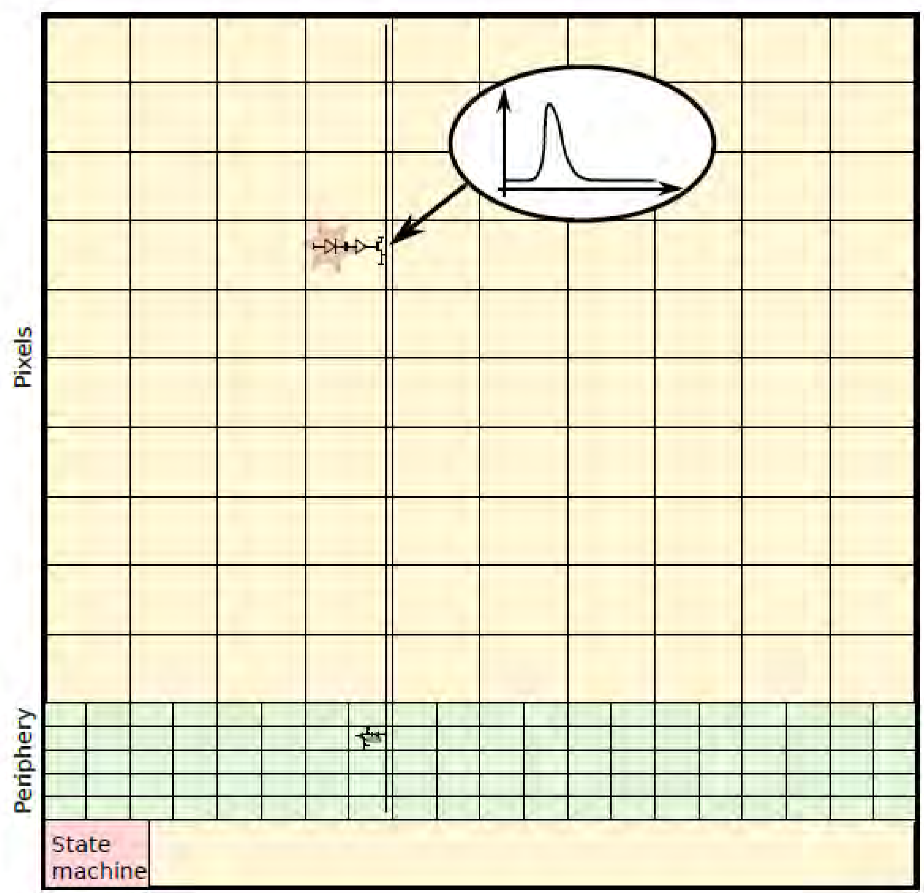
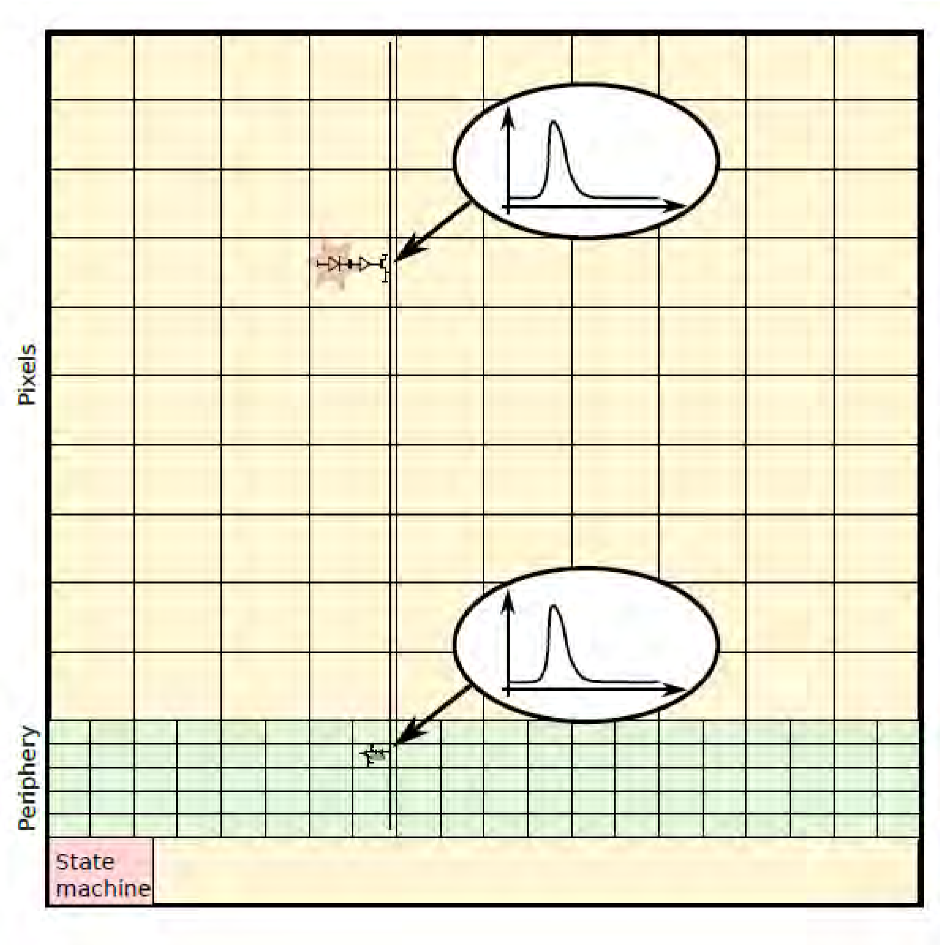


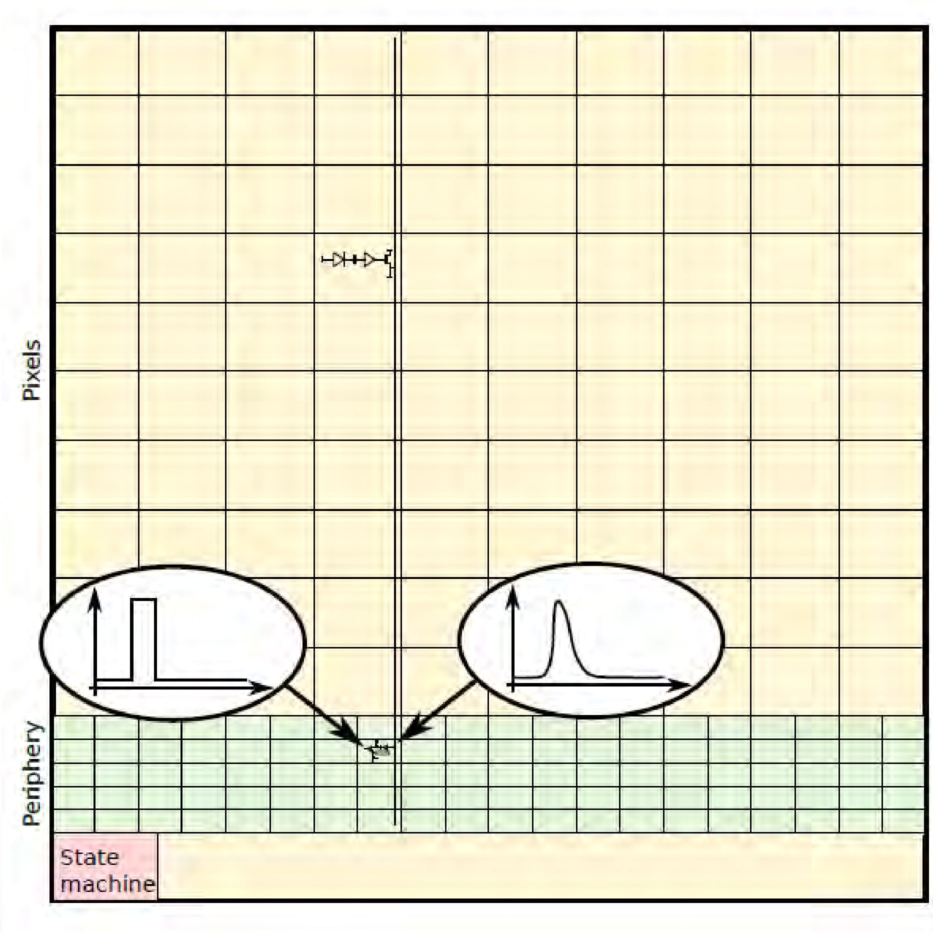
MuPix Readout



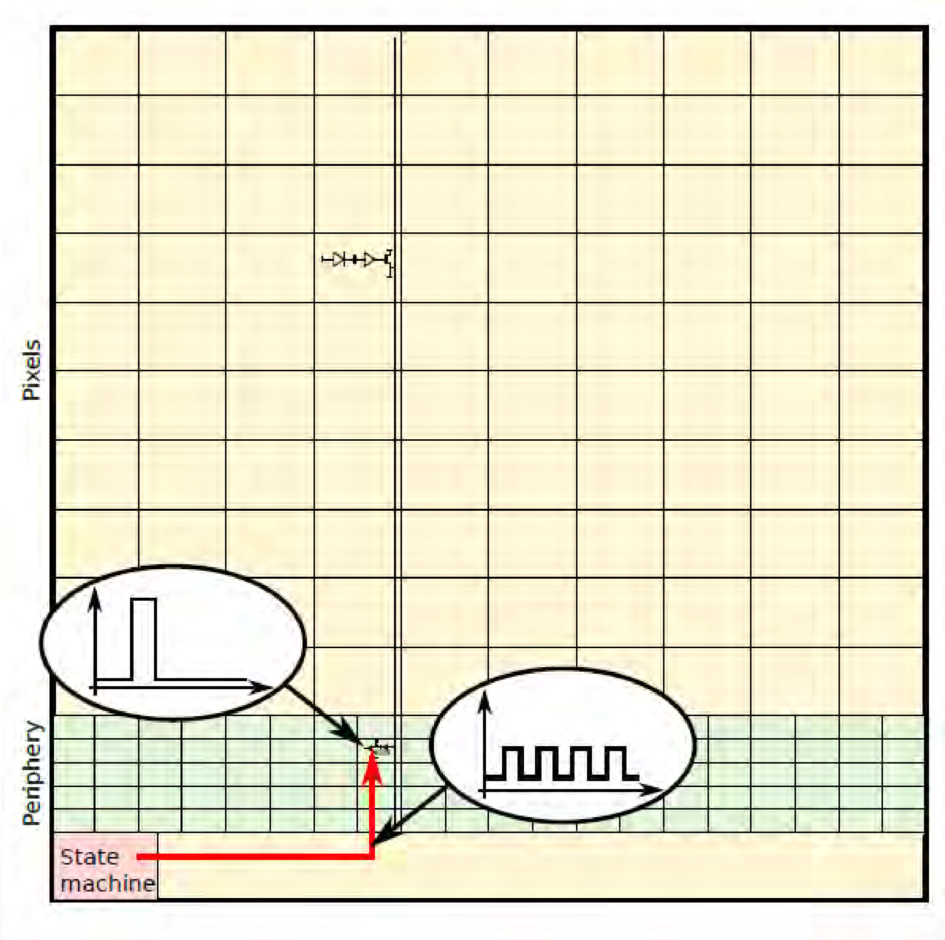
MuPix Readout



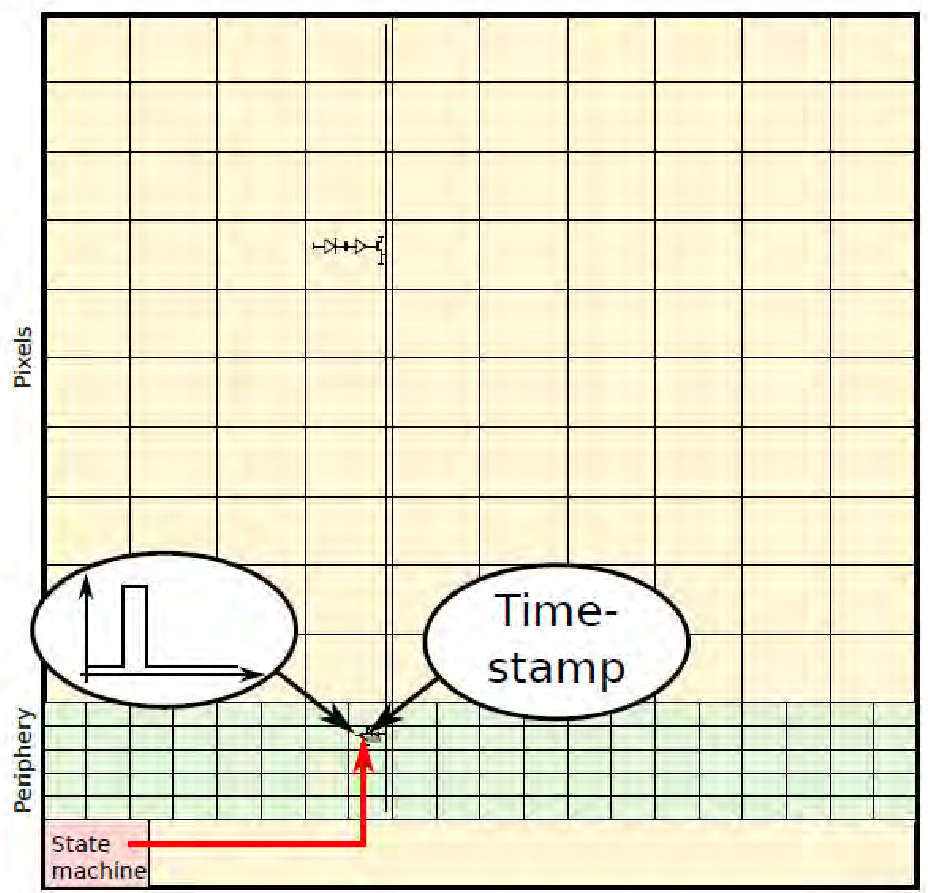
MuPix Readout



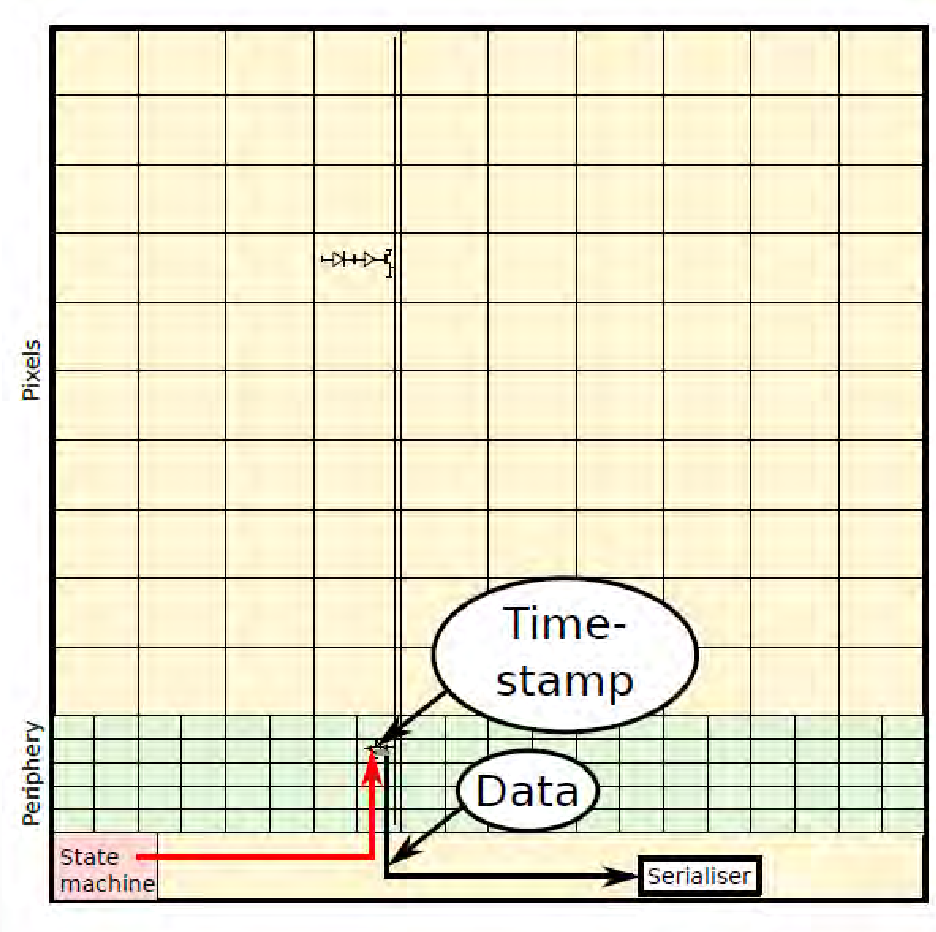
MuPix Readout



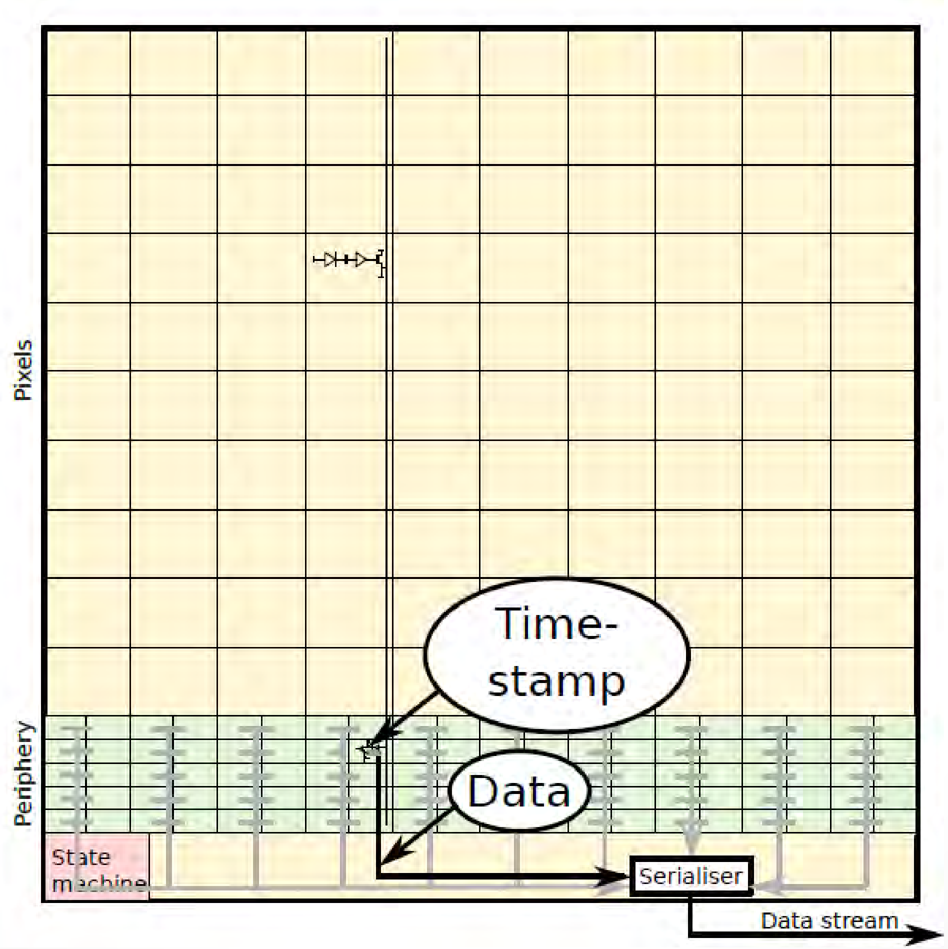
MuPix Readout



MuPix Readout



MuPix Readout

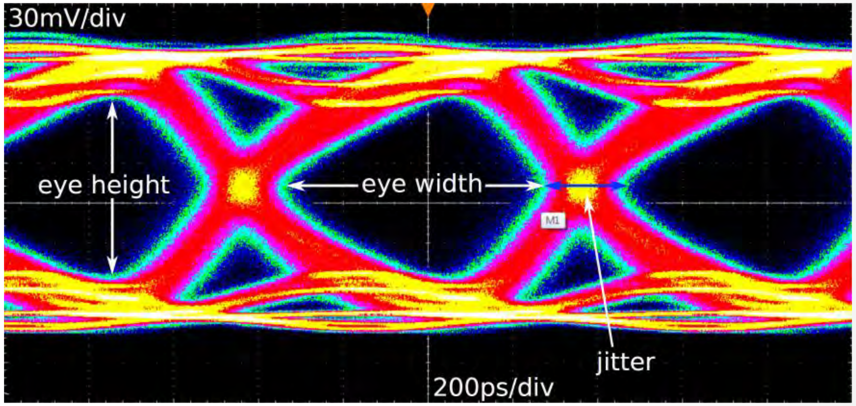


MuPix8 Readout

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

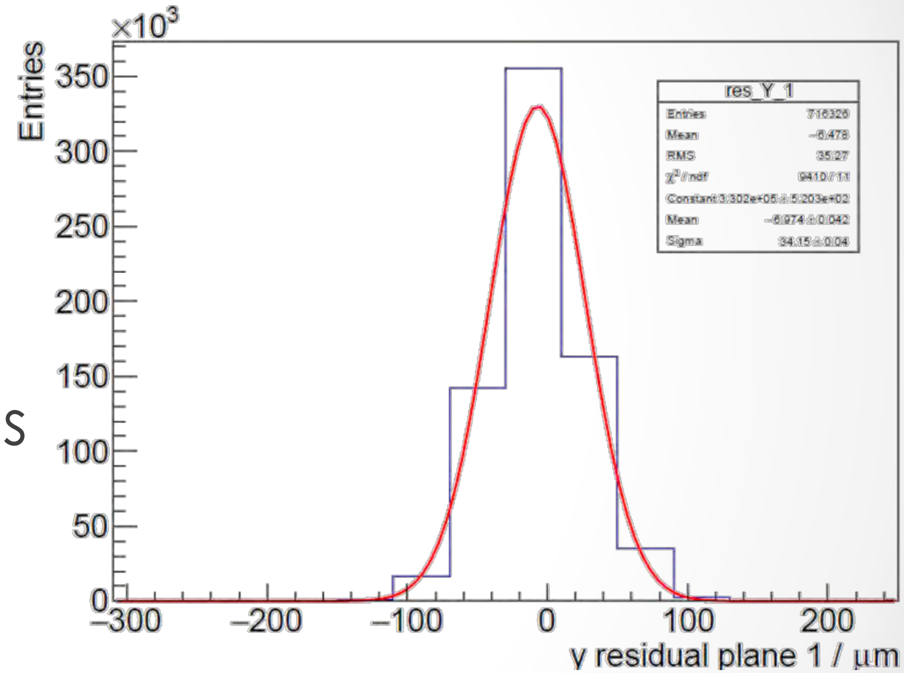
- DESY test beam
  - 4 GeV electrons
- MuPix8 telescope
  - Beam telescope
  - 4 layers of MuPix8 pixel sensors
  - Includes DUT
  - Plastic scintillators as time reference

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

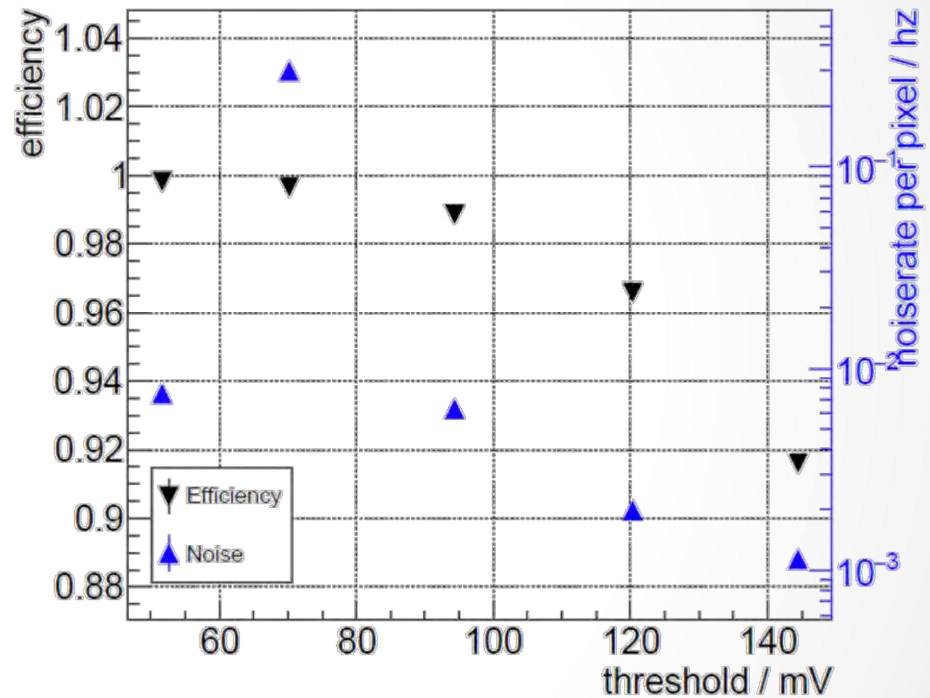
➢ In Mu3e spatial resolution is dominated by multiple Coulomb scattering



MuPix8 spatial resolution

Efficiencies

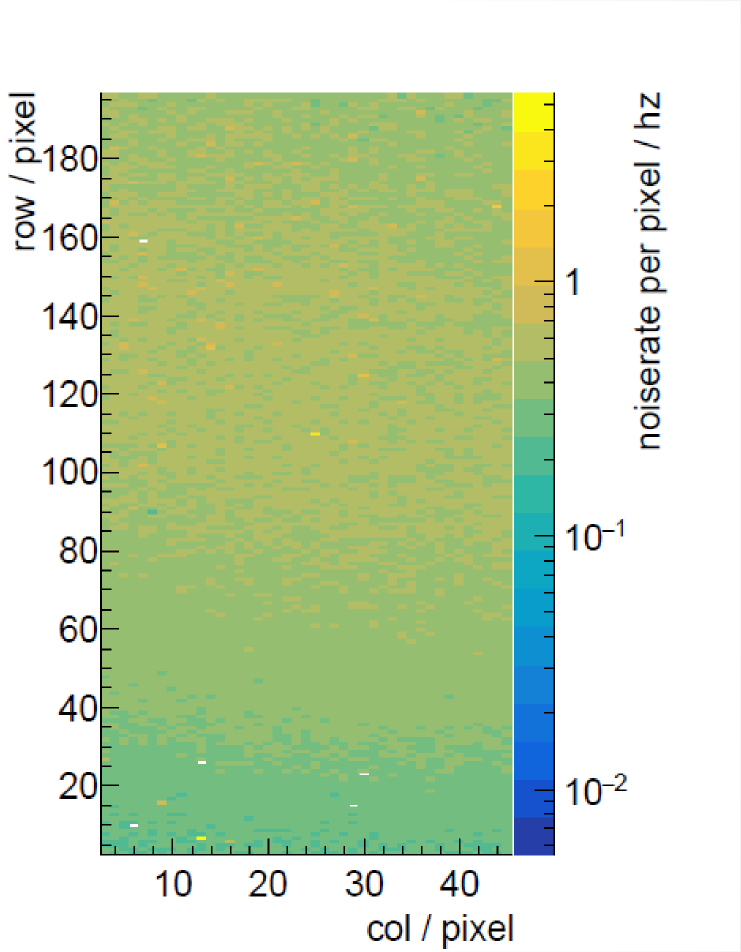
- **>99.5% efficiency**
  - 4 GeV electrons @ DESY
  - 90° impact angle
- Low pixel noise
  - Rate per pixel ~0.2Hz



MuPix8 Efficiency

and Noise

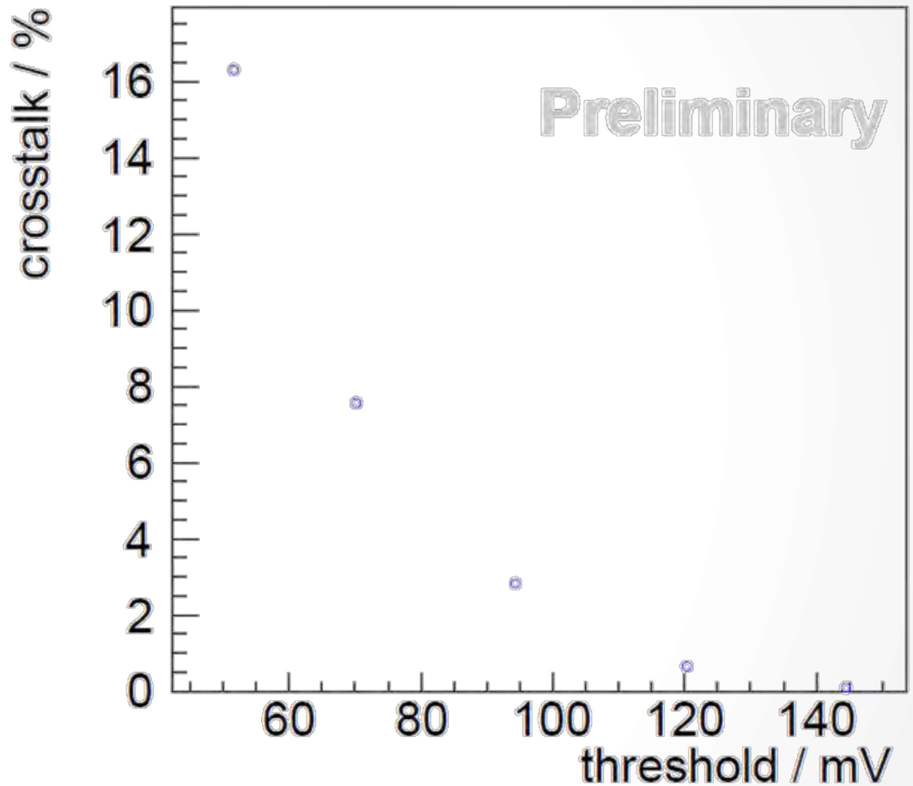
- >99.5% efficiency
  - 4 GeV electrons @ DESY
  - 90° impact angle
- **Low pixel noise**
  - Rate per pixel ~0.2Hz
  - Hot pixels masked



Noise map MuPix8

X-talk

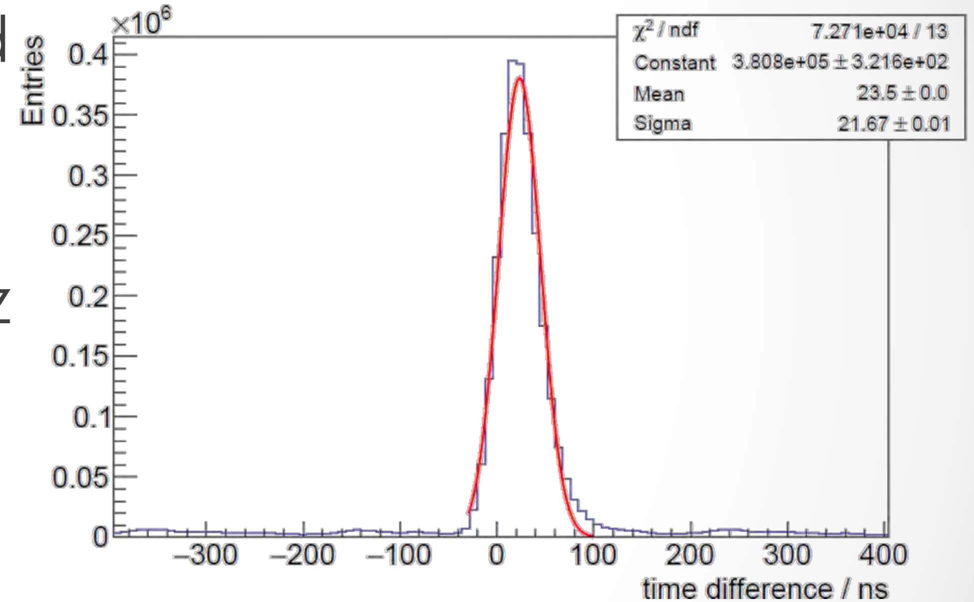
- MuPix8
- DESY November 2017
  - 4 GeV electrons@DESY
- X-talk between
  - **Rows**
  - ≤ 10% around working point



MuPix8 x-talk

Time Resolution

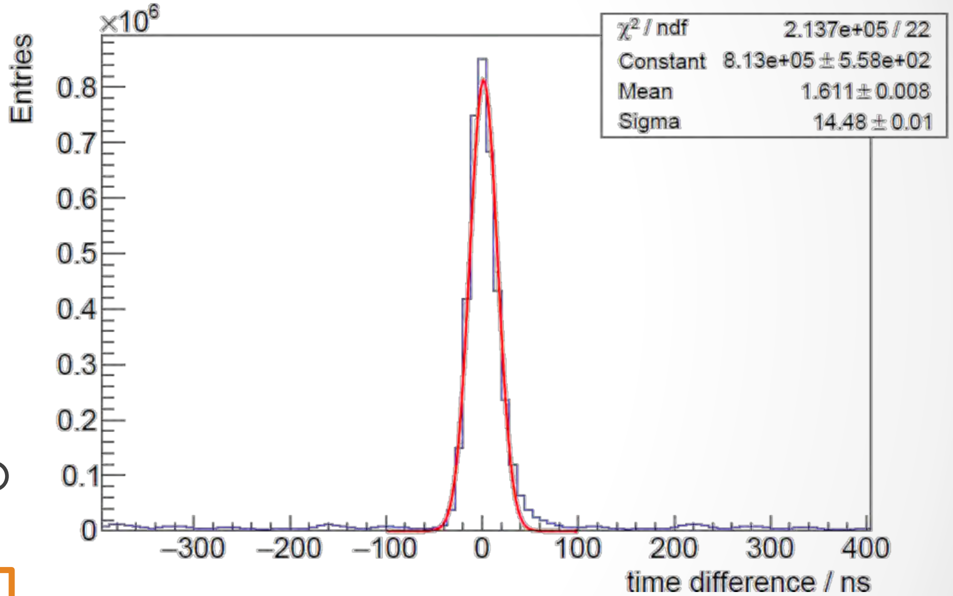
- Time difference of hits registered in MuPix8 and scintillator
- 4 GeV electrons
- Sampling rate is 125 MHz
- $\sigma = 21.67 \pm 0.01$ ns



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

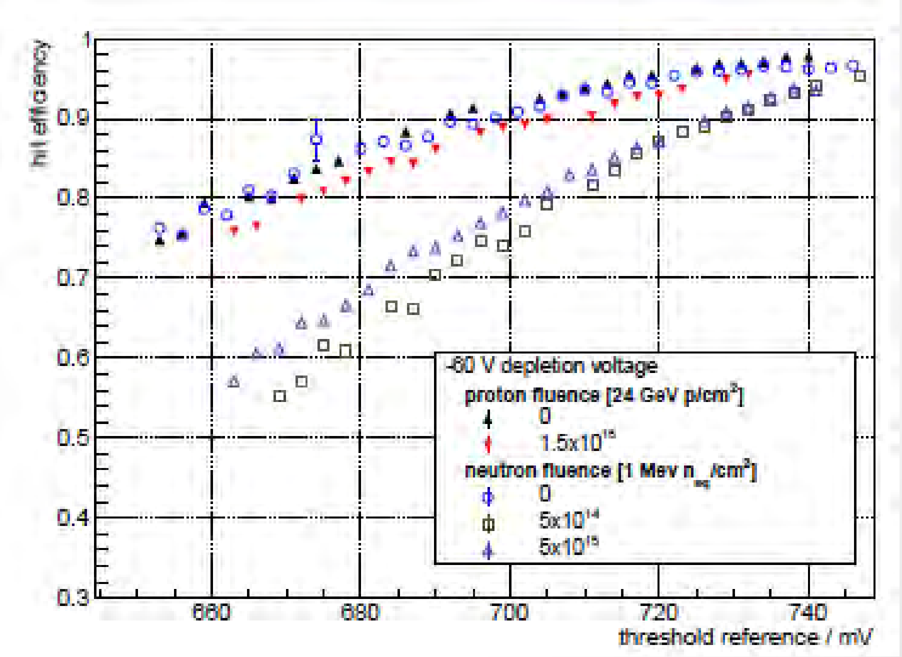


MuPix8 time resolution pixel delay corrected

Recent laboratory studies show much **improved time resolution** for optimized bias current settings

Irradiation Studies

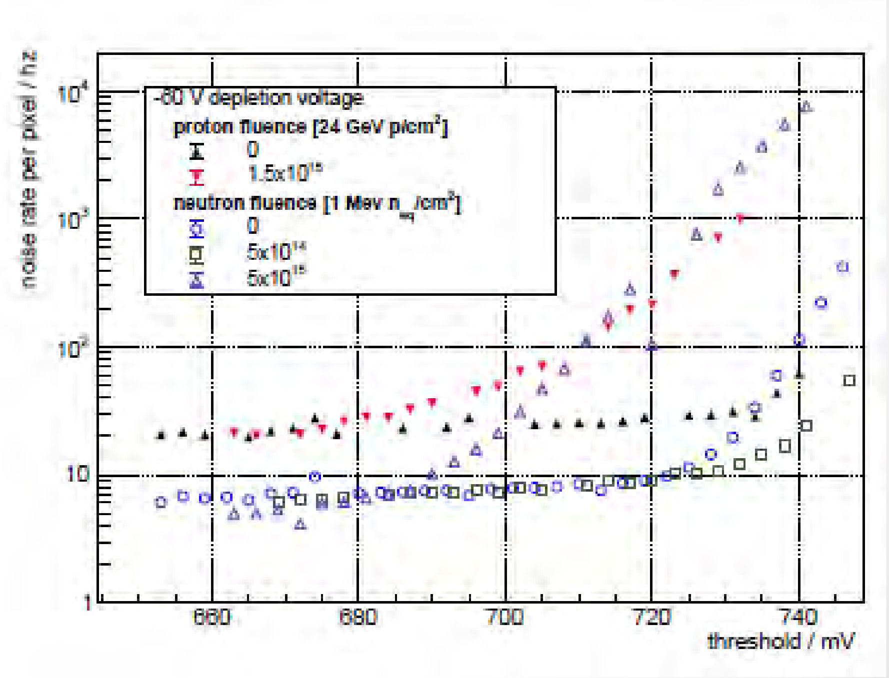
- Irradiation with neutrons and protons
- **MuPix7** irradiated with:
  - o neutrons up to
    - $5.0 \times 10^{15}\ n_{eq}/cm^2$
  - o 24 GeV protons up to
    - $7.8\ \ 10^{15}$ protons/cm^2
- Efficiencies of >90%
- Time resolution < 22ns
- Data transmission at 1.25Gbit/s



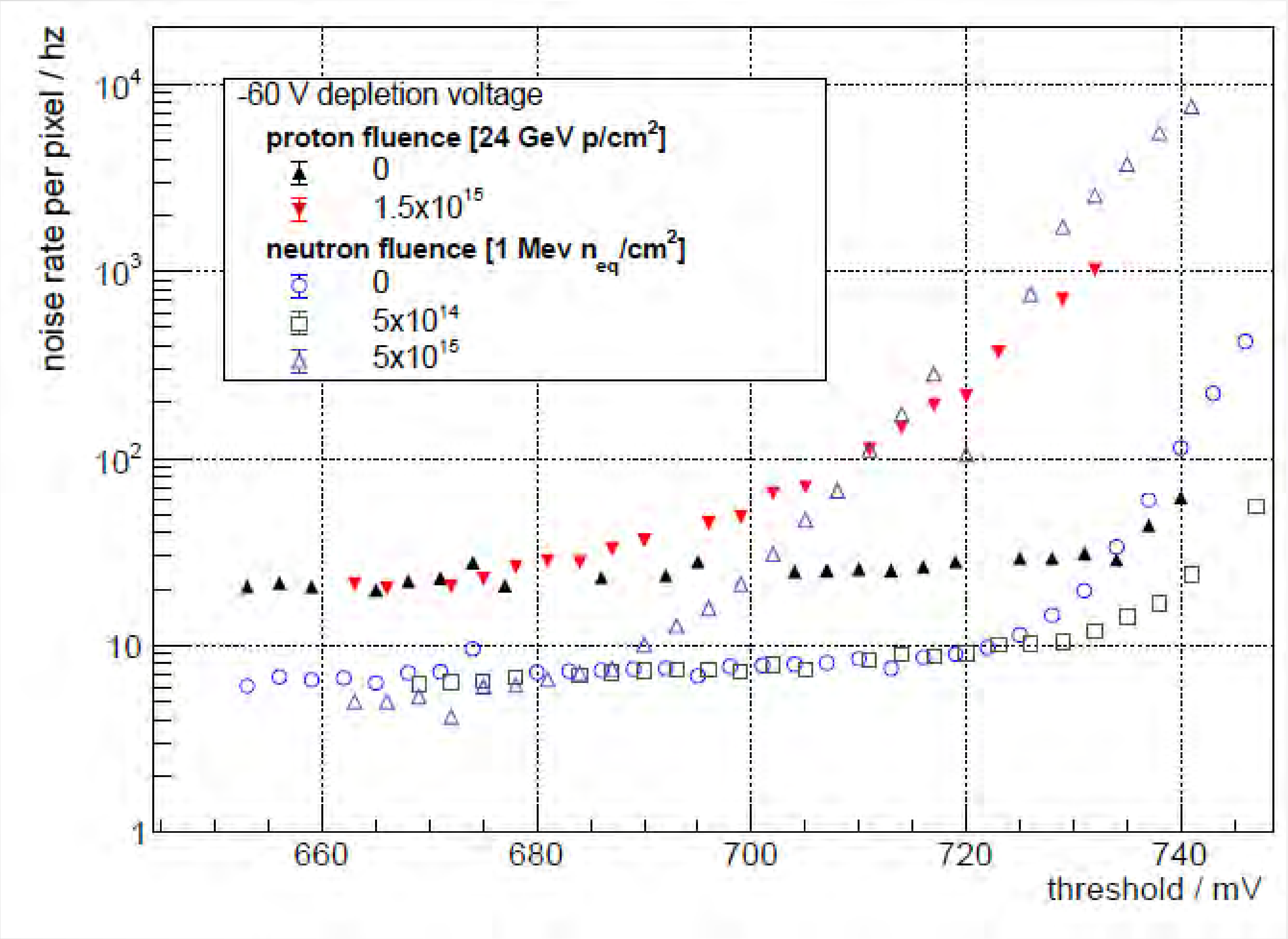
Efficiencies after neutron irradiation

Irradiation Studies

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

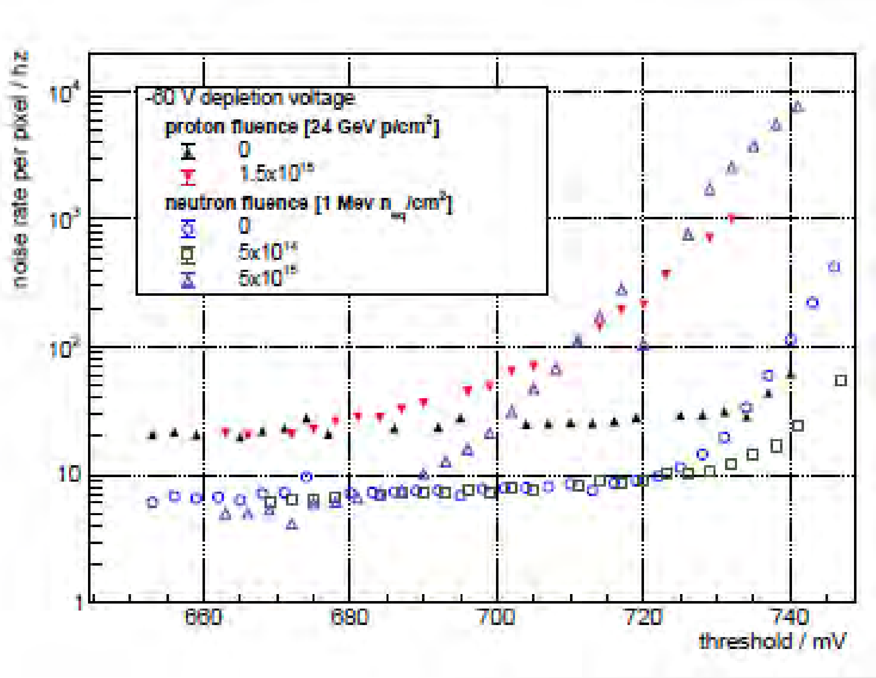


Noise increase with irradiation


-60 V depletion voltage
proton fluence [24 GeV p/cm²]
0
1.5x10¹⁵
neutron fluence [1 Mev n_eq /cm²]
0
5x10¹⁴
5x10¹⁵
noise rate per pixel / hz
threshold / mV
1
10
10²
10³
10⁴
660
680
700
720
740

Irradiation Tests

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

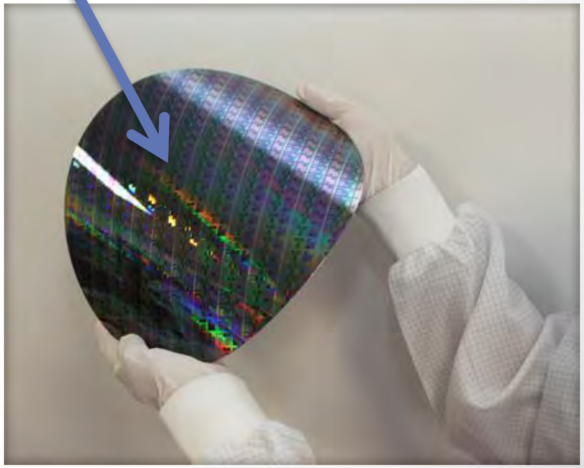


Summarized in:
H. Augustin et al.
Irradiation study of a fully monolithic HV-CMOS pixel sensor design in AMS 180 nm
https://arxiv.org/abs/1712.03921v2

Thinning

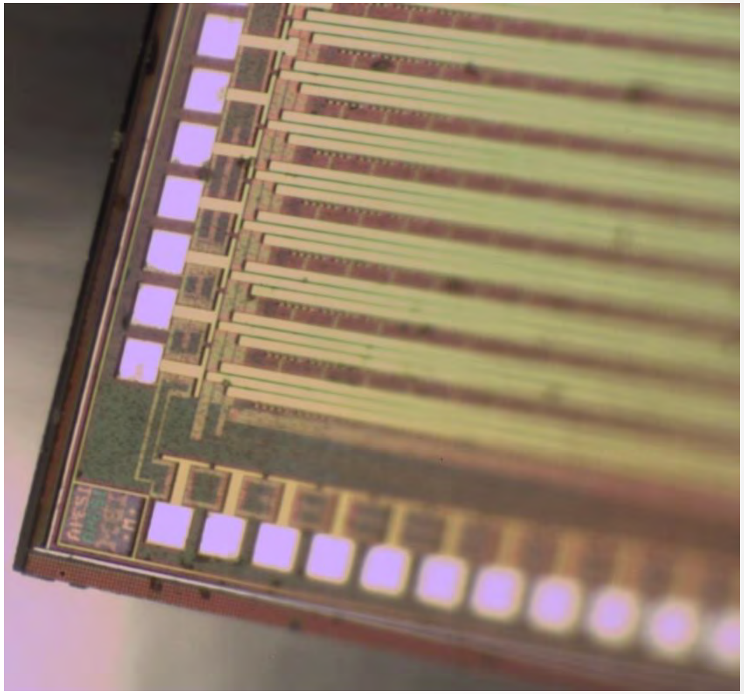
50 µm Si-wafers

- 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 62.5 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



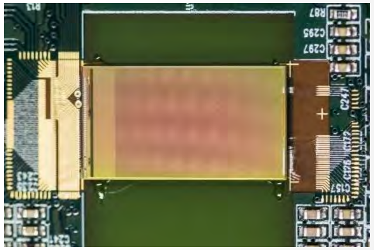
MuPix4 thinned to 50µm

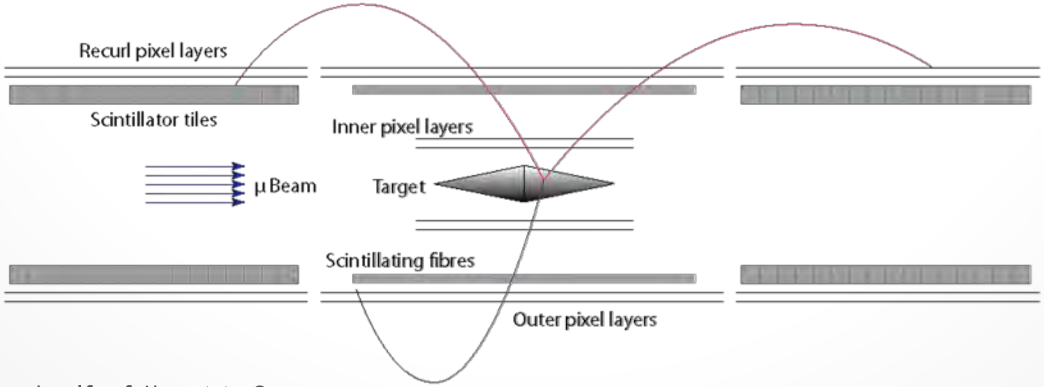
Summary

- Mu3e searches for lepton flavor violation
- Ultra thin tracker with ~178 M pixel

➢ **H**igh **V**oltage **M**onolithic **A**ctive **P**ixel **S**ensors

- Prototypes exceed requirements



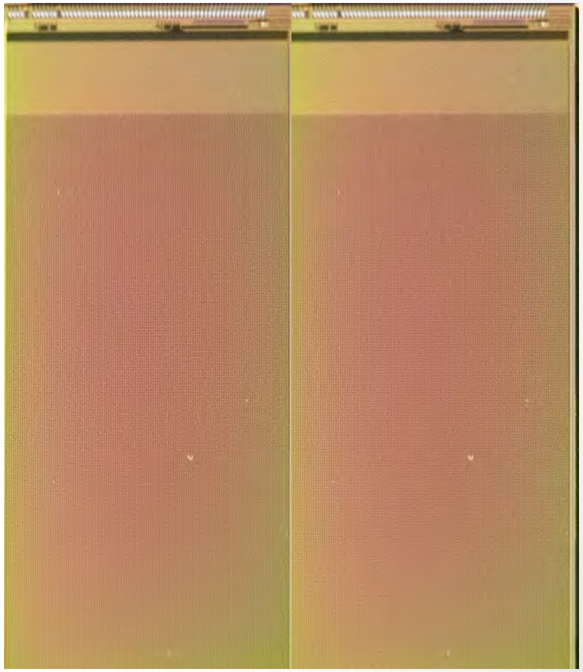


Schedule

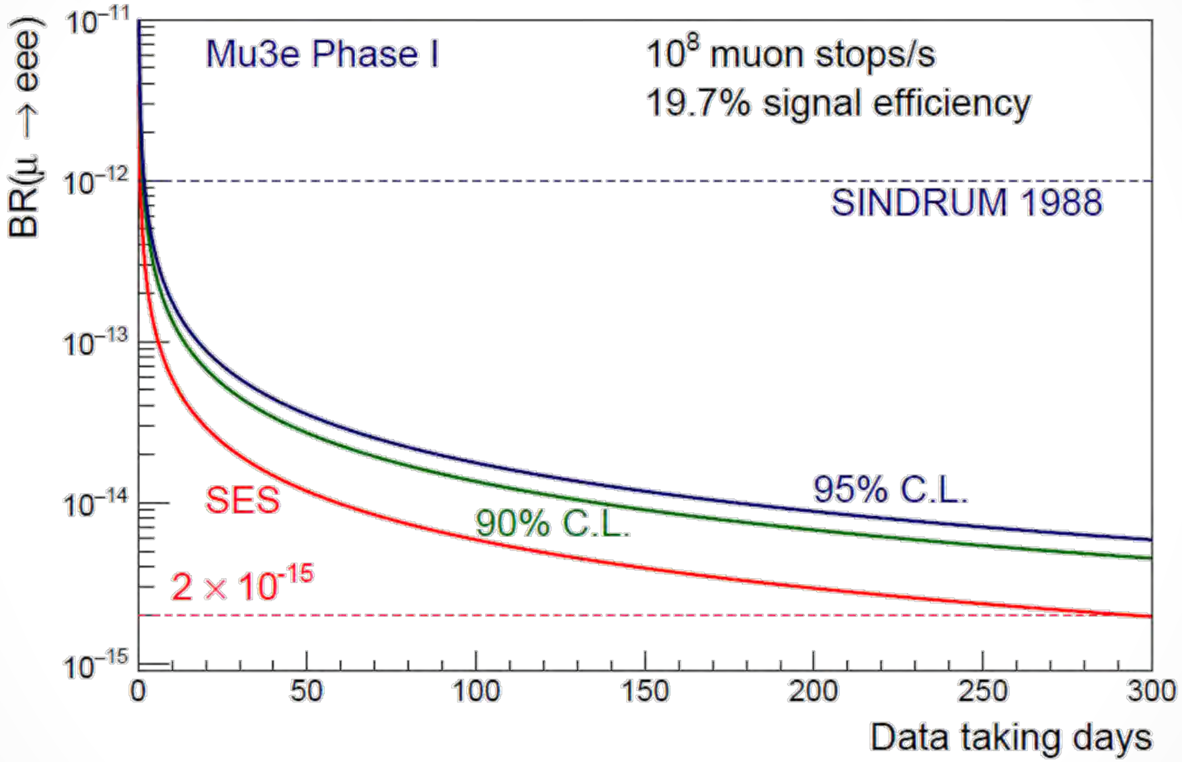
- **2018** Design of full size HV-MAPS chip
- **2019** Magnet delivery and detector **construction**
- **2020** Installation and **commissioning** at PSI
- **2021** Data taking at up to a few **10^8 μ/s**

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 time resolution?
- On chip ADC
  - o 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

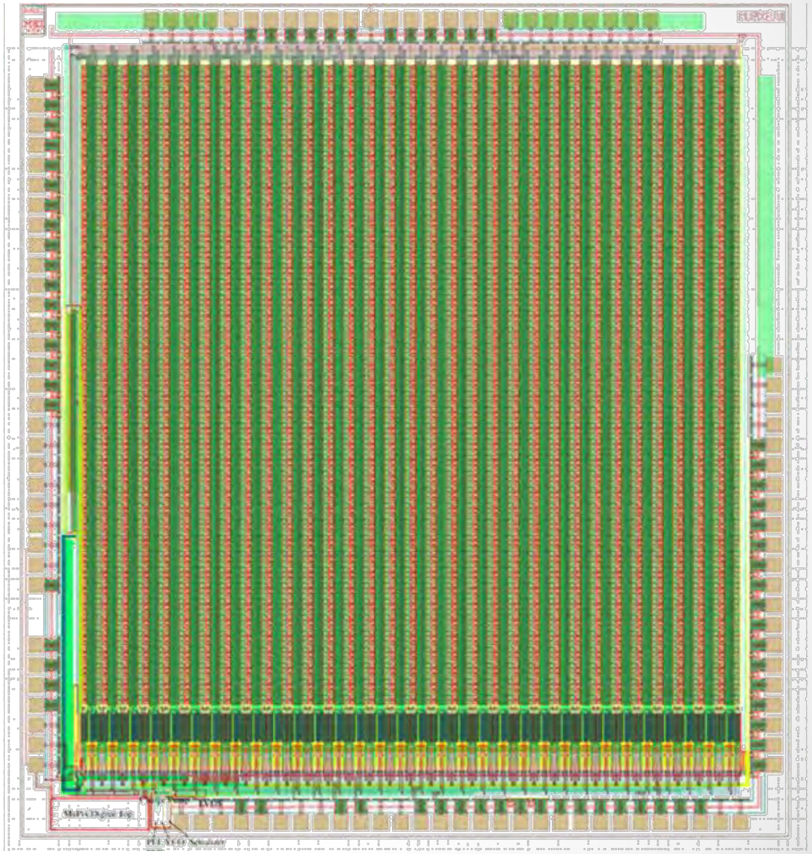
• • •

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	166 mm^2	Large S.o.C.	Bad power distribution, x-talk	Large, Time walk correction

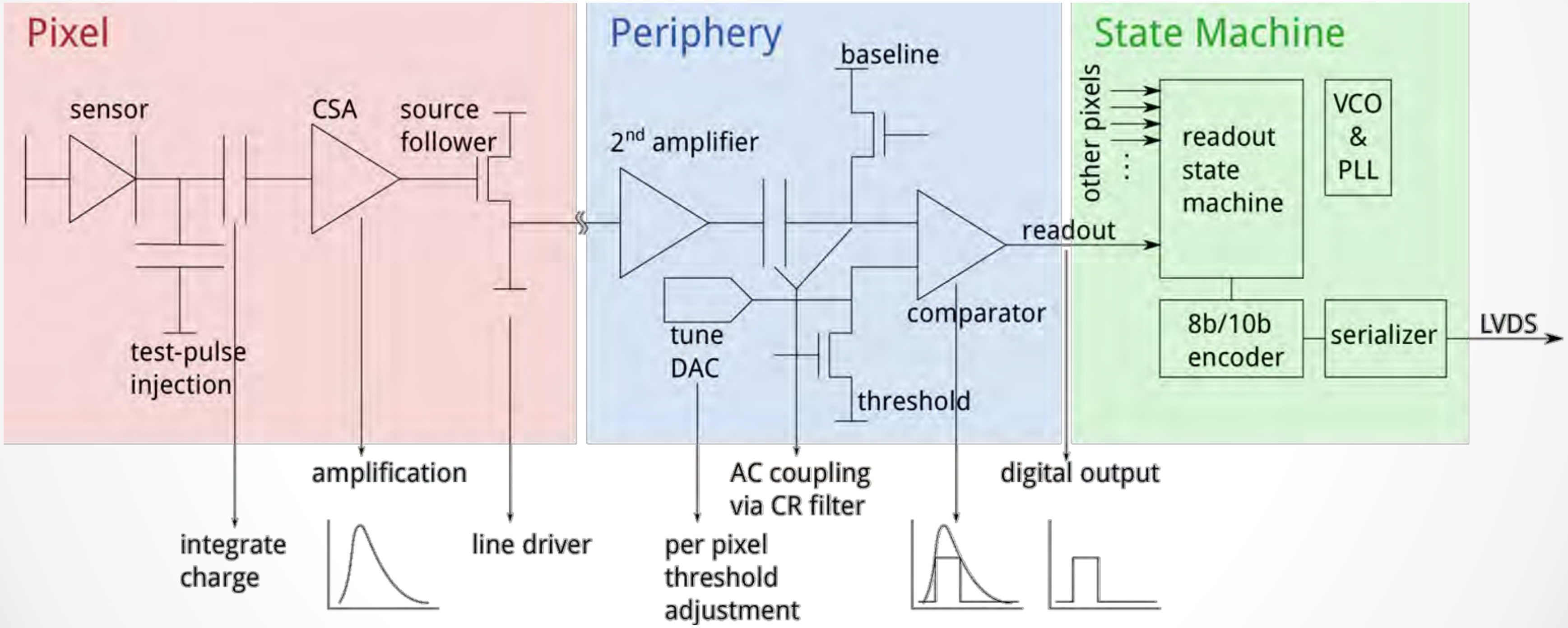
Full System on Chip

- 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

Sensor + Analog + Digital

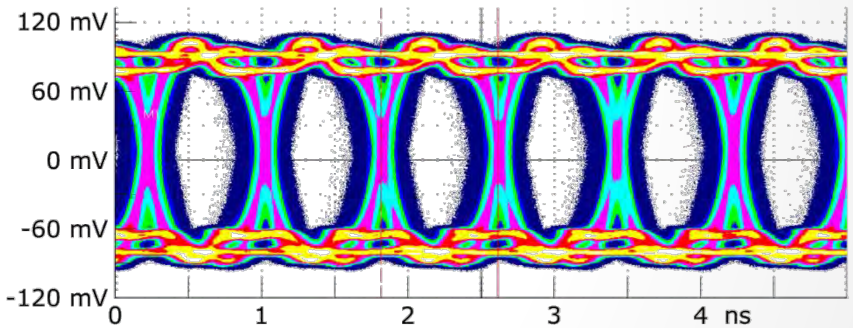


Chip Readout

On Chip:

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

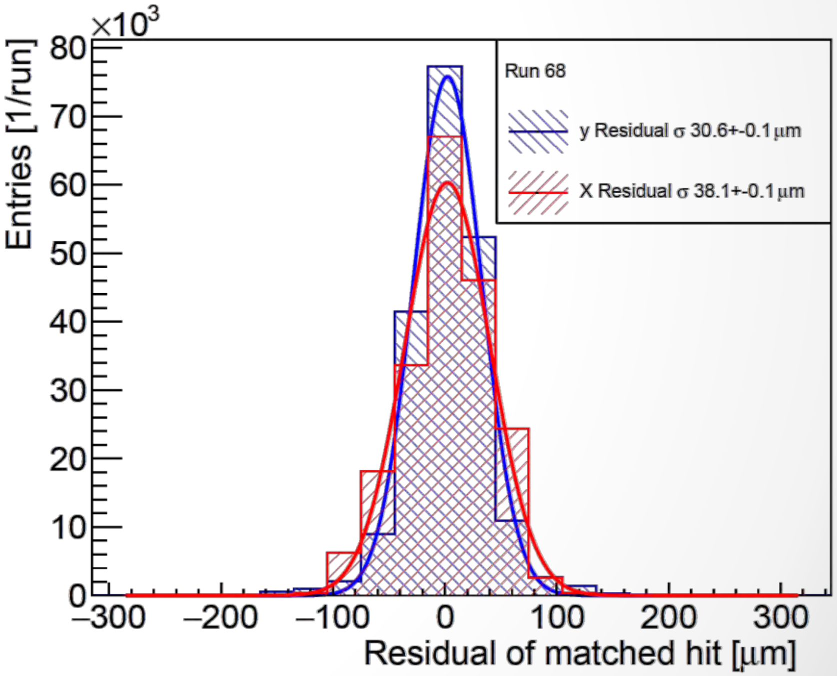
➢ 1.25 Gbit/s LVDS output



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

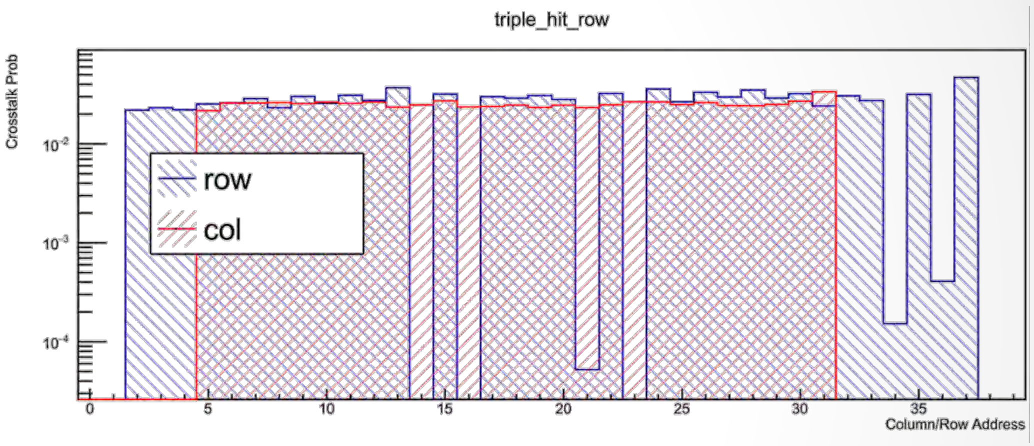
Spatial Resolution

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



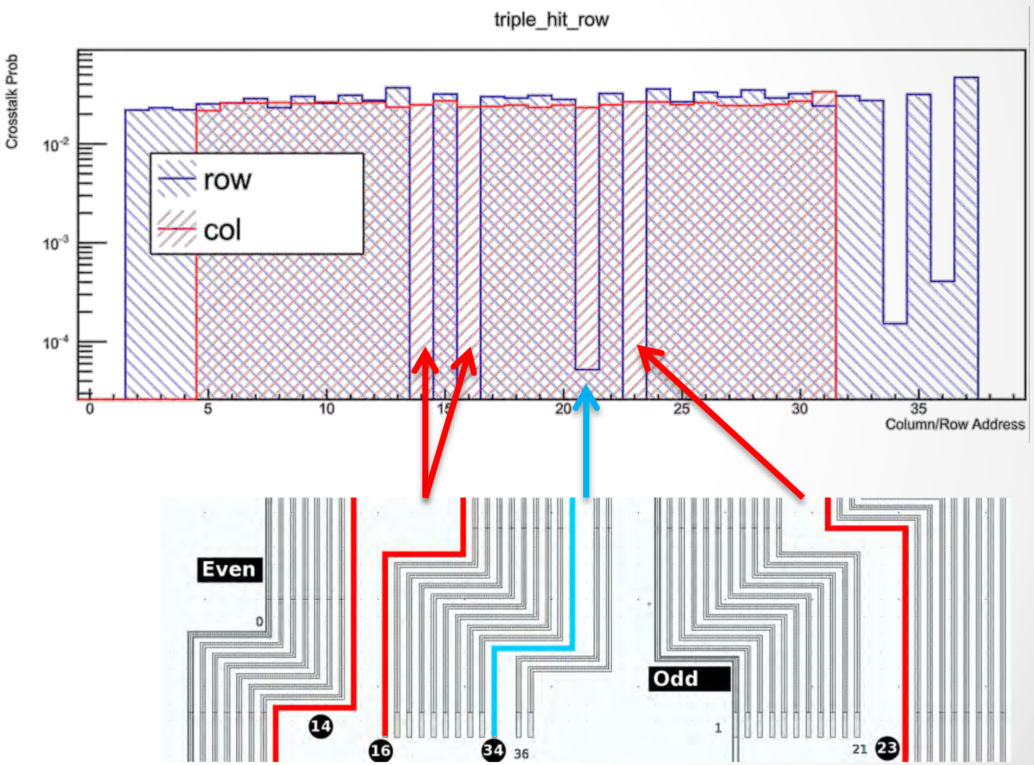
X-talk

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



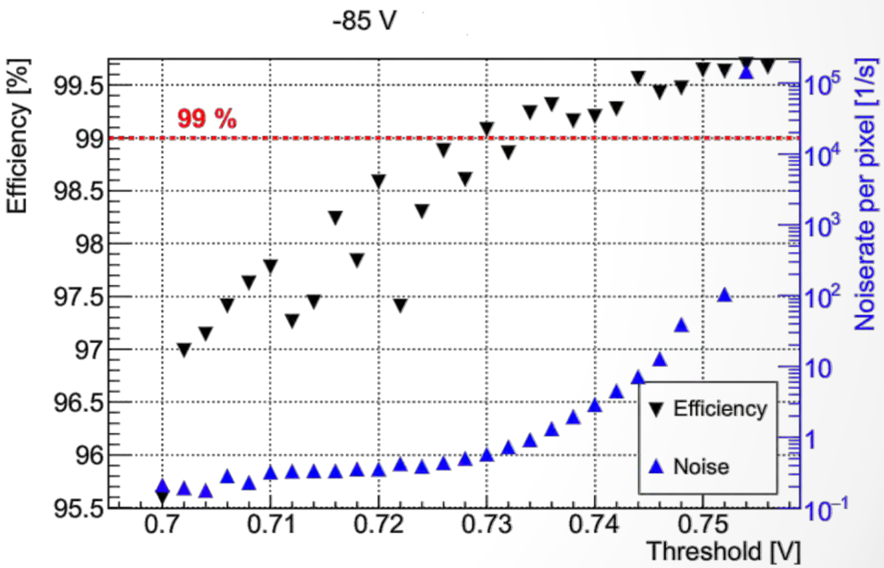
X-talk

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



Efficiencies

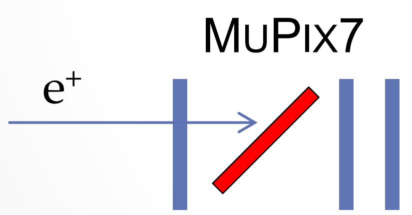
- **>99.5% efficiency**
  - 4 GeV electrons@DESY
  - 90° impact angle
  - Individual pixel thresholds



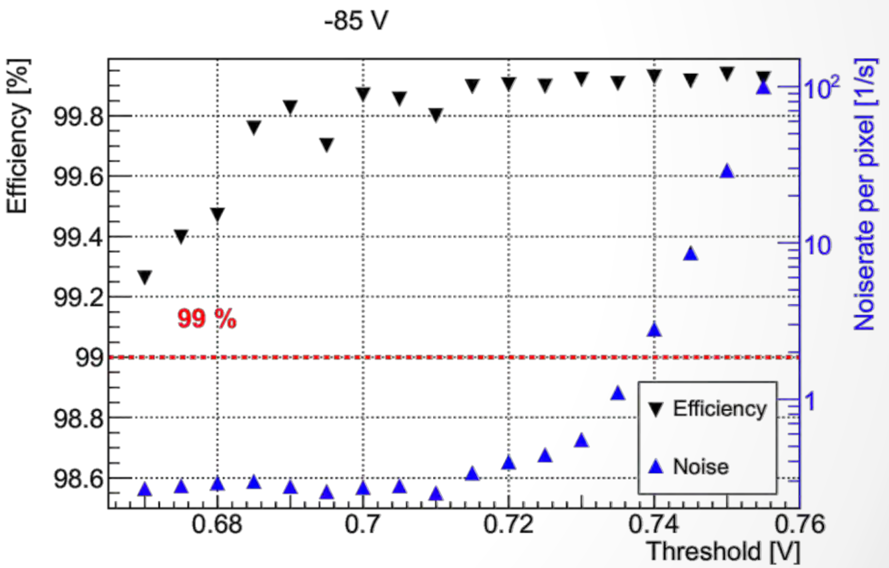
MuPix7 Efficiency

Efficiencies rotated Sensor

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



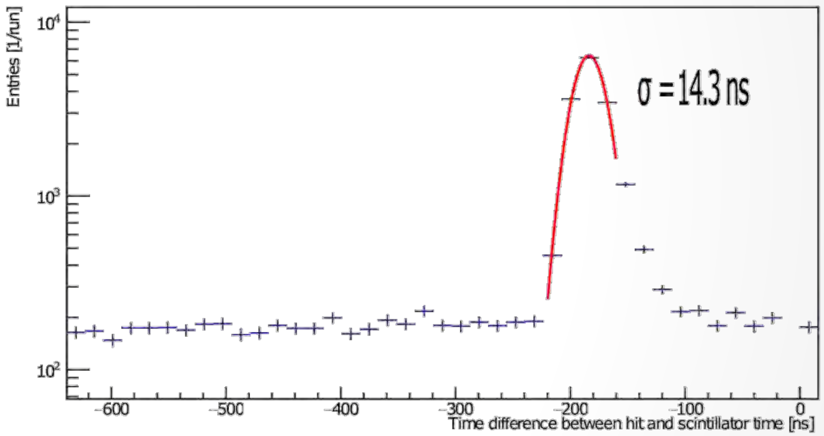
MuPix7 under angle



MuPix7 Efficiency

Time Stamps

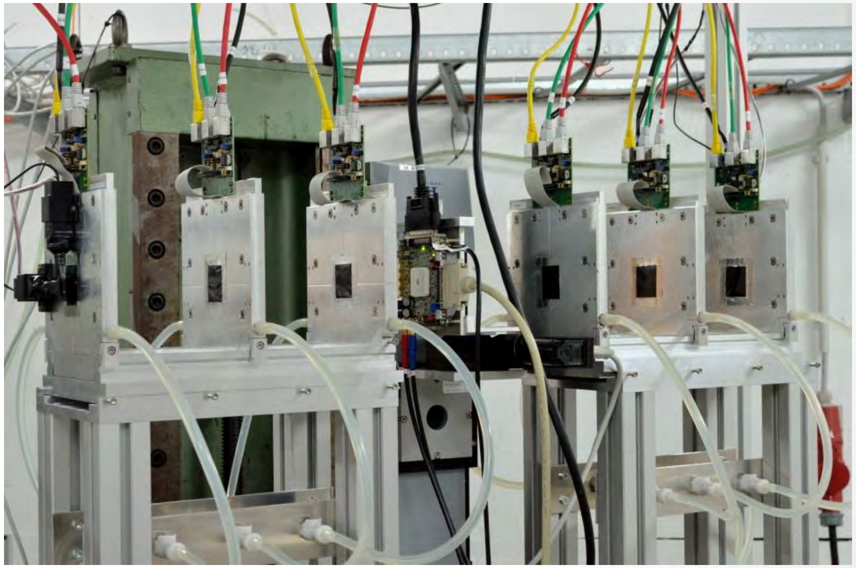
- Time difference of hits registered in MuPix 7 and scintillator
- 4 GeV electrons
- Sampling rate is 62.5 MHz



Time Resolution of Pixels

Setup March 2016 Test-Beam @ DESY

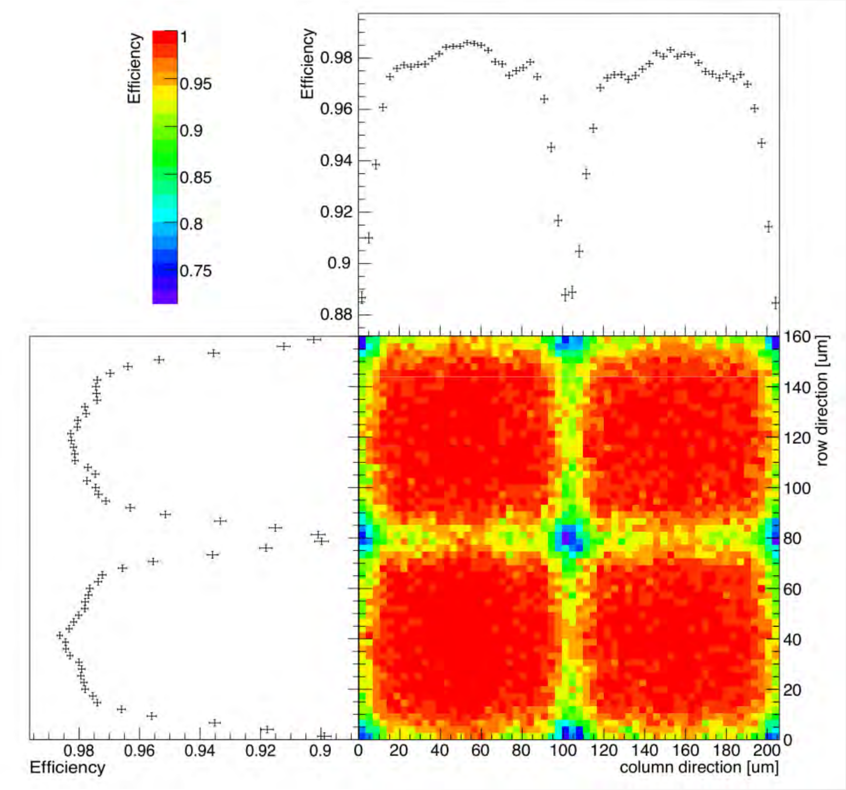
- Beam-line TB22
  - up to **5 GeV** electrons
- Aconite telescope
- MuPix7 prototype
- Readout setup from PI Heidelberg



MuPix7 @ DESY test-beam in EUDET telescope

Sub-Pixel Efficiencies

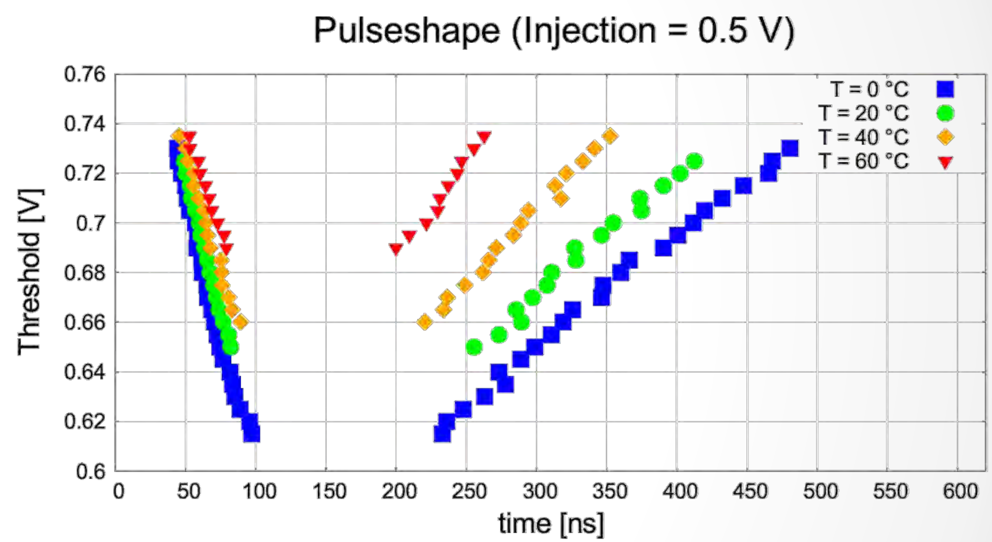
- Hit efficiency map and projections for 2×2 pixel array
- 4 GeV electrons
- Bias voltage −40V to enhance the inefficient regions
- Studies for **MuPix8** ongoing



MuPix7

Temperature Dependence

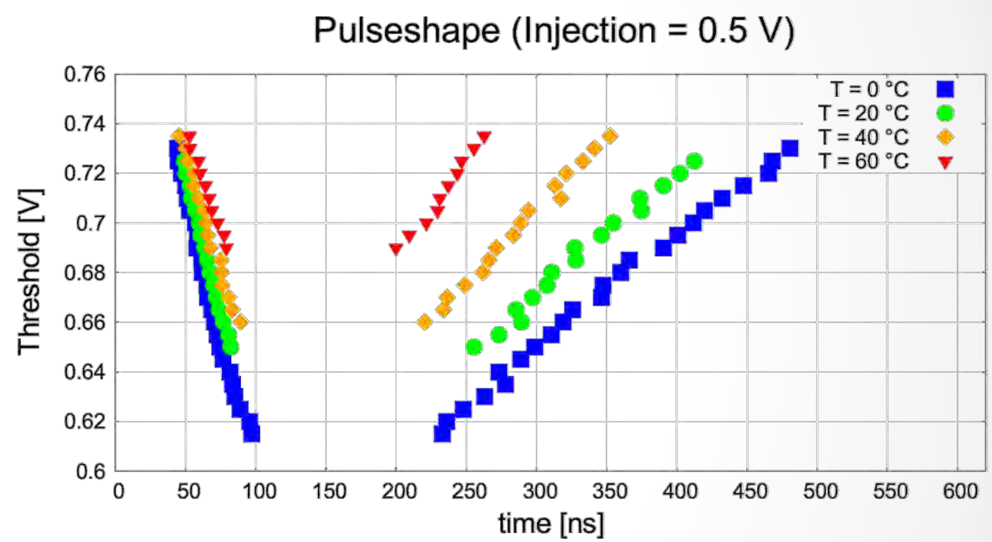
- Pulse shape vs temperature
  - Injection pulse to pixel discriminator output
- Climate chamber
  - 0°C, 20°C, 40°C, 60°C
- Significant change to
  - Pulse shape
  - Signal amplitude
- Slight change to time resolution
  - Re-calibration



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



Temperature is ambient temperature, MuPix7 was even hotter.
MuPix8 still under investigation

Challenges

…

Challenges

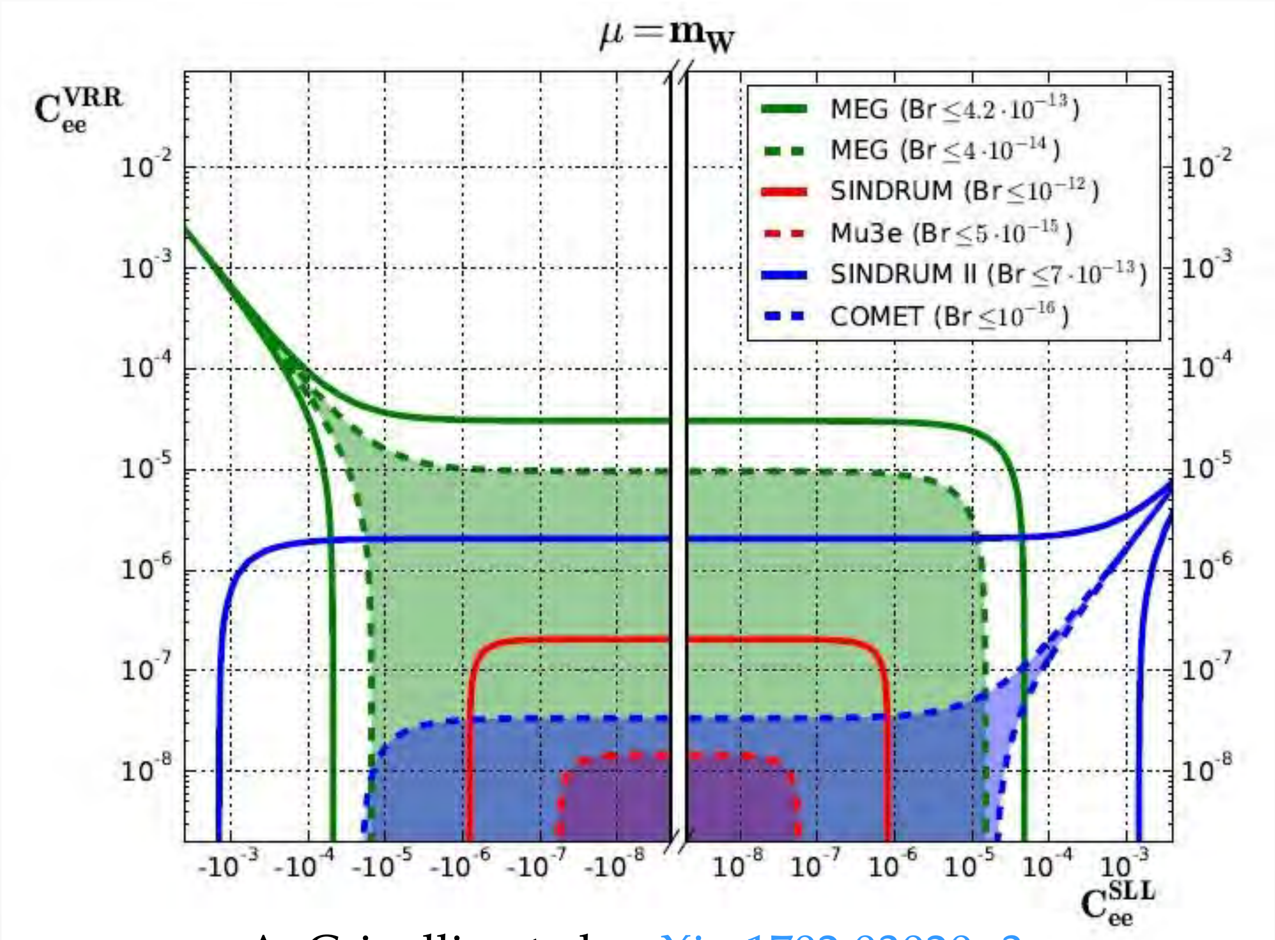
- High rates: 10^8 μ/s
- Good timing resolution: 100 ps
- Good vertex resolution: ~200 μm
- Excellent momentum resolution: ~ 0.5 MeV/c^2

➢ 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

$\mu \to eee$ vs. $\mu \to e\gamma$ and $\mu N \to eN$

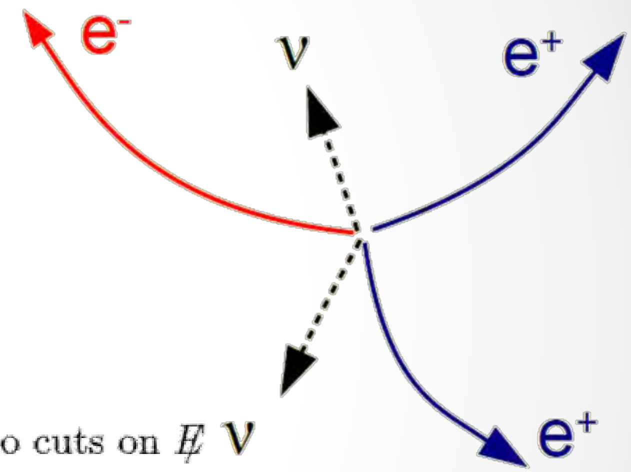


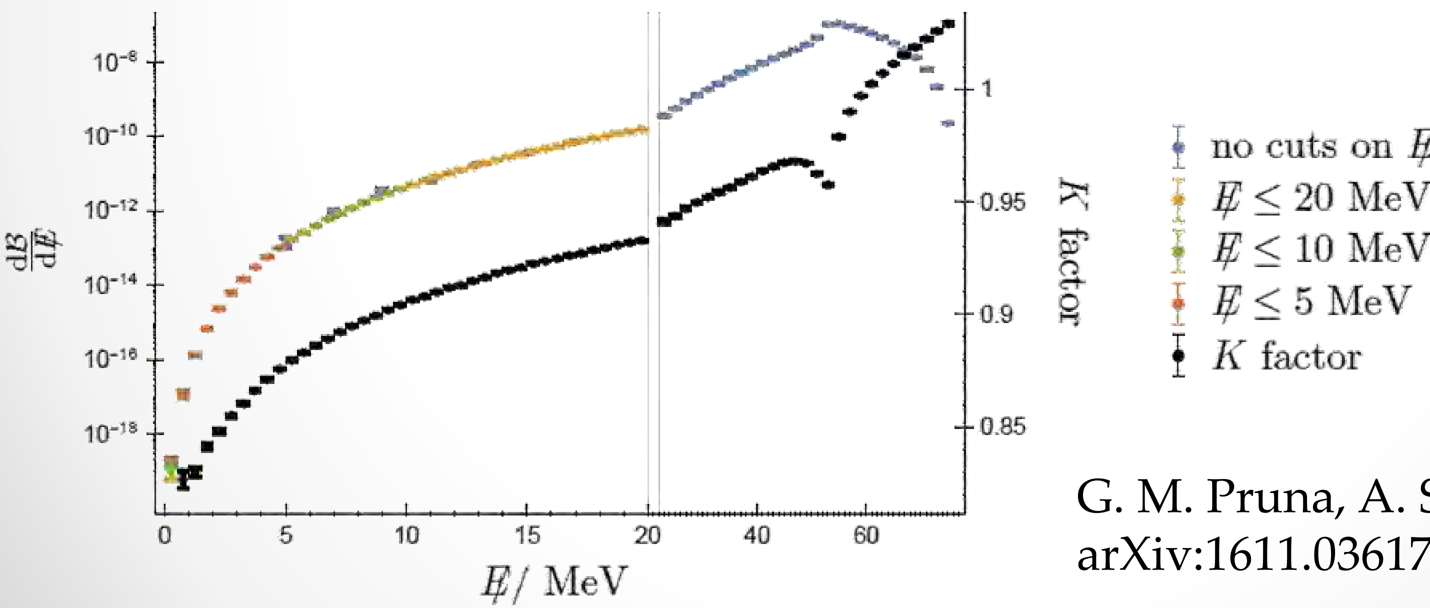
A. Crivellin et al. arXiv:1702.03020v3

The Mu3e Background

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

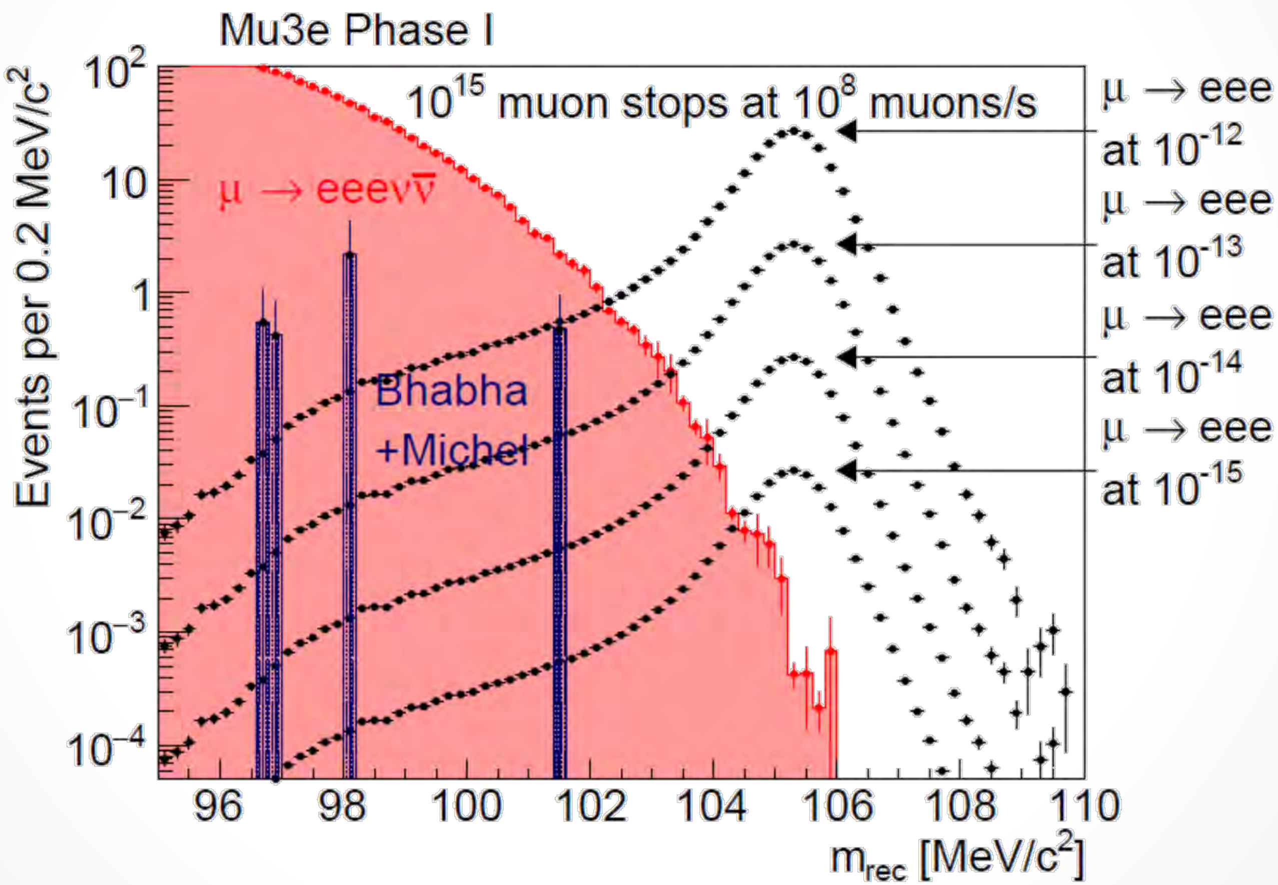
➢ **Good momentum resolution**





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

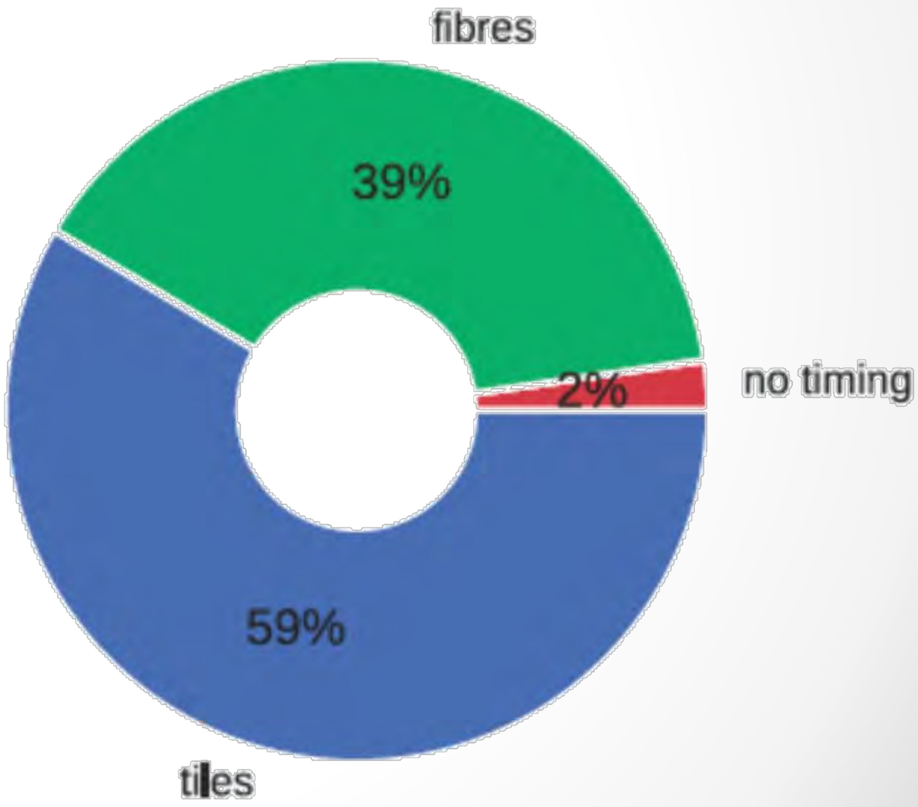
Outlook: Phase I performance Simulation

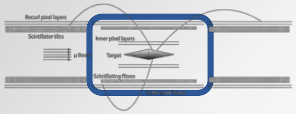


SciFi Backup

Timing Detectors

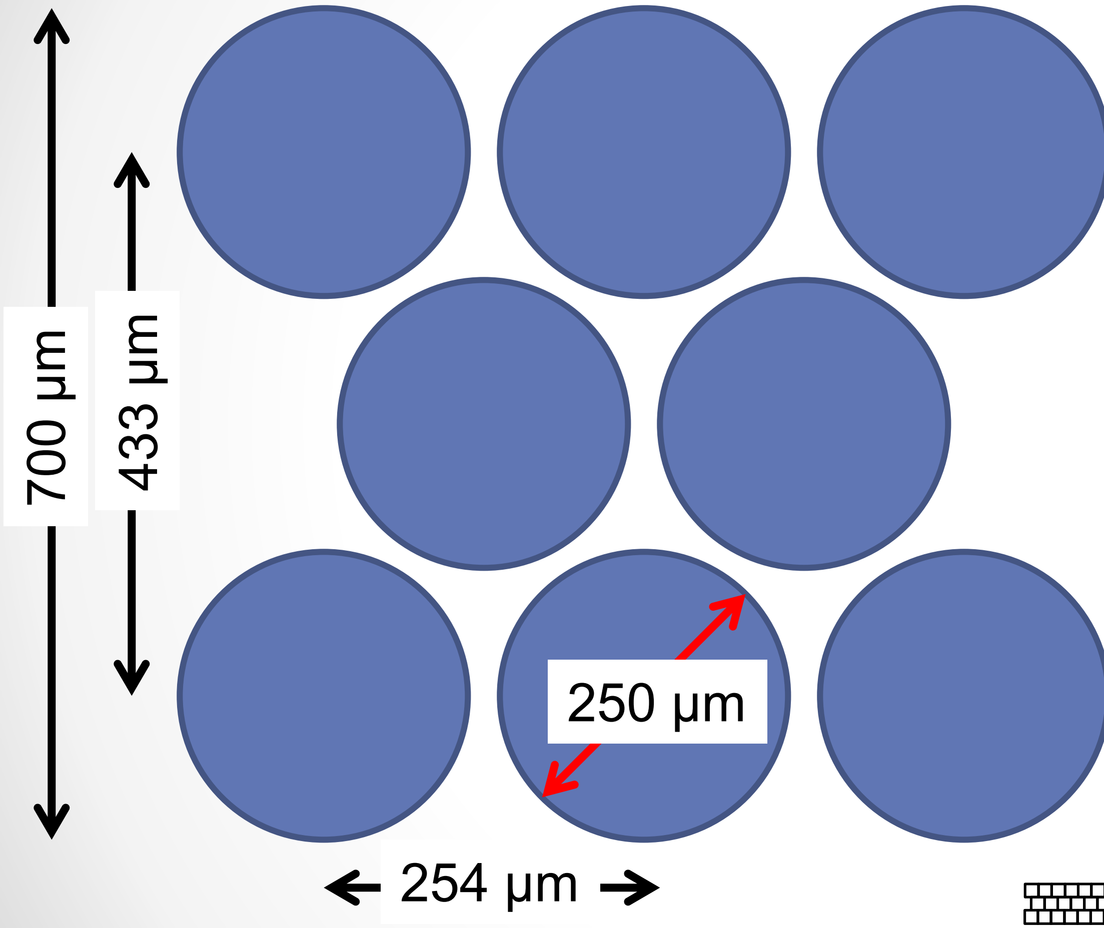
- Combinatorial background: suppression by a factor of 100 needed





Details …

staggered layers

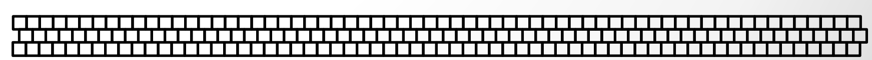


Thickness:

- theoretical ~ 683 µm
- measured ~ 750 µm

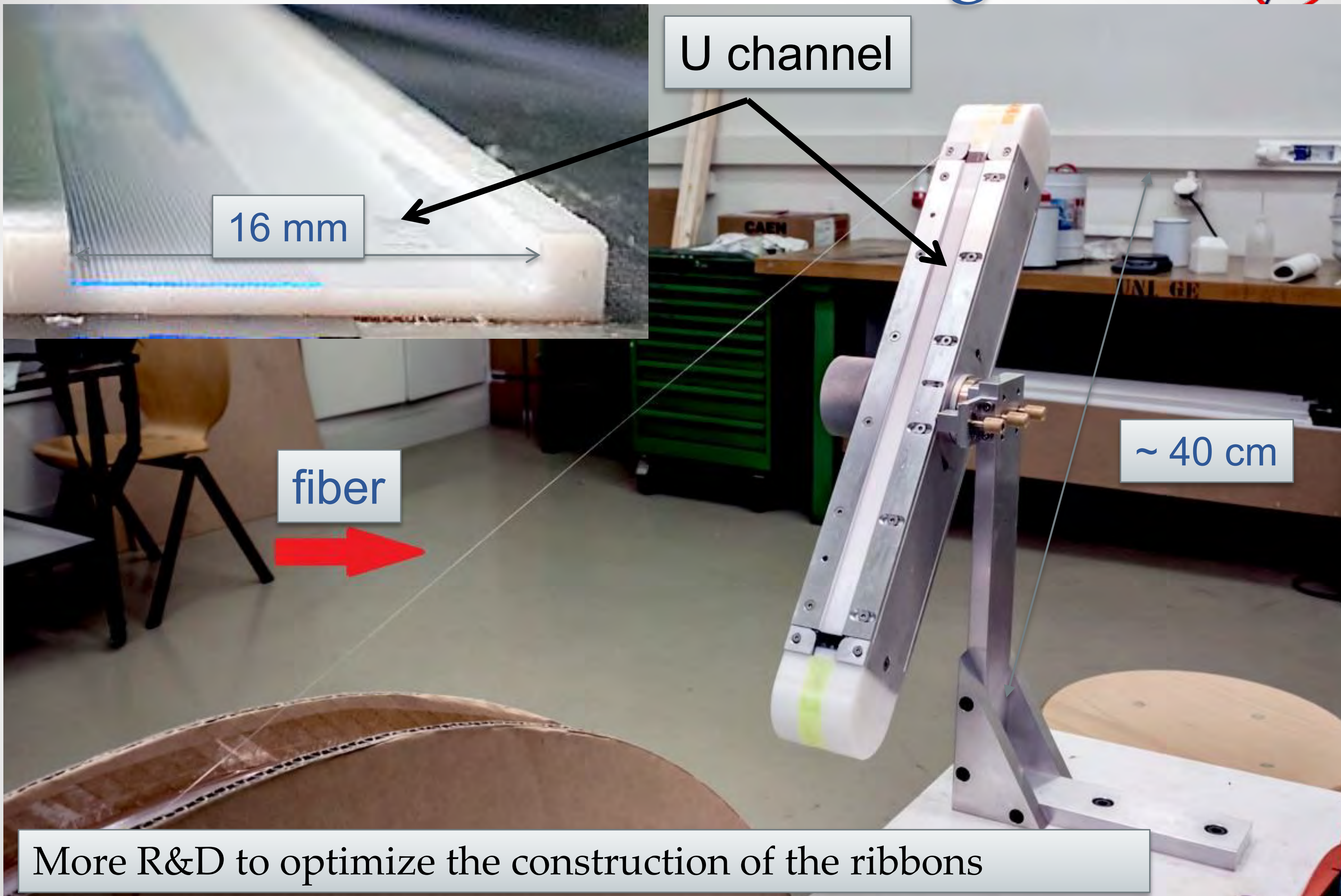
< 1 g of glue / ribbon

Alternative:
Square shape fibers

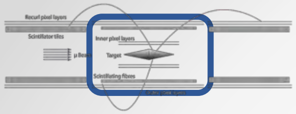


Horizontal gap between fibers ~ 4 µm

Fiber Winding Tool



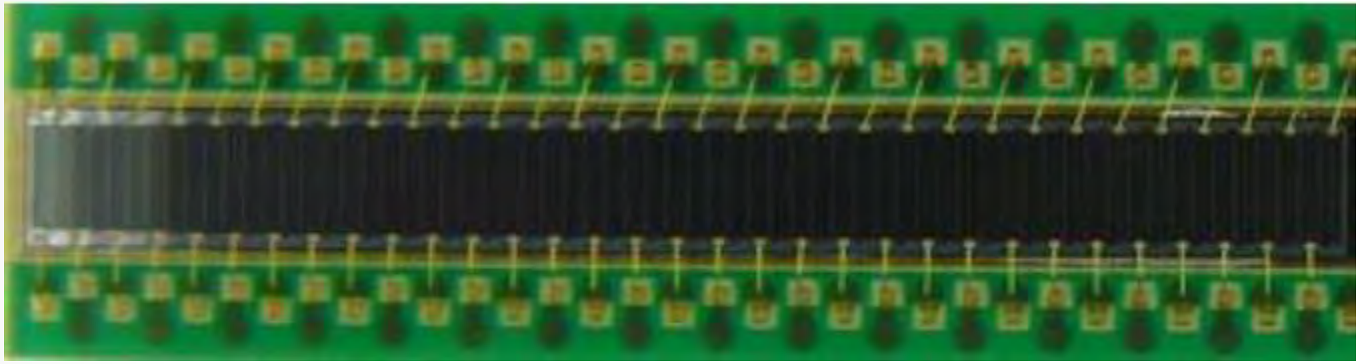
More R&D to optimize the construction of the ribbons



Readout of Fibers

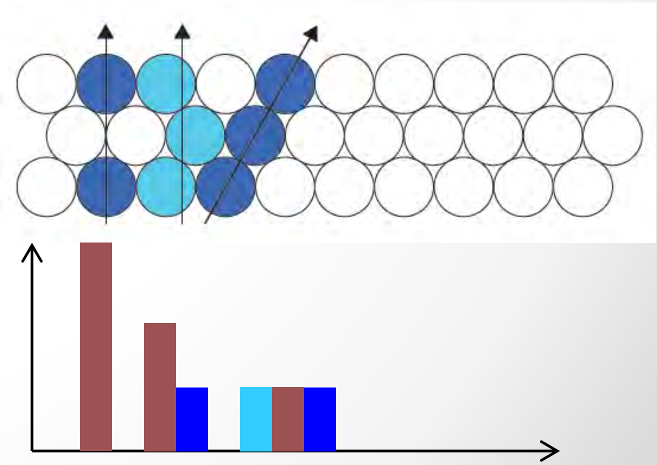
Si-PMs (MPPCs) at both fiber ends

SciFi column readout with Si-PM arrays



LHCb type detector

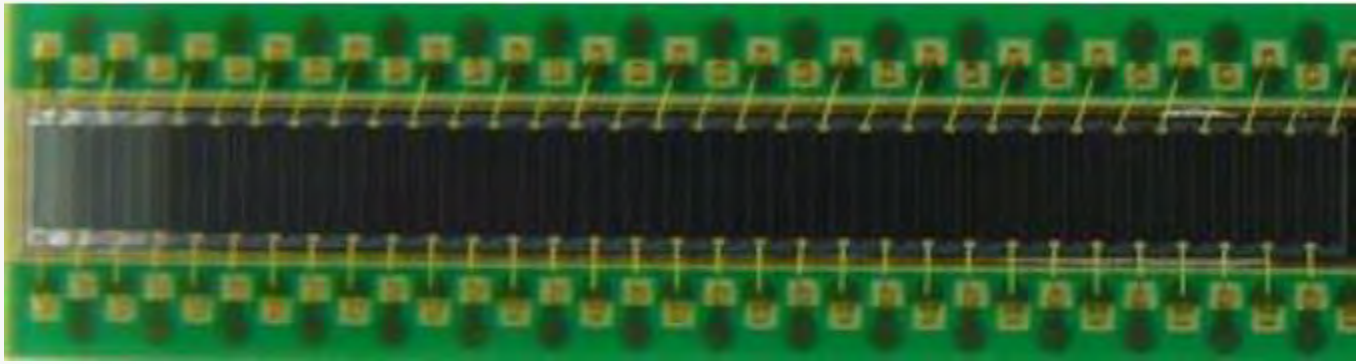
- 64 channel monolithic device (custom design)
- ~250 μm effective "pitch"
- 50 μm × 50 μm pixels
- Grouped in 0.25 mm × 1 mm vertical columns
- Common bias voltage



Readout of Fibers

Si-PMs (MPPCs) at both fiber ends

SciFi column readout with Si-PM arrays



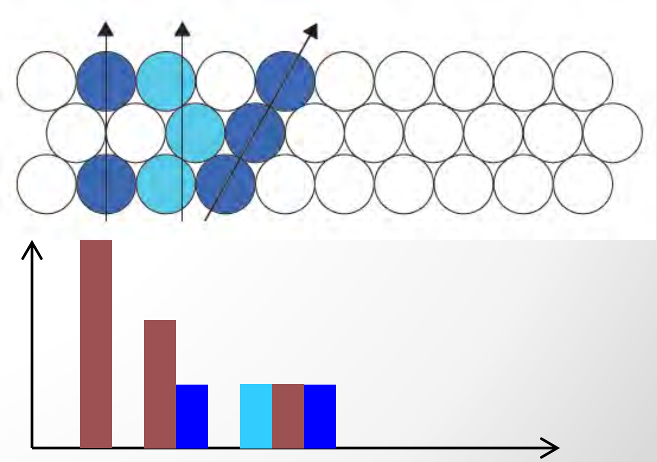
LHCb type detector

☺Reduced # of readout channels (2 × 64)

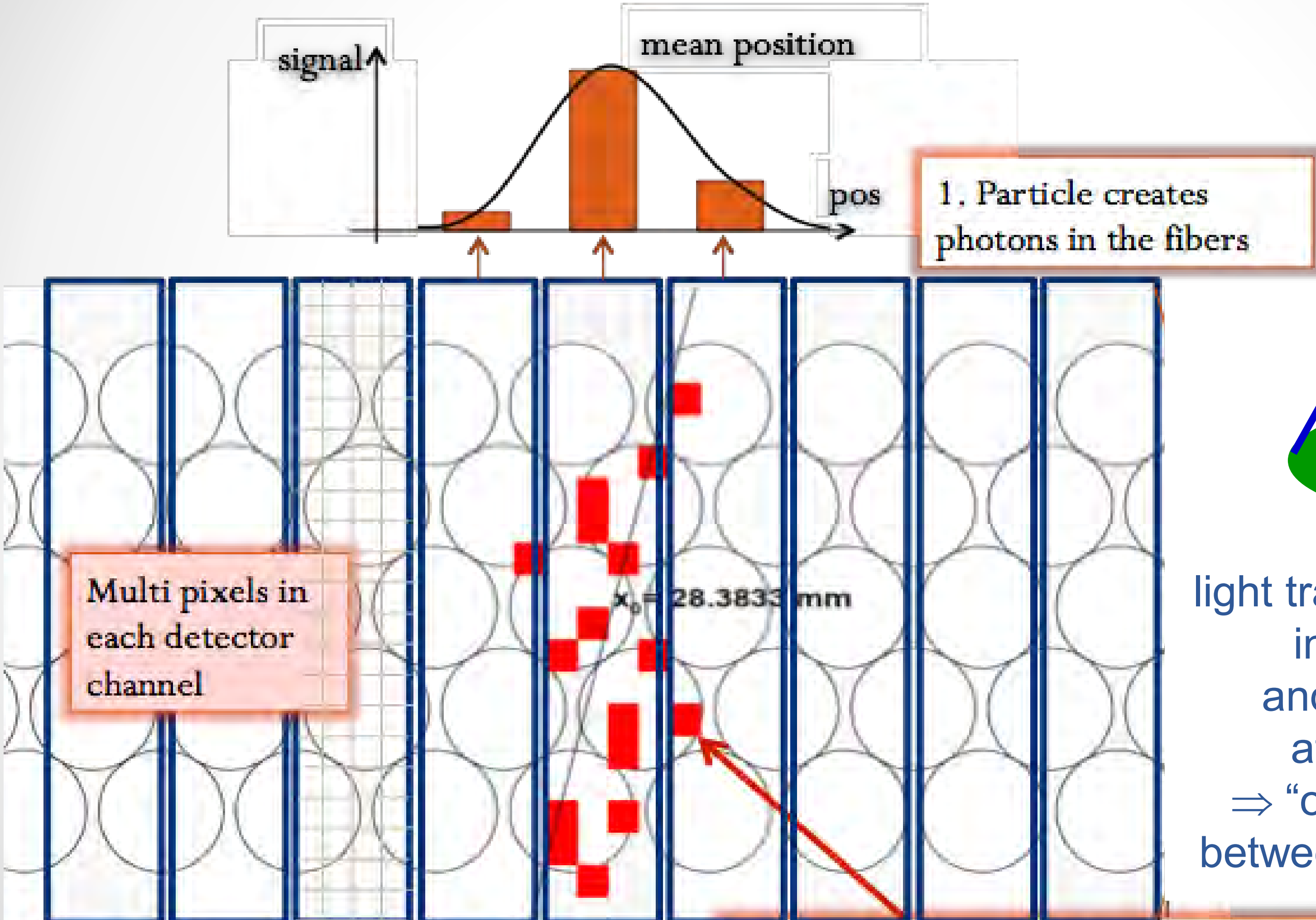
☺Easy, direct coupling

☹ Higher occupancy

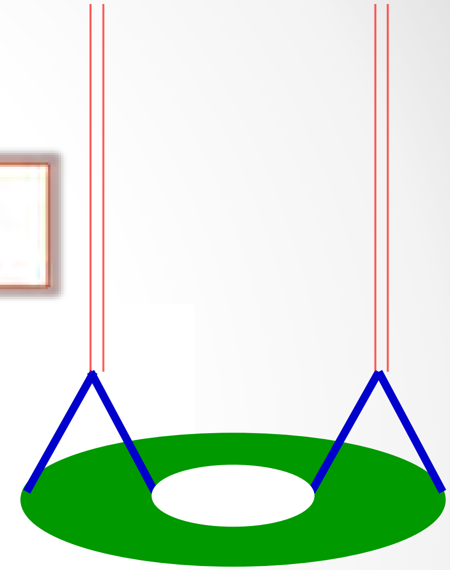
☹ "Optical" cross talk



SciFi Column Readout



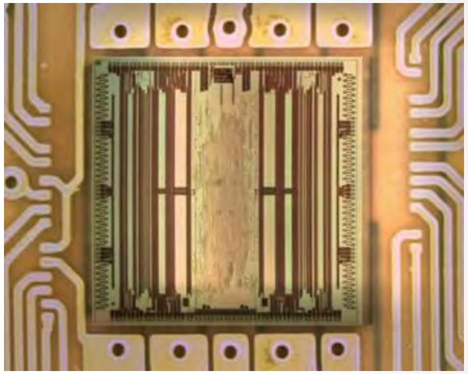
2. Pixel (red squares) detect photons propagated through the fibers



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

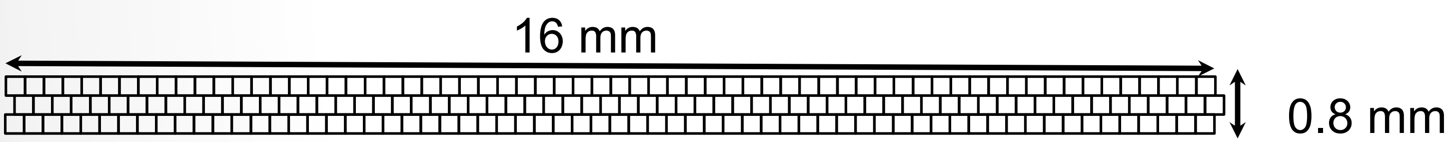
First test beam results encouraging!

Alternative Design with Square Fibers

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

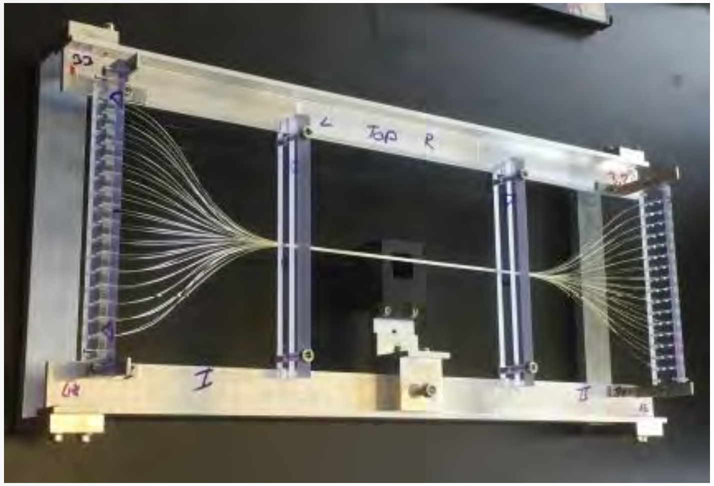
128 fibers/layer

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



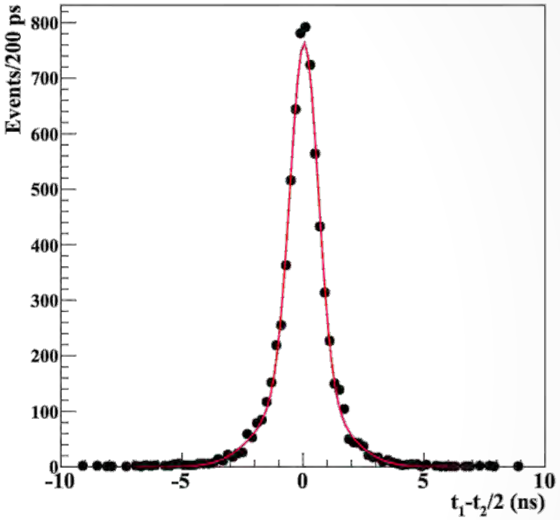
Testing Square Fibers

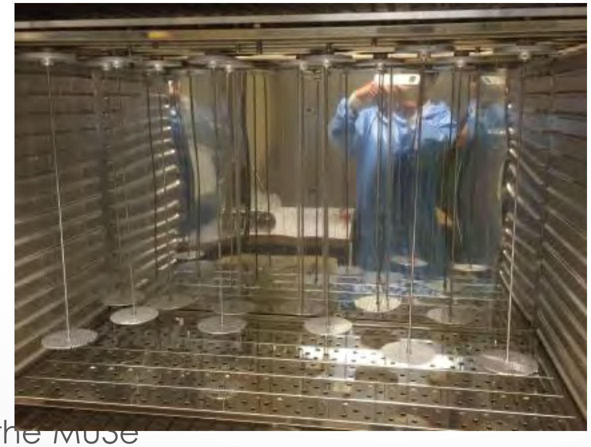
Fiber test setup developed at PSI



250 µm square fiber

timing performance





Cross talk:

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

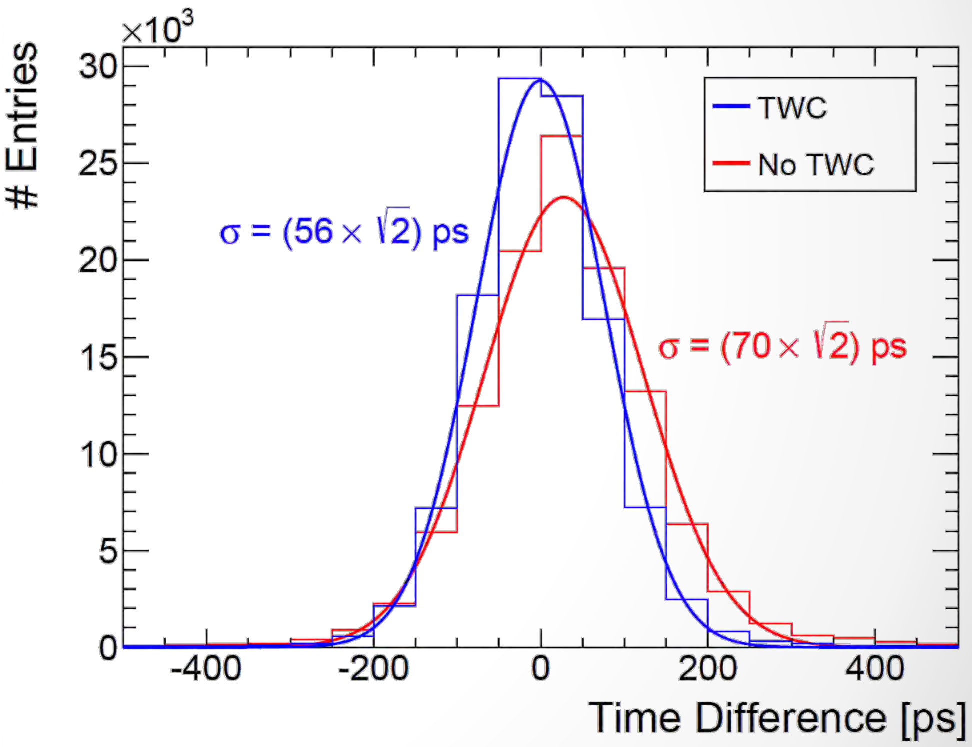
0.5 Nphe threshold

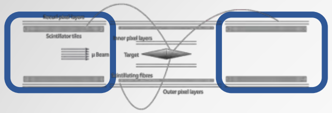
$\sigma = 750 \pm 17$ ps

Tile Detector Backup

Tile Time Resolution

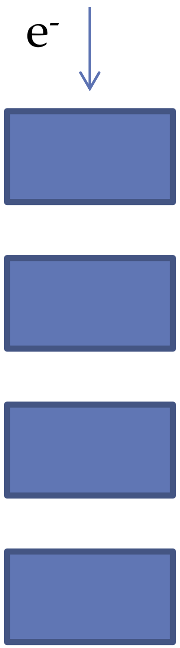
- Coincidence between 2 tiles in a row
- Time resolution ≈ 70 ps
- Time-walk effect ≈ 14 ps

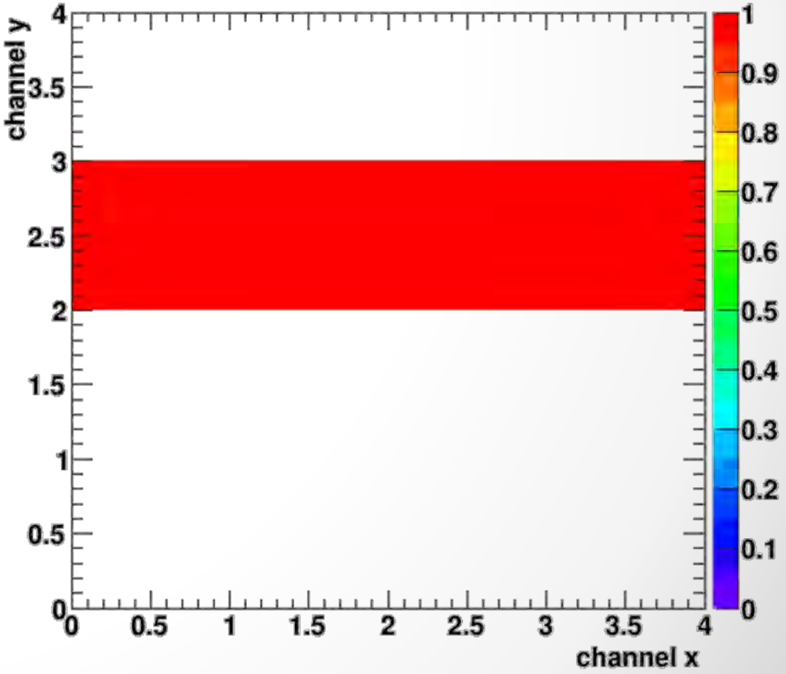




Efficiency

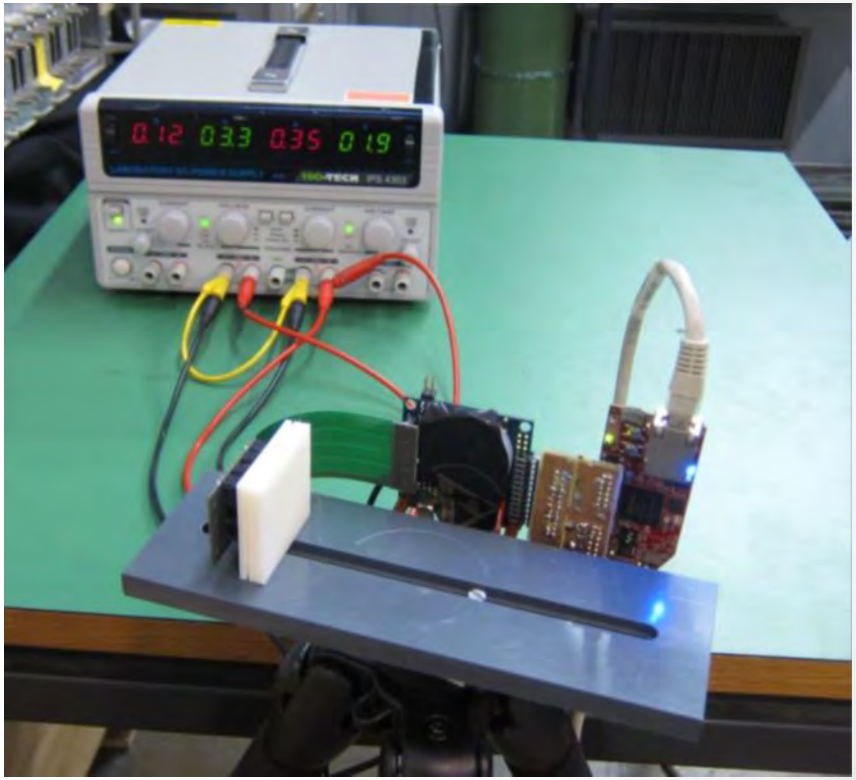
- Require hit in first & last column
- Look for hit in middle channel
- Efficiency > 99.5%



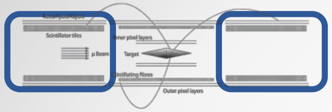


Tile Detector

- 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

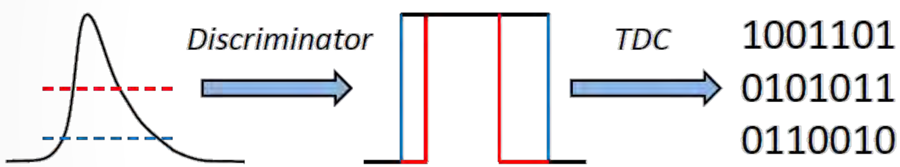


Tile detector 4 x 4 prototype



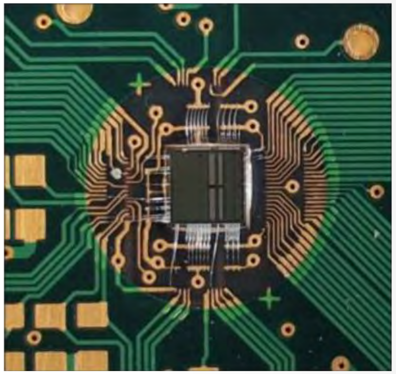
STiC Readout

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

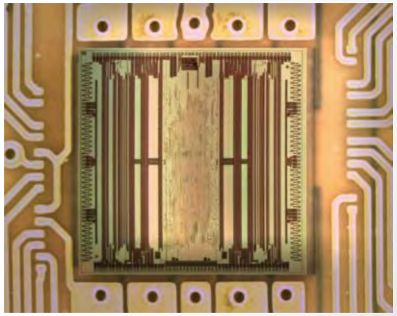


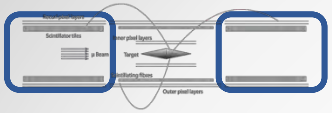
  - 64 channels (version 3.0)
  - 50 ps TDC bins
  - SiPM bias tuning
  - SiPM tail cancelation possibility (version 3.0)
  - Currently ≈ 1 MHz hit rate / chip
  - Up to ≈ 20 MHz in future version
- Version 2.0 successfully operated in test-beam

STiC 2.0



STiC 3.0





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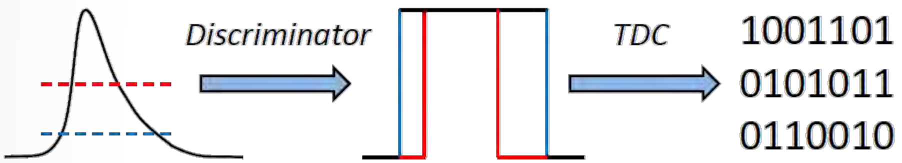

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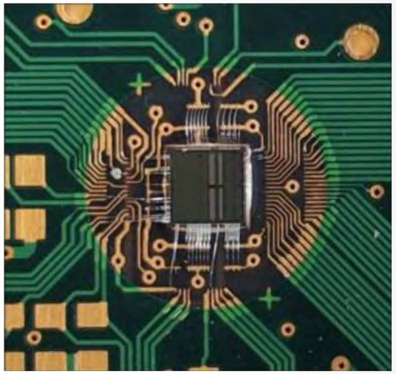
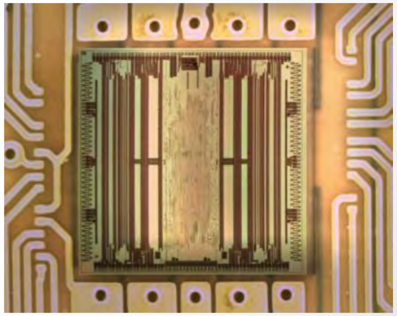
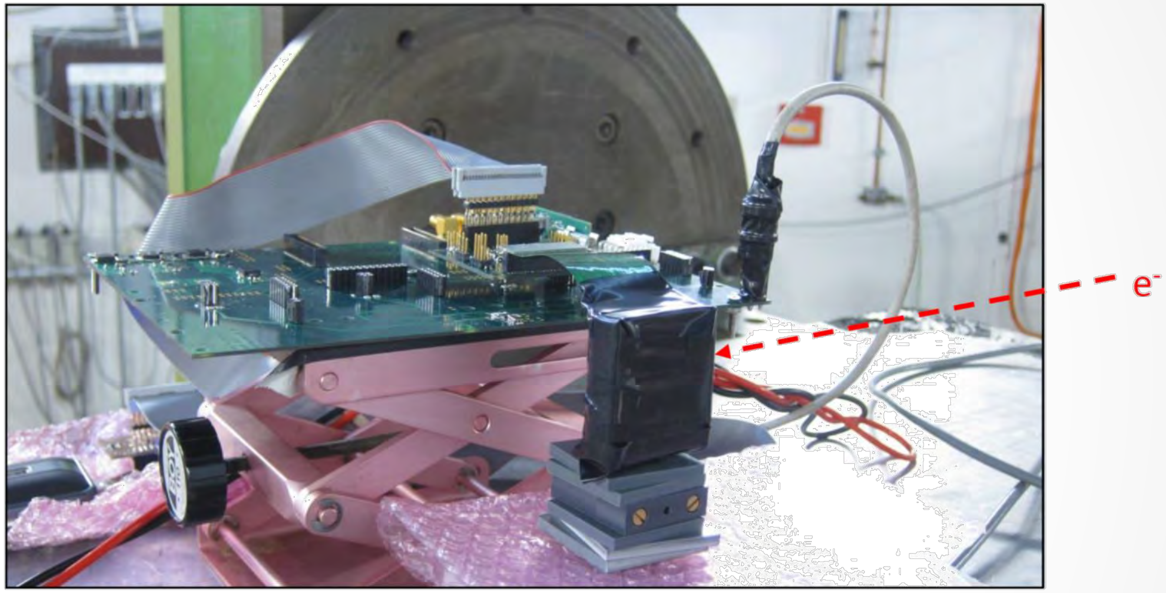


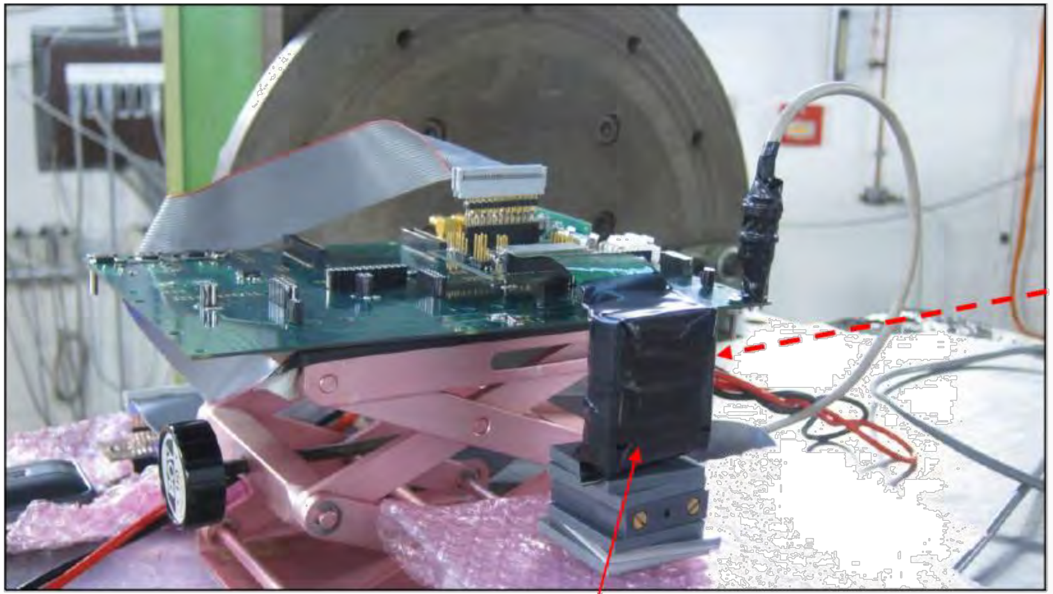
STiC 3.0

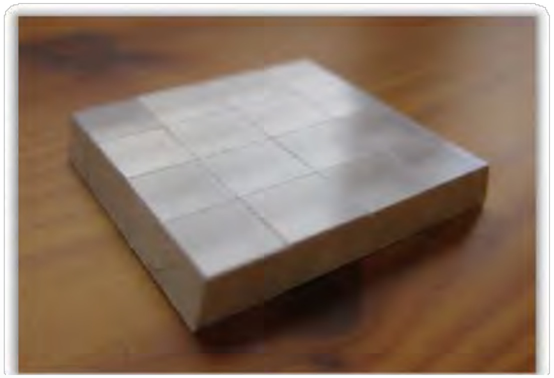


STiC Test Beam



STiC Test Beam

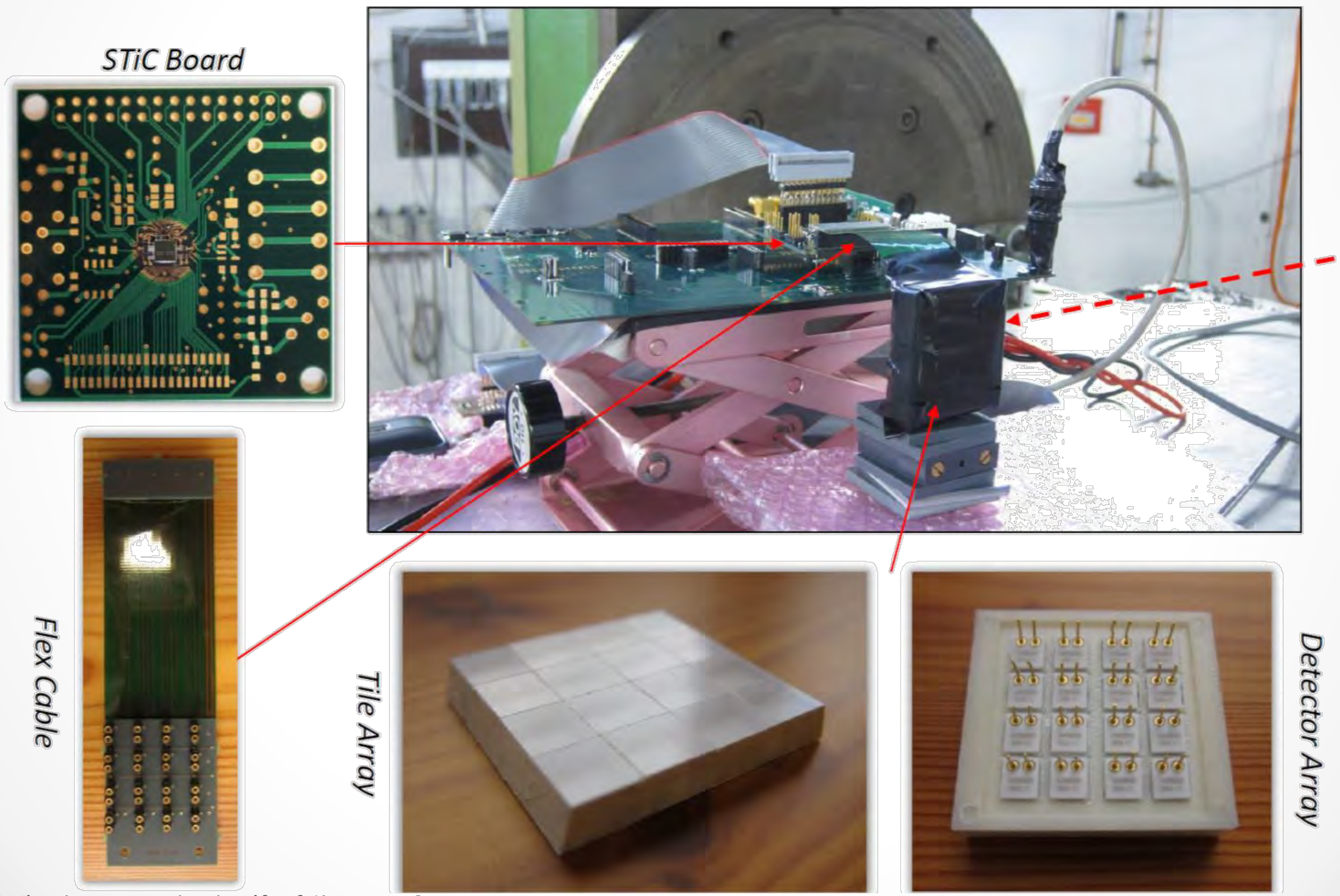


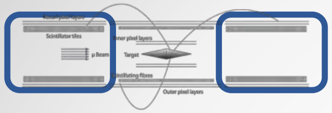


Tile Array

Detector Array

STiC Test Beam

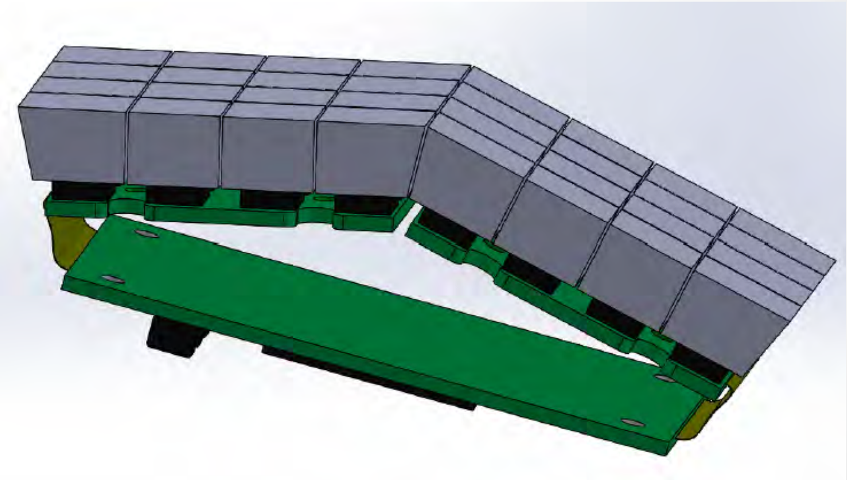




Tile Detector

Submodule:

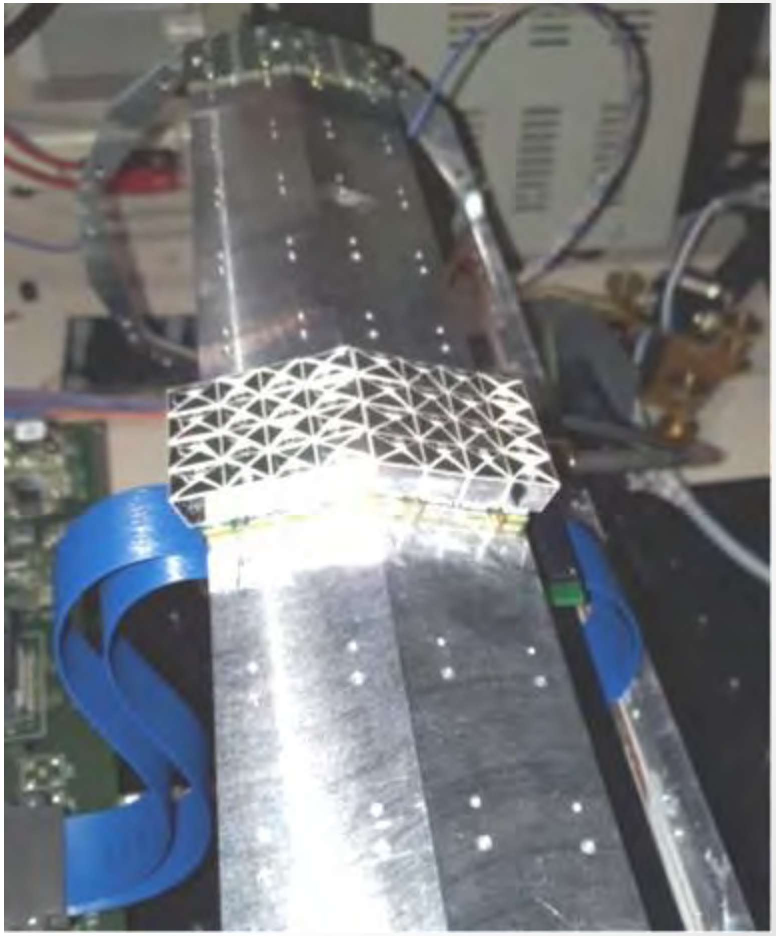
- In total 32 channel
- 3 x 3mm^2 SiPMs
- FEBA – flex printed PCB
- MuTrig ASIC in BGA package
- Scintillator tiles Ej-228
  - 6.5 x 6.5 x 5mm^3
  - two types: center and edge
- ESR reflected foil, individual tile wrapping



Rendering of old Tile Detector sub module

Tile Prototype

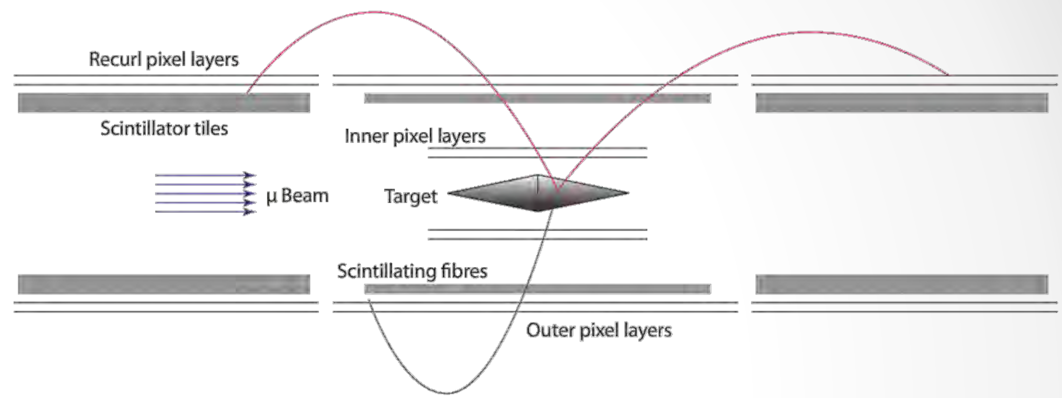
- Technical prototype build this year
- Develop assembly tools for mass production
- Tested with electron beam @ DESY (2-7 GeV)
- Excellent light yield
- Low crosstalk



Prototype on cooling structure

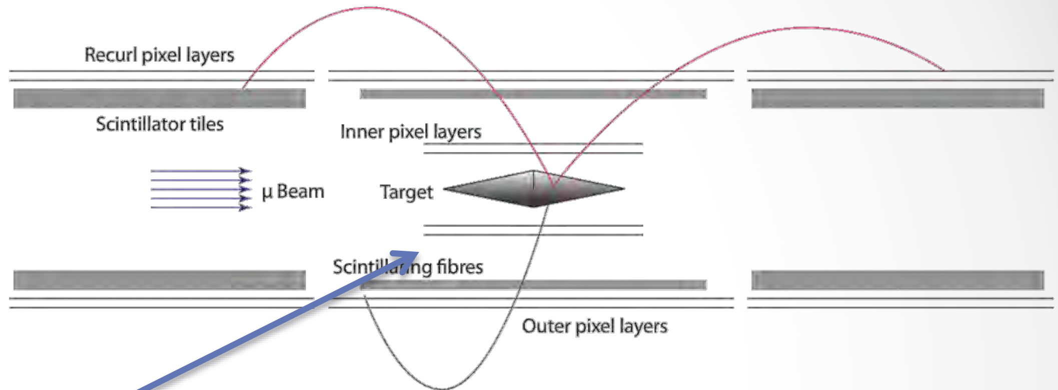
Mechanics Backup

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



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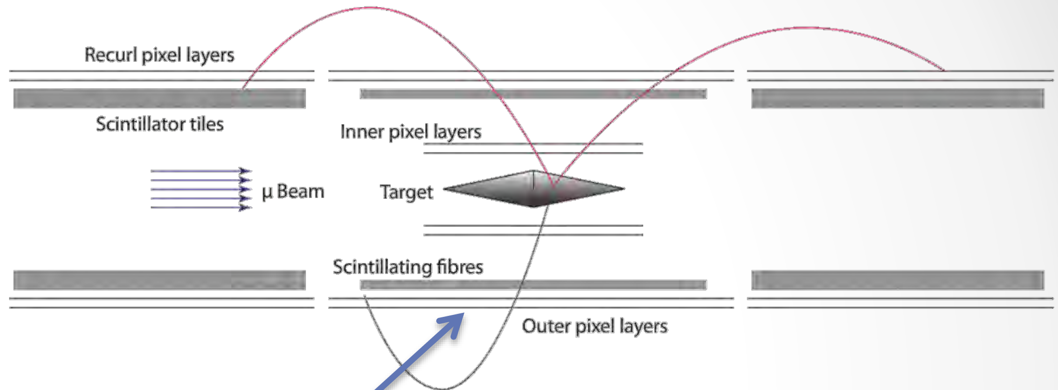

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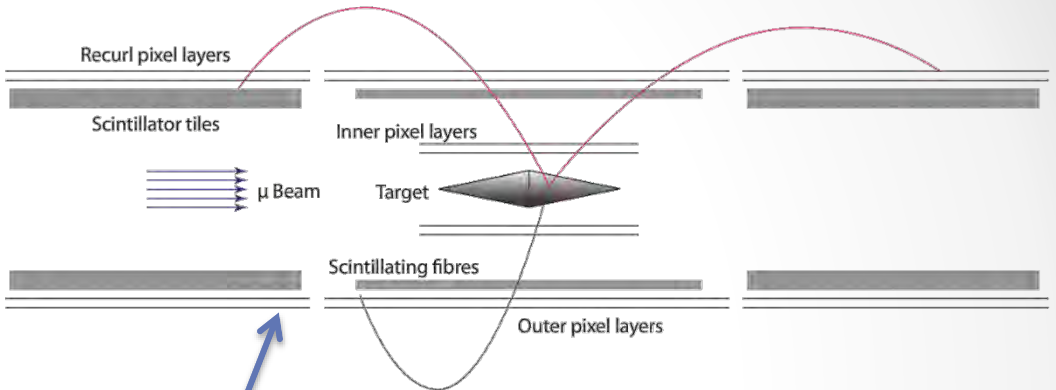

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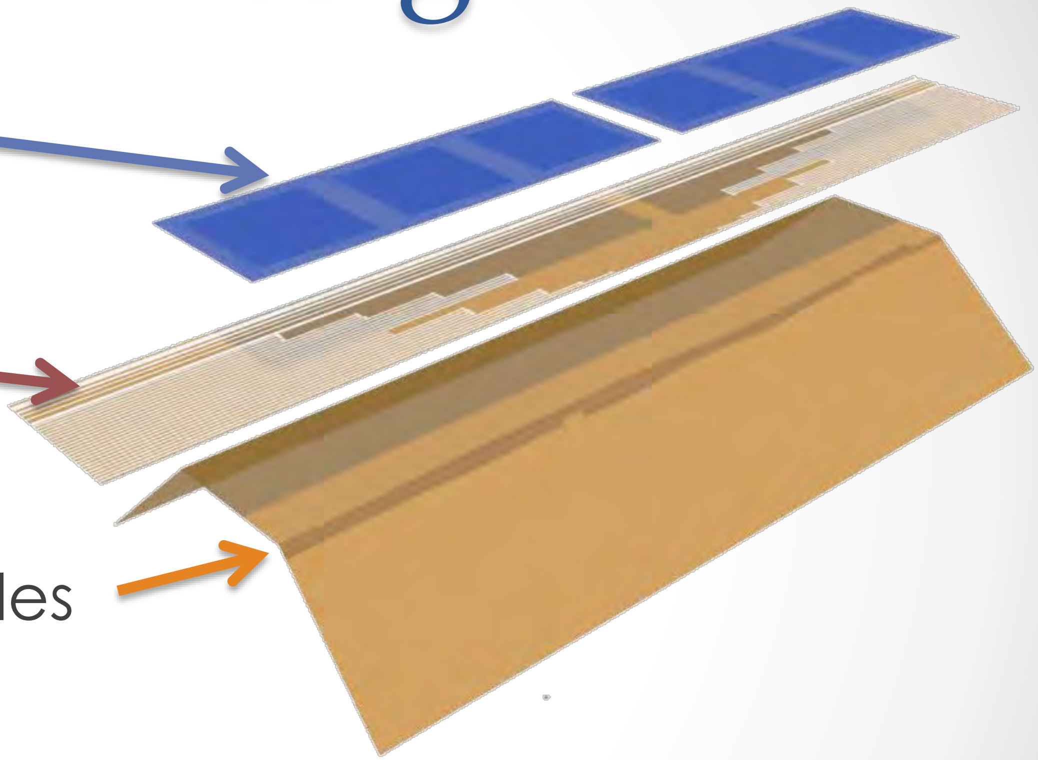
- Outer double layer
  - 24 and 28 sides of 2 x 36 cm^2
- Re-curl layers
  - 24 and 28 sides of 2 x 36 cm^2
  - Both sides

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™
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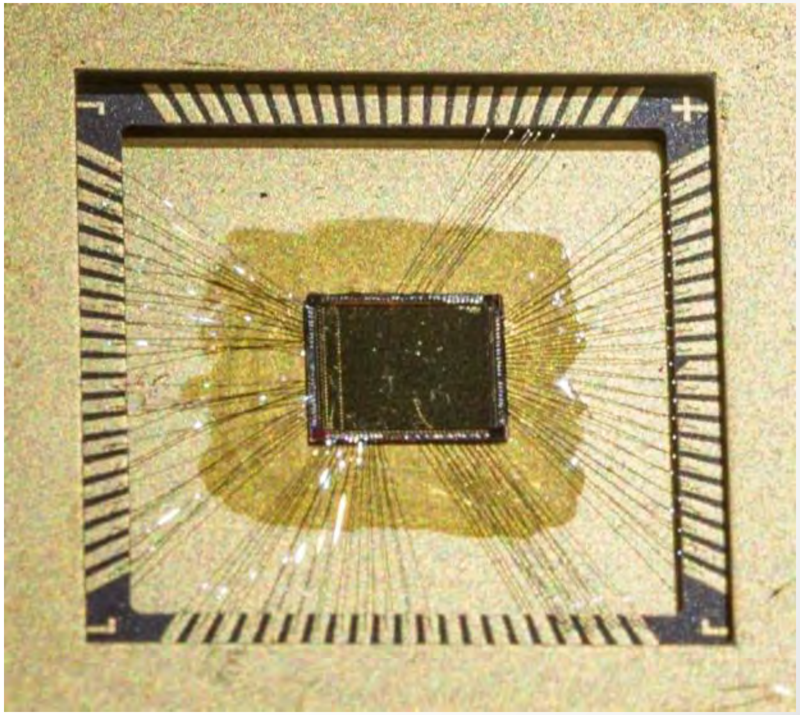

MuPix3 thinned to < 90µm

Kapton™ Flex Print

- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm²
- **Kapton™ flex print**
  - 25 µm Kapton™
  - 14 µm Alu traces
- Kapton™ Frame Modules
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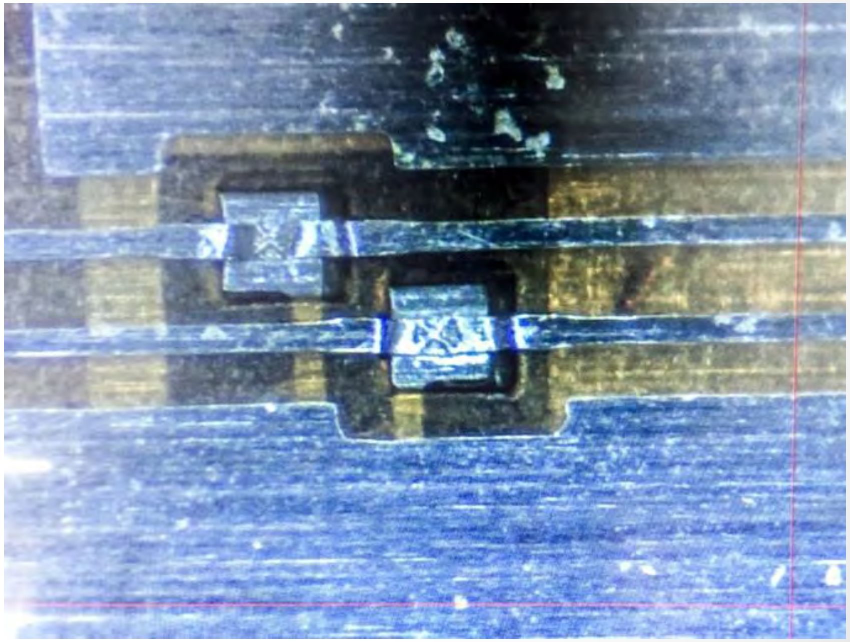

Laser-cut flex print prototype

Pixel Modules

- HV-MAPS
  - Thinned to 50 μm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 μm Kapton™
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- **Kapton™ Frame Modules**
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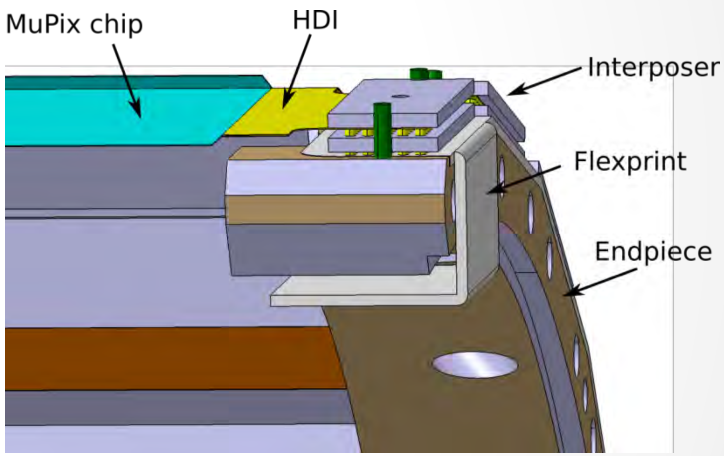
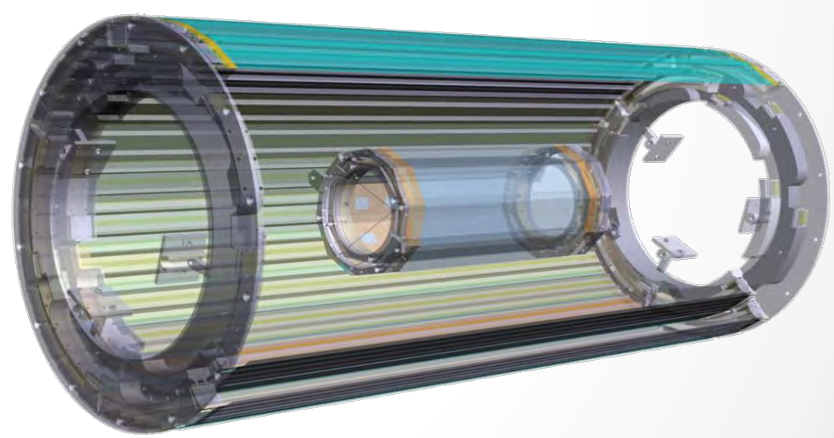


CAD of Kapton™ frames

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

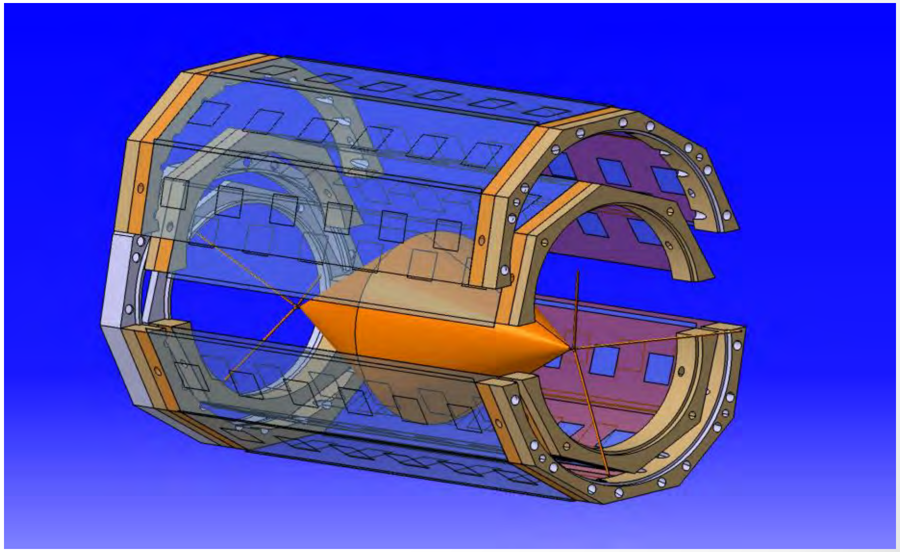
- Two halves for layers 1+2
- 6 modules in layer 3
- 7 modules in layer 4



Old CAD of Kapton™ frames

Inner Layers

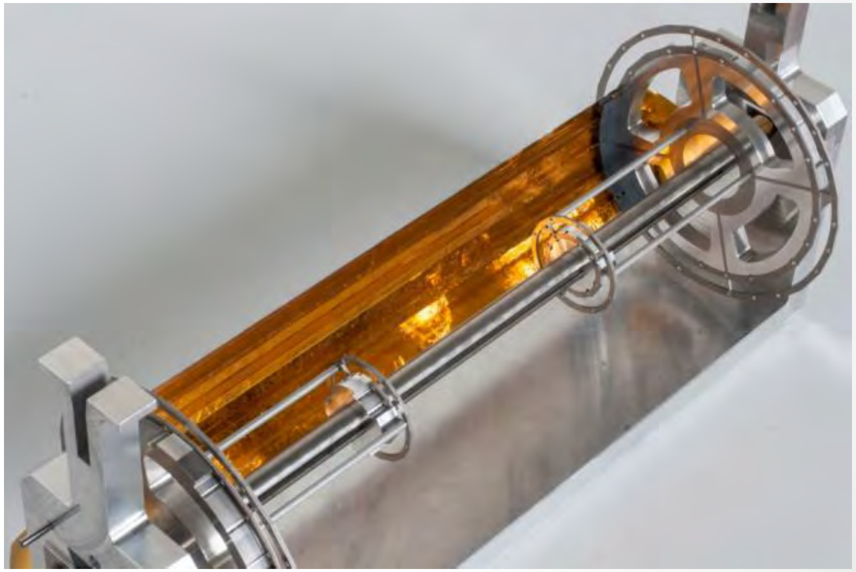
- HV-MAPS
  - Thinned to 50 μm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 μm Kapton™
  - 14 μm Alu traces
- **Kapton™ Frame Modules**
  - 25 μm foil
  - **Self supporting**
- Alu end wheels
  - Support for all detectors



Rendering of old vertex detector CAD

Outer Module

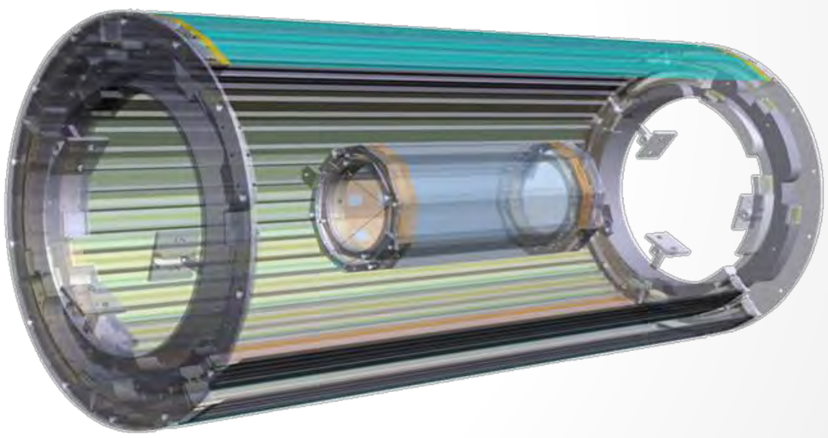
- HV-MAPS
  - Thinned to 50 µm
  - Sensors 2 x 2 cm^2
- Kapton™ flex print
  - 25 µm Kapton™
  - 14 µm Alu traces
- **Kapton™ Frame Modules**
  - 25 µm foil
  - **Self supporting**
- Alu end wheels
  - Support for all detectors



Old 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

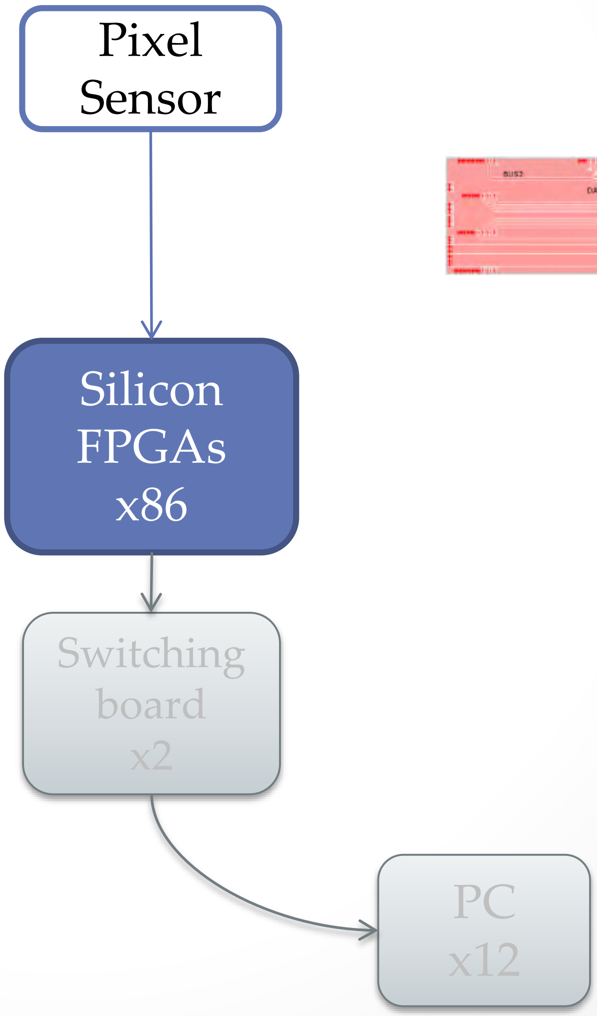


Old pixel detector CAD rendering

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
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  - Timing detector readout
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  - Off-detector read out boards
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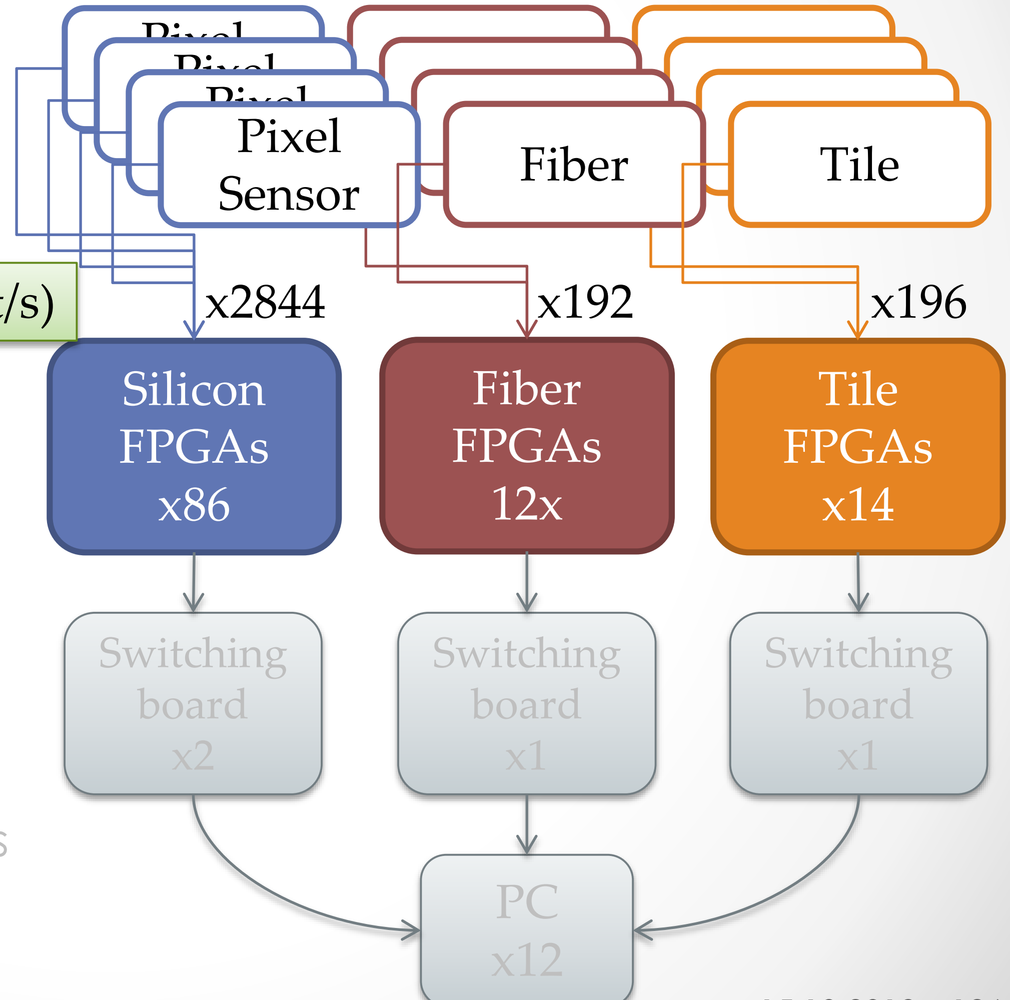
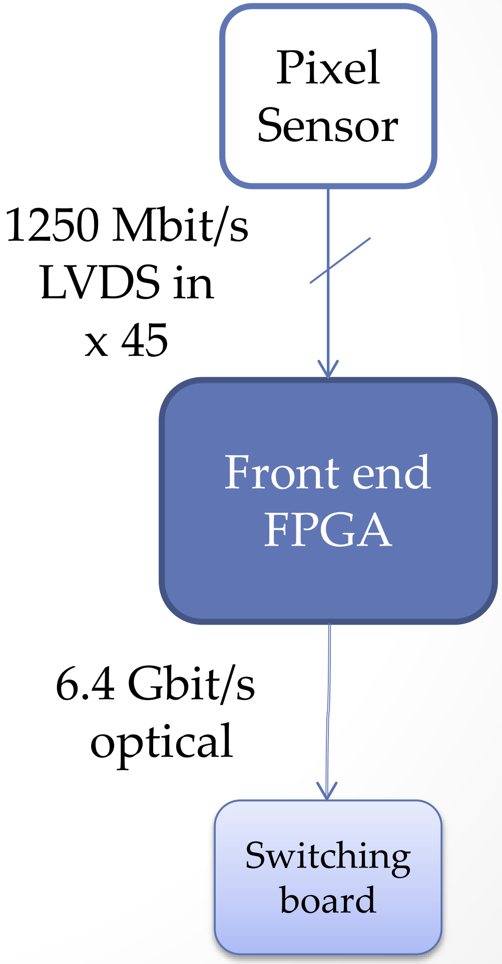
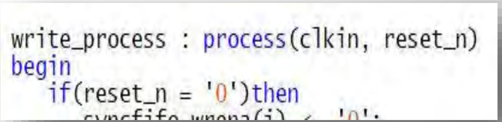


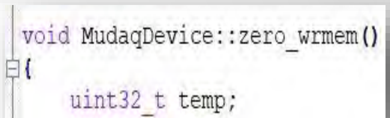
Front End FPGAs

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

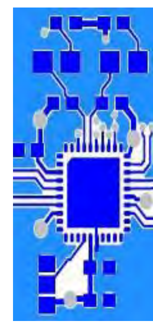


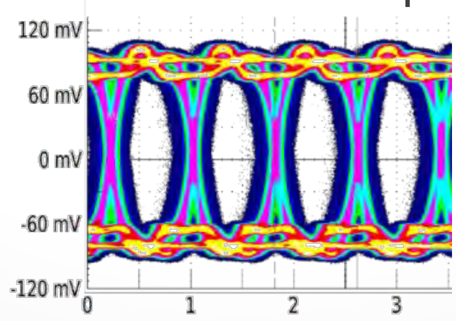
Tasks, problems, challenges





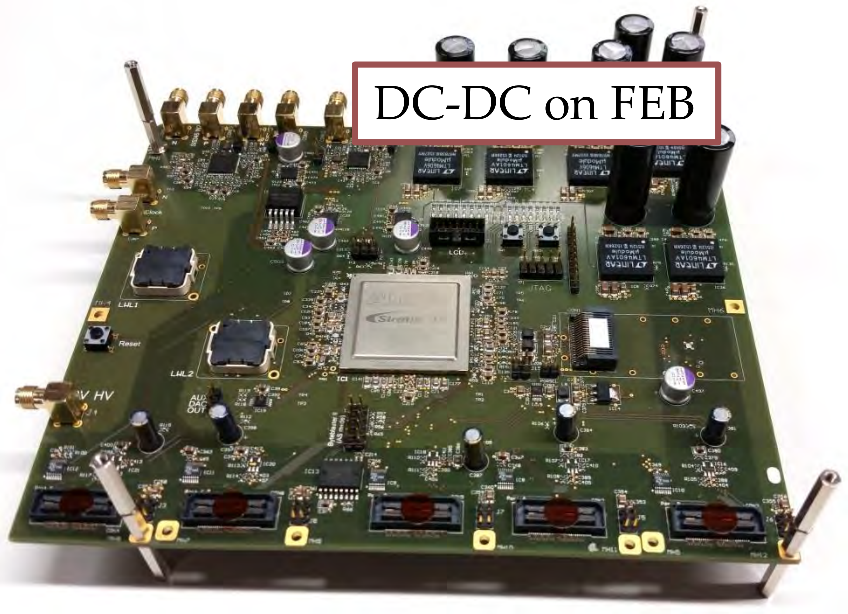
- Hard-, firm- and software developments
- Testing custom designed front-end boards and bringing them to operation
- Data transmission studies
  - Electrical links
  - Optical links
- Data reduction at front-end:
  Up to 45 × 1.25 Gbps → 1 × 6 Gbps
  with as little logic utilization as possible





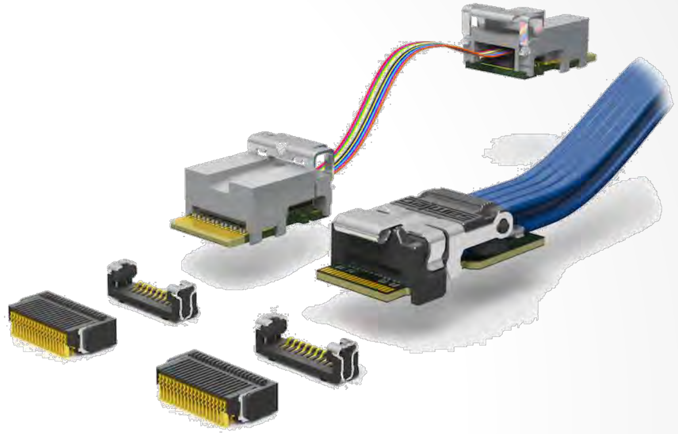
Front End Board V1.02

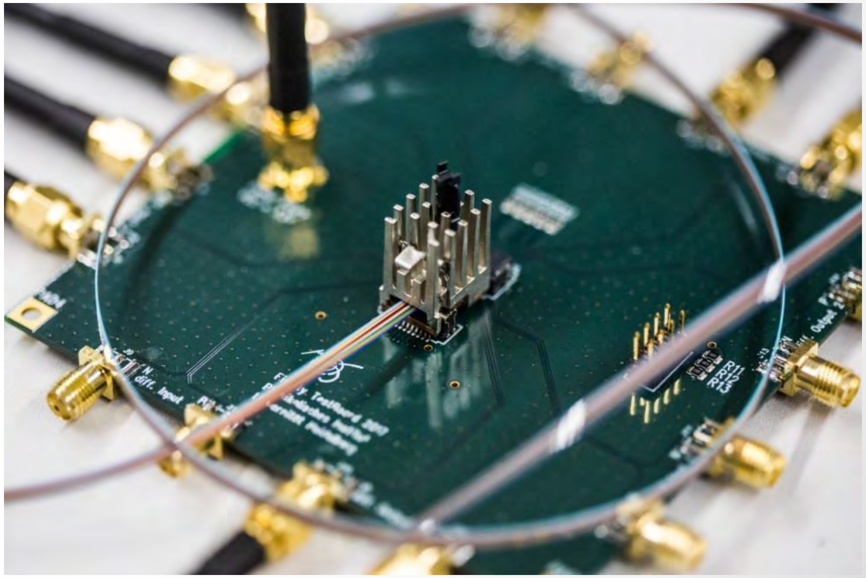
- Bug-fix of Front End Board V1.0
  - Extra resistors
  - Extra voltage regulator
- DC-DC for entire partition
- Eight PCBs produced
  - Tested and ok



Front End Board V2.0

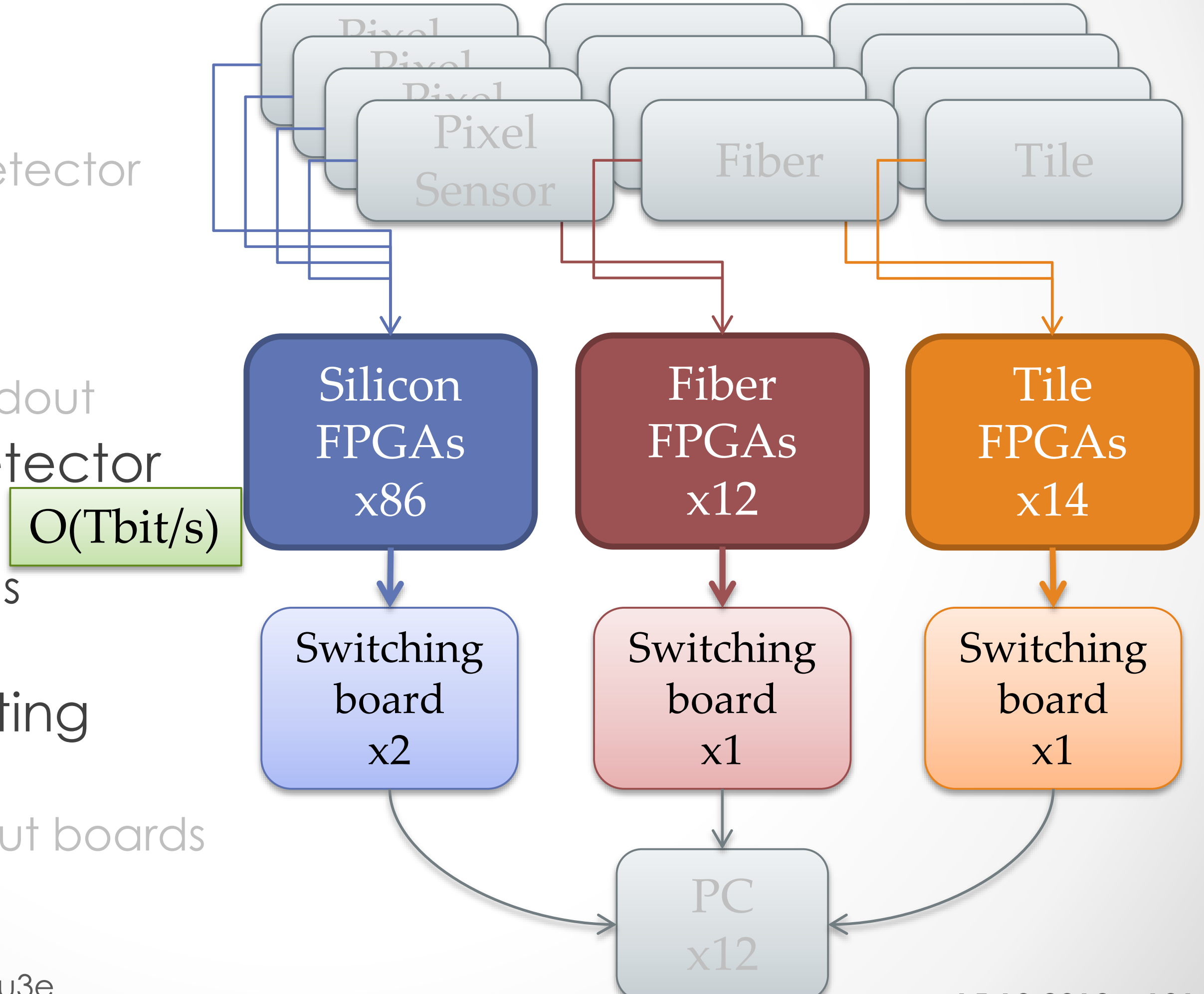
- Better FPGA
- FireFly optical transceivers
  - o Replace
    - MiniPods and
    - QSFP with
    - 2x Samtec FireFly 4-fold optical transceiver
  - o Smaller, cheaper,…
  - o Performance currently under evaluation
    (B.Sc. Thesis Benjamin Weinlaeder)





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
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  - … to switching boards
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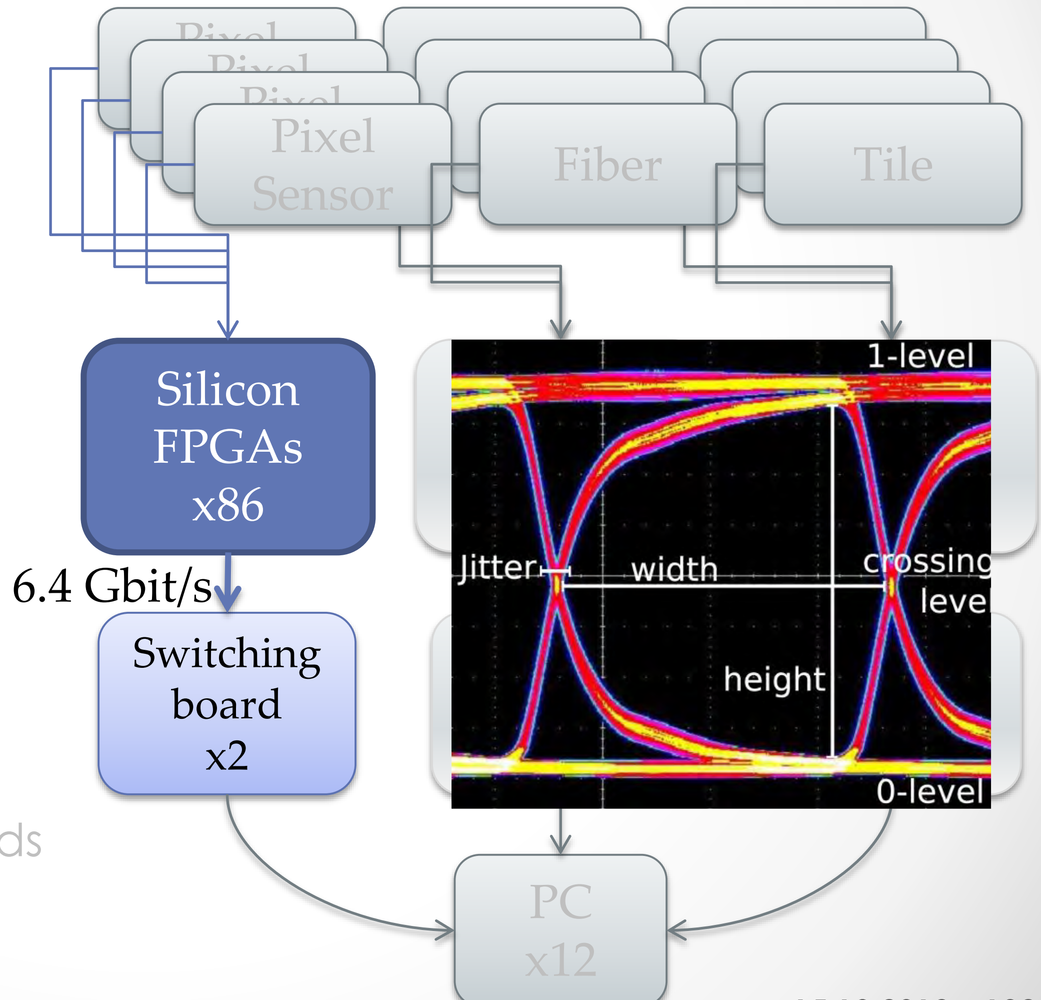
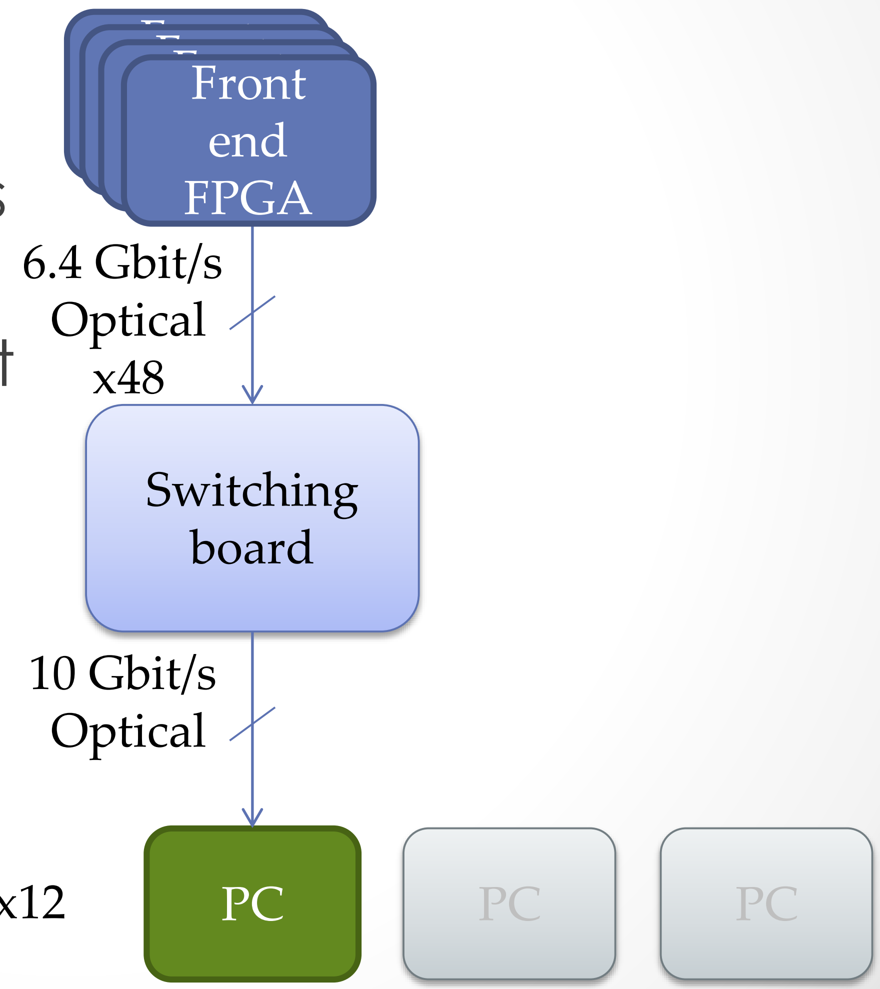


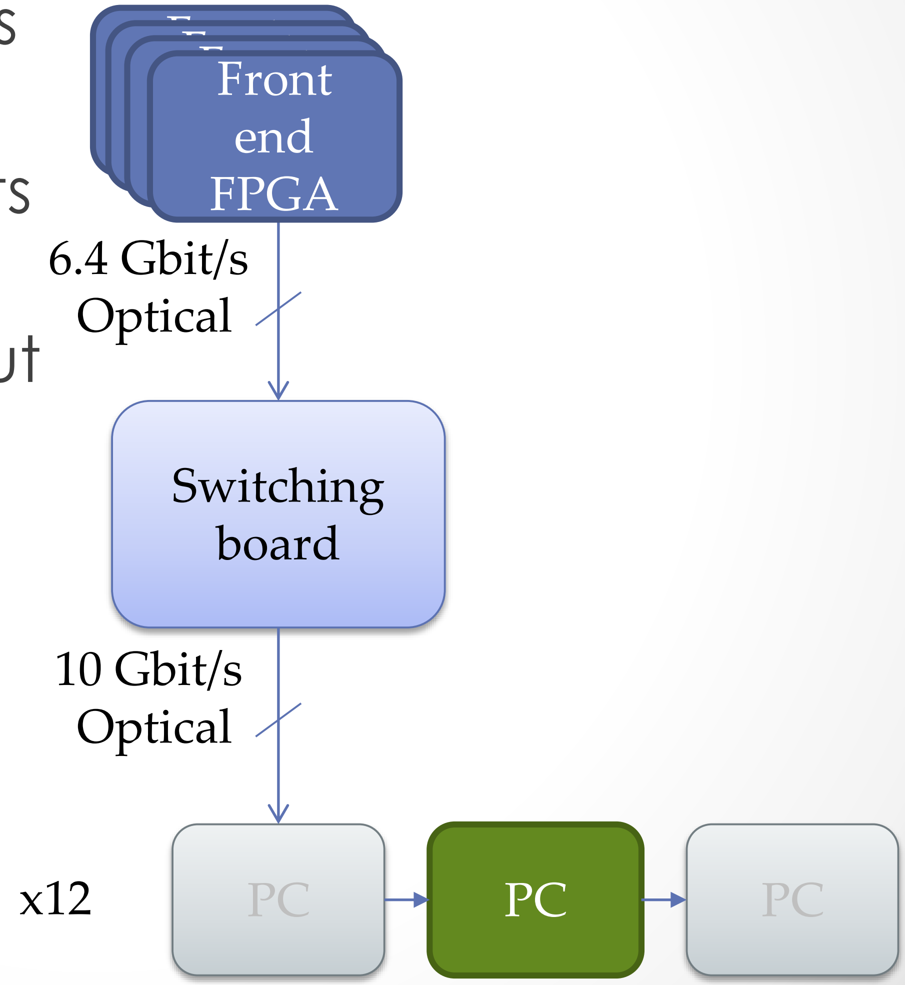
Switching Board

- 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
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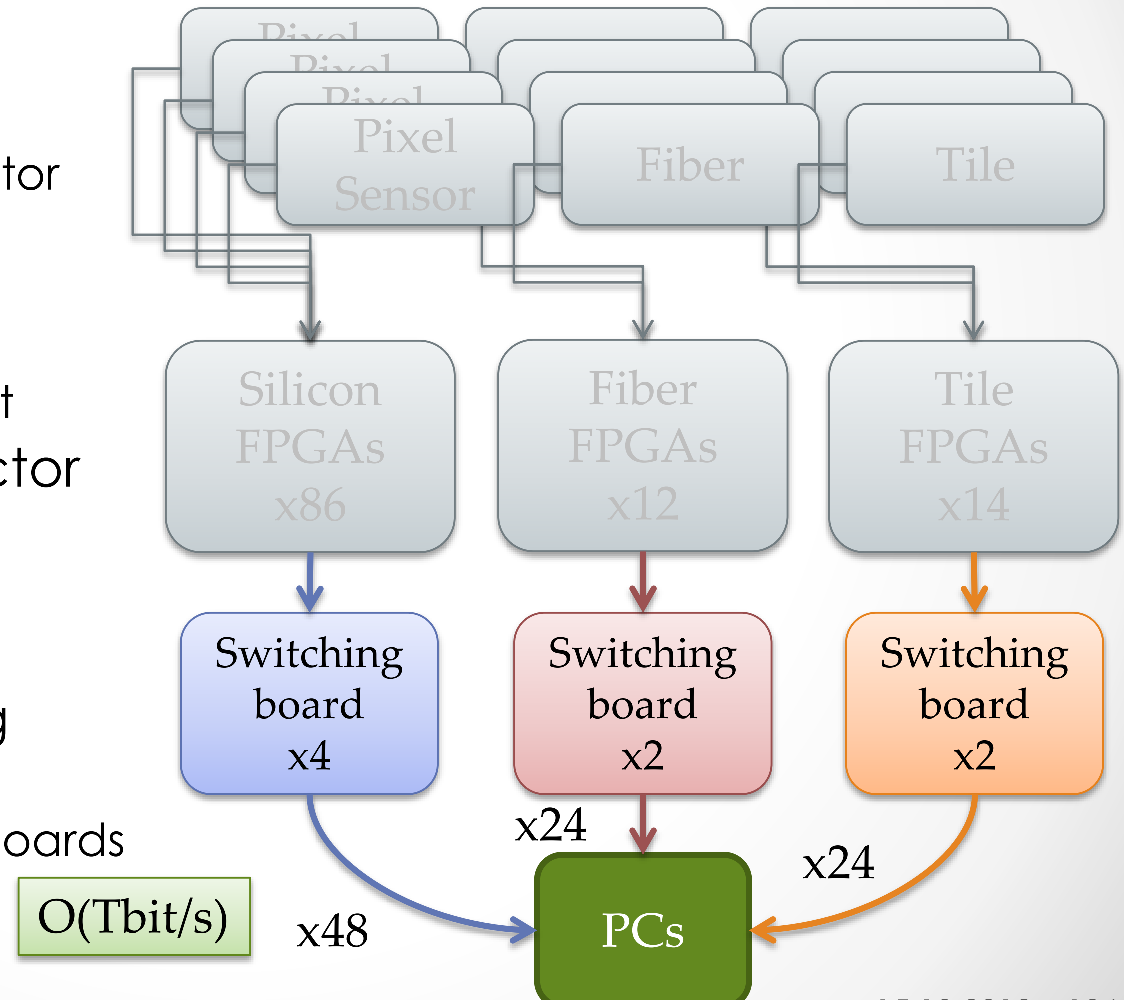


GPU-PC

- 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

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

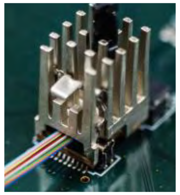
Receiving FPGA board PC side

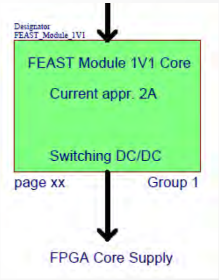
- De5a-NET boards from Terasic
- Successfully tested at Mainz
- 8 out of 12 boards already acquired

DAQ tests
Backup

Front End Board V2.0

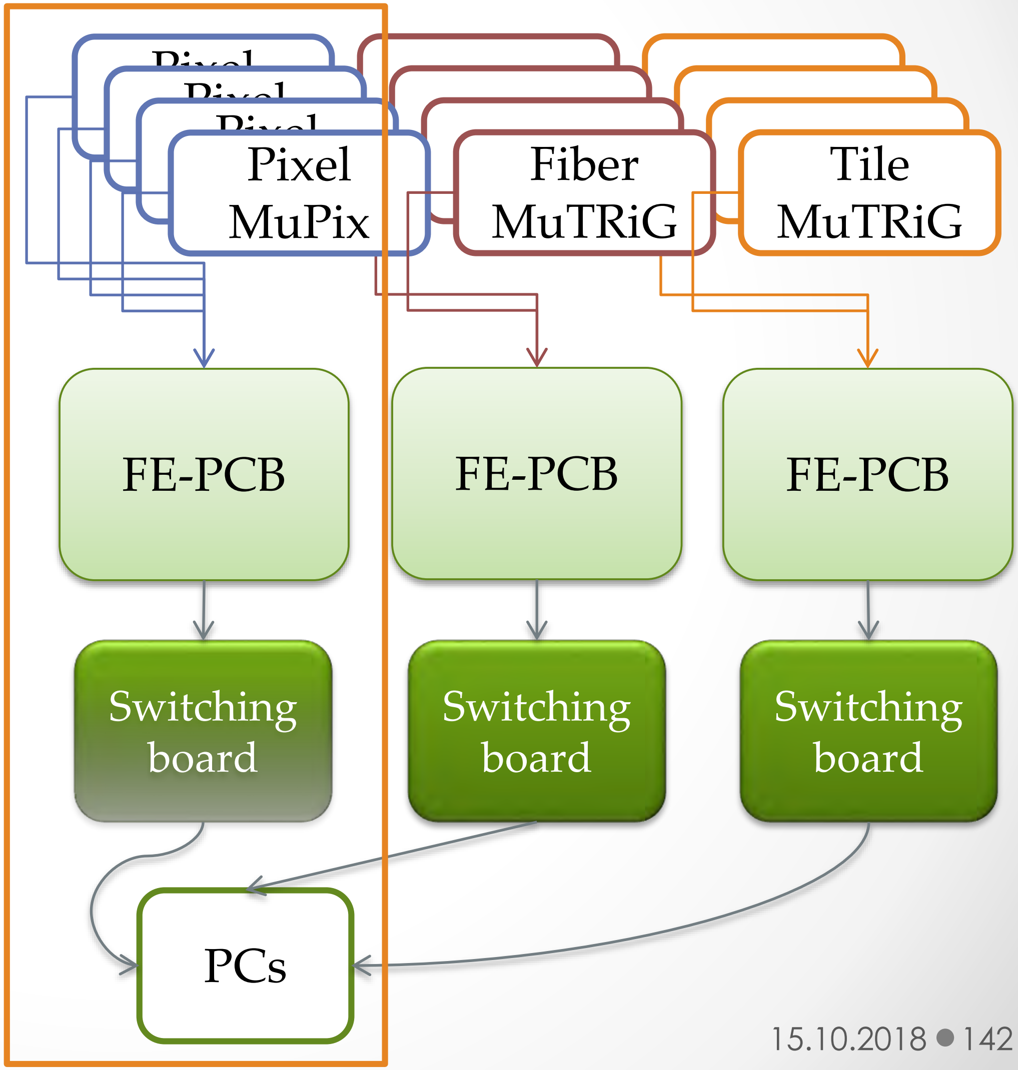
- Better FPGA
  - ArriaV instead of StratixIV
  - Lower power consumption
    - 6.6W → 3.3W (<10W)
- FireFly optical transceivers
  - 2 x 2W
- Clock distribution chips
  - SI5345 2 x 1W
- DC-DC only for FEB
  - FEAST2MD compatible
  - Or based on TI chip set i.e. LM27403





Readout Vertical Slice Test

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



Readout Vertical Slice Test

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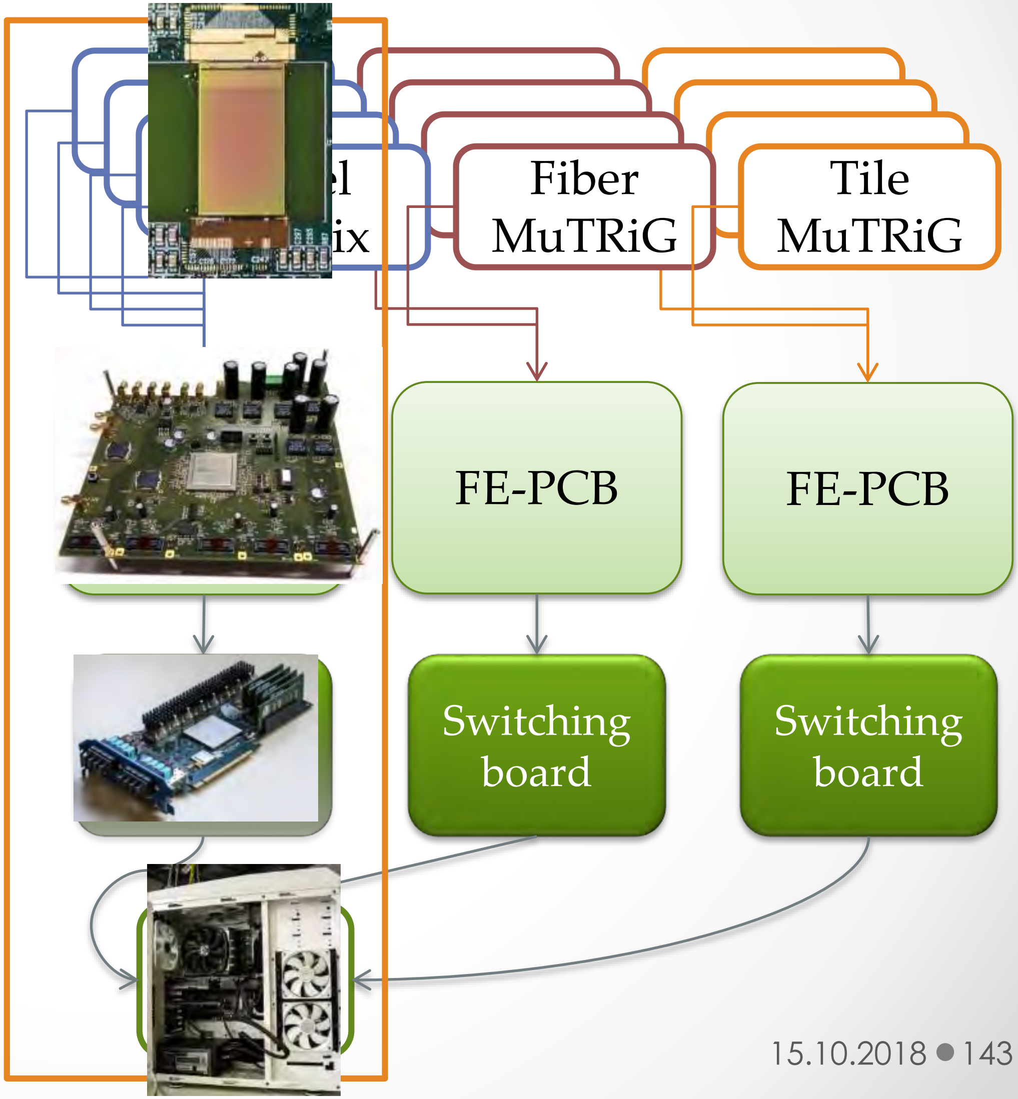
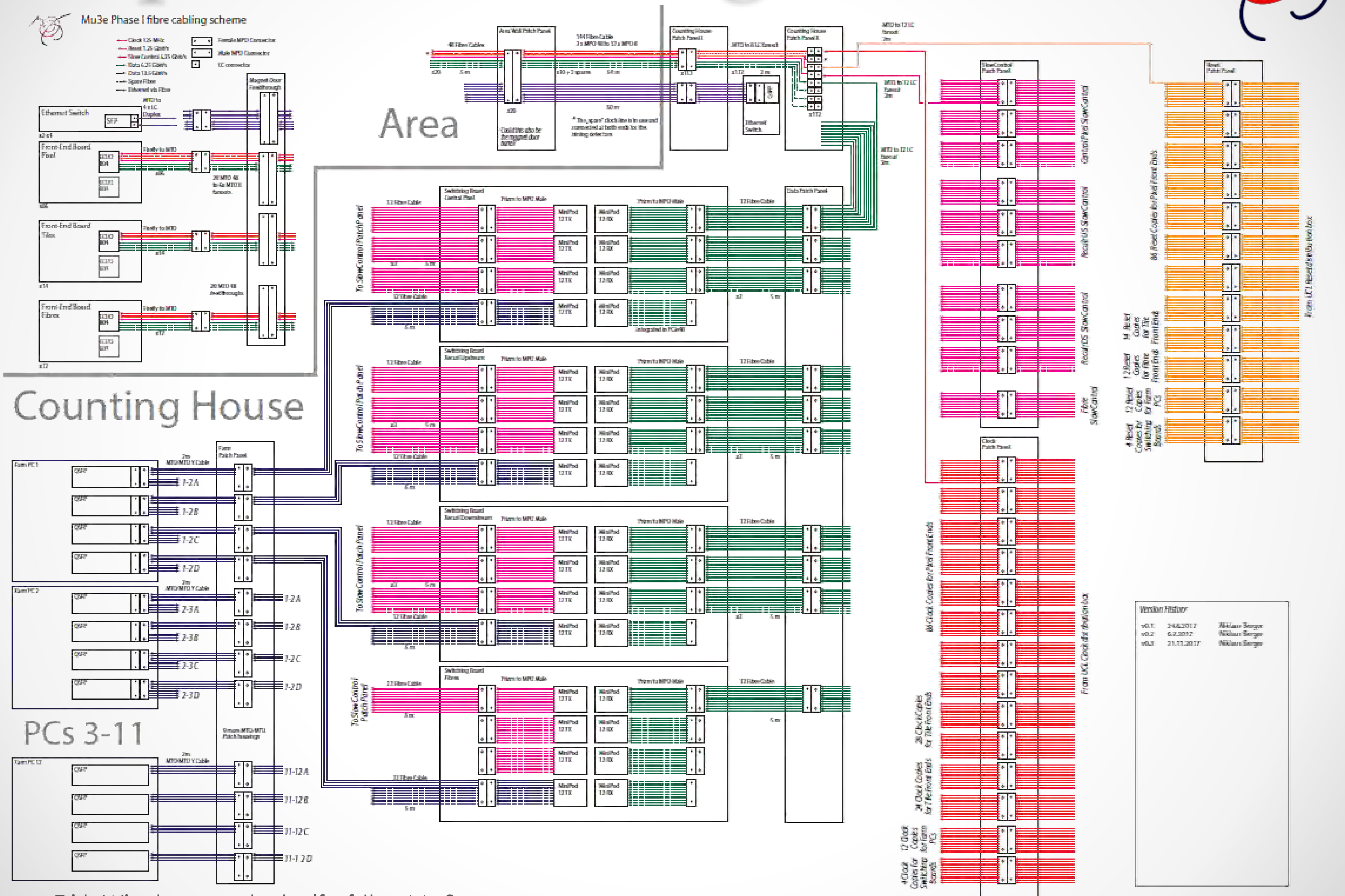


Optical cabling scheme

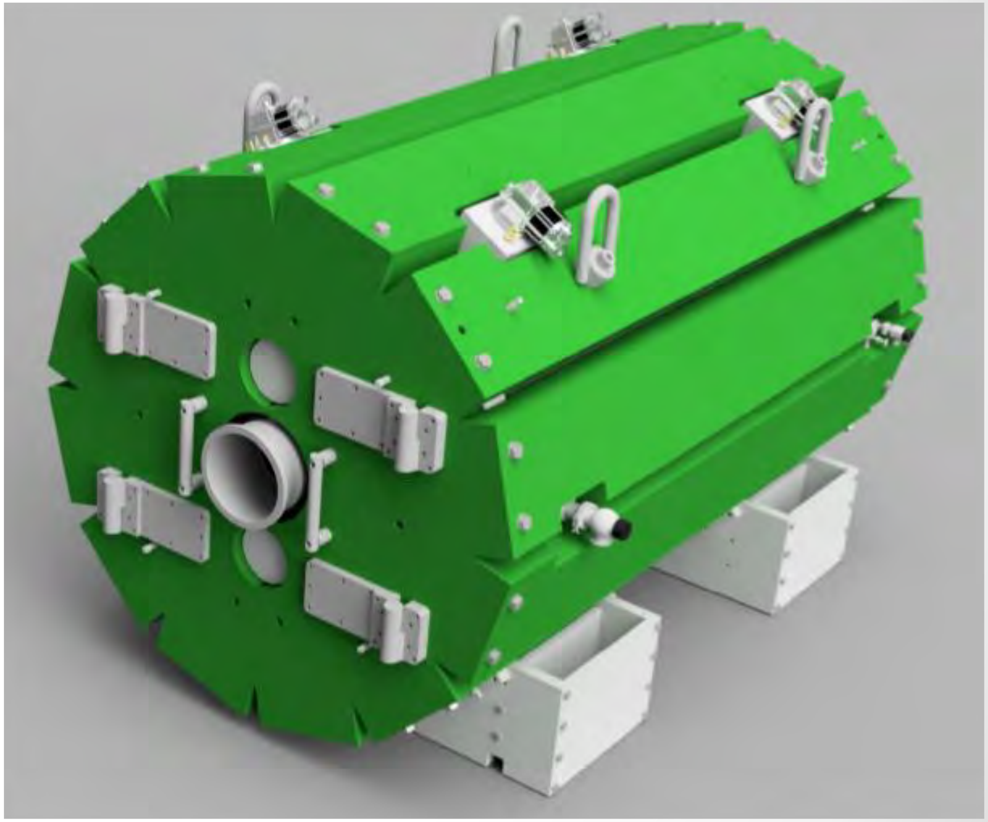


Backup Area Planning

• • •

Mu3e Magnet

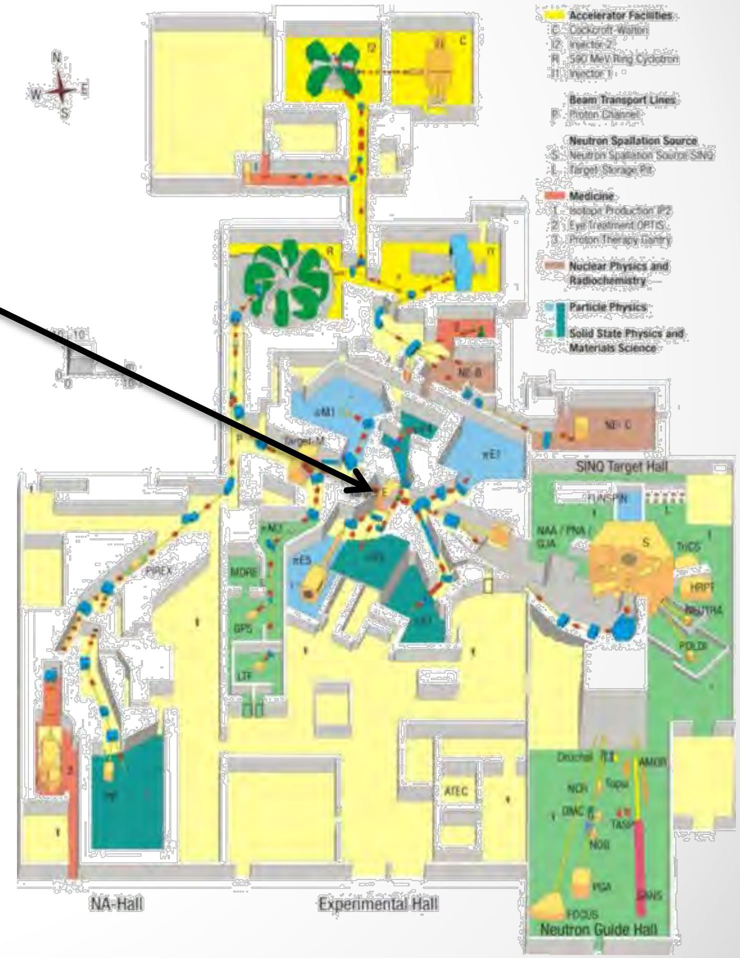
- 1T solenoid
- 3m long
- 1m bore diameter
- Superconducting coil
- Dry cryo system
- Magnet TDR ready
- Delivery early 2019



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



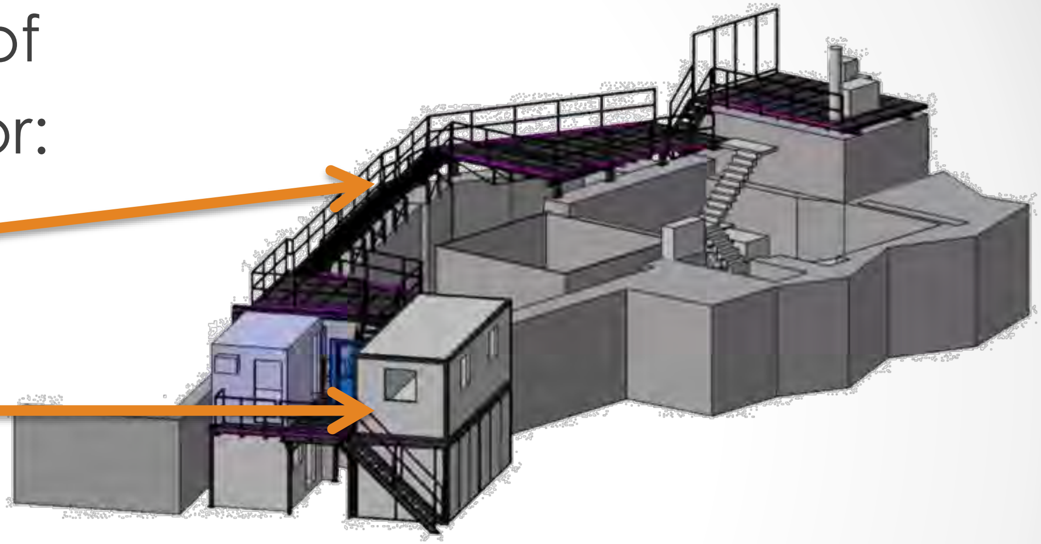
Area Planning

Good progress in terms of CAD, civil engineering for:

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

Remark:

- Space in area **extremely** limited



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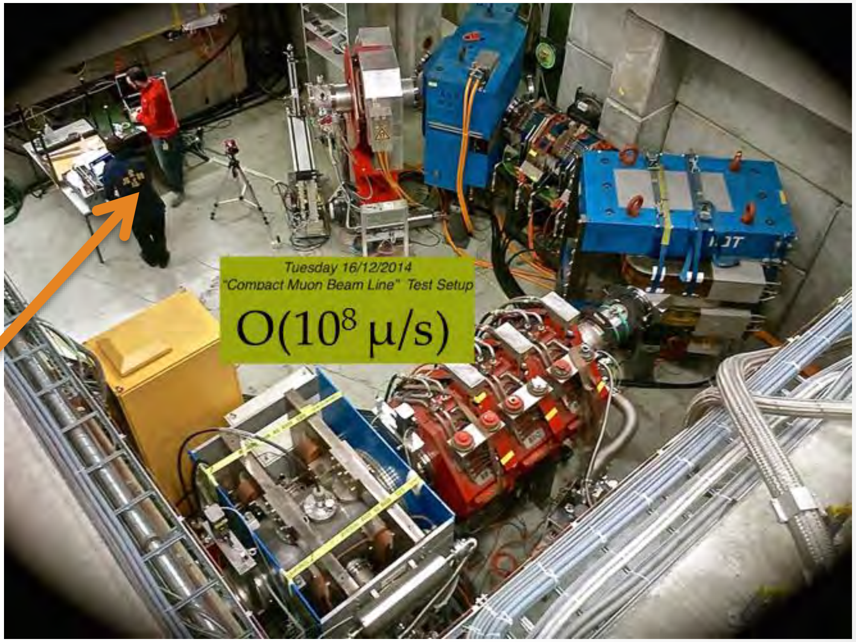

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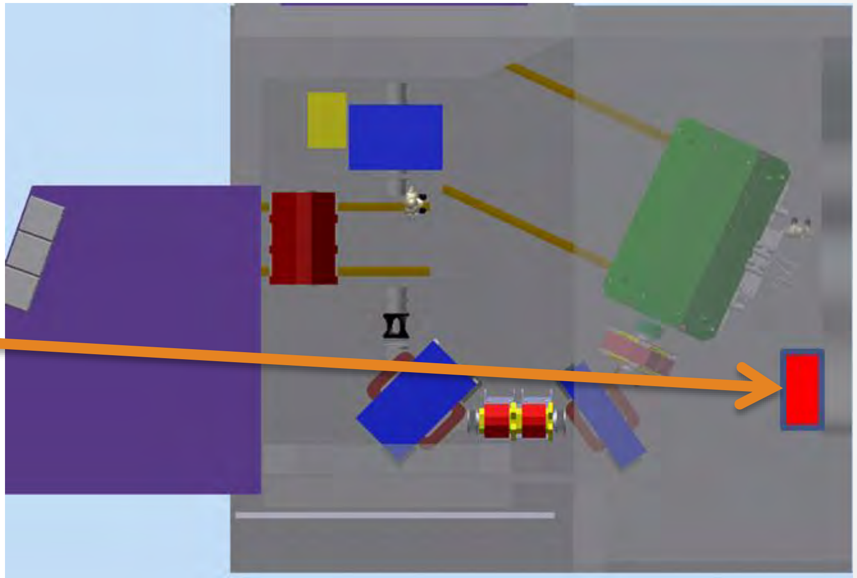

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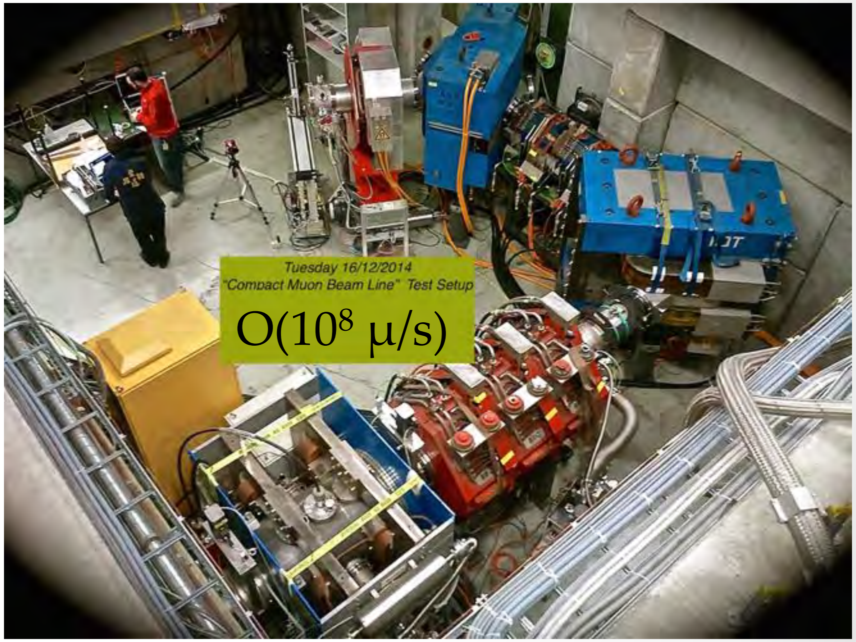
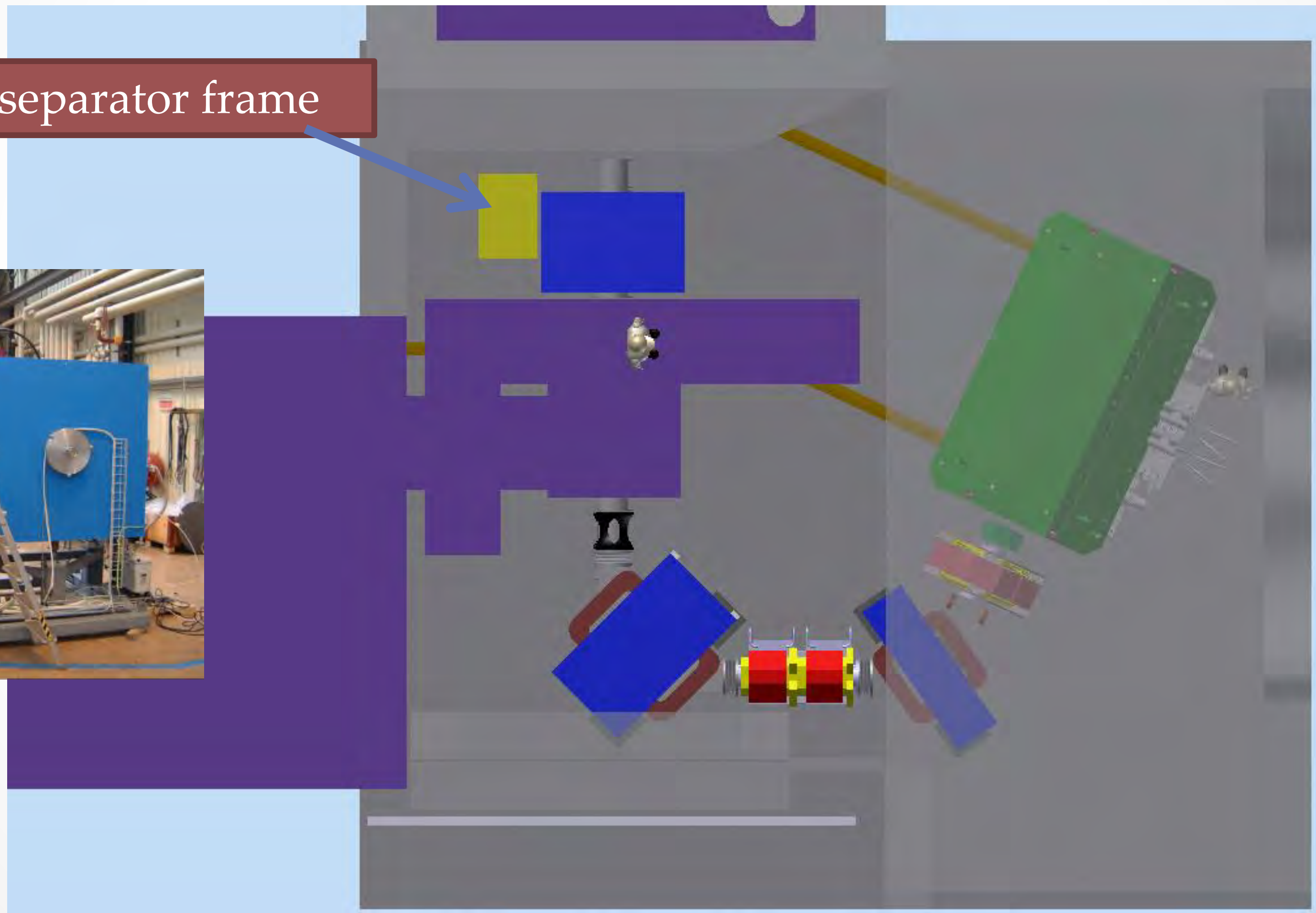
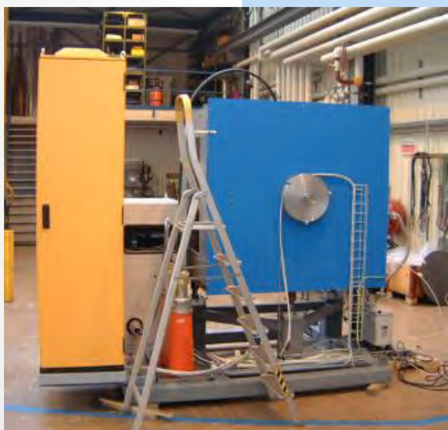


Area Layout

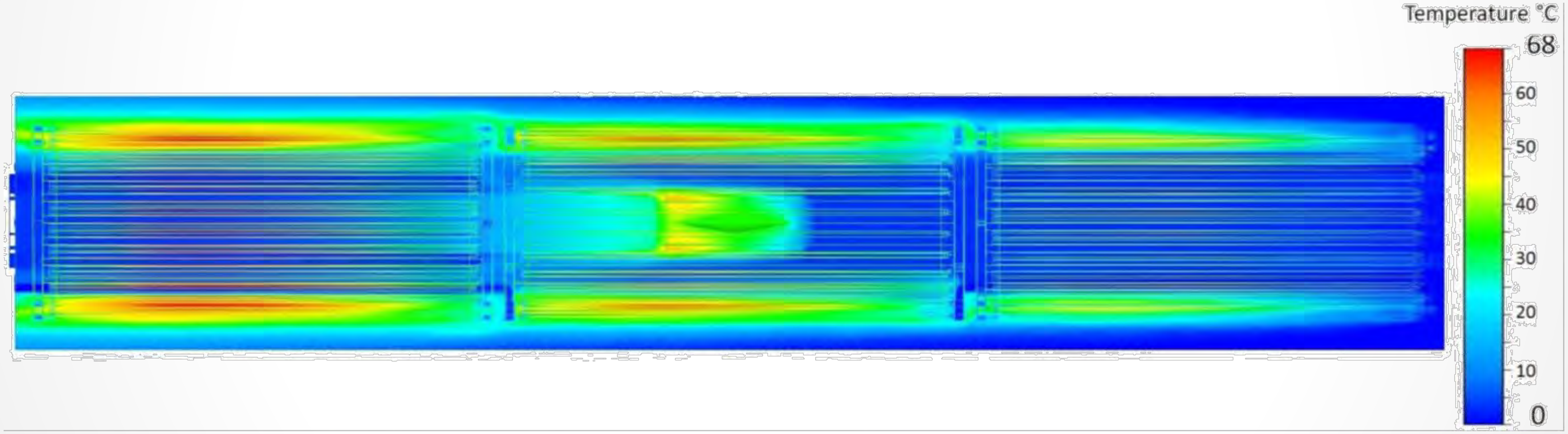




Cooling Backup

…

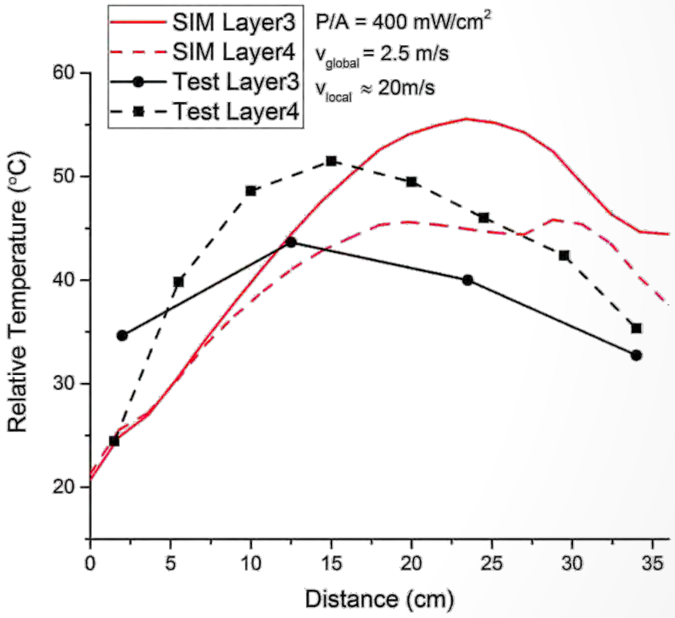
Old Simulation



He cooling
400mW/cm^2

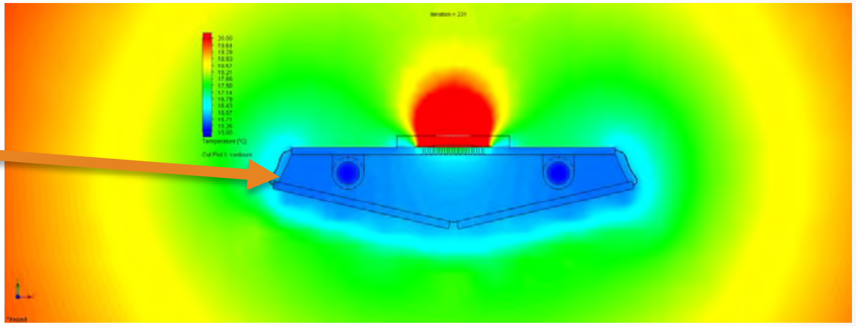
Old Test Results

- 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**

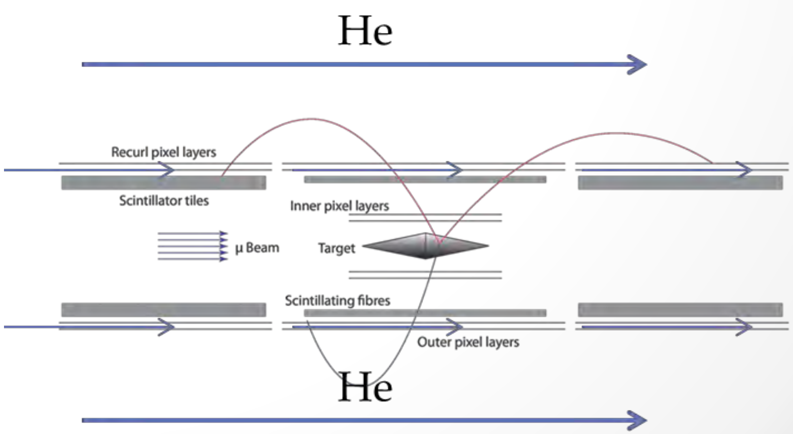


Cooling Concept

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

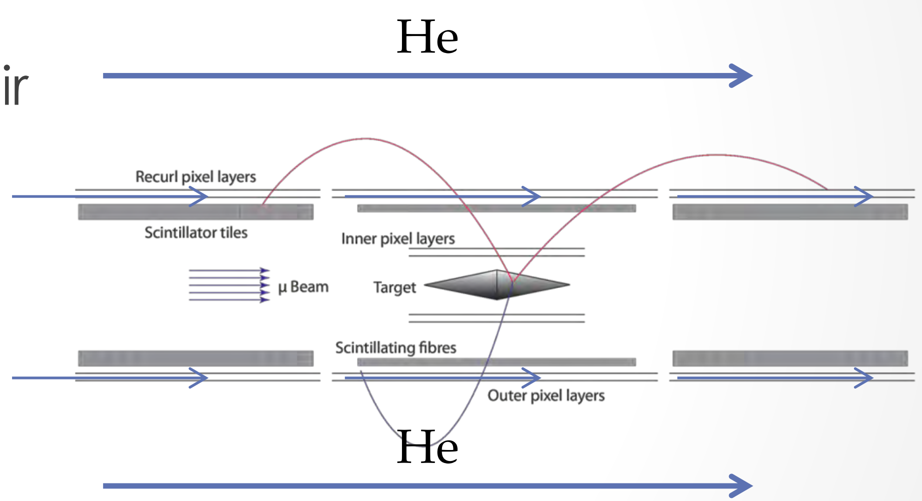


Tile cooling simulation



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



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

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

33 / 52

Pixel helium cooling BVR49

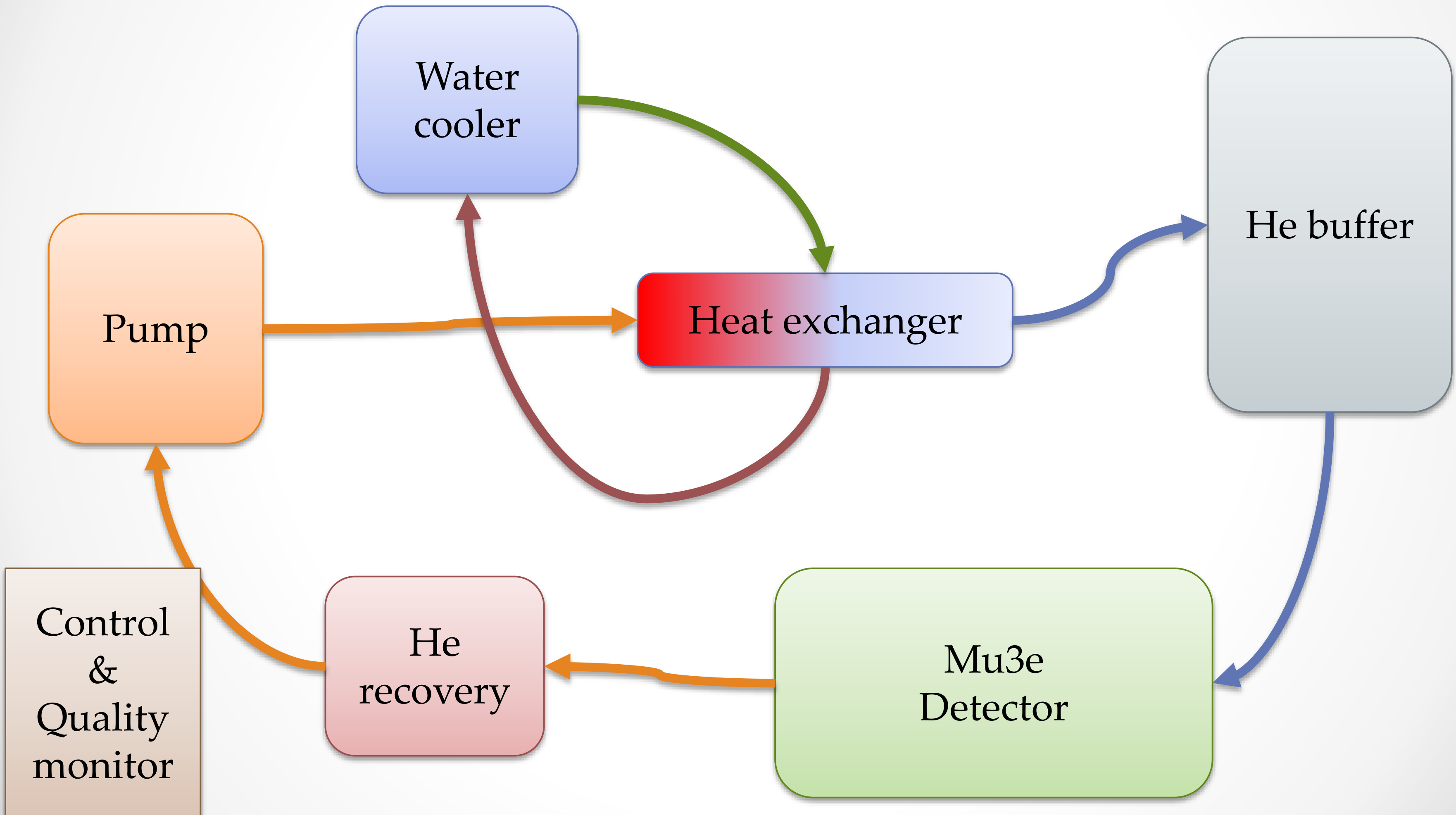
- Multiple He cooling circuits
- Volumetric flow between
  - 0.72 m^3/min. and
  - 23 m^3/min.
- Separately fine adjustable
- Segment overall He system?
  - Introduce redundancy

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 cooled PC

He cooling system

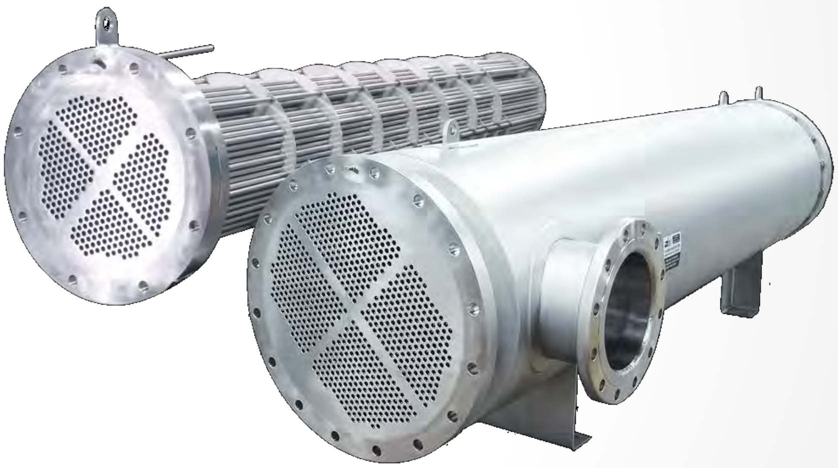


Water cooler

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

Heat exchanger

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

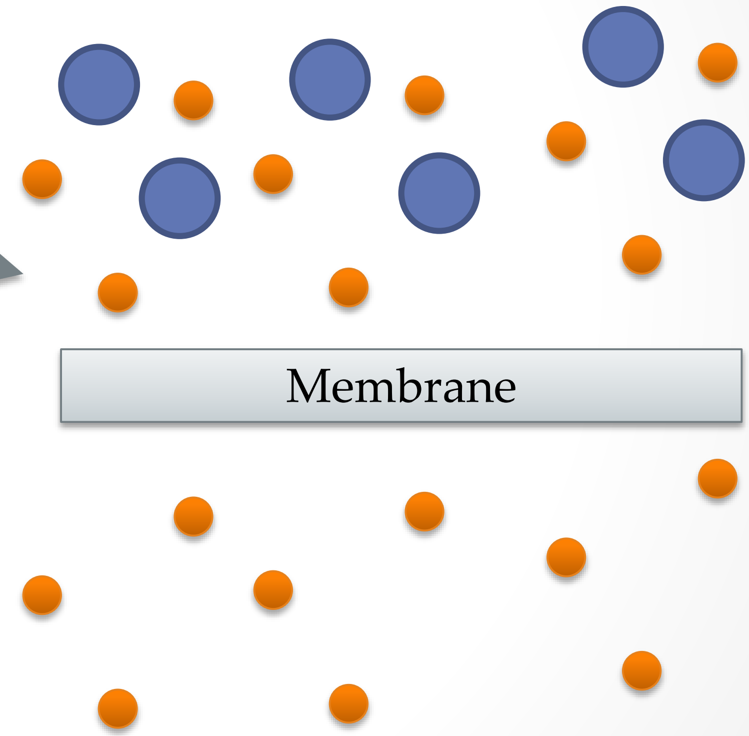


Helium buffer

- 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

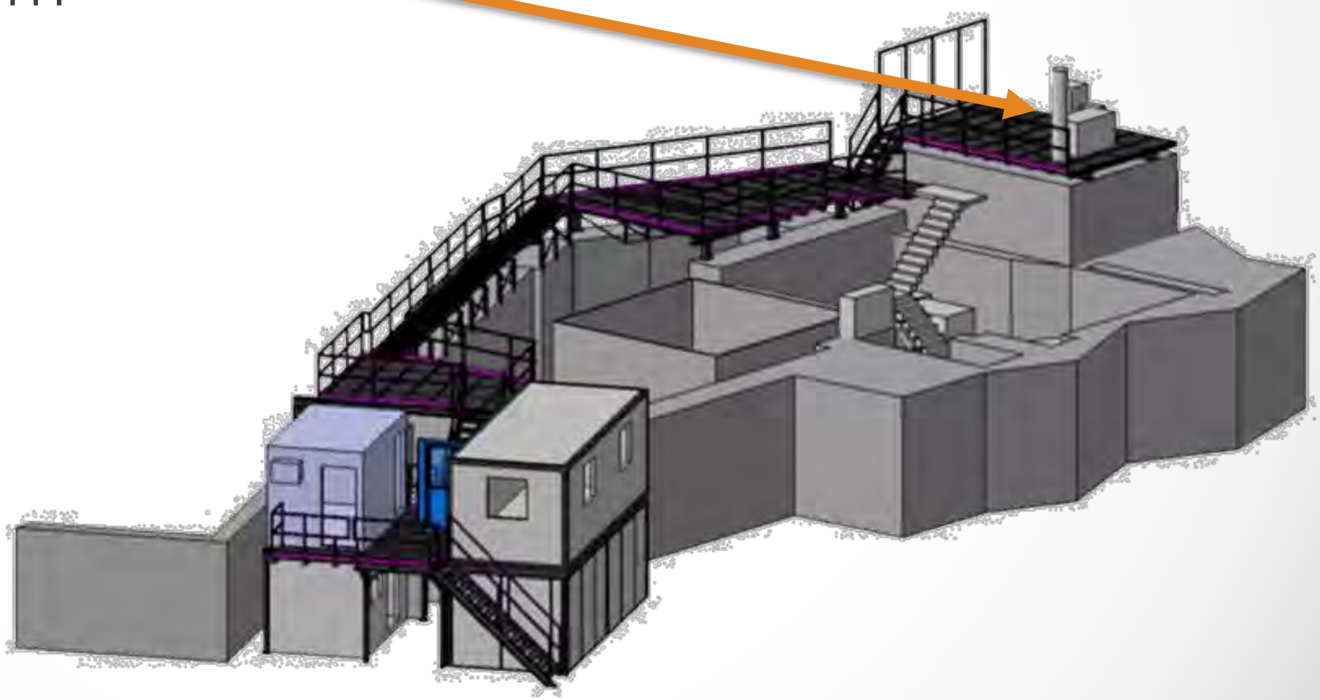
- Volumetric flow high
  - 50m^3/min.
- ≥20cm diameter pipes
- Insulated
- Flexible (?)

Pump(s)

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

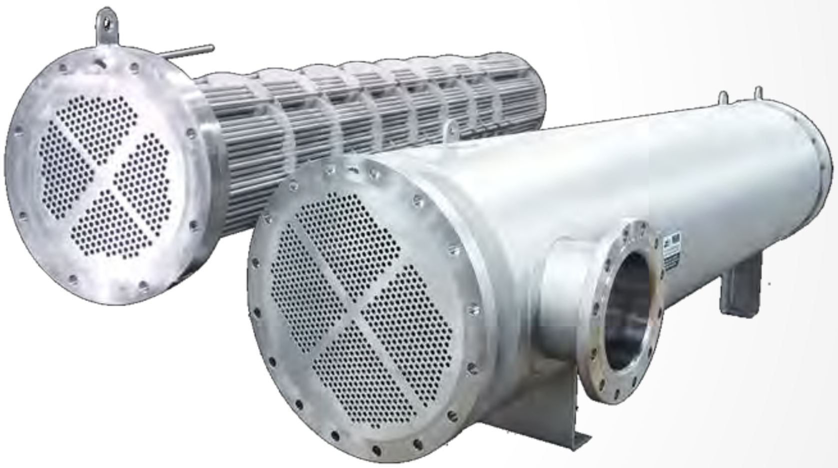
Installation space

- 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

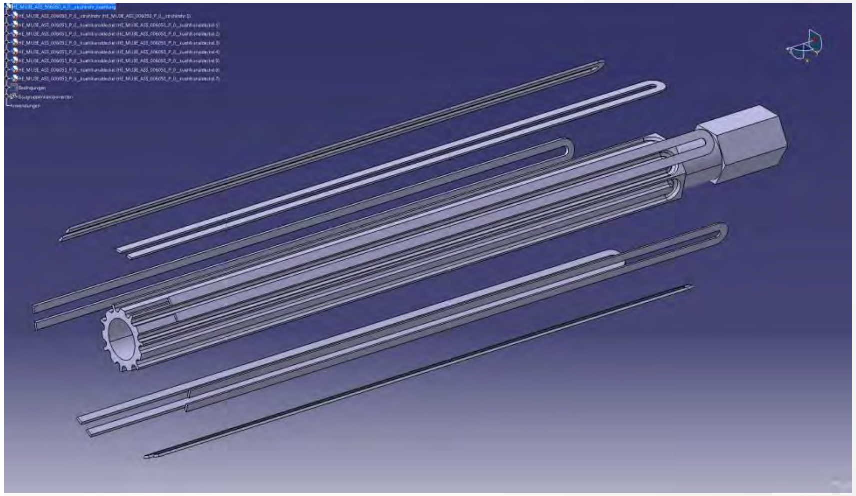
- Molecular weight : 4.0026 g/mol
- Gaseous phase
- Gas density (1.013 bar at boiling point) : 16.752 kg/m^3
- Gas density (1.013 bar and 15 °C (59 °F)) : 0.1692 kg/m^3
- Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)) : 1.0005
- Specific gravity : 0.138
- Specific volume (1.013 bar and 25 °C (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

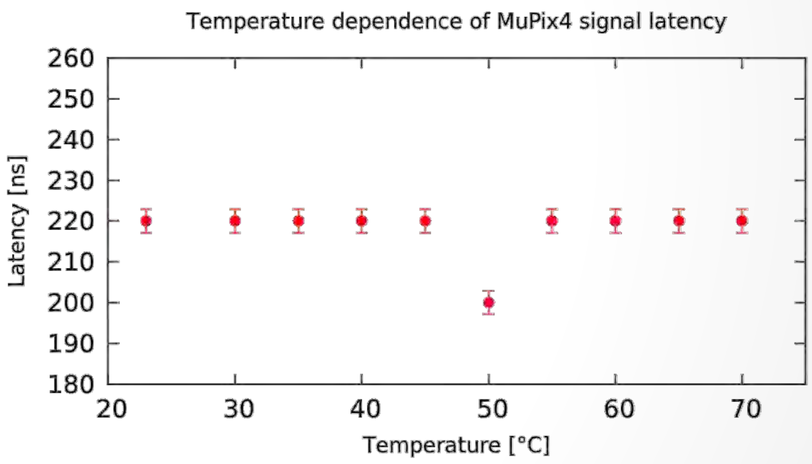
- Beam pipe cooling (abandoned)
  - With cooling liquid
  - 5°C temperature
  - Significant flow possible
  - … using grooves in pipe
- For electronics
  - FPGAs and
  - Power regulators
  - Mounted to cooling plates
- Total power several kW



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

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  - He more effective than air
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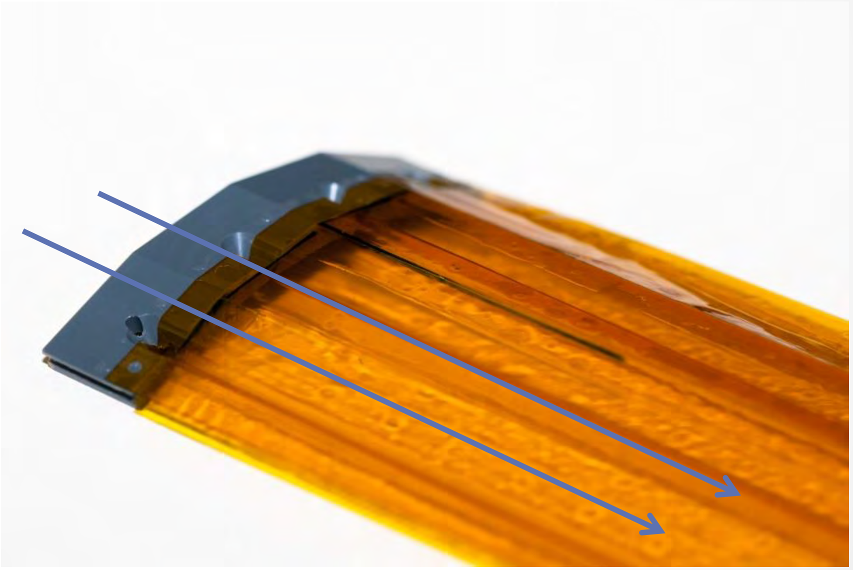
- **Local flow for Tracker**
  - Distribution to Frame
    - V-shapes
    - Outer surface



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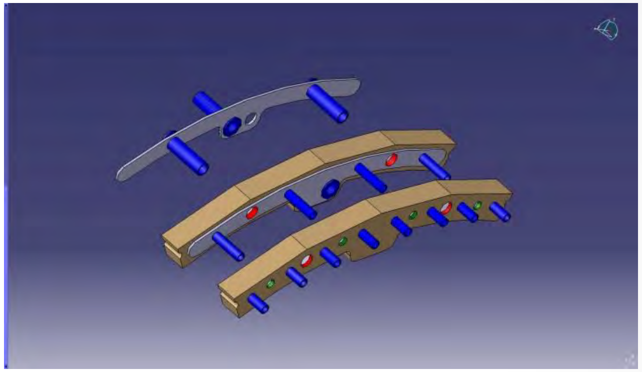
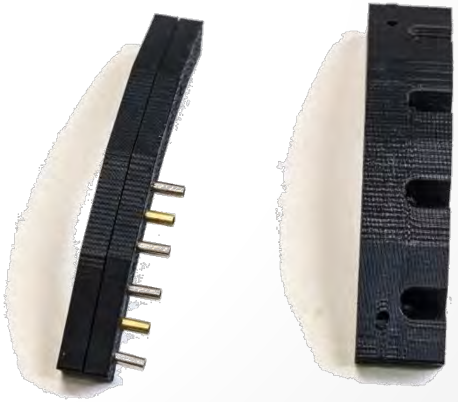


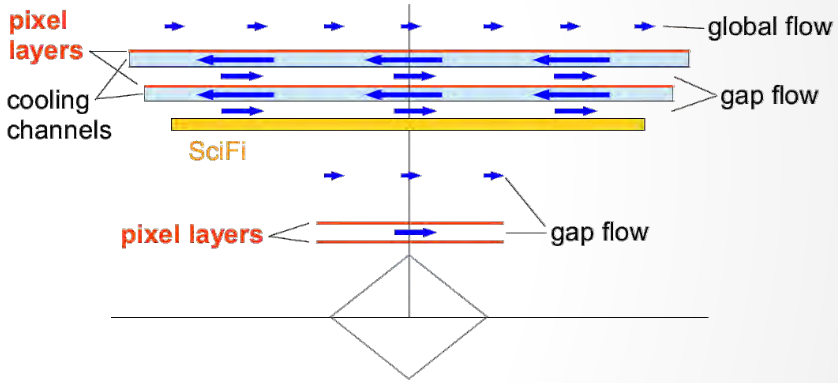


Old design study

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

Old design study



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

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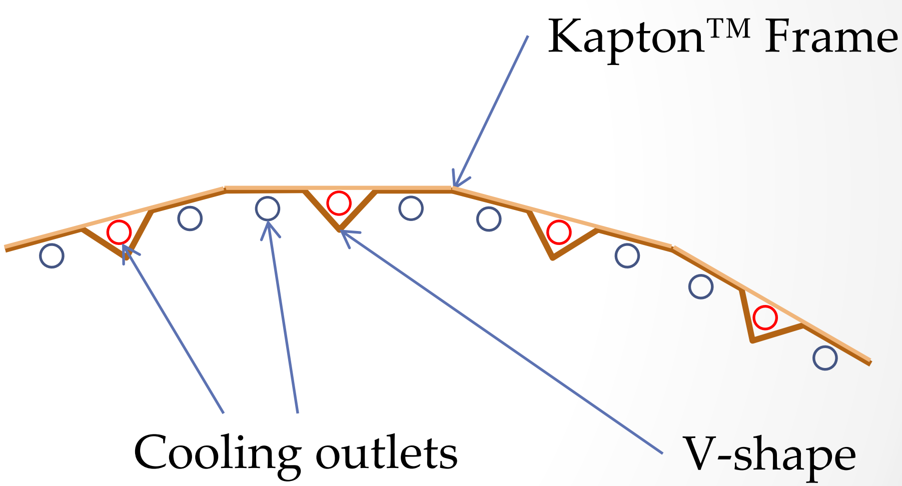
  - o Distribution to Frame
    - **V-shapes**
    - **Outer surface**



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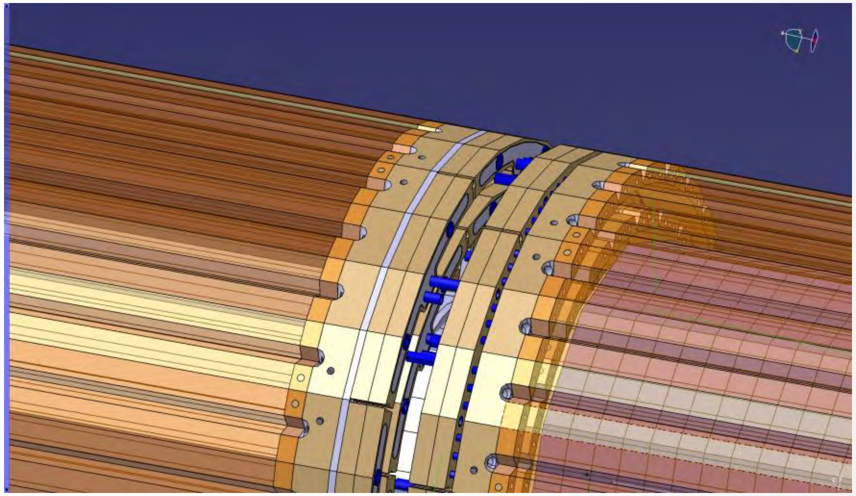
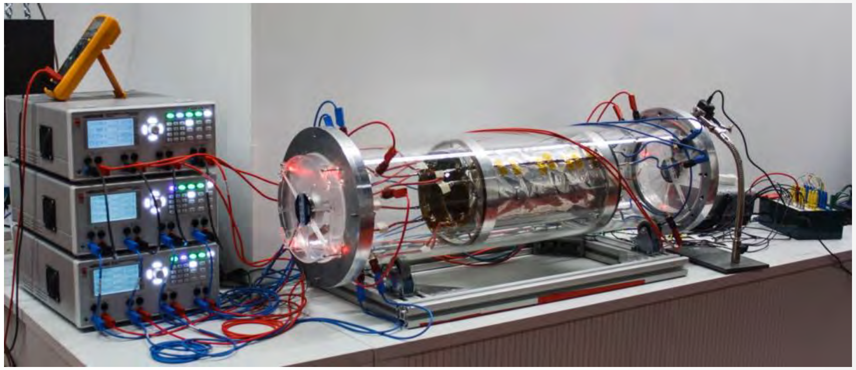
    - V-shapes
    - Outer surface

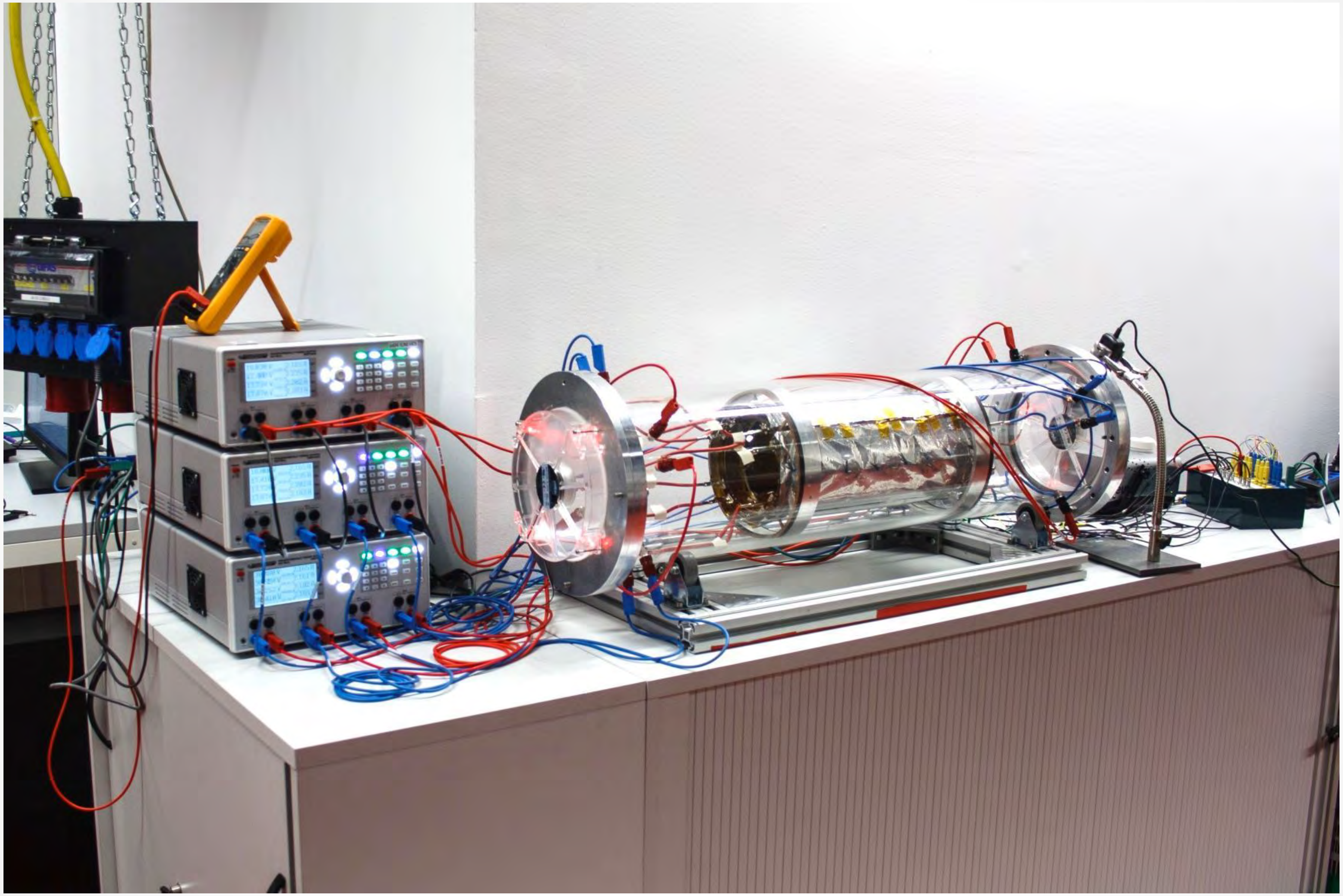


Old design study

Tests

- **Full scale prototype**
  - Layer 3+4 of silicon tracker
  - Ohmic heating ($150 mW/cm^2$)
  - 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™**
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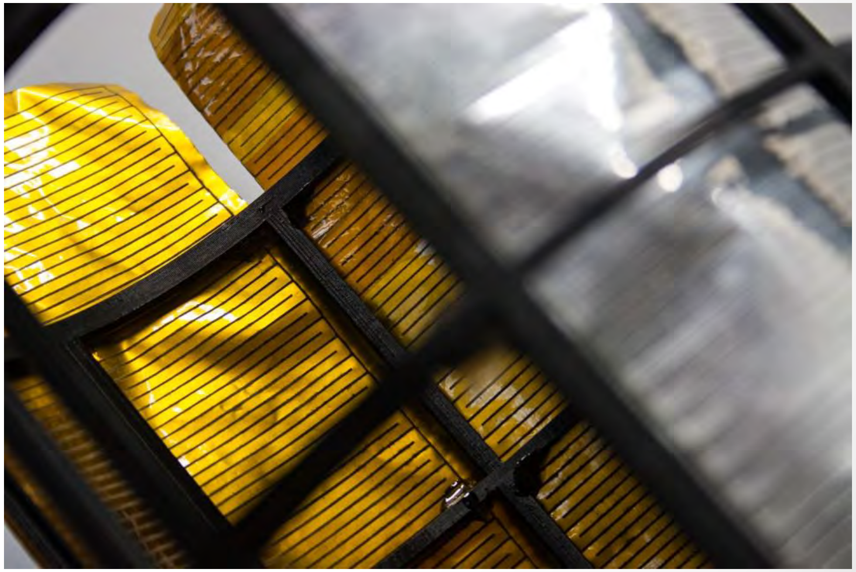
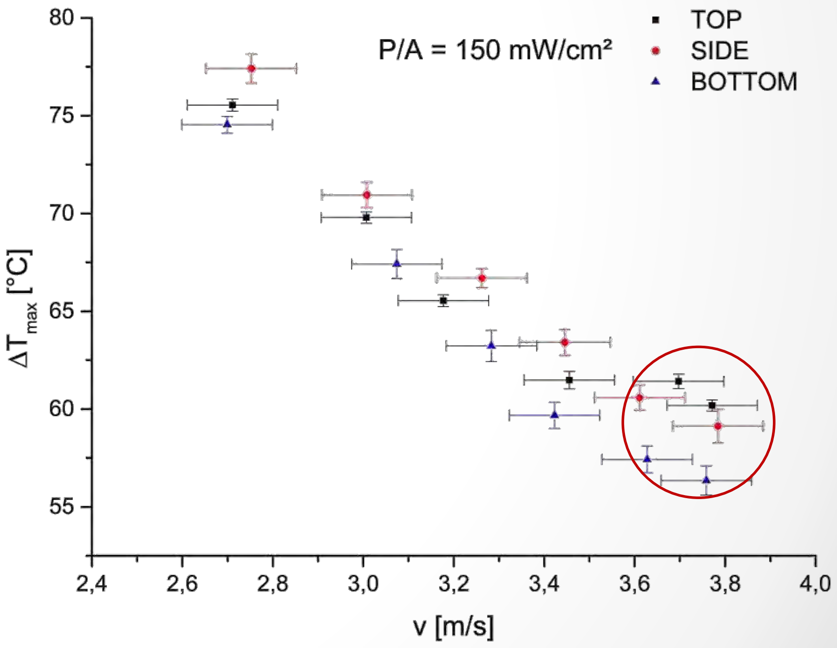
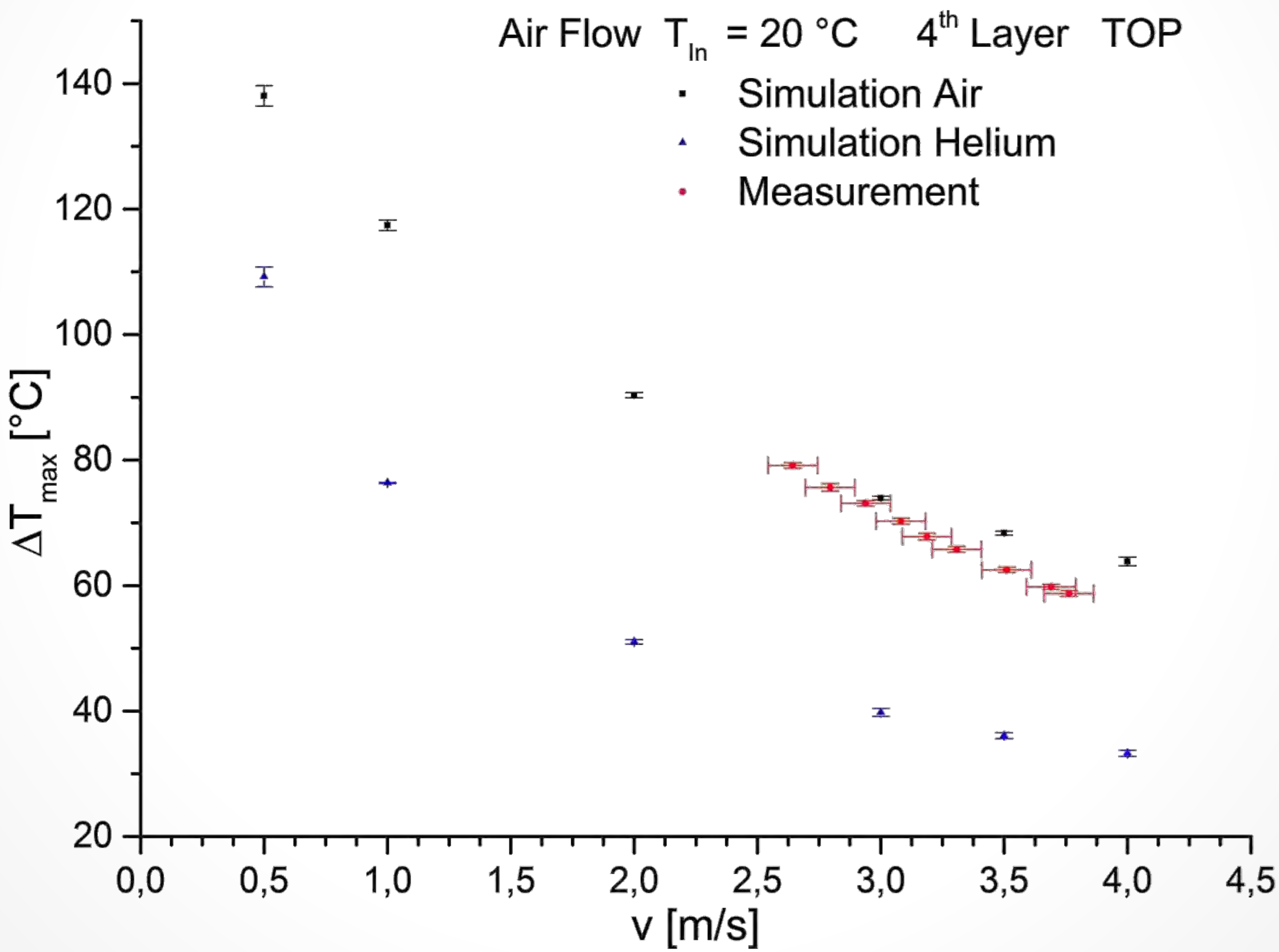


Test Results

- 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**

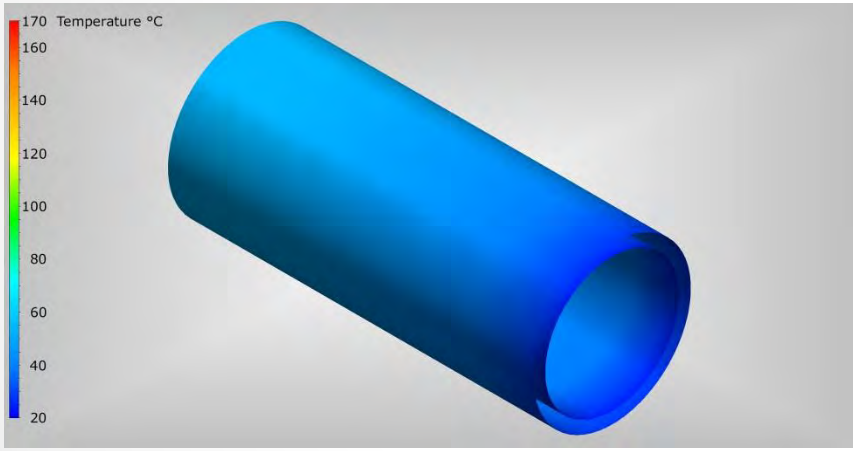


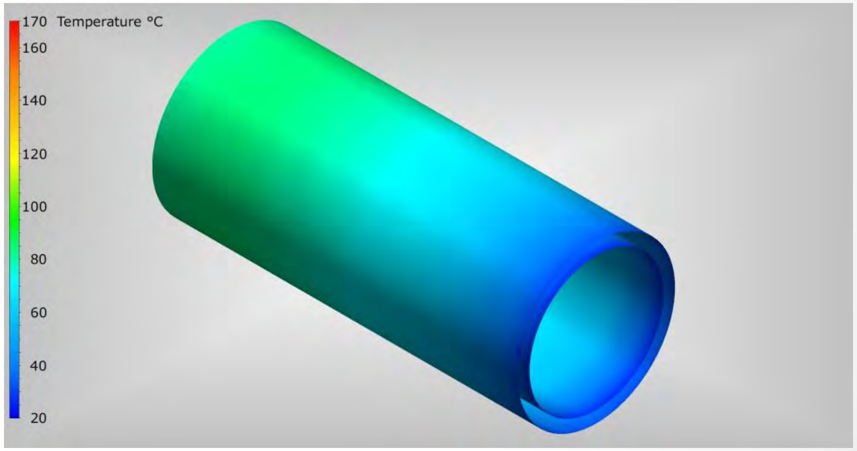
Comparison Simulation and Tests



Comparison Old Simulation He and Air

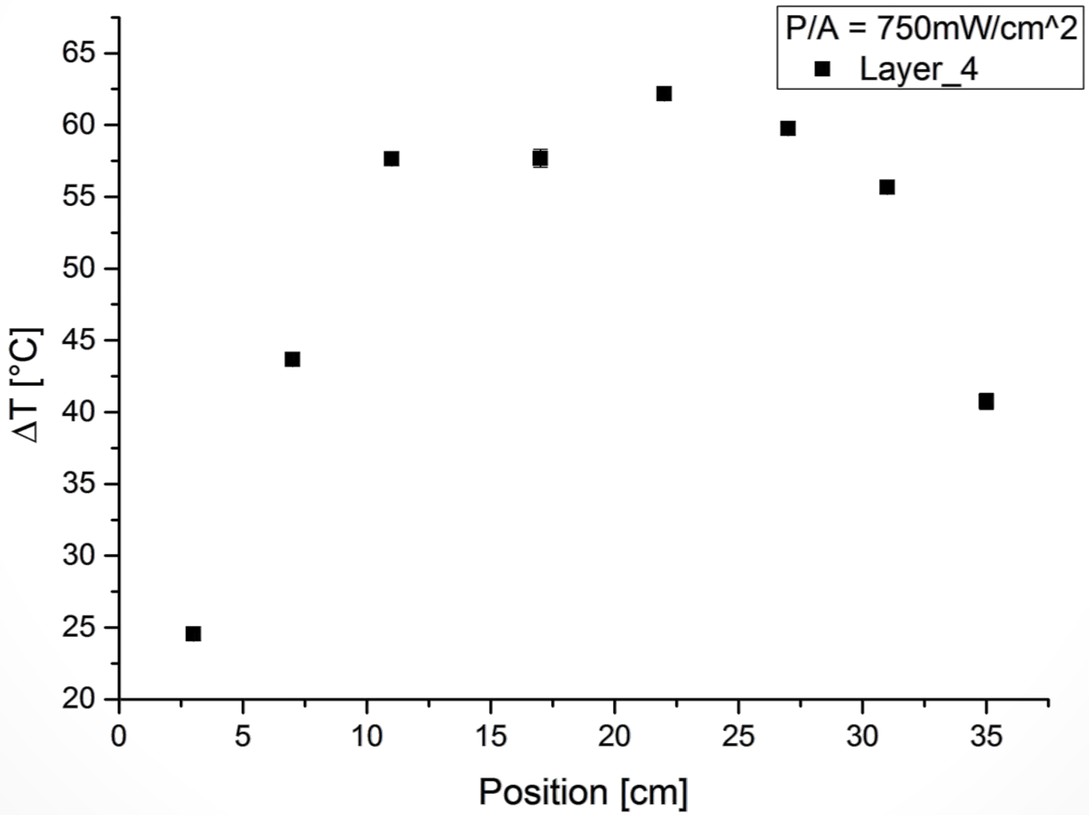
He | Air





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

He Cooling 750 mW/cm^2



New He Cooling

- The He distribution was redesigned
  - New detector design
  - New He distribution concept
- Thermo mechanical mockups
  - New mockups are built
  - New institutes involved (UK, CH)
- Simulation for new design
  - Well on the way