

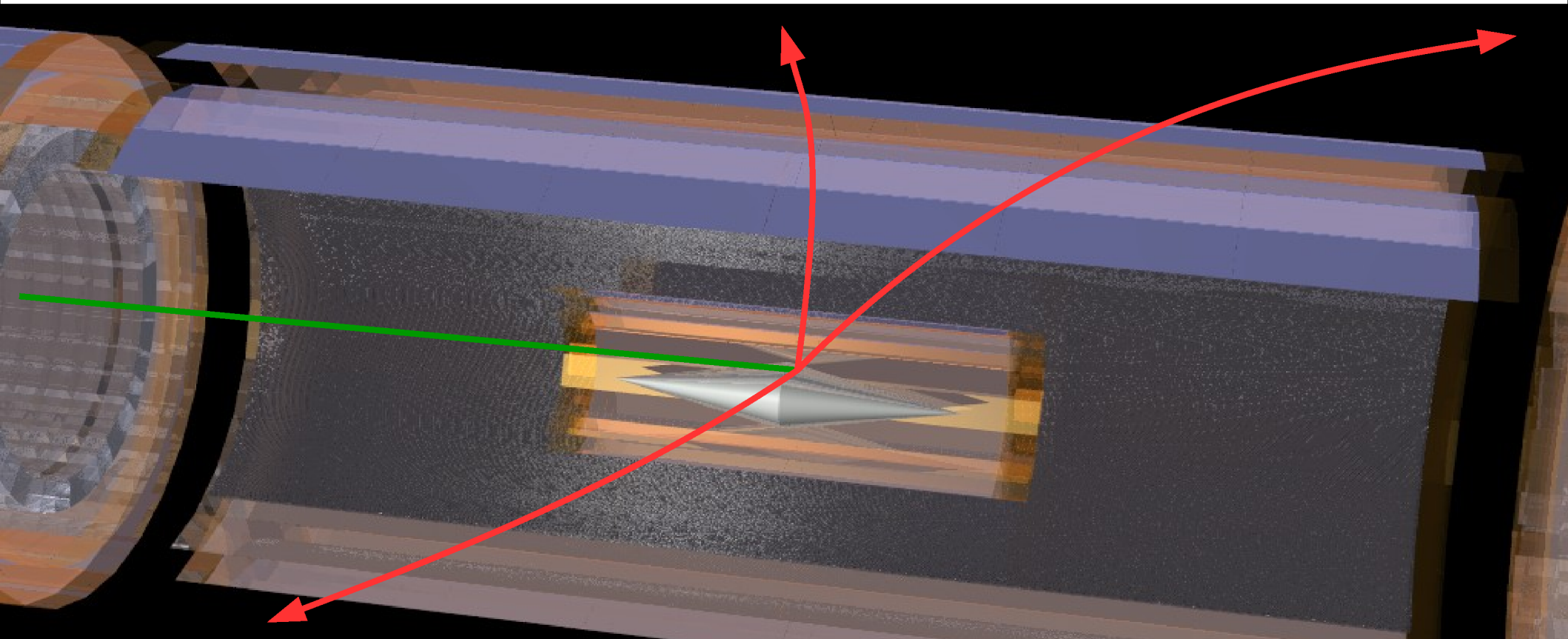


The Mu3e Pixel Detector

Vertex 2016, 26.-30. September, 2016

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Physikalisches Institut, Universität Heidelberg





Overview

- Introduction (physics, backgrounds, requirements, recurlers)
- Mu3e detector and concept
- Pixel Tracker
 - Ultralight Mechanics
 - The MuPix Sensor (HV-MAPS)
 - Flexprint
 - Helium Gas Cooling
 - Readout and the MuPix telescope
- Outlook + Schedule
- Summary



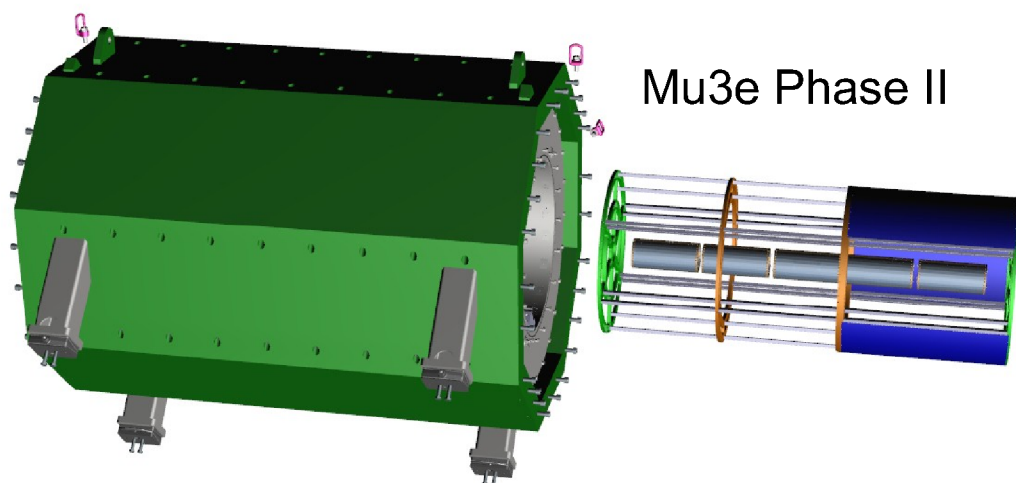
Mu3e Experiment at PSI

Mu3e Research Proposal, A.Blondel et al., arXiv:1301.6113

Search for lepton flavor violating decay

- $\text{BR}(\mu^+ \rightarrow e^+ e^+ e^-) < 10^{-12}$ (SINDRUM 1986)
- **$\text{BR}(\mu^+ \rightarrow e^+ e^+ e^-) < 10^{-15}$** (phase I, PiE5 beamline)
- $\text{BR}(\mu^+ \rightarrow e^+ e^+ e^-) < 10^{-16}$ (phase II, High Intensity Muon beamline)
- **high sensitivity to physics beyond the SM (complementary to LHC)**

Mu3e Solenoid B=1 Tesla



Requirements:

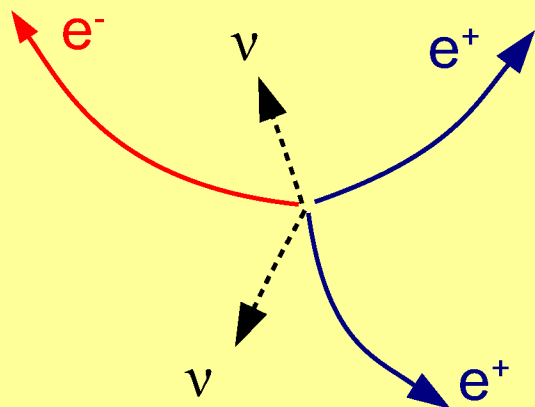
- $10^8 - 10^9$ muon stops / second
- electron energies **$< 53 \text{ MeV}$**
 - multiple scattering dominated
- high precision silicon pixel tracker
 - relative momentum resolution **$< 1\%$**
- scintillating timing detectors
 - **$100\text{-}500 \text{ ps}$** resolution



Backgrounds

Irreducible SM background

$$B(\mu^+ \rightarrow e^+ e^+ e^- \nu \nu) = 3.4 \cdot 10^{-5}$$



Requirements

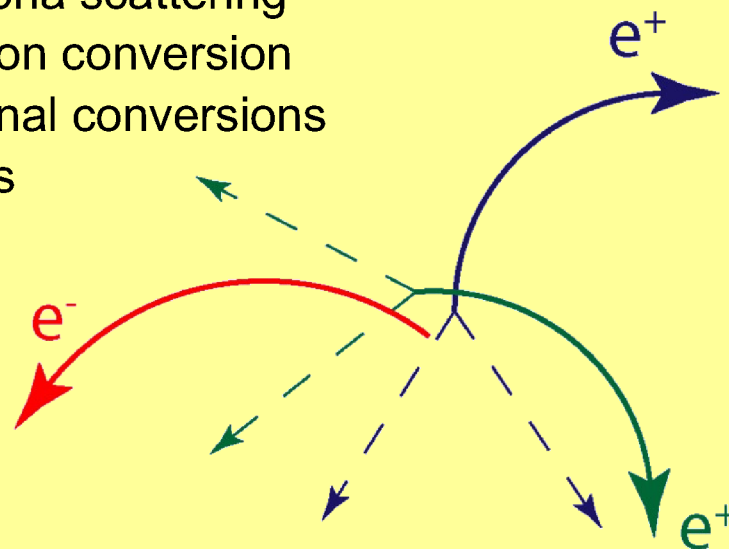
- O(0.5%) energy (momentum) resolution to reconstruct missing energy from neutrinos

Accidental background

Main decay: $\mu^+ \rightarrow e^+ \nu \nu$

electrons from:

- Bhabha scattering
- photon conversion
- internal conversions
- fakes

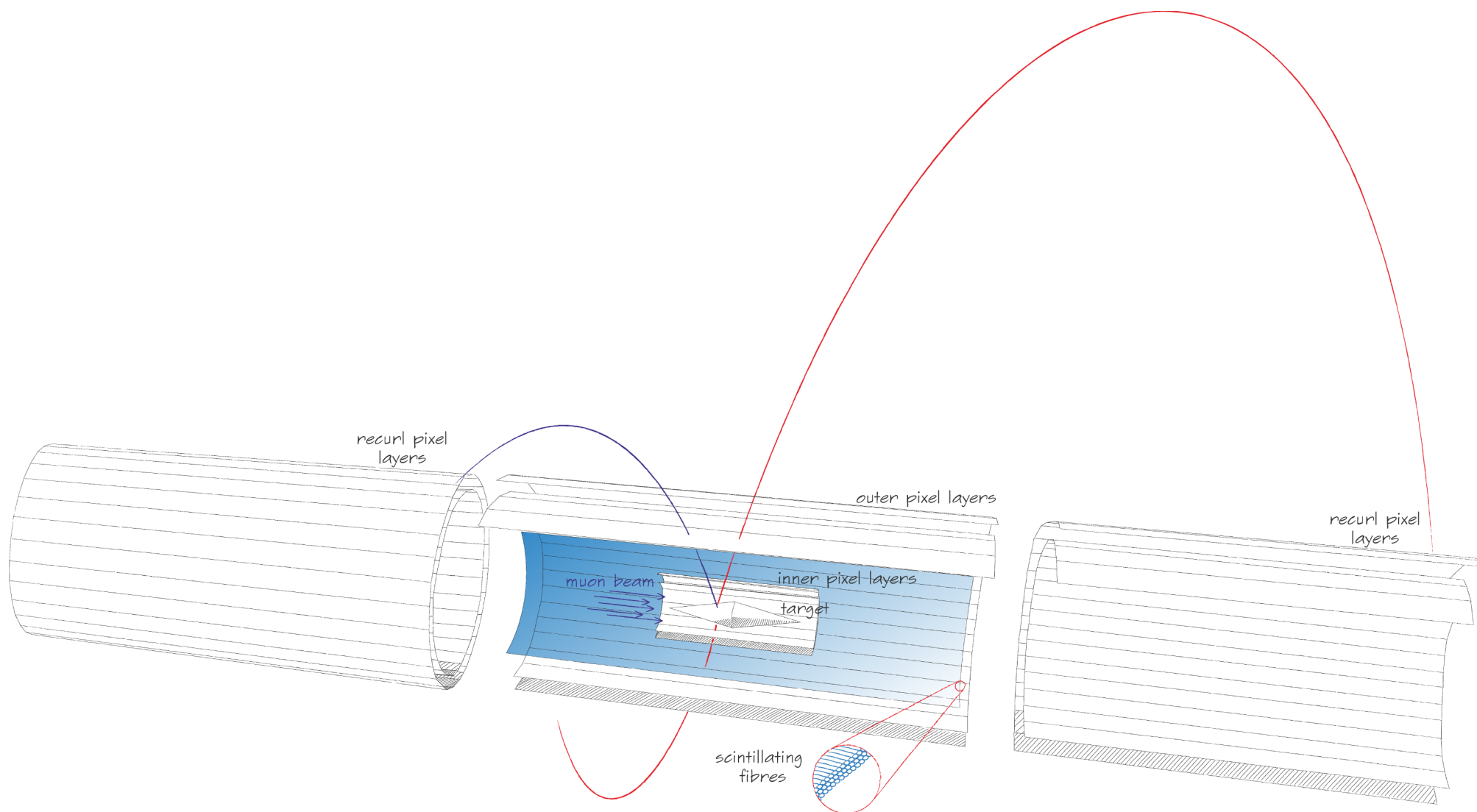


Requirements:

- DC μ^+ beam
- good energy resolution
- good pointing (vertex) resolution
- good timing resolution

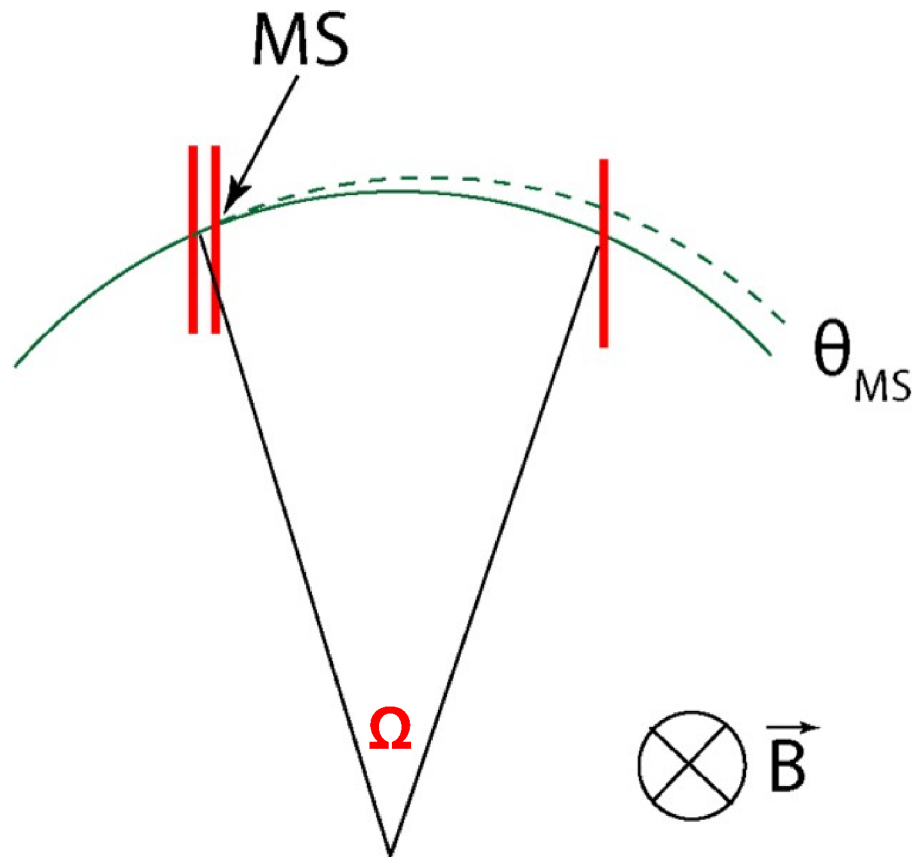


Mu3e Detector Layout Concept



Momentum Resolution in MS Regime

- Muon decay: $p(\text{electron}) < 53 \text{ MeV}/c \rightarrow \text{multiple scattering}$
- Standard spectrometer:



$$\Theta_{MS} \sim \frac{1}{P} \sqrt{X/X_0}$$

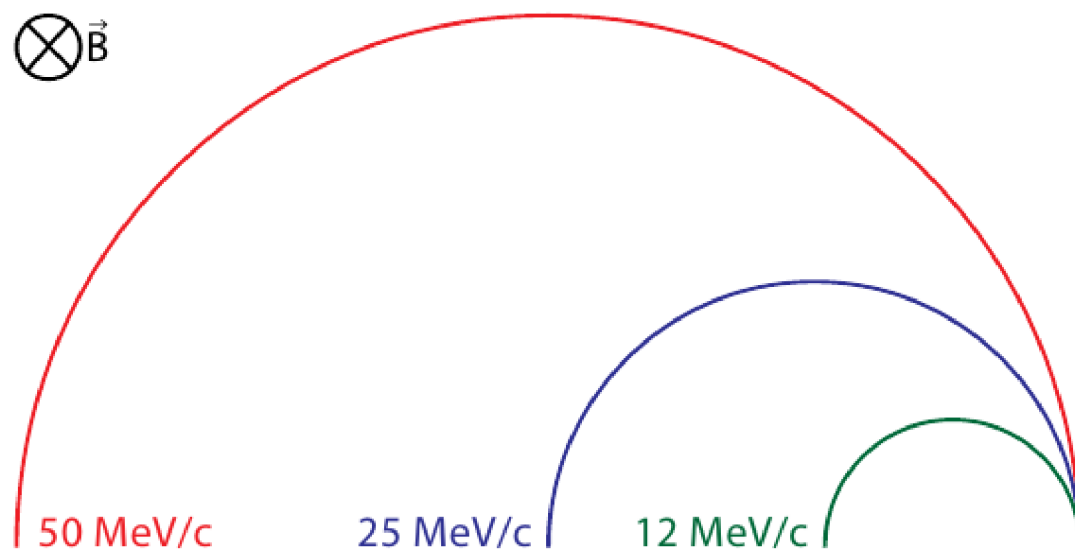
precision requires
 $\rightarrow$ little material **X**

$$\frac{\sigma_P}{P} \sim \frac{\Theta_{MS}}{\Omega} \quad (\text{linearised})$$

precision requires lever arm
 $\rightarrow$ large bending angle **Ω**

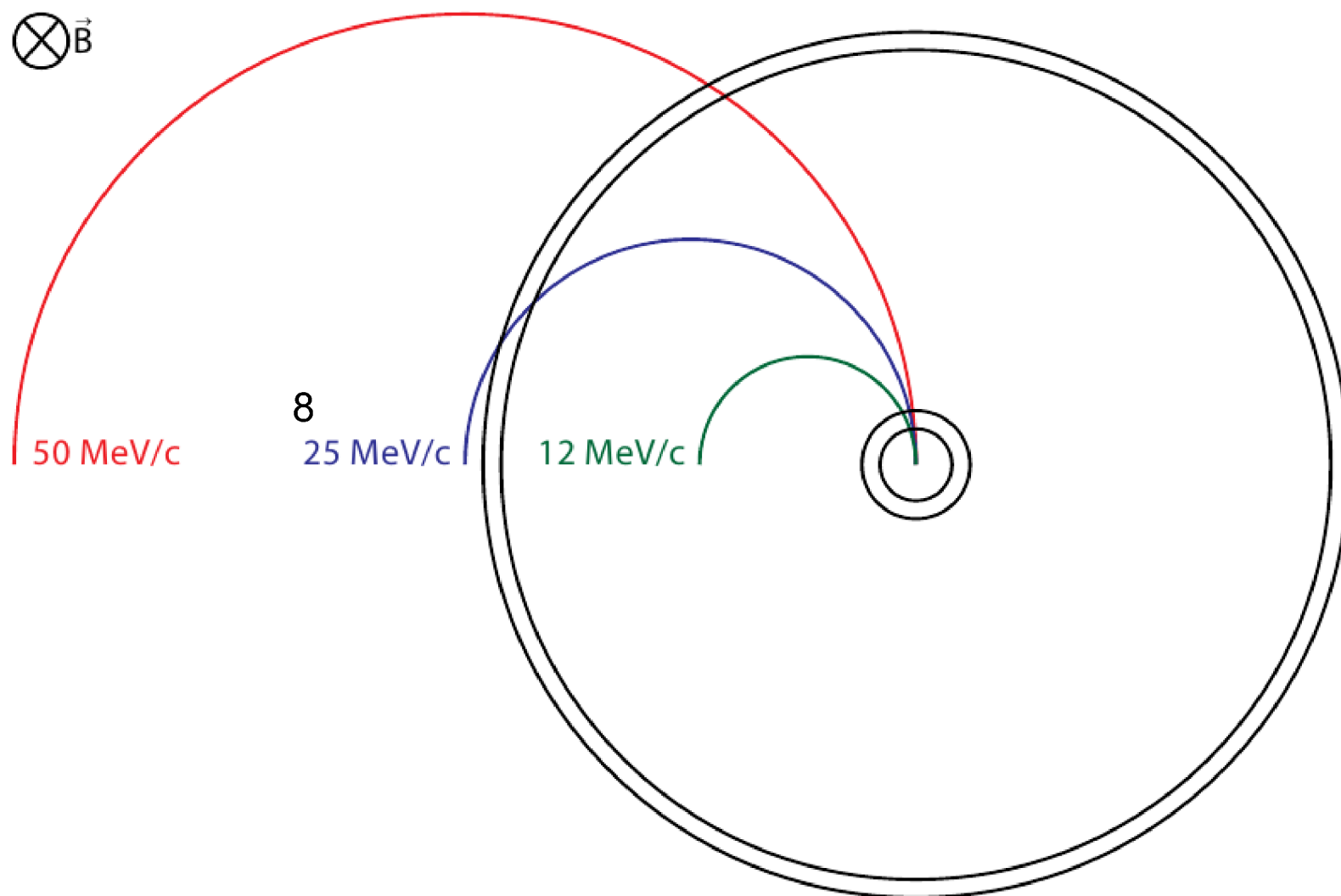


Tracking Design Considerations



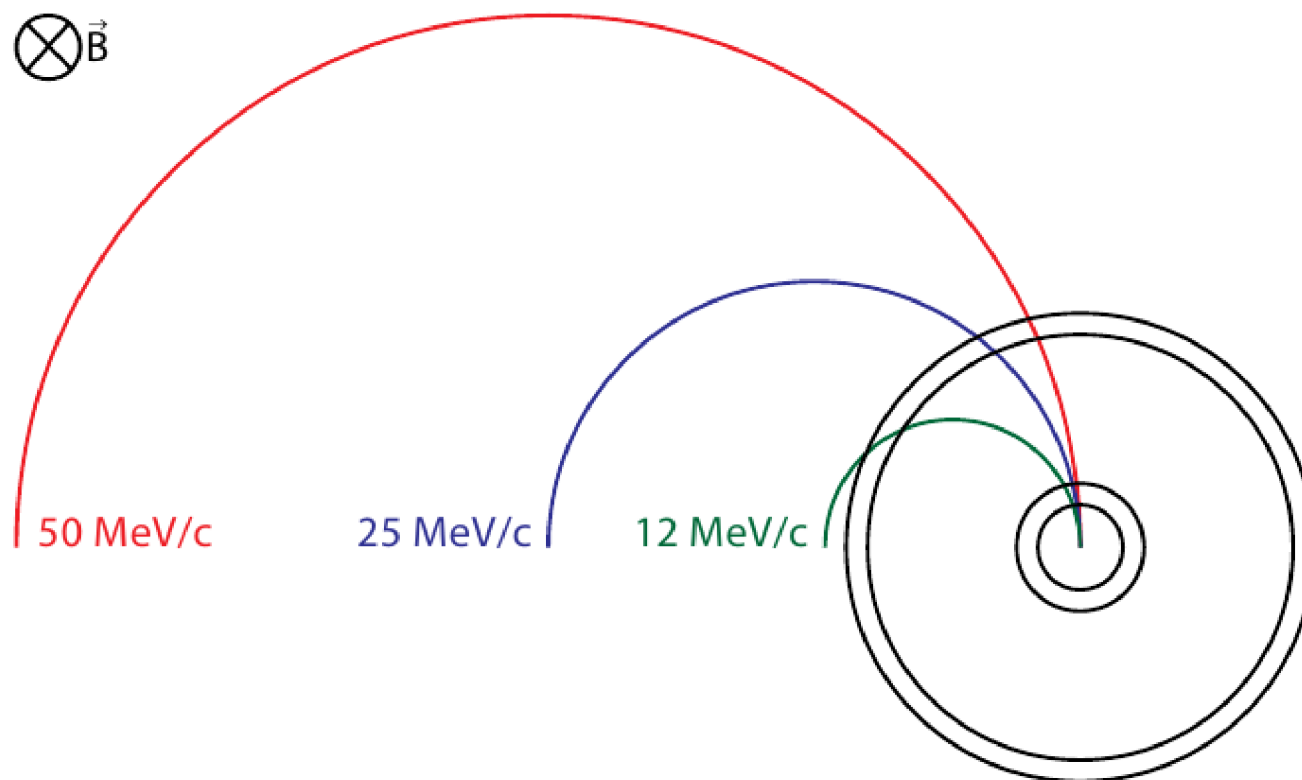


Tracking Design Considerations



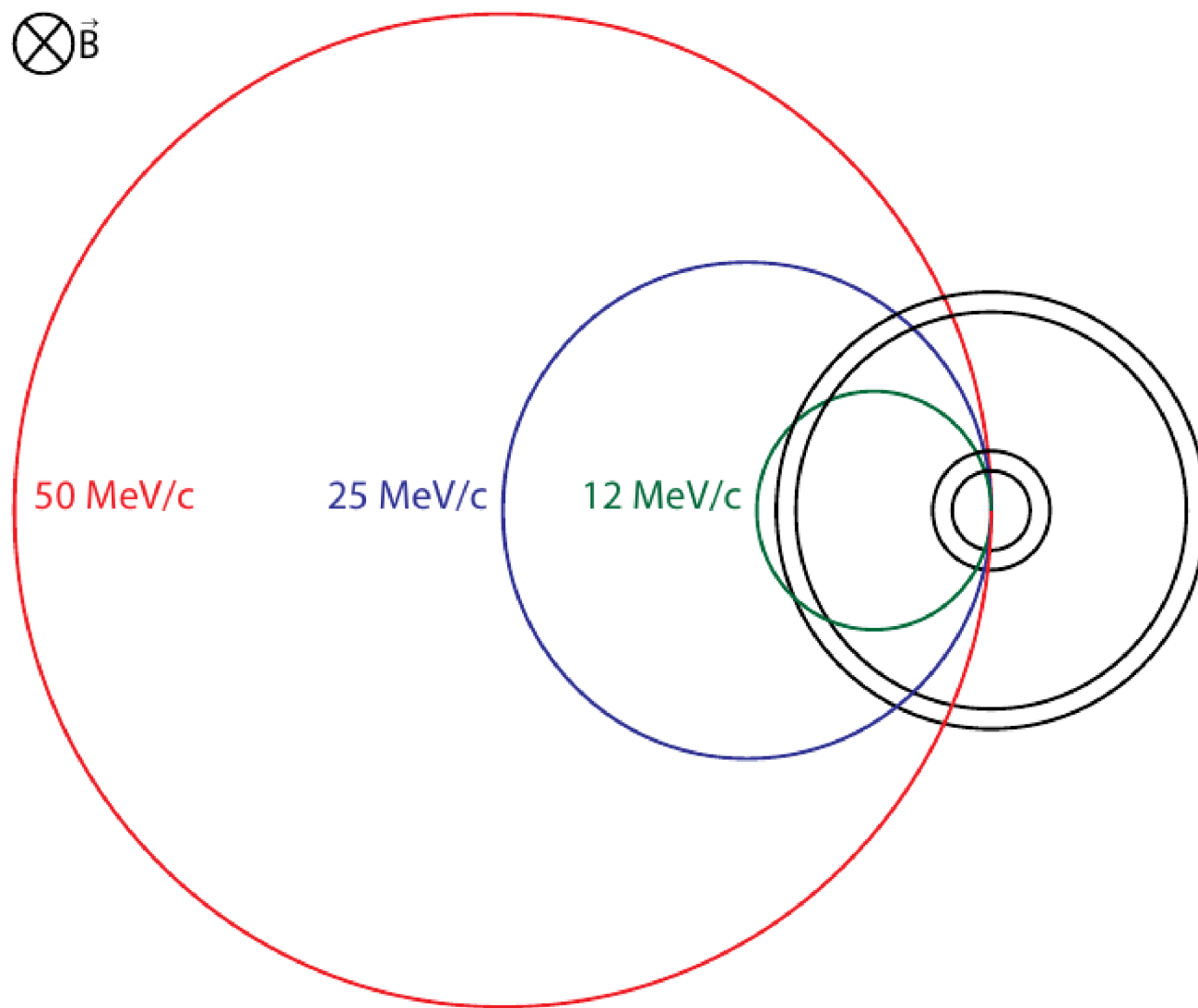


Tracking Design Considerations



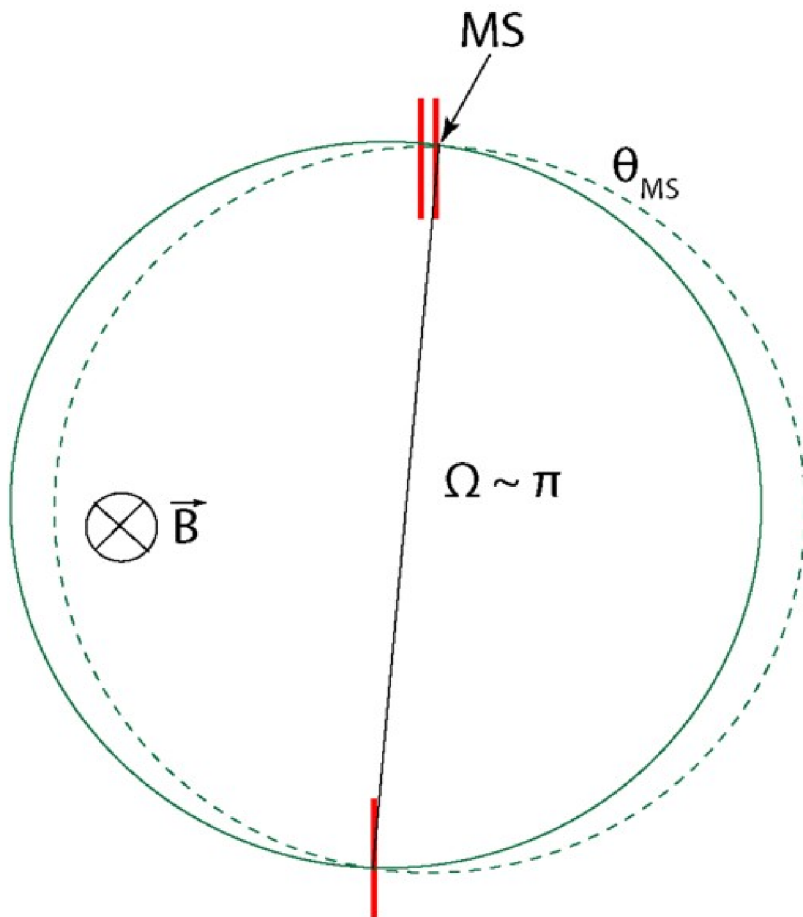


Tracking Design Considerations



Momentum Resolution in MS Regime

- “Half turn” spectrometer:



$$\frac{\sigma_p}{P} \sim O(\Theta_{MS}^2)$$

- best precision for **half turn** tracks
- measure **recurling** tracks

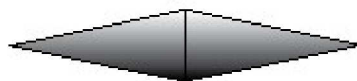


Mu3e Design

$$E_{\text{kin}} = 28 \text{ MeV}$$

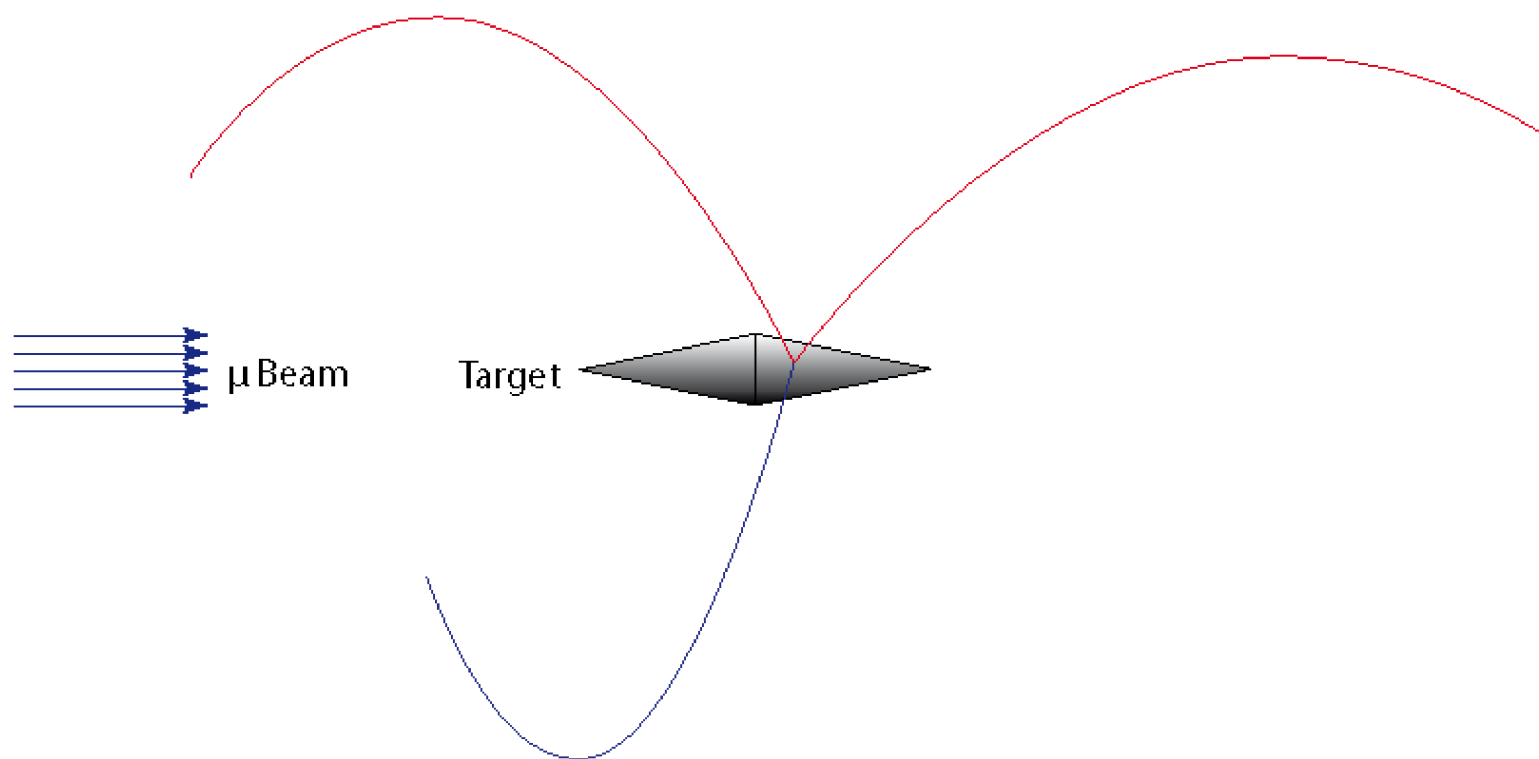


Target



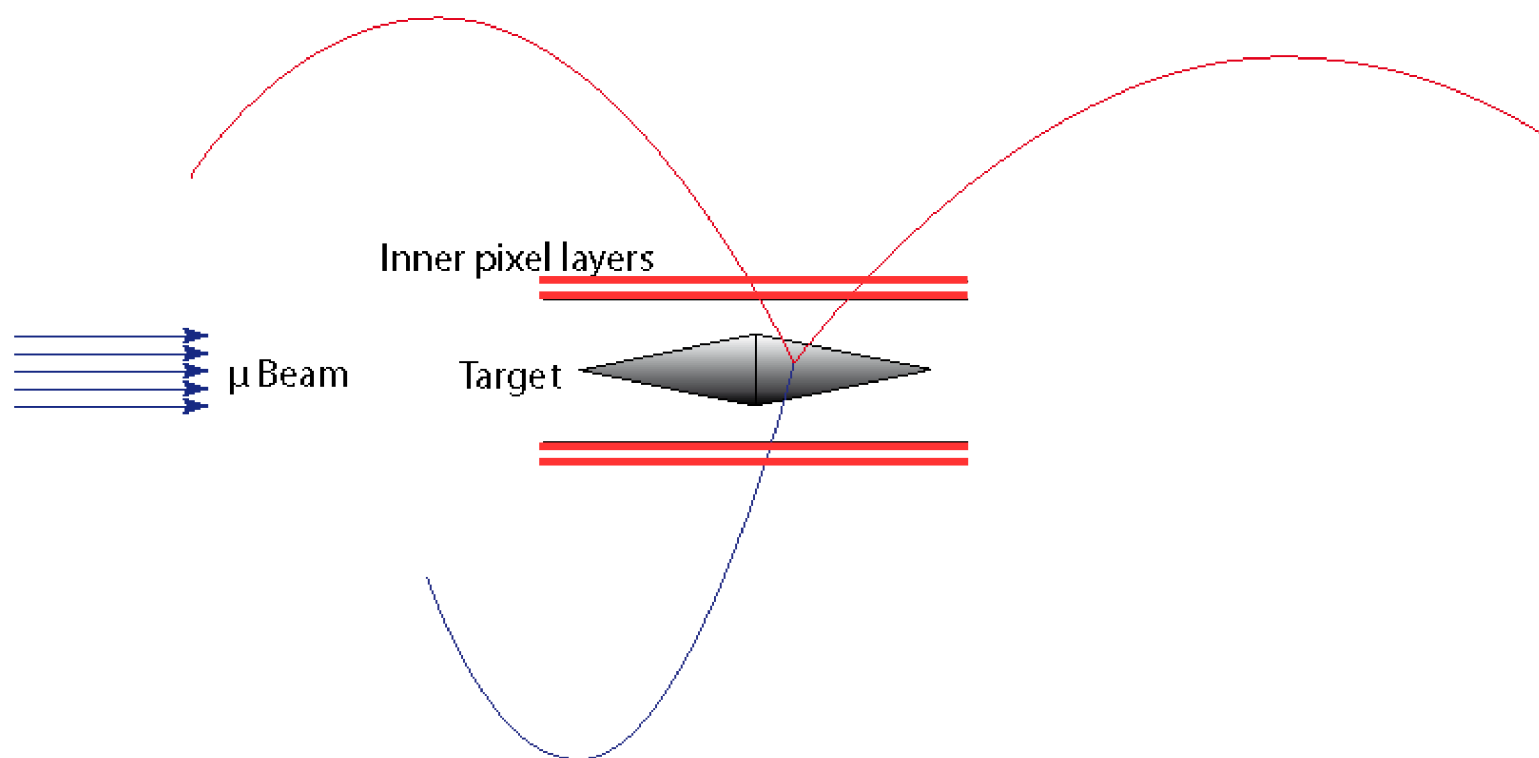


Mu3e Design



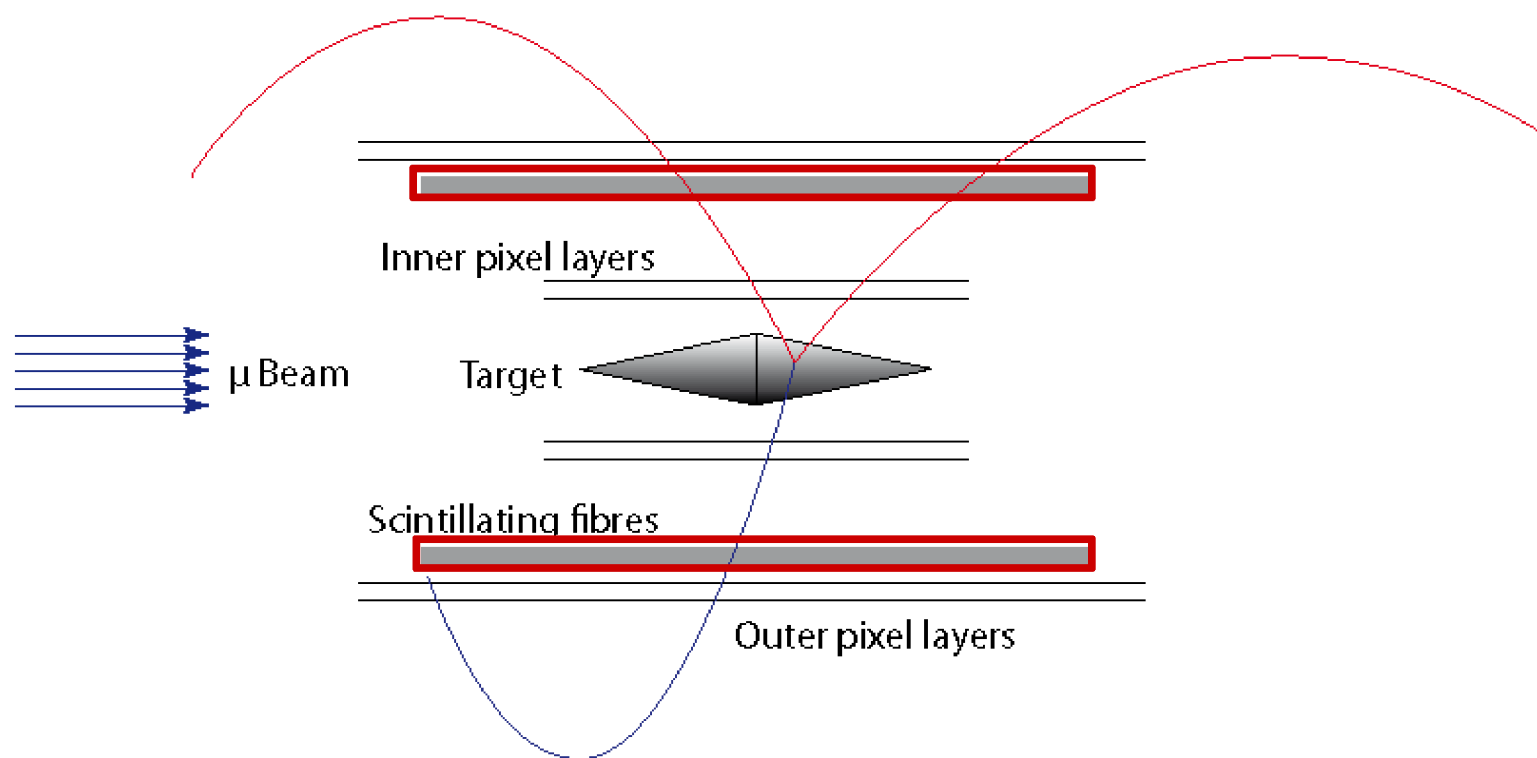


Mu3e Design



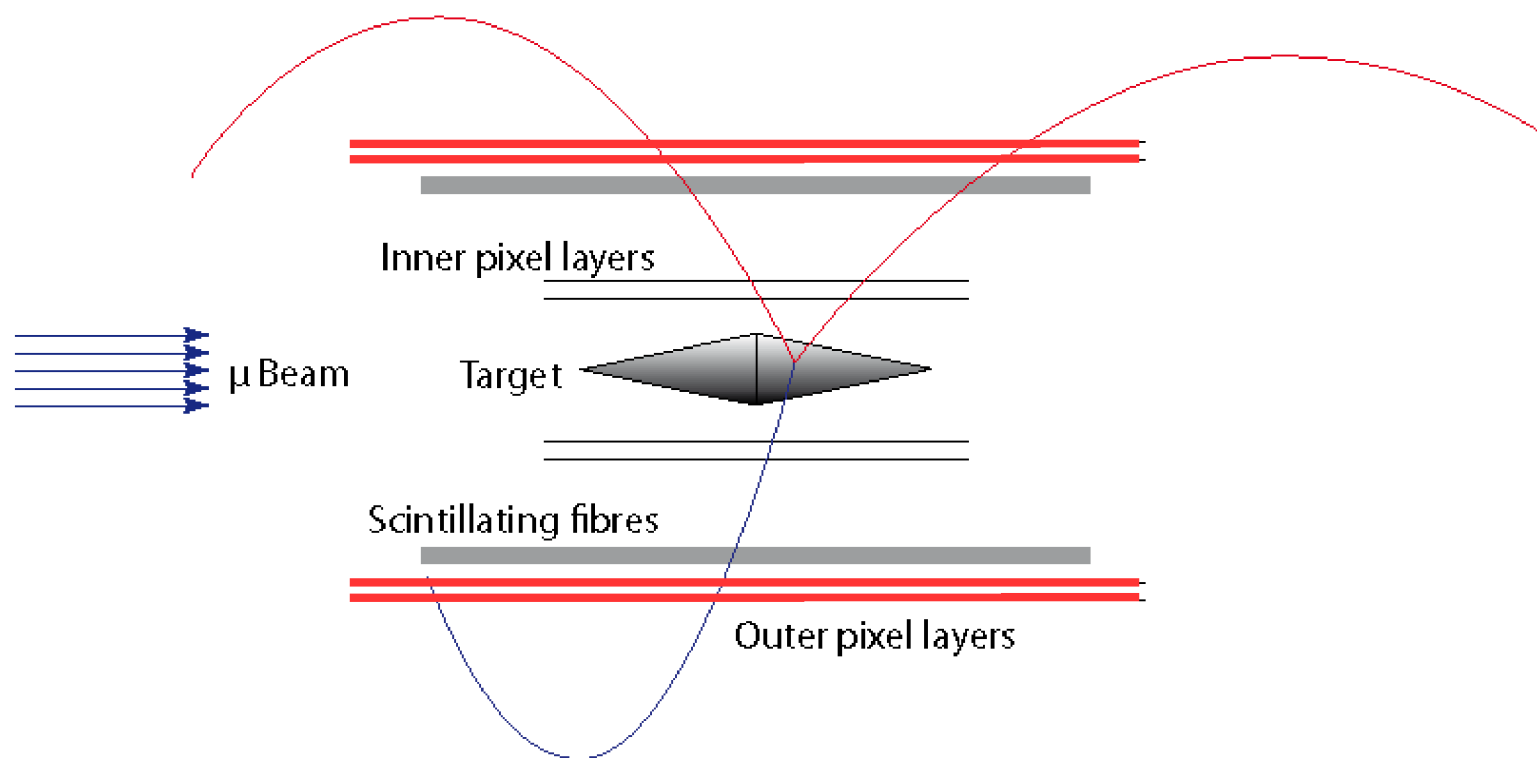


Mu3e Design



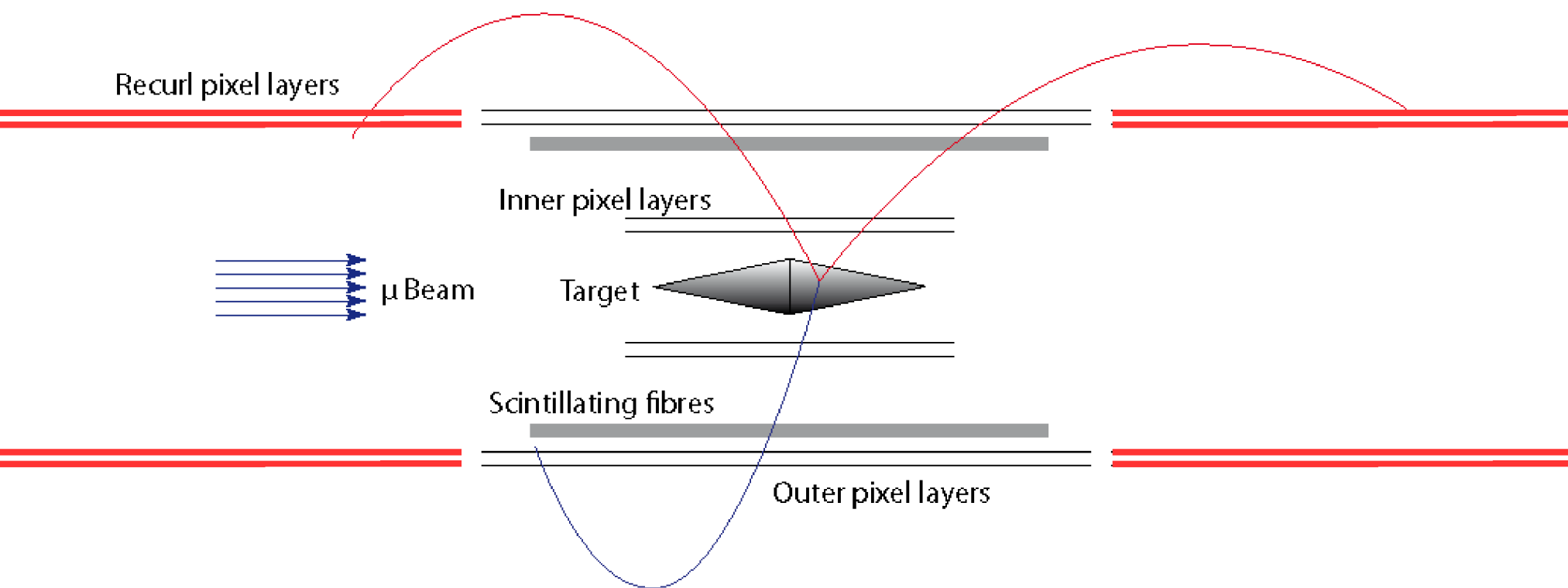


Mu3e Design



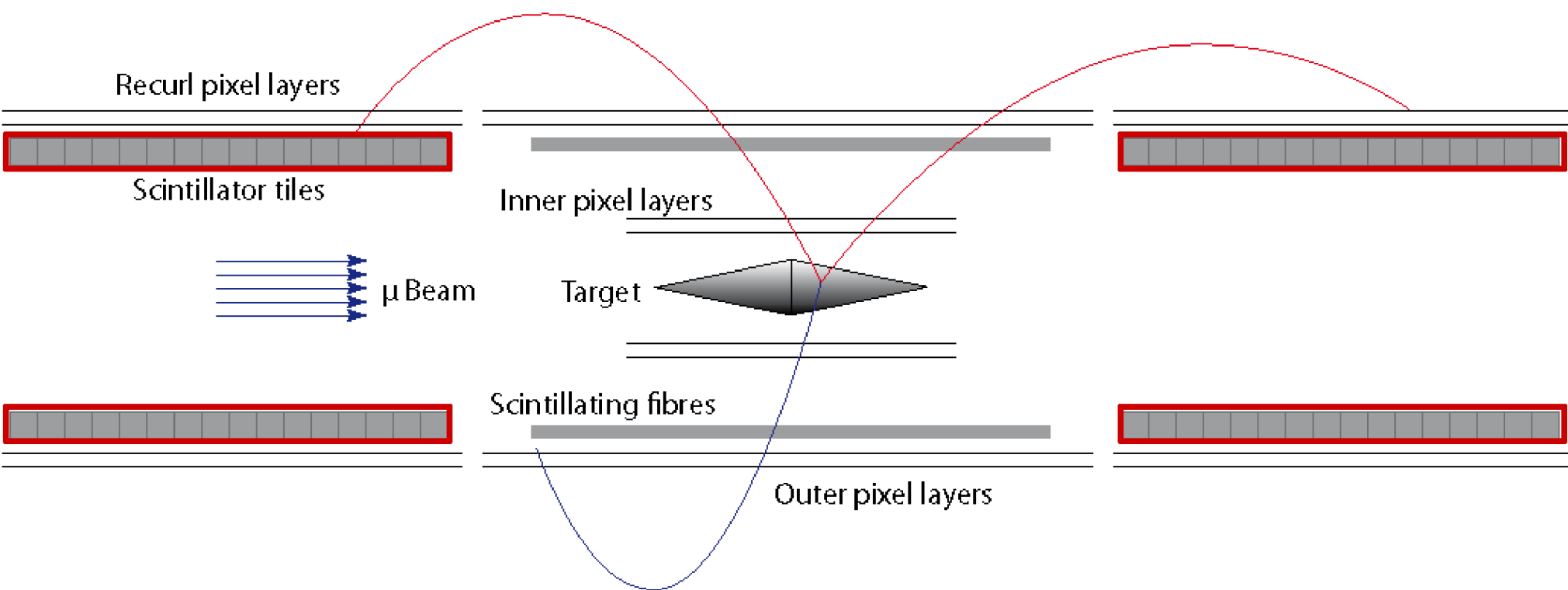


Mu3e Design



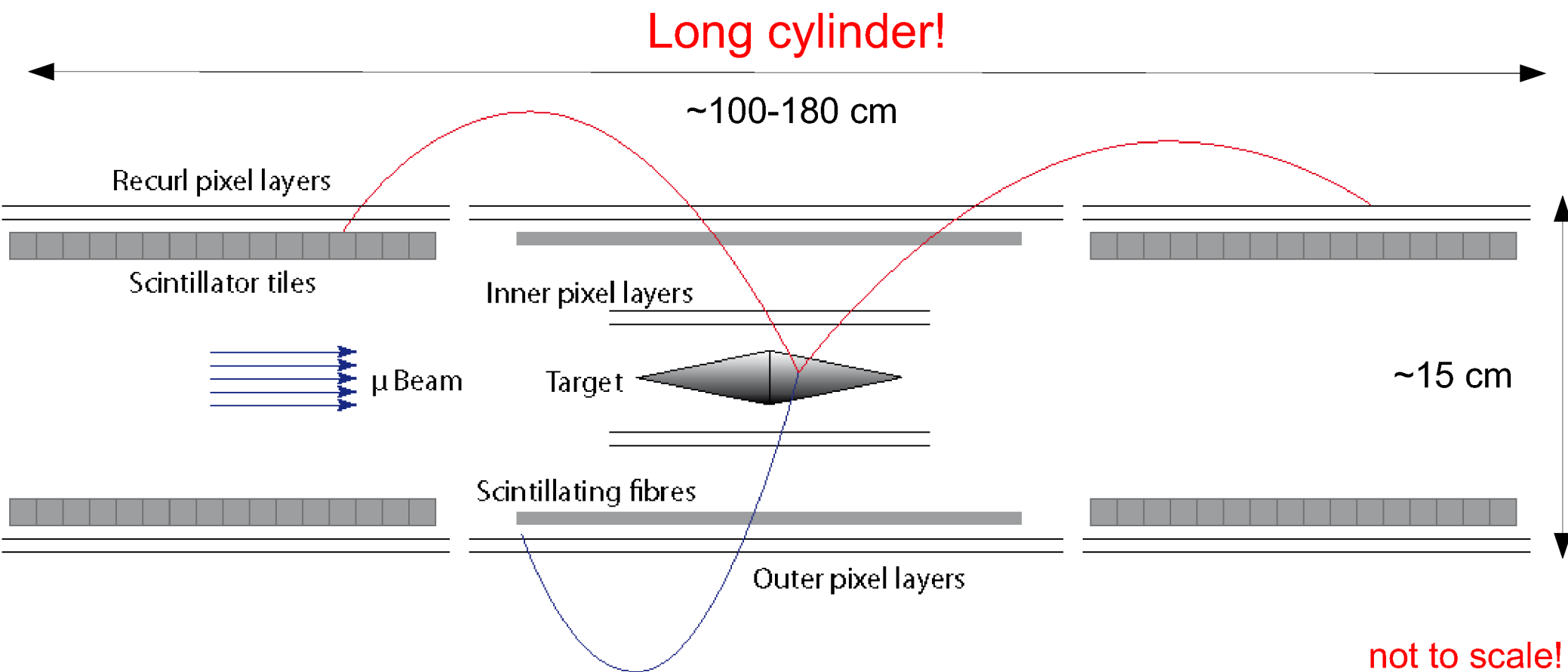


Mu3e Design



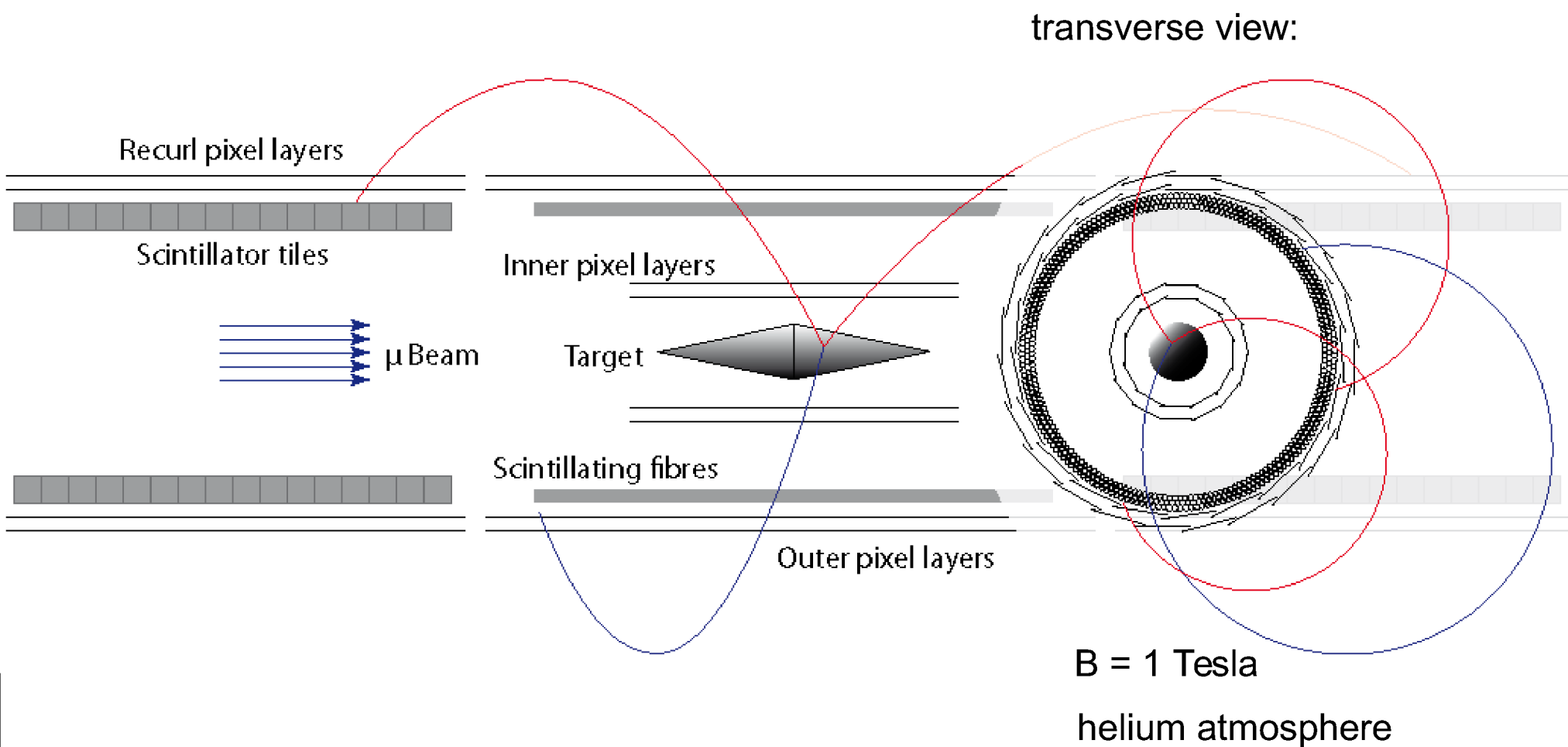


Mu3e Design



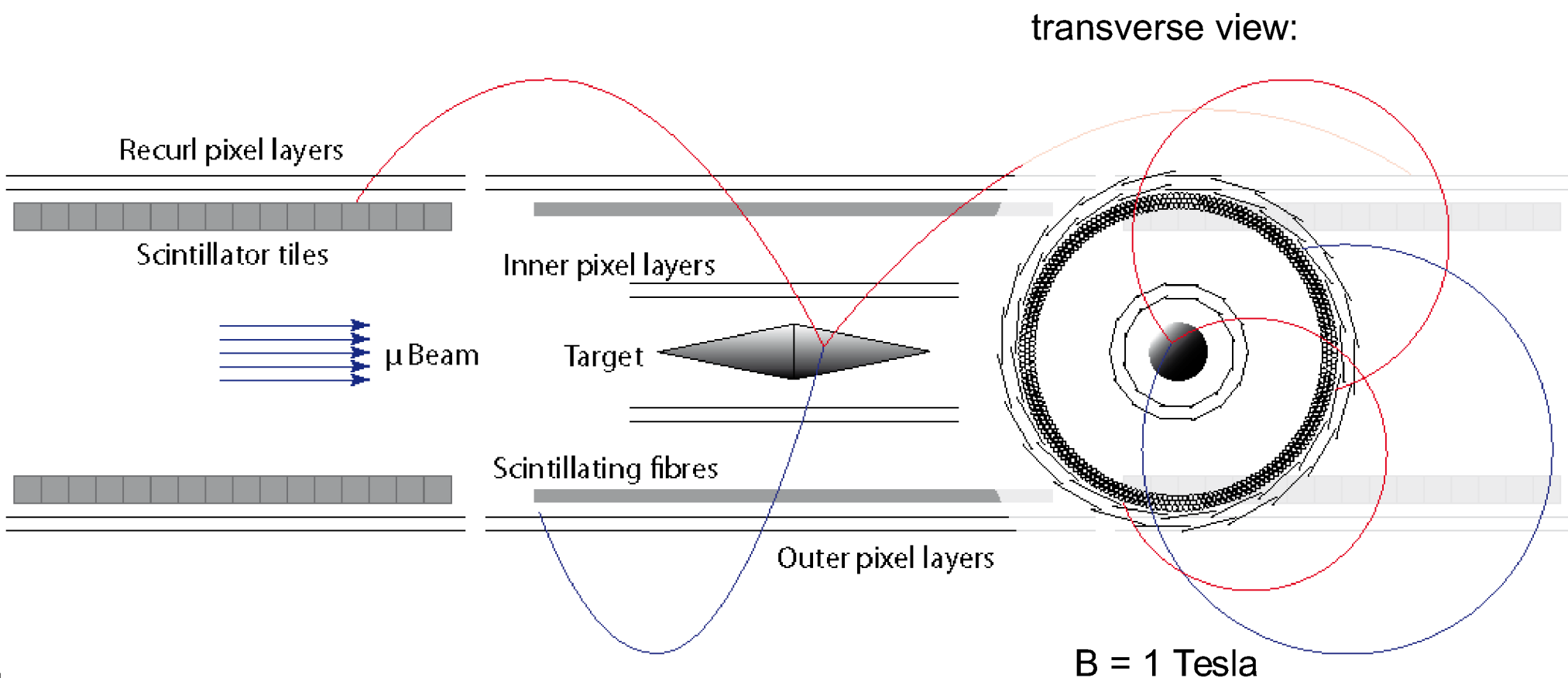


Mu3e Design





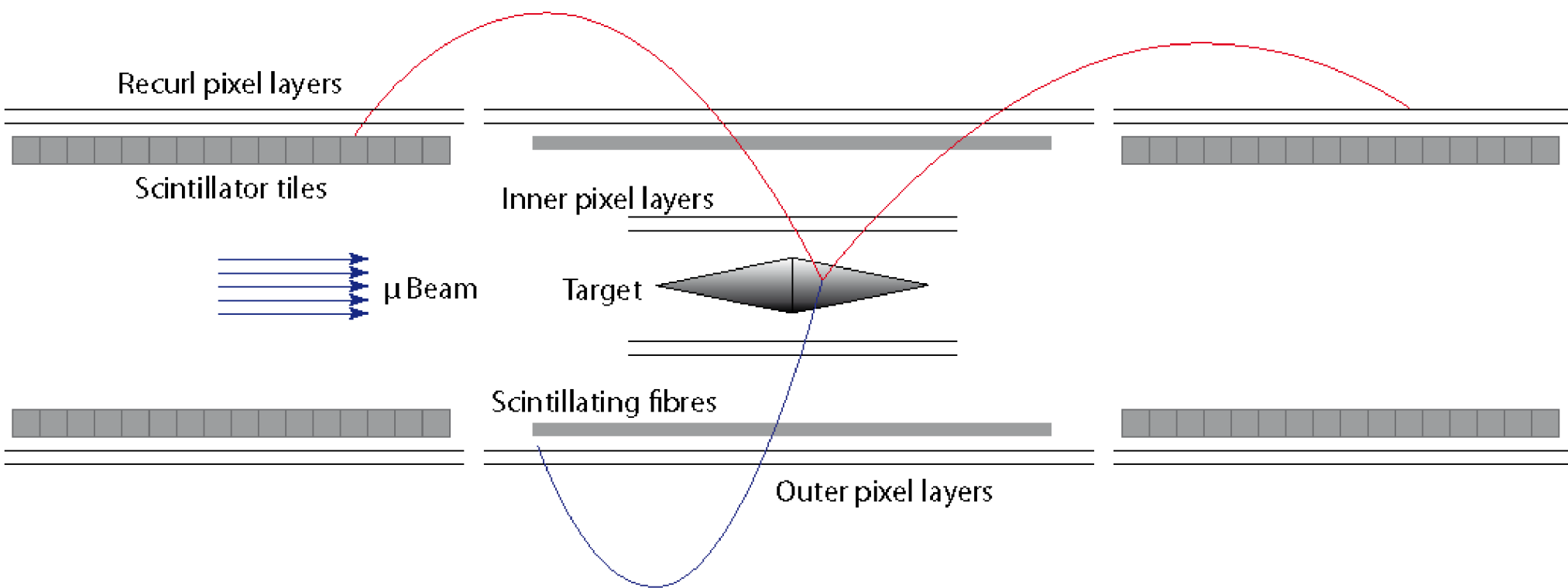
Mu3e Design



Geometrical acceptance **$\sim 70\%$** for $\mu^+ \rightarrow e^+e^+e^-$ decay



Mu3e Design

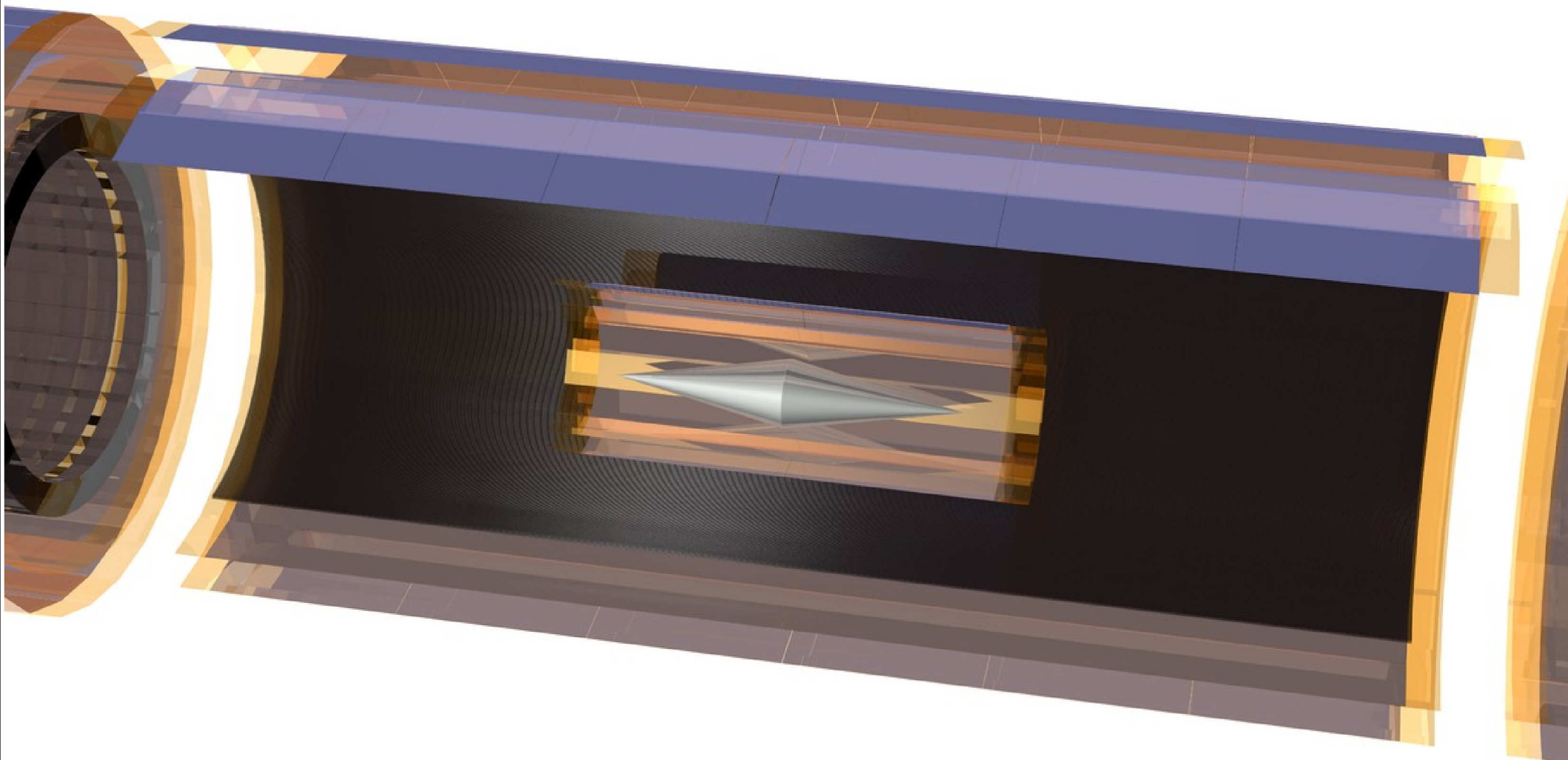


Main technological Challenges

- Large area $O(1\text{m}^2)$ monolithic pixel detectors with $X/X_0 = 0.1\%$ per tracking layer
- Novel **helium gas cooling** concept
- Thin scintillating fiber detector with $\leq 1\text{mm}$ thickness
- Timing resolution **100-500 ps**
- Filter farm reconstructing and processing **10^8 - 10^9 tracks per second**



Mu3e Pixel Tracker





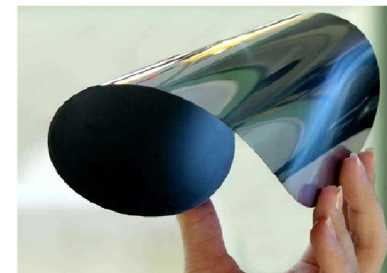
Mu3e Pixel Mechanics

Mu3e physics sensitivity:

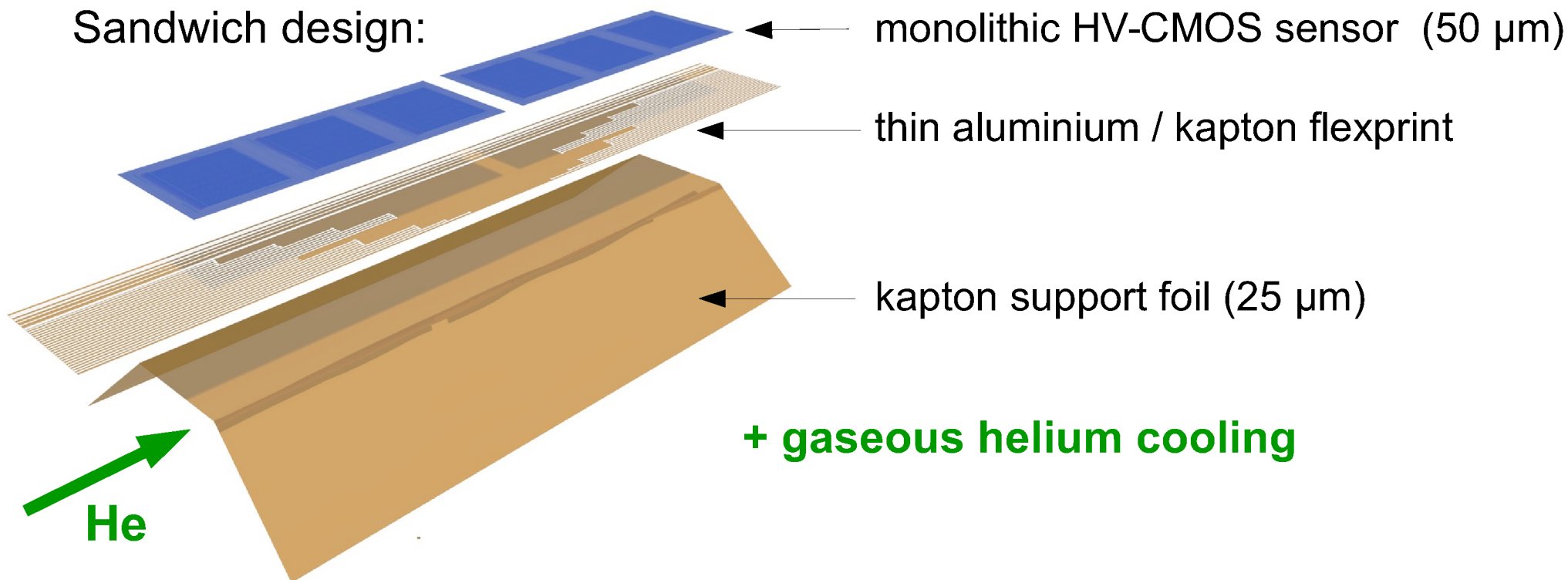
$$\sim (X/X_0)^3$$

Most challenging requirement:

$$X/X_0 \leq 0.1\%$$



Sandwich design:



+ gaseous helium cooling

$X \leq 0.1\% X_0$ per layer possible



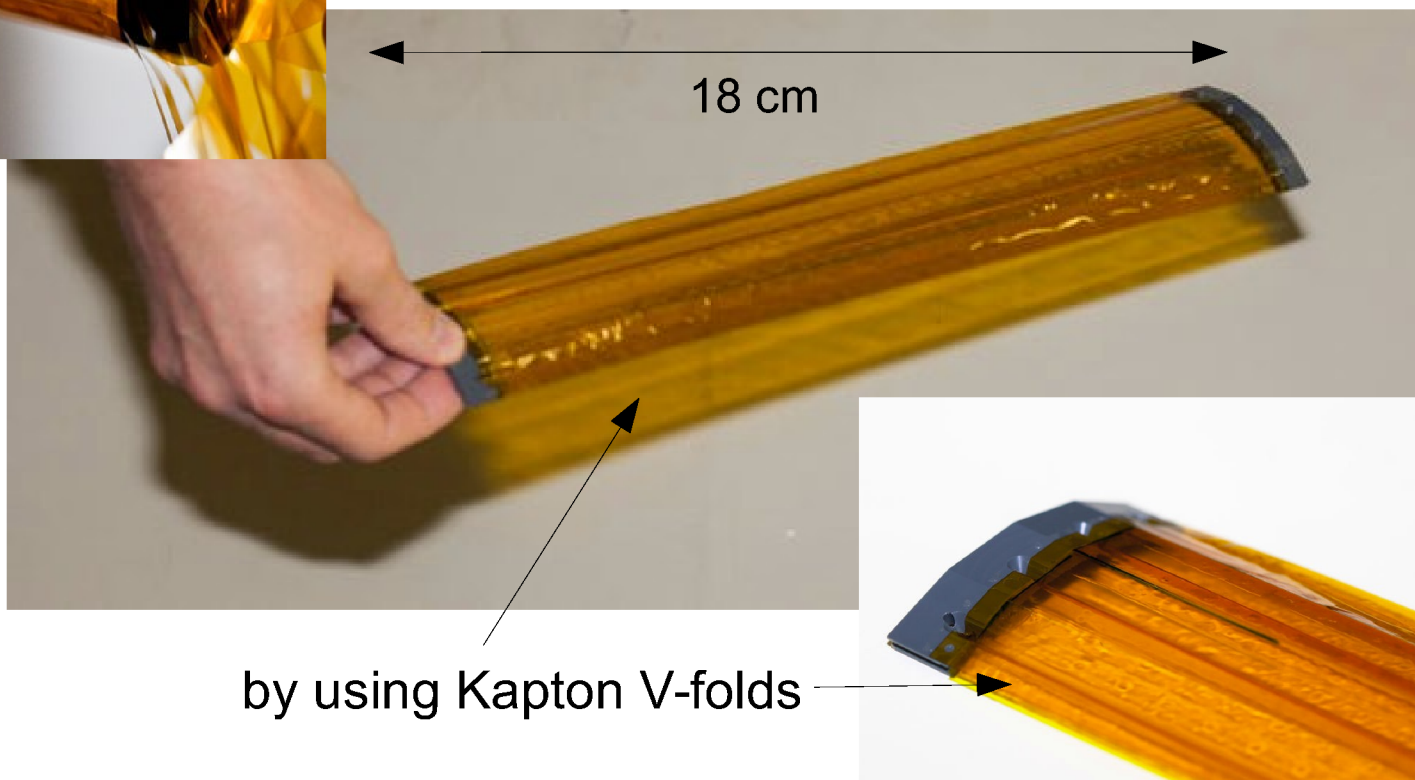
Mechanical Mockups



Ultra-thin mechanical mockup:

- sandwich of 25 μm Kapton[®]
- here 50 μm glass (instead of Si)

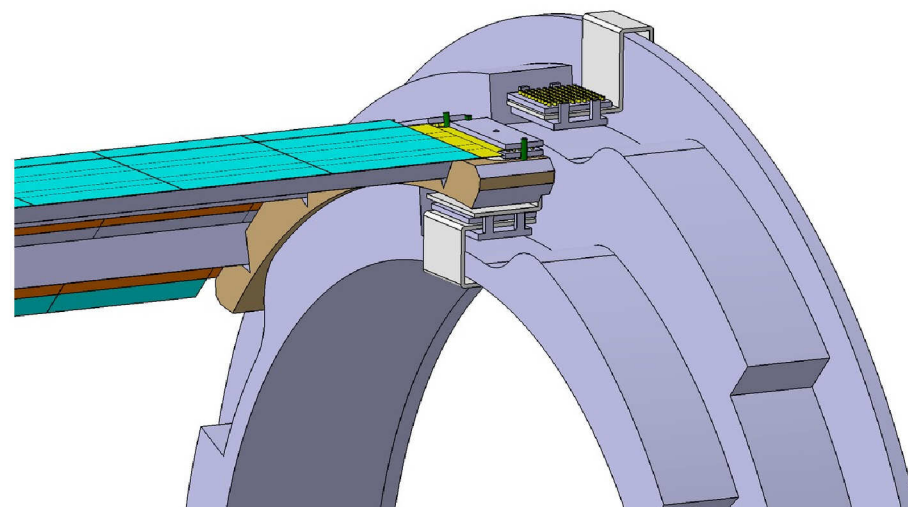
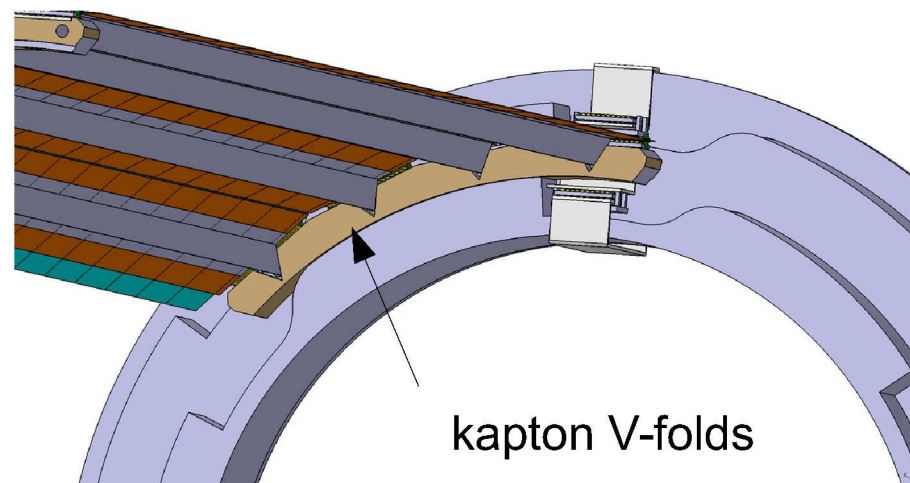
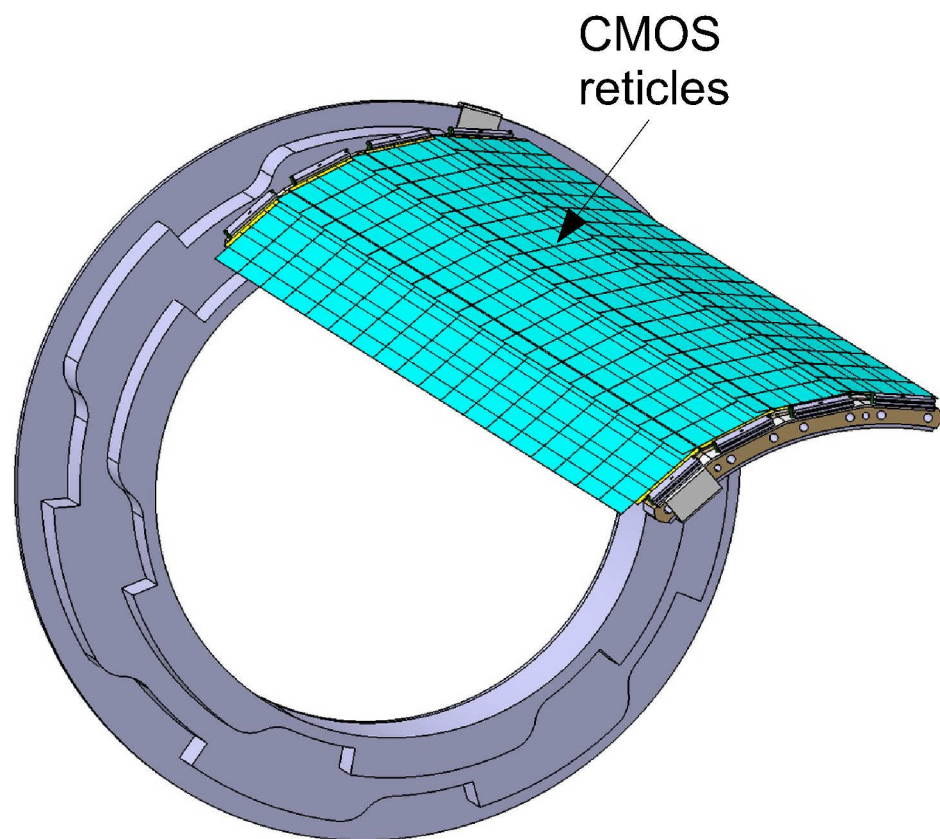
Even larger stable structures possible





Pixel Module Design

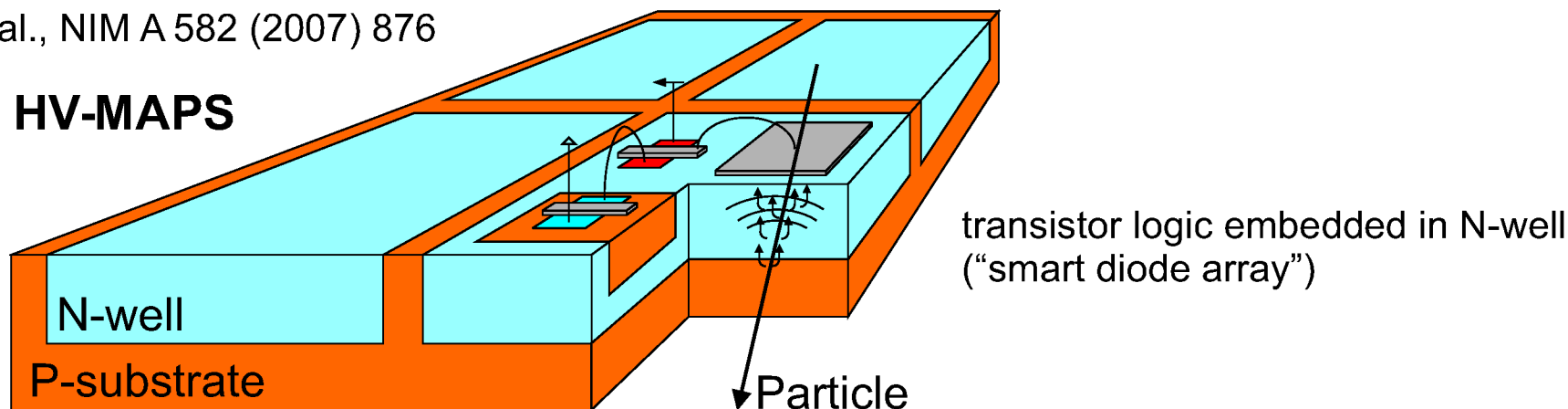
Outer pixel layers





The MuPix Sensor for Mu3e

I.Peric, et al., NIM A 582 (2007) 876

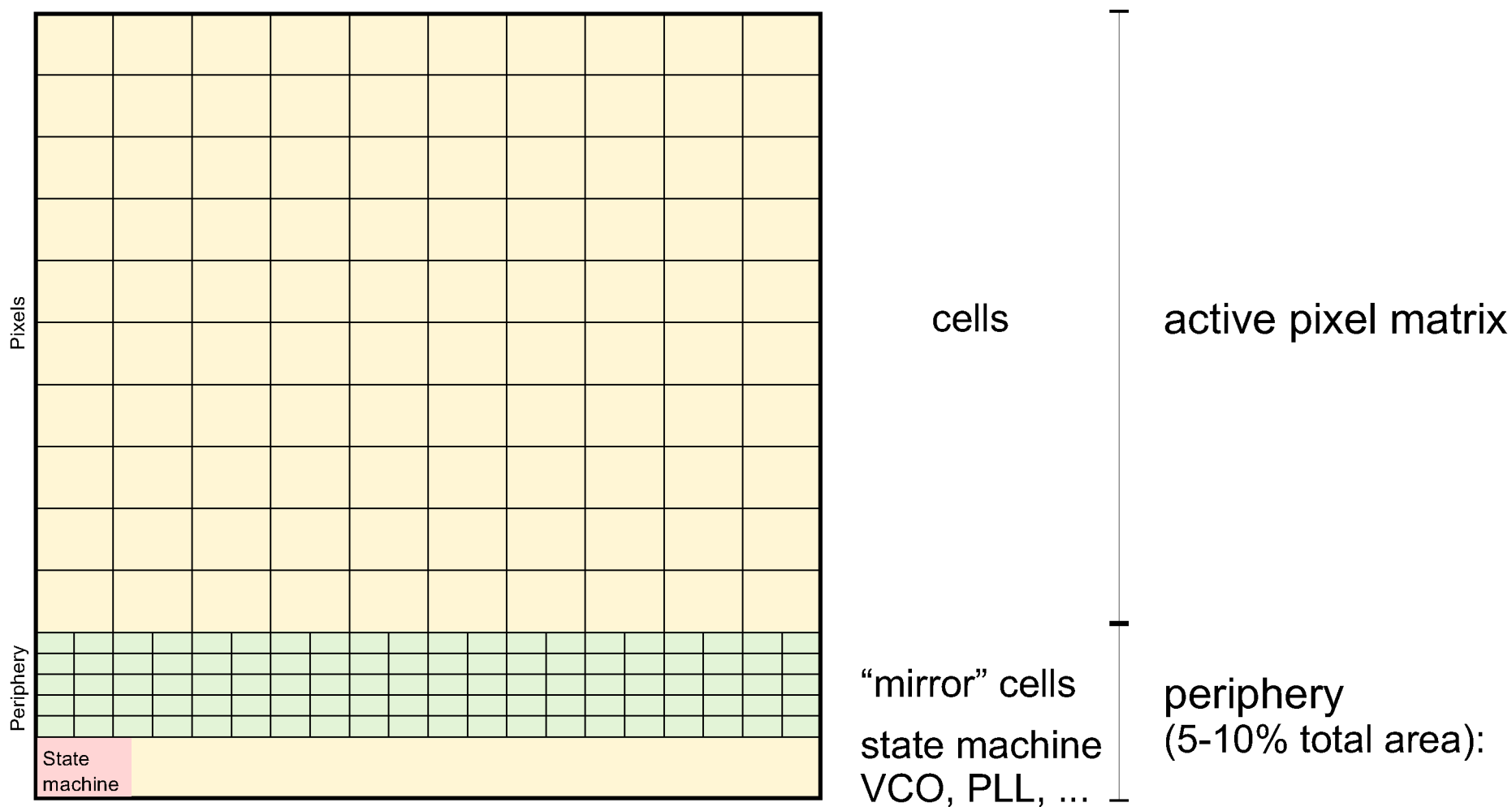


High Voltage - Monolithic Active Pixel Sensor (HV-MAPS)

- **active sensor** → hit finding + digitisation + zero suppression + readout
- high precision → pixels $80 \times 80 \mu\text{m}^2$
- low noise $\sim 40 - 50e$ → low threshold
- small depletion region of $\sim 10 \mu\text{m}$ → thin sensor $\sim 50 \mu\text{m}$ ($\sim 0.0005 X_0$)
- standard HV-CMOS process, $60 - 90 \text{ V}$ → low production costs
- continuous and fast readout (serial link) → online reconstruction

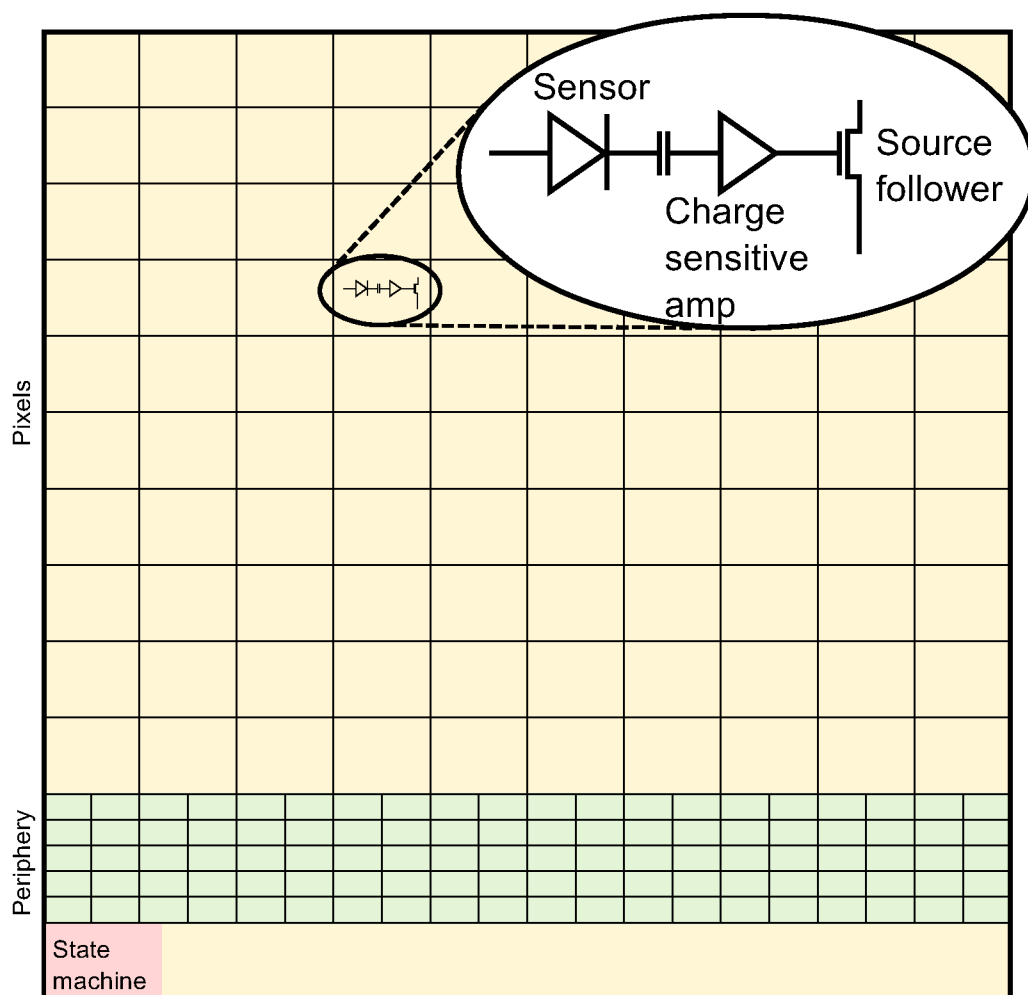


MuPix Chip Design





MuPix Chip Design

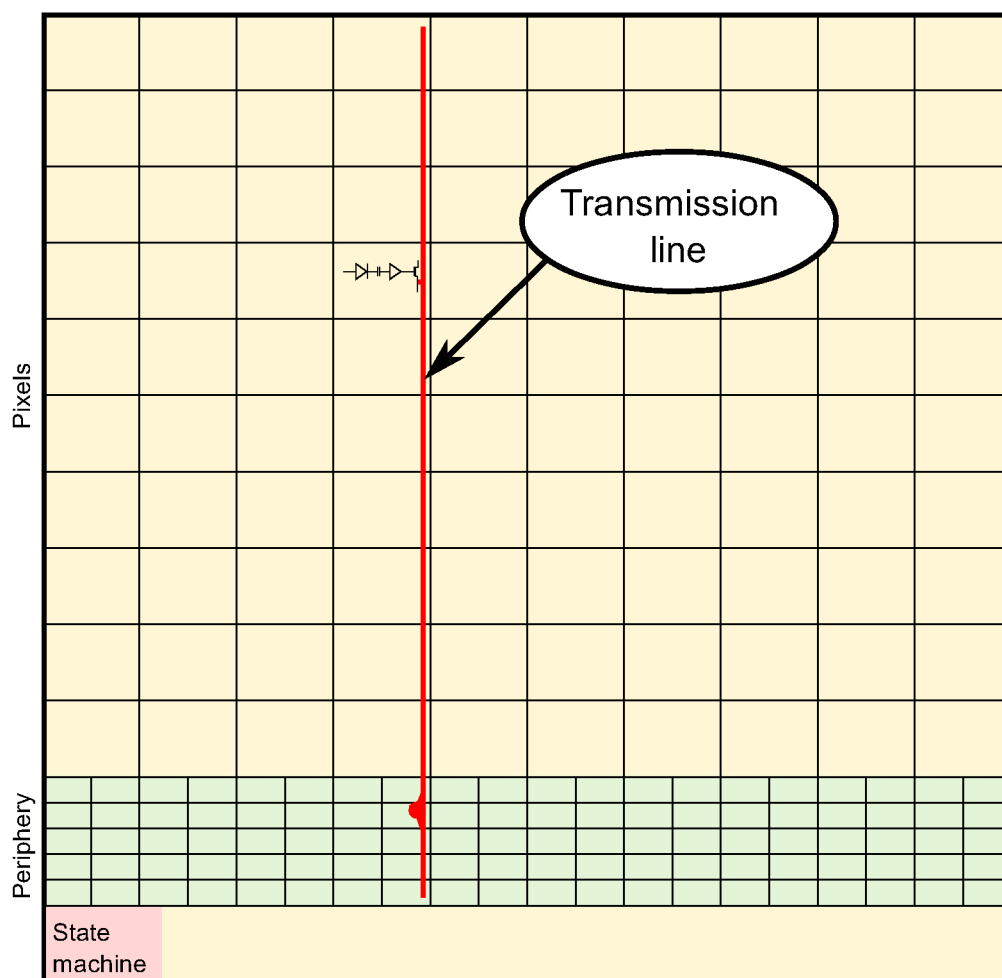


analog cell:

- reverse biased -85V
- charge sensitive amplifier
- source follower



MuPix Chip Design

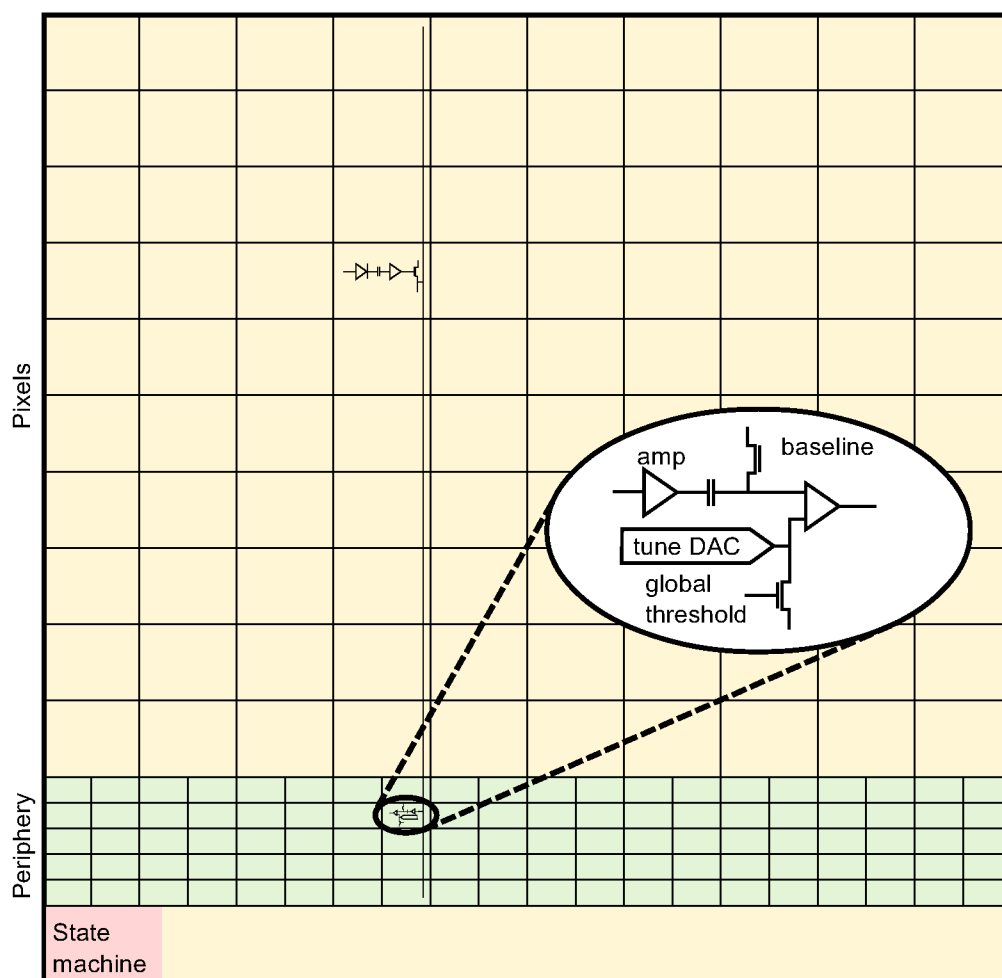


transmission line:

- send signal to corresponding mirror cell



MuPix Chip Design

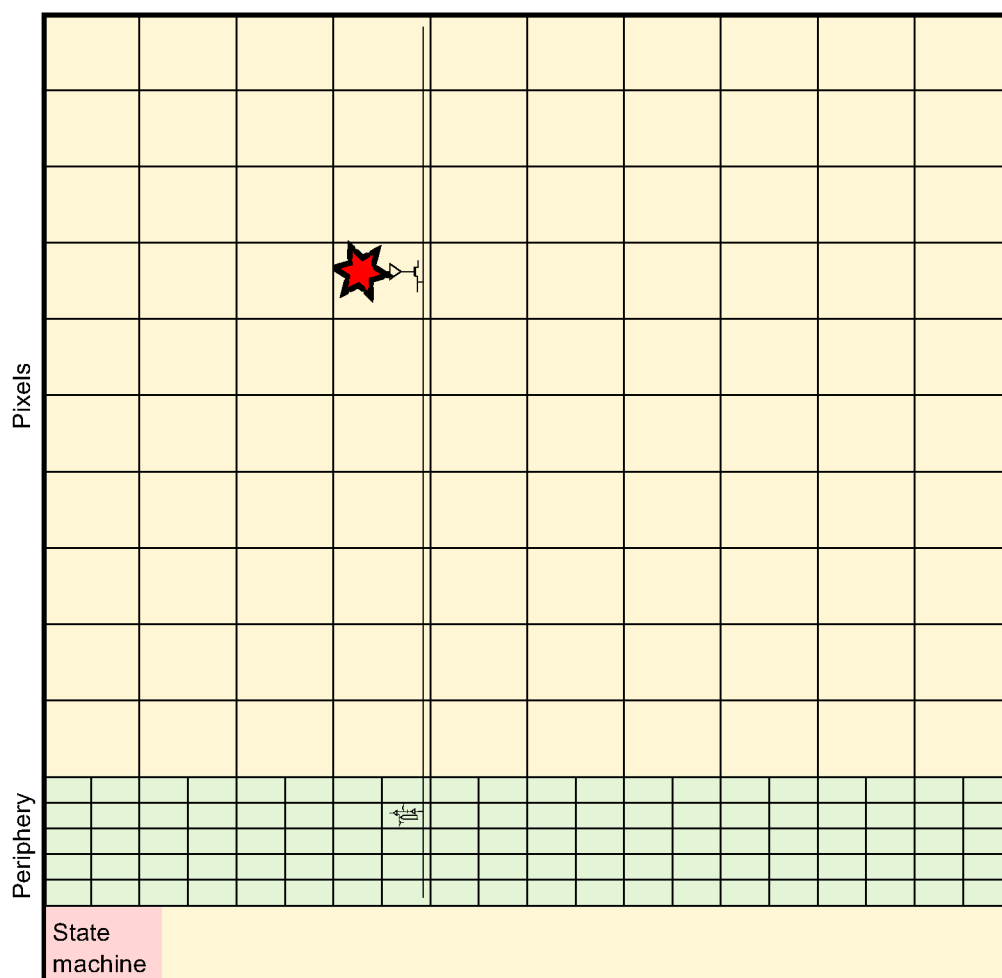


mirror cell:

- 2nd amplifier
- comparator for discrimination
- threshold and baseline by tuning DACs



MuPix Hit Detection

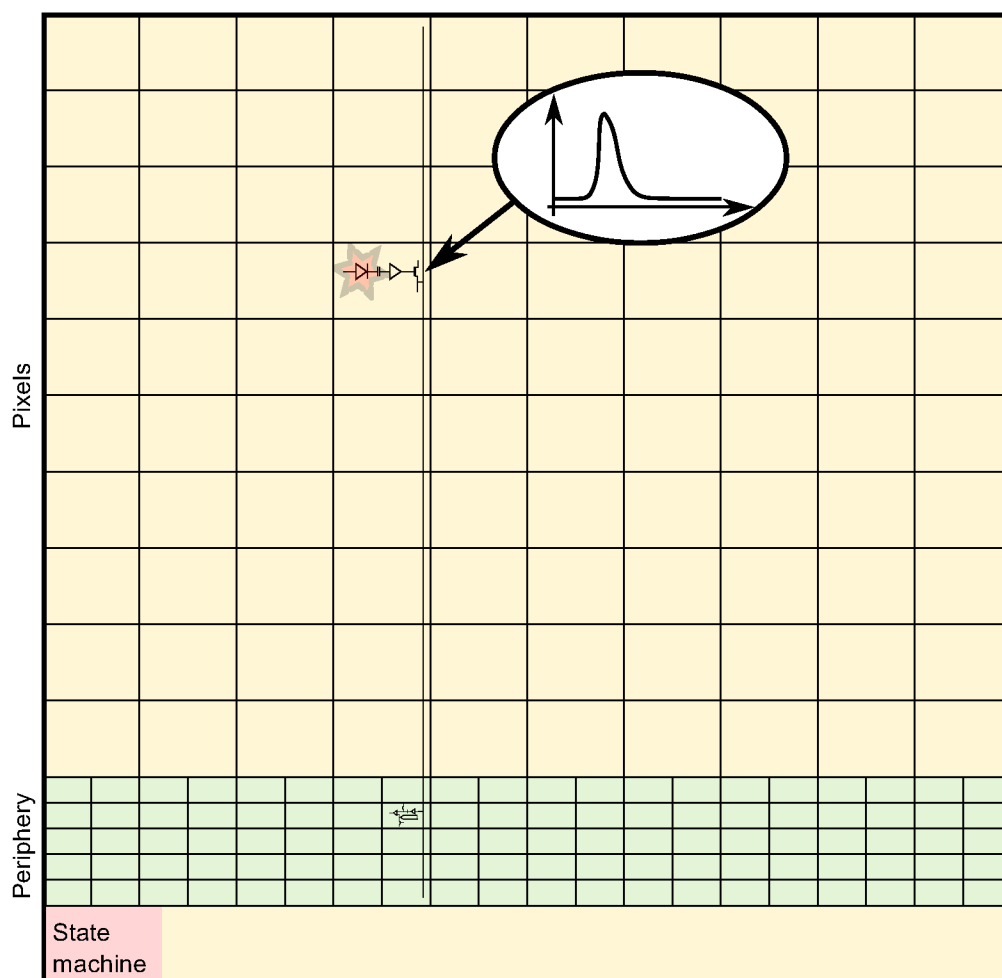


hit sequence:

- signal generation



MuPix Hit Detection

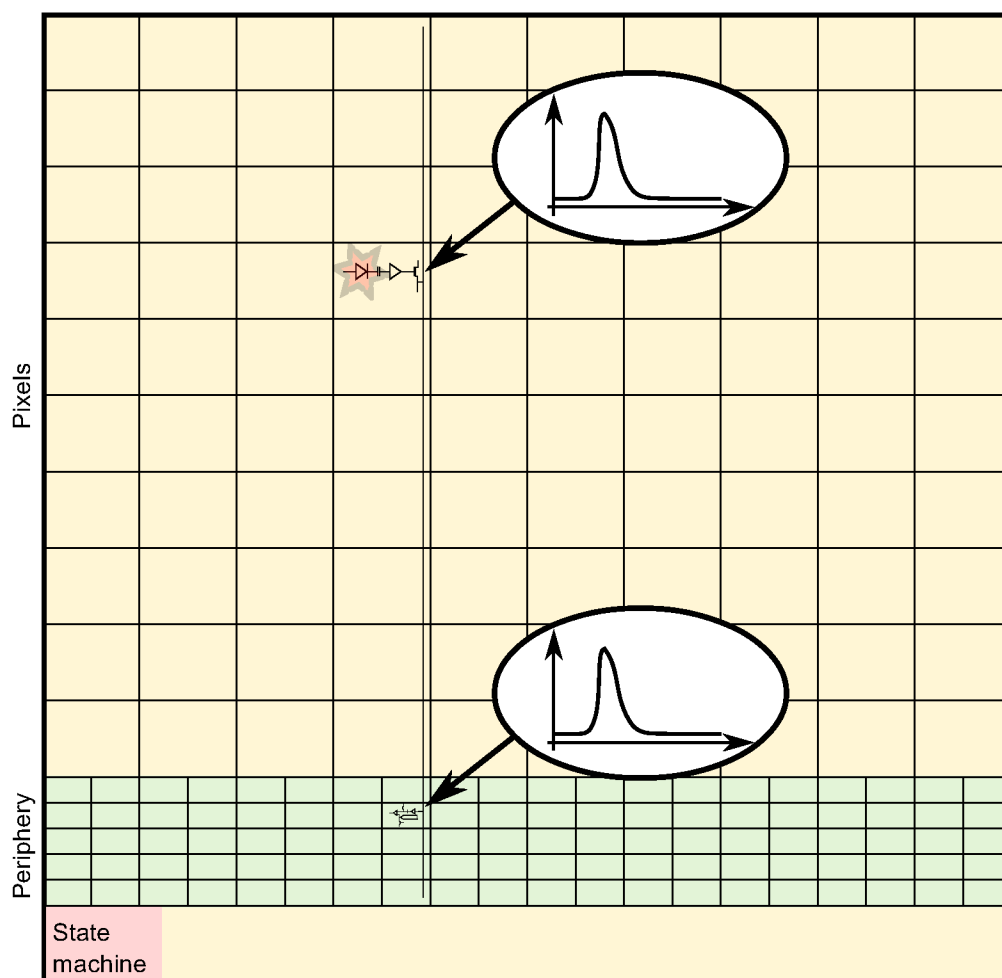


hit sequence:

- signal generation
- **amplification**



MuPix Hit Detection

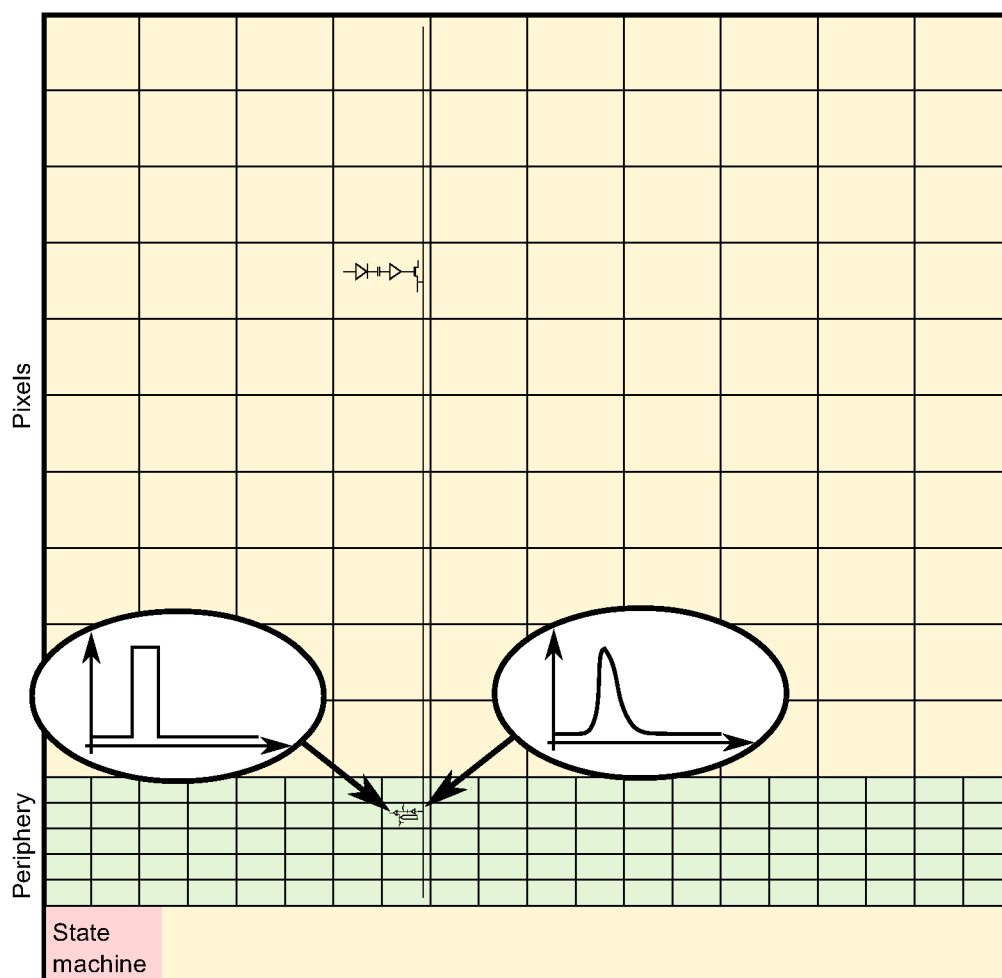


hit sequence:

- signal is generated
- charge amplified
- **received in mirror pixel**



MuPix Hit Detection

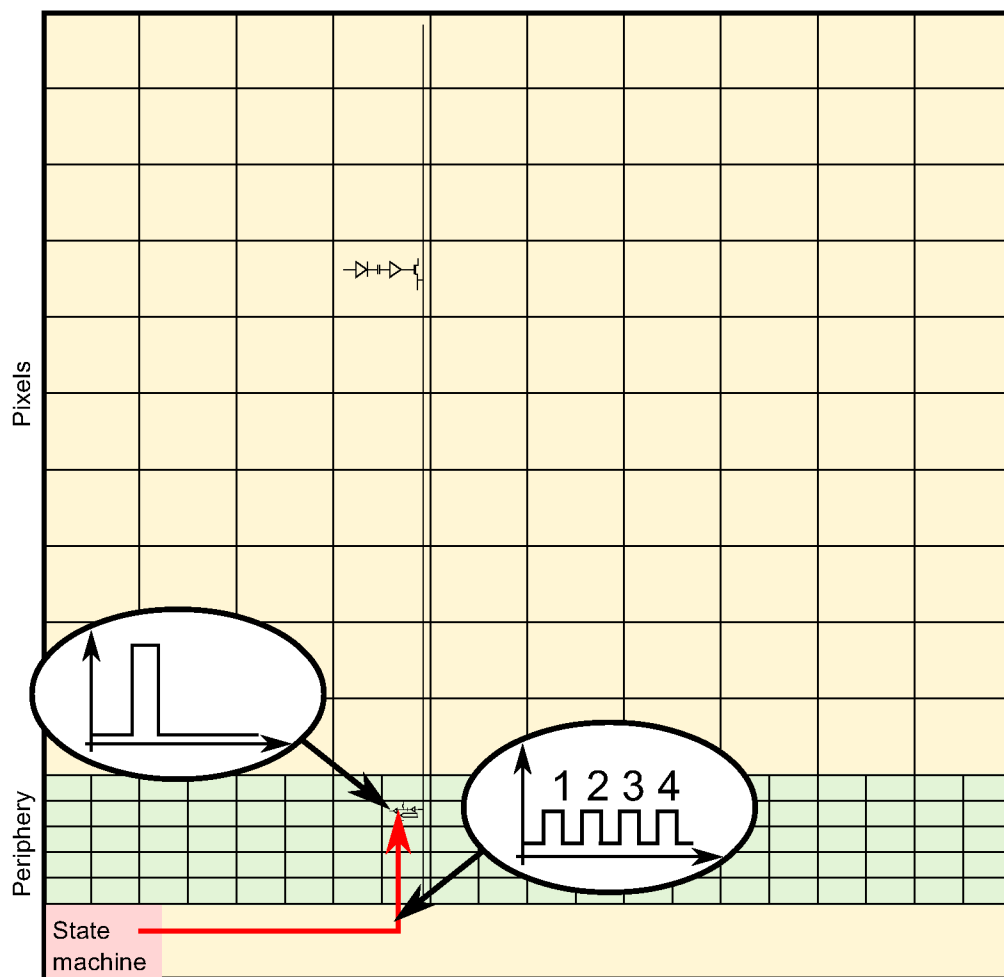


hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- **discriminated**



MuPix Hit Detection

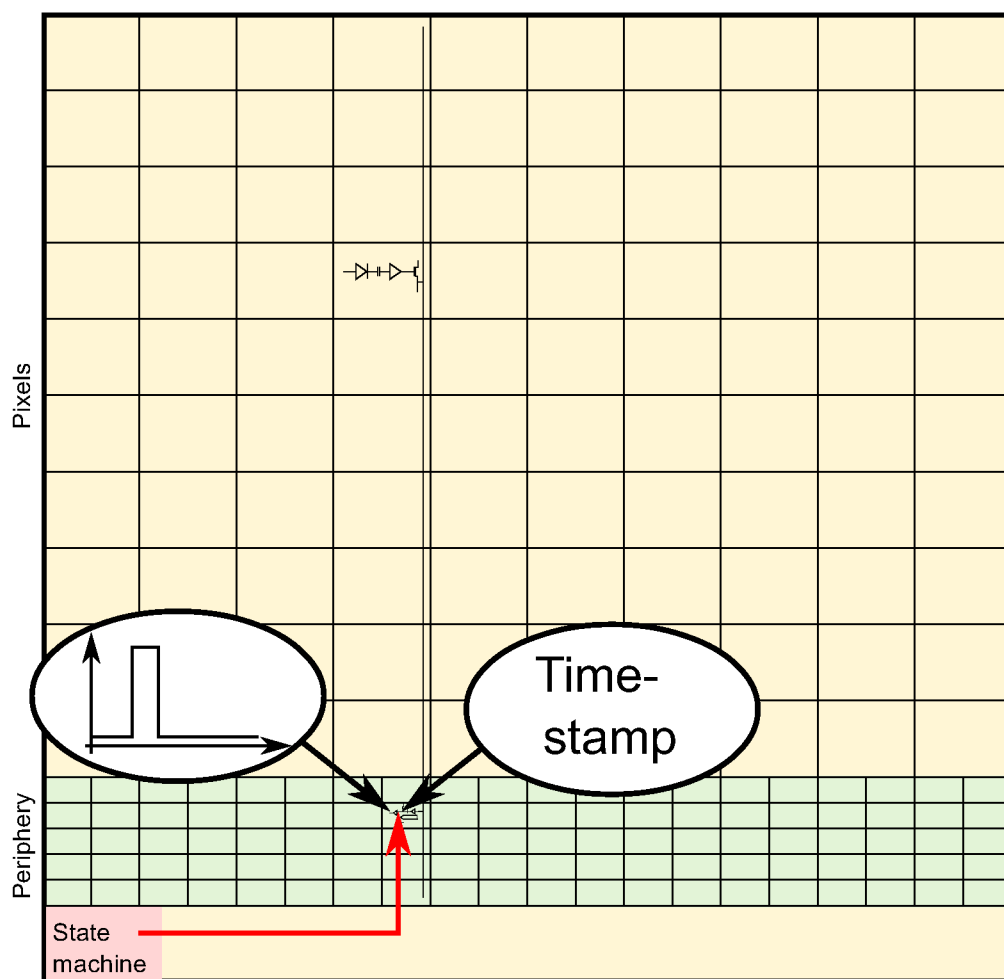


hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated
- **scaler generated from clk**



MuPix Hit Detection

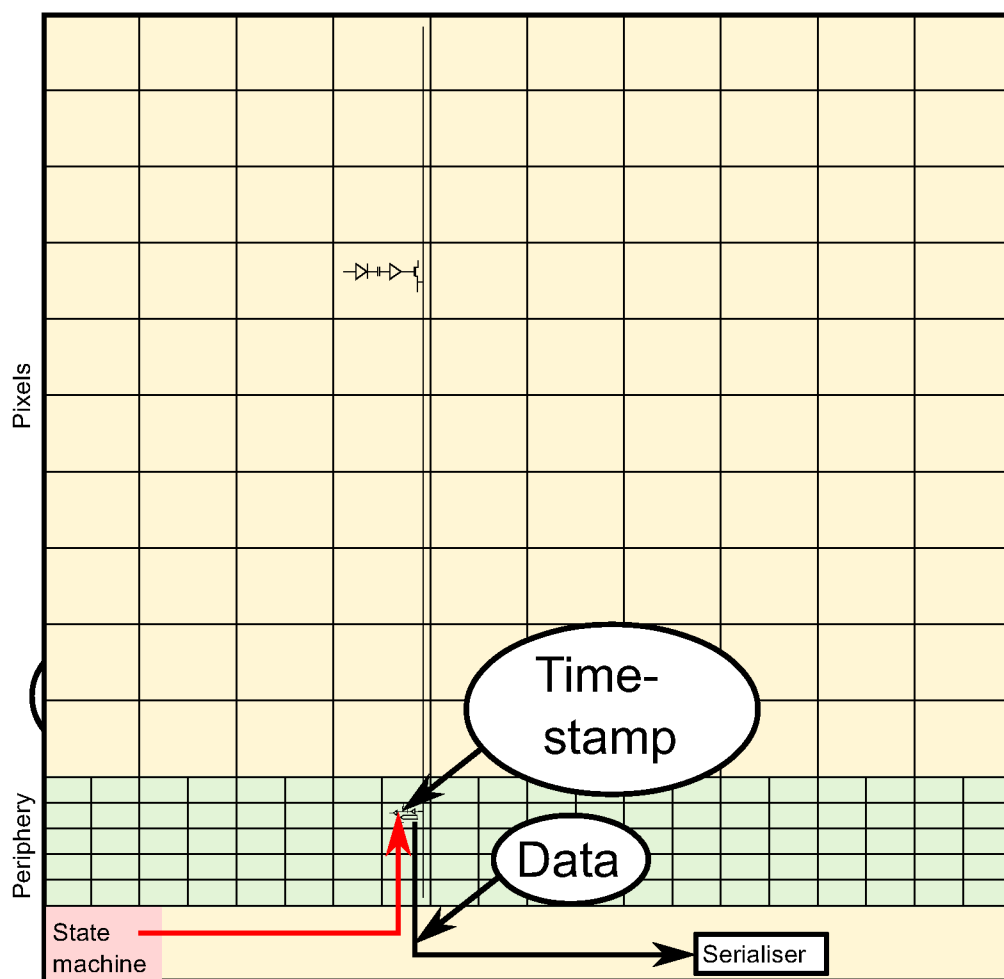


hit sequence:

- signal is generated
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk
- **timestamp generation**



MuPix Hit Detection

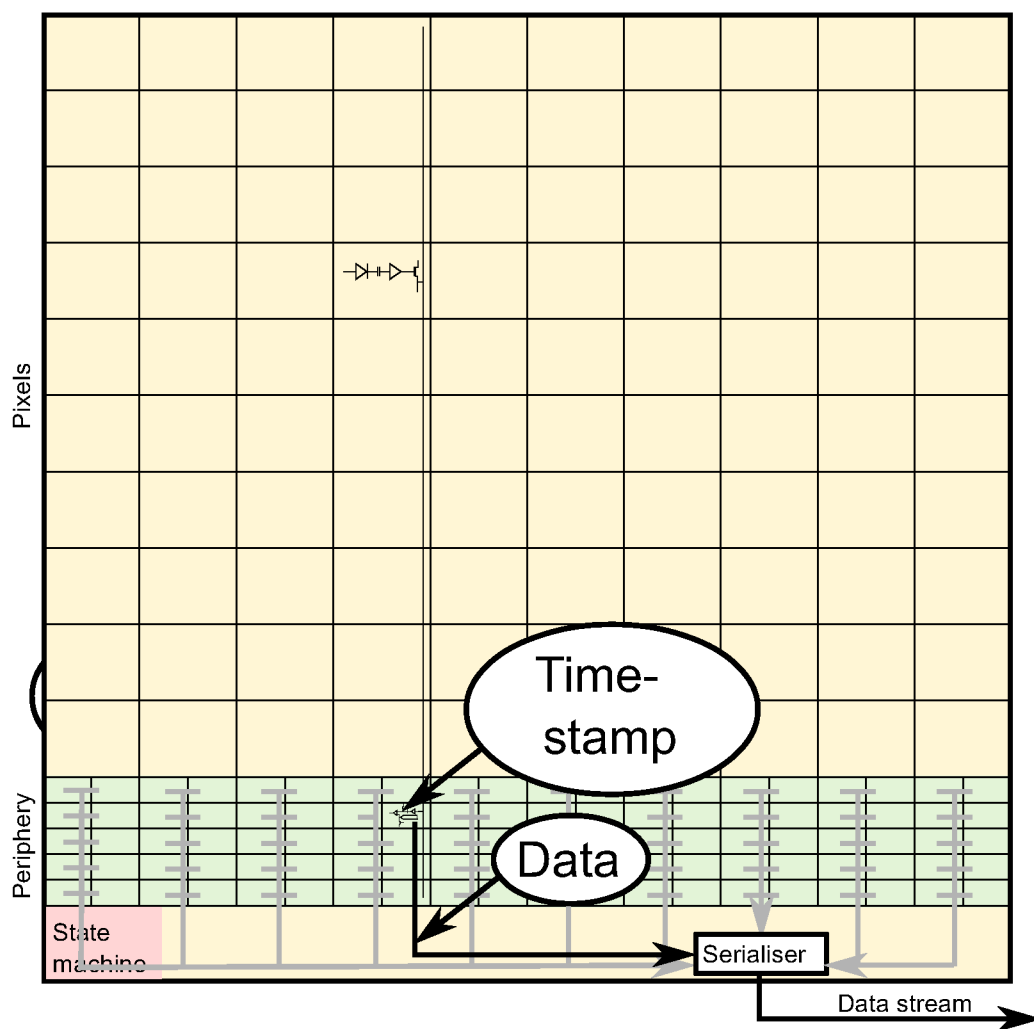


hit sequence:

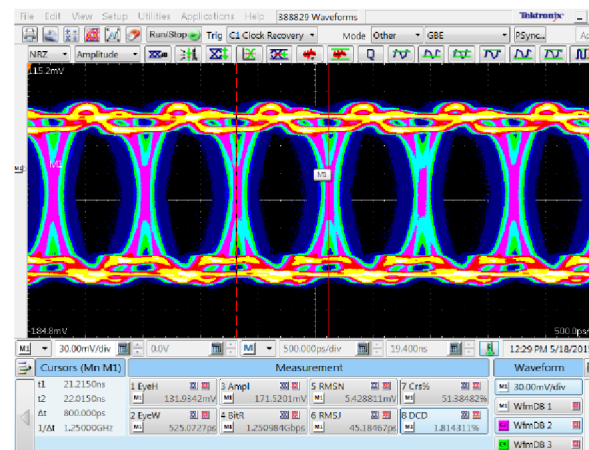
- signal is generated
- charge amplified
- received in mirror pixel
- discriminated
- scaler generated from clk
- timestamp generation
- hit address and timestamp send to serializer



MuPix Hit Detection



Finally, all detected hits are sent out via a **1.25 Gbit/s** serial link



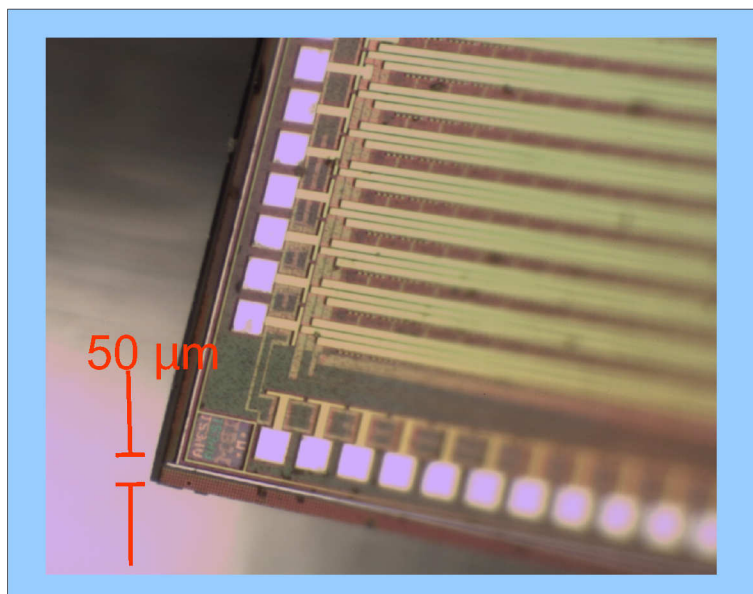
Eye diagram measured with Mupix7 prototype

Maximum readout rate is 33 Mhits/s per link

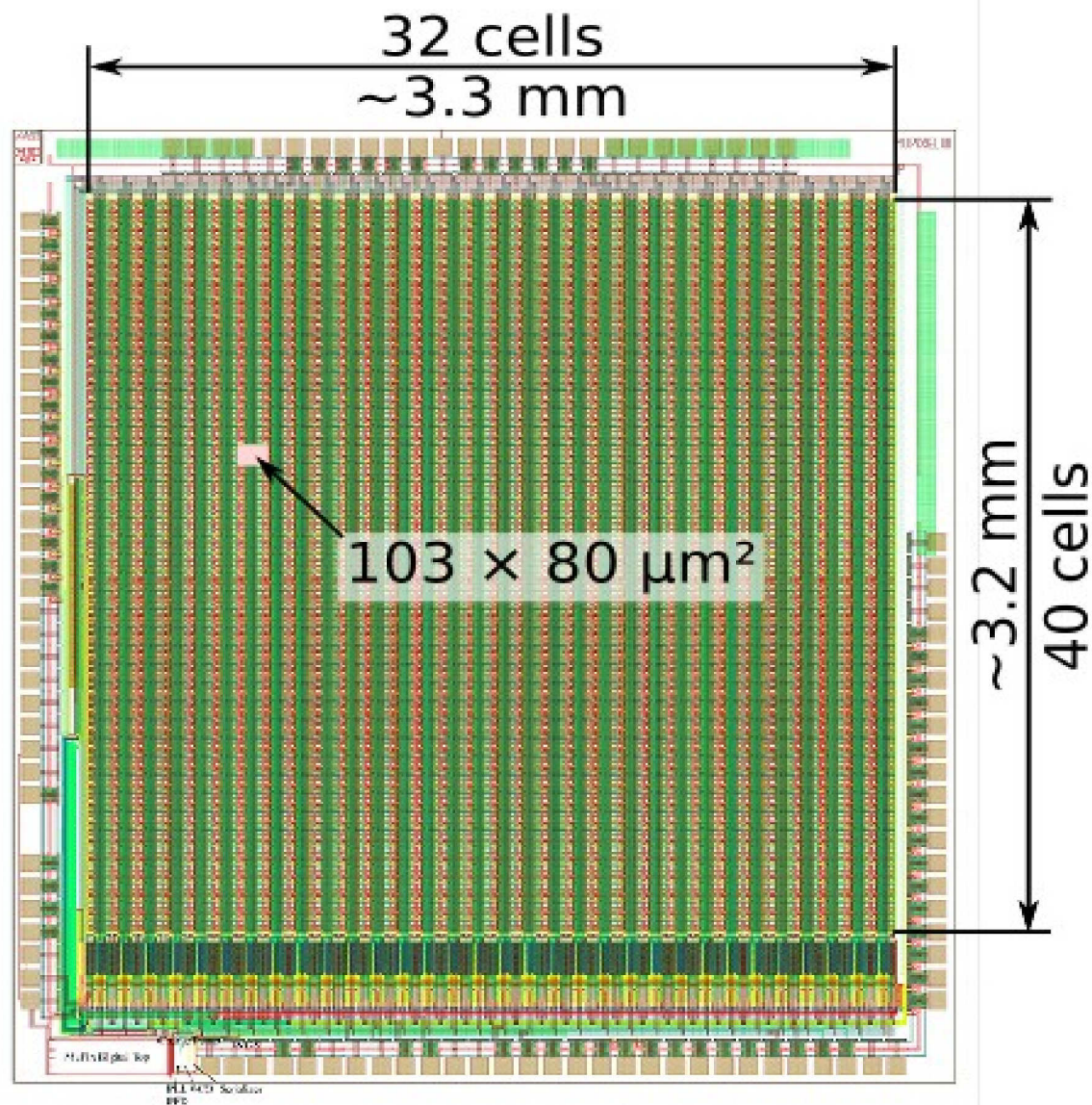


MuPix7 Prototype

Institutes: Heidelberg, Karlsruhe, Mainz



Austria Microsystems (AMS)
HV-CMOS 180 nm
20 Ω cm p-substrate

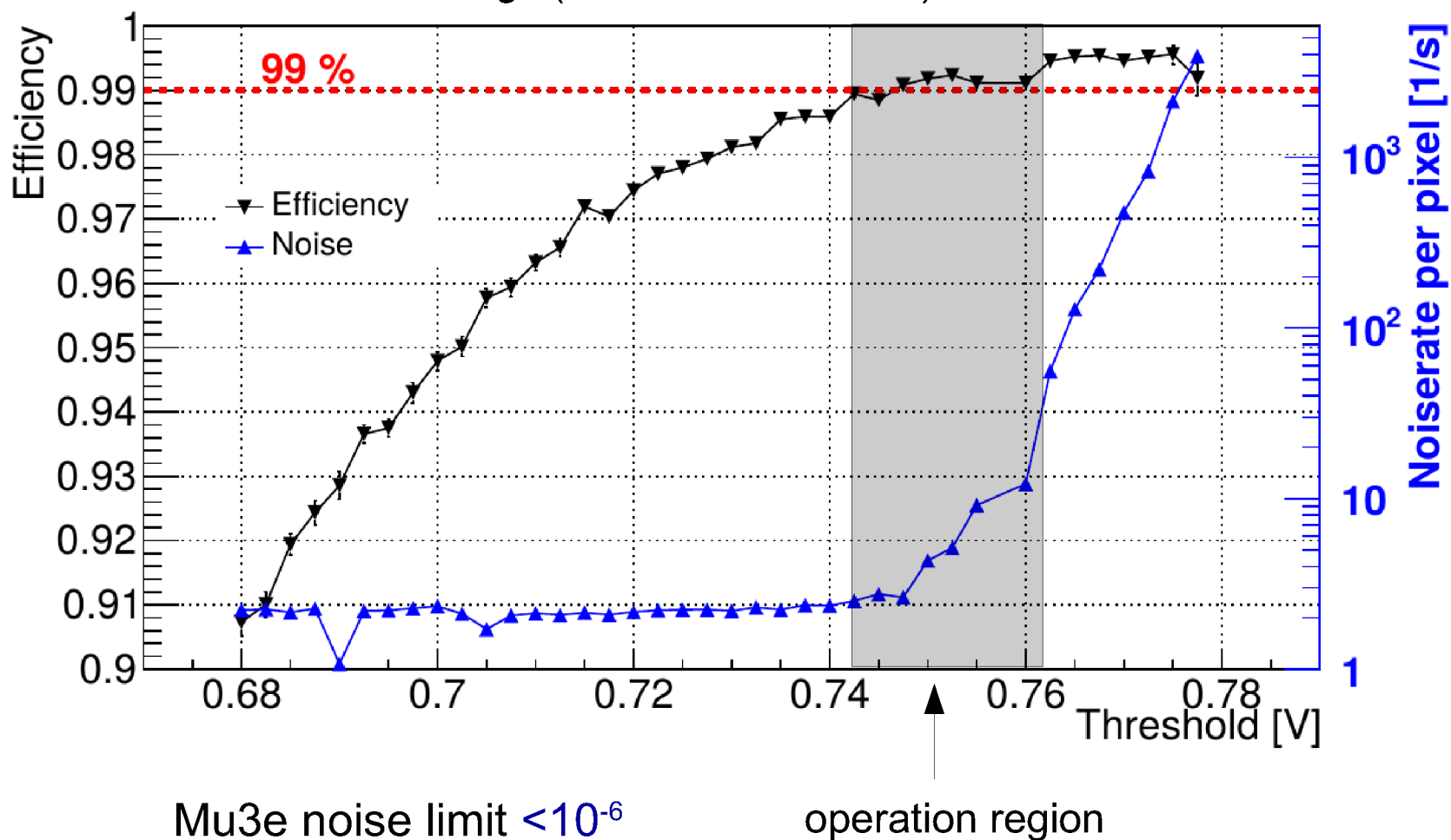




MuPix7 Efficiency and Noise

Data obtained from PSI beamtest (PiM1) using MuPix telescope

defaults settings (-85V, 300 mW/cm²); vertical tracks

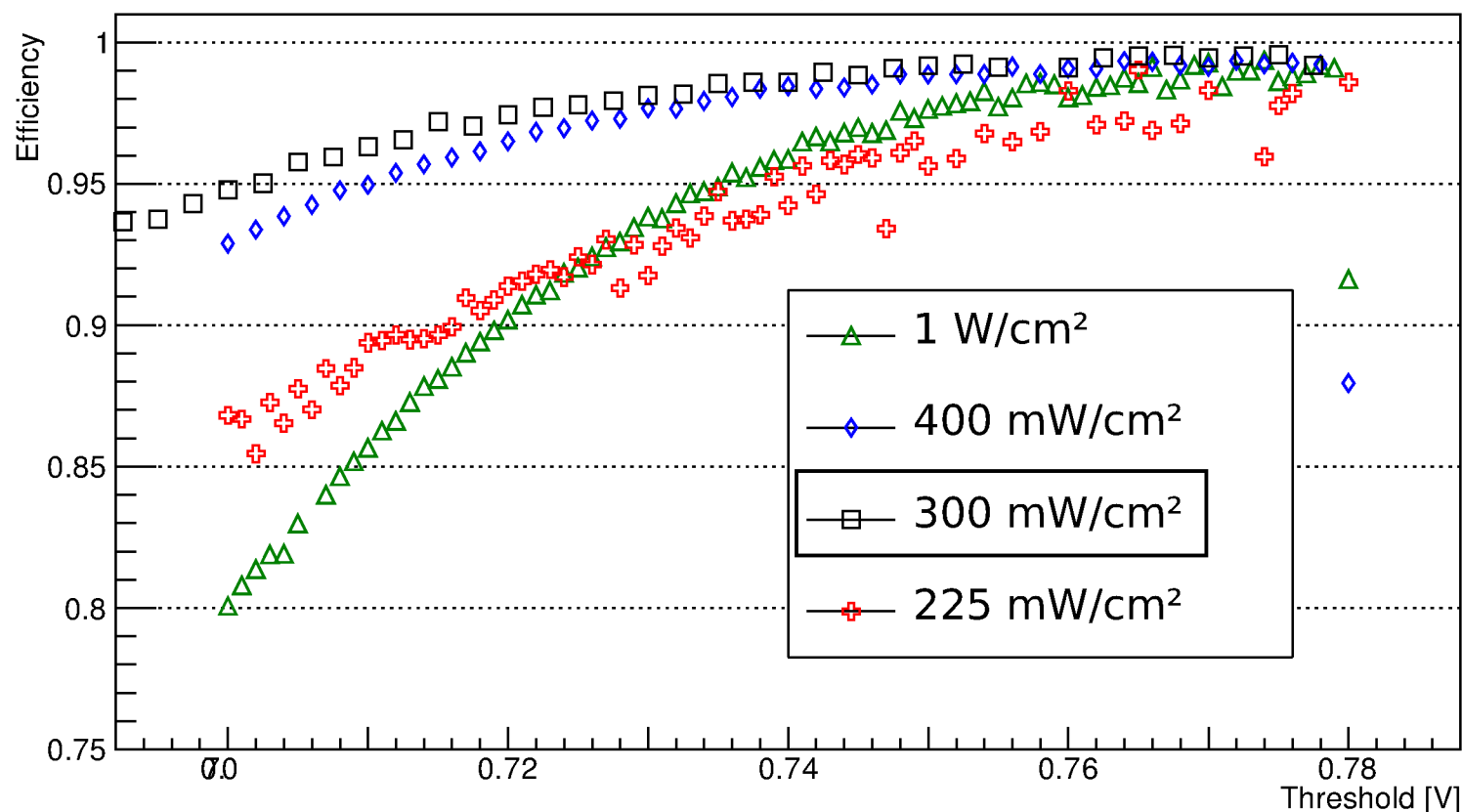




MuPix7 Operation Parameters

Operation point defined by 13 DAC settings → scan

-85V; vertical tracks, data taken at PSI

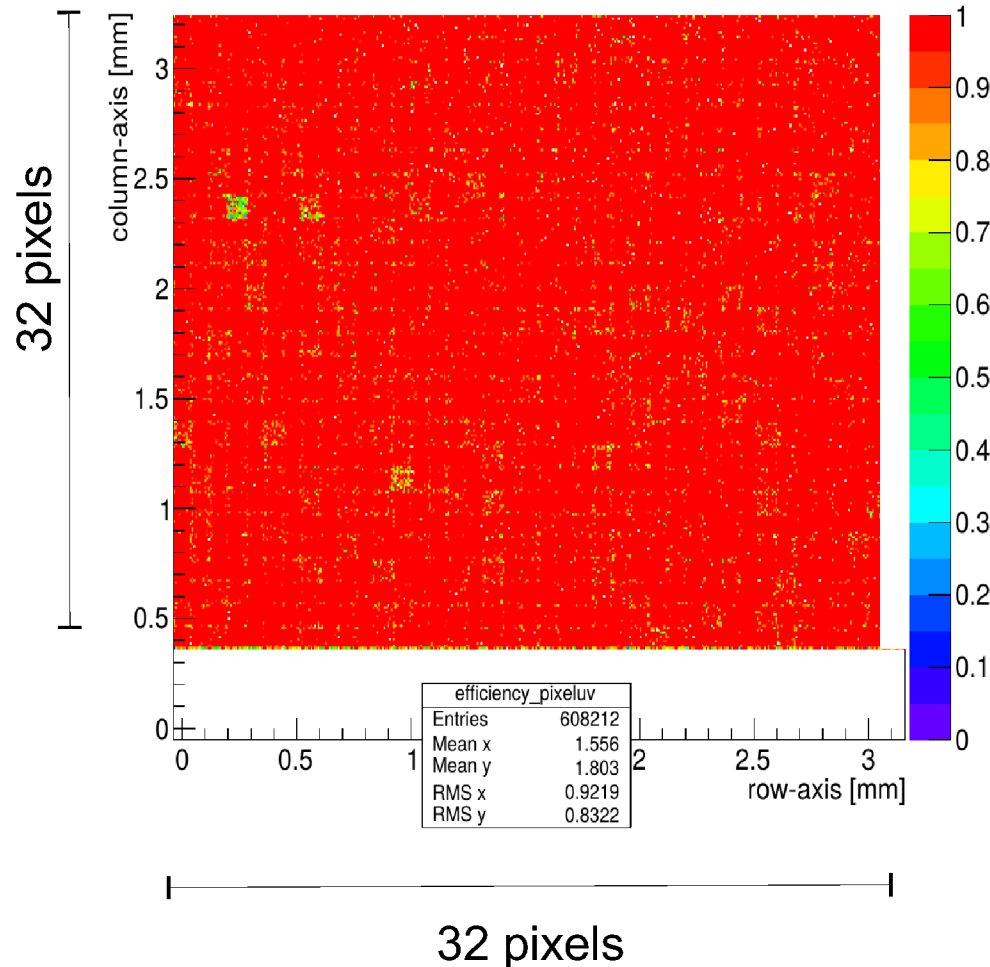


more power does not improve performance

MuPix7 (In-)Efficiency Investigations

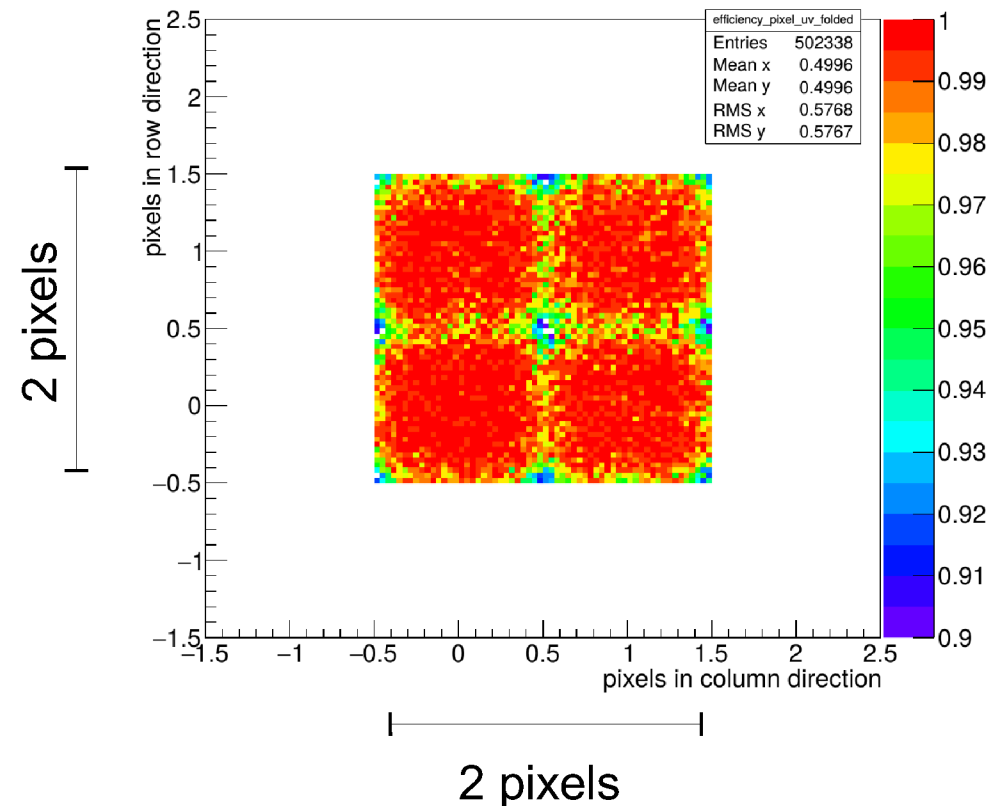
Efficiency map with increased threshold

Mupix7, 720 mV threshold, HV = -85 V



DESY testbeam with EUDET telescope

Mupix7, 720 mV threshold, HV = -85 V



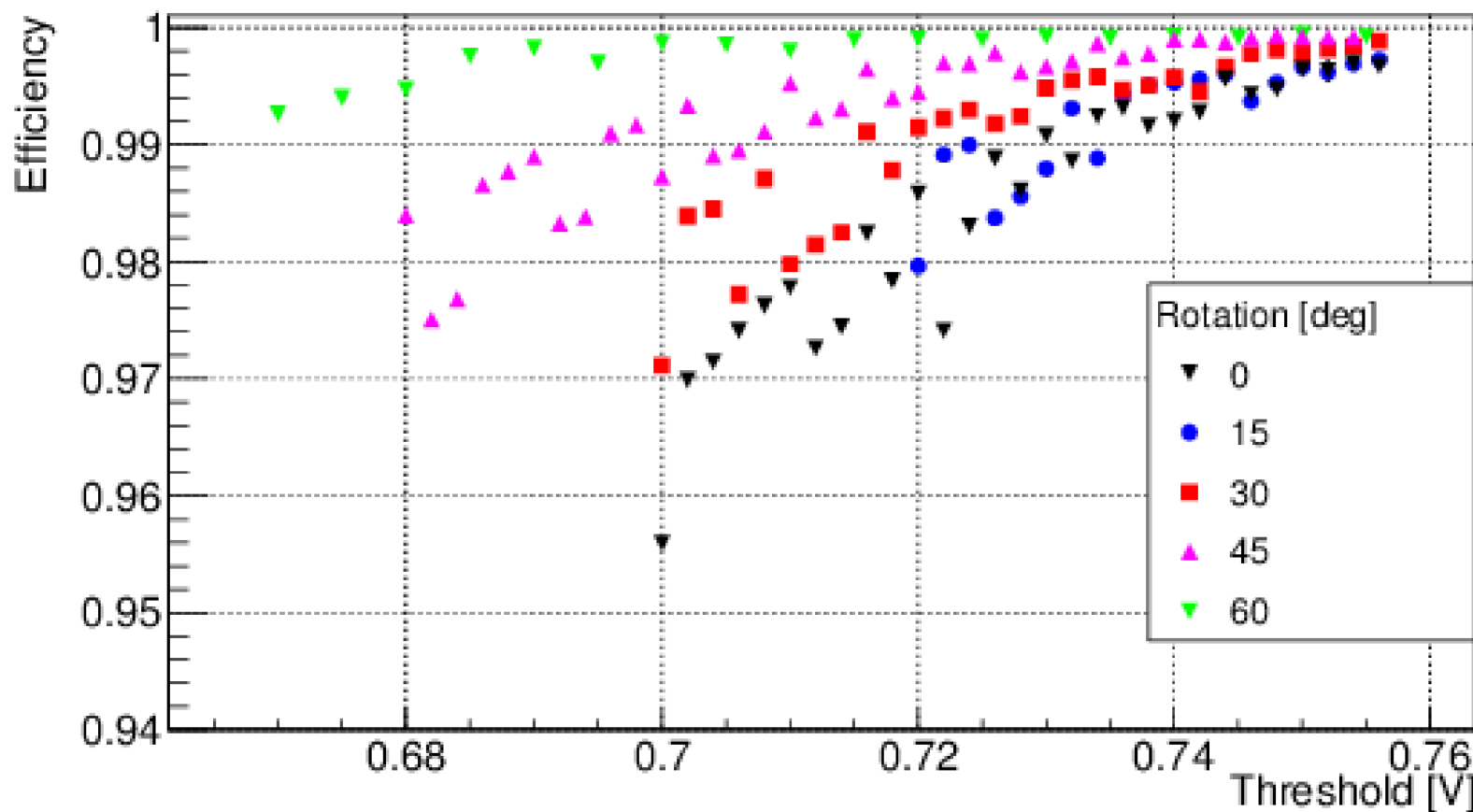
inefficiency due to charge sharing
at edges and corners



Efficiency with Rotated Sensors

Increase deposited ionisation charge by using tilted sensor

default settings; -85V; ± 48 ns search window



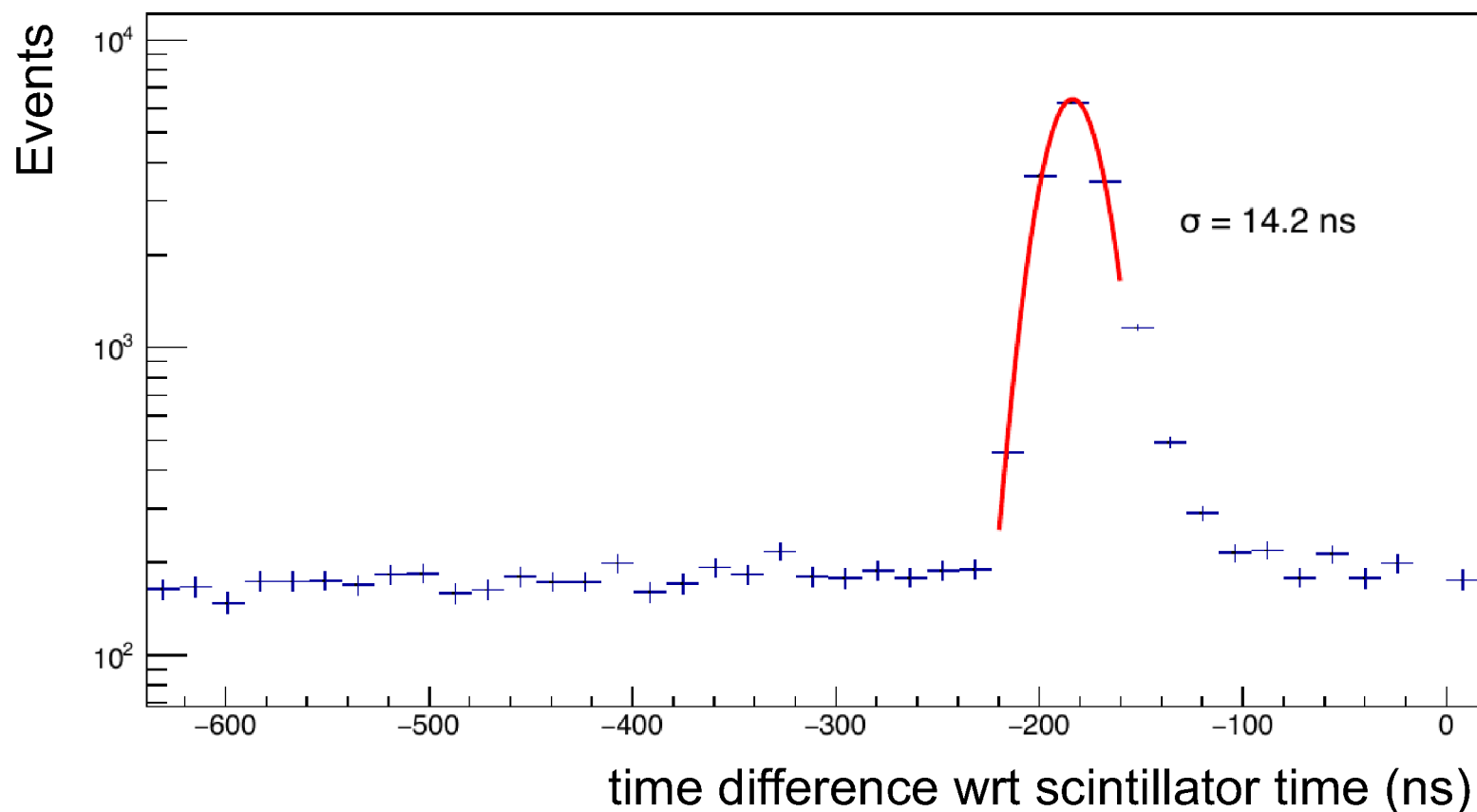
with factor 2 more charge (rot=60°) → 100% efficiency



MuPix7 Time Resolution

MuPix telescope with scintillator as time reference:

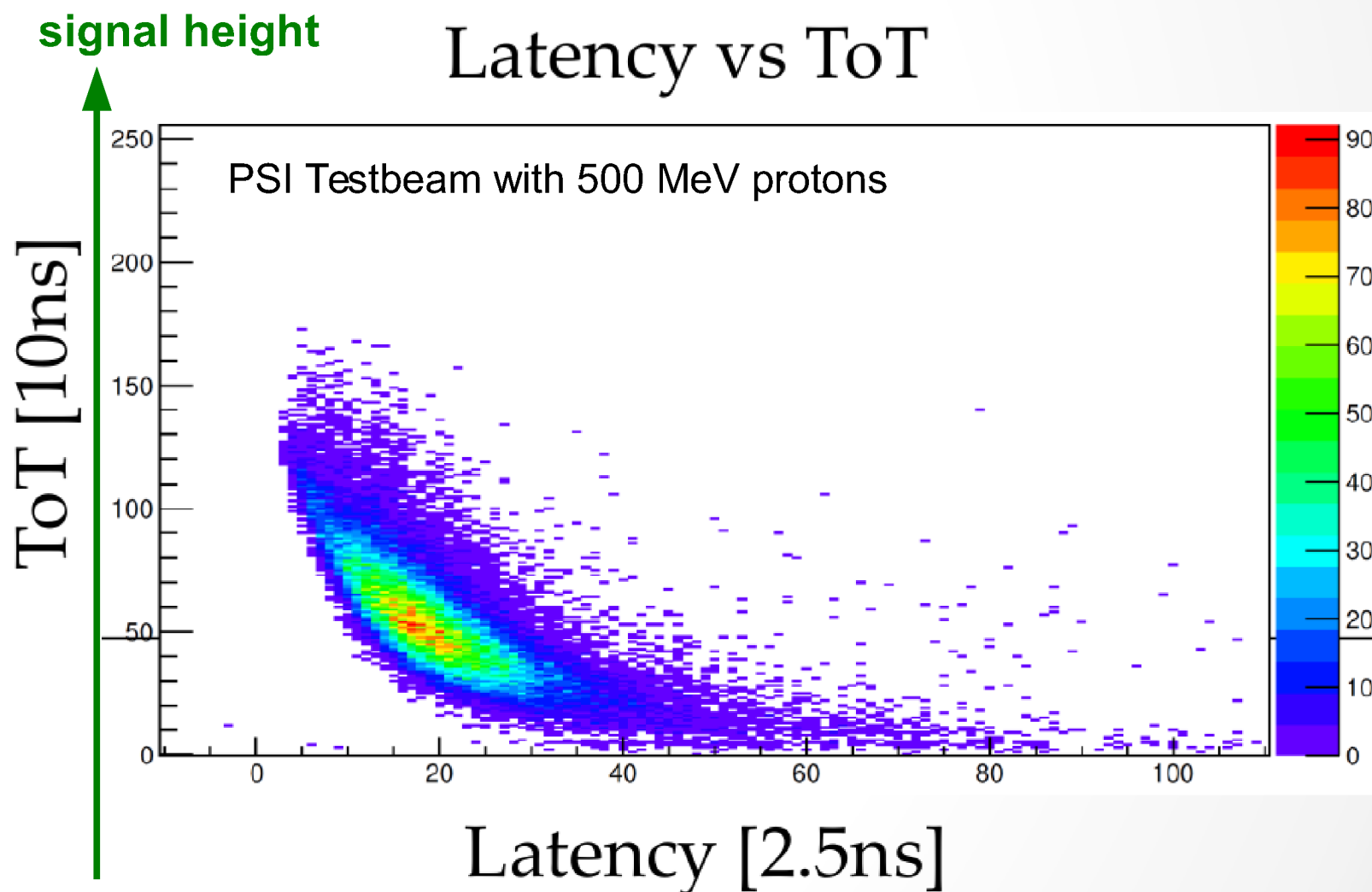
default settings; -85V; 300 mW/cm²



Mu3e requirement $\sigma(t) < 20 \text{ ns}$ fulfilled



MuPix7 Time Resolution

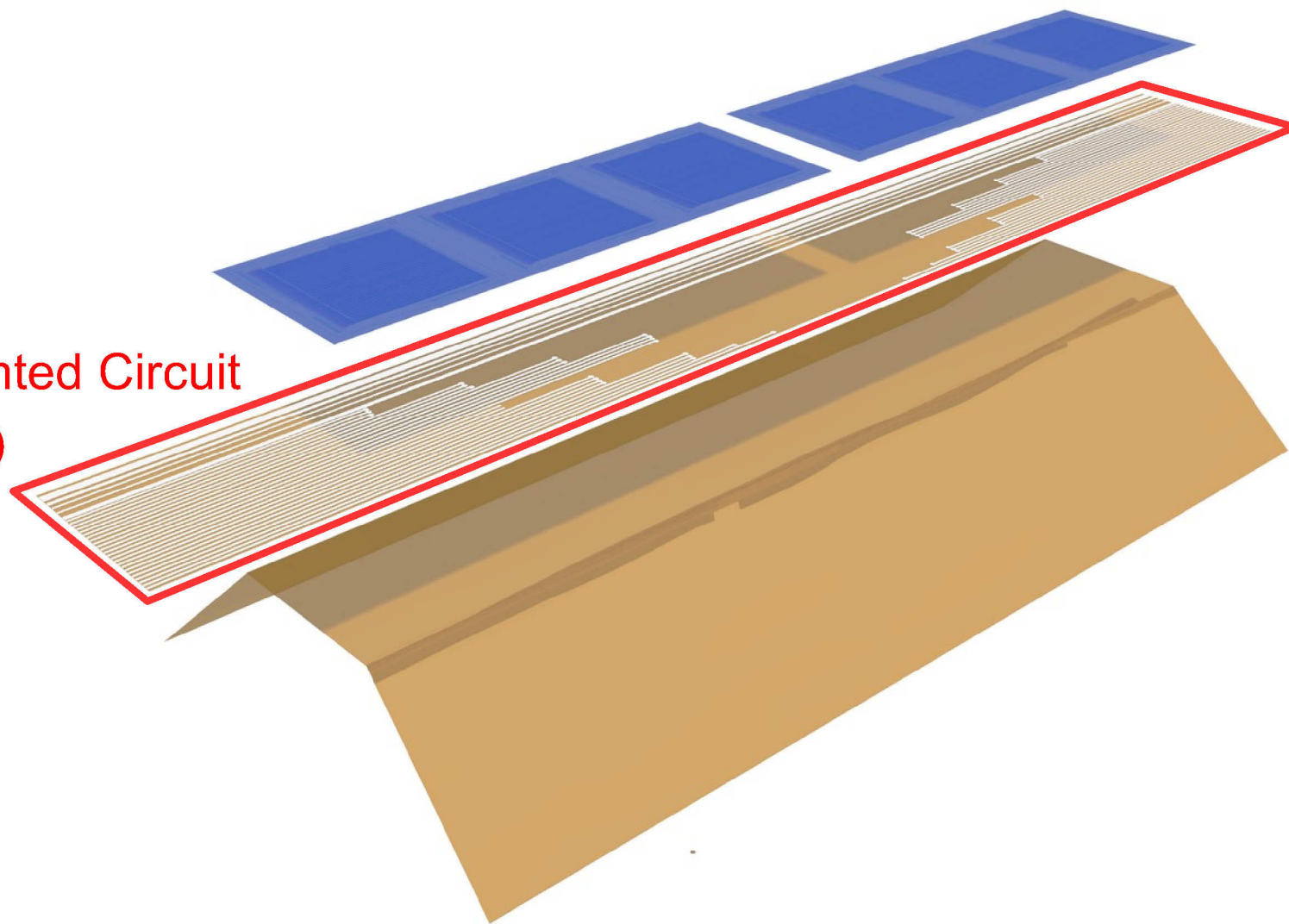


- timewalk correction possible
- in test chips $\sigma(t) \sim 5 \text{ ns}$ achieved (I. Peric et al. KIT)



Mu3e Flexprint

Flexible Printed Circuit
Board (FPC)





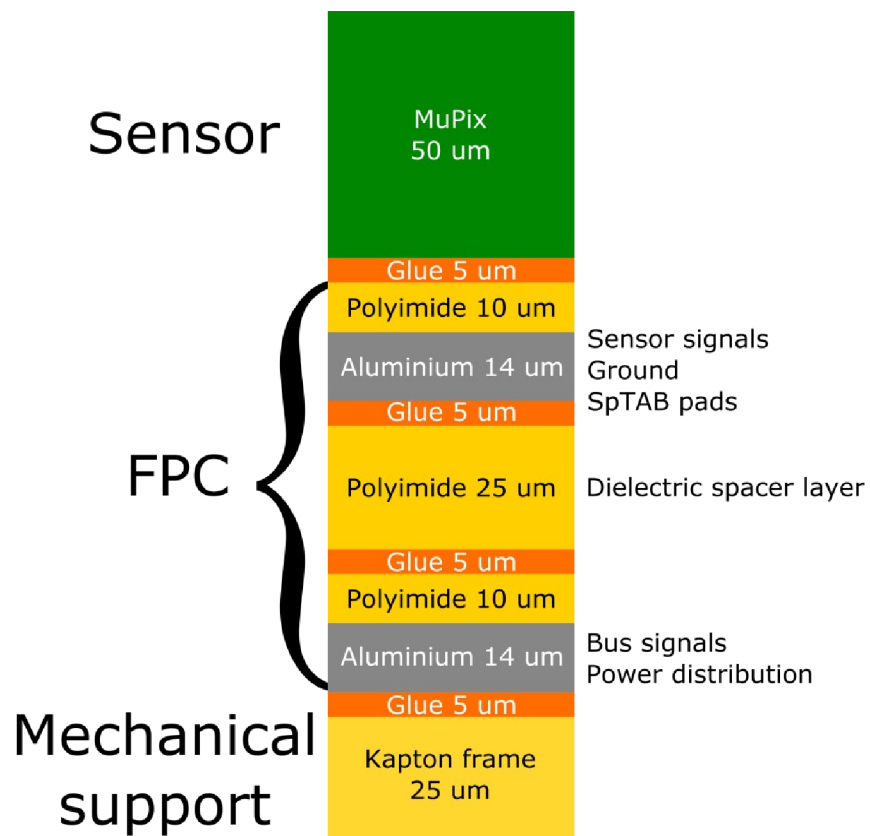
Mu3e Flexprint

Two layer aluminium (LTU Ltd.)

- 14µm Al + 10µm polyimide per layer
- Structure sizes $\geq 65\mu\text{m}$
- Dielectric spacing 45µm

SpTAB technology

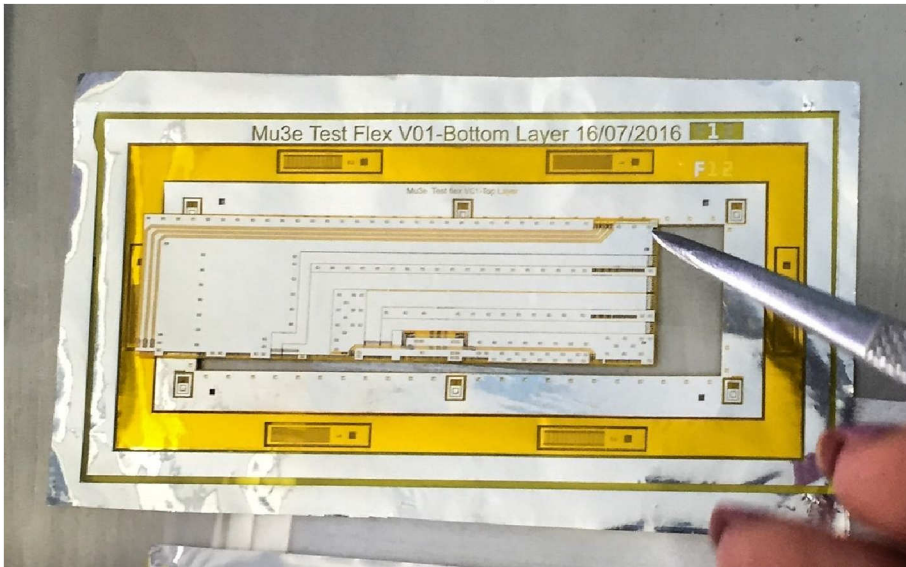
- Single point Tape Automated Bonding
- No additional (high Z) material for bonding!





Flexprint Production and Bonding

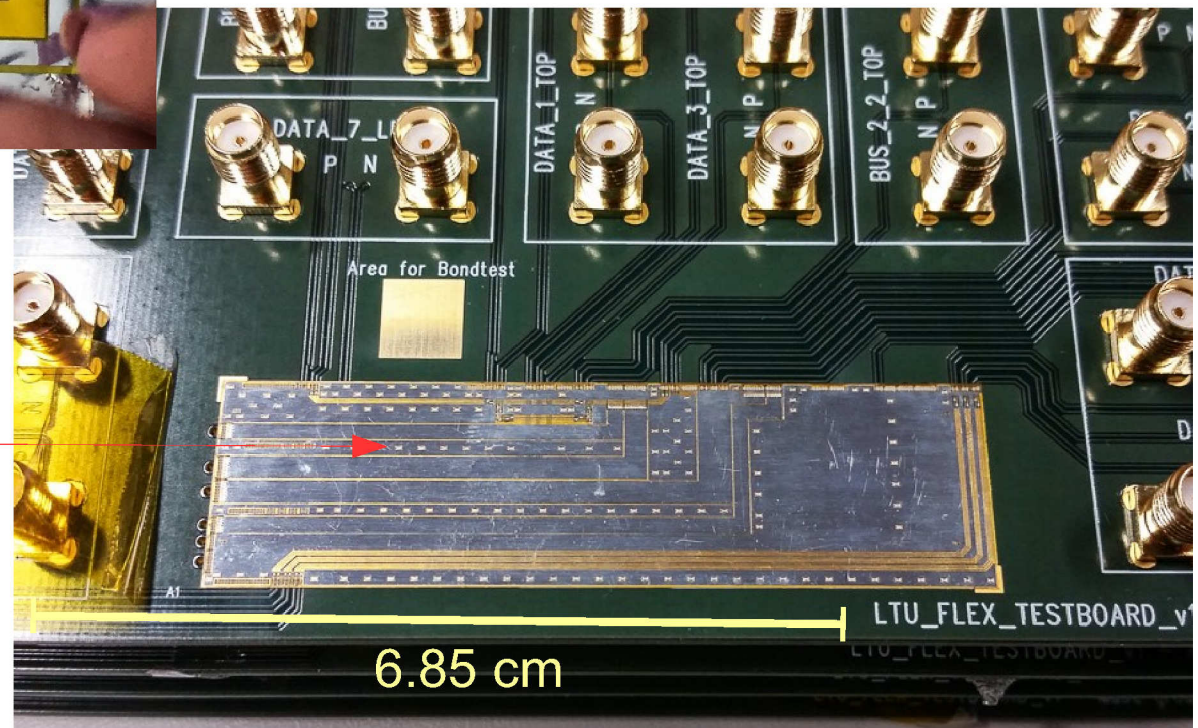
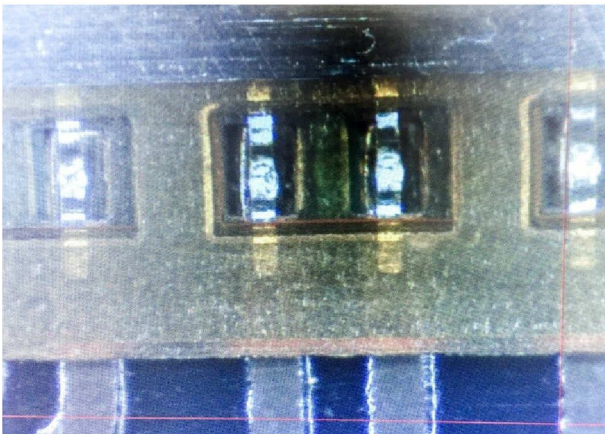
FPC Production by LTU Ltd



→ bonding yield 100%

FPC SpTAB bonded on test board

SpTAB bond zoomed in

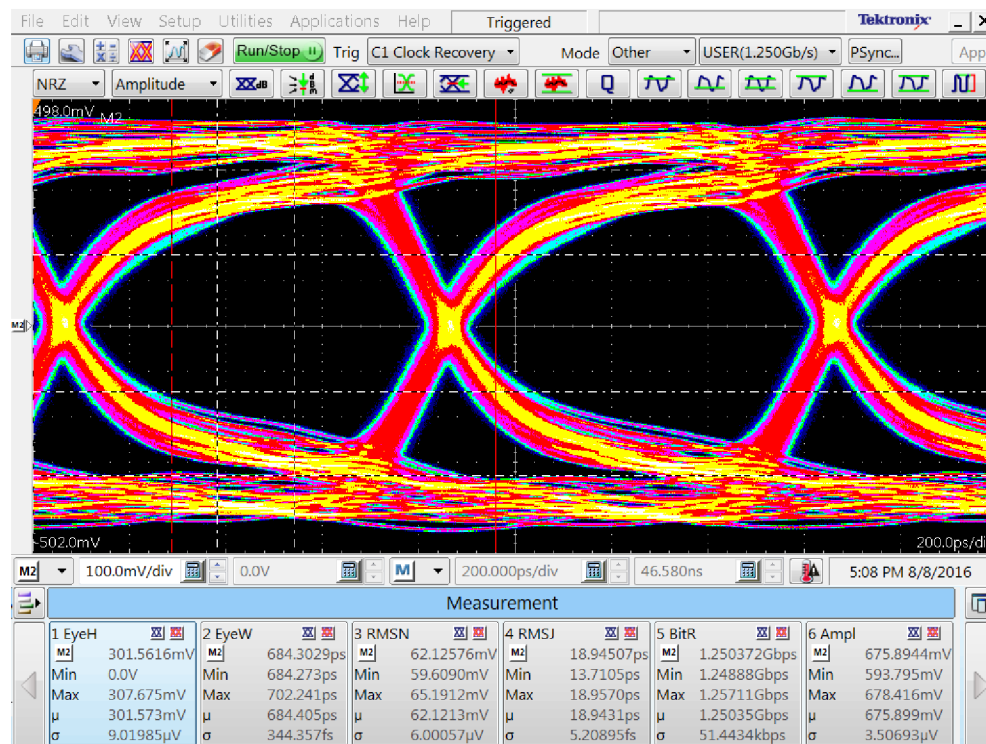




Flexprint Test Results

Bit error rate measurements

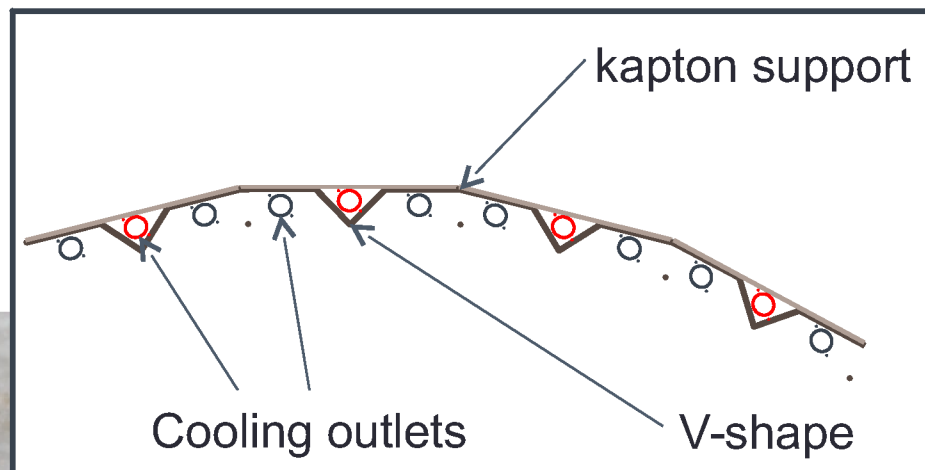
- 10 differential pairs
- No bit errors at 1.25 Gbit/s
 - $\text{BER} < 2 \cdot 10^{-13}$ per pair
- No bit errors at 2.5 Gbit/s
 - $\text{BER} < 3 \cdot 10^{-13}$ per pair





Mu3e Helium Gas Cooling Concept

V-shapes for local
cooling channels



Helium cooling:

- global flow
- flow between layers
- flow in V-shapes



Mu3e Cooling Simulation

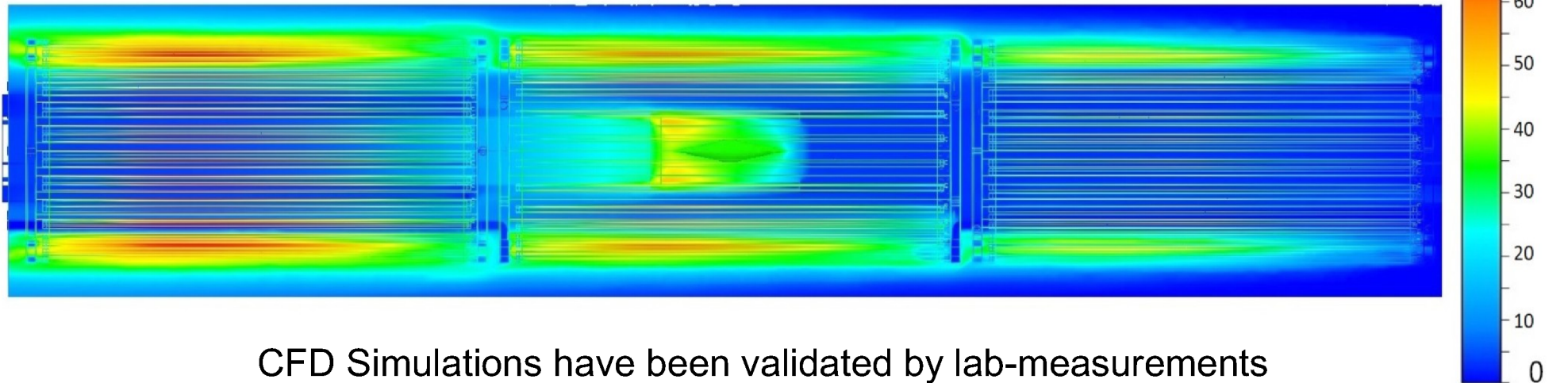
Helium input temperature $T=0^{\circ}\text{C}$

$v_{\text{local}} = 16 \text{ m/s}$ (V-folds)

$v_{\text{layer1-2}} = 4 \text{ m/s}$

$v_{\text{layer3-4}} = 3.5 \text{ m/s}$

$v_{\text{global}} = 3.5 \text{ m/s}$

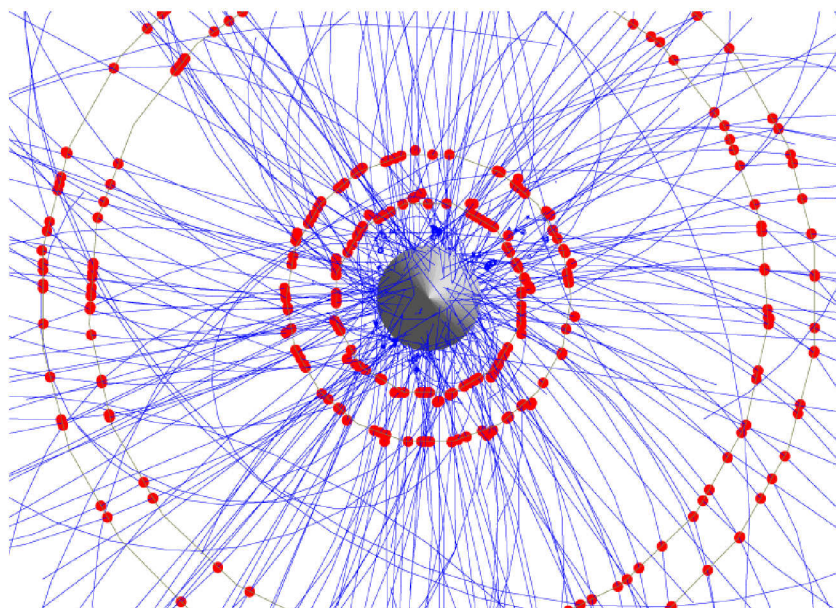


- Target power consumption ($P=250 \text{ mW/cm}^2$) seems feasible
- Maximum power consumption ($P=400 \text{ mW/cm}^2$) requires higher flow velocities



Mu3e Readout

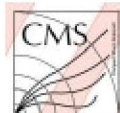
Mu3e reconstructed tracks



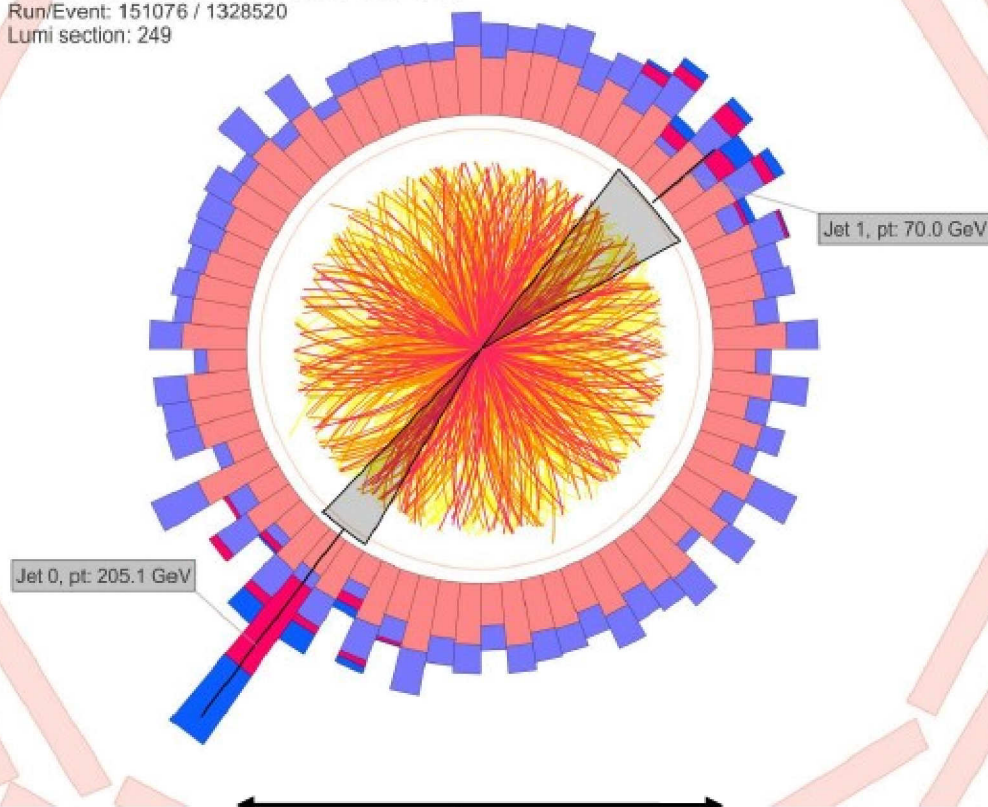
≈16 cm

Readout in frames of 50 ns

$E \sim 10\text{-}50 \text{ MeV}$



CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249



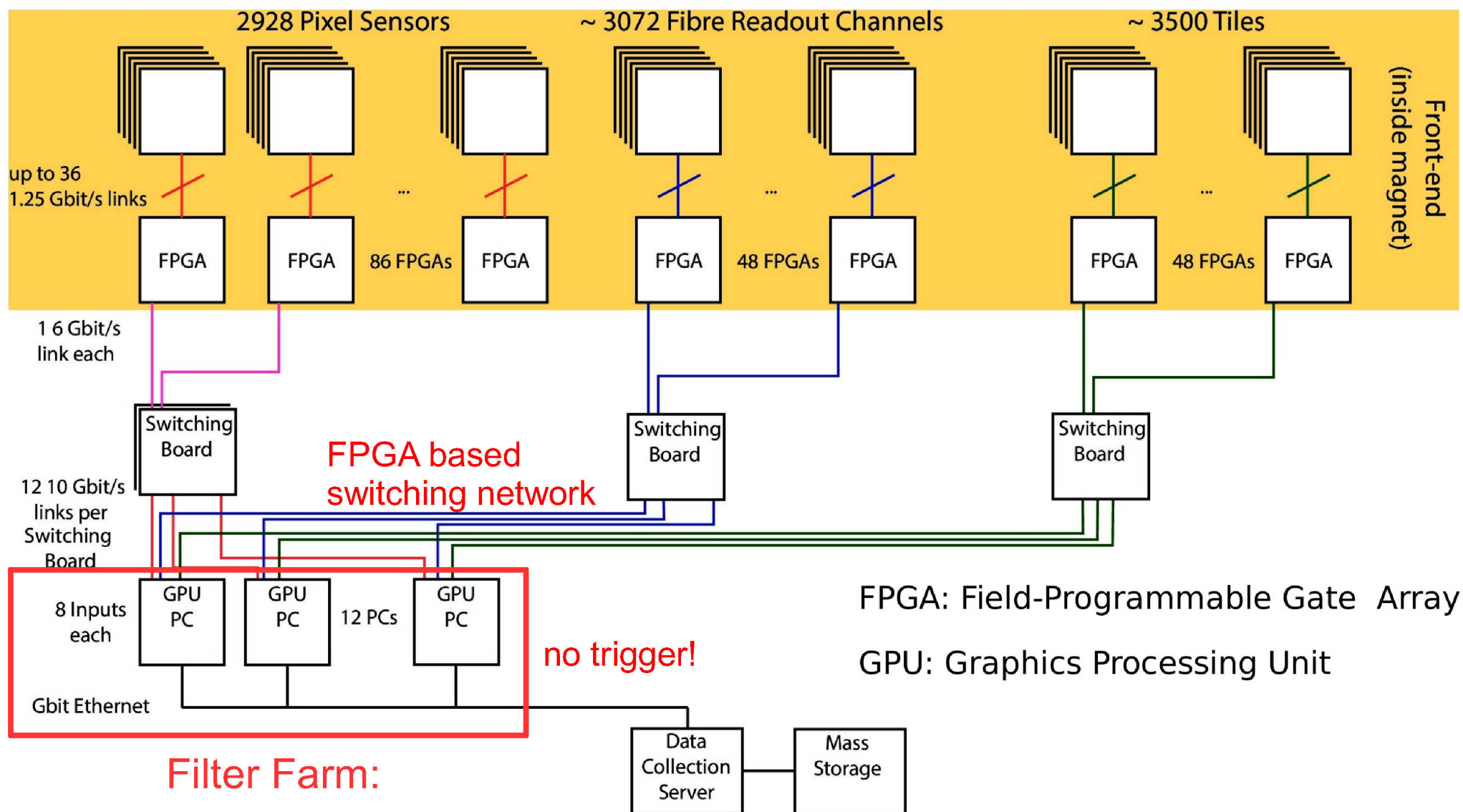
≈2.5 m

Collision every 25 ns

$E \sim 200 \text{ GeV}$



Mu3e Readout Concept



Online track reconstruction using fast algorithm → [arXiv:1606.04990](https://arxiv.org/abs/1606.04990)



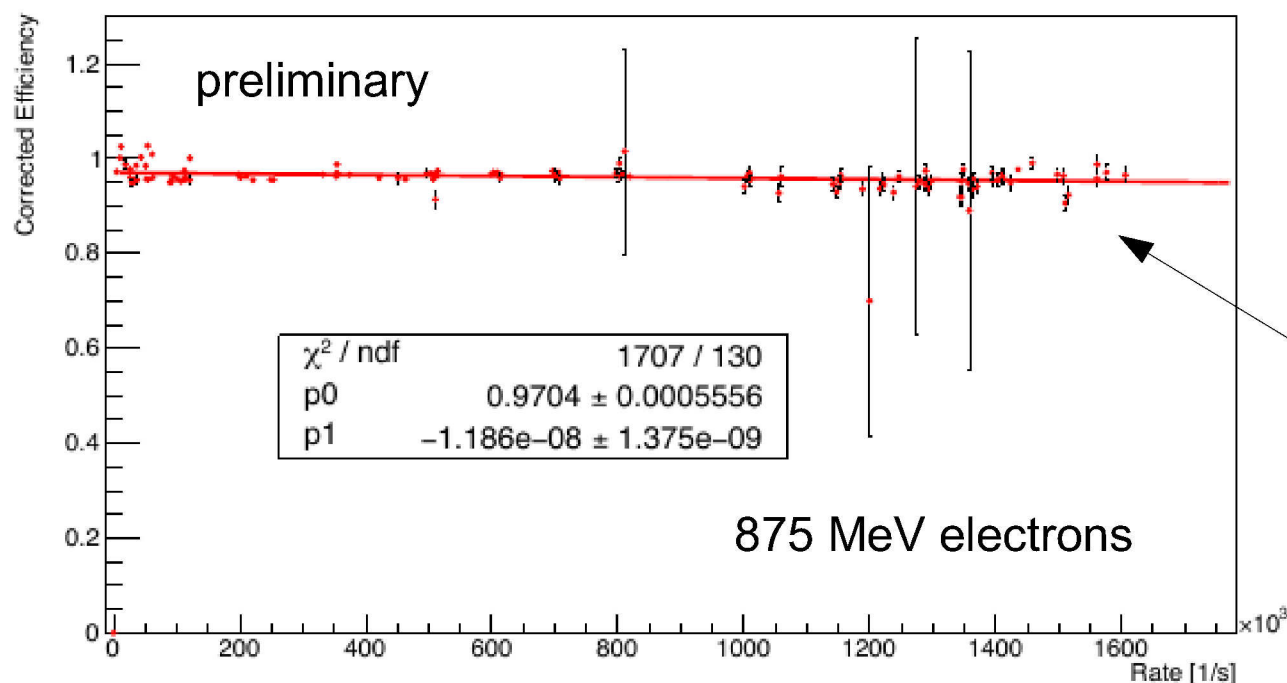
MuPix Telescopes + Rate Tests

Mu3e readout architecture (DMA transfer) implemented in beam telescopes

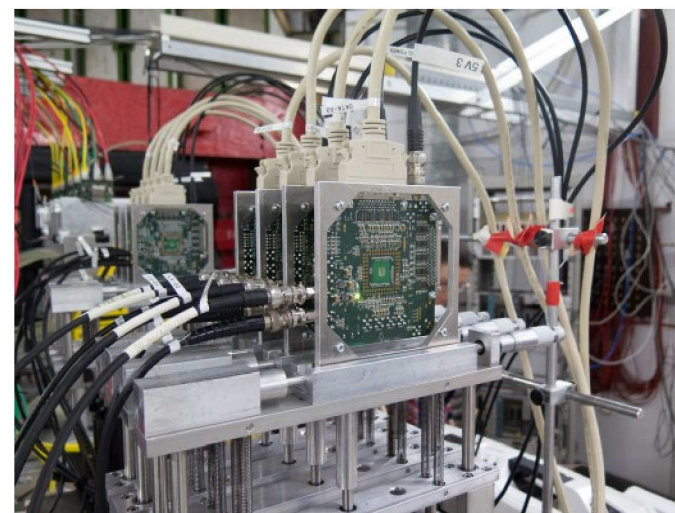
- one telescope with 8 stations
- two telescopes with 4 stations
- successfully used at CERN, DESY, MAMI, PSI

Rate test at MAMI:

Efficiency vs rate



→ very small rate dependence of efficiency!



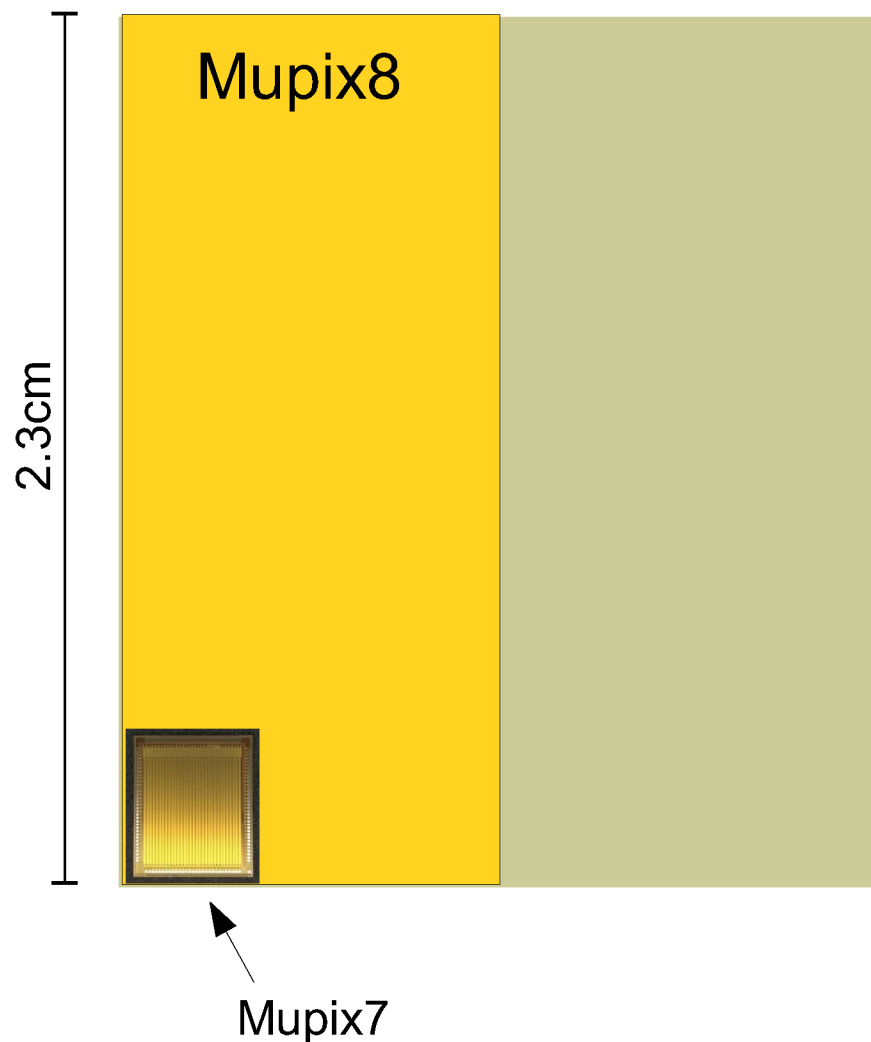
MAMI rate test

- **875 MeV e^-**
- maximum rate rate of **1.6 MHz / 5x5 pixels**
- corresponds to **780 Mhits/cm²/s**



Outlook

Mupix8 submission in AMS HV 180nm in October 2016
(Heidelberg, Karlsruhe, Liverpool, Mainz)



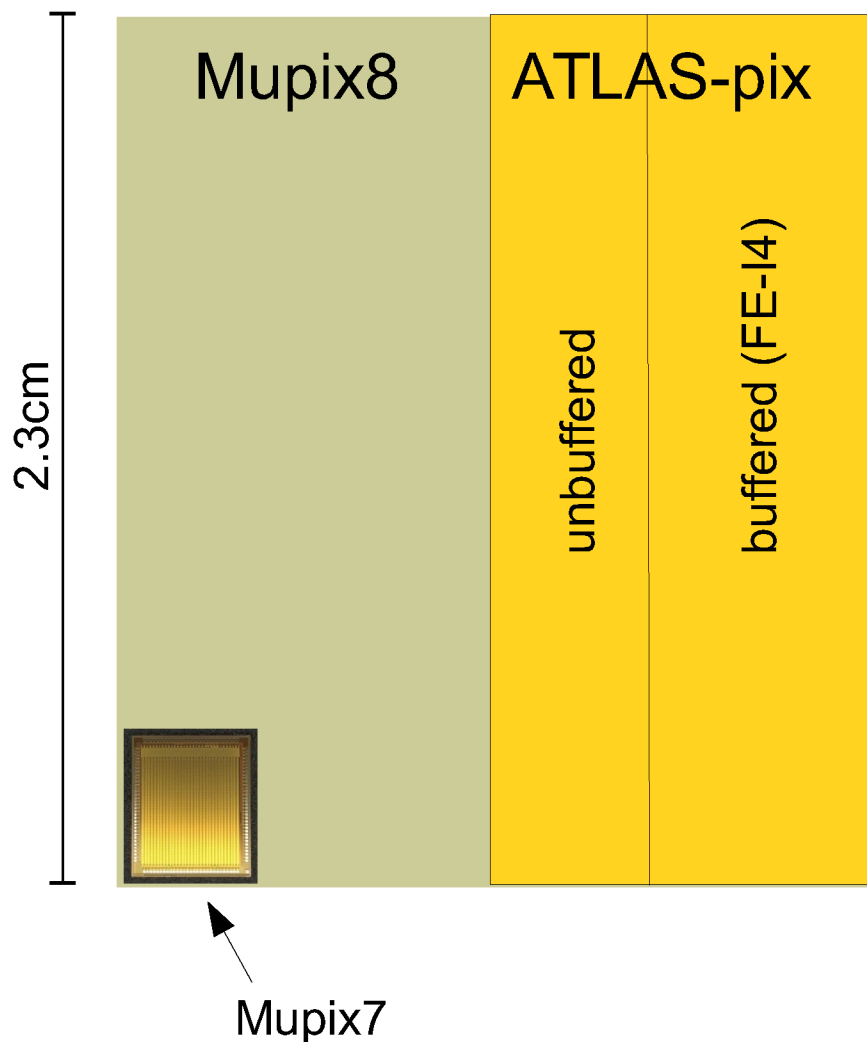
Features and main changes

- 31250 pixel of size $80 \times 80 \mu\text{m}^2$
- 36 bond-pads per chip (+ extra test pads)
- four serial links a 1.25 Gbps
- two time walk correction schemes
 - two threshold method
 - ToT with voltage ramp
- change substrate: $80 \Omega\text{cm}$ (before $20 \Omega\text{cm}$)
 - larger depletion
- current drivers for transmission lines
- some fixes and changes
(cross talk, state machine, no 2nd amplifier...)



Outlook

ATLAS-pix submission in AMS HV 180nm in October 2016
(Bern, BNL, CPPM, Geneva, Heidelberg, Karlsruhe, Liverpool)



ATLAS-pix Features

- monolithic design
- one half is unbuffered similar to MuPix
 - allows for 40 MHz track trigger!
- the other half with FE-I4 RO architecture
- digital cells (comparator in cell)
- Different substrates/process (std. 20 Ωcm):
 - 80 Ωcm
 - 200 Ωcm
 - 200 Ωcm with deep P-well

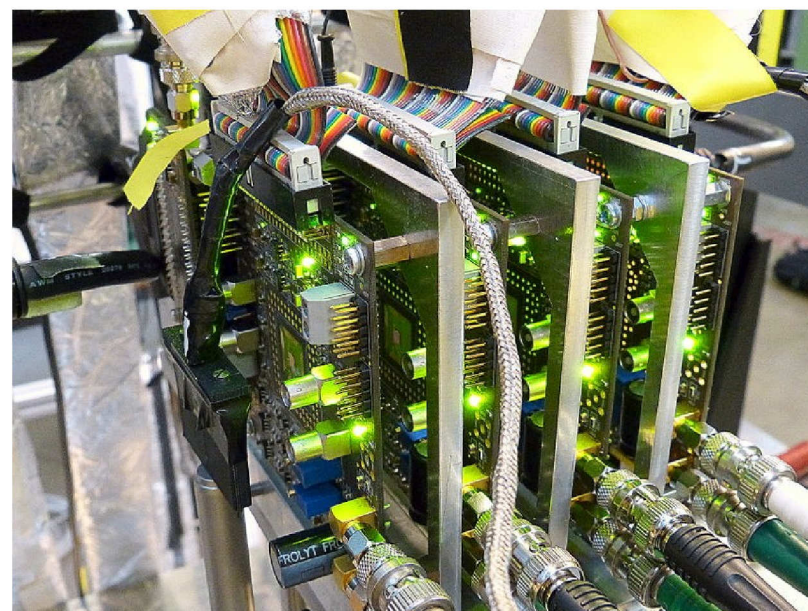
AMS HV process is rather **radiation hard**
→ see talk by [Fabian Huegging](#)



Mu3e Experimental Status

- **Technical Design Report for Phase almost ready**
- **Detector construction will start in 2017**
- **Commissioning of the two inner HV-MAPS pixel layers in 2018**
- **Delivery of solenoid magnet in 2018**
- **First data (Phase I) earliest in 2019**

Mupix beam telescope
in July 2014 at PSI





Summary

Mu3e Pixel tracker with several innovations + challenges

- **recurler geometry**
- **ultralight mass design with $0.1\% X_0$ per layer**
- **pixel tracker based on HV-CMOS**
- **fast monolithic sensors with continuous readout**
- **helium gas cooling**
- **fast readout of all hits**



Backup



Mu3e Collaboration

- DPNC Geneva University



UNIVERSITÉ
DE GENÈVE

- Physics Institute, University Heidelberg



- Kirchhoff Institute, University Heidelberg



KIRCHHOFF-
INSTITUT
FÜR PHYSIK

- IPE @ KIT, Karlsruhe



- Institute for Nuclear Physics, Mainz



- Paul Scherrer Institute



- Physics Institute, University Zurich



Universität
Zürich^{UZH}

- Institute for Particle Physics, ETH Zurich



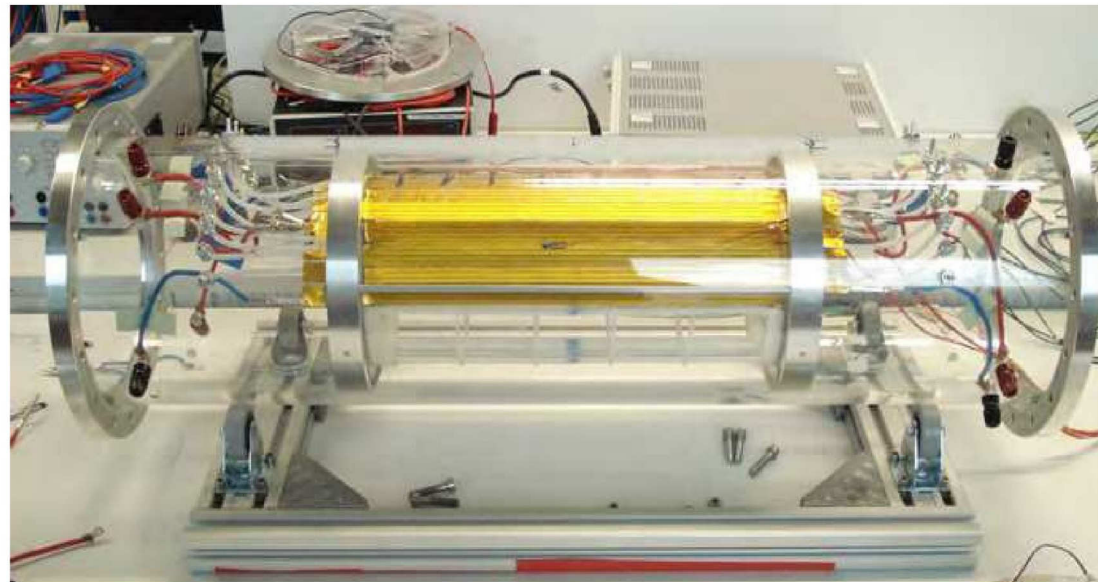
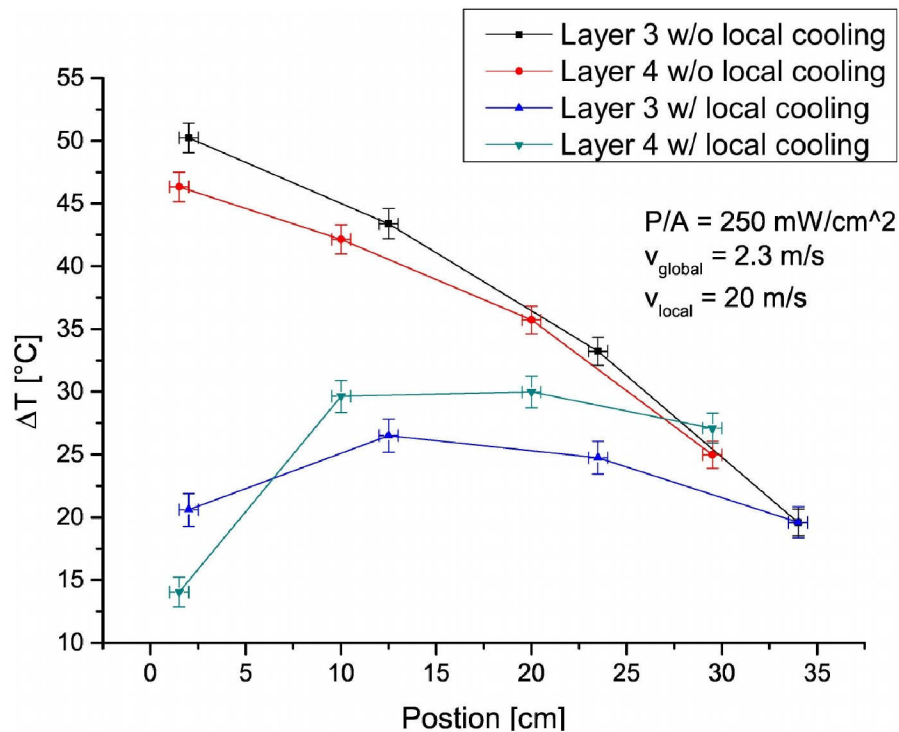
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

- University of Liverpool



Pixel Detector + Helium Gas Cooling

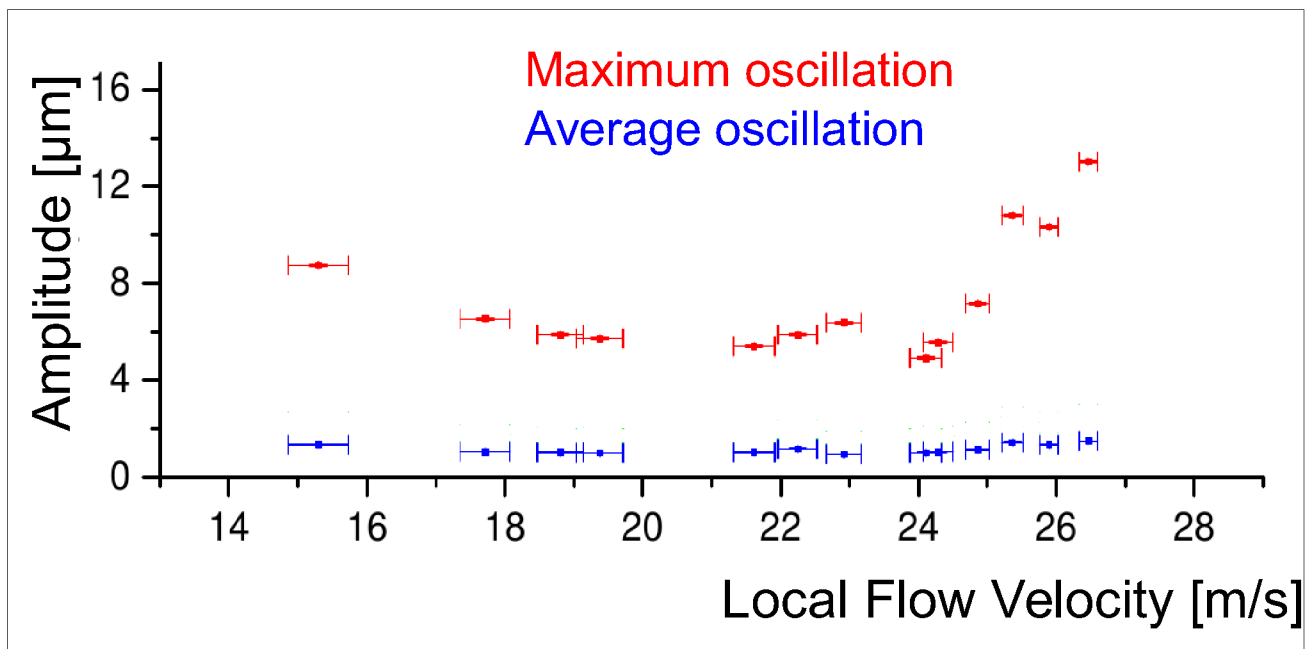
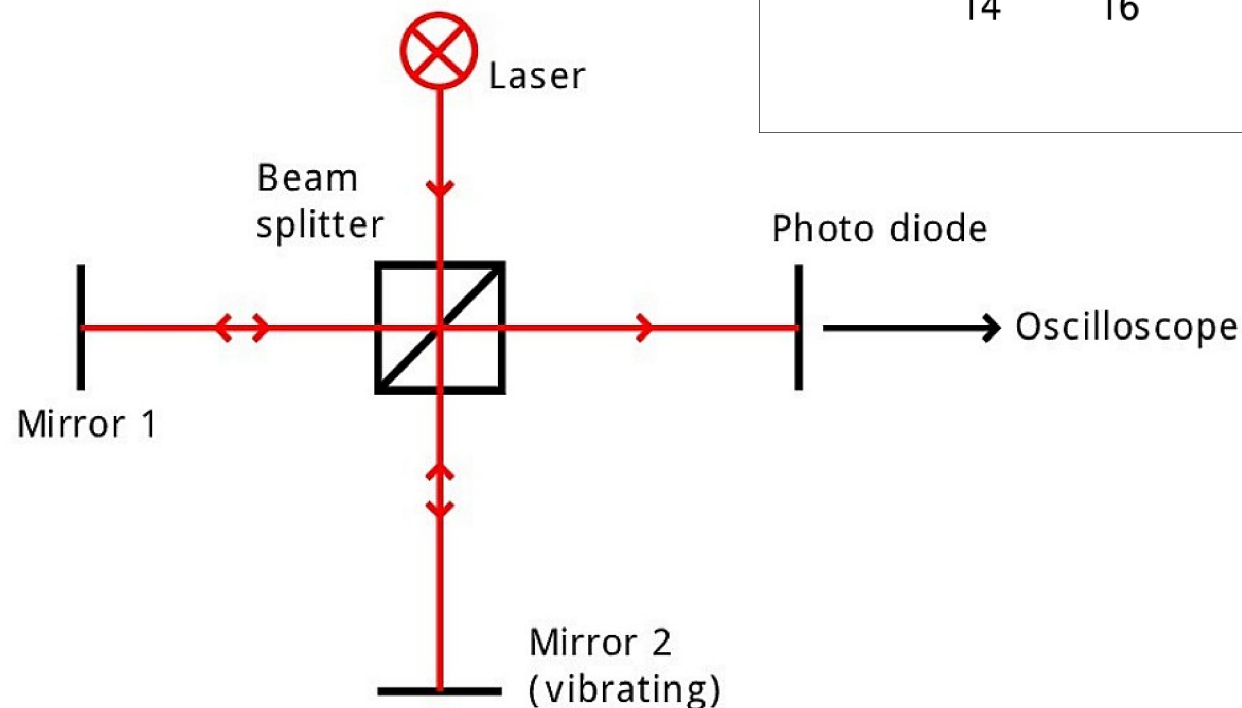
- Heatable module prototypes
- Temperature sensors
- Flow container
- Local and global helium flow





Vibration Measurements

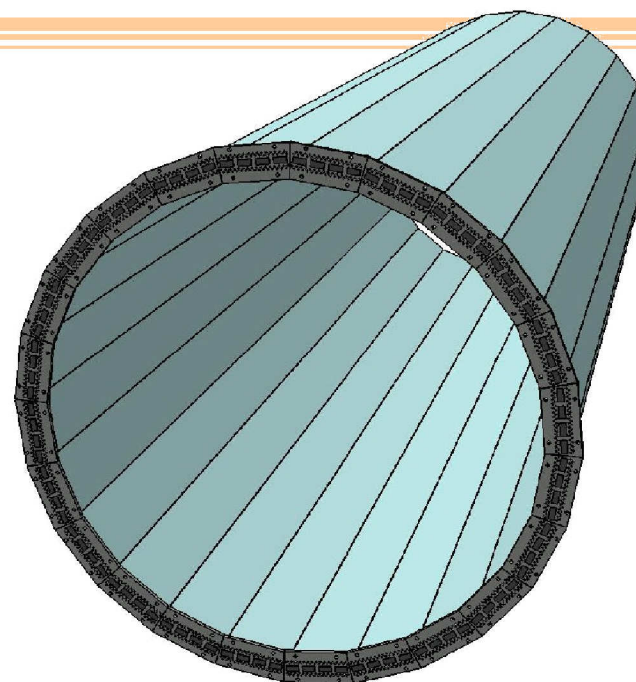
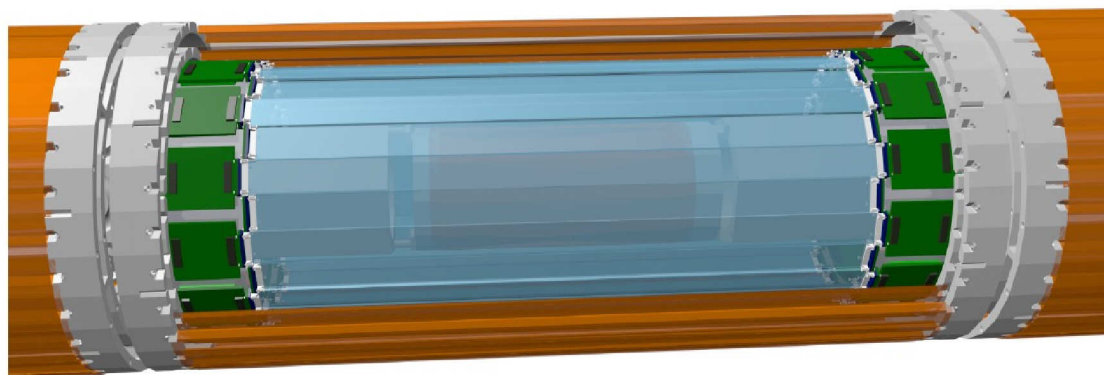
Measurement of flow-induced vibrations with Michelson interferometer



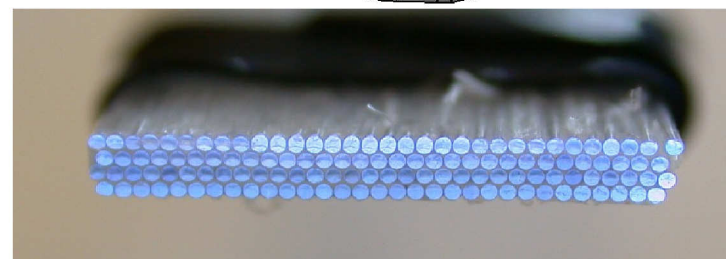
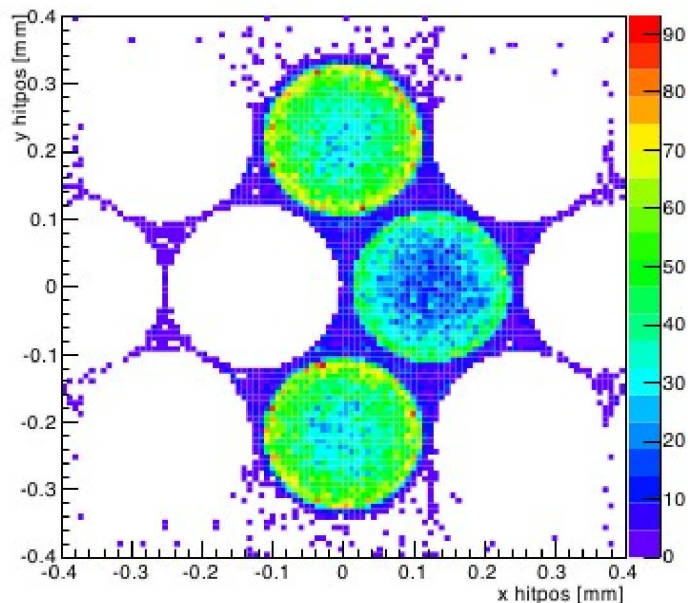
→ maximum vibrations
in tolerable range



Scintillating Fiber Tracker



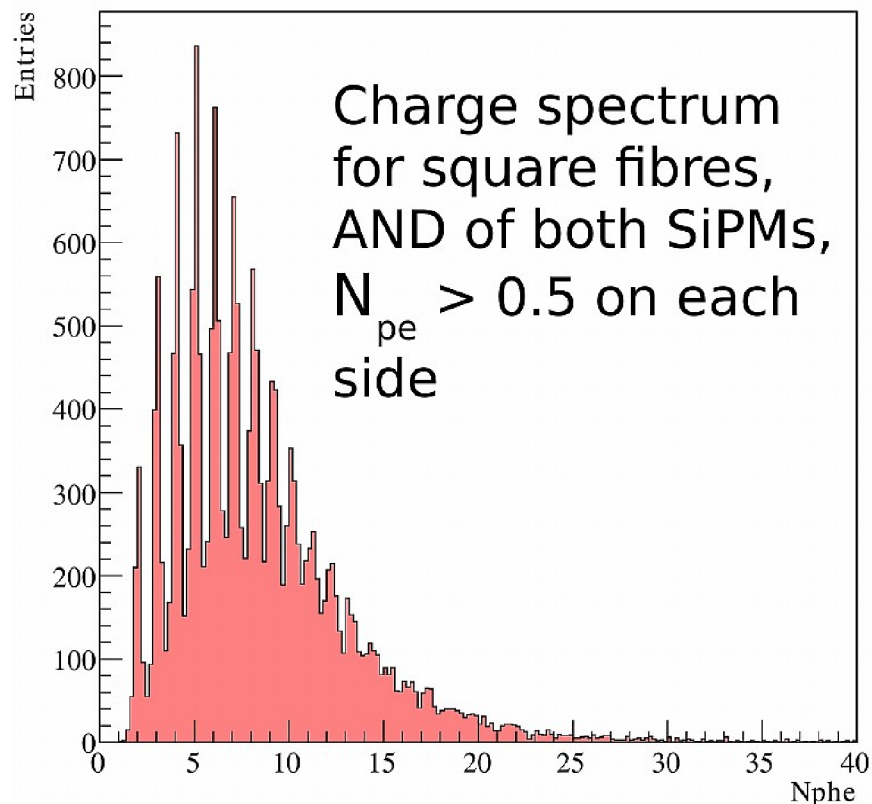
simulation



- 2-3 layers of scintillating fibers $\varnothing = 250 \mu\text{m}$
 - readout by silicon photomultipliers (SiPMs) and custom ASIC (MuSTic)
 - 100 nm Al coating by evaporation (instead of Ti)

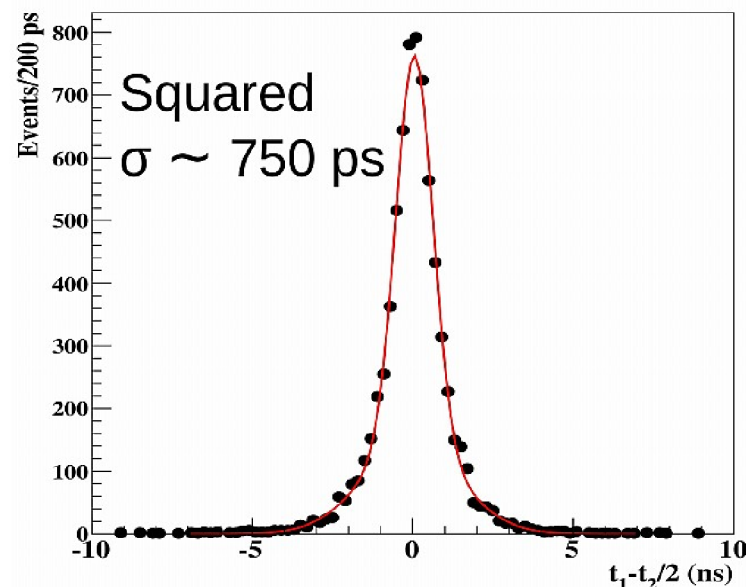
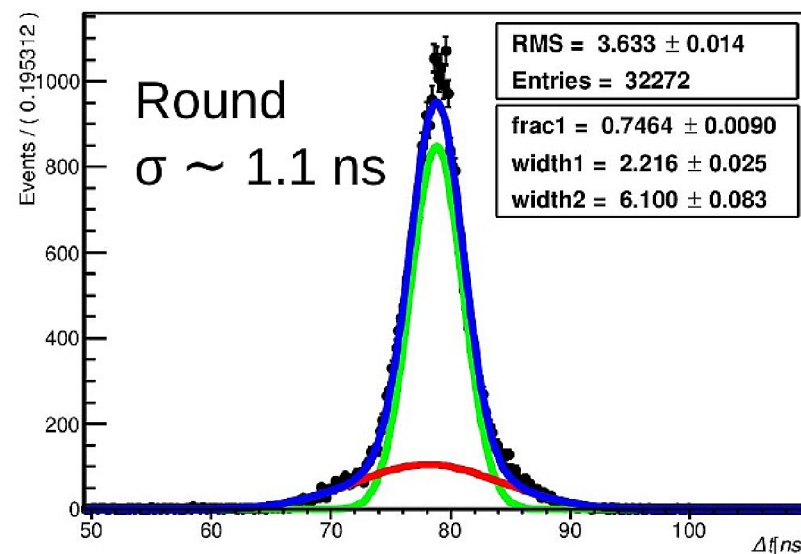


Sci-Fi Results from Prototypes



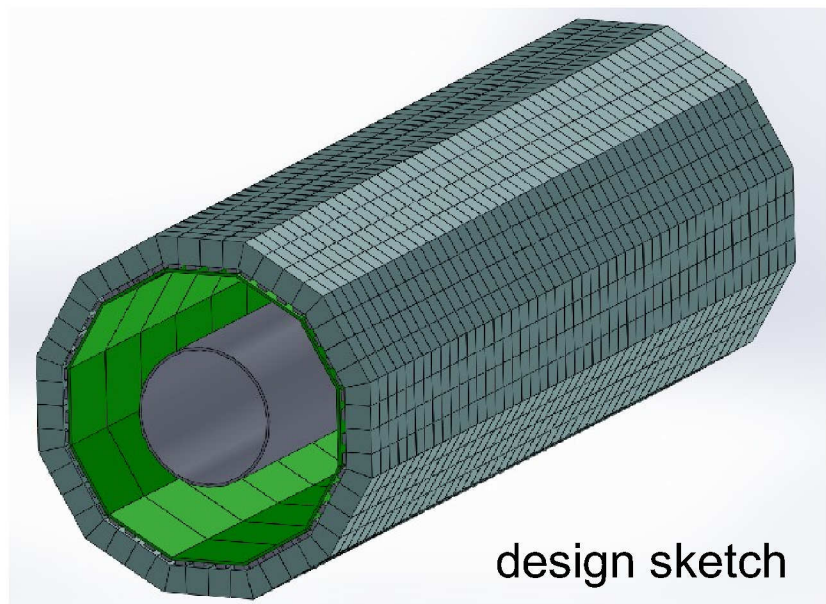
Double layer square
fibres, AND configuration,
 $N_{pe} > 0.5$: 93 % efficiency

Single fiber time resolutions





Scintillating Tile Detector

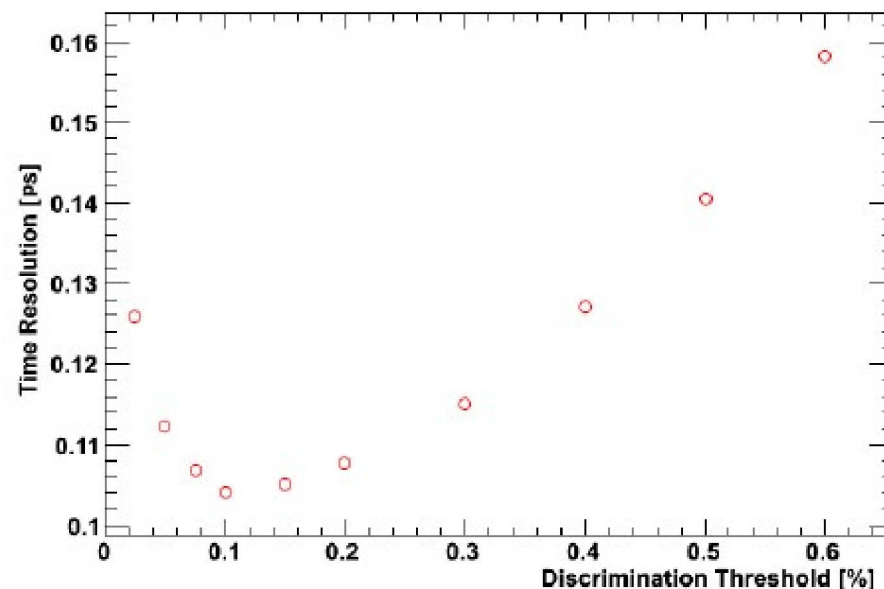


design sketch

simulated (phase 2)

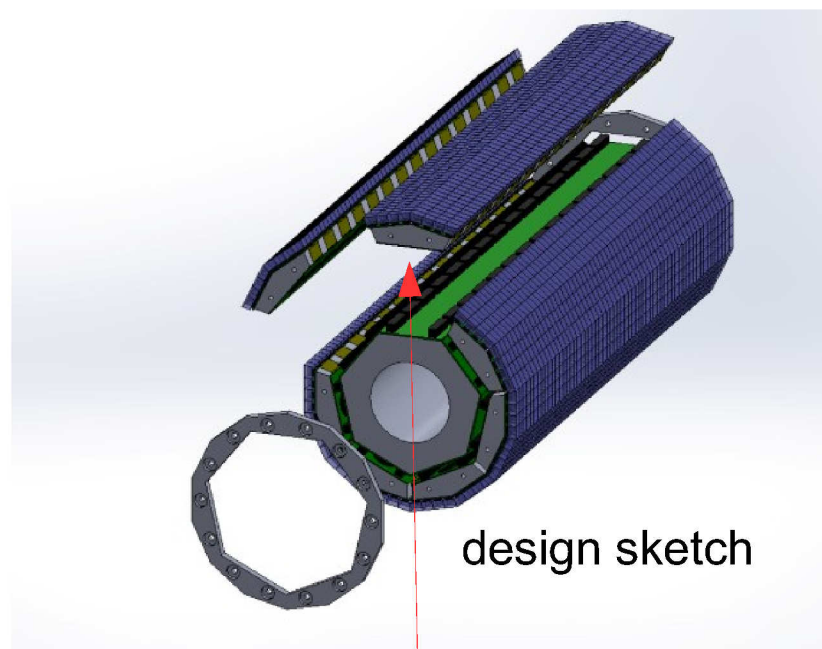
- scintillating tiles of size $\sim 1 \text{ cm}^2$
- timing resolution of about 100 ps
- photosensors (SiPM)
read-out by custom ASICs

DESY beam test results (March 2013)

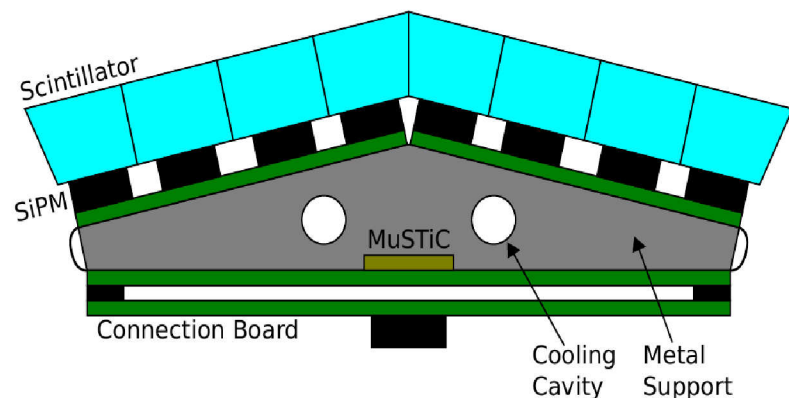




Scintillating Tile Detector

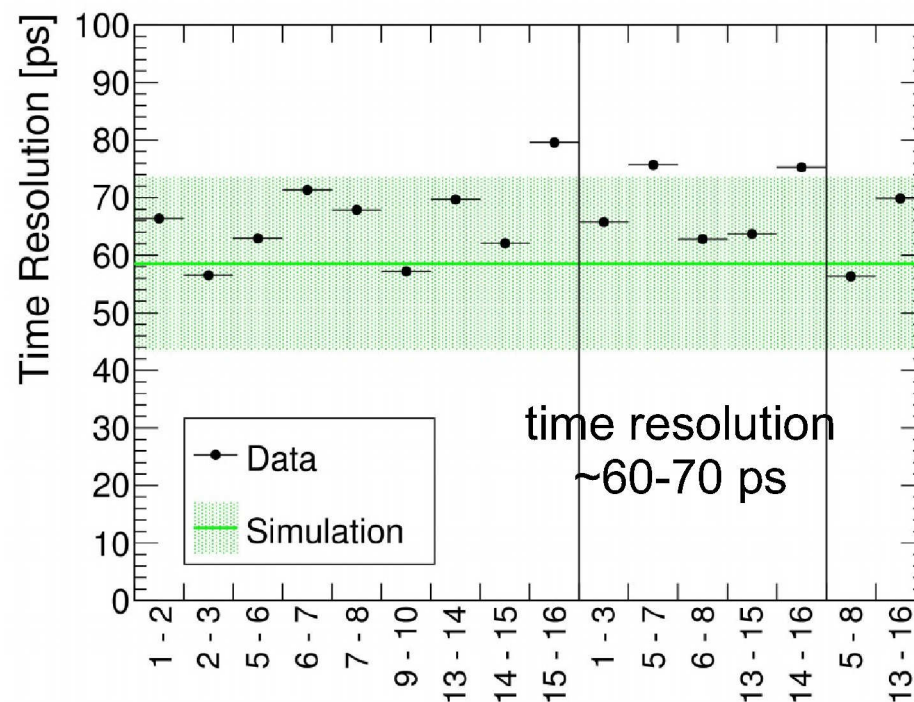
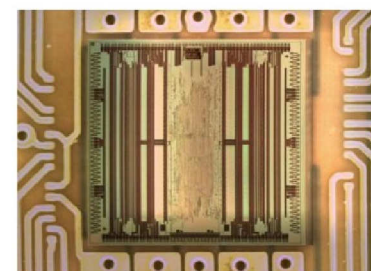


design sketch



- scintillating tiles of size $\sim 1 \text{ cm}^2$
- timing resolution of about $< 100 \text{ ps}$
- photosensors (SiPM) readout by custom-made ASIC:

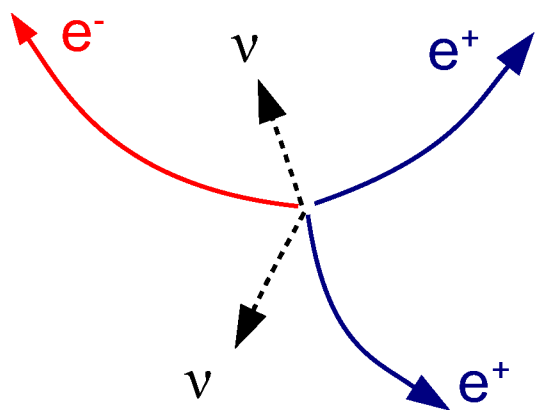
StiC 3.1



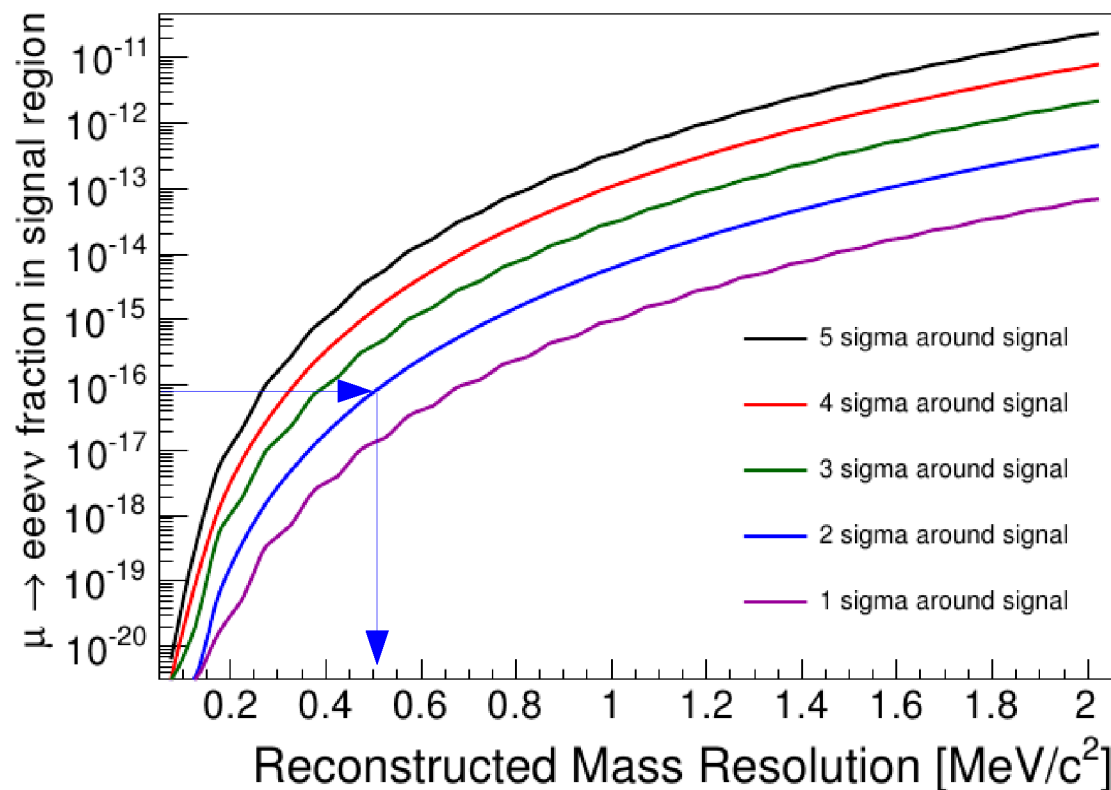
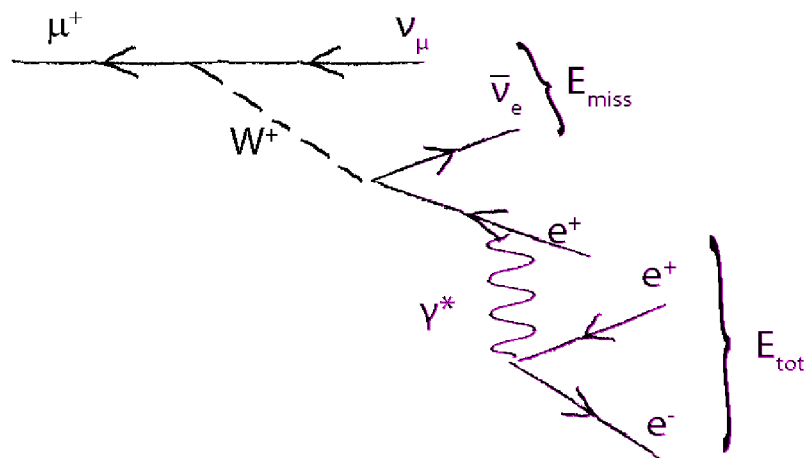


Backgrounds

Irreducible BG: radiative decay with internal conversion



$$B(\mu^+ \rightarrow e^+ e^+ e^- \nu \bar{\nu}) = 3.4 \cdot 10^{-5}$$



**very good momentum +
total energy resolution required!**



Cross Talk in Mupix7

transmission lines between matrix and periphery

