Development of an ultra-thin tracking detector for Mu3e

Sebastian Dittmeier
Physikalisches Institut - Universität Heidelberg

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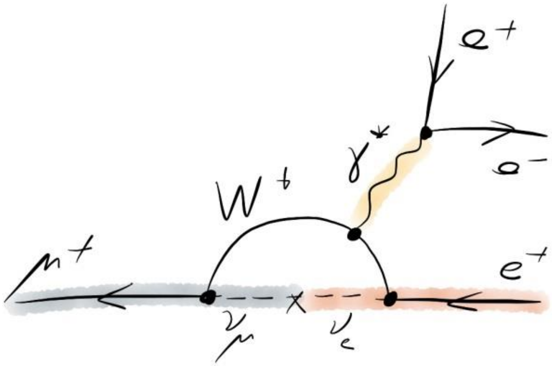
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

The Mu3e Experiment

Search for the charged lepton flavor violating decay $\mu^+ \rightarrow e^+ e^- e^+$

Standard Model
Highly suppressed branching ratio
$\mathbf{BR_{SM} < 10^{-54}}$



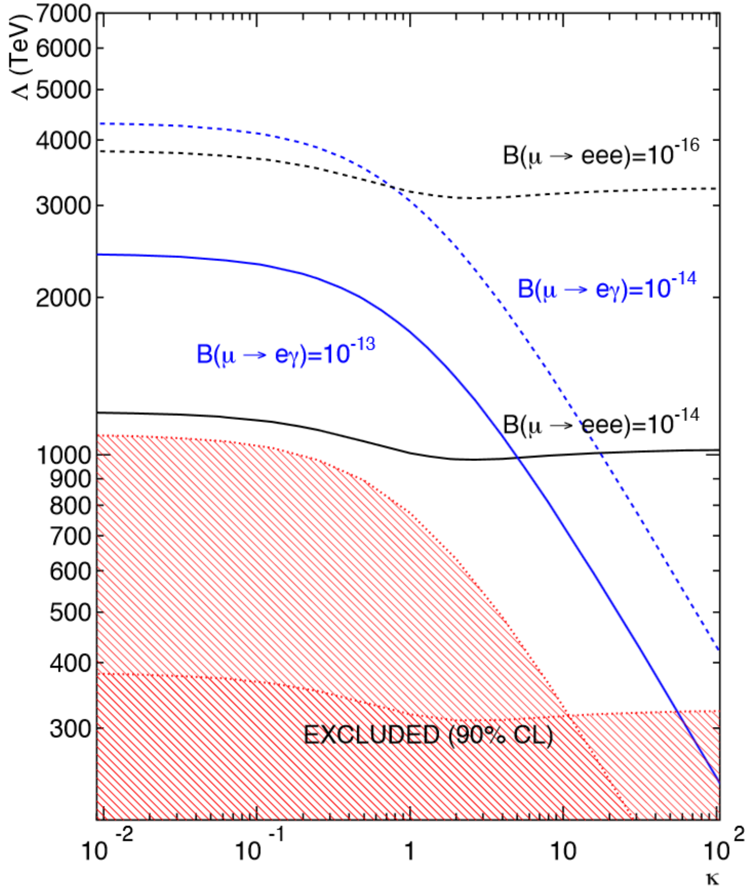
Probe physics beyond SM
Any observation is a clear sign for new physics!

Current limit on $\mu^+ \rightarrow e^+ e^- e^+$ $\mathbf{BR_{meas} < 10^{-12}}$ (SINDRUM 1988)

Goal of Mu3e

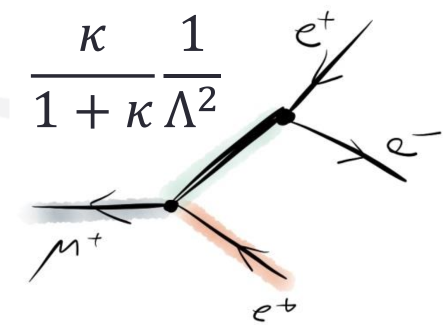
Enhance sensitivity to $\mathbf{BR < 10^{-16}}$

Searching for New Physics with Mu3e



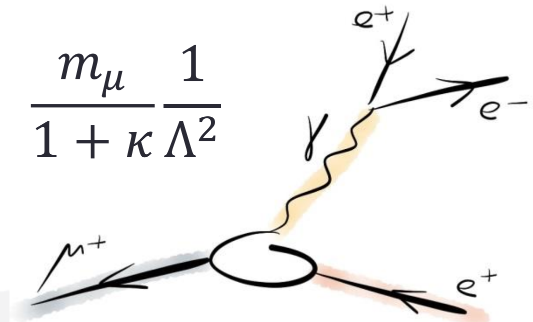
André de Gouvêa, Petr Vogel,
Lepton flavor and number conservation, and physics beyond the standard model,
Progress in Particle and Nuclear Physics, 71 (2013) 75-9

$$\frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}$$



+

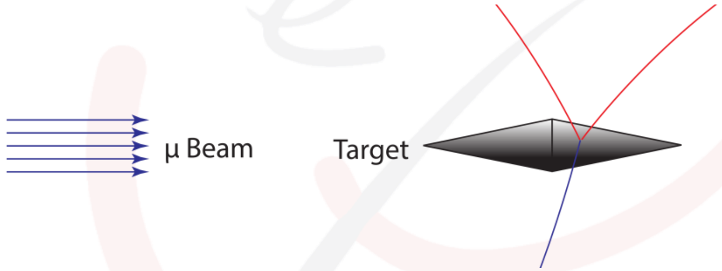
$$\frac{m_\mu}{1+\kappa}\frac{1}{\Lambda^2}$$



Experimental Concept

How to achieve BR < 10^{-16} within a reasonable time?

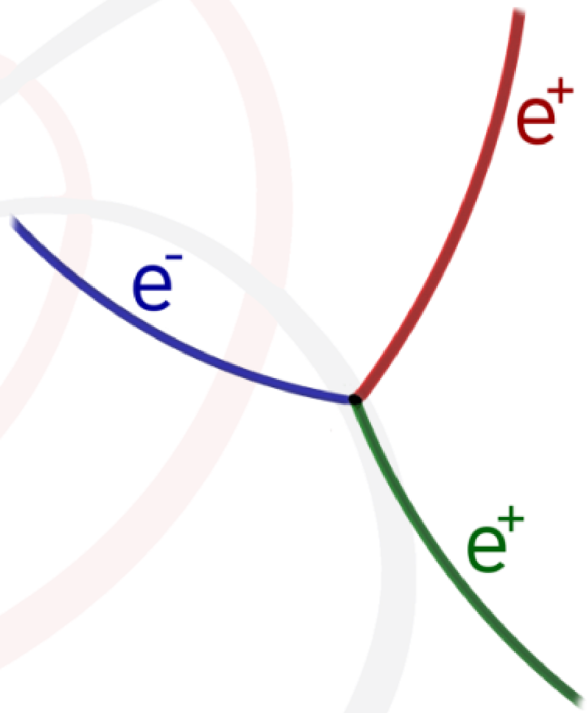
- High rate of muons $\mathcal{O}(10^{9}\ \mathrm{s}^{-1})$ at PSI (CH)



How to measure this extremely rare decay?

- Stop the muons on a thin target
- Measure decay vertex and momentum of the electrons

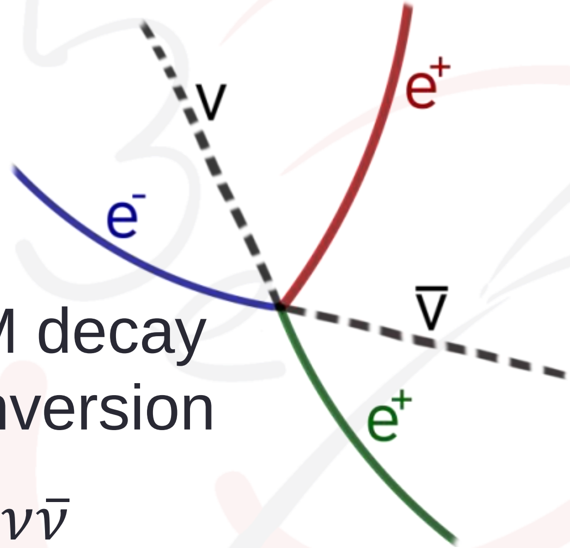
The Signal Decay



Experimental Signature

- Common vertex
- Coincident
- $\sum \vec{p} = 0$
- $\sum E = m_\mu$

Main Sources of Background



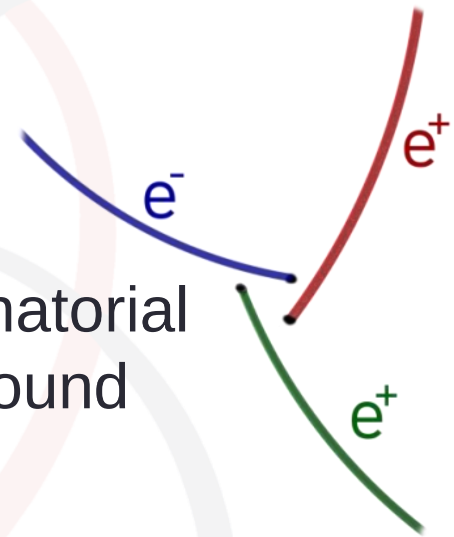
Radiative SM decay
+ photon conversion

$\mu^+ \rightarrow e^+ e^- e^+ \nu \bar{\nu}$

Experimental Signature

- Common vertex
- Coincident
- $\sum \vec{p} \neq 0$
- $\sum E \neq m_\mu$

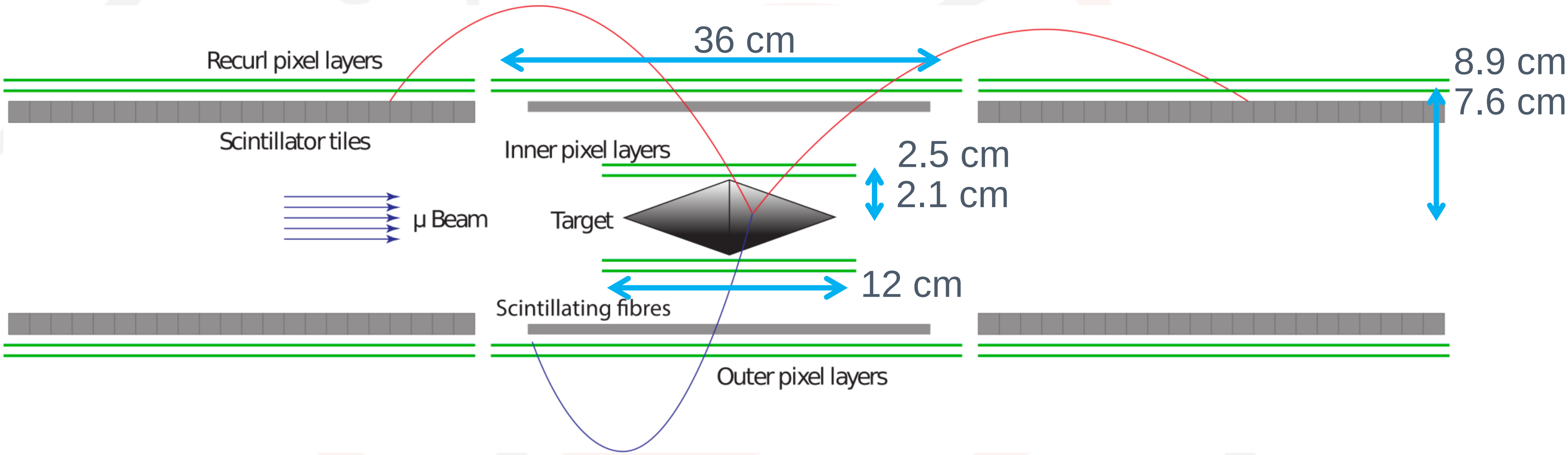
Combinatorial background



Experimental Signature

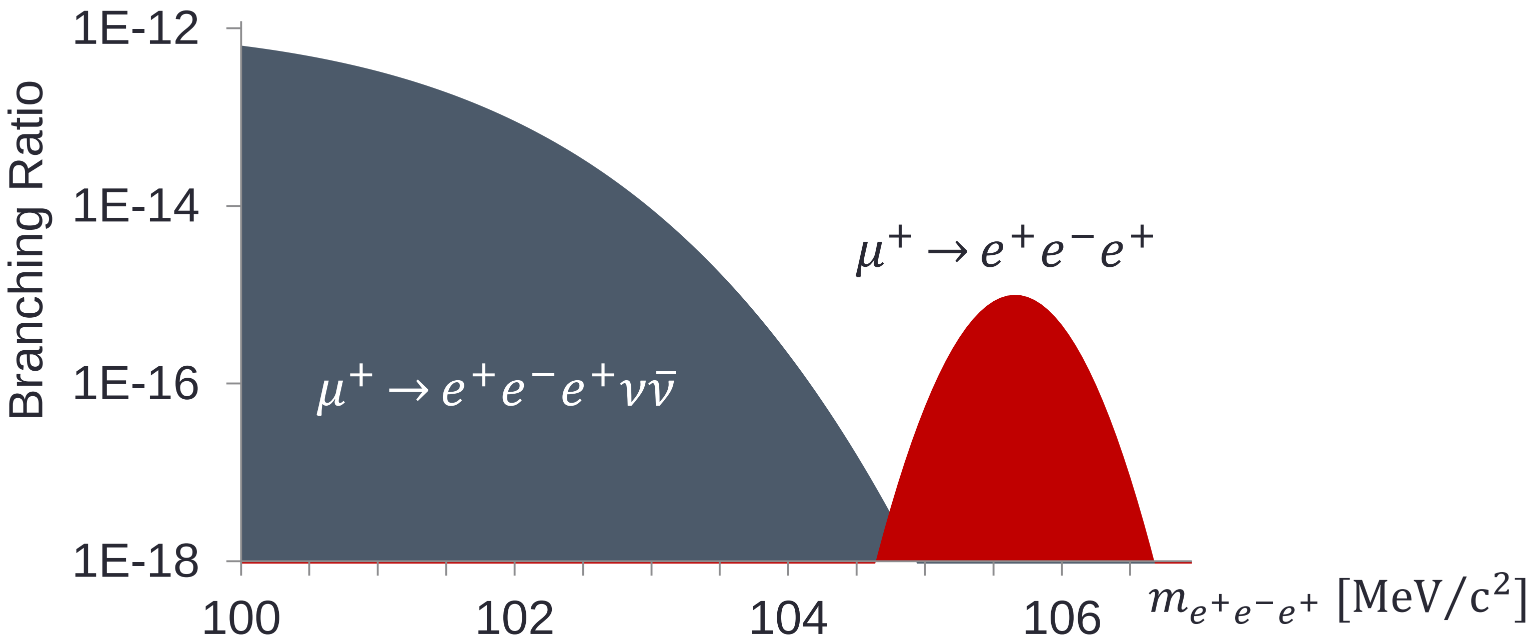
- No common vertex
- Not coincident
- $\sum \vec{p} \neq 0$
- $\sum E \neq m_\mu$

The Mu3e Detector



- Excellent momentum, vertex and time resolution required
  - ➢ Silicon pixel tracking detector
  - ➢ Scintillating timing detectors
- Detector inside solenoidal magnetic field $B = 1T$

Invariant Mass Resolution



- Requires momentum resolution $\sigma_p < 0.5\ \mathrm{MeV/c}$
- Multiple scattering dominates momentum resolution $\sigma_p/p \propto \sqrt{x/X_0}$

Material budget $x \leq 1‰\ X_0$ per layer

Material Budget of Selected Pixel Detectors

Experiment	Material budget per layer
ATLAS IBL‡	$1.9\ \%\ X_0$
CMS (current) †	$\sim 2.0\ \%\ X_0$
CMS (upgrade) †	$\sim 1.1\ \%\ X_0$
ALICE (current)*	$1.1\ \%\ X_0$
ALICE (upgrade)*	$0.3\ \%\ X_0$
STAR ◊	$0.4\ \%\ X_0$
BELLE II △	$0.2\ \%\ X_0$
Mu3e	$\mathbf{0.1\ \%\ X_0}$

‡ ATL-INDET-PROC-2015-001

† CERN-LHCC-2012-016 ; CMS-TDR-11

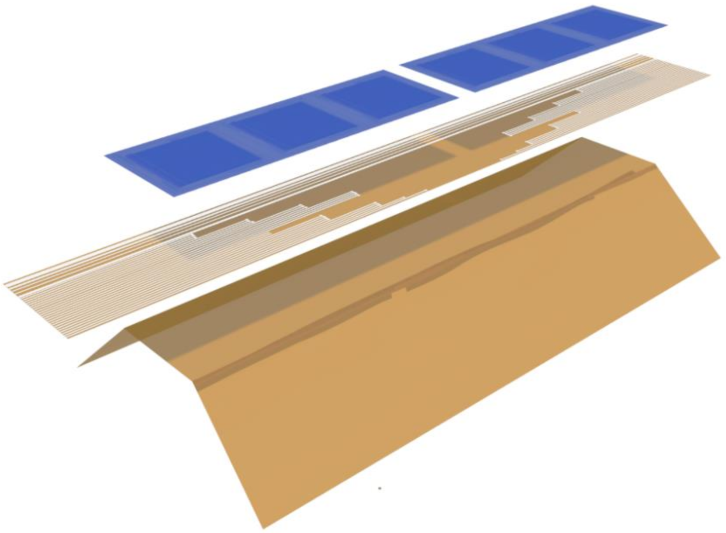
* arXiv:1211.4494v1

◊ talk by G. Contin at PIXEL 2016

△ talk by C. Koffmane at PIXEL 2016

How to Reach the Material Goal?

Approach for a Mu3e tracking detector layer

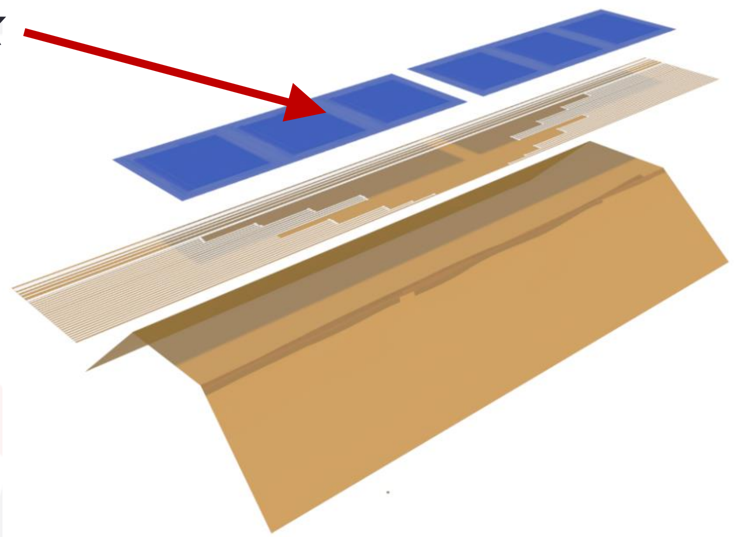


How to Reach the Material Goal?

Approach for a Mu3e tracking detector layer

High Voltage Monolithic Active Pixel Sensors

MuPix



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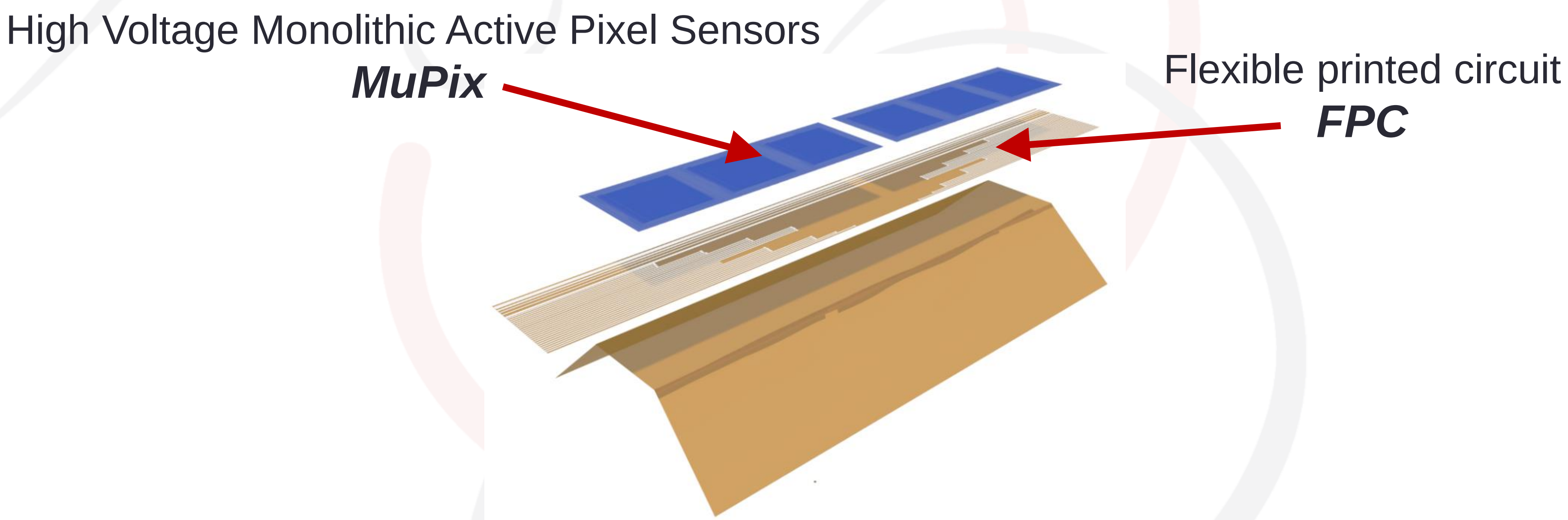

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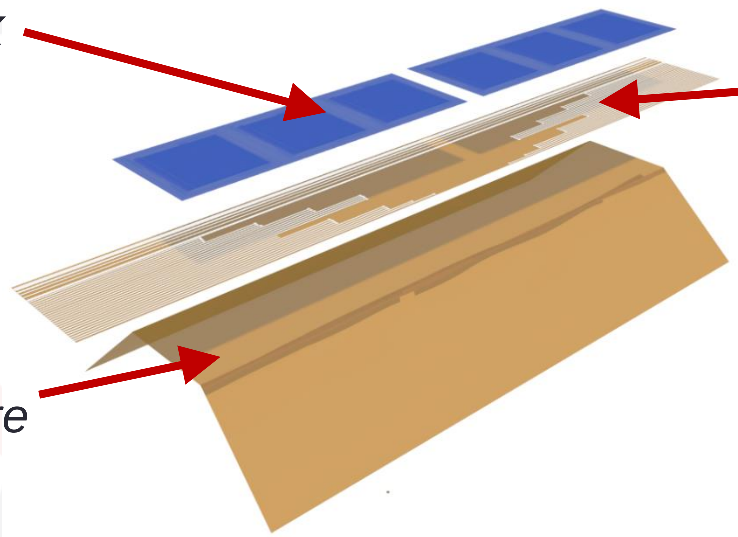
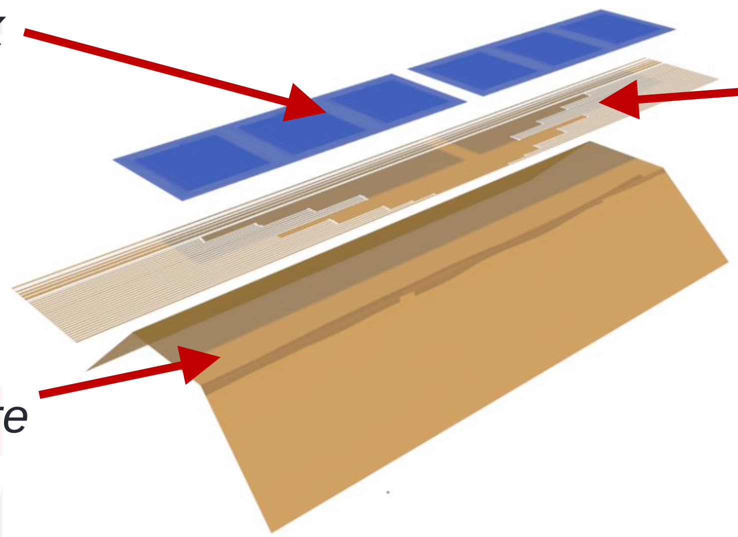
Approach for a Mu3e tracking detector layer



How to Reach the Material Goal?

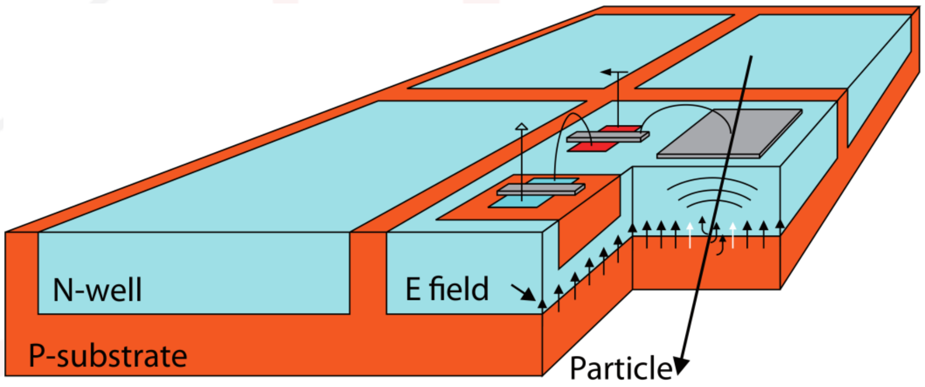
Approach for a Mu3e tracking detector layer



HV-MAPS

High Voltage Monolithic Active Pixel Sensors

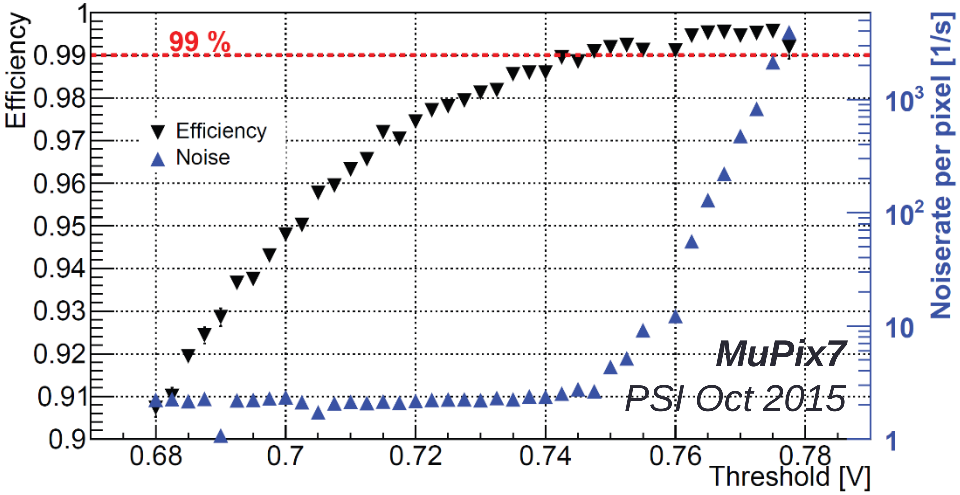
- 180 nm HV-CMOS technology
- Reverse biased HV ≤ – 85 V
- Depletion zone $\sim 10 - 20\ \mu\mathrm{m}$
- Charge collection via drift
- Integrated digital readout
- Can be thinned to $50\ \mu\mathrm{m} \sim 0.5\ ‰\ X_0$

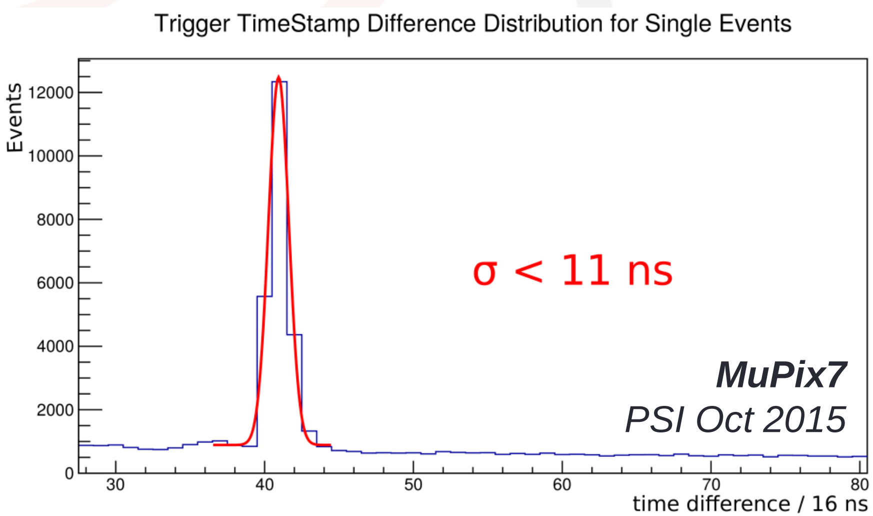


I. Peric et al., NIM A 582 (2007)

MuPix – HV-MAPS for Mu3e

- Latest prototype: ***MuPix7***
  - Active area 3 x 3 mm^2
  - Pixel size 103 x 80 μm^2
  - Integrated state machine
  - Untriggered readout
  - Serial data output at 1.25 Gb/s
- Next prototype: ***MuPix8***
  - Large chip ≈ 2 x 1 cm^2
  - Submission this month

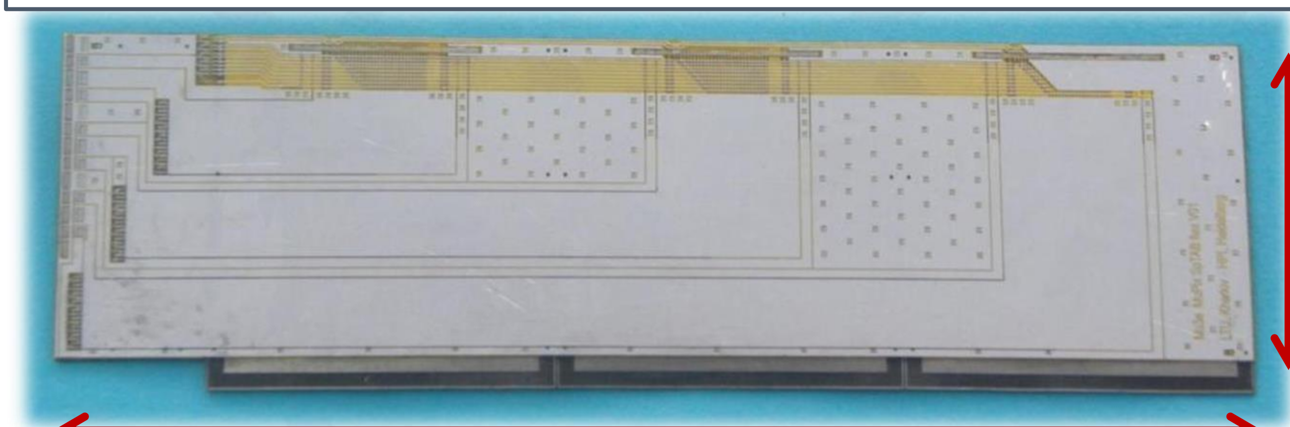




Flexible Printed Circuits

- Supplies sensors with
  - Power ($P_{MuPix} \leq 400\ \mathrm{mW/cm^2}$)
  - High Voltage ($\approx -85\ \mathrm{V}$)
  - Clock, reset, configuration signals
- Fast data transmission lines

Prototype with dummy chips of half an inner detector layer



1.90 cm

6.85 cm

FPC Technology

Two layer aluminium (LTU Ltd.)

- 14μm Al + 10μm Kapton per layer
- Dielectric spacing 45μm (Kapton + glue)
- Structure sizes ≥ 65μm
- SpTAB technology

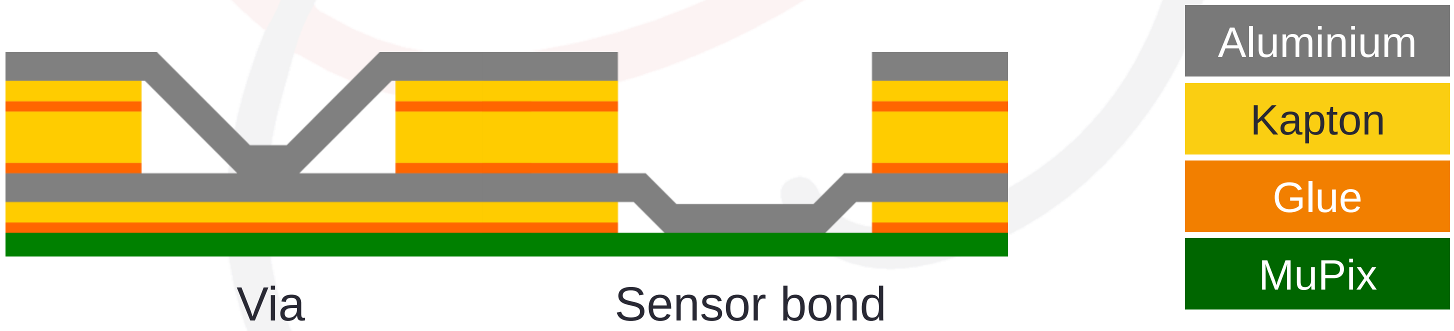
  Single point Tape Automated Bonding

➢ No additional (high Z) material for bonding!

Material budget

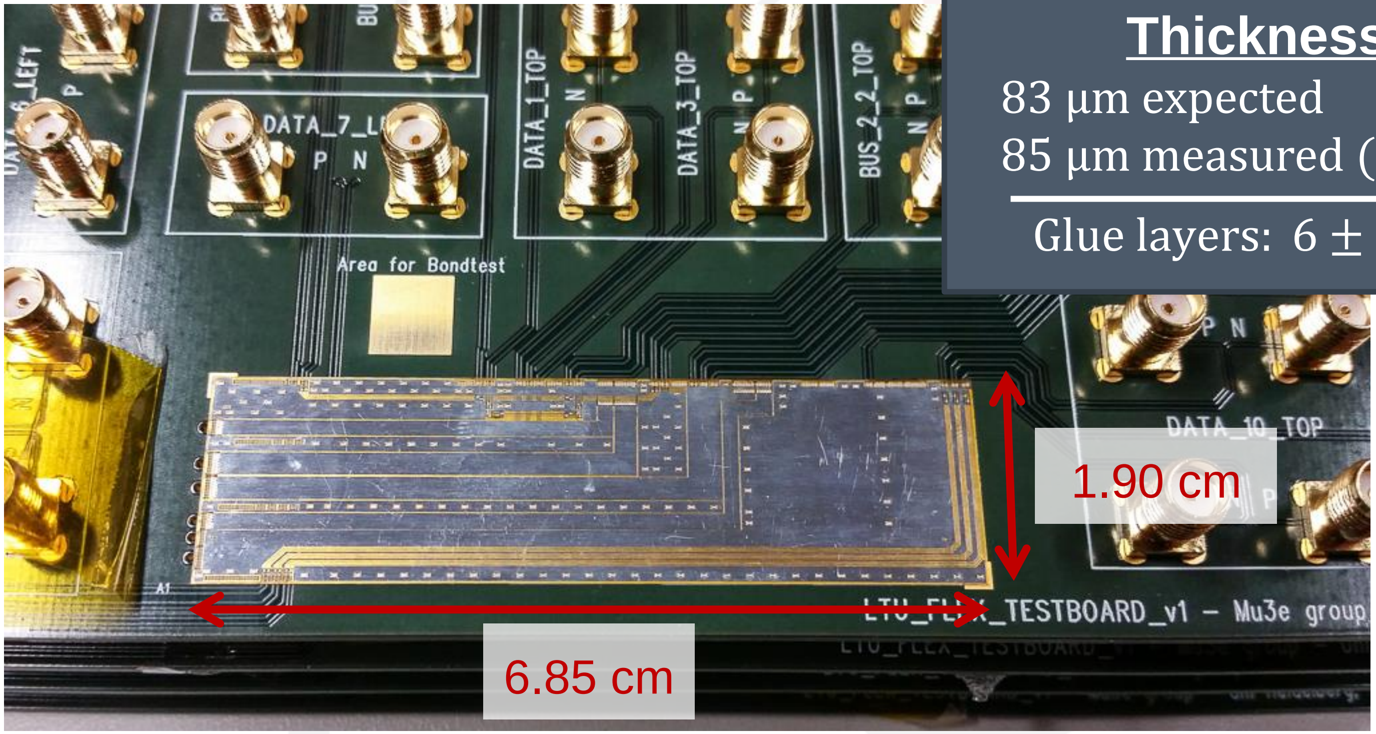
45 μm Kapton
+ 28 μm Aluminium
+ 10 μm Glue

$\sim 0.5‰\ X_0$



FPC Feasibility Studies

Two layer FPC with test structures bonded to testboard



Thickness

83 µm expected

85 µm measured (avg)

Glue layers: 6 ± 3 µm

Data Transmission Studies

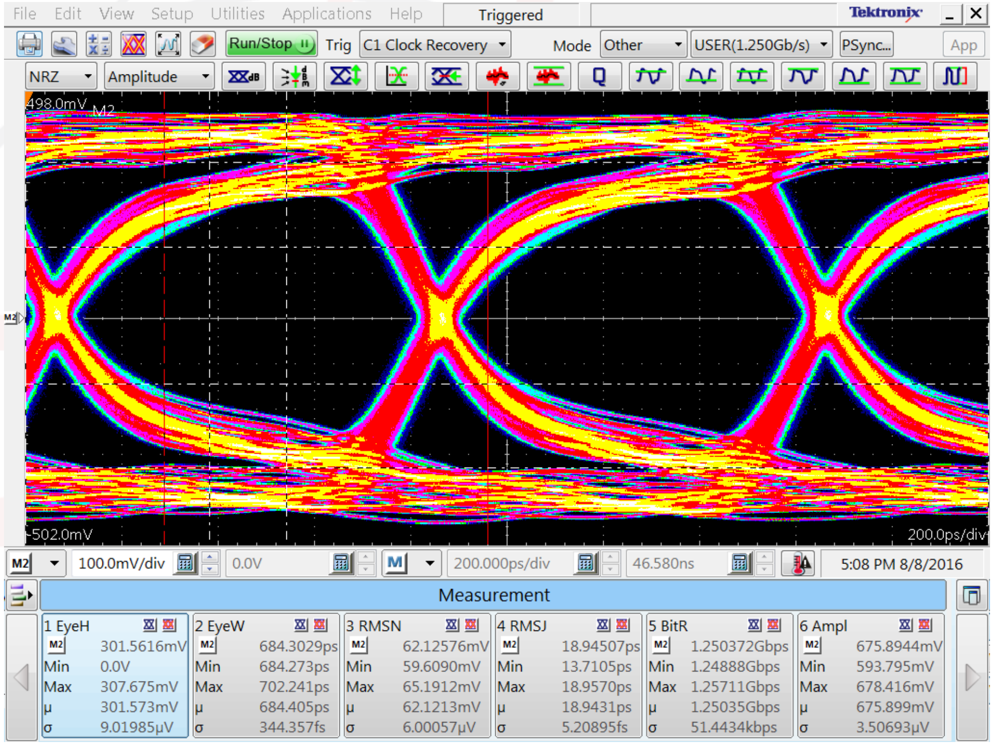
Signal integrity is crucial for stable operation of the experiment!

Bit error rate measurements

- Transmit pseudo random binary sequence
- Receiver: check for errors
- Data rate = 1.25 Gbit/s
- No bit errors observed

  BER < $2 \cdot 10^{-13}$
- Up to 2.5 Gbit/s: no bit errors

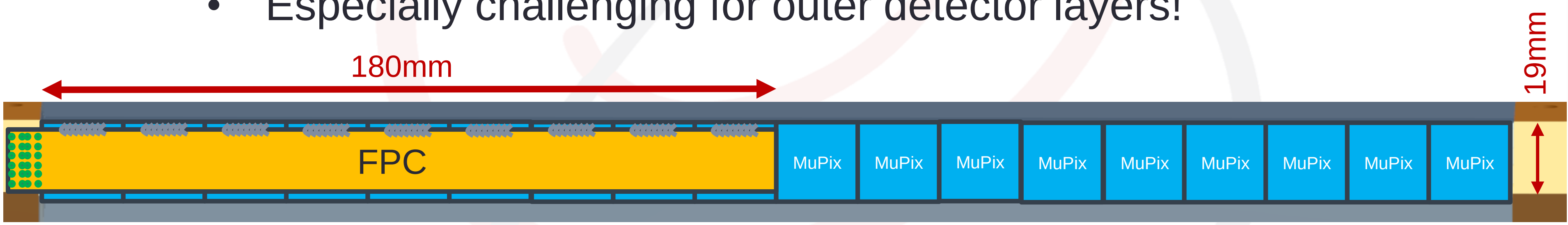
  BER < $3 \cdot 10^{-13}$



Further Electrical Studies

Control of voltage drop along the FPC is crucial for stable operation of the experiment!

- Sensor power consumption up to $400\ \mathrm{mW/cm^2}$
- Supply voltage differences between chips $\leq 20\ \mathrm{mV}$
- Especially challenging for outer detector layers!



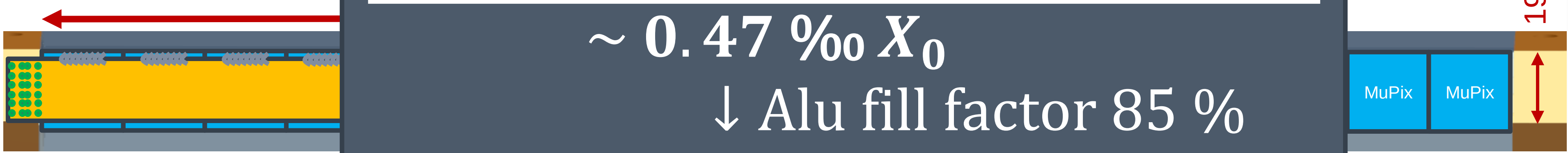
<u>Resistance measurements on test FPC</u>

- Resistance of tested power traces: $50 - 120\ \mathrm{m\Omega}$
- Actual aluminium thickness $12.3 \pm 0.3\ \mu\mathrm{m}$

Further Electrical Studies

Control of voltage drop along the FPC is crucial

- Sen
- Sup
- Esp



Material budget

$$45\ \mu\text{m Kapton}$$
$$+\ 25\ \mu\text{m Aluminium}$$
$$+\ 10\ \mu\text{m Glue}$$

$$\sim \mathbf{0.47\ ‰}\ \boldsymbol{X_0}$$
$$\downarrow \text{Alu fill factor } 85\ \%$$
$$\sim \mathbf{0.42\ ‰}\ \boldsymbol{X_0}$$

Resist

- Resistance of tested power traces: $50 - 120\ \text{m}\Omega$
- Actual aluminium thickness $12.3 \pm 0.3\ \mu\text{m}$

How to Reach the Material Goal?

Approach for a Mu3e tracking detector layer

High Voltage Monolithic Active Pixel Sensors

MuPix

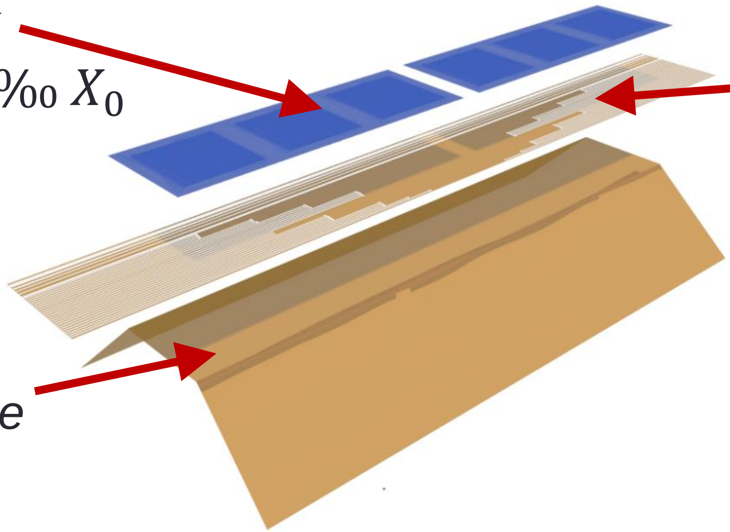
50 µm ~ 0.5 ‰ X_0

Flexible printed circuit

FPC

0.42‰ – 0.47 ‰ X_0

Helium gas cooling



Kapton support structure

25 µm ~ 0.1 ‰ X_0

How to Reach the Material Goal?

Approach for a Mu3e tracking detector layer

High Voltage Monolithic Active Pixel Sensors

MuPix

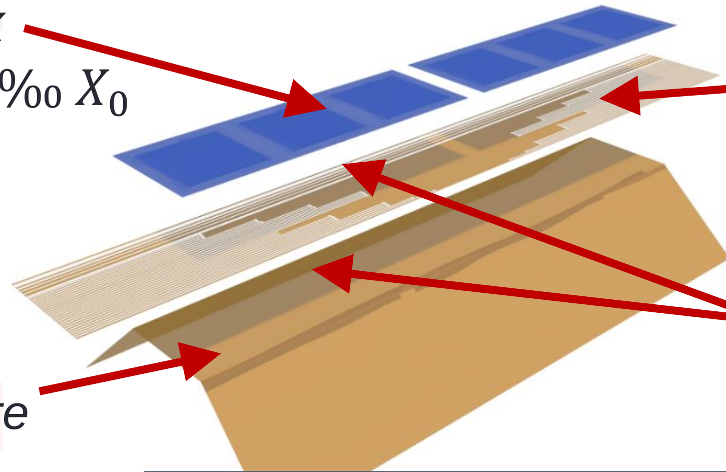
$50\ \mu m \sim 0.5\ ‰\ X_0$

Flexible printed circuit

FPC

$0.42‰ - 0.47\ ‰\ X_0$

Helium gas cooling



$+\ 10\text{-}20\ \mu m$ Glue

$\sim 0.05\ ‰\ X_0$

Kapton support structure

$25\ \mu m \sim 0.1\ ‰\ X_0$

Material budget per layer

Avg: $x \approx \mathbf{1.07\ ‰}\ X_0$

Peak: $x \approx \mathbf{1.12\ ‰}\ X_0$

Summary and Outlook

- Ultra-low material tracking detector using HV-MAPS for Mu3e
- Average material budget of $\sim \mathbf{1.07}$ **‰** $\boldsymbol{X_0}$ per layer
- Aluminium FPC prototype works very well: BER < $2 \cdot 10^{-13}$ @ $1.25\ \mathrm{Gb}/s$

- Coming soon: ***MuPix8*** – first large HV-MAPS
- Integration of ***MuPix8*** with FPC

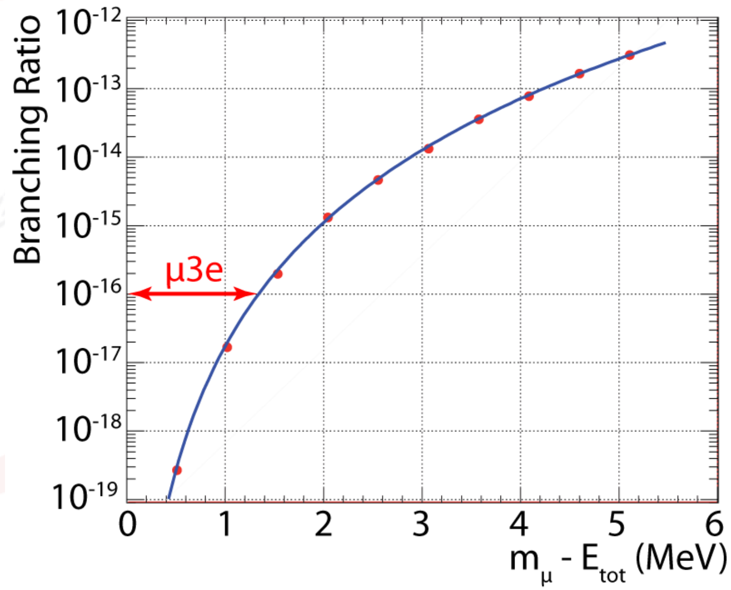
➢ Big step towards production of detector modules

Backup

Material budget constraints

Major background contribution

Radiative SM decay $\mu^+ \rightarrow e^+ e^- e^+ \nu \bar{\nu}$



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

- Momentum resolution

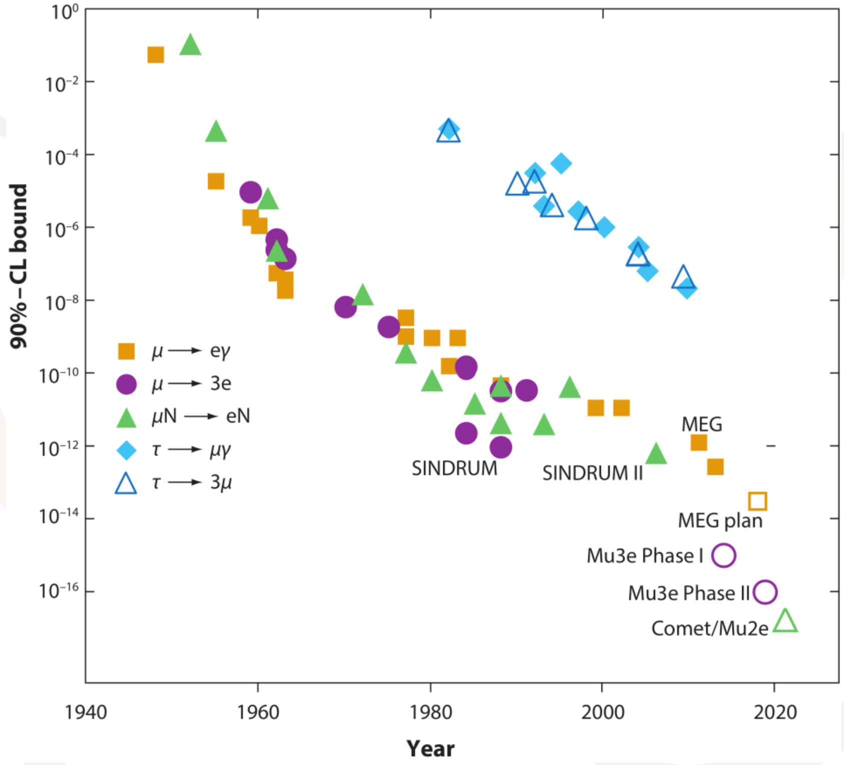
$$\sigma_p / p \propto \sqrt{x/X_0}$$

- Requirement

$\sigma_p < 0.5\ \mathrm{MeV/c}$

Material budget required
$x \leq 1‰\, X_0$ per layer

History of CLFV Experiments

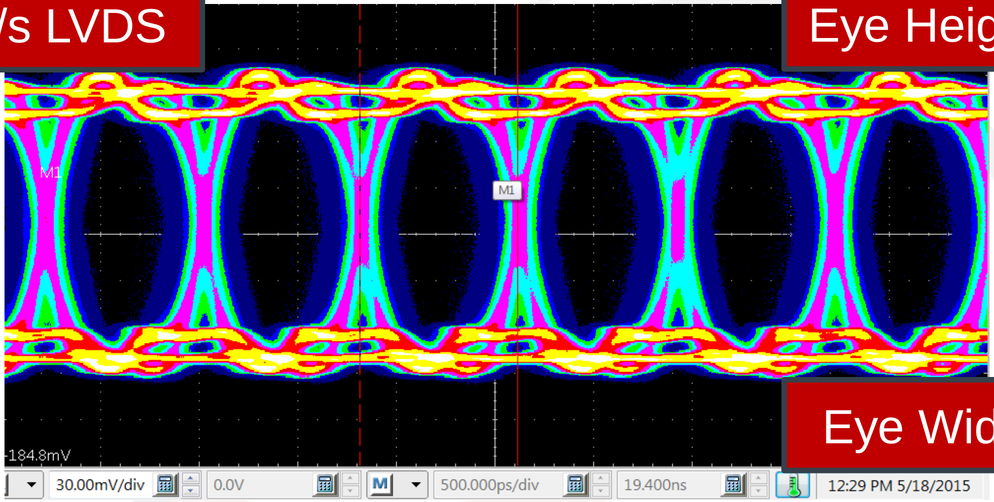


Updated from W.J Marciano et al., Ann.Rev.Nucl.Part.Sci. 58, 315 (2008)

Serial Readout of the MuPix7

1.25 Gbit/s LVDS

Eye Height > 100 mV

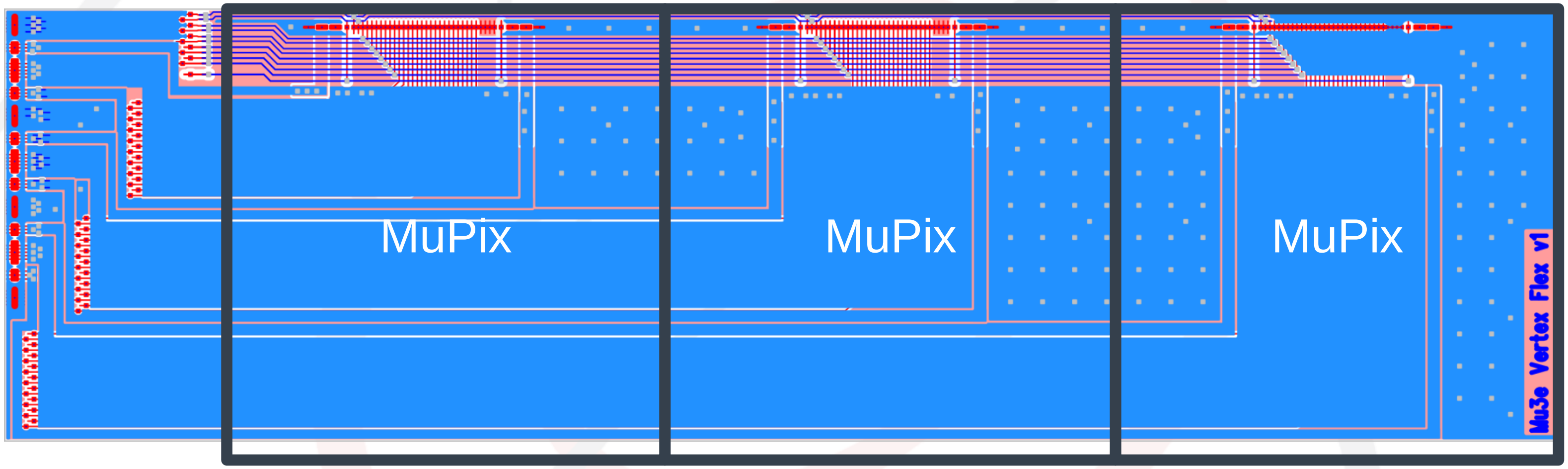


Eye Width > 0.65 UI

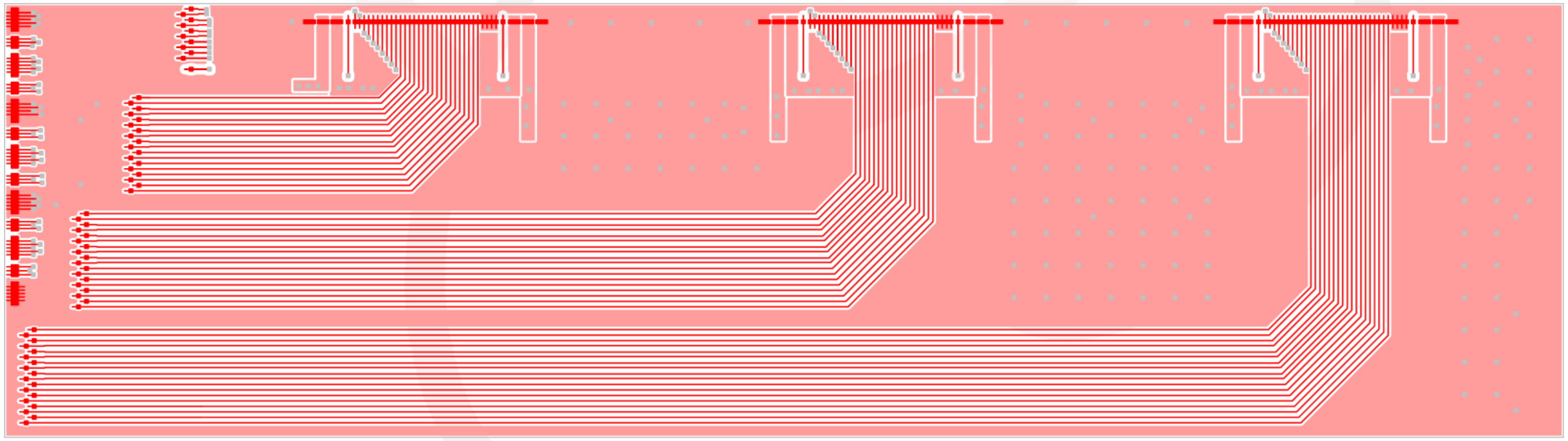
- DSA8300 serial analyzer with clock recovery
- True amplitude is a factor of 2 larger!

FPC design study – two layers

Composite View



Bottom Layer

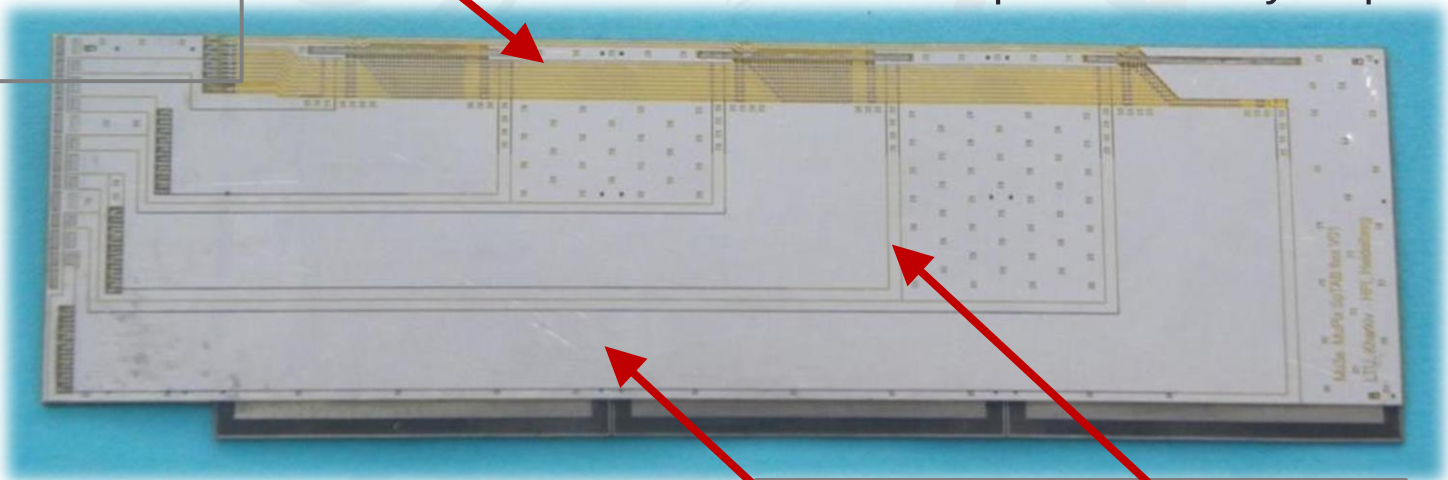


Inner detector – FPC design study

<u>Signal bus</u>

- Clock, reset
- Configuration
- HV

Mock-up with dummy chips



<u>Power lines</u>

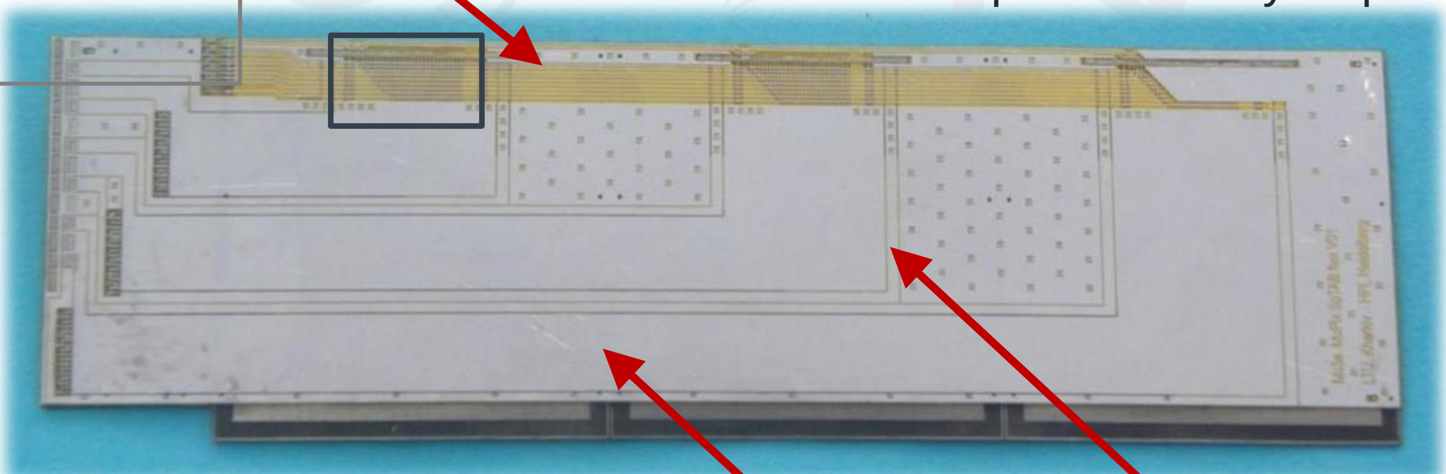
Estimated voltage differences between sensors below 50 mV

Inner detector – FPC design study

Signal bus

- Clock, reset
- Configuration
- HV

Mock-up with dummy chips



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Inner detector – FPC design study

Signal bus

- Clock, reset
- Configuration
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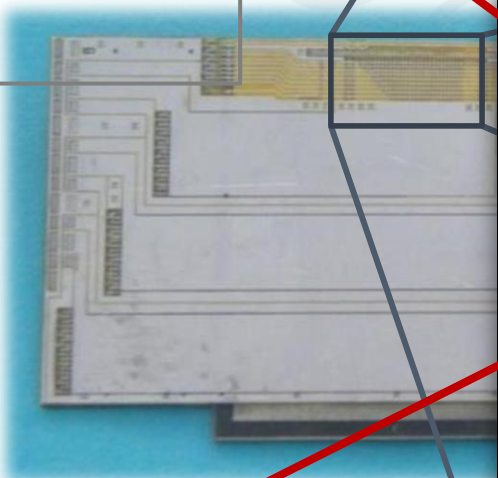
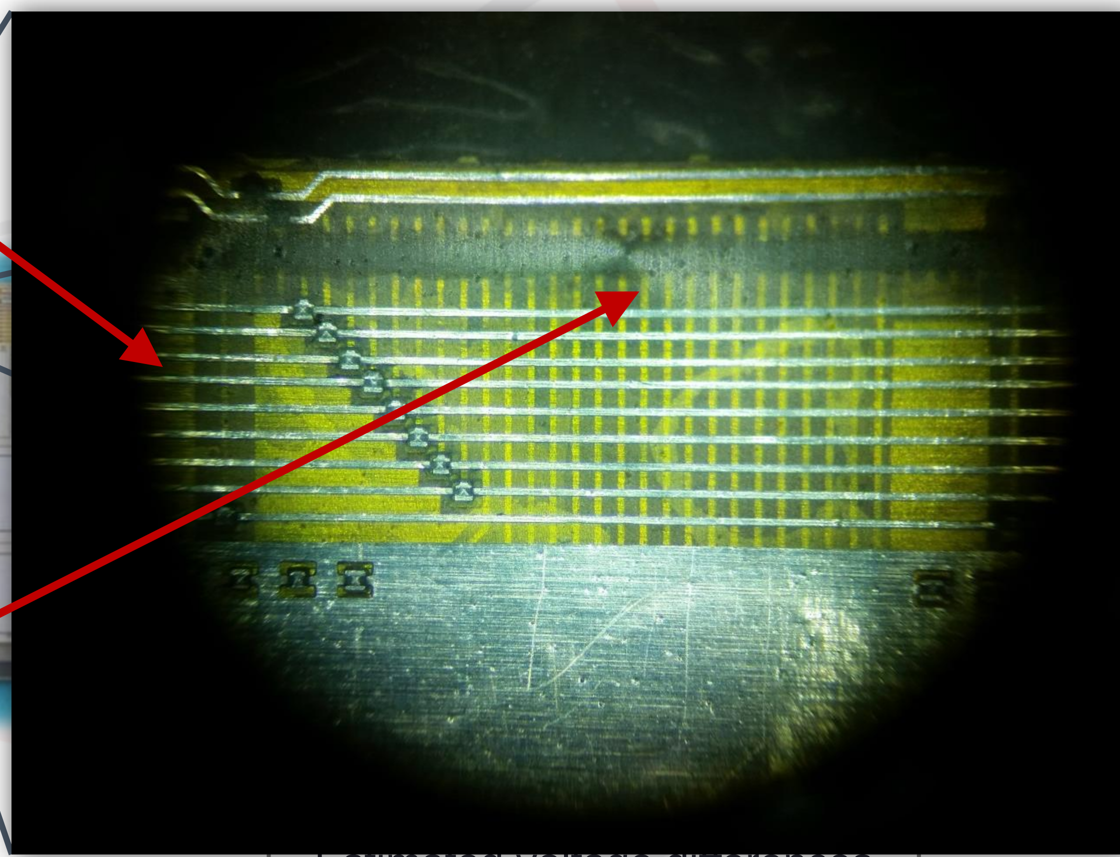




Individual signals

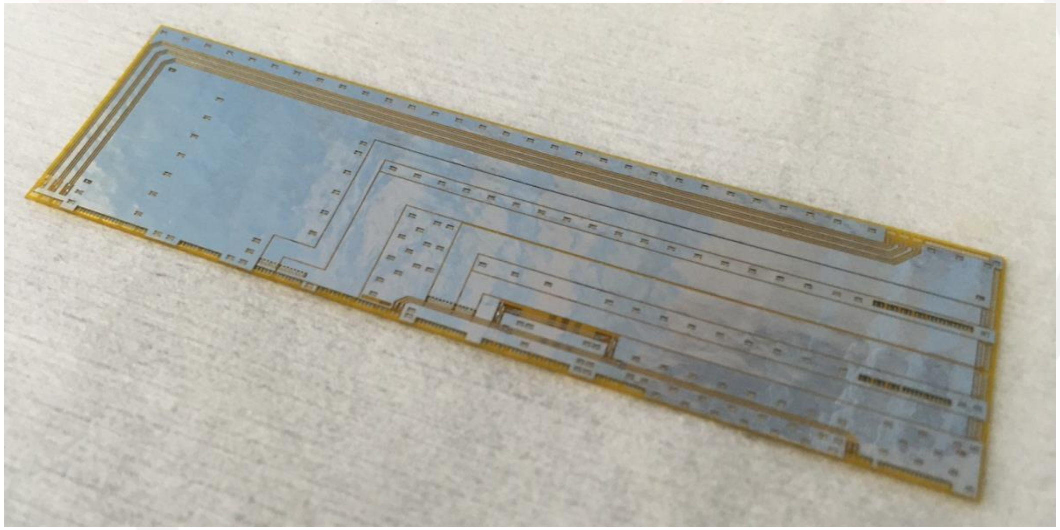
Up to 9 differential pairs per sensor

Estimated voltage differences between sensors below 50 mV

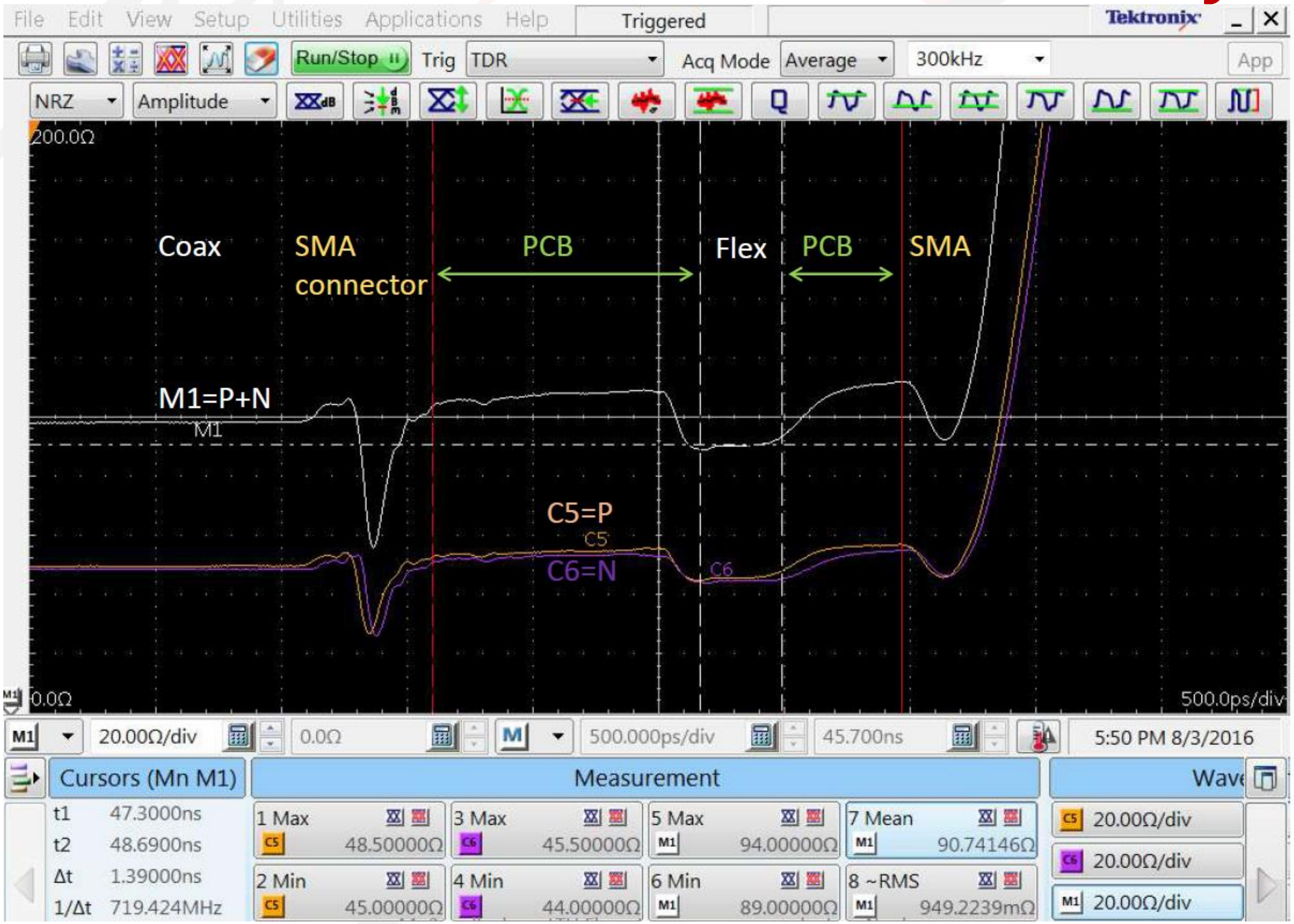
FPC feasibility studies

Two layer FPC with test structures

- Impedance measurements using Time Domain Reflectometry
- Bit error rate measurements
- Resistance and voltage drop measurements



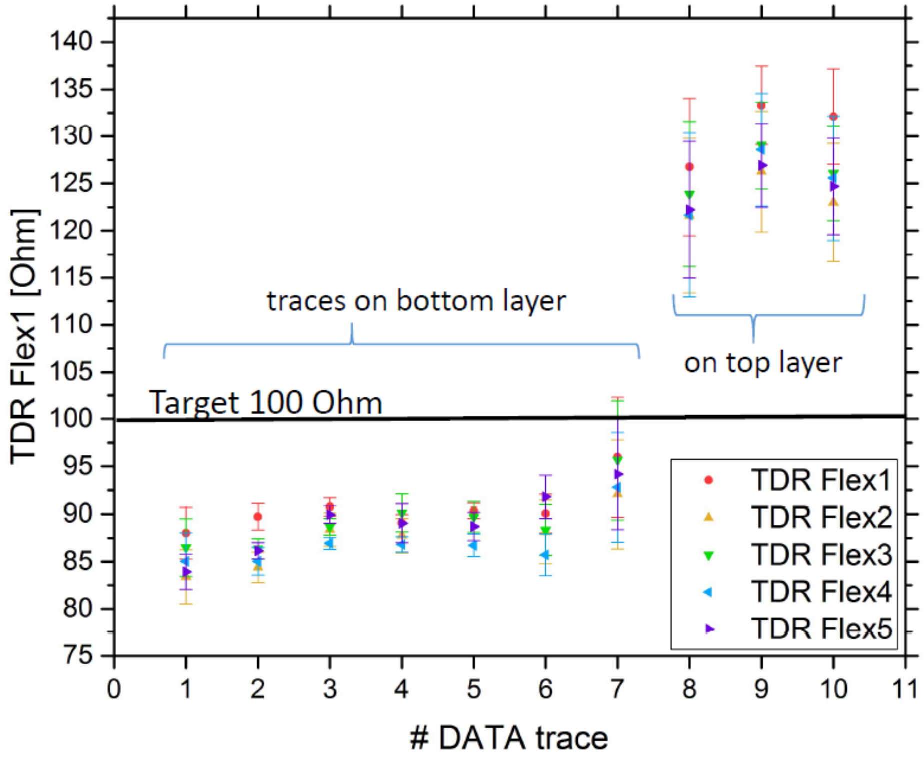
FPC - Time Domain Reflectometry



FPC - Time Domain Reflectometry

- 17.5 cm long differential pair
- Glue thickness variations → gradient in impedance

FPC studies – preliminary results



Time Domain Reflectometry

- Differential target impedance
  $$Z_{diff} = 100\ \Omega$$
- Off by more than 10%
- Bottom: glue and board coating

  Will behave differently with MuPix
- Top: missing Kapton foil

Also tested:

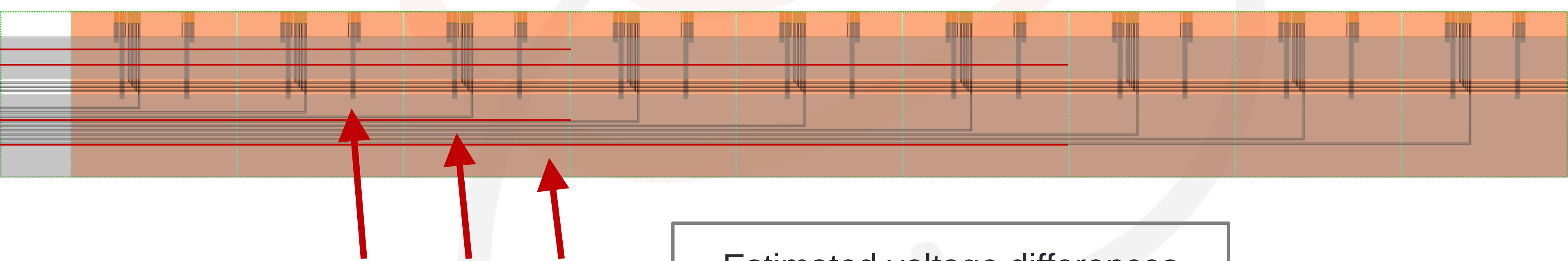
- Resistance of power lines: $50 - 120\ \mathrm{m}\Omega$

  $\rightarrow$ compatible with actual conductor thickness $\sim 12.3\ \mu\mathrm{m}$

Outer detector – FPC design study

<u>Two layer FPC for 9 sensors</u>

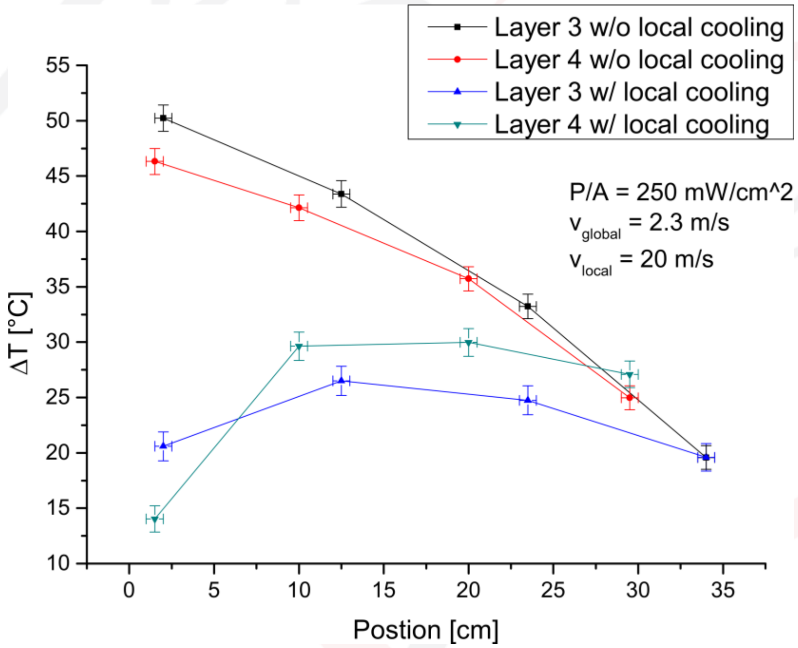
- Minimum number of signals
  - 1 LVDS data link per sensor
  - Clock, Reset, configuration as bus signals
- Supply different voltages to compensate voltage drop



$U_1 < U_2 < U_3$

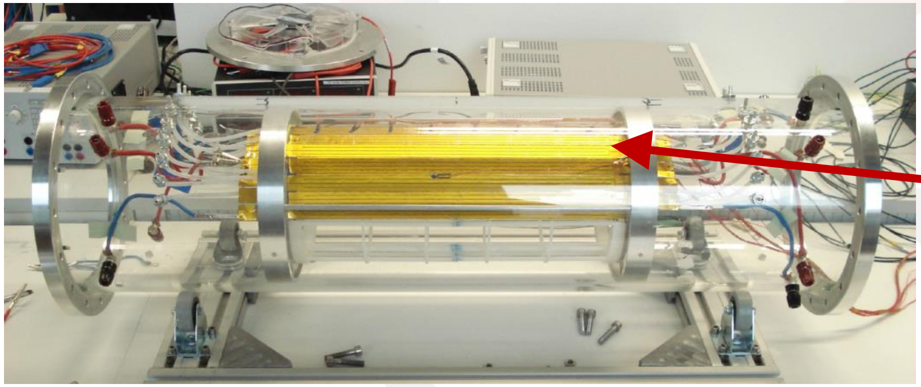
Estimated voltage differences between sensors around 10 mV

Cooling tests with detector model



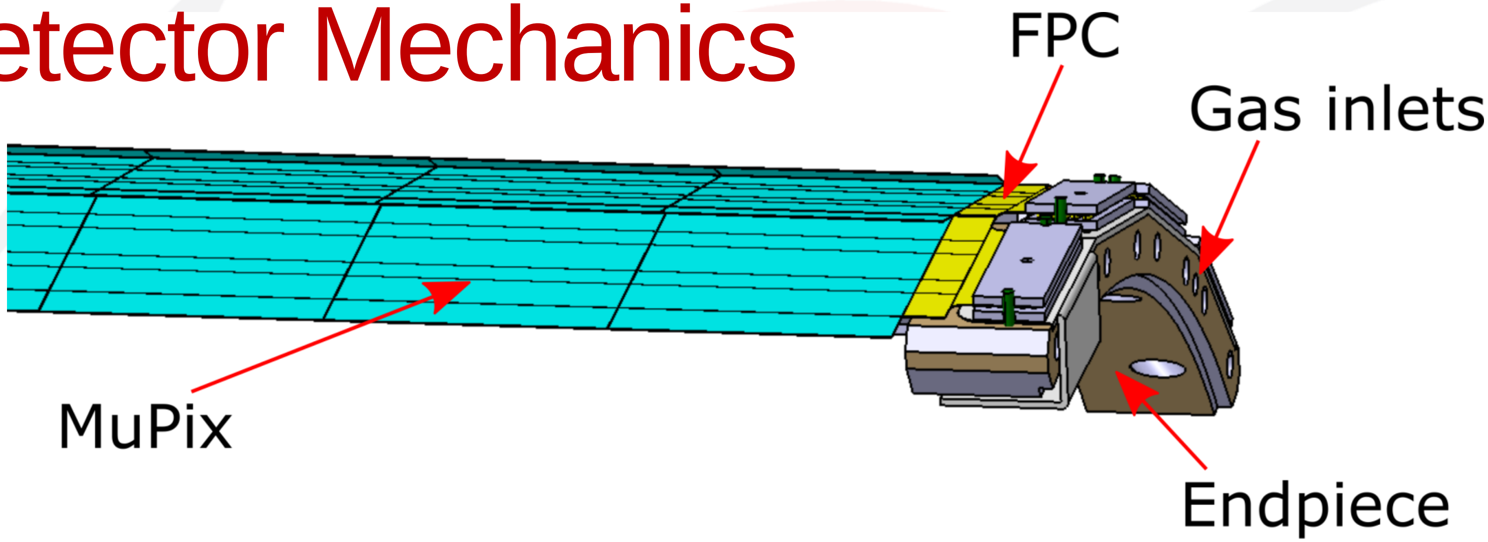
<u>Measurement</u>

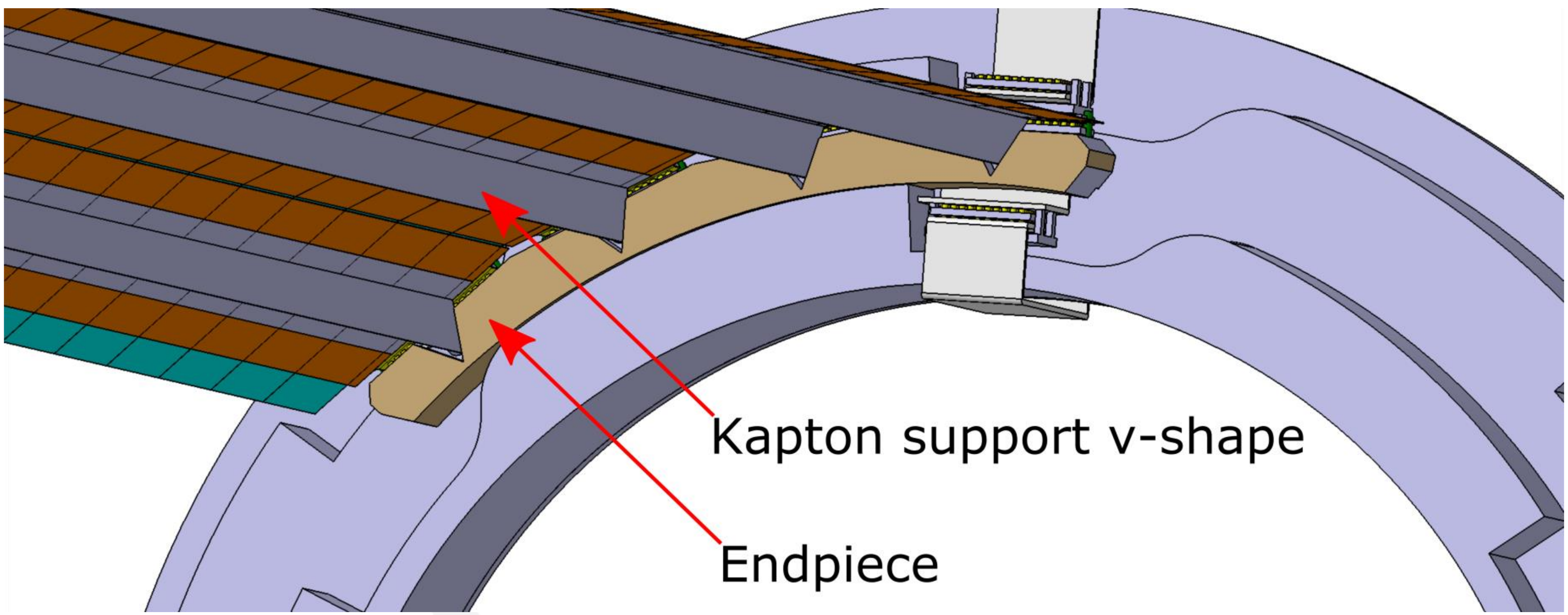
- Large benefit from local cooling in outer detector layers
- Reduces maximum temperature by 20°C



Heatable Kapton and glass staves

Detector Mechanics

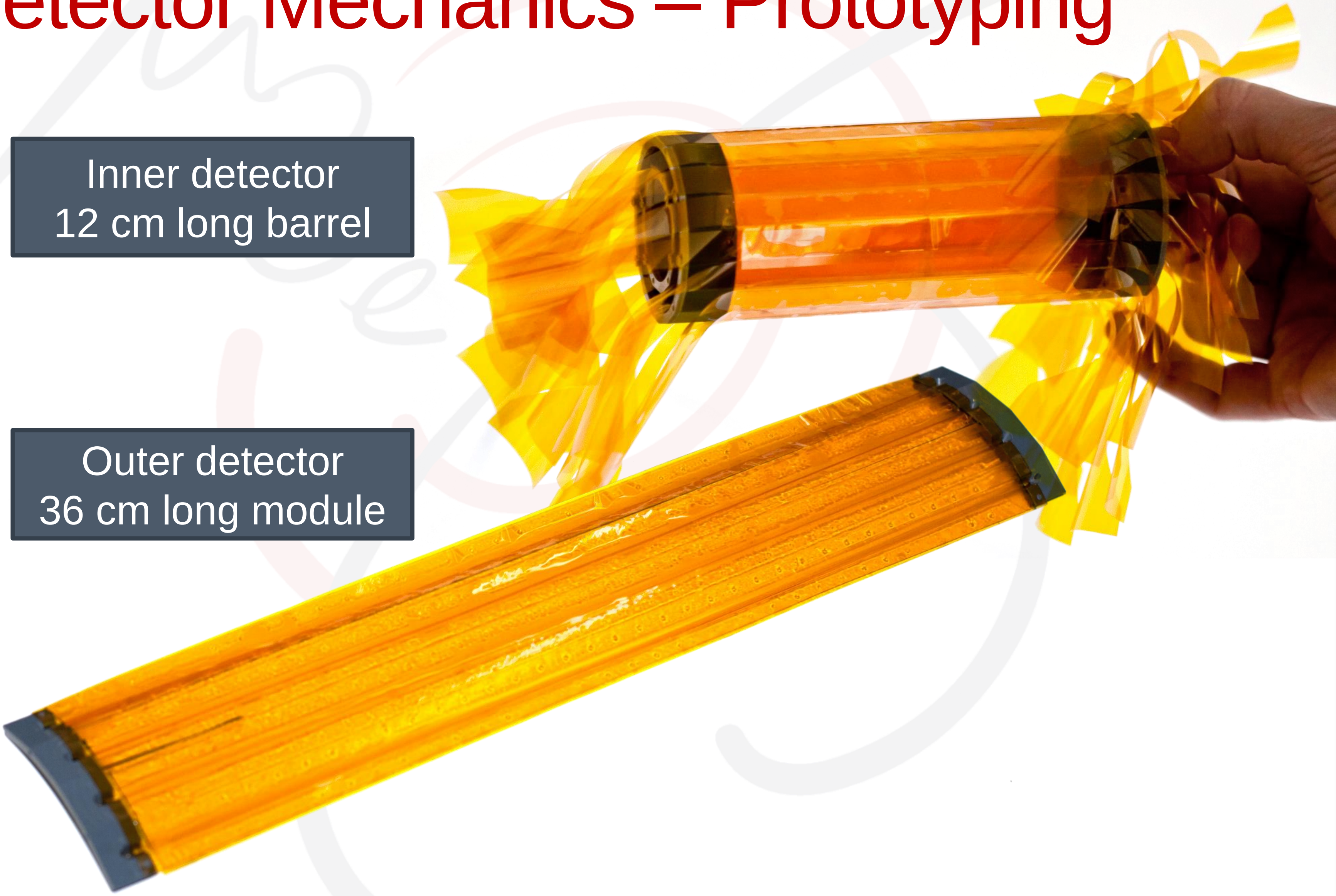




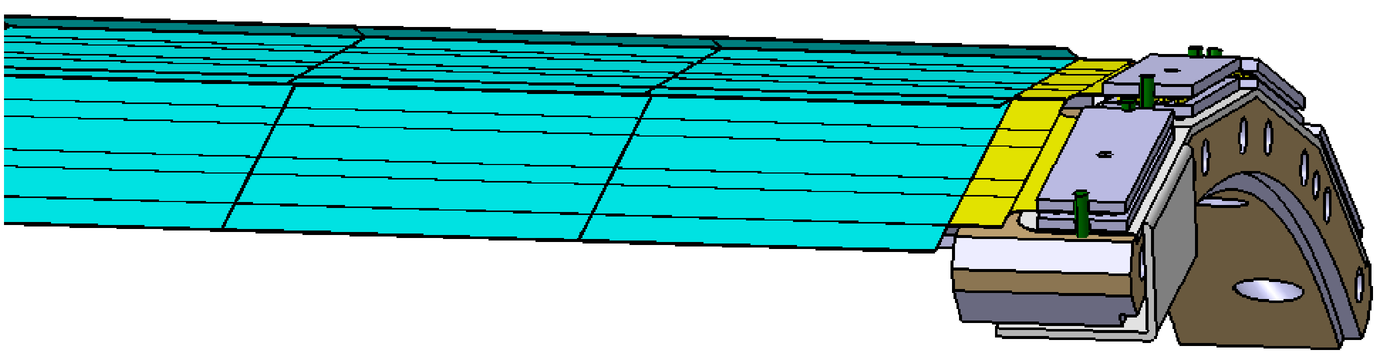
Detector Mechanics – Prototyping

Inner detector
12 cm long barrel

Outer detector
36 cm long module



Helium Gas Cooling for Mu3e



- Cool sensors below $70℃$ for up to $400\ \mathrm{mW/cm^2}$
- Minimize material budget of cooling in active volume
- Gaseous Helium: low density, reasonable cooling capabilities

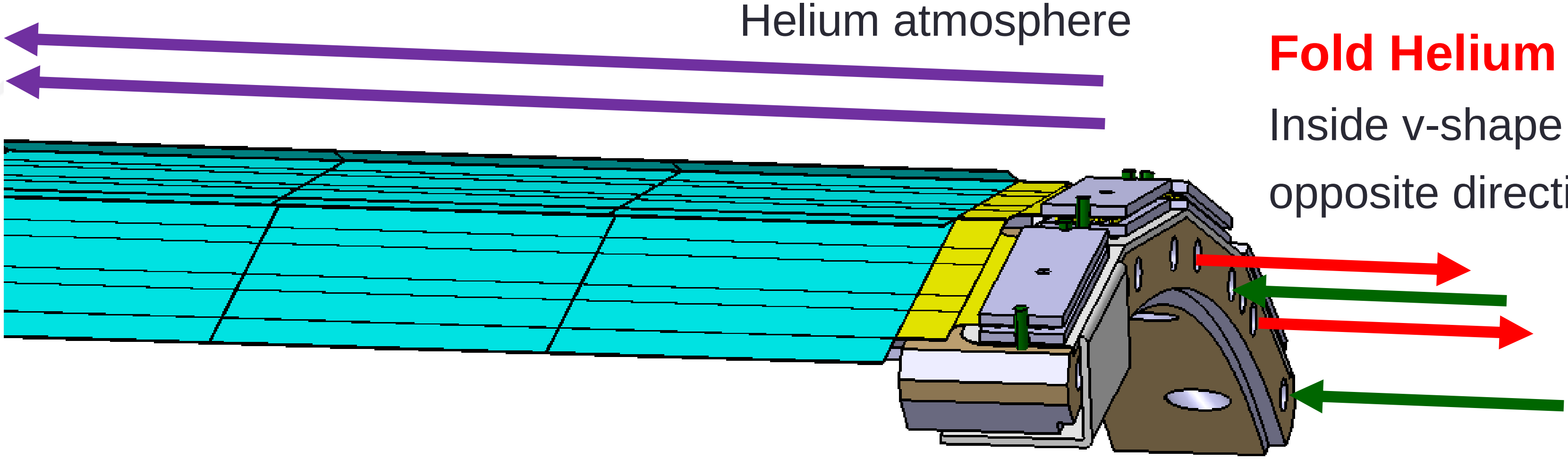
Helium Gas Cooling for Mu3e

Global Helium Flow

Whole detector located inside Helium atmosphere

Fold Helium Flow

Inside v-shape folds in opposite direction

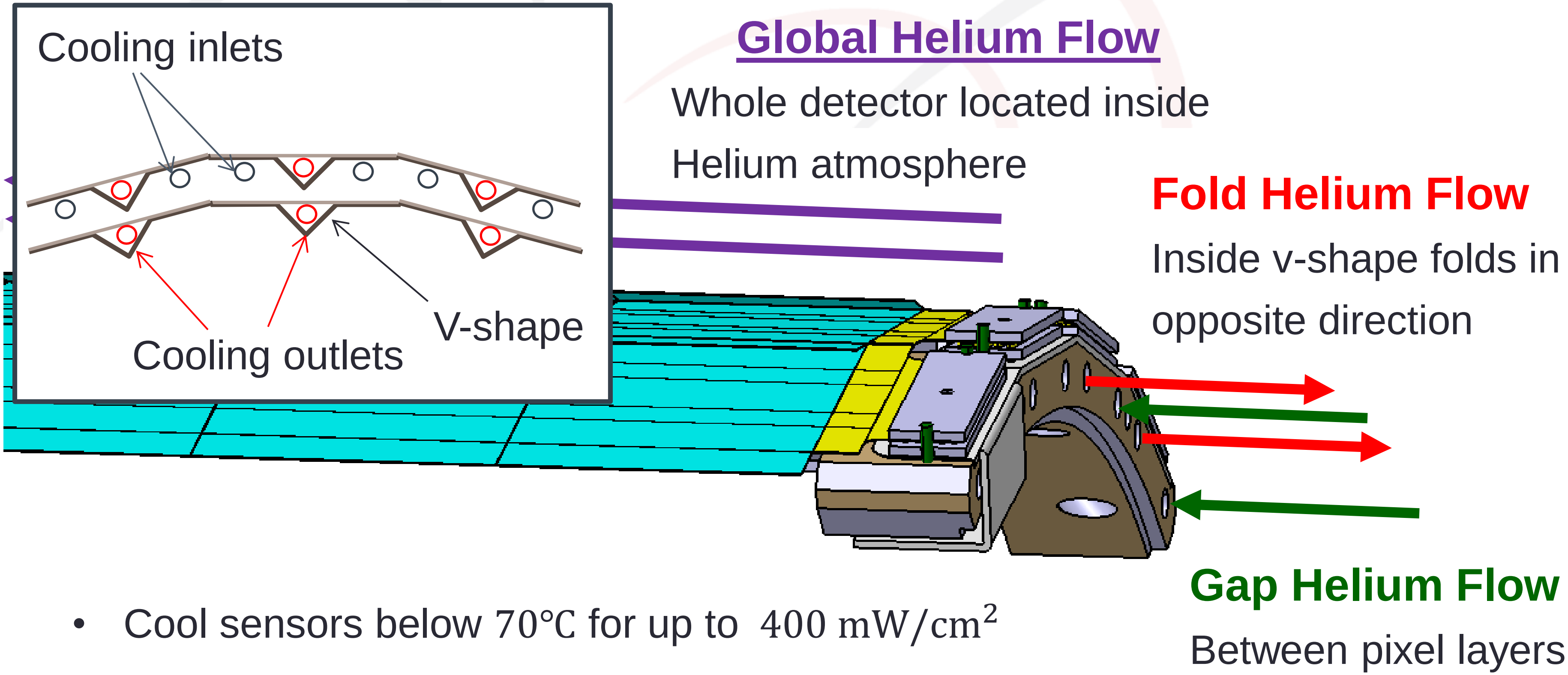


Gap Helium Flow

Between pixel layers

- Cool sensors below $70℃$ for up to $400\ \mathrm{mW/cm^2}$
- Minimize material budget of cooling in active volume
- Gaseous Helium: low density, reasonable cooling capabilities

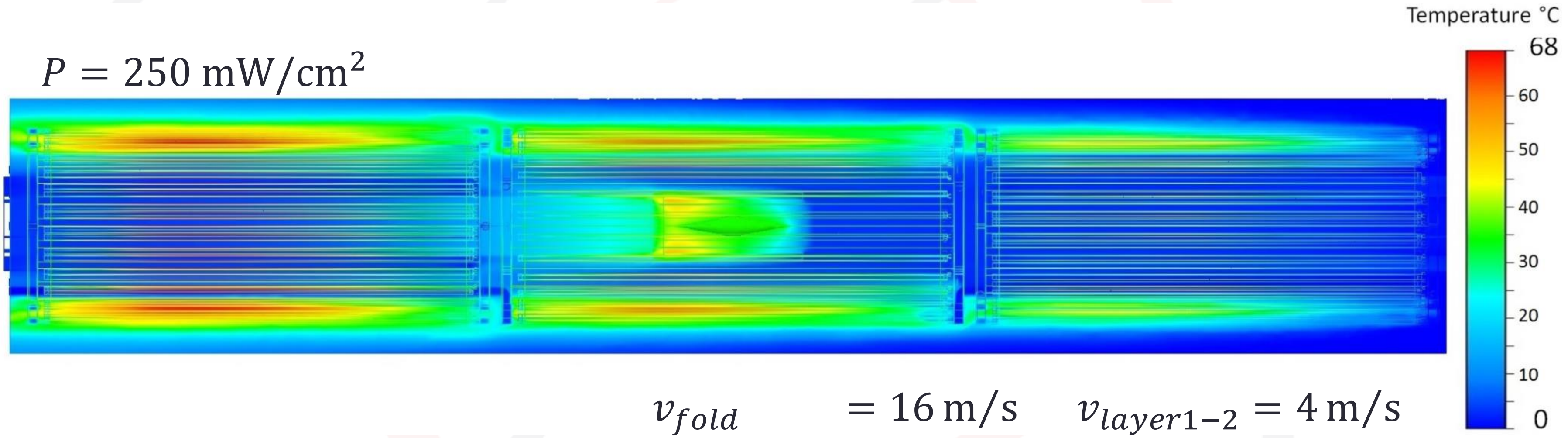
Helium Gas Cooling for Mu3e



- Cool sensors below $70℃$ for up to $400\ \mathrm{mW/cm^2}$
- Minimize material budget of cooling in active volume
- Gaseous Helium: low density, reasonable cooling capabilities

Simulation of Mu3e Helium Cooling

$P = 250\ \mathrm{mW/cm^2}$



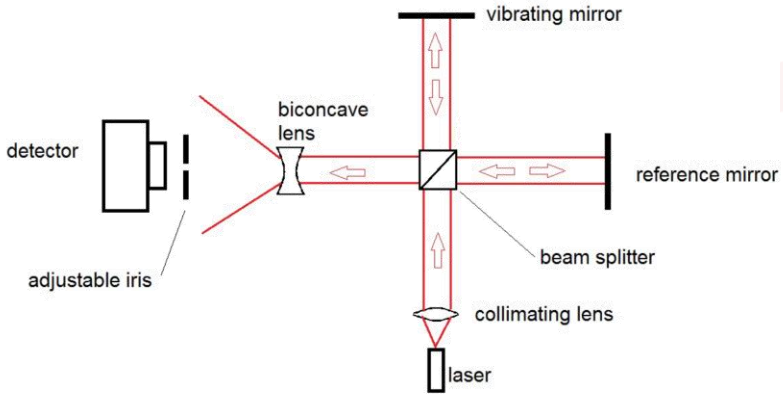
$v_{fold} = 16\ \mathrm{m/s}$ $\quad v_{layer1-2} = 4\ \mathrm{m/s}$

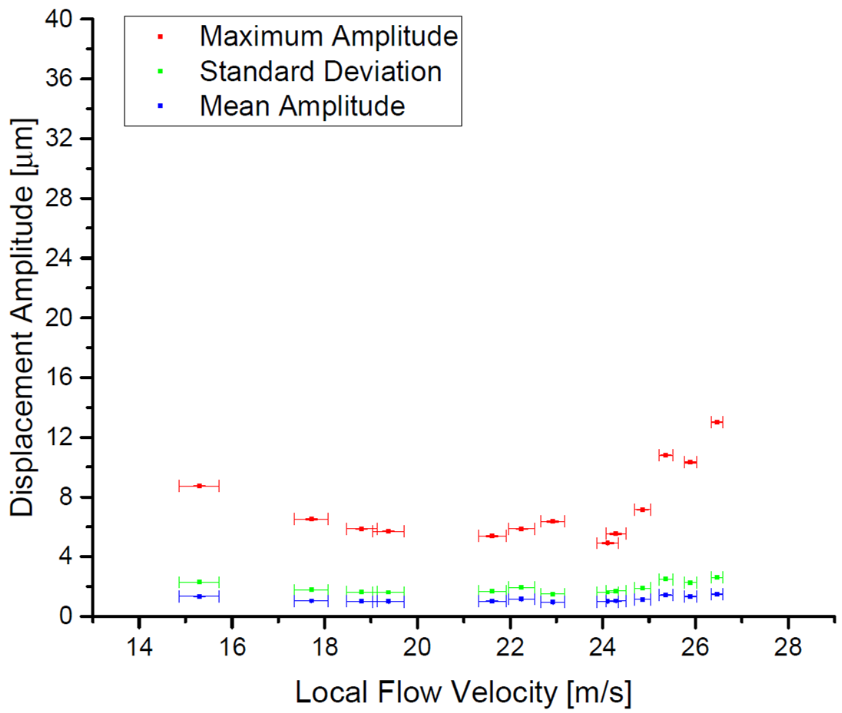
$v_{layer3-4} = 3.5\ \mathrm{m/s}$ $\quad v_{global} = 3.5\ \mathrm{m/s}$

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

Helium cooling – Vibration studies

- Helium flow velocities $\approx 20\,\mathrm{m/s}$
- Thin detector:
  - HV-MAPS $50\,\mu\mathrm{m}$
  - FPC $\approx 80\,\mu\mathrm{m}$
  - Kapton support $25\,\mu\mathrm{m}$
- Vibrations induced by Helium flow?
- **Michelson Interferometer**





$\leq 10\,\mu\mathrm{m}$ amplitude for typical flow velocity