Ultra-low material pixel layers for the Mu3e experiment

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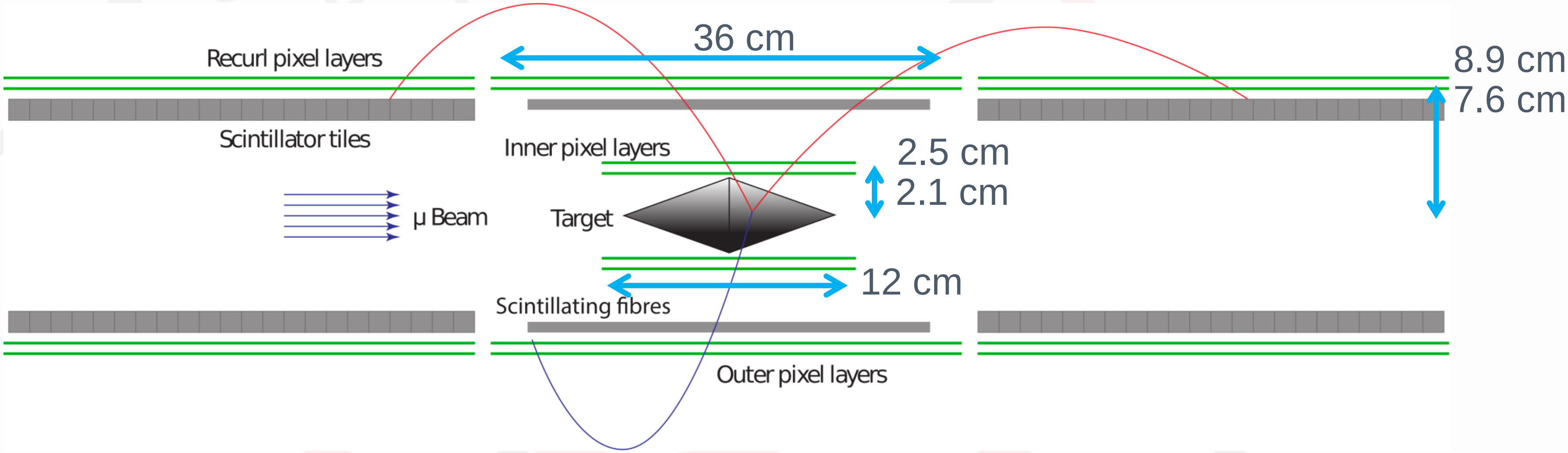
Sestri Levante – 9 September 2016

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

PTFS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

Mu3e - Experimental Concept

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



- Decays of stopped muons → low momentum electrons
- Design sensitivity $\mathrm{BR} < 10^{-16}$ requires
  - High muon rates $\mathcal{O}(10^8 - 10^9\ \mathrm{s}^{-1})$
  - Excellent momentum resolution $\sigma_p < 0.5\ \mathrm{MeV/c}$
- Multiple Coulomb scattering dominates momentum resolution

➢ Thin silicon pixel detector: 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

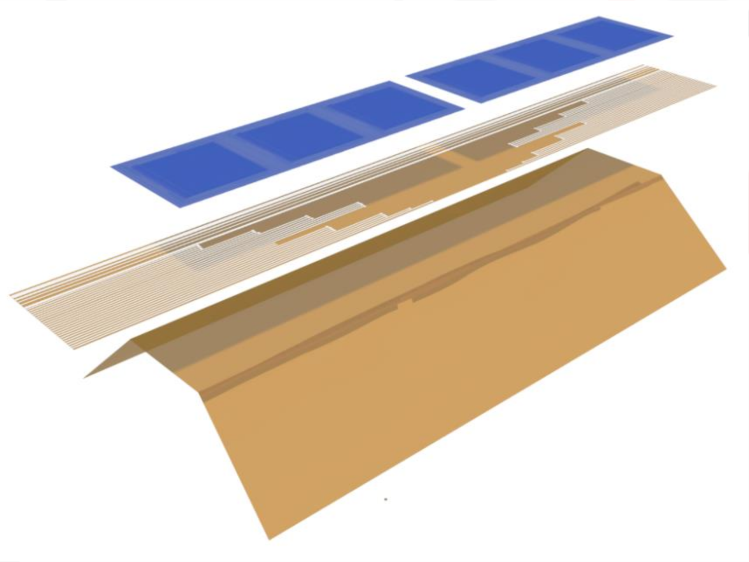
* arXiv:1211.4494v1

◊ talk by G. Contin

△ talk by C. Koffmane

How to reach the material goal?

Approach for a Mu3e tracking detector layer



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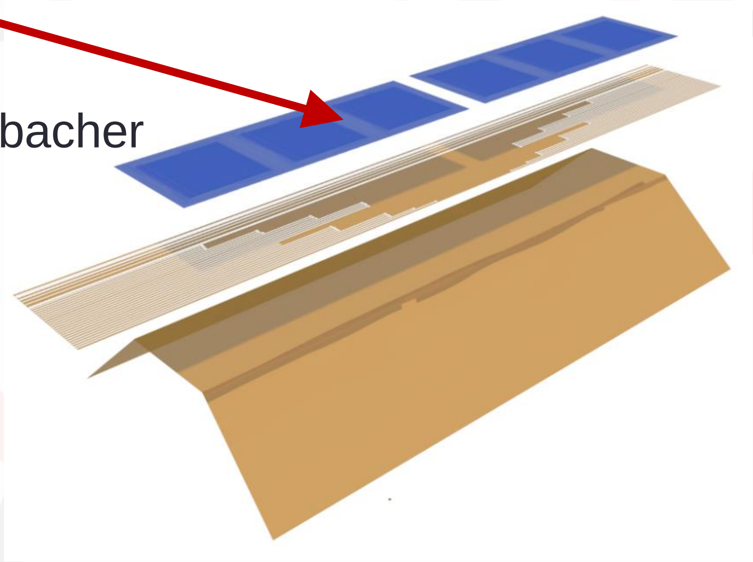
HV-MAPS
MuPix
50 µm ~ 0.5 ‰ X_0
Talk by Frank Meier Aeschbacher
about MuPix 7



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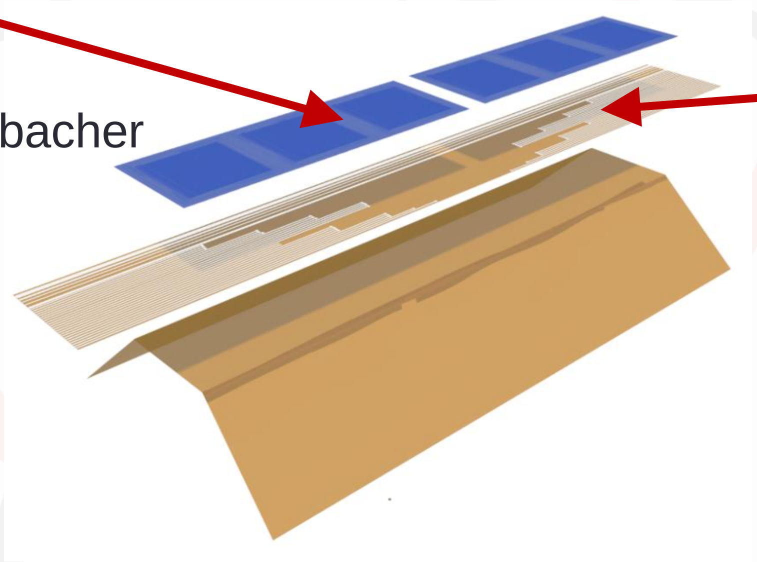

FPC
Flexible printed circuit
Sensor powering
Signal transmission
45 μm Kapton
+ 28 μm Aluminium
+ 10 μm Glue
~ 0.5‰ X_0

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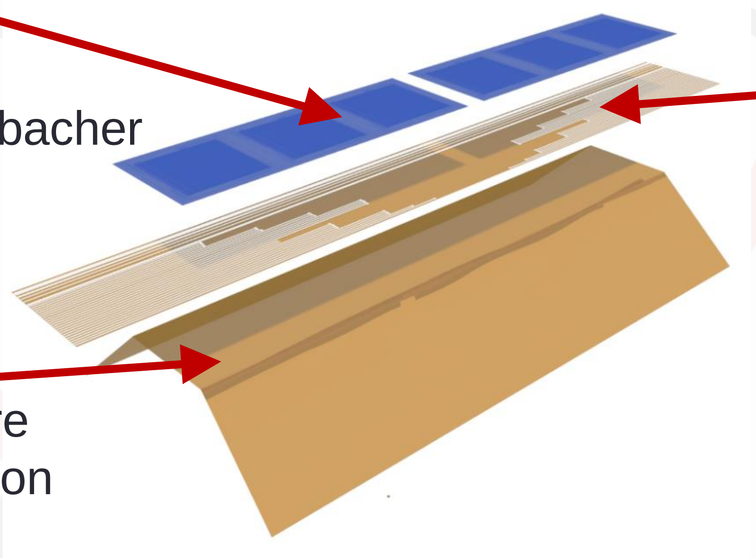

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Kapton support structure
Helium cooling distribution
25 µm ~ 0.1 ‰ X_0

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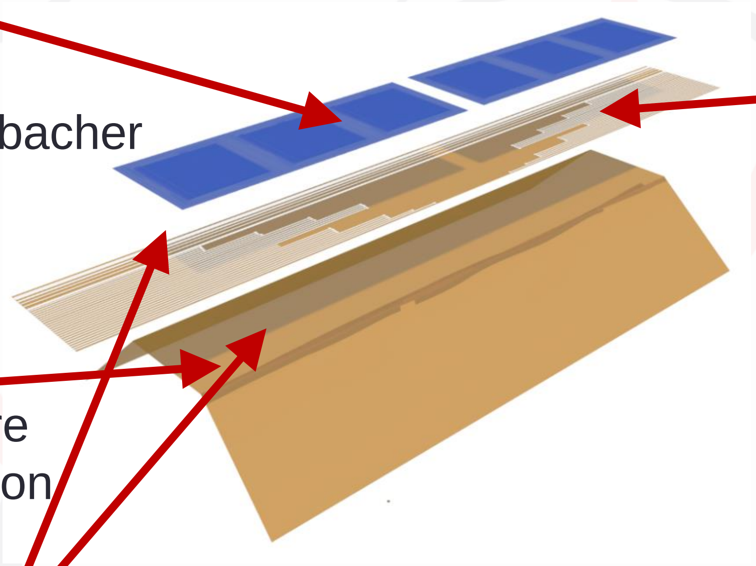

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+ 10-20 µm Glue
~ 0.05‰ X_0

Material budget estimated
x ~ 1.15‰ X_0 per layer

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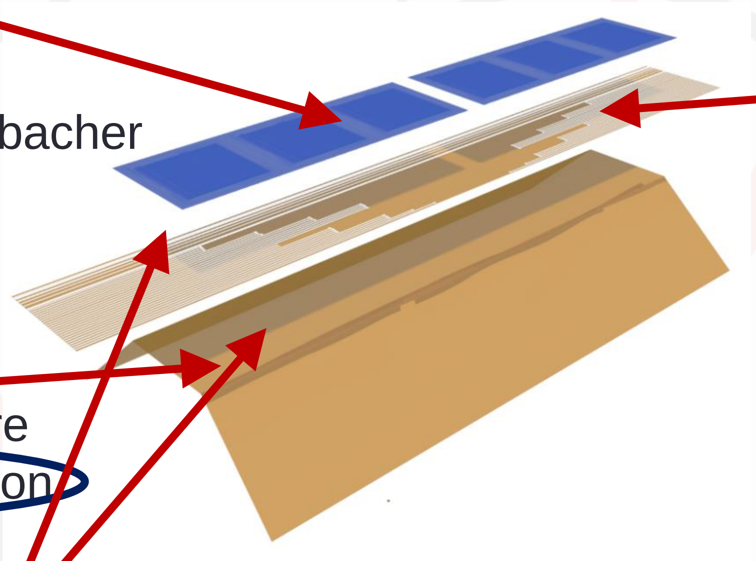

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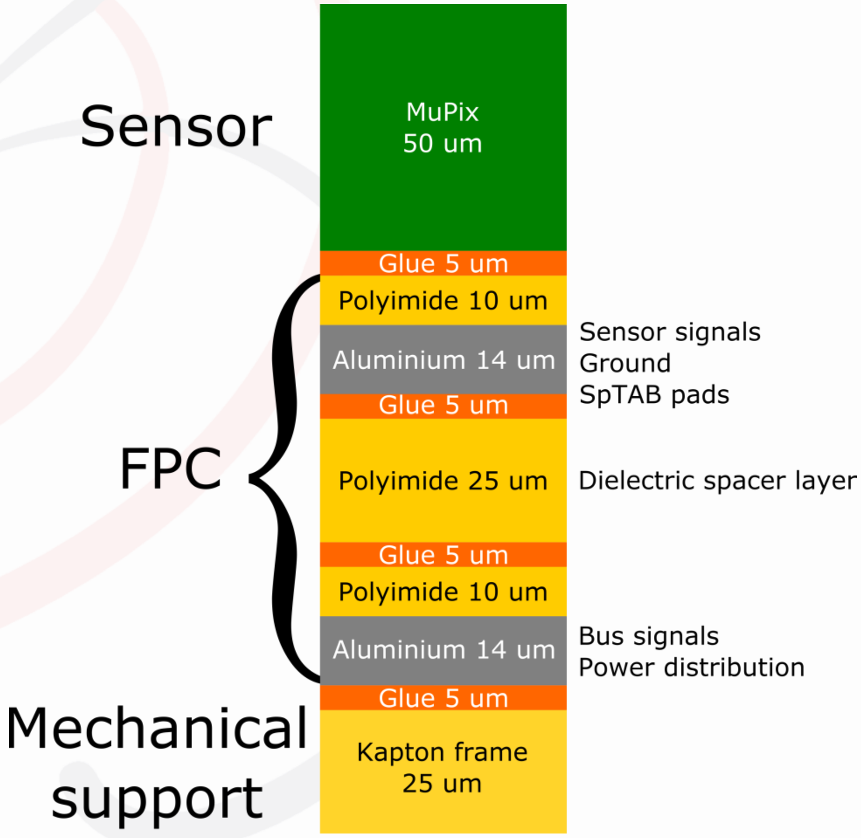
FPC technology

Two layer aluminium (LTU Ltd.)

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

Layer stack



FPC technology

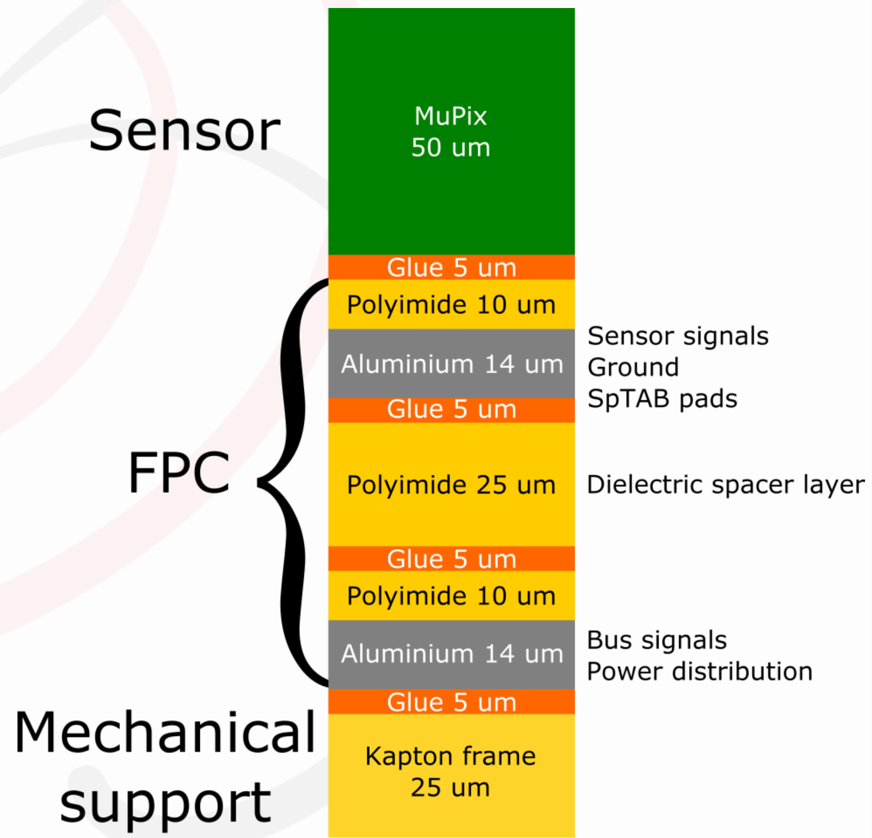
Two layer aluminium (LTU Ltd.)

- 14μm Al + 10μm polyimide per layer
- Structure sizes ≥ 65μm
- Dielectric spacing 45μm
- SpTAB technology (by LTU)

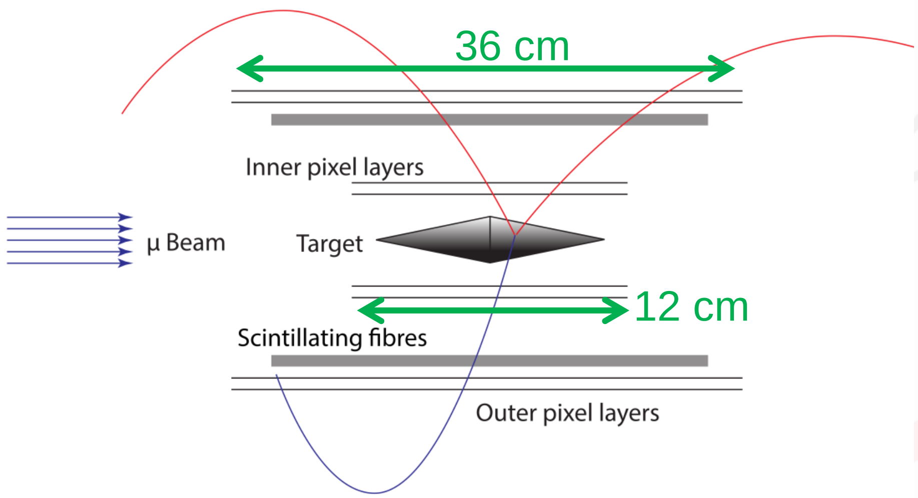
  Single point Tape Automated Bonding

➢ No additional (high Z) material for bonding!

Layer stack



FPC design considerations

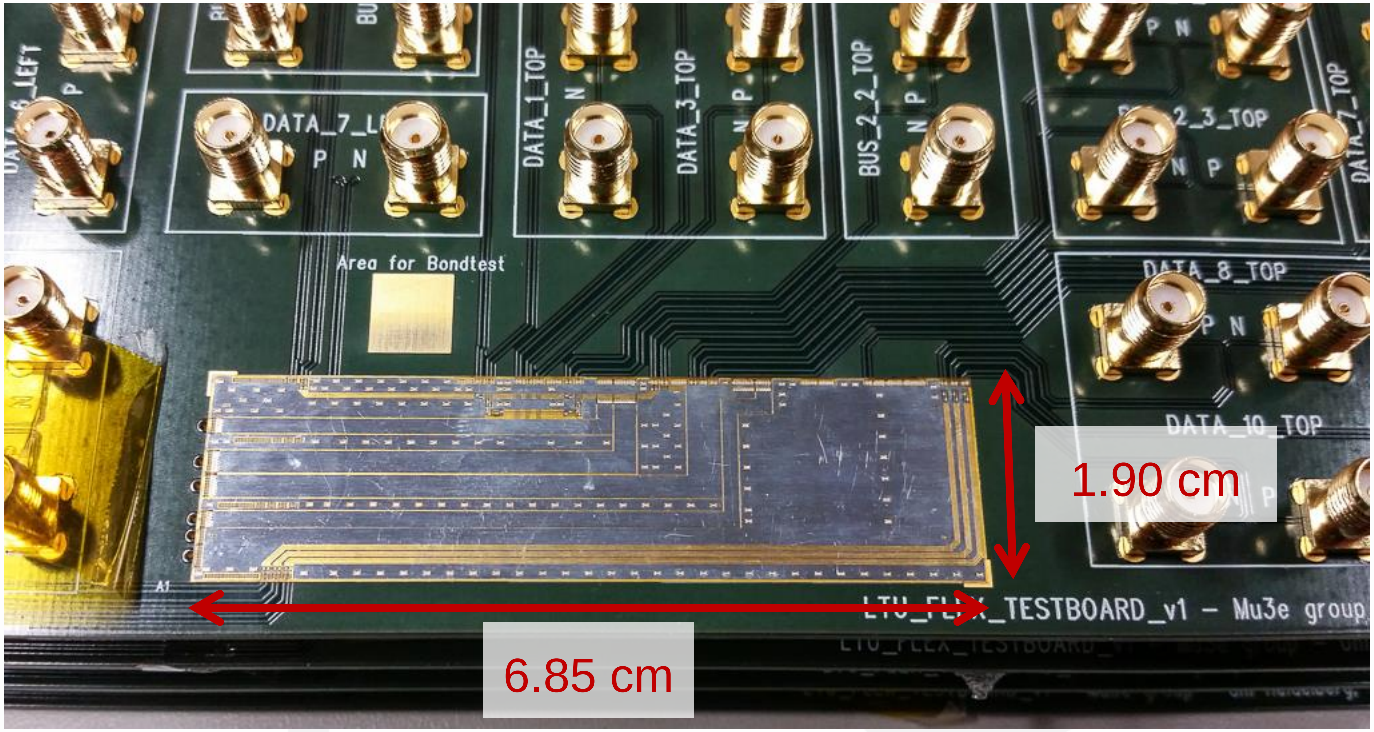


- Clock, reset, configuration as bus
- High Voltage ($\approx 85\ V$)
- Power ($P_{MuPix} \leq\ 400\ \mathrm{mW/cm^2}$)
- Readout at both ends

FPC	Length	Sensors	LVDS links @ 1.25 Gb/s
Inner layers	12 cm	6	3 per sensor
Outer layers	36 cm	18	1 per sensor

FPC feasibility studies

Two layer FPC with test structures bonded to testboard



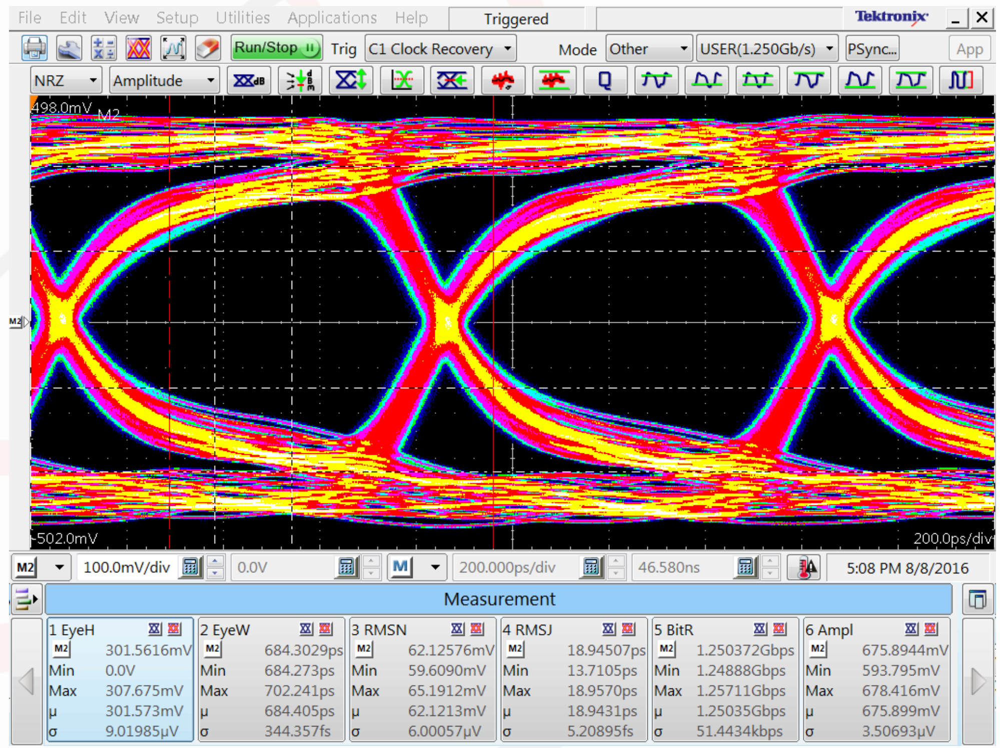
FPC studies – preliminary results

Bit error rate measurements

- 10 differential pairs
- Data rate = 1.25 Gbit/s
- No bit errors observed

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

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

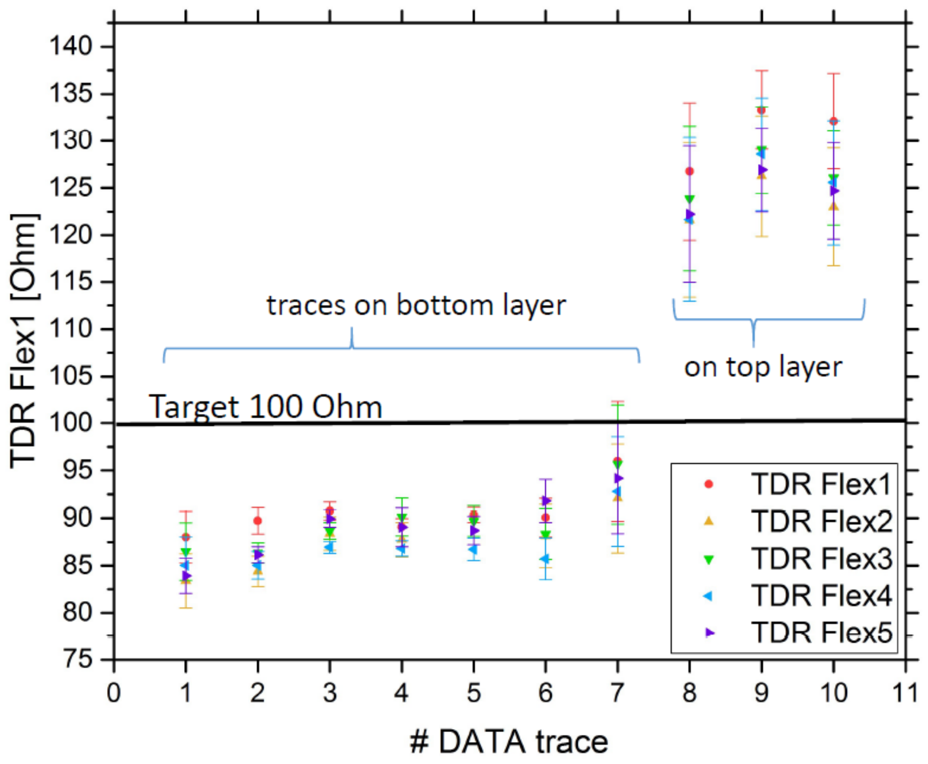


FPC studies – preliminary results

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



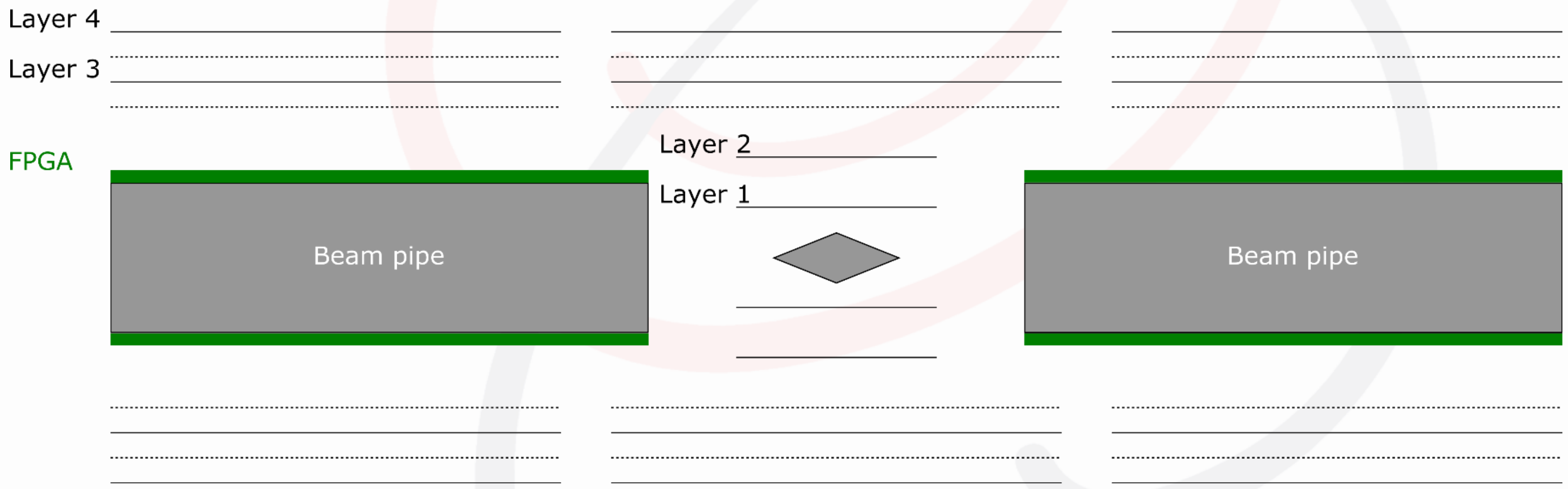
Also tested:

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

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

Mu3e cooling concept

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



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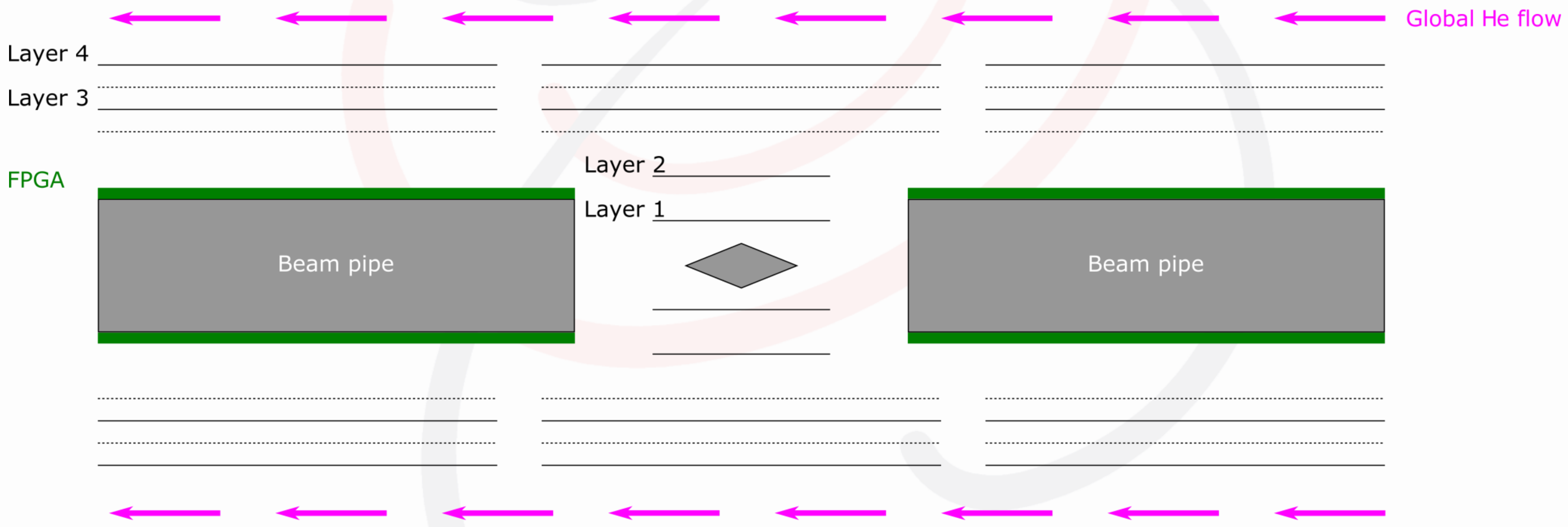

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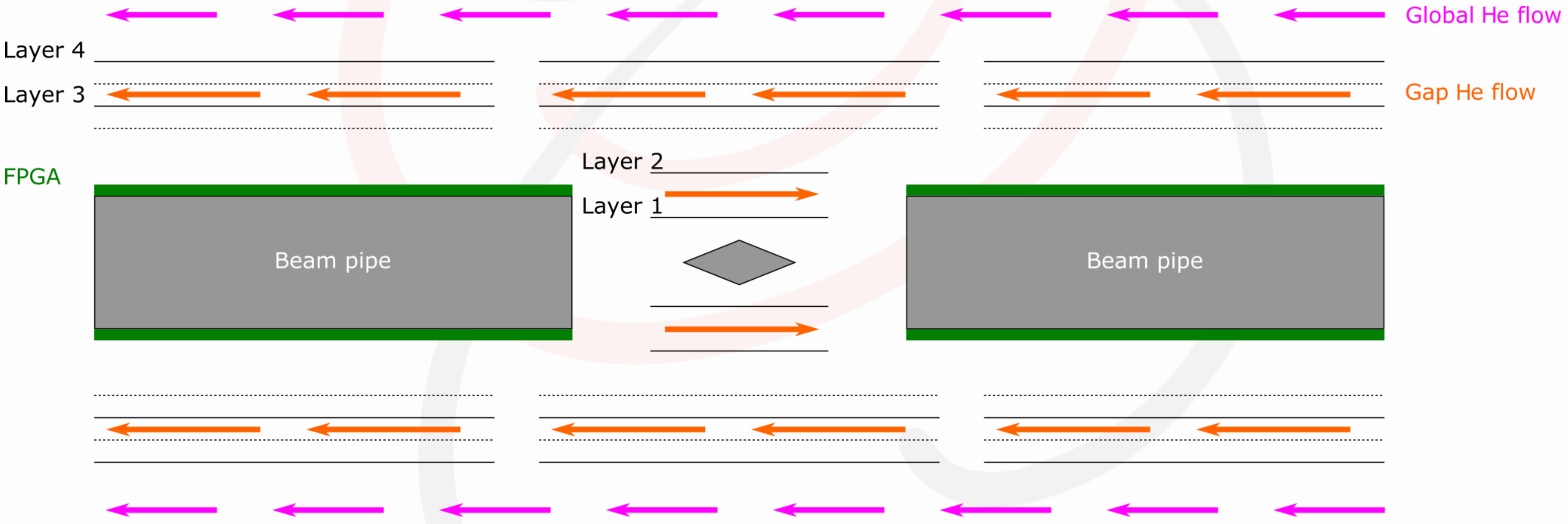
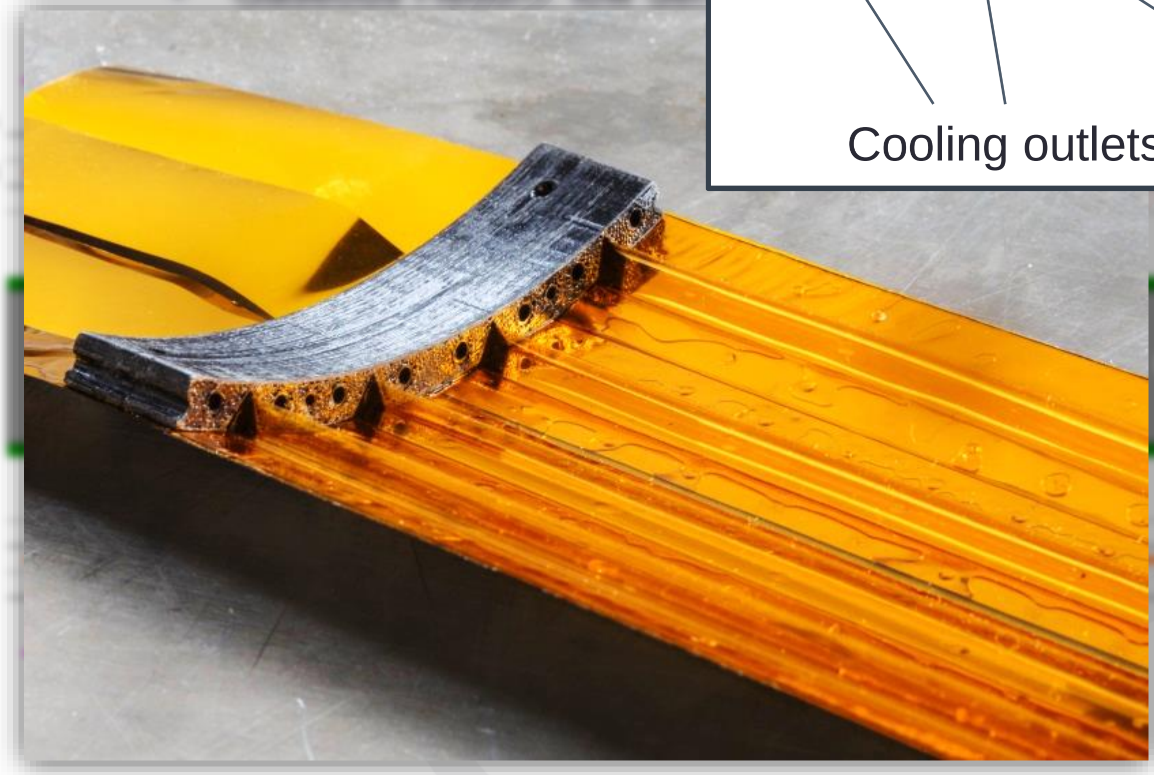
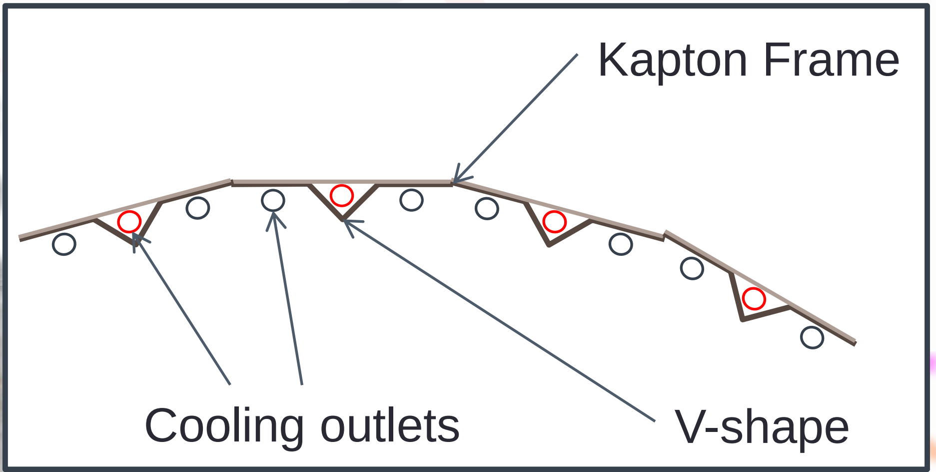


Mu3e cooling concept

V-shapes for local cooling channels





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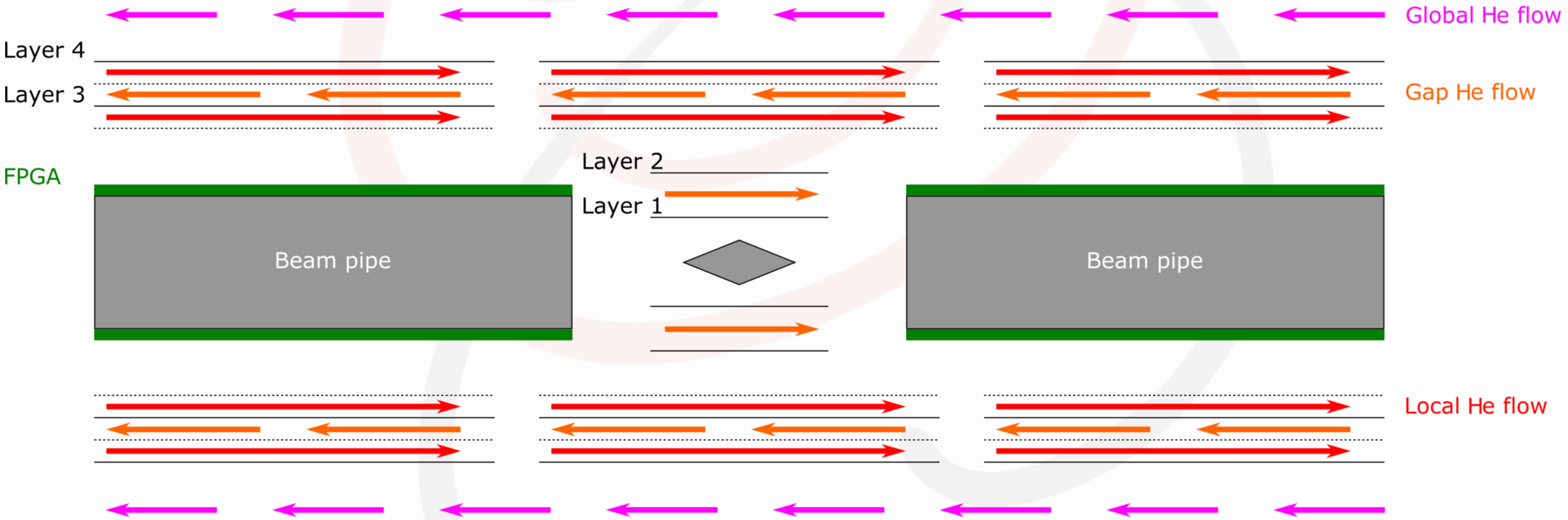

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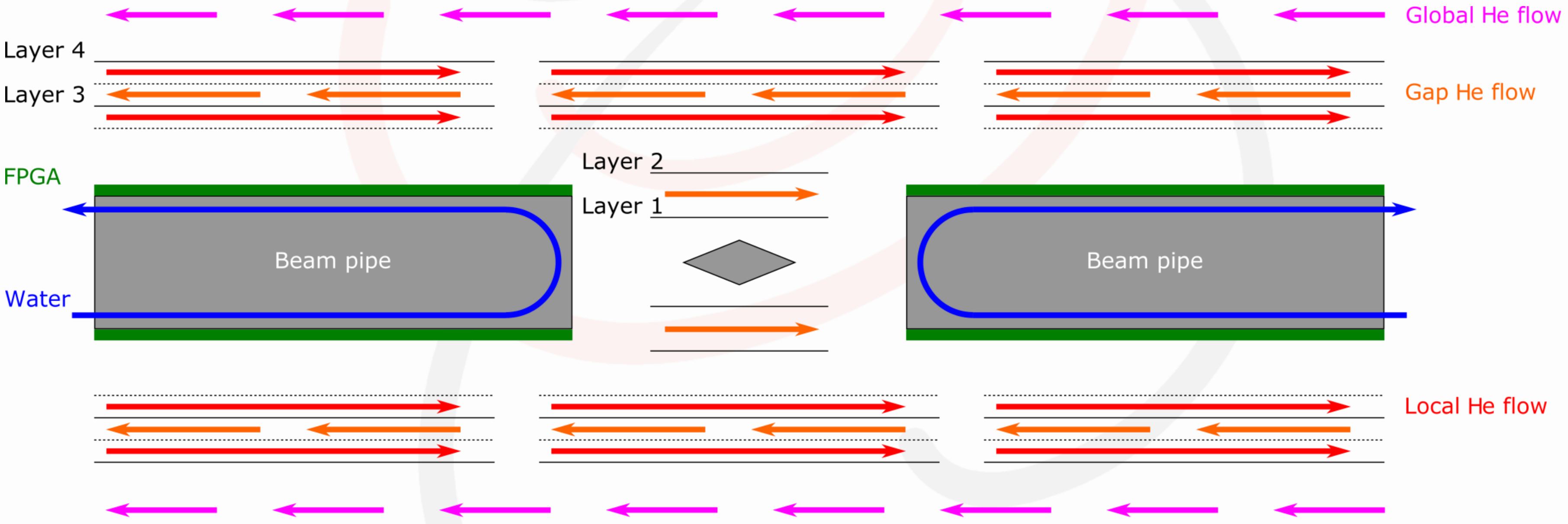
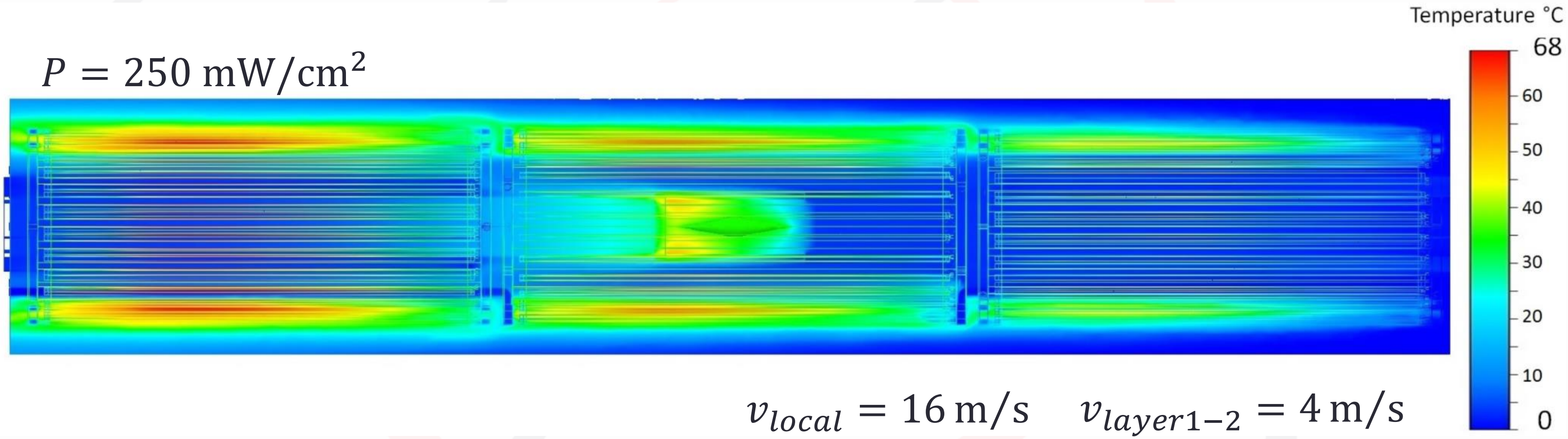


Simulation of Mu3e helium cooling

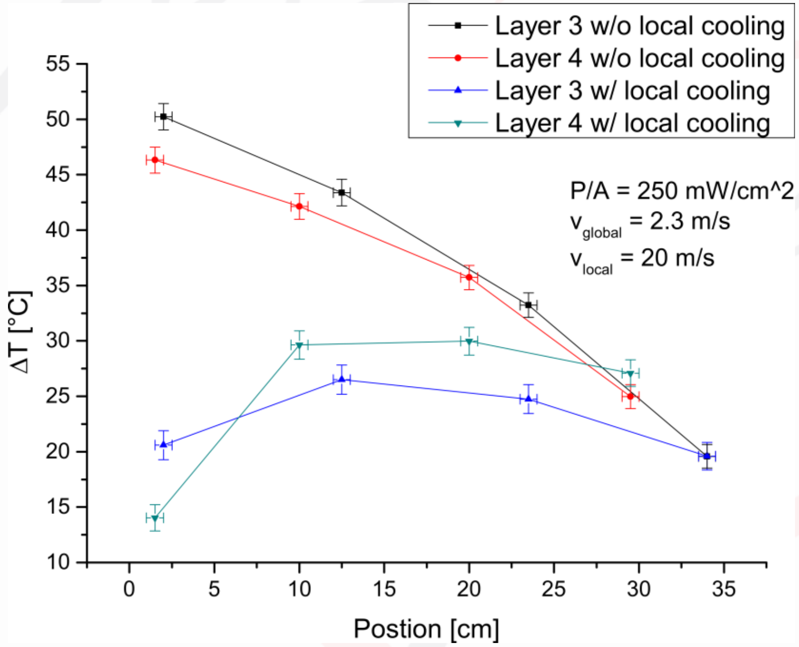
$P = 250\ \mathrm{mW/cm^2}$



$v_{local} = 16\ \mathrm{m/s}$ $v_{layer1-2} = 4\ \mathrm{m/s}$
$v_{gap} = 3.5\ \mathrm{m/s}$ $v_{global} = 3.5\ \mathrm{m/s}$

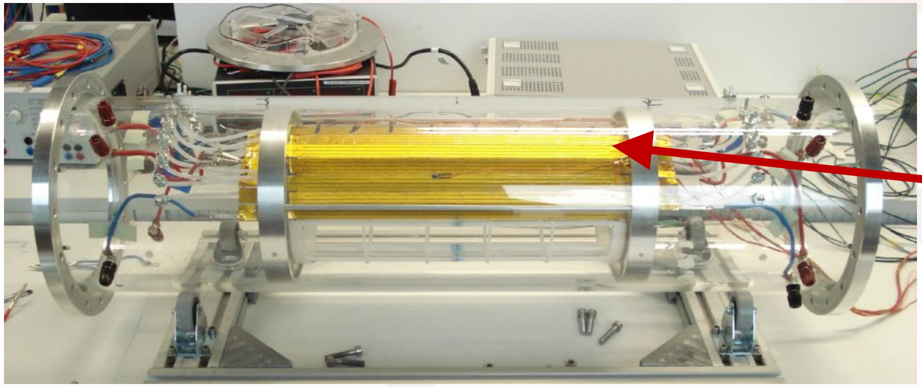
- Target power consumption ($P = 250\ \mathrm{mW/cm^2}$) seems feasible
- Higher power consumption ($P = 400\ \mathrm{mW/cm^2}$) requires higher flow velocities

Cooling tests with detector model



Measurement

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



Heatable Kapton and glass staves

Summary and Outlook

- Ultra-low material tracking detector using HV-MAPS for Mu3e
- Material budget of $\sim \mathbf{1.15‰}\, \boldsymbol{X_0}$ per layer
- Aluminium FPC prototype works very well: BER < $2 \cdot 10^{-13}$ @ $1.25\ \mathrm{Gb}/s$
- Cooling of sensors with Helium gas seems feasible

- End of this year: MuPix 8 ($\approx 2 \times 2\ cm^2$)
- Integration of MuPix with FPC

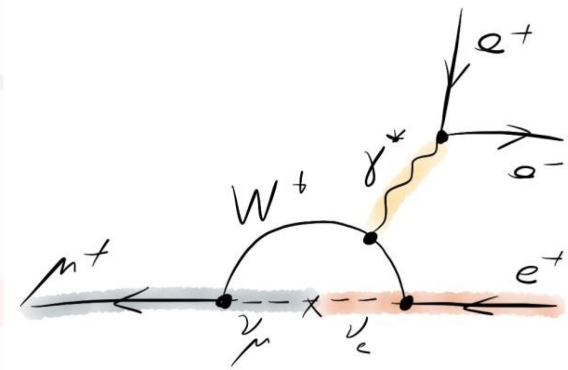
➢ First inner detector modules

Backup

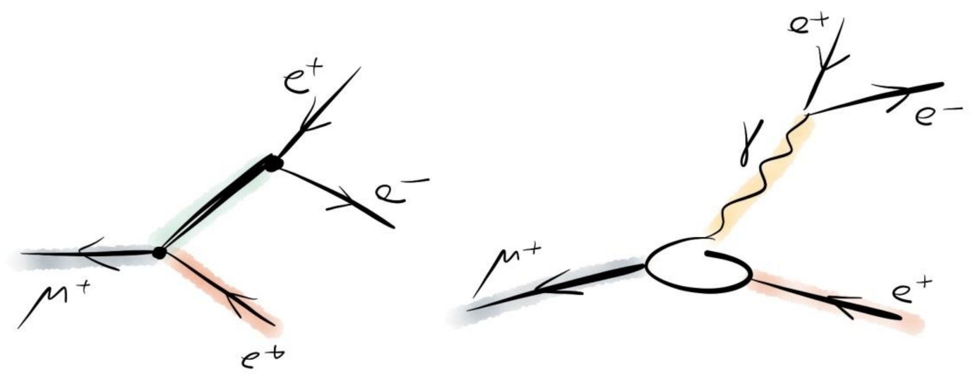
The Mu3e Experiment

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

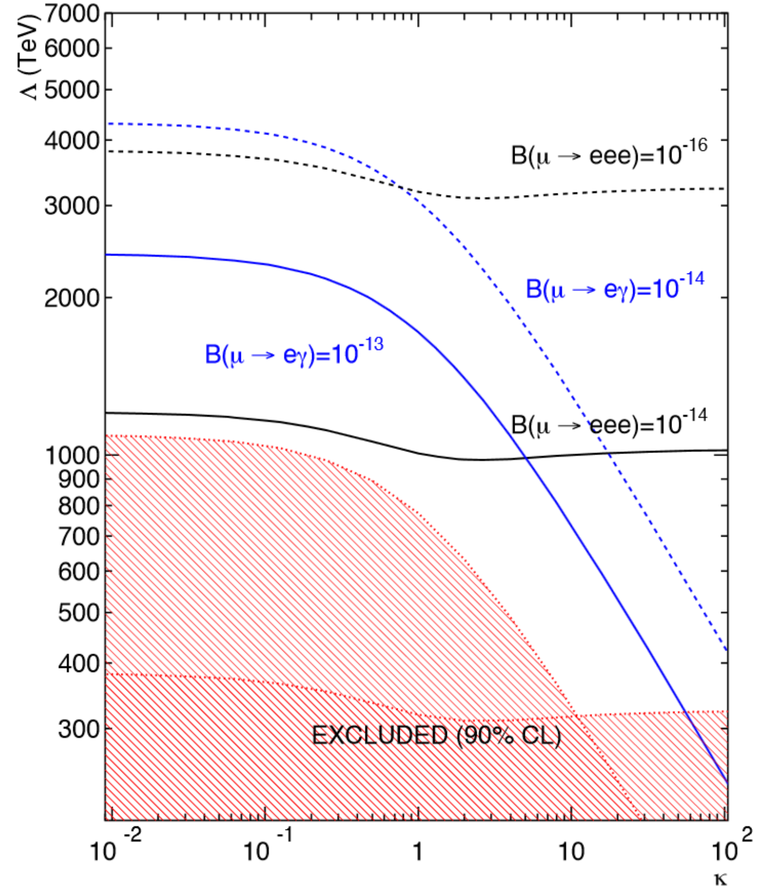
<u>Standard Model</u>
Highly suppressed branching ratio
$\mathbf{BR_{SM} < 10^{-54}}$



<u>Probe physics beyond SM</u>
Any observation is a clear sign for new physics!

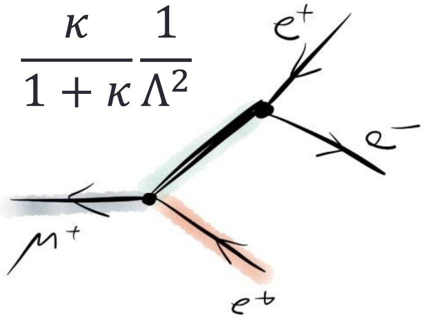


Searching for New Physics with Mu3e



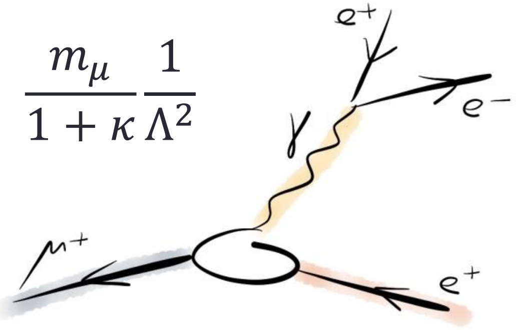
André de Gouvêa, Petr Vogel,
Lepton flavor and number conservation, and physics beyond the standard model,
Progress in Particle and Nuclear Physics, 71 (2013) 75-9

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



+

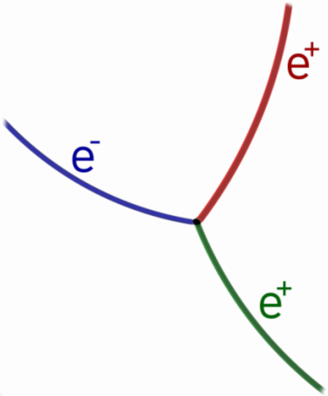
$$\frac{m_\mu}{1+\kappa}\frac{1}{\Lambda^2}$$



The Mu3e Experiment

Current limit on $\mu^+ \rightarrow e^+ e^- e^+$

$\mathbf{BR}_{\boldsymbol{meas}} < \mathbf{10^{-12}}$ (SINDRUM 1988)



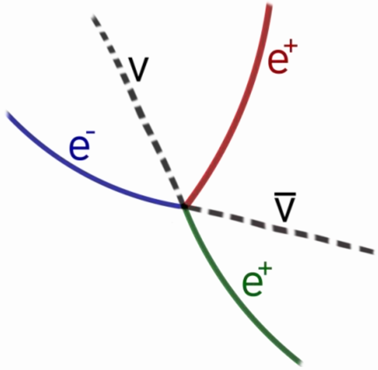
Goal of Mu3e

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

How to achieve this in a reasonable time?

- High muon rate $\boldsymbol{\mathcal{O}}\left(\mathbf{10^{9}\ s^{-1}}\right)$

➢ Beamline at PSI (CH)

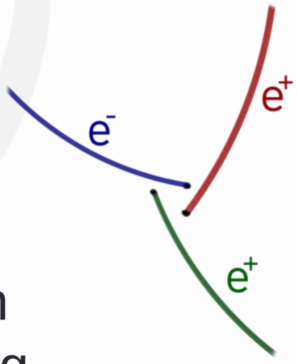


What are the main backgrounds?

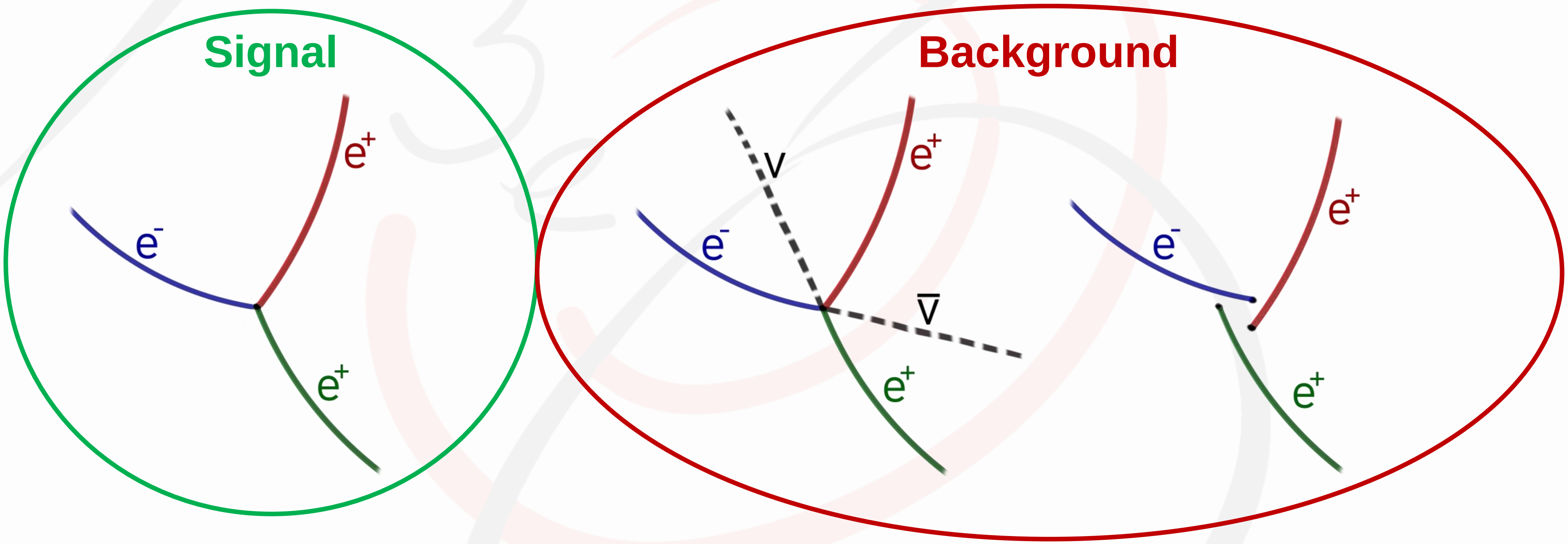
- Radiative SM decay $\mu^+ \rightarrow e^+ e^- e^+ \nu \bar{\nu}$
- Accidental combinations

➢ Excellent momentum and vertex resolution

➢ Fast detector electronics and precise timing



Event Topologies



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

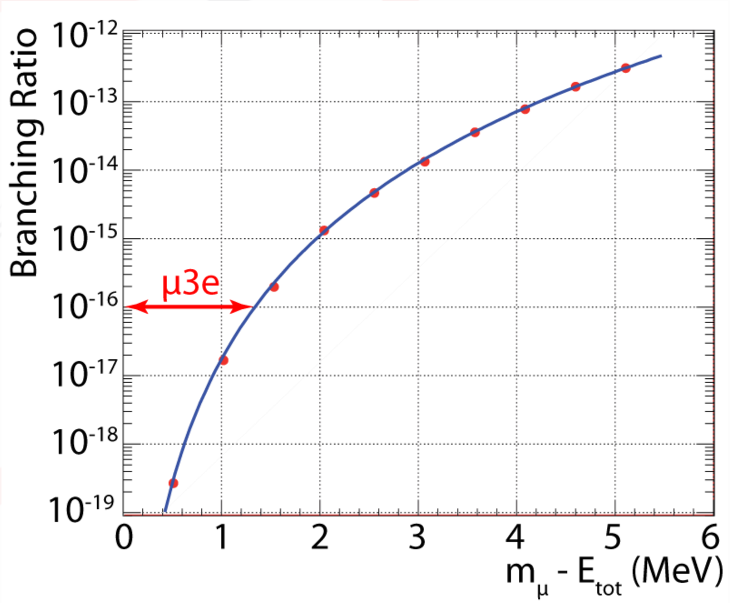
- Common vertex
- Coincident
- $\sum \vec{p} \neq 0$
- $\sum E \neq m_\mu$

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

Material budget constraints

Major background contribution

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



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

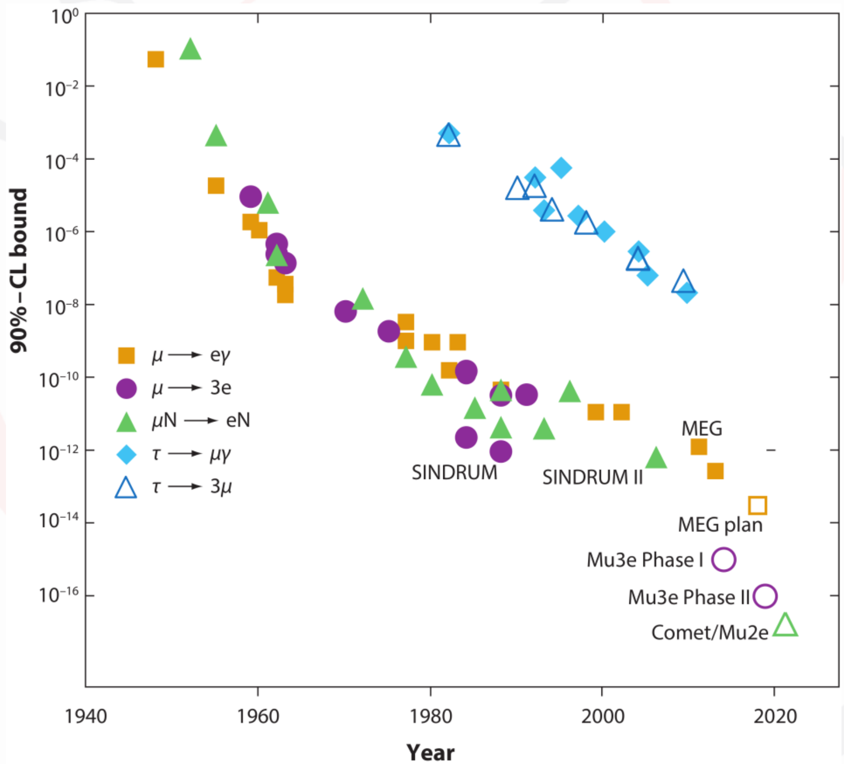
- Momentum resolution

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

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

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

History of CLFV Experiments



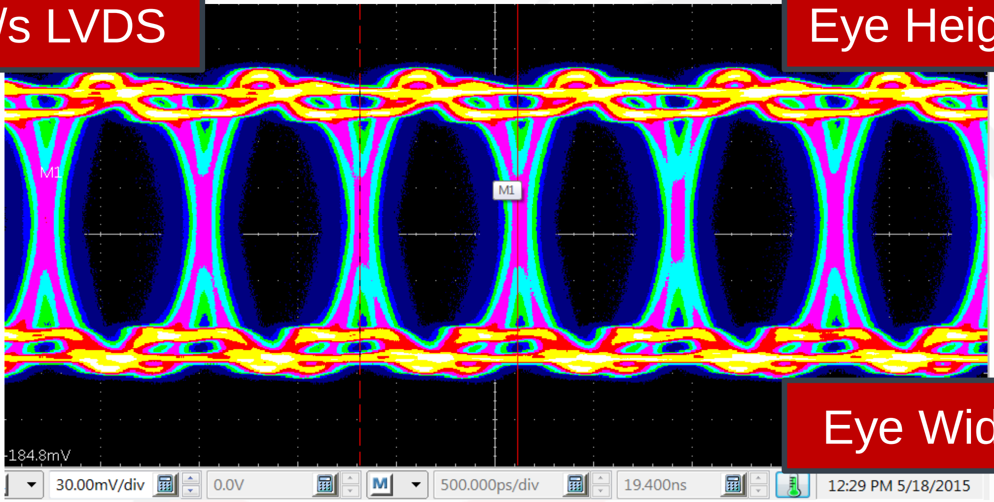
Updated from W.J Marciano et al., Ann.Rev.Nucl.Part.Sci. 58, 315 (2008)

Serial Readout of the MuPix7

1.25 Gbit/s LVDS

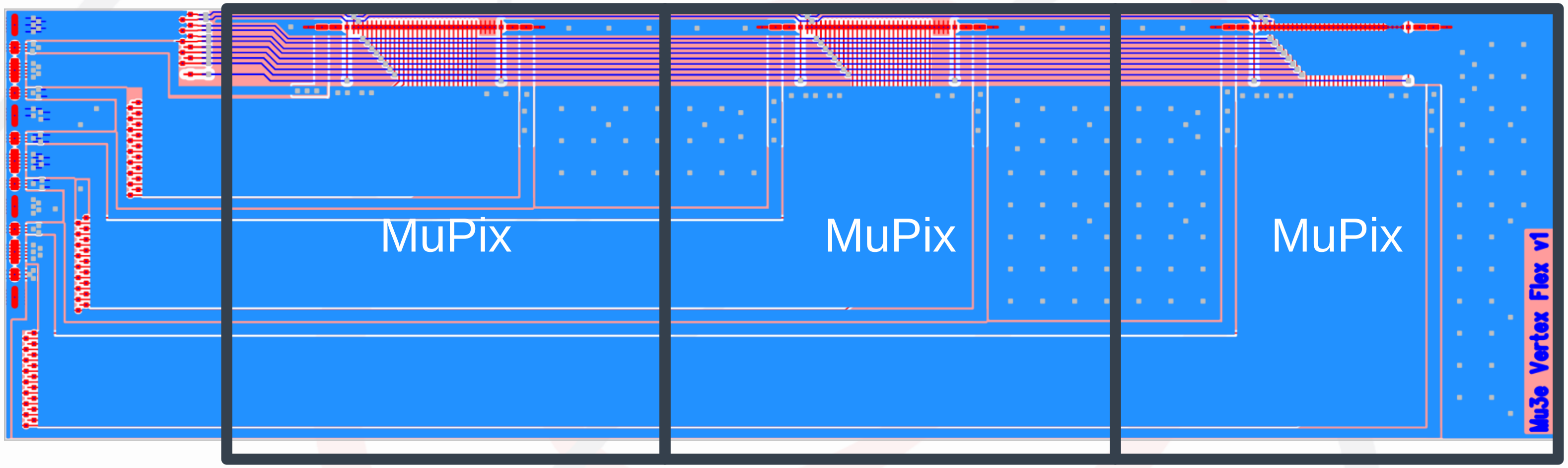
Eye Height > 100 mV

Eye Width > 0,65 UI

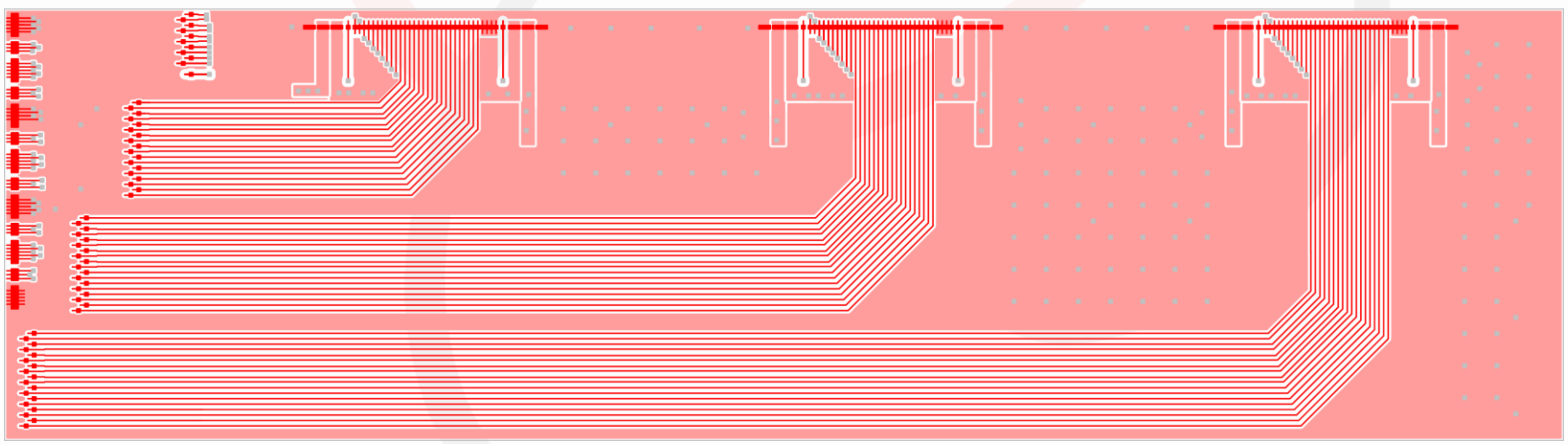


FPC design study – two layers

Composite View



Bottom Layer

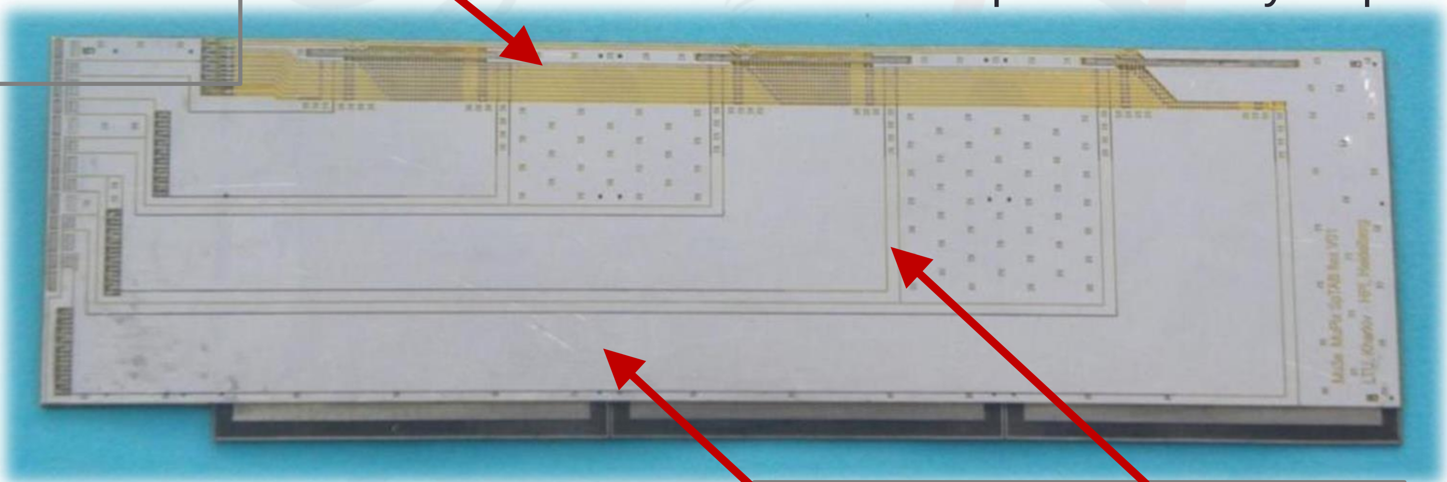


Inner detector – FPC design study

<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

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- Clock, reset
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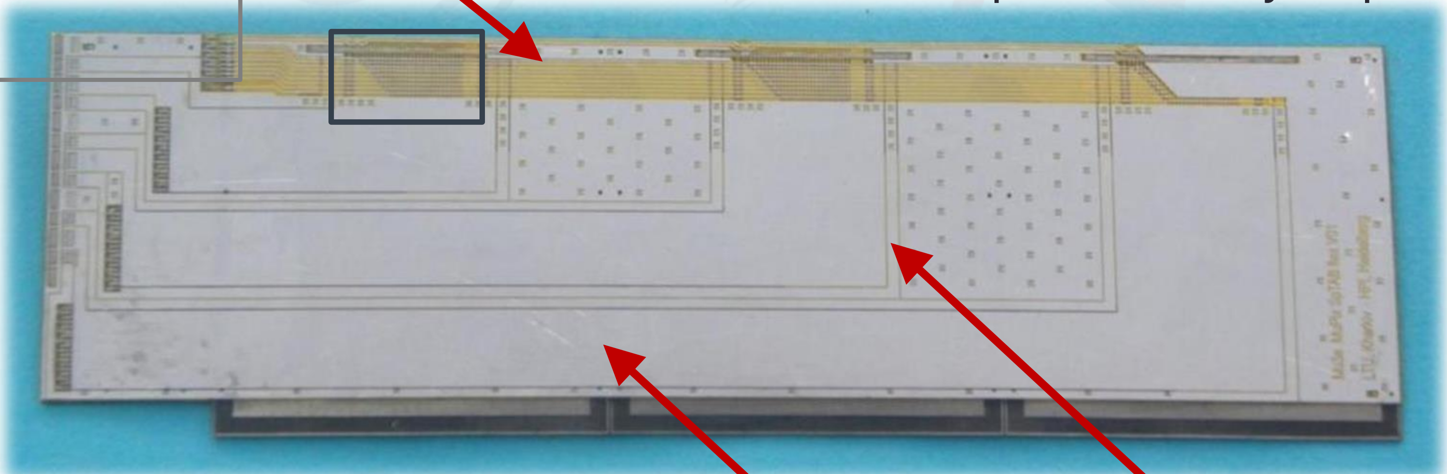

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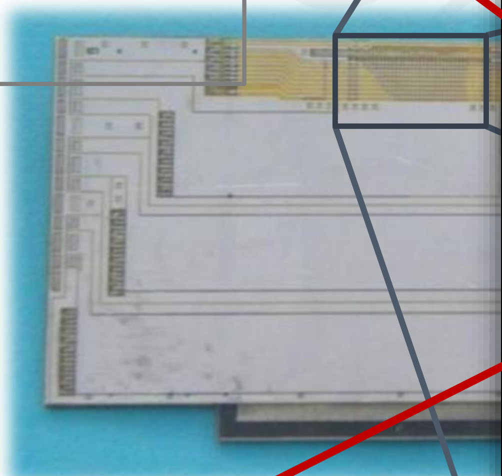
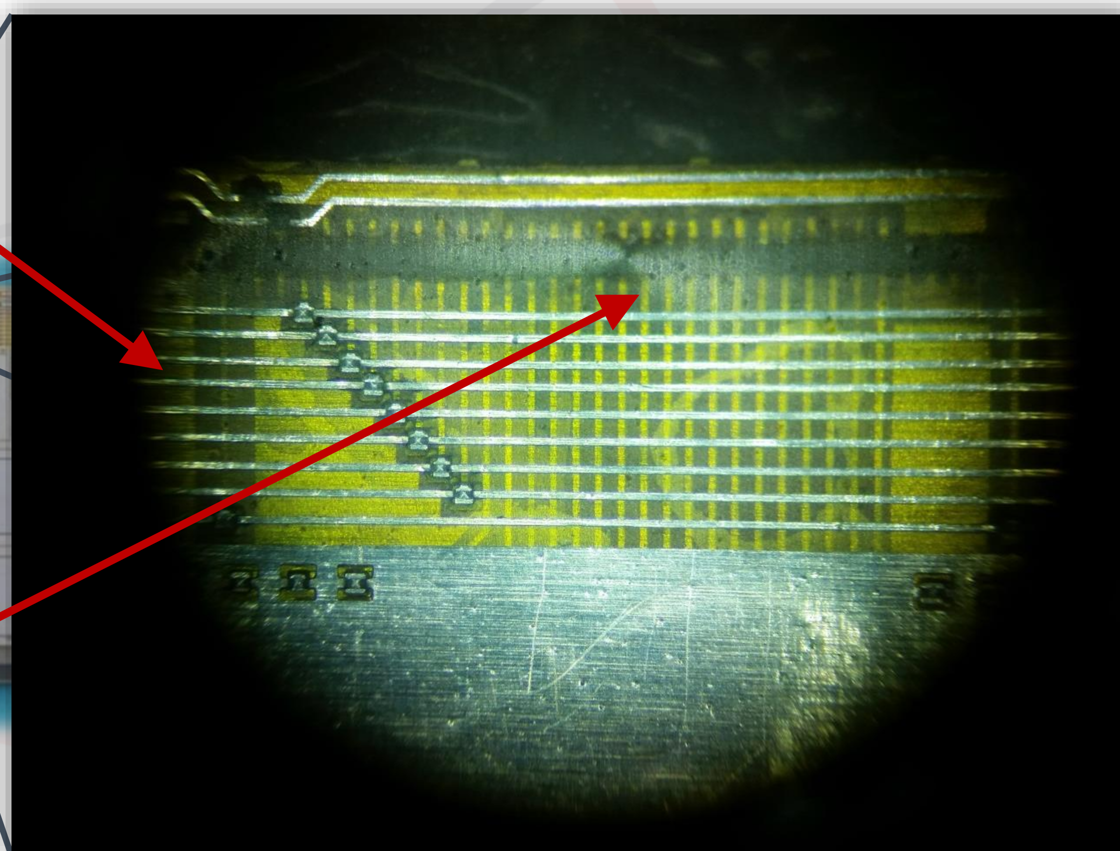




<u>Individual signals</u>

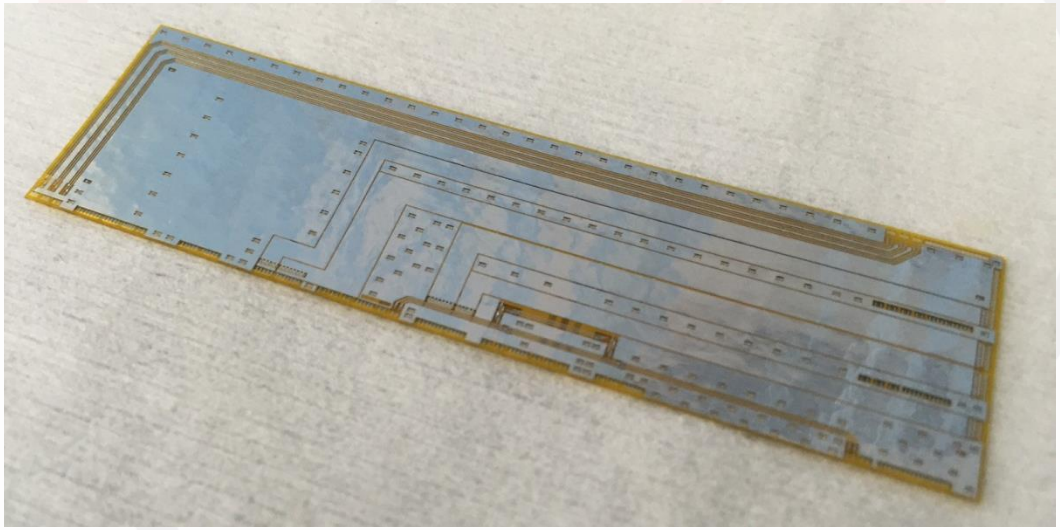
Up to 9 differential pairs per sensor

Estimated voltage differences between sensors below 50 mV

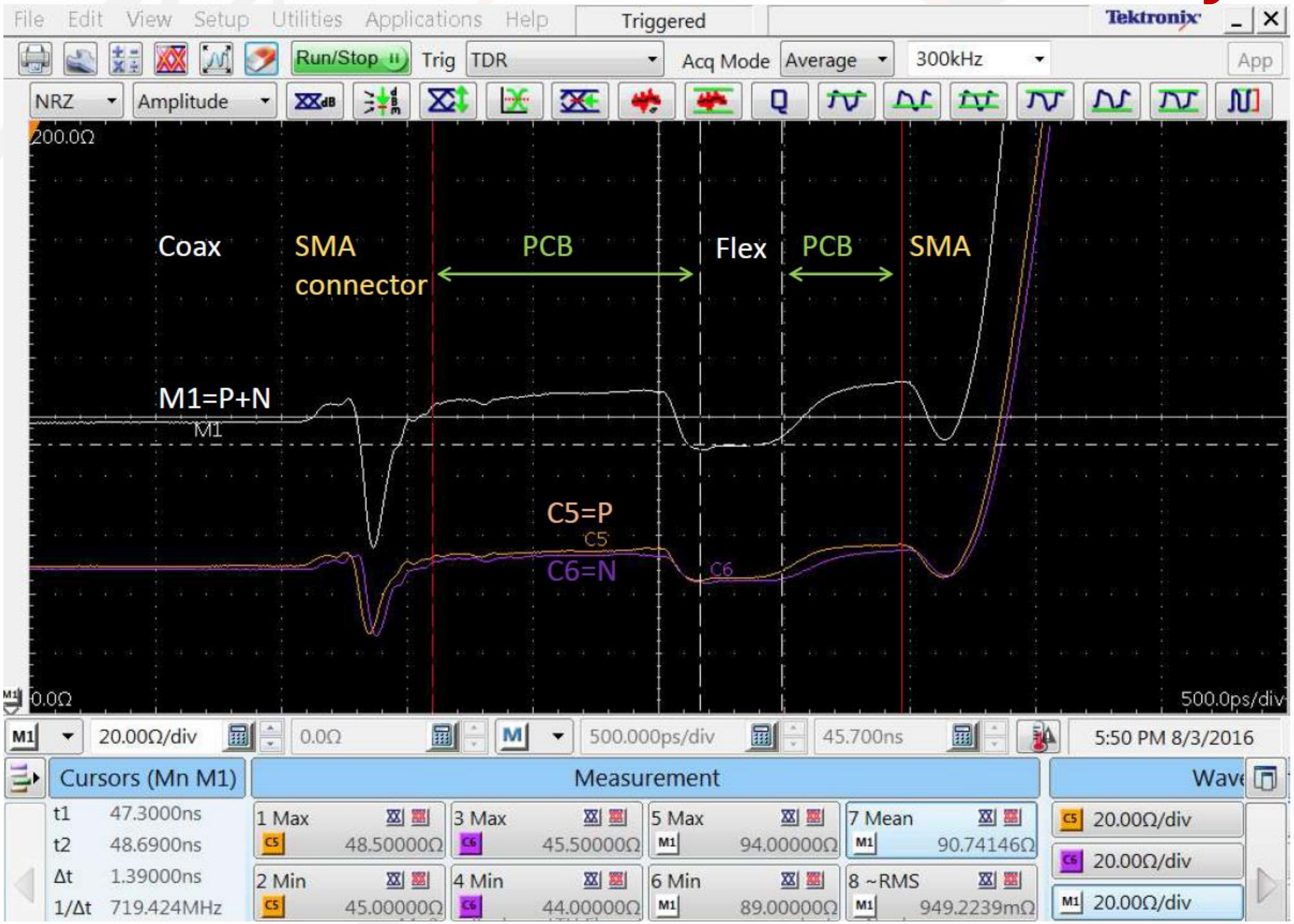
FPC feasibility studies – ongoing

<u>Two layer FPC with test structures</u>

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



FPC - Time Domain Reflectometry



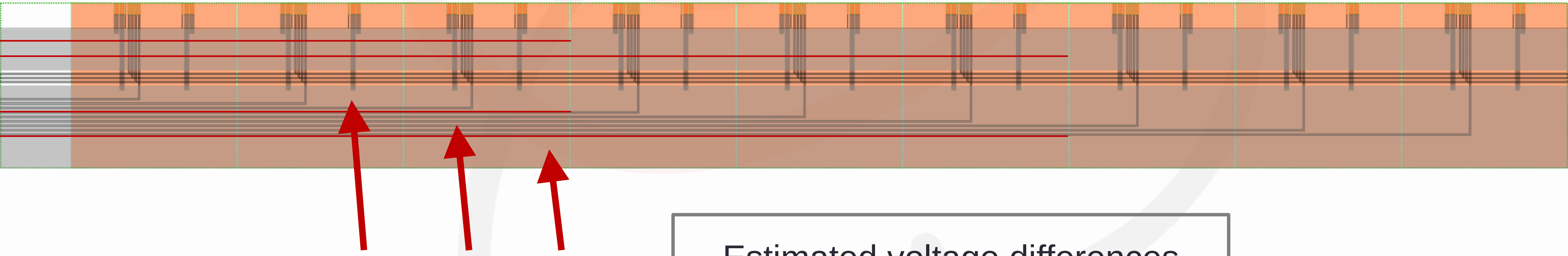
FPC - Time Domain Reflectometry

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

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

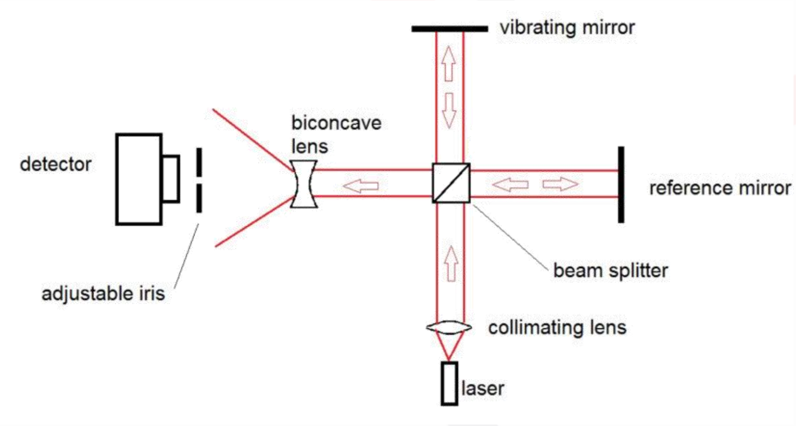


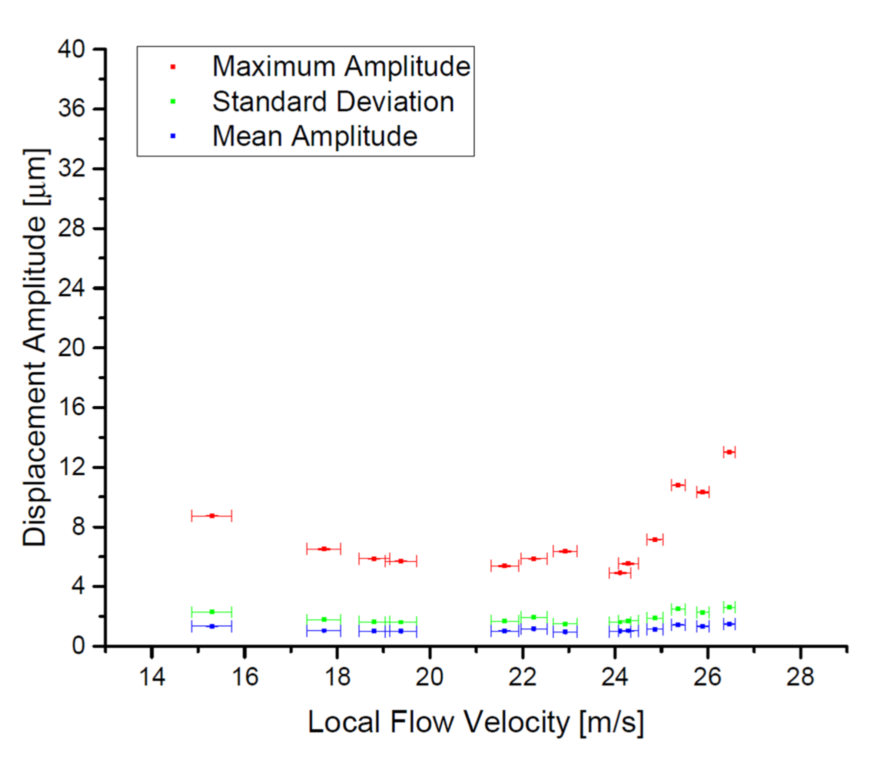
$U_1 < U_2 < U_3$

Estimated voltage differences between sensors around 10 mV

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