# Time Resolution of the Mupix8, a large HV-MAPS prototype

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## The Mu3e Experiment





- Search for cLFV decay  $\mu^+ \rightarrow e^+ + e^- + e^+$
- Mylar target stops  $\mu^+$
- $p_{max} = m_{\mu}/2$

- 1T magnetic field
- Gaseous helium cooling
- Pixel tracker 20 ns resolution
   + 50 µm thick





I.Peric, P. Fischer et al., NIM A 582 (2007) 87

- Deep n-well in p substrate
- Reversed biased diode
- Depletion zone as sensitive volume (20 - 30 μm)
- Charge collection via drift
- Thinning to  $\leq$  50 µm possible
- Amplifier in the analog pixel cell
- Readout and State Machine on chip
- Commercial HV-CMOS process

Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
MuPix	(8				

- First large HV-MAPS prototype for Mu3e
- $\blacksquare~19.5\times10.8~mm^2$
- $80 \times 81 \ \mu m^2$  pixel
- 200 × 128 pixel
- Amplifier in the analog pixel
- Digital partner cell in the periphery
- Production issues and bad yield



Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
	Deedeut				



- 3 submatrices with different line drivers
- $\rightarrow$  A with Source Follower
- $\rightarrow$  B+C with Current Driver

4 LVDS links with
 1.25 Gbit/s
 (A,B,C and copy or Mux)

Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Perfor	mance				

- Matrix A >99.5% efficient
- Low noise
- Sensors untuned







- Voltage signal driven from pixel to periphery
- Point to point connection
- Parallel lines cause capacitive coupling
- $\rightarrow$  Signal loss
- $\rightarrow$  Extra hits





Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
	o — II				
line (	ross lalk				

- Line cross talk can be measured at the analog pixel output
- Linear with line length
- Almost 20% at long lines



- Time resolution = σ of Gaussian fit to (hit TS - ref TS)
- MuPix8 has 8 ns time binning (10bit)
- 6bit Time over Threshold (ToT)
- Timewalk reduction circuits
- Only single hit clusters
- Source: Sr90
- Reference: Scintillator



Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Dela	γS				

- Hits have significant delays to the reference depending on the pixel position
- Line length + cross talk losses
- Power gradient
- DAC Settings
- Corrected by slanted plane fit





# Threshold Dependence

- Timing can be improved by reducing the timing threshold
- Limit by noise floor (Baseline @ 500 mV)
- Complete chip better than 7 ns
- Resolution < 6.25 ns possible





# Single Pixel Resolution



- Position dependent delay does not contribute
- Mean better than 6 ns
- Lower pixel in the matrix even better than 5 ns



# Current Mode Matrices

- Worse due to critical power and design issue
- Fully efficient and no cross talk
- Resolution worse but still within Mu3e specs
- Detailed efficiency studies planed



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## Current Mode Matrices - Single Pixel Resolution





- Gradient to top center
- Mean better than 11 ns
- Better than 8 ns possible

Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Summ	narv				

- MuPix8 first fully integrated large prototype for Mu3e
- Despite issues excellent performance (>99.5% efficient)
- Corrections improve time resolution significantly to ≈ 6 ns



Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary

Outlook

- MuPix10 submission planed this year
- Future R&D for Phase II
- Synergies with ATLAS R&D (ATLASPix)



**Pixel Matrix** 

**Pixel Periphery** 

Sub-Matrix Periphery Common Chip Periphery

# BACKUP







- Lepton flavor violated in the neutrino sector
- Charged LFV not observed so far

- νSM BR's for cLFV are immeasurable (O(< 10<sup>-50</sup>))
- Possible in BSM models via loops or tree level decays at measurable rates
- $\mu^+ \rightarrow e^+ + \gamma$  (MEG)
- $\mu + N \rightarrow e + N$ (Mu2e, Comet)
- $\mu^+ 
  ightarrow e^+ + e^- + e^+$  (Mu3e)

Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Mu3e	Decay				



- Search for the cLFV decay  $\mu^+ \rightarrow e^+ + e^- + e^+$
- $\nu$ SM BR  $\approx 2.1 \times 10^{-55}$
- Experimental limit: BR
   < 10<sup>-12</sup> (SINDRUM 1988)
- Planned sensitivity:
   2 × 10<sup>-15</sup>





- Background from Internal Conversion  $\mu \rightarrow eee\nu\nu$ (BR  $\approx 1.4 \times 10^{-5}$ )
- Suppression requires excellent momentum resolution



Djilkibaev, Konoplich (arXiv:0812.1355)

# Irradiation ATLAS\_pix

HV-MAPS

# Summary of Efficiencies after Irradiation

no tuning of pixels;

≤ 81/10000 pixel masked

Efficiency <sub>40 Hz</sub>	sub- thick- strate ness		bias voltage (#masked pixel)			
fluence (neq/cm²)	(Ω cm)	(µm)	60 V	70/75 V	80/85 V	90/95 V
n 2e15	80	62	98.5% (81)	98.4% (81)	98.6% (81)	
n 1e15	80	62	99.3% (38)		99.5% (38)	99.5% (39)
n 5e14	80	62	99.5% (19)			
n 2e15	200	100	96.5% (55)		98.7% (60)	98.7% (55)
n 1e15	200	100/725	98.7% (18)	99.4%	99.5%	99.4%
n 5e14	200	100	99.2% (14)			
p 5e14 (50 MRad)	200	100	≥ 99.6% (9)	≥ 99.7% (9)	≥ 99.9% (9)	
p 1e14 (10 MRad biased)	200	725	≥ 99.7%			

≥ means that the 40 Hz/pixel noise limit was not reached

Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Reticle					



~19.5 mm

#### 27.3.19





 Exploit kinematics in muon rest frame

$$\bullet \ \Sigma \vec{p} = 0$$

$$|p_e| \le \frac{m_\mu c}{2} \approx 53 \frac{MeV}{c}$$

Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Backg	rounds II				

- High beam rate  $(10^8 \mu^+/s)$
- Accidental Combinations
- Bhabha scattering
- Miss-reconstruction
- Detector resolution



Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Sensitiv	ity				



Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
<u> </u>					
Signal	+BG				





- Mu3eγ
- Search for Dark Photons
- Search for Familons
- $\pi^0 \rightarrow e^+ + e^-$  from factors







$$\theta_{ms} \propto \frac{\sqrt{x/X_0}}{p}$$
$$p_{max} \approx 53 \frac{MeV}{c}$$

- → Multiple Coulomb Scattering dominates resolution
- → Minimal material budget crucial



- Pixel layer:  $\approx 0.1\% X_0$
- Polyimide support structure
- Fiber tracker :  $\approx 0.3\% X_0$
- Gaseous helium cooling
- MS cancels after recurl

Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
A 1					
Analog	g Cell				



Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Digita					
Digita	i Celi				



Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary

# CM Transmission



- Constant current from digital to analog cell
- Signal is modulated as load on the current
- Apparently transistor forgotten
- Working point at the edge of the DAC space

Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Timing	Detectors				





- Timing detectors for charge ID and combinatorics
- Fibers: Hamamatsu S13552-HRQ SiPM (LHCb array)
- Tiles: Hamamatsu MPPC S13360-3050PE
- Both readout via custom ASIC (MuTrig)
- 32 Channel, 35mW/channel
- 650/1200kHz per channel
- 50 ps binning
- 1.25 Gbit/s LVDS link

Mu3e HV-MAPS MuPix 8 Performance Time Resolution Summary
Cross Talk and Cluster

- Cross talk only along column
- Can not be discriminated from clusters
- $\rightarrow$  Only single hit clusters analyzed



Custers removed





Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Amplif	ier				

- Amplitude does not depend on the row
- Amplifier linear over large range (Fe55(5.9 keV)  $\approx 250 \,\mathrm{mV}$ )
- Shaping can not be significantly improved





Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Variat	zions				



- Large fluctuations in efficiency
- Partially wafer correlated
- Reasons not entirely clear

Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
T:					



Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Setup					





Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
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Pixel	Mechanics				

- Thin polyimide support structure
- V-Folds for outer layers
- Additional cooling through V-Folds
- Power + Readout by Al-Polyimide laminate







Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Corre	ctions				



- Correct Delay first
- Then ToT correction
- ToT correction calculated from region without cross talk

**Delay Correction** ToT [64ns] entries 35 -5 0 5 10 Delay corrected Hit TS - Trigger TS [8ns] **Timewalk Correction** ToT [64ns] entries 35

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Time-Walk corrected Hit TS - Trigger TS [8ns]



- BC-408 Tiles (2 × 2 cm<sup>2</sup>) in reflective foil
- Hamamatsu MPPC S13360-3050CS
- Tile PCB with comparator
- Resolution ≈ 2 ns (coincidence)
- Sampled by the FPGA with 500 MHz
- Analysis in 8 ns (MuPix) base





Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
ТоТ					

- ToT is measured as difference between two timestamps
- Hit flag is raised on the rising edge
- $\rightarrow\,$  Hit can be read out before ToT is sampled
  - Problem can be reduced by slowing the State Machine down
  - Timewalk visible

### ToT of Fe55



Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Fitting					

- No track information
- $\rightarrow\,$  Correlate everything with everything
  - Clusters removed
  - Background by random coincidences
- $\rightarrow$  Triangle shape
  - Time Resolution given by the σ of the fit function:



$$f(x) = A \times (1023 - |x|) + B \times exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right)$$

Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Readout Sneed					



Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary

egend
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0	232-1-4 725 $\mu m$ unsorted 50V 200 $\Omega cm$	1.1	84-1-10 725 $\mu m$ 60V 80 $\Omega cm$ 1.8 V
•	232-1-4 725 $\mu m$ sorted 50V 200 $\Omega cm$		84-1-10 725 $\mu m$ 60V 80 Ωcm 1.8 V
0	265-1-3 62.5 $\mu m$ AE Off 50V 80 $\Omega cm$ 1.8V	0	84-1-10 725 μm 20V 80 Ωcm 1.8 V
•	265-1-3 62.5 $\mu m$ AE On 50V 80 $\Omega cm$ 1.8V	•	84-1-10 725 $\mu m$ 40V 80 $\Omega cm$ 1.8 V
•	265-1-3 62.5 $\mu m$ AE On 50V 80 $\Omega cm$		84-1-10 725 μm 60V 80 Ωcm 1.8 V
	265-1-3 62.5 μm AE Off 15V 80 Ωcm		FEB 1k Ωcm
	265-1-3 62.5 $\mu m$ AE Off 50V 80 $\Omega cm$	0	84-3-8 62.5 μm AE Off 50V 80 Ωcm
	84-3-25 100 $\mu m$ AE Off 05V 200 $\Omega cm$	0	84-2-3 725 μm 60V 80 Ωcm
•	84-3-25 100 $\mu m$ AE Off 15V 200 $\Omega cm$	•	84-2-6 725 $\mu m$ sorted 50V 80 $\Omega cm$
•	84-3-25 100 $\mu m$ AE Off 50V 200 $\Omega cm$	0	84-2-6 725 $\mu\text{m}$ muxed 50V 80 $\Omega\text{cm}$
0	84-3-25 100 μm AE On 50V 200 Ωcm		

Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Cluste					
Cluste	r				









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#### 

80

60

40

20

0

# 1 Hit Cluster A 2 Hit Cluster A 1 Hit Cluster B

60

40

20

40

column / pixel



### 2 Hit Cluster B



20 30



10

10-1

row







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Mu3e	HV-MAPS	MuPix 8	Performance	Time Resolution	Summary
Cluster					

### Single



## Triple



### Double



### Quadruple

