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The MuPix Monolithic Active Pixel Sensor for the Mu3e Experiment

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Abstract:

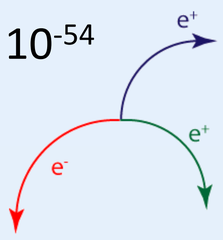
Mu3e is a novel experiment searching for charged lepton flavor violation in the rare decay μ→eee. In order to reject both combinatorial and physics background, decay vertex position, time and particle momenta have to be precisely measured.

A pixel tracker based on 50 μm thin high voltage monolithic active pixel sensors (HV-MAPS) in a magnetic field will deliver precise vertex and momentum information. The novel MuPix HV-MAPS chip developed for the Mu3e pixel tracker has been thoroughly tested in the laboratory and at test beams.

These measurements give evidence of very good detection efficiency well above 99%, a signal to noise ratio of better than 20, good spatial resolution and sub 20 ns time resolution for single pixel hits. High rate tests have shown that the MuPix chip can be read out at event rates of over one MHz.

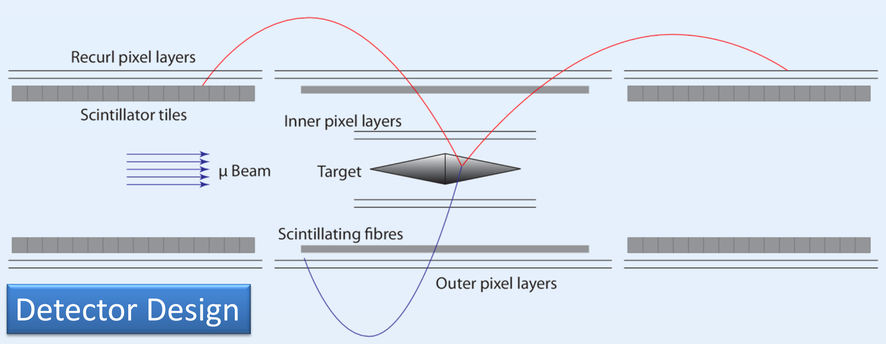
Mu3e Signal:

- Decay μ→eee at rest
- Standard Model BR < 10^{-54}
- Single vertex
- Coincident in time
- $\sum \vec{p_i} = 0$

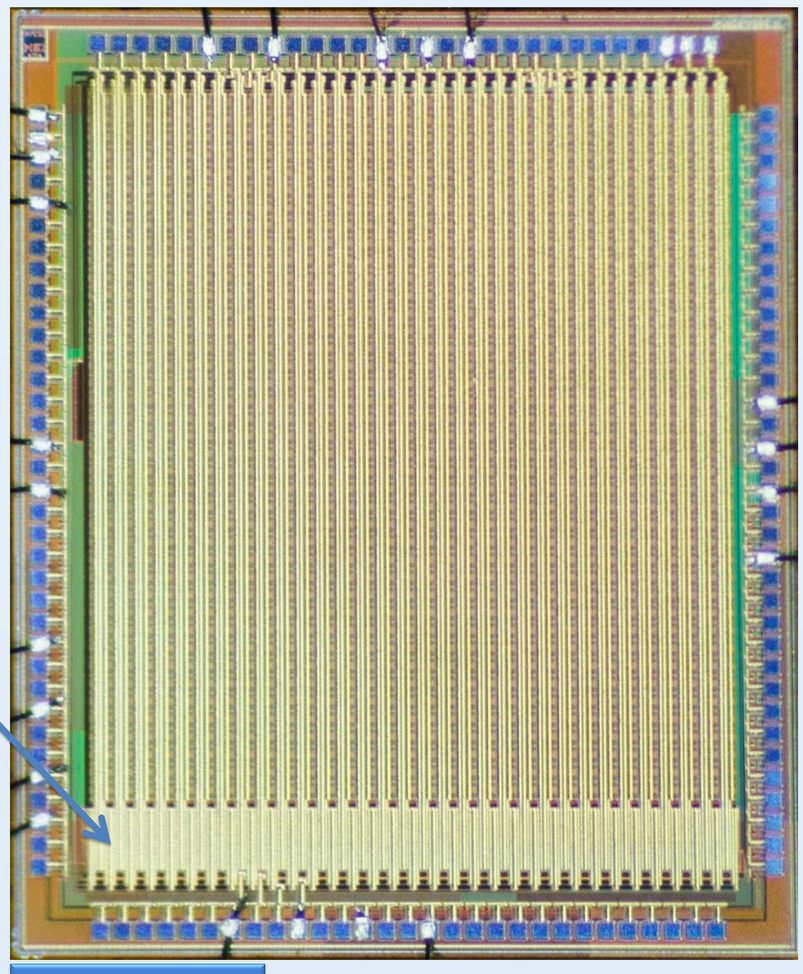


Challenges:

- **High rates**
- **Great vertex resolution**
- **Precise timing resolution**
- **Excellent momentum resolution**
- **Extremely low material budget**



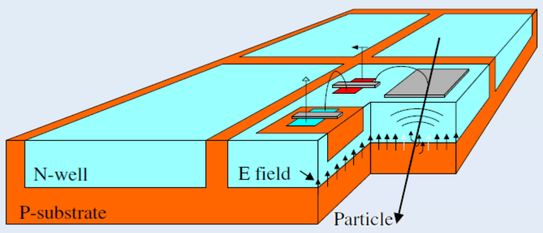
Detector Design



MuPix Prototype

HV-MAPS:

- **H**igh **V**oltage **M**onolithic **A**ctive **P**ixel **S**ensors combine advantages of:
  - Fast hybrid pixel detectors
  - Thin monolithic active pixel sensors (MAPS)
- Analog and digital electronics integrated
- First stage amplifier inside the pixel
- ➢ Good signal to noise ratio
- Compact digital readout logic placed below the pixel matrix
- Reduced digital crosstalk
- High voltage (≈ 50 V)
  - ➢ Small depletion zone (≈10 μm)
  - ➢ Fast charge collection within 1 ns
- Most of substrate passive
  - ➢ Wafer can be thinned to < 50 μm



Ref.: I. Peric, A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology Nucl.Instrum.Meth., 2007, A582, 876

Mu3e Detector Concept:

Long Tube:

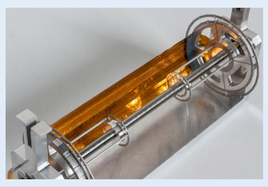
- Long (~2 m) detector for high acceptance of recurling particles
- Only central ~25 cm needs to be thin
- ➢ Simplifying mechanics
- ➢ Precise timing in thick scintillator tiles

Target:

- Double cone target
- 30 μm to 80 μm Al
- Large area for good vertex separation

Mechanics:

- Sensors supported on 25 μm thick Kapton™
- Signal and power traces printed in Aluminum:
- ➢ Extremely light and surprisingly sturdy



Timing:

- 250 μm Ø scintillating fibres in central region
- ➢ First timing measurement
- Precise timing from ~1 cm thick scintillating tiles in the recurl tubes

Pixel Sensor:

- **80x80 μm²** pixels
- Sensor ladders 2×6 cm² or 1×6 cm²
- Thinned to **50 μm**
- Pixel layer ~ **1 ‰ of X_0**
- **~300 million pixels**
- Cooled by helium atmosphere
- Readout frequency ~20 MHz
- Binary readout

Readout:

- Triggerless readout with ~ 100 Gbyte/s to an online farm
- Fast track finding and reconstruction on GPUs (>10^9 tracks/s)
- Reduction to ~ 100 Mbyte/s for online storage and analysis

MuPix:

- High voltage monolithic active pixel sensor for Mu3e
- 80x80 μm² pixel size
- Total area of
  - 1×2 cm² for the inner pixel layers
  - 2×2 cm² for the outer pixel layers
- Sensors thinned to 50 μm
- Full analog and digital readout electronics integrated:
  - Each hit is converted on-chip into pixel address and time-stamp
  - Zero suppressed data sent through 1-4 serial LVDS output links at >800Mbit/s
- Chip prototype MuPix4 has
  - 32x40 pixels of size 80x92 μm²
  - Single stage amplifier for each pixel
  - ➢ Second amplification stage implemented from MuPix6 on
  - Full digital readout at >1 MHz event rate
  - Readout state machine running on an external FPGA
- ➢ New version including on-chip readout logic submitted

Test Beams:

Test beam campaigns for the MuPix prototypes:

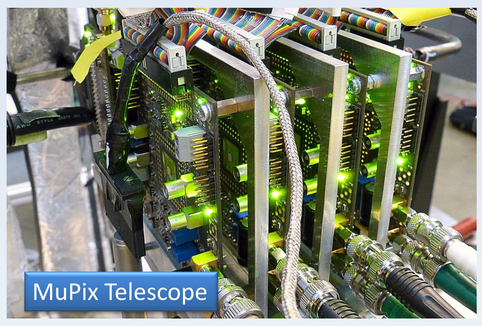
- 170 GeV SPS π-beam at CERN
- 5 GeV DESY electron beam
- 225 MeV π-beam at PSI

DESY test beam setup based on:

- One MuPix4 chip read out by a FPGA on an adjacent PCB
- Track information given by Aconite beam telescope based on MIMOSA

New **telescope** based on the MuPix chip built and tested

MuPix Setup at DESY



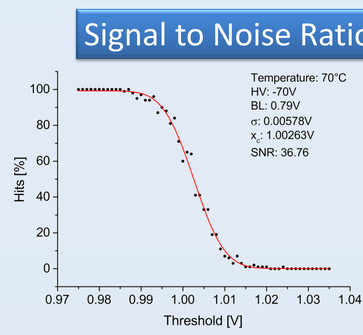
MuPix Telescope

MuPix Performance:

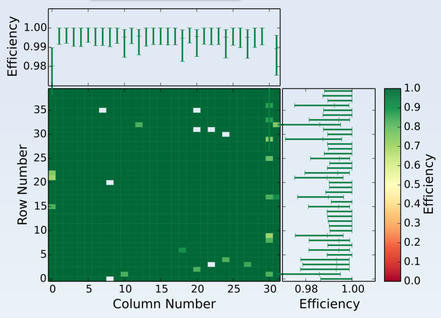
MuPix4 prototype performance studies at DESY 5 GeV electron test beam and with Aconite beam telescope:

- Electron detection **efficiency** above **99%**
- Hit resolution given by pixel cell size
- Pixel hit **time resolution** below **17ns**
- Laboratory measurements give **S/N of >20**

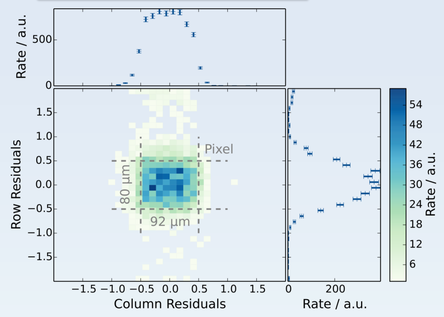
Signal to Noise Ratio



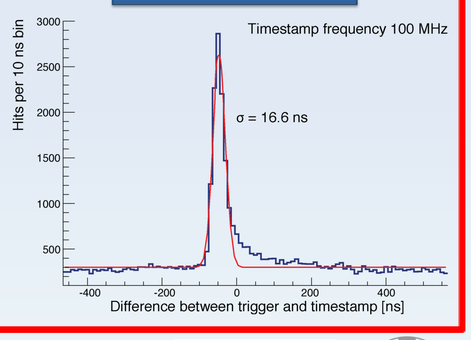
Efficiency



Spatial Resolution



Time Resolution



www.psi.ch/mu3e