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# The MuPix high voltage 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 $\mu \to eee$. In order to reduce background by up to 16 orders of magnitude, decay vertex position, decay time and particle momenta have to be measured precisely. A pixel tracker based on 50 $\mu$m thin high voltage monolithic active pixel sensors (HV-MAPS) in a magnetic field will deliver precise vertex and momentum information. Test beam results like an excellent efficiency of $> 99.5\%$ and a time resolution of better than 16.6 ns obtained with the MuPix HV-MAPS chip developed for the Mu3e pixel tracker are presented.

KEYWORDS: Electronic detector readout concepts (solid-state); Particle tracking detectors (Solid-state detectors)

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## Contents



## 1 The Mu3e experiment

The Mu3e experiment [1, 2] aims at measuring the rare charged lepton flavor violating decay $\mu^+ \to e^+e^-e^+$, which is highly suppressed in the standard model to a branching ratio (BR) $< 10^{-54}$. This means that an observation of the decay $\mu^+ \to e^+e^-e^+$ is a clear indication for new physics beyond the standard model. The goal of the Mu3e experiment is to search for $\mu \to eee$ events with a branching fraction sensitivity of $10^{-16}$ while the most successful previous experiment established an exclusion limit of BR $< 10^{-12}$ (90% CL) [3]. In order to achieve this precision in a few years of running, the decay of muons at rest has to be studied at rates of $10^9$ per second or more. Background comes from two main sources, which are combinatorial background and the radiative muon decay with internal conversion $\mu \to eee\nu\nu$. In order to discriminate between combinatorial background and the $\mu \to eee$ signal, precise vertex and timing information is required. Background from the decay $\mu \to eee\nu\nu$ can be suppressed by measuring the momentum sum of the decay products, since part of the momentum is carried away by the neutrinos. As the maximum momentum of positrons and electrons from the muon decay at rest is 53 MeV/c, the vertex position and the momentum measurement precision is dominated by multiple Coulomb scattering [4].

## 2 Detector concept

The Mu3e detector is designed as a cylindrical tube around a hollow double cone shaped muon stopping target, see figure 1. Around the target there are two layers of pixel vertex detectors, which help to measure the vertex positions [5]. Two more pixel tracker layers are further outside and allow for momentum measurement in the 1 T magnetic field. The outer two layers of the pixel detector are extended both upstream and downstream of the target. All pixel sensors have a pixel size of $80 \times 80\,\mu\text{m}^2$ and are arranged in sensor ladders. The full tracking detector has about 275

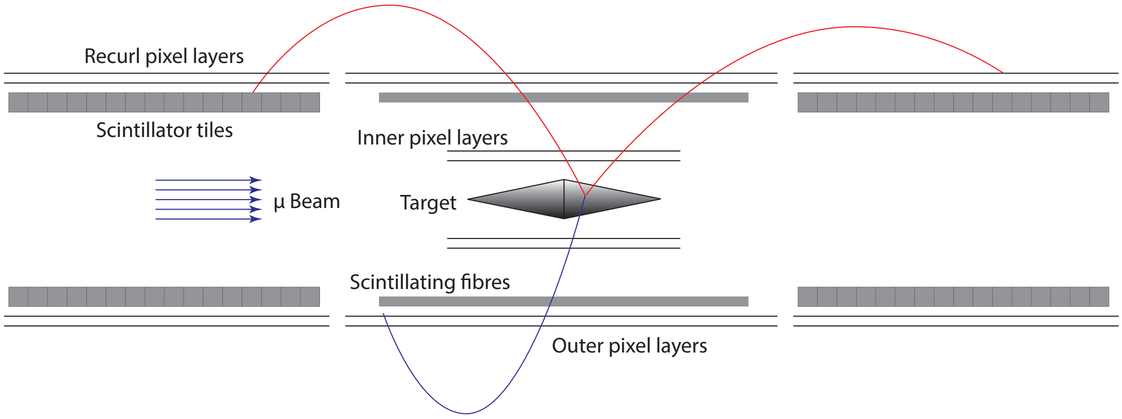


**Figure 1**. Mu3e detector with signal event: the muon beam hits a fixed target in the center and a stopped positive muon decays into two positrons (red) and one electron (blue). The vertex is determined by two inner pixel tracker layers, which are surrounded by a fiber hodoscope for time and two further pixel tracker layers for momentum measurement. In the forward and backward region the momentum and time of the re-curling electrons and positrons are more precisely determined with two more tracking stations and scintillating tile detectors.

million pixels. Since the pixel chips are thinned to 50 μm, one layer of the tracking detector has only 0.1% of a radiation length [6]. The thin pixelated tracking detectors allow for precise measurement of the vertex position and momenta of the charged particles, with a vertex resolution better than 200 μm [7, 8]. The momentum resolution is enhanced by measuring the charged particle tracks with the help of the outer two double layers of the pixel detector before and after curling in the magnetic field. In case of an exact half turn between exiting and entering the two outer double layers multiple Coulomb scattering effects cancel to first order, leading to a momentum resolution of well below 0.5 MeV/c. In addition to the pixel detector, two timing systems help to reject combinatorial background. The first timing detector is a fiber tracker which is positioned just inside the third layer of the central tracking station. With three layers of 250 μm thick fibers, it can measure the time of particle tracks with an accuracy of better than 1 ns [9, 10]. The second timing system is based on scintillating plastic tiles of $8.5 \times 7.5 \times 5\,\mathrm{mm}^3$ size [11–13]. This tile detector is placed inside the up- and downstream extensions of the pixel detector. Charged particles traversing the tile detector generate in the order of 1000 photons, which are used for precise time measurement of better than 100 ps accuracy.

The Mu3e detector has a trigger-less 100 GB/s readout to an event filter farm [14–18]. Fast online track finding and reconstruction on the graphical process units (GPUs) of the event filter farm allows data reduction to around 100 MB/s for online storage and analysis.

## 3 High Voltage Monolithic Active Pixel Sensors

The High Voltage Monolithic Active Pixel Sensors (HV-MAPS) [19–21] combine the advantages of fast hybrid pixel detectors and thin monolithic active pixel sensors (MAPS). The HV-CMOS technology in which the HV-MAPS are fabricated allow to integrate analogue and digital readout electronics in the same die as the silicon sensor. Figure 2 shows four pixel cells of a HV-MAPS

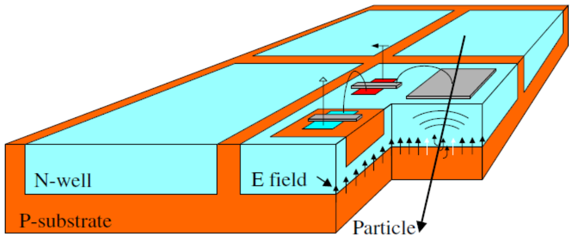


**Figure 2**. Working principle of a high voltage monolithic active pixel sensor (HV-MAPS).

sensor. A deep N-well on a P-substrate accommodates both P- and N-type transistors. Applying a reverse bias voltage of 60 V results in a depleted region of around 10 µm thickness. The charge produced by passing ionization in this active layer is collected via drift in less than 1 ns. Since the first amplification stage is on top of the active region inside the pixel, the input capacitance and with it the noise can be kept low. The HV-MAPS chips can be thinned to 50 µm without compromising the performance and thus make ultra low material budget tracking detectors possible.

## 4 The MuPix HV-MAPS chip

The MuPix chips are high voltage monolithic active pixel sensors for the Mu3e pixelated tracker [22, 23]. While the single pixel size is $80 \times 80\,\mu\text{m}^2$, the entire sensor chip measures around $1 \times 2\,\text{cm}^2$ for the inner pixel layers and $2 \times 2\,\text{cm}^2$ for the outer pixel layers. To keep multiple Coulomb scattering low, the sensors are thinned to 50 µm. Analogue and digital readout electronics are integrated on the MuPix chips, see figure 3. Every hit is converted on-chip into a pixel address and an 8-bit time stamp. This zero suppressed data is serialized and output via 1 to 4 LVDS links at rates of 0.8 to 1.25 GB/s each.

The chip prototype MuPix4 has $32 \times 40$ pixels of $80 \times 92\,\mu\text{m}^2$ size. Inside the pixel cells there is a single stage amplifier. MuPix4 has a digital zero suppressed readout electronic supplying pixel address and time stamp on parallel outputs, which runs stably at hit rates in excess of 1 MHz. The readout state machine of MuPix4 is running on an external FPGA. A second amplification stage is implemented from MuPix6 prototype on, in order to enlarge the efficiency plateau. The latest version of the MuPix chip, MuPix7, with the complete system on a chip (SoC), including on-chip readout control and a fast data serializer has been submitted recently.

## 5 Test beams

Test beam campaigns carried out to characterize the MuPix chip prototypes were performed at a 170 GeV $\pi$ beam at CERN SPS, a 5 GeV electron test beam at DESY and a 250 MeV $\pi$ beam at PSI [24]. The test setup used for the DESY test beam is based on the MuPix4 prototype, together with a FPGA based readout card directly plugged onto the MuPix4 test board, see figure 4 left side. The MuPix chip was characterized in the device under test position inside the Aconite beam telescope, using three upstream and three downstream layers of MIMOSA26 pixel sensors as reference planes. The MIMOSA26 consists of 576 by 1152 pixels with a pitch of 18.5 µm thinned to 50 µm. The resulting pointing resolution makes sub-pixel details of the MuPix prototypes accessible.

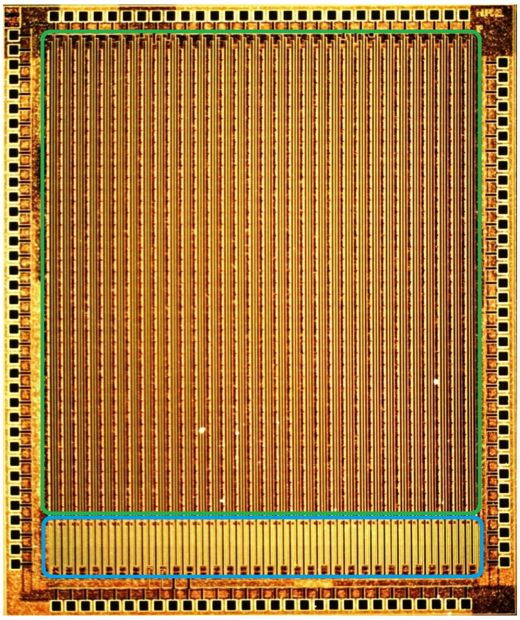

**Figure 3**. MuPix4 HV-MAPS prototype, the pixel matrix is marked in green, the digital part is marked in blue.

**Figure 4**. Test beam setups for the MuPix chip. *Left side*: MuPix4 test setup used in the DESY test beam October 2013. *Right side*: MuPix-telescope consisting of 4 planes equipped with MuPix6 prototypes.

As a next step a four layer beam telescope purely based on the MuPix chip prototypes has been developed and successfully tested [25], see figure 4 right side.

## 6 MuPix performance

The signal to noise ratio has been studied for various temperatures and high voltage settings in the laboratory. The signal for this study was injected with the help of a pulse generator, the pulse height was calibrated with a $^{55}$Fe source. A threshold scan for the MuPix4 chip with these pulses was carried out at a high-voltage of $-70$ V and a temperature of 70 °C, see figure 5 left side. By fitting an s-curve to this scan, taking the 50% point and subtracting the baseline voltage of 0.780 V, the voltage corresponding to the $^{55}$Fe signal can be determined. A second threshold scan without

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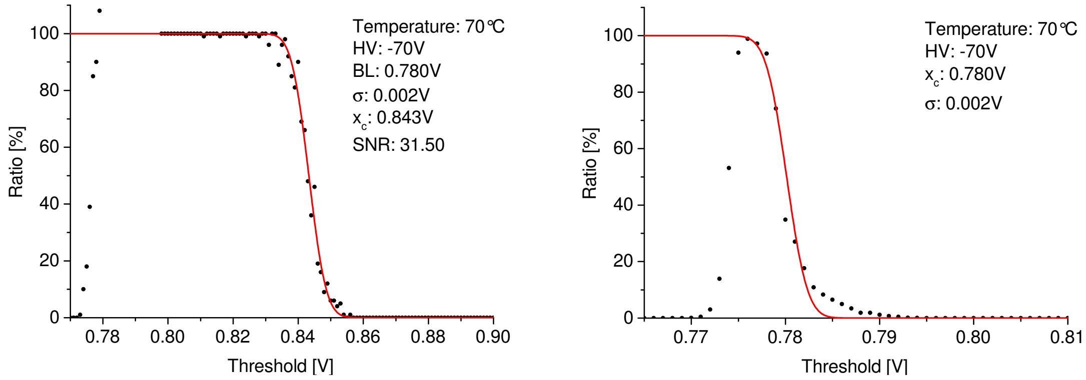


**Figure 5**. Signal to noise ratio of the MuPix4 prototype. *Left side*: threshold scan with injected pulses, signal is defined by the 50% point of the s-curve. *Right side*: threshold scan without injection, noise is defined by the 50% point of the s-curve.

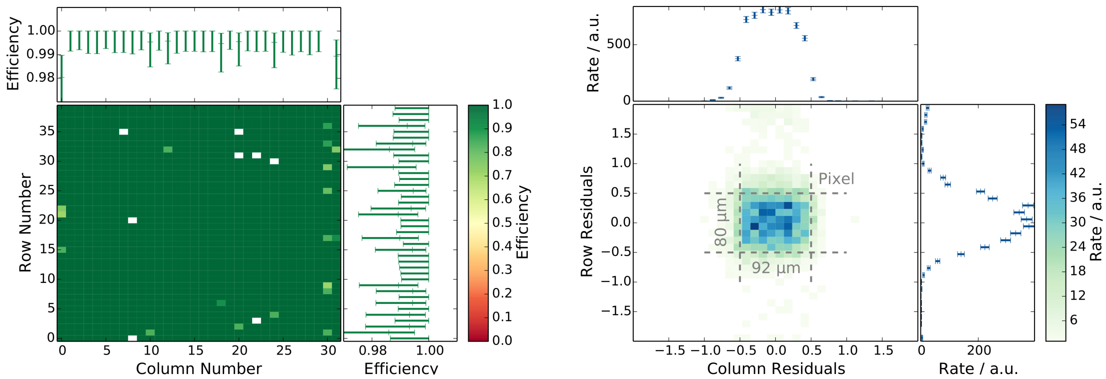


**Figure 6**. Performance of the MuPix4 prototype for 5 GeV electron tracks. *Left side*: detection efficiency. *Right side*: pixel cell track residuals in units of the pixel pitch.

injection was fitted with an s-curve and the 50% point minus the baseline is used to determine the noise, see figure 5 right side. The signal to noise ratio from this measurement was 31.5.

Efficiency, spatial resolution and time resolution have been investigated with the help of the 5 GeV electron beam at DESY and the Aconite beam telescope as a reference tracking system. After careful alignment to sub-micron precision with the help of the EUDET telescope software, the detection efficiency for electron tracks has been determined. Figure 6 left side shows the efficiency of the MuPix4 prototype at a depletion voltage of $-70$ V. The average efficiency of the MuPix4 chip is 99.672 ($-0.068$ $+0.060$)%. For the same data, the spatial resolution of the MuPix4 pixel, which are $80 \times 92\,\mu\text{m}^2$ in size, has been determined, see figure 6 right side. The resolution is dominated by the pixel size as expected. The pixel time stamp resolution was studied in the DESY electron test beam by taking the difference between trigger time stamp and MuPix4 pixel time stamp, see figure 7, right side. The 8-bit MuPix4 time stamp is generated with the help of a Gray counter running at 100 MHz, the trigger time stamp stems from the Trigger Logic Unit (TLU) of the Aconite beam telescope. The distribution of the time difference between the pixel time stamps of the MuPix4 chip and the TLU time stamps has a width of $\sigma = 16.6$ ns, setting an upper limit to

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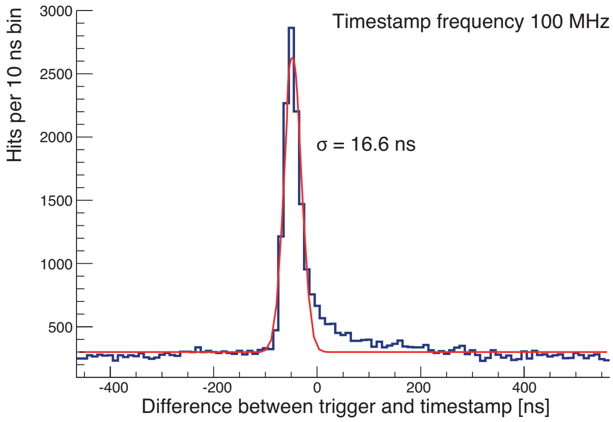


**Figure 7**. Time difference between MuPix4 time stamps and the Trigger Logic Unit (TLU) for 5 GeV electron tracks averaged over all pixels.

the actual single pixel time stamp resolution. While this time resolution measurement is based on an average over time stamps of all pixels of the MuPix4 chip, the resolution for a single pixel is expected to be better. For both efficiency and time resolution further improvements are expected by applying per pixel threshold tuning.

## 7 Summary and outlook

The Mu3e experiment is aimed at measuring the branching ratio of the charged lepton flavor violating decay $\mu \rightarrow eee$ with a sensitivity of $\text{BR} < 10^{-16}$. In order to suppress background, precise timing, good vertex and momentum resolution are required. The detector is based on two timing systems and an ultra light pixelated silicon tracker around a muon stopping target in a 1 T solenoidal field. In total the Mu3e detector has 275 million pixels of $80 \times 80\,\mu\text{m}^2$ size. The pixel sensors for Mu3e, MuPix, are implemented as high-voltage monolithic active pixel sensors (HV-MAPS), which combine fast charge collection via drift, in-pixel analogue electronics and on-chip digital readout electronics with a total thickness of 50 µm. The MuPix4 prototype has been extensively tested in the laboratory and at test beam campaigns. A signal to noise ratio at $-70$ V and 70 °C of 31.5 has been measured in the laboratory. Test beam studies with the 5 GeV electron beam at DESY have resulted in an average pixel efficiency of 99.672 ($-0.068$ $+0.060$)%, a hit resolution given by the cell size of $80 \times 92\,\mu\text{m}^2$ and an upper limit of the pixel time resolution of $\sigma = 16.6$ ns.

A telescope based on four planes of MuPix chips has been developed and successfully tested and a first MuPix chip with the complete system on a chip has been submitted. The production of a large $1 \times 2\,\text{cm}^2$ sized MuPix chip is planned for next year.

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