(ANPA Conference 2024) Research Article ©Nepal Physical Society
ISSN: 2392-473X(Print), 2738-9537 (Online) DOI: https://doi.org/10.3126/jnphyssoc.v10i1.72837

High-Voltage Monolithic Active Pixel Sensors Based Tracker for the Mu3e Experiment

Shruti Shrestha[a)]

Penn State Brandywine, 25 Yearsley Mill Rd, Media, PA 19063.

[a)] *Corresponding author: sxs1700@psu.edu*

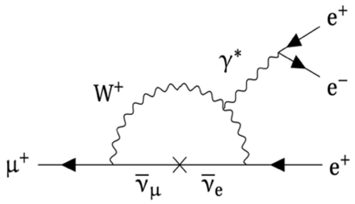
Abstract. The Mu3e experiment is searching for the decay $\mu^+ \to e^+e^-e^+$, which involves a violation of charged lepton flavor. The goal is to achieve a branching fraction sensitivity of four orders of magnitude higher than existing limits. To accurately measure the momentum and vertex position of low momentum electrons (10-53 MeV/c) produced by this rare decay, a tracking detector made from High-Voltage Monolithic Active Pixel Sensors (HV-MAPS) has been used. The MuPix7 chip has an HV-MAPS architecture and is manufactured using 180 nm High Voltage CMOS (HV-CMOS) technology. HV-MAPS are preferred due to their ability to be thinned to 50 μm, tolerance to radiation, high time resolution, and cost-effectiveness.
Additionally, to minimize the material used, the pixel readout electronics are embedded inside the sensor chip, supported by a low-mass mechanical structure built with 25 μm Kapton foil. The MuPix7 chip is the first HV-MAPS prototype that implements all functionalities of the final sensor, including a readout state machine. Based on a high-rate test beam, the it has a particle detection efficiency of 99% and meets all the requirements for a small-scale prototype.

Received: August 25, 2024; **Revised**: October 14, 2024; **Accepted**: October 23, 2024

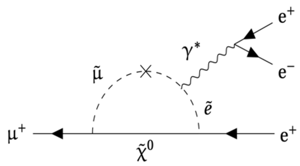
Keywords: Mu3e ; HV-MAPS ; MuPix; HV-CMOS

INTRODUCTION

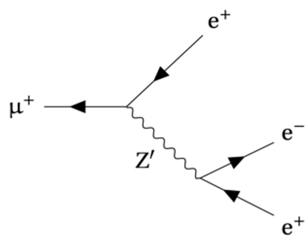
The mu3e experiment searches for physics beyond the Standard Model (BSM) via lepton flavor violating decay $\mu^+ \to e^+e^-e^+$. In the Standard Model (SM), lepton flavor is a conserved quantity. While in the neutrino sector, lepton flavor violation (LFV) has been observed in neutrino mixing [1–3]. The SM has to adapt to incorporate massive neutrinos; hence, LFV is also expected in the charged lepton sector. However, as the exact mechanism of charged LFV are unknown, its study is of great interest because it is associated with neutrino mass generation, CP violation, and new physics beyond the SM. The LFV muon day can occur via neutrino mixing in a loop, as shown Figure 1a. The branching fraction of this process is directly proportional to the factor $\frac{\Delta m^2}{M_w^2}$, where Δm^2 is the neutrino mass squared difference and M_w^2 is the W boson mass. Due to the minimal value of Δm^2 compared with the electroweak mass scale, the branching fraction is suppressed to an unobservable level of 10^{-54} in the SM. In BSM model [4], such decay can be mediated by supersymmetric particles in a loop in Figure 1b and at tree-level via $Z^{'}$ in Figure 1c. The current limit set by the SINDRUM experiment is at BR$< 10^{-12}$ at 90% confidence [5]. The Mu3e experiment searches for the lepton flavor violation decay with the sensitivity of one signal decay in 10^{16} observed muon decays; the branching ratio is four orders of magnitude better than previous searches [6]. When muons decay at rest, the resulting electrons and positrons have a maximum energy of 53 MeV/c. Detecting these particles requires specific experimental conditions, such as thin material budgets and precise time and spatial resolution. High-voltage Monolithic Active Pixel Sensors (HV-MAPS) are designed to be very thin to minimize multiple scattering and they also offer excellent time resolution. Modern silicon-based tracking detectors made of HV-MAPS provide high accuracy and low-mass tracking of particles, which is essential for studying rare muon decays. The conference proceeding paper discusses the results from the test beam measurement of the sixth version of the tracking detector's pixel chip.



(a) Neutrino mixing



(b) Supersymmetric particles in a loop



(c) At tree level via $Z^{'}$

FIGURE 1: Different channels of the process $\mu^+ \to e^+e^-e^+$.

SIGNAL AND BACKGROUND MODELING

The $\mu^+ \to e^+e^-e^+$ signal events are constituted by two positrons and an electron with opposite curvature in a solenoid magnetic field of 1 Tesla. Such decay products should coincide in time and originate from the same vertex, and the topology should be co-planar. Since the decay products are from a stopped muon that decays at rest, the vectorial sum of all decay particle momenta should vanish, and the total invariant mass must sum to the muon mass. Furthermore, the energies of the decay particles range from the electron mass up to half the muon mass, which is about 53 MeV. Two primary sources of backgrounds are the internal conversion and the combinatorial background. The combinatorial background is from Michel decay positron ($\mu^+ \to e^+\bar{\nu}_\mu \nu_e$) together with an electron from Bhabha scattering, proton conversion, or mis-reconstructed back-curls. The required criteria to suppress such background are an excellent vertex, timing, and momentum resolution. The second one, which is the radiative muon decay with internal conversion ($\mu^+ \to e^+e^-e^+\bar{\nu}_\mu \nu_e$), can only be identified through the missing energy carried away by neutrinos. Thus, a precise measurement of the momentum of the decay products is required. Hence, to determine the background from radiation muon decays with internal conversion, a momentum resolution < 0.5 MeV/c is needed, while, to minimize the combinatorial background, a precise vertex resolution of 200 μm and time resolution of < 100 ps is required. Such HV-MAP sensors provide spatial information at micrometer precision for particles in the momentum range from a few MeV to hundreds of GeV/c. They also allow for particle tracking at the highest rates and are easier to produce than standard hybrid pixel detectors. Monolithic sensors have the advantage that very thin tracking modules can be built, with a radiation length of only 0.11% for the Mu3e experiment.

DETECTOR DESIGN FOR THE MU3E EXPERIMENT

The Mu3e is a fixed target experiment based on a long tube design. The world's most intense muon beam provides the required enormous number of muons, producing over 10^9 muons per second decaying in the Mu3e detector. Muons are stopped on a thin hollow target with a double cone shape of thin Aluminum. The muons decay at rest, and the vertices of the positrons and electrons from these decays are measured by the first two layers of the barrel-shaped silicon pixel tracker. A scintillating fiber detector and two outer pixel layers help determine the decay electrons' arrival time and momentum outside these inner pixel layers. The inner pixel layers, the fiber detector, and two outer pixel detector layers form the central station of the Mu3e detector. For more accurate momentum and time measurement of charged particles recurring in the magnetic field of 1 Tesla, cylindrical curl stations are added on both sides of the central detector station. These curl stations consist of two layers of pixel sensors and scintillating tile layers [6].

SILICON PIXEL DETECTOR TECHNOLOGY

HV-MAPS is available in HV-CMOS technology. Such technology allows for a strong electric field. Reverse biasing the deep N-well in the P-substrate with -60 V to -85 V leads to a depletion zone of 15 μm thickness, as reported in [7]. Ionizing particles create electron hole pairs in the depletion zone. The electrons are collected via drift within 1 ns, and less prone to bulk damage due to radiation, see Figure 2, while in standard MAPS, the charge collection is by diffusion process. Due to a very thin ac-

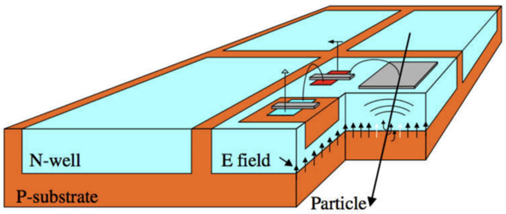


FIGURE 2: Schematic view of the HV-MAPS detector design from [8].

tive detection layer, thinning to 50 μm is possible. The unique feature of the sensor is CMOS analog and digital electronics can be implemented in the N-well, so no additional readout chip is required [8]. Such commercial HV-COMS process provides high reliability at affordable production cost.

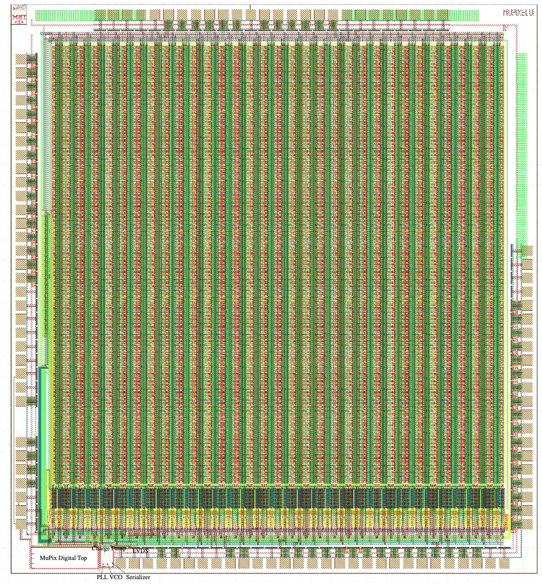


FIGURE 3: The MuPix7 chip layout.

DESIGN DETAIL OF THE MUPIX CHIP

Several iterations of the MuPix chip based on the HV-MAPS have been developed and tested for the tracking detector of the Mu3e experiment [9, 10]. The Mupix7 chip is the prototype, which, in this series, has the complete functionality required for the experiment. Signals are amplified in the pixel and driven to the chip periphery by a source follower. A comparator compares the input signal to an adjusted threshold for each pixel. An eight-bit Gray-encoded times stamp is stored once a hit is detected based on the standard threshold. A priority logic is coupled with a state machine that collects and serializes the three pieces of information: hit times and column and row addresses. It sends this information to off-chip using a 1.25 Gbit/s low-voltage differential signal readout link with 8bit/10bit encoding [11]. The pixel size is 103 μm in the column direction and 80 μm in the row direction. The active area of the chip is 3.2×3.2 mm^2, which incorporates a pixel matrix of 32×40 pixels. The reference provides a detailed description of the Mupix7 chip [12].

The test set-up for the MuPix7 chip

The Mupix7 chip performance was studied using the Detector R&D towards the International Linear Collider (EUDET) telescope [13] at the DESY-II beam test facility. The interaction of carbon fibers with the electron beam of the DESY-II synchrotron produces photons by the bremsstrahlung process. The photons convert into electron and positron pairs via a pair-production process in a metal target. Then, the magnetic field separates the electrons and positrons. Thus, 2 to 6 GeV/c positrons are used to study MuPix7 chip performance. Reference tracks were based on the EUDET telescope comprising six MAPS planes (Mimosa26 [14]). After the first three tracking planes, the MuPix7 chip was used as a device under test (DUT) on a rotational stage. Furthermore, the telescope has four scintillators, two before and two after the DUT. A track-based alignment of the telescope planes was based on the Millepede II algorithm [15].

RESULTS ON THE MUPIX7 CHIP PERFORMANCE

The time resolution of the MuPix7 chip was investigated using a 62.5 MHz Gray counter for sampling (see Figure 4). Plastic scintillators served as the time reference. The peak region of the relative time between the Mupix7 hit time and scintillator signals were fitted with a Gaussian function, yielding a time resolution of σ = 11 ns. This value serves as an upper limit for the time resolution required for particle detection, as the phase 1 requirement is less than 20 ns. This level of resolution is crucial for detecting the rare decay of muons, as it effectively reduces background events and accurately identifies rare decay events. Compared to other detectors, the MuPix7 chip offers an optimal balance of precision and practicality, making it well-suited for the search for rare muon decays.

The particle detection efficiency analysis is based upon a threshold scan for one global threshold with the help of the tune digital to analog converters. The EUDET telescope was used for the reconstruction of reference tracks

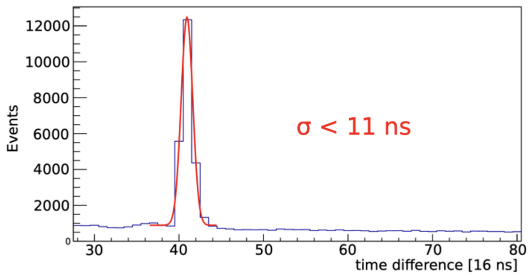


FIGURE 4: From the test results, MuPix7 chip time resolution of σ = 11 ns which is sufficient for the tracking detector of the Mu3e Experiment [12].

and the measurement of hit efficiencies. The readout events containing a single track of good quality and less than 50 hits on the MuPix7 chip serve as the reference sample. If a hit within 150 μm of the extrapolated track intersect with the MuPix7 chip is found, track and hit are matched [11]. In this scan, the noise of each pixel has equilibrated to 1 Hz. In the plateau, hit efficiencies of about 99.5% have been determined for the 250 MeV mixed positron, muon, and pion beam at PSI, see Figure 5 [12]. The noise in the efficiency plateau region is in the range of 2 to 12 Hz per pixel, with a power consumption of about 300 mW/cm^2, which is within the cooling budget of the Mu3e pixel detector. There is a sharp noise edge while tuning the threshold is due to possibility of increased in crosstalk sensitivity. Furthermore, it is observed that the amplifiers in the pixels and the digital mirror pixel dominates the power consumption.

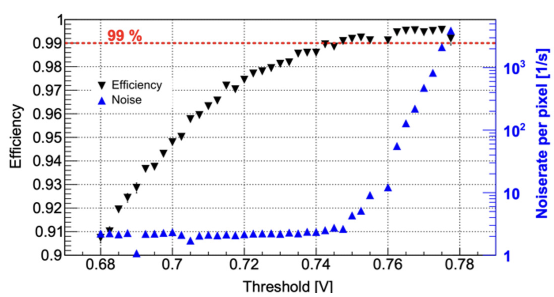


FIGURE 5: Hit efficiencies and noise versus threshold for the MuPix7 chip shows hit efficiency is about 99.5% in plateau region [12].

The efficiency dependency on the depletion zone thickness has been studied by rotating the MuPix7 chip at four different angles to the positron beamline using a 4 GeV/c positron beam at DESY. The measurement at angle 45^{o} shows a much broader efficiency plateau than the 0^{o} measurement. 45^{o} relative to the incoming particle direction leads to a signal enhanced because it corresponds to $\sqrt{2}$ times thicker effective depletion region compared to the perpendicular position, as shown in the Figure 6 [12]. This study also shows that dependency of depletion region on charge collection efficiency. Hence, the new version of MuPix chip has higher substrate resistivity compared to the resistivity which is (20 Ωm) for the analyzed chip.

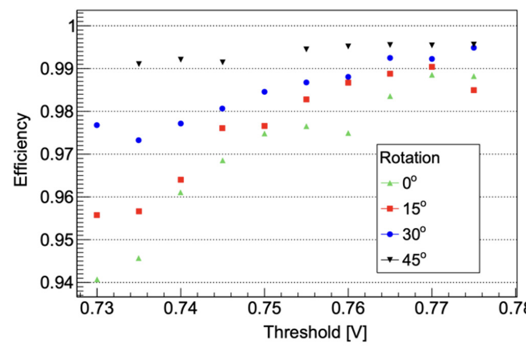


FIGURE 6: Hit efficiencies vs versus threshold for the MuPix7 chip of different angles shows that the hit efficiency is maximum for an angle 45^{o} with the incident beam [12].

The spatial resolution is calculated by projecting the MuPix7 chip perpendicular to the beam line. The tracks are reconstructed separately in the upstream and downstream sections of the telescope and interpolated to the target plane. The track residual is measured as the difference between hit position and the expected hit position from the fitted track. The hit residuals are $\sigma_x = 38.1\ \mu$ m and $\sigma_y = 30.6\ \mu$m [12]. It is consistent with the intrinsic single-cell resolution (pitch/$\sqrt{12}$) folded with uncertainties from multiple Coulomb scattering and tracking as shown in Figure 7.

CONCLUSION

The MuPix7 chip is the first complete system on the chip, combining pixel sensor, analog electronics, and full digital readout. It demonstrates the unique capabilities of HV-MAPS technology and has shown excellent performance, meeting the requirements for the upcoming Mu3e experiment. The test results show the time resolution of the MuPix7 chip is better than 11 ns. The spatial resolution is $\leq 38.1\ \mu$m. The entire system hit an efficiency of more than 99%. Not only the Mu3e Experiment but also the MuPix chip has been chosen as a detector for the antiProton ANnihilation at the DArmstadt (PANDA) experiment [16]. Since HV-CMOS sensors have demonstrated

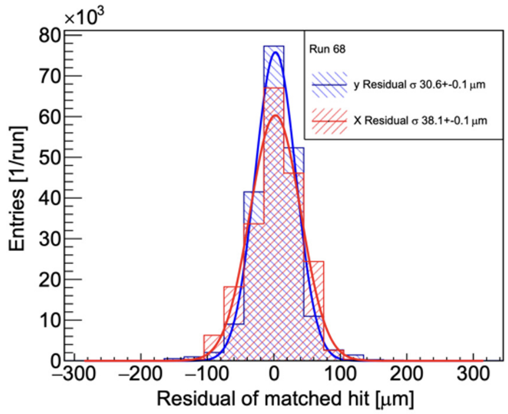


FIGURE 7: Spatial resolution of the MuPix7 chip $\sigma_x = 38.1\ \mu$m and $\sigma_y = 30.6\ \mu$m is consistent with the single cell resolution [12].

a significant radiation tolerance and good performance, making them an ideal choice of technology for the LHCb experiment [17]. HV-MAPS can be implemented in the tracking detectors depending on the requirements of future particle physics experiments.

ACKNOWLEDGMENTS

I want to thank Professor Dr. Niklaus Berger from Johannes Gutenberg-Universität Mainz, Andre Schöning from the University of Heidelberg for their support and suggestions while working on the Mu3e Experiment project, and Professor Dr. Ivan Perić from Karlsruher Institut für Technologie for the guidance on the design of the both Mupix6 and Mupix7 chips design and testing readout electronics.

EDITORS' NOTE

This manuscript was rigorously peer-reviewed and subsequently accepted for inclusion in the special issue of the Journal of Nepal Physical Society (JNPS) after it was submitted to the Association of Nepali Physicists in America (ANPA) Conference 2024.

REFERENCES

1. Y. Fukuda *et al.*, "Evidence of oscillation of atmospheric neutrino," Phys. Rev. Lett **81**, 1562–1567 (1998).
2. Q. R. A. et al. (Sno Collaboration), "Measurement of the rate of $\nu_e + d \rightarrow p + p + e^-$ interactions produced by ^{8}b solar neutrinos at the sudbury neutrino observatory," Phys. Rev. Lett **87**, 071301 (2001).
3. K. Eguchi *et al.*, "First results from kamland: Evidence for reactor antineutrino disappearance," Phys. Rev. Lett **90**, 021802 (2003).
4. Y. Kuno and Y. Okada, "Muon decay and physics beyond the standard model," Rev. Mod. Phys **73**, 151–202 (2001).
5. U. Bellgardt *et al.*, "Search for the decay $\mu^+ \rightarrow e^+e^-e^+$," Nuclear Physics B **260**, 1–31 (1995).
6. A. Blondel *et al.*, "Research proposal for an experiment to search for the decay of $\mu^+ \rightarrow e^+e^-e^+$," arXiv preprint arXiv:1301.6113 (2013).
7. I. Perić *et al.*, "Overview of hvcmos pixel sensors," Journal of Instrumentation **10**, C05021 (2015).
8. I. Perić, "A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology," Nucl. Instrum. Meth. A **582**, 876–885 (2007).
9. H. Augustine *et al.*, "The mupix high voltage monolithic active pixel sensor for the mu3e experiment," JINST **10**, C03044 (2015).
10. S. Shrestha, "The high-voltage monolithic active pixel sensor for the mu3e experiment," PoS (TIPP2014) **047** (2014).
11. H. Augustin *et al.*, "Efficiency and timing performance of the mupix7 high-voltage monolithic active pixel sensor," Nucl. Instrum. Meth. A **902**, 158–163 (2018).
12. H. Augustin *et al.*, "The mupix system-on-chip for the mu3e experiment," Nucl. Instrum. Meth. A **845**, 194–198 (2017).
13. H. Jansen *et al.*, "Performance of the eudet-type beam telescopes," EPJ Techniques and Instrumentation **3**, 1–20 (2016).
14. C. Hu-Guo *et al.*, "First reticule size maps with digital output and integrated zero suppression for the eudet-jra1 beam telescope," Nucl. Instrum. Meth. A **623**, 480–482 (2010).
15. V. Blobel, C. Kleinwort, and F. Meier, "Fast alignment of a complex tracking detector using advanced track models," Computer Physics Communications **182**, 1760–1763 (2011).
16. T. Weber *et al.*, "High voltage active pixel sensors for the panda luminosity detector," Verhandlungen der Deutschen Physikalischen Gesellschaft (2016).
17. J. Hammerich *et al.*, "Towards mightypix, an hv-maps for the lhcb mighty tracker upgrade," JINST **17**, C10005 (2022).