PROCEEDINGS OF SCIENCE

Searching for cLFV with the Mu3e experiment

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The Mu3e experiment at the Paul-Scherrer-Institut (PSI) searches for the charged lepton flavour violating decay $\mu^+ \to e^+e^-e^+$. This decay mode is extremely suppressed in the Standard Model, such that any observation would be a clear signature for new physics being at play. The experiment will be conducted in two phases. In Phase I, a single event sensitivity of 2×10^{-15} is projected to be reached using the Compact Muon Beamline present at PSI. To reach the ultimate sensitivity of 10^{-16} in Phase II, an upgrade of the detector as well as a higher intensity muon beamline will be required.

The detector system has to provide excellent tracking efficiency as well as momentum, vertex and time resolutions to reach the experimental goals. An unprecedentedly thin silicon pixel tracking detector is being constructed using HV-MAPS, ultra-light services and a gaseous helium cooling system. It is complemented by timing detectors consisting of scintillating fibres and tiles. The full detector is placed inside a solenoidal magnetic field of 1 T.

A first run integrating several subdetector prototypes was successfully conducted at PSI in 2021. A second run using cosmic muons took place in the first half of 2022. While the design of the final detector components is being completed, the Mu3e experiment is entering the production stage. Commissioning of the final Phase I detector is planned to start in 2023. In this publication, the status of the Mu3e experiment is presented.

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1. Experimental Concept

Searches for rare and forbidden muon decays have been conducted over many decades. The charged lepton flavour violating (cLFV) decay $\mu^+ \to e^+e^-e^+$ was last searched for by the SINDRUM experiment at the Paul Scherrer Institut (PSI) in the late 1980's, and their limit on the branching ratio of 10^{-12} [1] still holds to these days. The Mu3e experiment [2], currently being set up at the very same place, aims to find or exclude this decay with a superior sensitivity at branching fractions above 10^{-16}. The experiment will be conducted in two phases. In the first phase, Mu3e makes use of the Compact Muon Beam Line installed in the PiE5 area which can deliver up to 10^8 muons[1] per second to the experiment. It targets a single event sensitivity of a few 10^{-15}, running until the accelerator at PSI will be shut down for an upgrade and the installation of the High Intensity Muon Beam (HIMB) [3] line. In the second phase, Mu3e will benefit from the higher muon rates provided by HIMB, which should allow to reach the ultimate sensitivity goal of 10^{-16} within a few years of taking data.

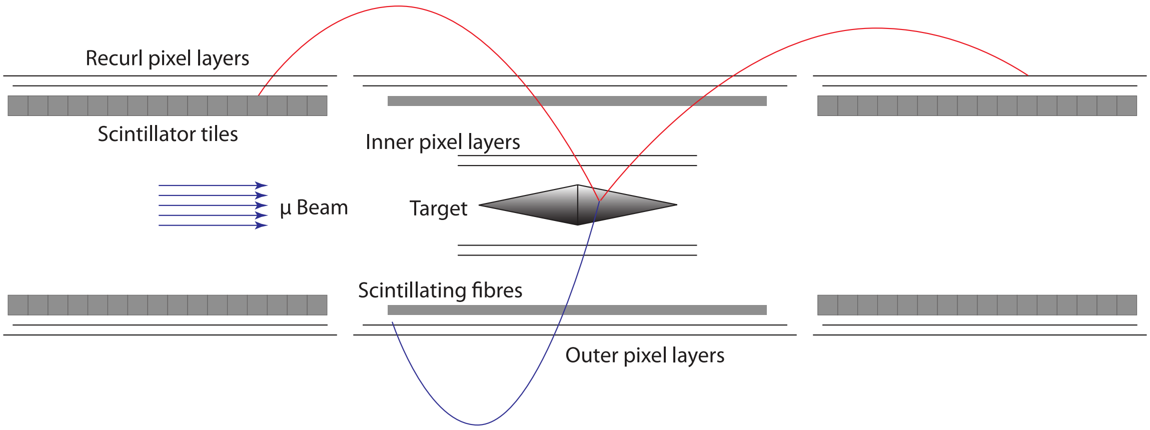

Figure 1: Detector concept of the Mu3e experiment in Phase I [2]

Mu3e will search for the cLFV decay by reconstructing the invariant mass of two positrons and one electron, hereinafter all referred to as electrons, that are coincident in time and share a common vertex. In order to reach the target sensitivity level, physics backgrounds like the decay $\mu^+ \to e^+e^-e^+\nu\bar{\nu}$ as well as combinatorial background from separate muon decays close in time and space need to be suppressed. Therefore, the momentum of all tracks needs to be measured with a precision better than 1 MeV/c, vertices need to be reconstructed with a resolution of a few 100 μm, and the decay time needs to be measured at the nanosecond level or better.

The experimental concept for the first phase of Mu3e is sketched in Figure 1. The muons enter the detector volume and are stopped on a thin, hollow double-cone shaped target where they decay at rest. The target is surrounded by a barrel shaped detector consisting of 4 thin layers of silicon pixel sensors enabling reconstruction of the decay electrons' trajectories. In between the inner and outer two pixel layers, three layers of scintillating fibres are installed to measure the arrival time of each particle seen by the pixels. This allows combinatorial background to be reduced, as well as wrong charge assignments to particles leaving ambiguous tracks in the detector to be prevented.

[1]Throughout the text, charge conjugation is implied.

Determination of the electrons' momenta is of utmost importance for the Mu3e experiment. Due to the low momentum of the electrons, the momentum resolution is dominated by multiple scattering effects. Hence, the detector is required to be as thin as possible. As the whole detector is placed inside a solenoidal magnetic field of 1 T, the electrons will curl back towards the beam axis. The design of the Mu3e experiment has been optimized to take advantage of this. By measuring the electrons when they re-enter the detector volume, the uncertainties related to scattering cancel to first order, and the momentum resolution can be enhanced greatly. To increase the geometric acceptance of the recurling electrons, so-called recurl pixel layers are installed up- and downstream of the central barrel. Below these layers, the electrons are stopped within scintillating tiles that deliver an even more precise time information for the tracks that reach this detector.

The detector design has been optimized using detailed simulation studies, which in turn also allow to evaluate the expected sensitivity. Within 300 days of taking data we expect to reach a single event sensitivity of a few 10^{-15} in phase I [2].

2. Pixel Tracking Detector

The strong requirements on momentum resolution pose stringent limits on the material budget for the Mu3e tracking detector. Within the active area, each layer is required to be as thin as 0.1 % of a radiation length. The sensors have to be above 99 % efficient while maintaining a moderate noise rate of less than 20 Hz/pixel. They are required to provide time information per hit with a resolution of better than 20 ns in order to reduce combinatorial background.

The pixel detector is segmented into ladders, i. e. 12 cm to 36 cm long strips that solely consist of pixel sensors and High Density Interconnects (HDI) made from aluminium and polyimide foils acting as mechanical mount and electrical service. In order to achieve the low material budget, the only option to cool the sensors is by using gaseous cooling. A novel and powerful gaseous helium cooling system has been developed utilizing miniature turbo compressors specifically designed for this task. The cooling system is designed to tolerate sensor power densities of up to 350 $\mathrm{mW/cm^2}$.

High-voltage monolithic active pixel sensors (HV-MAPS) [4] have been chosen as sensor technology for Mu3e. They can be thinned to 50 μm while still remaining above 99 % efficient, which allows ultra-thin detector layers to be produced. In addition, they provide time information per particle hit sufficiently good to meet the requirements of the Mu3e experiment. The MuPix10, a close-to-final prototype of the HV-MAPS family developed for Mu3e, was successfully tested to meet all criteria [5]. It's successor, the MuPix11, only features some minor modifications, e. g. an improved powering scheme and a new pixel routing scheme. It has been received back from fabrication in the second half of 2022 and is currently being tested.

Quality assurance test stands as well as production chains for the inner and outer pixel layers have been developed. The on-detector services are currently being finalized. Module pre-production for the inner pixel layers starts at the end of 2022, while full production is expected to start in 2023.

3. Timing Detectors

Both timing detectors, the scintillating fibre and tile detectors, make use of silicon photomultipliers (SiPM) and a common readout ASIC called MuTRiG. The MuTRiG features 50 ps binned time-to-digital conversion for 32 channels in parallel. Version 3 has been submitted in May 2022. It allows higher thresholds to be set, contains triple redundant configuration registers and a reduced number of IOs compared to previous versions.

The fibre detector [6] is divided into 12×30 cm long ribbons consisting of 3 staggered layers of 250 μm thin fibres connected to 128-channel Hamamatsu S13552-HRQ SiPM column arrays. For a prototype module a time resolution of 250 ps was measured, which satisfies the requirement of 500 ps for this detector. At the time of writing, the mechanical design including the liquid cooling system, which shall deliver temperatures down to −20 °C, is being finalized. Readout of the SiPM column array has successfully been tested using the MuTRiG version 2. On-detector readout boards are being finalized.

The tile detector [7] consists of about 6000 tiles of $5\times5\times5$ mm^3 size being read out individually using Hamamatsu MPPC S13360-3050VE. The required time resolution of 100 ps was confirmed to be met by detector prototypes with a single channel time resolution measured to be better than 50 ps. Over the last years, the impact of irradiation damage has been studied. An increase in dark count rate was found for a detector prototype that was irradiated up to the maximum dose the detector is expected to be exposed to during the full run time of Phase I. This effect can be mitigated by cooling the detector. Hence, a common cooling system is being developed for both timing detectors. The intrinsic time resolution after irradiation was still found to satisfy the Mu3e requirements. At the time of writing, production of final demonstrator modules has started and quality assurance test stands have been set up. A second version of the tile module board has been produced and found to be fully functional. The assembly of the final detector components is about to be started.

4. Data Acquisition

The Mu3e detector is operated in a fully synchronized manner, meaning that all pixel sensors and all timing readout ASICs receive a copy of a common clock source and a synchronous reset to define a fixed reference time [8]. A streaming readout of zero-suppressed data is provided by both pixel and timing detectors. Custom FPGA front-end boards are electrically connected to the pixel sensors and the timing readout ASICs. They are placed inside the solenoid magnet within the helium atmosphere. The front-end boards provide an optical link to transfer the data outside of the magnet into the counting house. In the counting house, the data from all sub-detectors is aggregated using PCIe40 boards and passed to the GPU filter farm for online event selection based on track and vertex reconstruction.

A working first batch of front-end boards has been produced, while more boards have to be produced for the full Phase I detector. The clock and reset distribution system is ready and provides up to 288 optical copies of clock and reset. The remaining components are all either commercial off-the-shelf and will be bought shortly before the start of Phase I, or are already available. Major firmware blocks for the FPGAs on the front-end boards, as well as for the PCIe40 boards and the cards serving as data receiver within the GPU farm, are available and tested in hardware. Integration of all components and scaling-up of the readout system is currently in progress. There have been concentrated efforts to achieve this during the Integration Run 2021 and the Cosmics Run 2022.

5. Integration Run 2021 and Cosmics Run 2022

In 2021 the so-called Mu3e Integration Run was conducted at PSI. The goal of this run was to integrate as many of the services required by the final experiment with demonstrator detectors, see Figure 2, and to operate it in a helium atmosphere within the Mu3e magnet with the muon beam turned on. A simplified demonstrator for the vertex detector based on MuPix10 on PCBs instead of HDIs has been built and was used for this purpose [9]. During operation it generated a heat load of about 100 W that was cooled using a simplified helium distribution system with a flow of helium of 2 g/s. Two scintillating fibre ribbon prototypes were installed as well. We observed correlations between pixel sensors from decay electrons originating from the target.

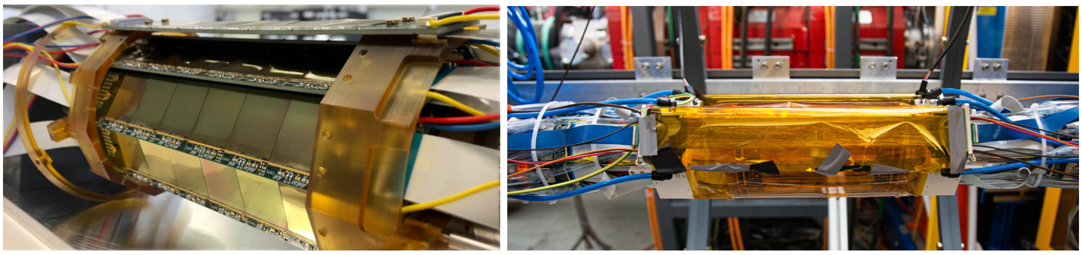

Figure 2: Demonstrator vertex detector (left) mounted on the experimental cage with cables attached and scintillating fibre ribbon in its front (right). The pixel detector is surrounded by Kapton foil as part of the simplified helium distribution.

In the first half of 2022, a second run was conducted at PSI using cosmic muons. The same vertex detector demonstrator was installed with a scintillating fibre ribbon, as well as additional scintillators on the top and bottom as a cosmic reference detector. During this run, we could establish synchronization between the pixel and the fibre detector.

6. Summary and outlook

The Mu3e experiment will search for the cLFV decay $\mu^+ \rightarrow e^+e^-e^+$. Demonstrator detectors have successfully been operated in a helium atmosphere inside the magnet and with the muon beam turned on. At the time of writing, all detectors are being prepared for mass production. Commissioning of the inner detector system is planned for 2023. Final integration of all sub-detectors including the outer pixel layers, commissioning of the full detector, and physics data taking are expected to start in 2024.

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