The ultra-lightweight support structure and gaseous helium cooling for the Mu3e silicon pixel tracker

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ABSTRACT: The Mu3e experiment searches for charged lepton flavor violation in the rare decay $\mu \rightarrow eee$. In order to reach a sensitivity of better than $10^{-16}$, more than $10^9$ muon decays per second have to be observed over a running time of one year. Precise determination of particle momentum, vertex position and time are necessary for background suppression. These requirements can be met by combining an ultra-lightweight tracker based on High-Voltage Monolithic Active Pixel Sensors (HV-MAPS) with a timing system which consists of a scintillating fiber detector and a tile hodoscope. As the momentum of particles from muon decay at rest is below 53 MeV/c, the silicon pixel tracker resolution is dominated by multiple Coulomb scattering. This leads to extreme requirements for the material budget of the tracking detector of below 0.1% of a radiation length per layer. Even though the target power consumption of the HV-MAPS detector is as low as 150 mW/cm$^2$, the detector cooling must be very efficient and at the same time avoid adding material inside the active tracking volume.

KEYWORDS: Detector cooling and thermo-stabilization; Overall mechanics design (support structures and materials, vibration analysis etc); Particle tracking detectors (Solid-state detectors)
1 The Mu3e experiment

The Mu3e experiment [1] searches for lepton flavor violation in the decay $\mu \rightarrow eee$. In the Standard Model this decay is possible through neutrino mixing, but it is suppressed to unobservable levels, $\text{BR} < 10^{-54}$. This means that any observed signal event would be a clear sign for new physics. While a branching ratio sensitivity of $10^{-12}$ has been reached by the best previous experiment [2], the sensitivity goal of the Mu3e experiment is $10^{-16}$. Well over $10^{16}$ muon decays have to be precisely reconstructed to reach this level of sensitivity, which leads to a required decay rate of $10^9$ muons/s and several years of running. In order to separate signal events from combinatorial background and from the radiative muon decay with internal conversion $\mu \rightarrow eee\nu\nu$, a very good time-, vertex- and momentum resolution is mandatory [3, 4]. Since the maximum momentum of decay electrons and positrons is $53 \text{MeV}/c$, the vertex- and momentum resolution are dominated by multiple Coulomb scattering. This requires all detector elements in the active region to be lightweight. The Mu3e detector consists of a tracking detector in a 1T magnetic field and two timing detectors around a muon stopping target, see figure 1. The tracking detector is a high voltage monolithic active pixel sensor (HV-MAPS) [5–7] tracker. It is composed of two vertex layers around the target, two central outer layers and further pairs of outer layers upstream and downstream of the central detector. The timing system consists of the scintillating fiber detector and the scintillating tile detector, which deliver precise timing information for the particle tracks [8–10]. The Mu3e experiment will be built in three phases, starting with the central vertex and outer tracker in phase Ia and adding fiber detector, tile detector, forward and backward tracking stations in phases Ib and II.
Figure 1. Mu3e detector with signal event: the muon beam hits a fixed target in the center and the positive muon decays into two positrons (red) and one electron (blue). The decay vertex is determined by two inner pixel layers, which are surrounded by a fiber detector 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.

Figure 2. The Mu3e pixel tracker modules are composed of the sensor chips in HV-MAPS technology, flex prints made from aluminum Kapton™ laminate and a Kapton™ frame. This picture shows the design of one side of a vertex layer.

2 Ultra-light support structure for the pixel tracker

In order to achieve a material budget of as little as 0.1% of a radiation length $X_0$ per tracking layer, the Mu3e pixel detector is built in a sandwich design from thinned HV-MAPS sensors, Kapton™ flex prints and Kapton™ frame Modules, see figure 2.

2.1 High Voltage Active Pixel Sensors

The pixel detector is based on High Voltage Monolithic Active Pixel Sensors (HV-MAPS). These novel chips contain the pixel sensor matrix, preamplifiers, discriminators and digital electronics which generate a fast (0.8 Gbit/s) zero suppressed serial data stream. As a consequence, no further readout electronics are required in the active tracking volume. In addition, they can be thinned to
Table 1. Material budget of one silicon pixel detector layer.

| Component      | % of a radiation length $X_0$ |
|----------------|-------------------------------|
| HV-MAPS        | 0.0534                        |
| Flex Print     | 0.0386                        |
| Frame Modules  | 0.009                         |
| Total          | 0.101                         |

50µm, since the depletion zone used for charge collection is only around 10µm thick. Thus, the pixel chips add as little as $5.34 \times 10^{-4}$ of $X_0$ to the material budget. The size of the sensor chips will be around 1 times 2 cm$^2$ for the vertex layers and 2 times 2 cm$^2$ for all outer pixel layers. Six to eighteen sensors share one Kapton$^\text{TM}$ flex print, the electrical connection between chips and flex print is established with wire bonds. The characterization of recent HV-MAPS prototypes [11–14], including chips which have been thinned to 80µm, confirm good performance and very little sensitivity to thinning.

2.2 Flex print

Kapton$^\text{TM}$ flex prints support the HV-MAPS chips, supply power, high voltage (60V) and signal lines for controls and readout. It is foreseen to use flex prints which are based on a laminate of 25µm Kapton$^\text{TM}$ and 12.5µm aluminum. The traces are cut into the aluminum layer with the help of a laser. If needed, two layers of laminated foil can be used for the flex print which would provide better grounding and shielding and relieve the very tight space constraints. A flex print with two layers, one with 25µm Kapton$^\text{TM}$ and 12.5µm aluminum for grounding and one layer with 25µm Kapton$^\text{TM}$ and half coverage of 12.5µm aluminum for the signal traces adds $3.86 \times 10^{-4}$ of $X_0$ to the material budget.

2.3 Frame modules

In order to support the flex prints inside the tracking volume, support structures made from Kapton$^\text{TM}$ foil have been developed. To increase the stability of the 25µm thick foil it is folded along the beam axis. In the case of the 12cm long vertex layers, two half-modules form the prismatic shaped detector frame which, together with the flex print and sensors, is fully self-supporting. For the 36cm long outer layers of the tracking detector frame, modules supporting four flex prints each have been designed. A v-shaped fold underneath each flex print adds stability to the three times longer outer layer frames. The 25µm thick Kapton$^\text{TM}$ frame modules add around $0.9 \times 10^{-4}$ of $X_0$ to the material budget. The material budget is summarized in table 1. Prototypes of frame modules have been built for all four detector layers, showing that they are fully self-supporting, see figure 3. Plastic end-pieces outside the acceptance and aluminum mounting wheels add further stability to the detector mechanics.

3 Cooling

The cooling of the Mu3e detector is based on liquid cooling for most of the readout electronics and gaseous helium cooling for silicon tracker sensors.
3.1 Liquid cooling

The beam pipes inside the Mu3e detector are realized as a pair of massive stainless steel tubes with u-shaped grooves for the cooling liquid. It is foreseen to mount the FPGAs for the detector readout and the power regulators directly onto the stainless steel covers of these grooves. The estimated combined power consumption of the over 100 front-end FPGAs is in the order of a few kW. As there is a separate beam pipe upstream and downstream of the target with seven cooling grooves each, the flow rate per groove can be moderate, i.e. 2.5 ml/s assuming 26.25 W per FPGA and $\Delta T$ of 20°C.

3.2 Gaseous helium cooling

In order to precisely measure the particle momentum it is important to minimize multiple Coulomb scattering and thus the material inside the tracking volume. This constrains the cooling options for the silicon pixel detector. Gaseous helium has been chosen because of its low nuclear charge number and good thermal transport capabilities. The estimated power dissipation of the pixel sensors is 150 mW/cm² which leads to a total power of 2.86 kW for all Mu3e pixel sensors. The target temperature range for the HV-MAPS operation is between 5°C and 70°C. It has been shown that the performance of recent prototypes is sufficiently constant up to at least 70°C. In order to cool the silicon pixel sensors the helium is inserted in multiple ways. There is a slow flow of cool helium inside the entire magnet volume of 3 m length and 1 m diameter, referred to as global helium flow. Since the global flow can only reach part of the HV-MAPS chips directly, an additional local flow of cool helium gas is foreseen. The helium for the local flow is distributed either to the v-shaped folds of the detector support structure or to its outer surface, see figure 4 left. In both cases, helium flows underneath the HV-MAPS chips along the beam axis. The local helium flow distribution is realized by means of the module end-pieces, see figure 4.
Figure 4. End-piece of a silicon pixel module. Left side: schematic picture of the distribution of cool helium gas at the end-piece. Right side: CAD drawing of the cooling gas distribution at the end-piece.

Figure 5. Simulation results for gaseous helium cooling of the 4th layer of the silicon pixel tracker. The temperature difference between the sensors and the helium at the insertion point (20°C at 400mm) is given as a function of the position along the beam axis. Temperature profiles are shown for gas speeds between 0.5 and 4 m/s.

3.3 Simulation of gaseous cooling

The effectiveness of the gaseous helium cooling concept has been tested with the help of a simulation [15]. This simulation has been performed for a station of the two outer layers of the silicon pixel tracker. The simulated power dissipation is 150 mW/cm², the gas speed is between 0.5 and 4 m/s and the simulation has been carried out for both, air and helium, see figure 5. The simulation indicates that in order to establish sensor temperatures between 20°C and 70°C gaseous helium of below 20°C must be inserted at velocities above 2 m/s. For otherwise identical conditions the maximum ΔT for the sensors is twice as large if air is used as coolant instead of helium.

3.4 Laboratory tests for gaseous cooling

Gaseous cooling for the silicon pixel tracker has been tested with a scale model of one outer pixel station [15, 16]. In the model the silicon pixel modules of layers 3 and 4 of one station are replaced by sheets of aluminum Kapton™ laminate foil which is ohmically heated. The laminated foil is
Figure 6. Test setup for the gaseous cooling of the Mu3e pixel tracker: scale model of the outer two pixel layers of one station, the pixel modules are replaced by aluminum Kapton™ foils heated ohmically. An air flow generated by two 30cm ventilators cools the model inside an acrylic glass tube.

Figure 7. Maximum $\Delta T$ for air cooling of layer 4 as a function of air speed. Temperature sensors are placed on the top, side or bottom of the model. The heating is 150mW/cm$^2$.

mounted to a cylindrical plastic frame, see figure 6. Temperature sensors are placed on the heated sheets of aluminum Kapton™ laminate foil along the axis of the station. The temperature sensors are read out via an ADC-unit (LogicBox) and LabView software. The setup was mounted inside an acrylic glass tube with 30cm diameter ventilators on both ends which act as a wind tunnel. The air velocity is determined with an anemometer placed close to the air inlet of the tube with an accuracy of 0.1 m/s. Tests have been performed for either 100mW/cm$^2$ or 150mW/cm$^2$ power dissipation and air speeds between 1.7 and 3.8 m/s. As shown in figure 7, air cooling requires relatively high flow velocities of 3.8 m/s in order to reach a maximum $\Delta T$ of below 60$^\circ$. Under the above conditions no mechanical vibrations of the thin aluminum Kapton™ foils (25µm + 25µm) could be observed by eye, quantitative studies are foreseen in the upcoming months. While the tests with air confirm the feasibility of gaseous cooling of the silicon pixel tracker, both simulation results and first laboratory test indicate that the maximum $\Delta T$ for helium cooling is about a factor two smaller, see figure 8.
Figure 8. Comparison of simulation of cooling with helium or air and measurement with air: maximum $\Delta T$ for air and helium cooling of layer 4 as a function of air speed. The heating is 150 mW/cm$^2$.

4 Summary and outlook

The Mu3e experiment searches for the lepton flavor violating decay $\mu \rightarrow eee$ with the help of a novel pixel detector based on high voltage monolithic active pixel sensors (HV-MAPS). In order to minimize multiple Coulomb scattering in the active tracking volume the HV-MAPS sensors, the support structure and the cooling system must be built from very thin and, if possible, low $Z$ material. An ultra-lightweight detector module sandwich structure composed of thinned HV-MAPS chips, aluminum Kapton$^{TM}$ laminate flex prints and an aluminum Kapton$^{TM}$ support frame has been designed. These detector modules have a thickness of approximately 0.1% of a radiation length per tracking layer. First mechanical prototypes have been assembled successfully and turn out to be self-supporting.

The cooling concept of the Mu3e detector foresees liquid cooling for most of the read out electronics and gaseous helium cooling for the silicon pixel detector. Both simulation and measurements carried out with at full scale model of one station of the outer tracking layers indicate that for the expected power dissipation of 150 mW/cm$^2$ and an operating temperature range between 5$^\circ$C and 70$^\circ$C sufficient cooling can be achieved with a moderate gas flow of around 4.0 m/s. Simulation results and preliminary measurements show that the maximum $\Delta T$ is a factor two lower for helium than for air.

In the upcoming months the gaseous helium distribution integrated in the ultra-lightweight detector module design will be tested.

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