PROCEEDINGS OF SCIENCE

The LHCb Mighty Tracker

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During the long shutdown 4 of the LHC the instantaneous luminosity will be increased by a factor of $\approx$ 10 to $1.5 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The expected data recorded with the LHCb detector will increase from $50\,\mathrm{fb}^{-1}$ to $300\,\mathrm{fb}^{-1}$. This will require an upgrade of the LHCb tracking systems. For the downstream tracker this upgrade detector is referred to as the Mighty Tracker. The innermost part of the Mighty Tracker is planned to be instrumented with monolithic CMOS sensors. The outer part will keep the scintillating fibre approach of the currently installed SciFi detector. There are several aspects that make this a unique environment for a tracking detector. The high occupancy in the high η region of LHCb (hit rates up to $18\,\mathrm{MHz/cm}^2$), the harsh radiation conditions ($6 \cdot 10^{14}$ 1 MeV $\mathrm{n_{eq}/cm^2}$), the streaming readout approach with low material budget ($X/X_0 < 1.5\%$) requirements are just naming a few key challenges. This can be achieved by newly developed HV-CMOS sensors which can provide a high timing resolution of $\approx$ 3 ns and are sufficiently radiation hard. The planned total instrumented pixel area is up to $18\,\mathrm{m}^2$ of silicon. This paper will describe the plans for the Mighty Tracker and initial beam tests with the precursor of the MightyPix chip.

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1. Introduction

The LHCb Detector [1] is a single-arm forward spectrometer instrumented to track, identify and measure particles coming from the collisions at point 8 of the LHC at CERN in a range of $2 < \eta < 5$. One of the main research focuses of LHCb is the study of b-hadron decays. For this purpose a tracking system with a high tracking and hence hit efficiency is needed.

The LHCb experiment plans [2] to increase the instantaneous luminosity for Run 5 (starting in 2035) of the LHC from $2 \cdot 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ to $1.5 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This will lead to a significant increase in radiation levels and the number of simultaneous hits, resulting in a higher number of tracks in the detector. One of the main challenges is to keep the streaming readout mode and the needed computing resources reasonable. The currently installed SciFi detector [3] has several limitations, including long fibres and the resulting combinatorics from multiple hits, as well as the radiation hardness of the fibres which will not be sufficient for operation at the increased luminosities.

2. The Mighty Tacker Mechanical Layout

The chosen solution to keep and exceed the current physics performance is a pixelated detector in the central beam region around the beampipe and keeping the low material and high resolution scintillating fibres for the outer parts as shown in figure 1. The detector is planned to be installed in the forth long shutdown of the LHC (2033-2034), in the earlier shutdown (2026-2028) a smaller version of the Mighty Tracker might be possible to install. The shape of the pixelated area is driven by the hit occupancy which is given by the LHCb dipole magnet and therefore not spherical around the beampipe, but shaped like a horizontal cat's eye. In total the detector consists of three stations each with two layers of silicon with an area of $3\,\mathrm{m}^2$ per layer. There are six layers planned. Therefore, the complete Mighty Tracker has an area of $18\,\mathrm{m}^2$ silicon. This article will mainly concentrate on the central silicon area, but as outlined in [2] there are several improvements planned for the fibre part as well.The main goal of the mechanical design of the inner silicon part is to keep the low material budget of the fibre detector as the cables and services run through the fibre area and allow the instrumentation of this large area. A layer is divided into 28 modules. Each module has the size of $53 \times 20\,\mathrm{cm}^2$ and consist of four submodules. All submodules will be identically equipped with 35 sensors on one side, except the four innermost modules next to the beampipe, which will be shorter and have 15 sensors less, to allow for the beampipe. One sensor is expected to be $2 \times 2.1\,\mathrm{cm}^2$. The two sides are aligned in a way such that the passive areas of one side is covered by the other side, allowing for the overlap of the not-sensitive periphery of the sensors. In the area between the sensors the auxiliary electronics will be placed. In total the Mighty Tracker is expected to consist of about 46 k sensors, with about 1.7 G pixels.

3. The MightyPix Requirements

To build this detector the technology of monolithic HV-CMOS [4, 5] sensors are planned to be used. This promises to provide the needed spatial and time resolution, while keeping the power consumption low and being radiation hard. The timing requirement stems from the streaming readout of LHCb, where the whole detector has to be continuously read out at 40 MHz. An offline

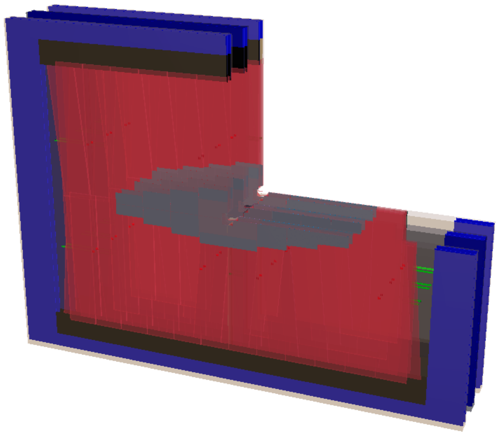


Figure 1: Schematic representation of the mechanical outline of the Mighty Tracker. The six layers of MightyPix modules are embedded into the fire stations.

reordering of hits will not be possible. Therefore, any hit outside the 25 ns bunch crossing window will be lost. Hence, a 3 ns gaussian Time Of Arrival (TOA) resolution is needed to reach a 99% efficient hit rate. The hit rate will be up to 18 MHz/ cm^2, allowing for a noise below 1 to 2 Hz/pixel at a maximum radiation level of $6 \cdot 10^{14}$ 1 MeV n_{eq}/cm^2. The hit rate decreases for the outer regions of the Mighty Tracker significantly. Thus a variable uplink speed is needed to save bandwidth. These requirements have to be met, tolerating a radiation damage corresponding to $6 \cdot 10^{14}$ 1 MeV n_{eq}/cm^2. One of the points to be clarified is the temperature the irradiated sensors have to operated at.

4. The MightyPix sensor

The first version MightyPix1 of the HV-CMOS sensor which is compatible with the LHCb readout was submitted early 2022 and arrived end of 2022. For this proceedings no measurements with this chip could be performed, but the precursor ATLASPix3.1 [5] was studied in detail. In order to understand the LHCb application, the main differences will be discussed.

The MightyPix has the size of $5 \times 20\,\text{mm}^2$, which is a 1/4 of the final chip in width. It has a separation into a pixel and a periphery region. The pixel matrix consists out of 29 columns and 320 rows. The pixels have a size of $55 \times 165\,\mu\text{m}^2$ and contain an amplifier and comparator. A digital signal will be transmitted to the periphery. There each hit is stored with a unique timestamp in the hitbuffer. For the data readout a single 1.28 Gbit/s connection is foreseen for the MightyPix1. For the final chip four 1.28 Gbit/s connections are planned, which can be multiplexed into a single 1.28 Gbit/s connection. To use the bandwidth and electronic components efficiently, the outer parts of the detector can be slowed to have readout speeds of 680 Mbit/s and 320 Mbit/s. The data format is for the current version $2 \cdot 30$ bit per hit and will contain address, TOA and time over threshold information. For the final chip it is planned to reduce this output to $1 \cdot 30$ bit per hit and only have the time over threshold and other more detailed information in a dedicated readout mode, that can be used to calibrate the detector. The data will be scrambled, balancing the binary output, using a parallel scrambler algorithm previously developed for the VeloPix [3]. The input to the chip is a

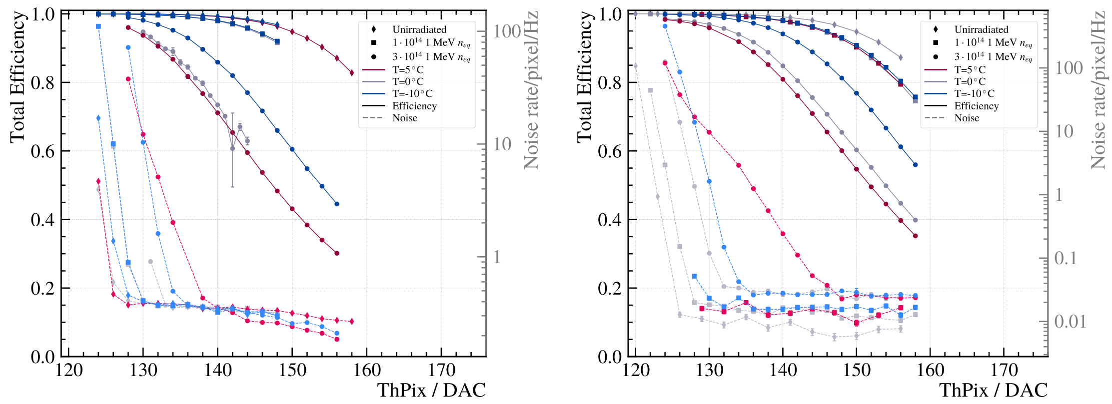
40 MHz clock, Timing and Fast Control (TFC) signal, a reset line and an I2C interface to configure the chip. As development connections a shift register input, additional 320 MHz, 640 MHz clock inputs and some analogue outputs are implemented.

In many ways the ATLASPix3.1 is similar to the MightyPix, with a comparable pixel size, distribution of in pixel and periphery electronics, signal transmission and pixel readout. From the digital part the main difference is that the ATLASPix3.1 has a more complex digital readout, allowing for instance a triggered and untriggerd readout mode and other Experiment specific functionalities. One of the changes with respect to the ATLASPix3.1 is the improved breakdown voltage. While previously the ATLASPix had an abnormal breakdown at 60 V, the MightyPix is improved to have an expected diode breakdown at about 200 V. This will allow a depletion zone up to 70 μm in the sensor. Also the PLL circuit is designed differently not only to allow for the 40 MHz input frequency, but also the generation of the other needed clocks. One other improvement is in the processing of the foundry. The sensors were build on a p-type substrate, serving as depleted collection region, with the electronics shielded from this p-type region by a deep n-well. In this deep n-well n and p-type wells can be used to construct PMOS and NMOS transistors. The drawback of this is that the PMOS transistors are sensitive to electronic noise of the deep n-well. Hence, they cannot be used in fast, low current circuits. This was changed for the MightyPix allowing an additional deep p-well to protect the PMOS transistors from electric noise in the deep n-well. This allows the use of CMOS amplifiers and comparators. It was shown to have a higher amplification and hence better time resolution of the TOA and higher efficiency for smaller signals [6].

5. ATLASPix3 Irradiation Tests

While there were several studies in the past, showing the radiation hardness of the MightyPix precursors [7], this was not the main focus of the research so far. In order to use this chip in LHCb, several key functionalities were tested during a test beam campaign in which ATLASPix3.1 was evaluated. The main focus was on the general functionality, the TOA resolution and temperature dependence of the irradiated chips.

The data was collected in two test beam campaigns at the DESY II facility [8] in June and December 2022. These datasets will be referred to as the PLL- and reference-clock data. The overall performance of the sensors were analysed with respect to temperature, irradiation level and threshold DAC setting. The data was collected using the ADENIUM telescope [9]. The device under test (DUT) data was processed with a DAQ system developed for the MuPix chip [10, 11]. The test beam data was analyzed using Corryvreckan [12]. For the results only a few noisy pixels were masked (less than 20 for the sensor with the most noise). The efficiency was determined by the number of tracks with one associated cluster in the DUT. The noise was extracted for each phase space point in periods with no triggers from the telescope. In figure 2 one can see the noise and efficiency for both test beam campaigns. While the PLL-clock data was collected using the PLL of the ATLASPix3.1 with an input frequency of 125 MHz, which is converted to 625 MHz internally, the second test beam did not use the PLL and the digital part of the ATLASPix3.1 was directly driven by a reference clock of 500 MHz, resulting in a slower readout speed and a maximum timestamp clock of 100 MHz.



(a) Efficiency and noise of the June 2022 test beam campaign with PLL clock.

(b) Efficiency and noise of the December 2022 test beam campaign with external clock.

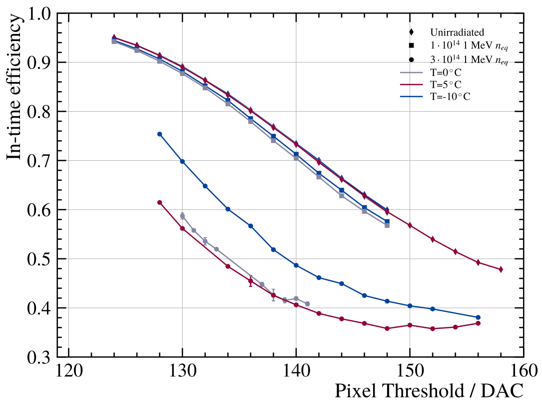
Figure 2: A comparison of the two test beam campaigns in June and December 2022 at the DESY test beam facility. In order to help the readability the darker colors are chosen to depict the efficiency, whereas the light colors show the noise of a specific temperature (indicated by the color) and radiation level (indicated by the marker).

For the data collected with the PLL-clock a clear trend is observable as shown in figure 2 (left). As expected the not irradiated and slightly irradiated sensor ($1 \cdot 10^{14}$ 1 MeV n_{eq}/cm^2) are fully efficient for a broad range of threshold settings and the change in temperature does not seem to have much influence in the performance. The noise analysis confirms this behaviour. The sensor irradiated to a higher level of $3 \cdot 10^{14}$ 1 MeV n_{eq}/cm^2 already shows some significant degradation in efficiency with an increase in noise for low thresholds. The dependence on the temperature is significantly larger, but even at -10°C there is no broad plateau, where the chip could be operated with sufficiently low noise.

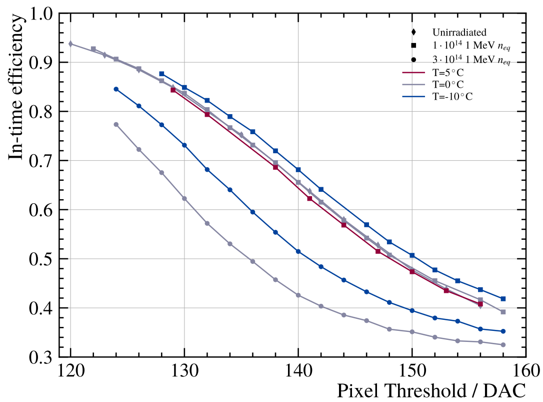
In order to understand this behaviour, further investigations have shown an influence of the PLL on the performance of the sensors. Hence a second test beam was performed, bypassing the PLL. The resulting noise and efficiency can be seen in figure 2 (right). One can see a clear reduction of the noise and hence the parameter scans could be started with lower DAC values. A clear improvement of the efficiency is visible for the sensor irradiated to $3 \cdot 10^{14}$ 1 MeV n_{eq}/cm^2. There is also a clear influence of the temperature visible and for a temperature of -10°C the sensor does have a range thresholds, where the efficiency is high and the noise is sufficiently low.

With the fast scintillators of the ADENIUM telescope a time analysis could be performed. For the PLL-clock data one can see in figure 3 (left) that the fraction of events that are in a 25 ns window is interdependent of temperature, decreases as a function of the threshold and stable for the sensors irradiated up to $1 \cdot 10^{14}$ 1 MeV n_{eq}/cm^2. For the higher irradiated sensor a clear worsening of the in time efficiency is visible, as expected from a reduced signal due to radiation damage, probably suffering from an unstable clock. The best in time efficiency is about (95.0 ± 0.1)%, which is compatible with previous results, showing a time resolution of about 6 ns. To achieve this high time resolution, two effects of the chip needed to be corrected. The first effect is the time walk due to the varying amplitude of the signals was corrected using the time over threshold information of this hit.

This is for the test beam not a as large effect as expected at the LHC because the used electrons have a sharp energy spectrum and there is not as much spread in the deposited energy. The second effect is due to the varying inductance of the metal layers used to transfer the time signal from the pixel to the periphery. This is a known feature and can be corrected as a function of the row address of the chip [7]. All hits in a window of 25 ns around the mean of the TOA distribution are considered to be in time. The uncertainty is propagated from the poisson uncertainty of the data and the uncertainty on the mean of this distribution. The analysis of the data collected with the reference clock, shown in figure 3 (right), shows a similar behavior. The sensor irradiated to $3 \cdot 10^{14}$ 1 MeV n_{eq}/cm^2 shows a much improved time resolution, but the best in time efficiency is still $(84.5 \pm 0.1)\%$. In total the in time efficiency seems to be slightly lower compared to the data using the PLL clock. This is probably due to the lower time clock frequency and the fact that the clock is not synchronised with any beam structure.



(a) In time efficiency of events for the June 2022 test beam campaign with PLL clock.



(b) In time efficiency of events for the December 2022 test beam campaign with external clock.

Figure 3: Fraction of events within one bunch-crossing of 25 ns.

6. Conclusion

The Mighty Tracker is an ambitious project, covering an area of 18 m^2 with HV-CMOS pixel sensors in addition to the low material fibre instrumentation. This technology allows for a low number of connections and the simplicity of the sensors, allowing a coverage of this large area. First prototypes of this technology have shown a promising chip performance. The test beam campaigns have shown that the precursors of the MightyPix have a efficiency of more than 99.9% and a very good in time efficiency of $95 \pm 0.1\%$, corresponding to a TOA resolution of about 6 ns. Radiation damage seems to affect the PLL of the ATLASPix3.1 and the in time resolution is not yet at the level needed for the streaming readout. With the change to CMOS amplifier and comparator and the improved breakdown voltage in the MightyPix1, is aimed to perform even better and meet the requirements. The operation temperature of the ATLASPix3.1 seems to have small effect up to the point, where of the radiation damage effects become visible. At this point the lowering of the operation temperature to -10°C does improve the performance.

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