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Towards MightyPix, an HV-MAPS for the LHCb Mighty Tracker upgrade

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Abstract: The Mighty Tracker is a proposed upgrade to the downstream tracking system of LHCb for operations at luminosities of up to 1.5×10^{34} cm^{-2} s^{-1} starting with the LHC Run 5 data taking period. It foresees the replacement of the most central area of the current scintillating fibre tracker with High Voltage CMOS (HV-CMOS) pixel sensors. Due to the increased luminosity, occupancy will be too high for track reconstruction in the fibre tracker and the fibres would no longer withstand the radiation damage. HV-CMOS sensors have demonstrated a significant radiation tolerance and good performance making them an ideal choice of technology for the LHCb experiment. Monolithic Active Pixel Sensors (MAPS) fabricated in HV-CMOS processes provide fast charge collection via drift and allow the implementation of the readout on the same die as the sensitive volume. Due to the use of commercial processes, these sensors can be fabricated at low cost as no hybridisation with bump bonds is required. Since they are not fully depleted, the inactive volume can be reduced by thinning to achieve a total die thickness of 50 to 100 microns. A dedicated sensor called the MightyPix is developed for this programme. It is based on the HV-MAPS families MuPix and ATLASPix and tailored to the requirements of LHCb. To demonstrate the feasibility of this technology for the LHCb environment, prototypes have been irradiated. These sensors are tested in terms of efficiency, time resolution and power dissipation in temperature controlled environments.

Keywords: Particle tracking detectors (Solid-state detectors); Radiation-hard detectors

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1 Introduction

The LHCb experiment [1] is a single arm forward spectrometer operating at the LHC at CERN. It is dedicated to the study of flavour physics at unprecedented precision and the search for physics beyond the standard model via indirect signatures. To achieve these goals highly precise tracking is required.

To improve the sensitivity to rare processes with the proposed upgrades to the LHCb luminosity and replace ageing detector components, LHCb is conducting and planning upgrades as shown in figure 1. Currently, in Long Shutdown 2 (LS2), the installation of new systems is underway. The cross section of the detector after the upgrade is depicted in figure 2. Among the changes to the tracking systems relative to the original detector are the construction of a new Vertex Locator (VELO), Upstream Tracker (UT) and the replacement of the inner and outer tracker with the new Scintillating Fibre (SciFi) Tracker.

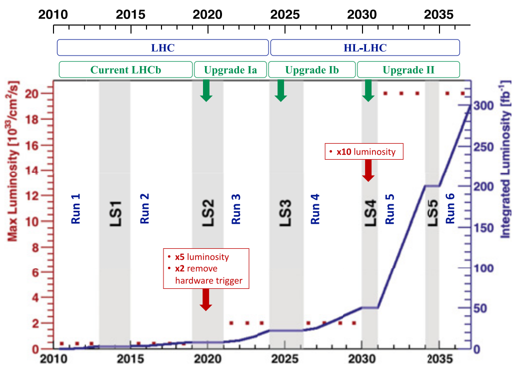

Figure 1. Time line of the current and proposed LHCb upgrades with the expected luminosity [2].

The SciFi consists of twelve $6\,\text{m} \times 5\,\text{m}$ detection layers, fabricated from scintillating fibres which are coupled to silicon photomultipliers at both ends. To reduce optical path length, increase light yield, and provide additional spatial information, the fibres are split in the centre by mirrors. Two-dimensional resolution is achieved by alternating layers at a stereo angle of $\pm 5^\circ$ [2].

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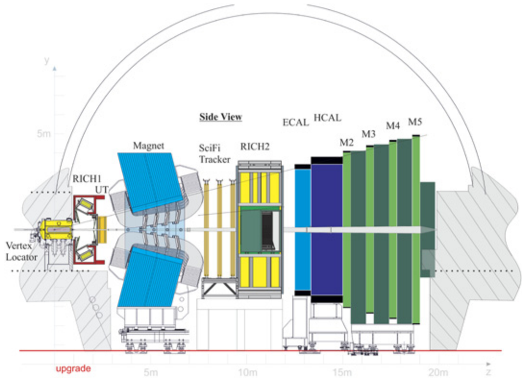

Figure 2. Cross section of the LHCb detector after LS2 [3].

2 The Mighty Tracker

The Mighty Tracker is a proposed upgrade to the SciFi Tracker for Run 4 and Run 5. The concept foresees the replacement of the area of the SciFi closest to the beam pipe with pixel detectors as shown in figure 3 to create a hybrid station. For the first stage in Run 4, only the closest region is to be instrumented with pixel sensors (rose coloured area in figure 3), which is called the Inner Tracker (IT). For the second stage, planned for after LS4, the area covered by silicon will be enlarged to allow running at higher luminosity as shown in blue in figure 3. In total an area of 18 m^2 will be covered with silicon.

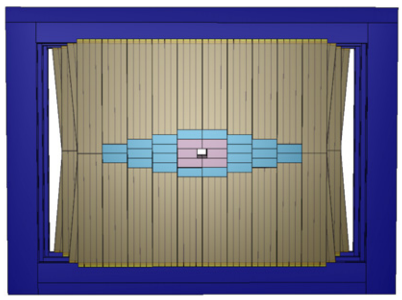

Figure 3. Concept of one tracking station of the Mighty Tracker. The rose coloured area will be instrumented with pixel detectors in for Run 4. For Run 5, the blue regions will be added [2].

The motivation for this proposal are performance studies for the SciFi at increased luminosities, shown in figure 4. While the luminosity does not change between Run 3, for which the SciFi was designed, and Run 4, the rate would be too high for Run 5. At high occupancy, a ghost rate of 90% and an efficiency of between 50% and 60% would result in an unacceptable performance for the SciFi Tracker only case while the Mighty Tracker scenario shows significant improvement over the SciFi configuration. Additionally, the radiation damage in the fibres due to the high fluence close to the beam pipe will reduce their efficiency rapidly.

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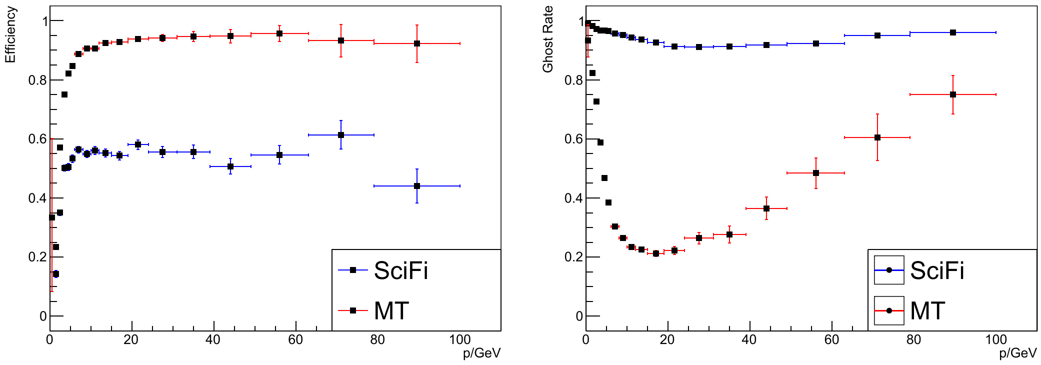

Figure 4. Simulated reconstruction efficiency (left) and ghost rate (right) as function of momentum for the Run 5 luminosity of $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. SciFi (blue) denotes the geometry of the scintillating fibre tracker of Run 3 while MT (red) represents the Run 5 geometry of the Mighty Tracker as shown in figure 3. Adapted from [2].

3 MightyPix development

The technology chosen for the development of the pixel sensor for the Mighty Tracker, the MightyPix, is the HV-CMOS Monolithic Active Pixel Sensor (HV-MAPS) concept [4]. It allows the fast charge collection in the order of a nanosecond [5] via drift in a depleted diode and the implementation of sophisticated readout electronics in one piece of silicon. The usage of commercial processes without the requirement of bump bonding steps makes this technology very attractive for instrumenting large areas. Sensors can be thinned to 50–100 micron thickness to reduce material budget and have shown radiation tolerance with an efficiency of greater than 99% with an average noise rate below 40 Hz at a fluence of $1 \times 10^{15}\,\mathrm{n_{eq}/cm^2}$ for an ATLASPix1 sample of 62 micron thickness [6].

To demonstrate the suitability of this technology for the Mighty Tracker, prototypes developed for other experiments, namely MuPix10 [7] and ATLASPix3 [8], are investigated in terms of efficiency, time resolution, power dissipation, and temperature dependence (figure 5). The input from results of these large scale prototypes will be used for the design of MightyPix1. Both sensors share a very similar architecture with the key difference being the placement of the comparator. Each analogue pixel has a corresponding digital partner cell to which it is point-to-point connected. In MuPix10, the comparator of each pixel is placed in the digital partner cell while in the ATLASPix3, the comparator is placed already in the analogue cell. For MightyPix1 the ATLASPix architecture is preferred. For ATLASPix3 a time resolution of around 4 ns has been measured [9].

Samples have been irradiated with neutrons at the JSI TRIGA reactor [10] in Ljubljana with a fluence of up to $9 \times 10^{15}\,\mathrm{n_{eq}/cm^2}$. The samples are still under investigation and results are pending.

A cooling setup has been developed at the University of Liverpool to study the performance of unirradiated and irradiated samples as shown in figure 6. A copper chuck which can be either heated or cooled by a Peltier element is thermally connected to the backside of the circuit board the sensor is mounted on. The heat of the Peltier element is carried away by a commercial CPU cooler.

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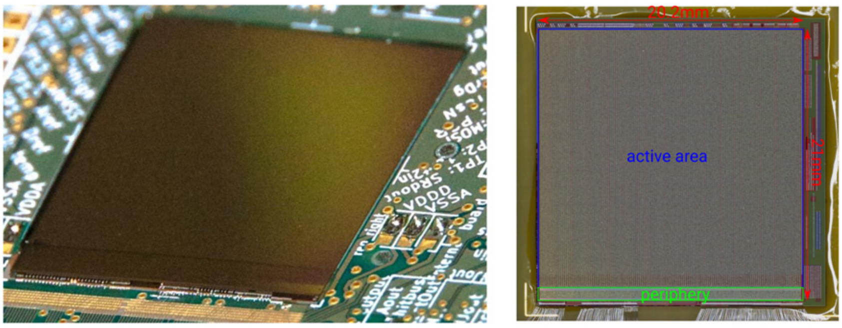

Figure 5. Pictures of the investigated sensors: MuPix10 (left, adapted from [7]) and ATLASPix3 (right) [9] (original credit: Lars Noehte).

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To prevent ice formation the setup is constantly flushed with dry nitrogen. Thermistors in the chuck and a humidity sensor are used to monitor the system.

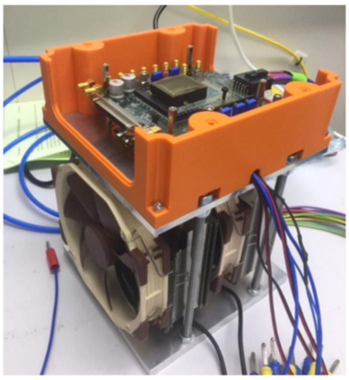

Figure 6. Setup developed for the characterisation of HC-CMOS sensors at temperatures above and below room temperature.

In order to prepare for the characterisation of irradiated sensors, unirradiated MuPix10 samples have been measured in a testbeam at CERN in August 2021 at various temperatures above and below room temperature. Analysis is currently ongoing.

The design of MightyPix1, the first dedicated sensor for the Mighty Tracker, is ongoing. It will have the full column length of about 2 cm with a reduced width of approximately 5 mm. Its readout architecture will be compatible with the LHCb readout scheme. Submission is foreseen for early 2022.

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