HV-MAPS for the LHCb Upgrade-II Mighty Tracker

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Outline

1 Introduction

- The LHCb Experiment and Upgrade-II
- The Mighty Tracker
- The MightyPix and friends

2 Activities and Studies

- Overview
- DESY Testbeam June 2022
- Lab measurements

3 Conclusion

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Large Hadron Collider beauty (LHCb) Experiment

- The LHCb experiment is a forward-arm spectrometer.
- Used to study CP Violation, beauty decays, hadron spectroscopy, charm physics, rare decays, and more!
- 9 fb⁻¹ recorded in Run 1 + Run 2.
- Upgrade-I: replaced much of the detector for Run 3
 - No hardware trigger: GPU-based HLT1 & CPU-based HLT2.
 - \blacksquare \rightarrow Now in operation / commissioning!



LHCb Upgrade-II

 The second LHCb detector Upgrade is planned for Long Shutdown 4 (LS4) of the LHC.



LHCb Upgrade-II

- The High Luminosity LHC (HL-LHC) will see
 - an order of magnitude increase in instantaneous luminosity to $1.5\times 10^{34}~{\rm cm}^{-2}{\rm s}^{-1}.$
 - an increase in expected interactions per bunch crossing (≈ 40).
- LHCb detector requires upgrades to cope with the new operating conditions
 - Higher radiation dose.
 - Increased particle multiplicities and rates.
- This talk will focus on the upgrade of the downstream tracking system: the Mighty Tracker.



LHCb Upgrade-II & The Mighty Tracker (MT)

- What if we keep Sci-Fi approach for downstream tracking?
- Based on simulation: at the expected instantaneous luminosity → very high detector occupancy close to the beam pipe.



Detector occupancy per fibre per event (averaged over forty fibres in top half of the downstream tracker) and Ghost Rate with and without MT-MAPS. From [5].

The Mighty Tracker (MT)

- The Mighty Tracker is a hybrid approach making use of both scintillating fibres (SciFi) and HV-MAPS technology.
 - Hybrid solution balances cost and physics/detector performance needs
- Three MT tracking stations (T1-T3) downstream of the magnet.
- Scintillating Fibre detectors covering outer region: 4 SciFi layers per station (12 total) with 6 modules per layer.





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The Mighty Tracker

- Expected high-occupancy region to be covered by HV-CMOS sensors.
- High granularity, timing resolution, and radiation hardness.
- Each tracking station has two silicon panels (or one layer). One layer has 28 modules (see below).



Red – Inner Tracker modules (6). Blue – Middle Tracker modules (22). Active pixel area: 3 m² / layer.

The Mighty Tracker: MT-MAPS modules



A single Mighty Tracker module. Each grey rectangle represents a MAPS chip. The other side has an offset arrangement such that the entire plane is covered. From [5].

LS3 Enhancements

After Run 3, radiation damage expected in the inner region of SciFi

- Light yield from Scintillating Fibres degraded leading to less efficient tracking \rightarrow replacement required.
- Opportunity to introduce MightyPix HV-CMOS sensors (MT-MAPS).
- Two or three layers of MAPS.
- 6 modules per layer (red).
- Inner tracker region only.





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MightyPix R&D: requirements

Programme dedicated to developing a HV-CMOS sensor that meets the following requirements for the Mighty Tracker:

Pixel Size	$< 100 \times 300 \mu \mathrm{m}$	
Timing resolution	pprox 3 ns within 25 ns window	
In-time efficiency	>99% within 25 ns window	
Radiation tolerance	$6 \times 10^{14} \ \mathrm{n_{eq} cm^{-2}}$	
Noise limit	5 Hz/pixel	
Power consumption	$< 150 \ { m mW} \ { m cm}^{-2}$	
32-bit data word.		
Compatible with LHCb Readout system		

From [1].

N.B. Studies are ongoing, and these requirements may evolve.

MightyPix1

- The first HV-CMOS sensor dedicated to the Mighty Tracker!
- Designed by Karlsruhe Institute of Technology.
- Submitted May Delivery expected Dec 2022.
- Fabrication with TSI (180 nm node).

Pixel Size	$55 \ \mu m \times 165 \ \mu m$	
Pixel Matrix	320 rows \times 29 columns	
Chip Size	$5 \text{ mm} \times 20 \text{ mm}$	
Readout Format (not final) compatible with LHCb readout		

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ATLASPix3.1

- Well-characterised HV-CMOS prototype.
- MightyPix1 is based on the ATLASPix3.1.
- Fabrication with TSI (180 nm node) as with MightyPix1.

Pixel Size	$50 \ \mu m \times 150 \ \mu m$
Pixel Matrix	372 rows \times 132 cols
Chip Size	$20.2 \text{ mm} \times 21 \text{ mm}$

- Triggered / untriggered readout
- Can be used as a proxy to evaluate key parameters
 - \rightarrow both in lab and at testbeam.
- Designed for another experiment don't expect to exactly fulfill MP requirements.



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Overview of testbeam activities

- Testbeams have been conducted at DESY Testbeam (Hamburg) and SPS North Area (CERN), since 2020.
- Much experience gained, and infrastructure developed.
- Results presented in this talk: Testbeam at DESY, June 22



DESY Testbeam June 2022

Three ATLASPix3.1 sensors were tested at the DESY-II testbeam facility [3]

- Unirradiated
- Irradiated $10^{14} n_{eq} cm^{-2}$
- Irradiated $3 \times 10^{14} n_{eq} cm^{-2}$
- Temperatures -10, 0, 5 °C. 4.8 GeV electrons, at a rate O(10 kHz).
- We have another testbeam in December this year we would like to test ATLASPix3.0.



We thank DESY for smooth operation of the testbeam facility!

DESY Testbeam June 2022: Beam Telescope

- The EUDET2 adenium beam telescope was used (we were the first users!)
 - six ALPIDE [6] sensor layers
 - Device Under Test (DUT) situated between third and fourth layers.
 - Trigger scintillator providing timestamp from AIDA TLU
 - EUDAQ system (triggered telescope) + MUDAQ (untriggered readout device under test)





DESY Testbeam June 2022 - Efficiency Results

- Telescope events are reconstructed using analysis software corryvreckan [2]. Tracks reconstructed with General Broken Lines.
- Total efficiency: fraction of reference tracks with associated DUT hit.



Diagram demonstrating tracking and DUT hit association (simplified straight line traj., no multiple scattering)

DESY22 – Efficiency (Unirradiated, Irradiated 1×10^{14})

- Unirradiated: Starts high $\approx 100\%$ at low thres. largely the same between temperatures. (Baseline: 109 DAC)
- $1 \times 10^{14} n_{eq} cm^{-2}$: noticeably faster drop in efficiency vs. threshold.



DESY22 – Efficiency $(3 \times 10^{14} \text{ fluence})$

- $3 \times 10^{14} n_{eq} cm^{-2}$: steeper decreases, and greater dependence on operating temperature. >98% efficiency achieved at -10 °C.
- Lower statistics available. Less repeats and a misaligned trigger scintillator. Sensors operated at the same settings. More work to do optimising settings for better performance.



DESY22 – Time of Arrival Resolution

 Time resolution measured by a crystal ball fit to the central portion of the time residual histogram for DUT hits

residual = $t_{\text{track}} - t_{\text{hit}}$, ToA resolution = $\sqrt{\sigma^2 - (8 \text{ ns}/\sqrt{12})^2}$.

 Trigger scintillator in setup provides t_{track} timestamp. Time delay, time-walk corrected offline. 8 ns binning correction also applied.



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DESY22 – Time of Arrival Resolution (to $10^{14} n_{eq} cm^{-2}$)

• 5 ns resolution with > 99% chip efficiency for up to $10^{14} n_{eq}$ cm⁻². Observe similar trend for both AP3.1 sensors



DESY22 – Time of Arrival Resolution (up to 3×10^{14})

- $3 \times 10^{14} n_{eq} cm^{-2}$: degraded time resolution (possibly due to non-optimal chip settings, and lower stats)
- Possible to revisit these measurements at an upcoming testbeam this December.



DESY22 – Noise estimates (WIP)

- Due to DESY beam structure, we tried estimating the noise per pixel from the ATLASPix3.1 hits registered out of trigger.
- \blacksquare For up to $10^{14}~n_{eq} {\rm cm}^{-2},$ the noise rate per pixel is approximately below 1 Hz for thresholds above 128 DAC



Lab measurements: Amplifier plots

- S-curves used to measure amplifier gain
- AP3.1 has nominal resistivity of $200 400 \ \Omega$ cm. Expect $\approx 30 \ \mu$ m depletion depth at 60 V bias voltage. 2400*e* per MIP.



Lab: IVs

Leakage current vs. Bias Voltage for different temperatures and fluences.
 Large temperature dependence.



Rate measurements

- X-ray tube used in lab to determine rate limitations for AP3.1
- Experimental data agrees with theoretical limits. Now waiting for MightyPix1.



Anode current is linearly dependent on photon rate.

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Looking Forward

- MightyPix1 submitted this year and back in December.
- Aim to characterise early next year.
- Testbeam with MightyPix1: Summer 2023 earliest.
- After that: Submit full size chip.
- Plan to publish LHCb internal note on testbeam results this year.

Conclusion

In conclusion

- DESY Testbeam results with ATLASPix3.1 show
 - a high total efficiency (> 99%) for the lowest thresholds.
 - a time resolution down to ≈ 5 ns (lowest thresholds).
 - Noise estimate below ≈ 1.25 Hz after ≈ 130 DAC ($< 10^{14}$ n_{eq} cm⁻²).
 - We hope for a timing performance closer to our target requirements with the MightyPix1.
 - The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).
 - Much experience gained along the way, in testbeam, lab setups, and analysis.
 - MightyPix1 submitted and on the way, with more testbeams planned.



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Thank you for listening!

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ATLASPix1

Summary of Efficiencies after Irradiation

- no tuning of pixels;
- ≤ 81/10000 pixel masked

Efficiency _{40 Hz}	sub- strate	thick- ness		bias v (#mask	oltage ed pixel)	
fluence (neq/cm²)	(Ω cm)	(µm)	60 V	70/75 V	80/85 V	90/95 V
n 2e15	80	62	98.5% (81)	98.4% (81)	98.6% (81)	
n 1e15	80	62	99.3% (38)		99.5% (38)	99.5% (39)
n 5e14	80	62	99.5% (19)			
n 2e15	200	100	96.5% (55)		98.7% (60)	98.7% (55)
n 1e15	200	100/725	98.7% (18)	99.4%	99.5%	99.4%
n 5e14	200	100	99.2% (14)			
p 5e14 (50 MRad)	200	100	≥ 99.6% (9)	≥ 99.7% (9)	≥ 99.9% (9)	
p 1e14 (10 MRad biased)	200	725	≥ 99.7%			

≥ means that the 40 Hz/pixel noise limit was not reached

From this talk here.

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ATLASPix1 & ATLASPix3

TABLE I ATLASPIX3 SPECIFICATIONS

Chip area/thickness	2 cm × 2 cm / 250 μm
Pixel size	50 μm × 150 μm
Detection efficiency	99% in 25 ns time window
Noise rate per pixel	5 Hz – 40 Hz/pixel
Power consumption	<500 mW/cm ² (preferably 150 mW/cm ²)
Current consumption	<240 mA/cm ²
Radiation doses	800 kGy TID & 1.5 10 ¹⁵ n _{eq} /cm ² NIEL
Operating temperature	- 25 °C (maximum ratings - 55 °C to +60 °C)
Signal, Noise and	S > 2.06 Th for 99% of signals and pixels
threshold	

ATLASpix3 specifications.

From [7].

- 132×372 pixel matrix.
- Measured time resolution $\sigma = (5.0 \pm 0.1)$ ns [4].

corryvreckan analysis chain

- Event loading from EUDAQ (TLU and telescope)
- Event loading from MuPixDAQ
- Clustering (clusters are typically size-1)
- Tracking with General Broken Lines.
 - A track must have a hit on all telescope planes.
 - No DUT in tracking.
 - Momentum 4.8 GeV.
- Filter events with no tracks or more than one track
- DUT cluster association to tracks.

Large spatial and time cut used (deemed unnecessary to tighten)

- AP3.1 (DUT): Time delay and time walk correction
- Analysis of DUT efficiency and timing (track $\chi^2/N_{dof} < 5$).

DESY22 – Delay correction

- A row-dependent delay is observed in AP3.1 time residual distributions, and a time offset over the entire sensor.
- This delay is caused by differing lengths of the wires from pixels. A correction for each row is calculated per metal layer in the sensor.
- The time offset is determined for each run from the peak position of the time correlations between DUT hits and a chosen telescope reference plane.

DESY22 – Time Walk correction

- After the delay correction, a ToT-dependence is observed in the time residual.
- Each ToT bin is shifted by using the peak postion of the time residual in 250ns ToT slices centred on that bin.
- Corrected during analysis (ideally not needed for MightyPix)



Left - Uncorrected for time-walk. Right - corrected for time walk

Backup

DESY22 – noise estimate



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DAC units

baseline 0x6D = 0d109
 1 DAC = 1.8 V / 256 ≈ 7 mV

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