Testbeam Analysis for the LHCb Upgrade-II Mighty Tracker

Ryunosuke O'Neil

The University of Edinburgh
r.oneil@cern.ch

on behalf of the LHCb Mighty Tracker Group

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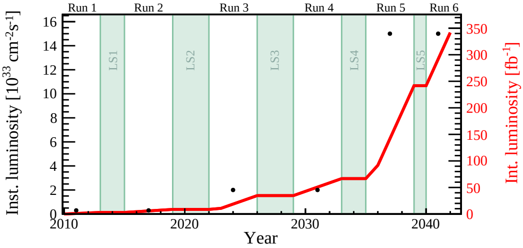
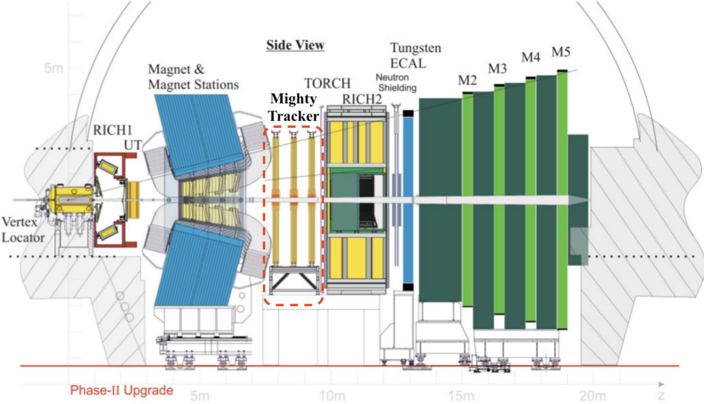
Outline

LHCb Upgrade-II

- The High Luminosity LHC (HL-LHC) will see
    - an order of magnitude increase in instantaneous luminosity to 1.5×10^{34} cm^{-2}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.

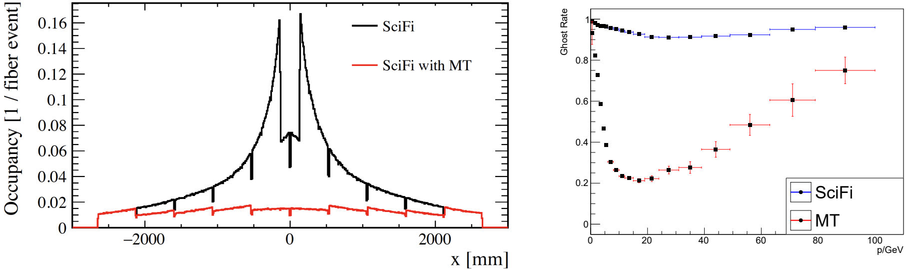


LHCb Upgrade-II



LHCb Upgrade-II & The Mighty Tracker (MT)

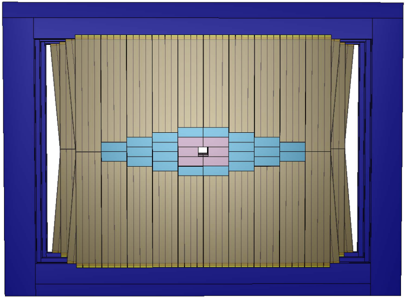
- What if we keep Sci-Fi approach for downstream tracking?
- Based on simulation: at the expected instantaneous luminosity → very high detector occupancy close to the beam pipe.

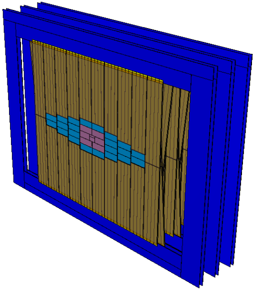


Detector occupancy per fibre per event (averaged over forty fibres in top half of the downstream tracker) **and** Ghost Rate with and without MT-MAPS. From [5].

The Mighty Tracker (MT)

- The Mighty Tracker is a hybrid approach making use of both scintillating fibres (SciFi) and HV-MAPS technology.
- 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.





MightyPix R&D: requirements

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

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

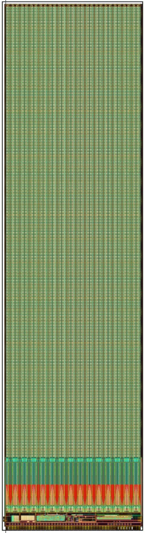
From [1].

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.
- Fabrication with TSI (180 nm node).
- Submitted May – delivered Dec 2022.

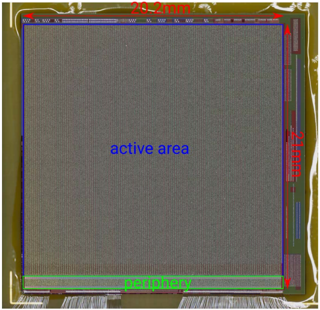
Pixel Size	$55\ \mu m \times 165\ \mu m$
Pixel Matrix	320 rows × 29 columns
Chip Size	5 mm $\times$ 20 mm (1/4 size)
Readout Format (not final) compatible with LHCb readout	



ATLASPix3.1

- Full-size, 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 × 132 cols
Chip Size	$20.2\ mm \times 21\ mm$



- Can be used as a proxy to evaluate key parameters
  → both in lab and at testbeam.
- Different Comparator and Amplifier
  → no 3 ns time resolution.

Outline

1 Introduction
- LHCb Upgrade-II
- The Mighty Tracker
- The MightyPix and friends

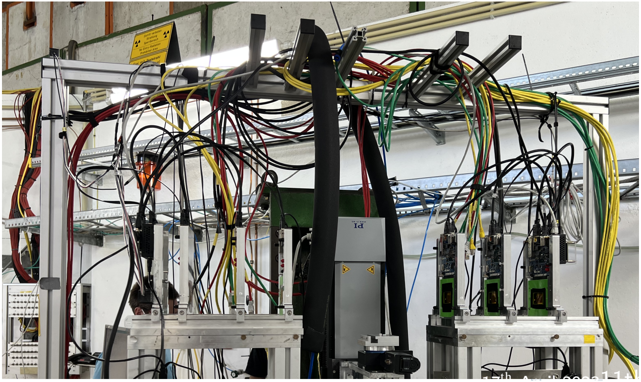
2 Activities and Studies
- Overview
- DESY Testbeam June and December 2022

3 Conclusion

4 Backup

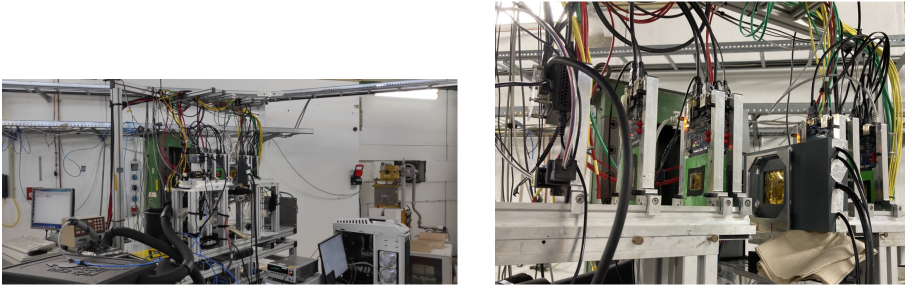
Overview of testbeam activities

- Two testbeam campaigns were conducted at DESY Testbeam Facility in June and December 2022
- Why two testbeams?
  - Build experience and analysis infrastructure - fix issues encountered during June datataking (?)



DESY Testbeam: Beam Telescope

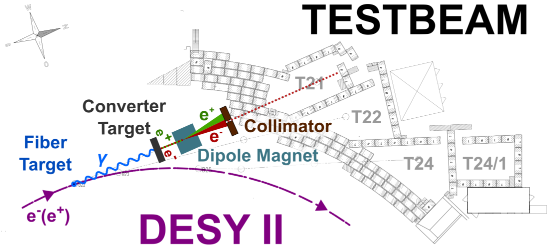
- The EUDET2 `adenium` beam telescope was used (first users!)
  - six ALPIDE [6] sensor layers
  - Device Under Test (DUT) situated between third and fourth layers.
  - Trigger scintillator providing timestamp from AIDA TLU
  - EUDAQ system (triggered – telescope) + MUDAQ (untriggered readout device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



Pictures from June testbeam.

DESY Testbeam June 2022

- Three ATLASPix3.1 sensors were tested at the DESY-II testbeam facility [3] (later slide) over 5 days.
- Temperatures $-10,\ 0,\ 5$ °C. 4.8 GeV electrons, at a rate $O(10\,\mathrm{kHz})$.
- Data quality issues encountered e.g. runs cut short by issues when using internal chip clock leading to lower statistics.



We thank DESY for smooth operation of the testbeam facility!

DESY Testbeam December 2022

- Same facility, but different beam area (T24). More time – 10 days.
- More ATLASPix3.1 sensors and the ATLASPix3.0 were able to be tested (next slide)
- Temperatures $-10, \ 0, \ 5$ °C.
- 2.8 GeV electrons.
  - Lower beam energy than June.
  - In T24, a higher beam energy could not be achieved without significantly reducing beam rate.
- An external clock is used rather than the internal chip clock to avoid chip operation stability issues seen in June. e.g. out of address pixels.

Measurements covered in June and December 2022

Table: DUT summary and statistics obtained at different operating temperatures in June and December.

Sensor ID	**Sensor Type**	**Irradiation Level** 1MeV n_{eq}/cm^2	**-10°C** **Jun/Dec**	**0°C** **Jun/Dec**	**5°C** **Jun/Dec**
L5	3.1	Unirradiated	✓ ✓	✓ ✓	✓ ✓
L6	3.1	$1 \cdot 10^{14}$	✓ ✓	✓ ✓	X ✓
L9	3.1	$3 \cdot 10^{14}$	✓ ✓	✓ ✓	✓ ✓
L10	3.1	$1 \cdot 10^{15}$	X ✓	X ✓	X ✓
L13	3.1	$3 \cdot 10^{15}$	X ✓	X ✓	X ✓
L3	3.0	Unirradiated	X ✓	X ✓	X ✓

Analysis workflow

- Testbeam data from both EUDET2 telescope and MuPixDAQ are loaded and reconstructed using analysis software Corryvreckan [2].
- A `snakemake` workflow defines
  - which configuration of `corry` to run for the many hundreds of runs obtained.
  - which plotting scripts to run
- Scripts written to semi-automate the telescope and DUT alignment process.
- Highly automated analysis workflow → faster analysis. Reusable analysis code for future testbeams.
- Code and analysis preservation in `git` repository (GitLab) for each testbeam campaign.

Efficiency

- Telescope tracks reconstructed with General Broken Lines (GBL) tracking model. DUT not included in track fit.
- Total efficiency: fraction of reference tracks with associated DUT hit.

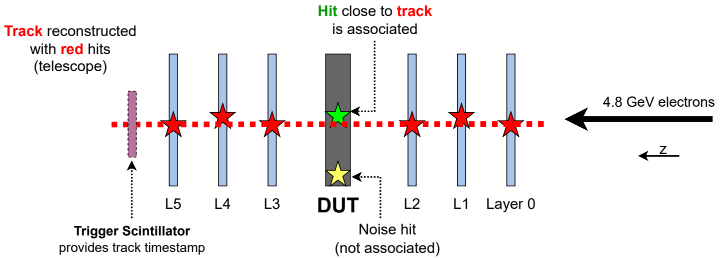
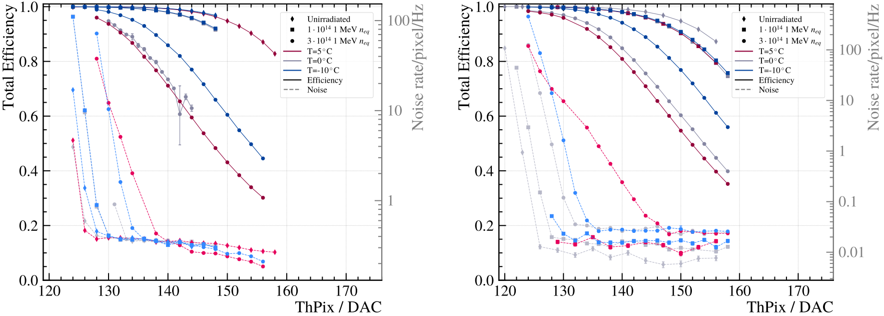


Diagram demonstrating tracking and DUT hit‘ association (simplified straight line traj., no multiple scattering)

Total Efficiency $(0,\ 1\cdot10^{14},\ 3\cdot10^{14})$ 1MeV n_{eq}/cm^2

- 100% achieved at lower thresholds. Efficiency drops at a higher rate with increasing threshold as irradiation level increases.
- December results validate those from June.



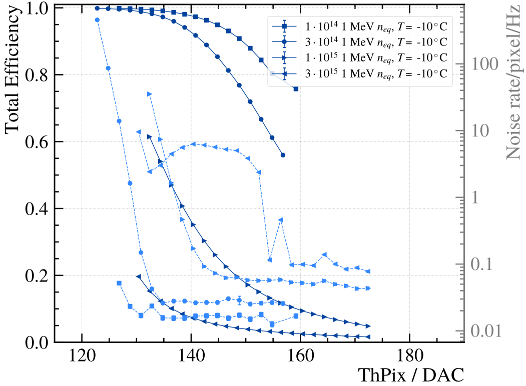
Left: June results. **Right:** December results.

Diamond – Unirradiated. *Square* – 1×10^{14}. *Circle* – 3×10^{14}.

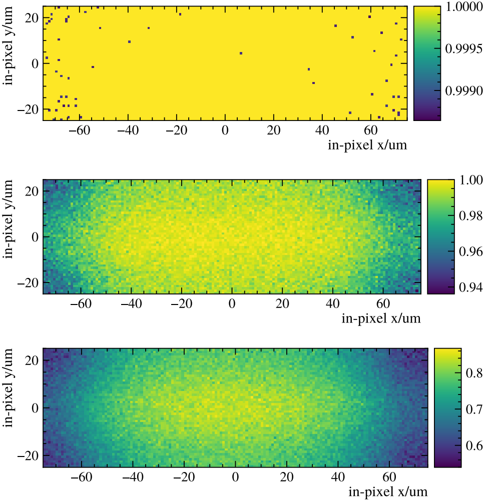
Dashed lines represent noise rate estimates (grey axis).

Efficiency ($> 3 \times 10^{14}$ fluence, -10 °C)

- Sensors are operable, but high noise observed and low efficiencies at $< 60\%$ $(1 \cdot 10^{15})$ and $< 20\%$ $(3 \cdot 10^{15})$.



Quick look at the in-pixel efficiency



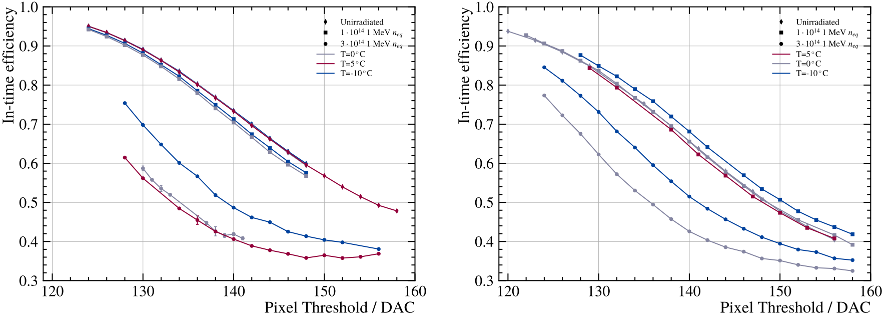
- AtlasPix3.1. HV: 60 V.
- From top: 120, 140, 160 DAC
- Lower efficiency towards the corners.

In-time efficiency

- In-time efficiency is the preferred measure of timing performance, over Time of Arrival (ToA) resolution.
- Defined as the fraction of DUT hits registered within a 25 ns window.
    - In the HL-LHC: 25 ns is the time between each bunch crossing.
- This fraction can be measured using the time resolution histogram, and does not require a fit (and the instabilities that come with it) - making this quantity more reliable.

In-time efficiency $(0,\ 1\cdot 10^{14},\ 3\cdot 10^{14})$ $1\mathrm{MeV}\,\mathrm{n}_{\mathrm{eq}}/\mathrm{cm}^2$

- $\geq 99\%$ not achievable with AP3.1 and 3 ns not reached (This is expected.)
- Worse performance at higher fluences.



Left: June results. **Right:** December results.

⧫ Unirradiated. ■ 1×10^{14}. • 3×10^{14}.

Red 5 °C. Grey 0 °C. Blue −10 °C.

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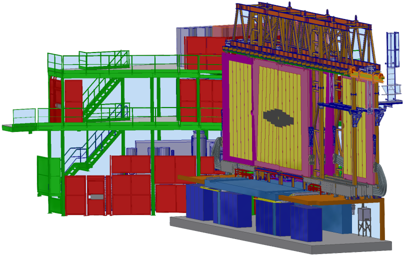
MightyPix: Looking Forward

- LHCb internal note on all AtlasPix3.1 testbeam results in preparation.
- MightyPix1 was received in December 2022
  - Found to have a mistake in the design
  - Resubmission MP1 / repairs / other: all avenues being explored.
- Next Testbeam: Scheduled at DESY 11/Jun/2023 ~ 25/Jun/2023
  - We must push forward with alternative, similar chip
  - Unirradiated + sensors irradiated at Bonn
  - Similar analogue pixel design
  - Different pixel size, better timing expected.

In conclusion

- DESY Testbeam results with ATLASPix3.1 show
  - a high total efficiency ($> 99\%$) for the lowest thresholds.
  - $\geq 99\%$ in-time efficiency not reached for AP3.1.
  - December results cover more ground and validate June results.
  - We hope for a timing performance closer to our target requirements with the MightyPix1.

- Much experience gained along the way, in testbeam, lab setups, and analysis.
- Next testbeam this June 2023!



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).

Thank you for listening!

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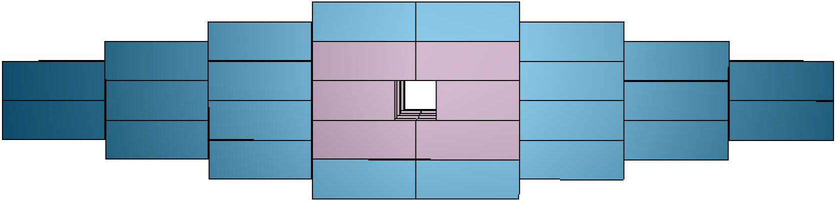
The Mighty Tracker

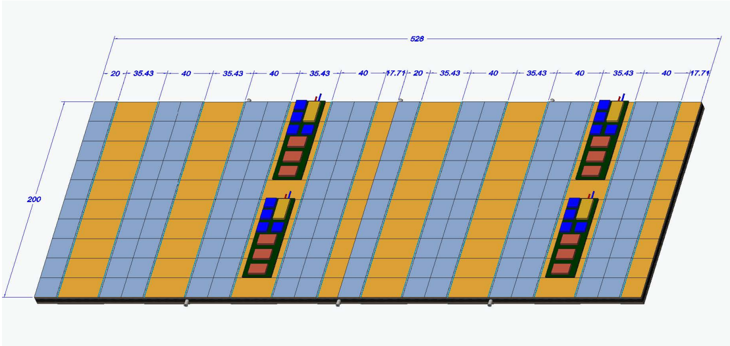
- Expected high-occupancy region to be covered by HV-CMOS sensors.
- High granularity, timing resolution, and radiation hardness.
- Each tracking station has two silicon panels (or one layer). One layer has 28 modules (see below).



Red – Inner Tracker modules (6). **Blue** – Middle Tracker modules (22).

Active pixel area: 3 m^2 / layer.

The Mighty Tracker: MT-MAPS modules

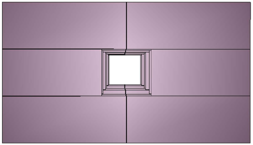


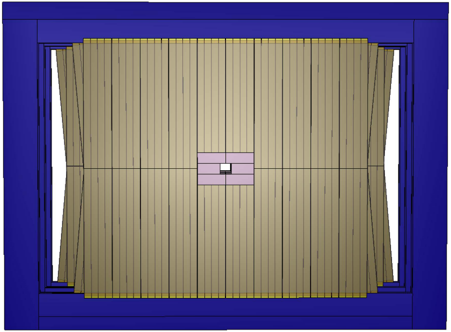
A single Mighty Tracker module. Each grey rectangle represents a MAPS chip. The other side has an offset arrangement such that the entire plane is covered. From [5].

LS3 Enhancements

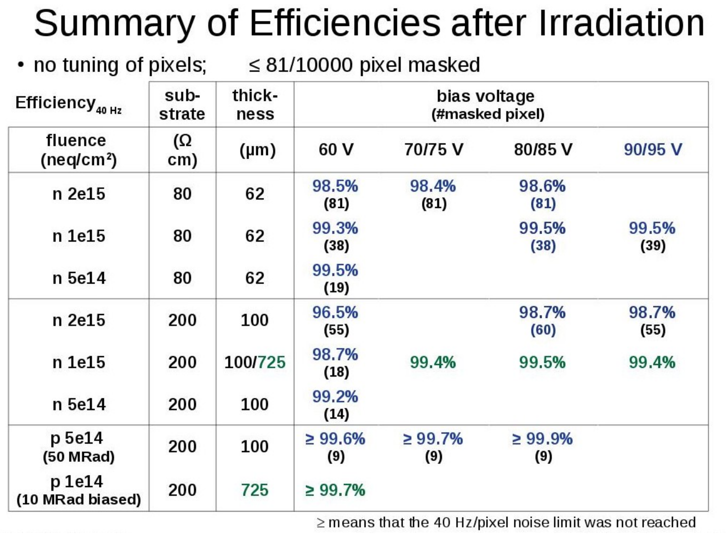
- After Run 3, radiation damage expected in the inner region of SciFi
  - Light yield from Scintillating Fibres degraded leading to less efficient tracking → replacement required.
- Opportunity to introduce MightyPix HV-CMOS sensors (MT-MAPS).

- Two or three layers of MAPS.
- 6 modules per layer (red).
- Inner tracker region only.





ATLASPix1



Summary of Efficiencies after Irradiation

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

Efficiency$_{40\ Hz}$ fluence (neq/cm²)	sub-strate (Ω cm)	thick-ness (μm)	bias voltage (#masked pixel) 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.**

ATLASPix1 & ATLASPix3

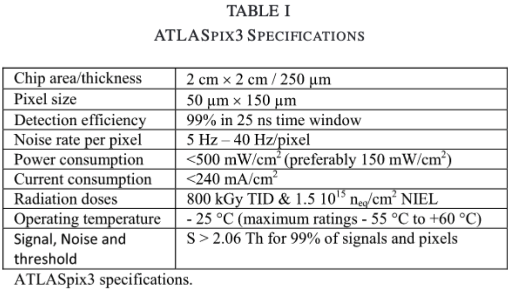


TABLE I
ATLASPIX3 SPECIFICATIONS

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 threshold	S > 2.06 Th for 99% of signals and pixels

ATLASpix3 specifications.

From [7].

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

`corryvreckan` analysis chain

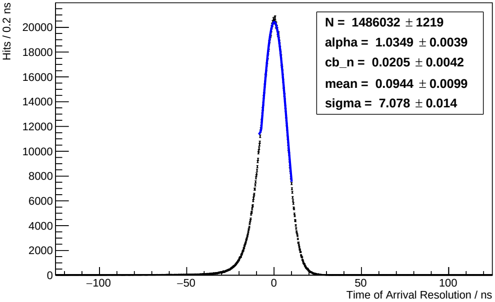
- Event loading from EUDAQ (TLU and telescope)
- Event loading from MuPixDAQ
- Clustering (clusters are typically size-1)
- Tracking with General Broken Lines.
  - A track must have a hit on all telescope planes.
  - No DUT in tracking.
  - Momentum 4.8 GeV (2.8 GeV in December).
- Filter events with 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 $\chi^2/N_{dof} < 5$).

June22 – Time of Arrival Resolution

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

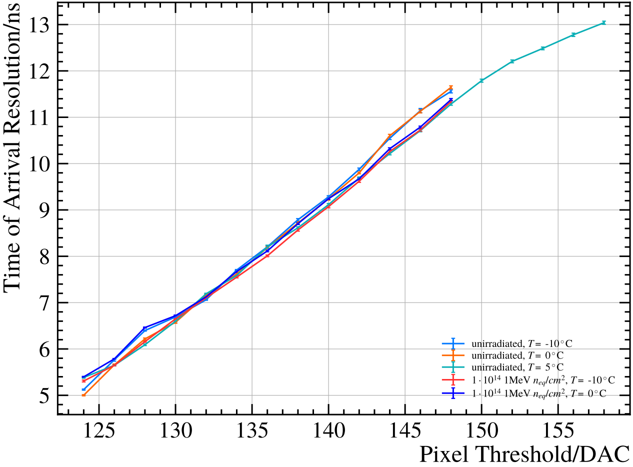
$$\text{residual} = t_{\text{track}} - t_{\text{hit}}, \qquad \text{ToA resolution} = \sqrt{\sigma^2 - (8\text{ ns}/\sqrt{12})^2}.$$

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



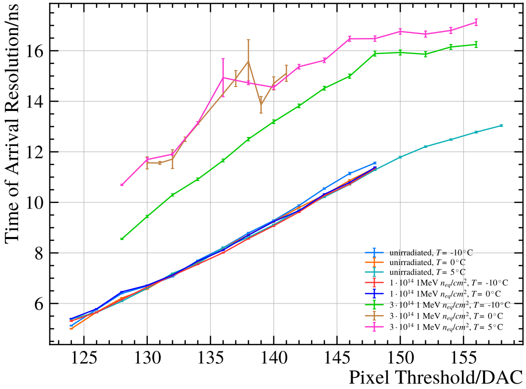
June22 – Time of Arrival Resolution (to 10^{14} $n_{eq}cm^{-2}$)

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



June22 – Time of Arrival Resolution (up to 3×10^{14})

- $3 \times 10^{14}\ \mathrm{n_{eq}cm^{-2}}$: degraded time resolution (possibly due to non-optimal chip settings, and lower stats)
- Measurements revisited in December testbeam.

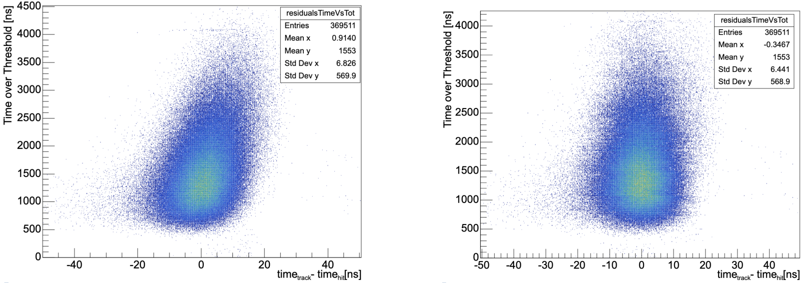


DESY22 – Delay correction

- 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.

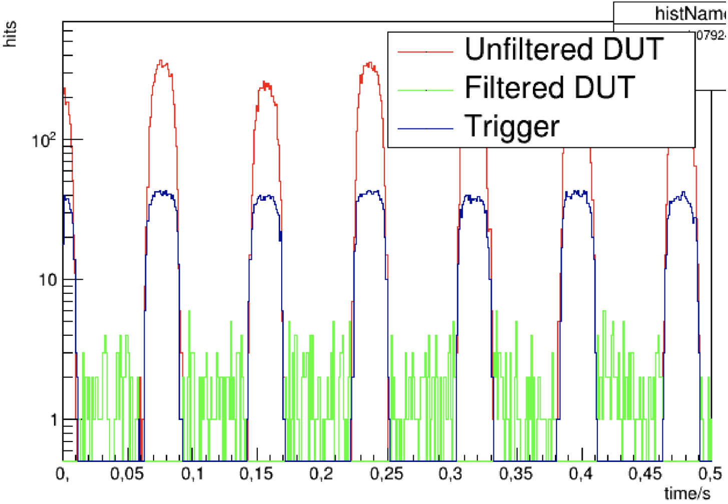
DESY22 – Time Walk correction

- 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

DESY22 – noise estimate



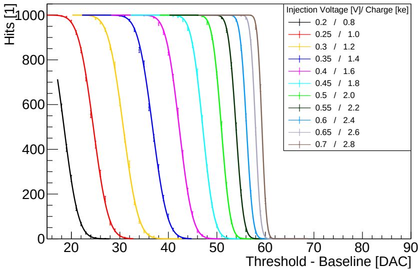
Green – noise hits (considered "between bunch" – no trigger from beam).

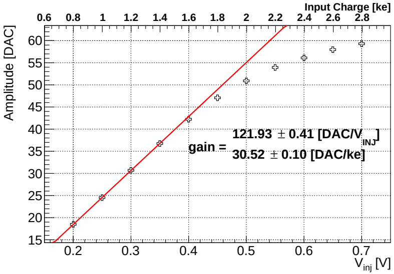
DAC units

- baseline 0x6D = 0d109
- 1 DAC = 1.8 V / 256 $\approx$ 7 mV

Lab measurements: Amplifier plots

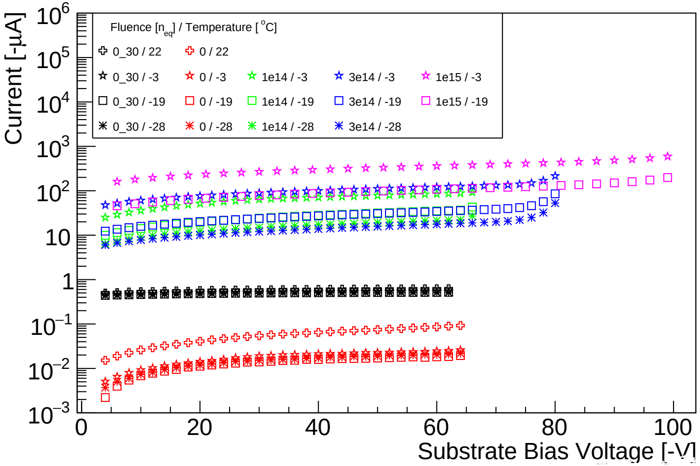
- S-curves used to measure amplifier gain
- AP3.1 has nominal resistivity of $200 - 400\ \Omega$ cm. Expect $\approx$ 30 μm depletion depth at 60 V bias voltage. $2400e$ per MIP.





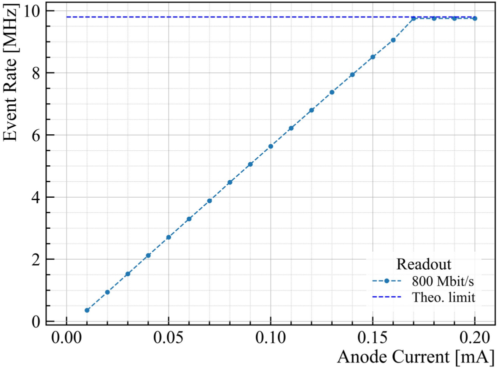
Lab: IVs

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



Lab: 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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