# Testbeam performance of RD53a hybrid pixel detectors for the ATLAS ITk

Adam Rennie on behalf of the ATLAS ITk pixel testbeam community

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# Testbeam performance of RD53a hybrid pixel detectors for the ATLAS ITk

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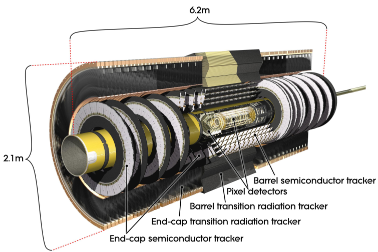
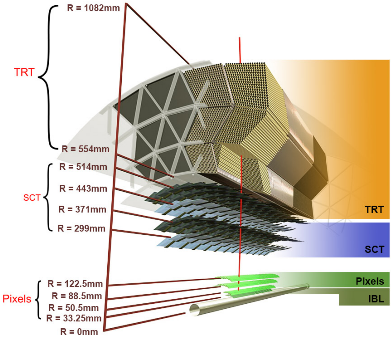
# The ATLAS Inner Detector (ID)

- Pixel Detector (pixels), Semiconductor Tracker (SCT, strips), Transition Radiation Tracker (TRT, drift tubes)
- Tracking out to $|\eta| < 2.5$
- Inner B-Layer (IBL) - innermost layer - installed during LS1



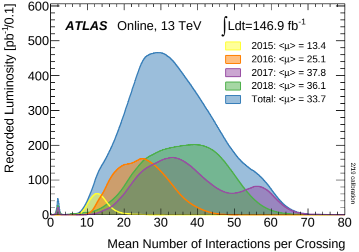



# The ATLAS Inner Tracker (ITk)

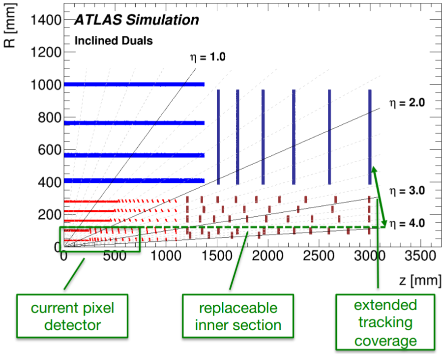
- Run 2 pileup was $\langle\mu\rangle \sim 30$. Pileup during high-luminosity LHC (HL-LHC) expected to be $\langle\mu\rangle \sim 200$.

- Instantaneous Run 2 luminosity peaked at $2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, same expected for Run 3. At HL-LHC, instantaneous luminosity expected to peak at $7.5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, accumulating 4000 fb$^{-1}$ of data.

- New tracker required for HL-LHC - the ITk!



- ITk is an all-silicon tracking system replacing the ID with a system of silicon pixel and strip layers
- Extends coverage out to $|\eta| < 4.0$
- Five layers of pixels, formed of barrel, outer barrel, and endcap regions



- Must have:
  - Sufficient radiation hardness (inner section to be replaced halfway through lifetime)
  - Increased granularity
  - Reduced material budget
- Achieved with combination of planar and 3D sensors, ITkPix readout chip based on RD53 prototype

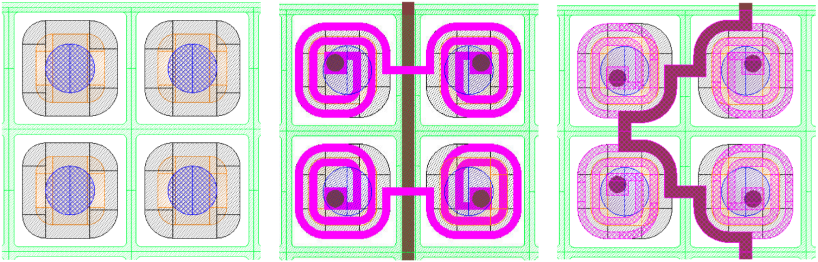
| PIXELS | **Pitch** | **Thickness** | **Channels** | **Modules** | **Area** |
|---|---|---|---|---|---|
| **ID*** | $50 \times 400$ μm$^2$ | 250 μm | $9 \times 10^7$ | 2024 | 1.9 m$^2$ |
| **ITk**** | $50 \times 50$ μm$^2$ | 150 μm | $5 \times 10^9$ | 9164 | 12.8 m$^2$ |

*IBL thickness 230 μm, 200 μm for 3D, planar sensors respectively. IBL pitch $50 \times 250$ μm$^2$

*L1 planar sensors 100 μm thickness, $25 \times 100$ μm$^2$ pitch for barrel 3D modules

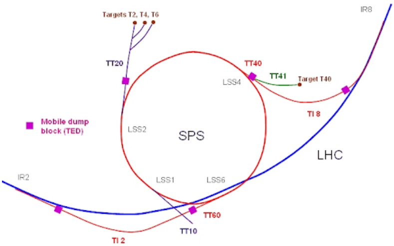
# Devices under test (DUTs)

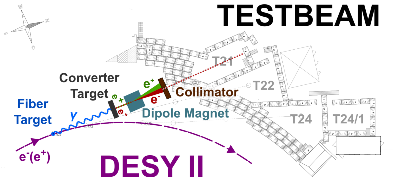
- Devices presented here are RD53A bump-bonded to 150 μm thick *n*-in-*p* planar sensor, pixel pitch $50\times50$ μm$^2$
- Different punchthrough bias (PTB) structures on different devices - not required for operation but very useful for QC in production
- Modules irradiated with a fluence of $3.4 \times 10^{15} n_{\text{eq}}/\text{cm}^2$
- Evaluated with reference to ATLAS planar sensor market survey efficiency criteria:
  - 97% for 150 μm sensor irradiated to $2 \times 10^{15} n_{\text{eq}}/\text{cm}^2$ at 400 $V_{\text{bias}}$
  - 97% for 150 μm sensor irradiated to $5 \times 10^{15} n_{\text{eq}}/\text{cm}^2$ at 600 $V_{\text{bias}}$



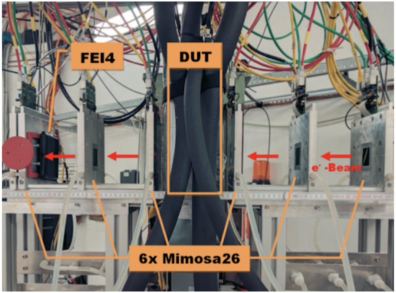
# Testbeam setup

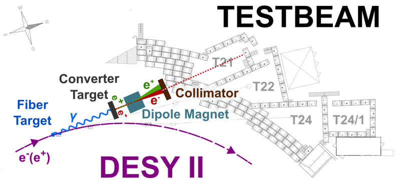
- Data taken over two testbeam campaigns
- 120 GeV pions at the SPS in October 2018, 4 GeV electrons at DESY in December 2018



- Data taken using BDAQ
- EUDET-type telescopes on both occasions: six MIMOSA26 telescope planes with high spatial resolution along with an FEI4 plane to provide timing information
- Trigger logic unit (TLU) used in tandem with a scintillator either end of the telescope to feed trigger to DUTs and telescope planes
- EUDAQ combines data streams from each planes into single output to be used for reconstruction & analysis



# Reconstruction and analysis

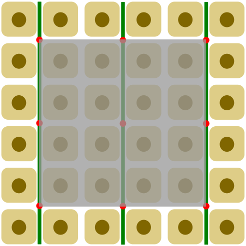
- Reconstruction performed using EUTelescope, standard staged approach:

  1. CONVERTER: put data into common format. Flag *noisy pixels* which fire above some *firing frequency*.
  2. CLUSTERING: group pixels into clusters, remove clusters containing noisy pixels.
  3. HITMAKER: transform from local to global coordinate system, construct correlations between planes. Pre-alignment.
  4. ALIGNMENT: With track candidates, minimise residuals between telescope planes to adjust plane positions.
  5. FIT: Use updated geometry to then fit the tracks to the DUTs, output for analysis.

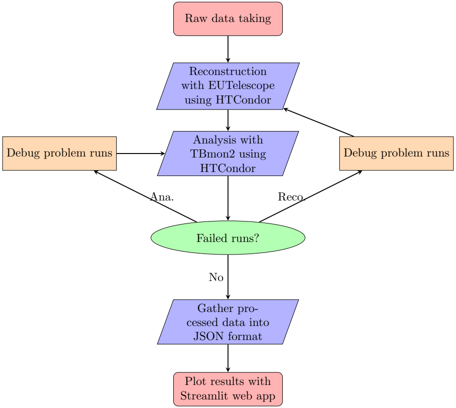
- Analysis with TBmon2, primarily to investigate:

    1. Global efficiency - to compare against efficiency criteria as a function of $V_{bias}$ and threshold

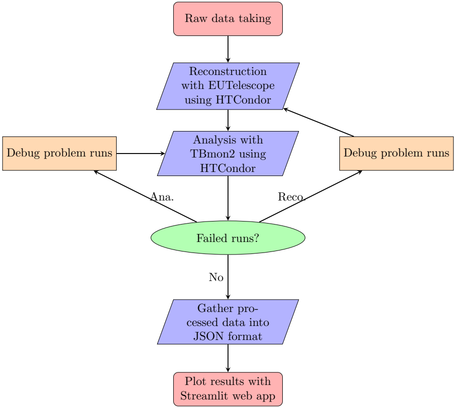
    2. In-pixel efficiency maps - overlaying $4 \times 4$ groups of pixels across the full sensor to accumulate statistics and see how the efficiency is affected by PTB structure



- New approach developed during work on MS
- Common git repository established to control processing with common config files, geometries, etc.
- Derive reconstruction and analysis parameters with single run & small event numbers locally
- Use HTCondor batch processing to handle reconstruction and analysis

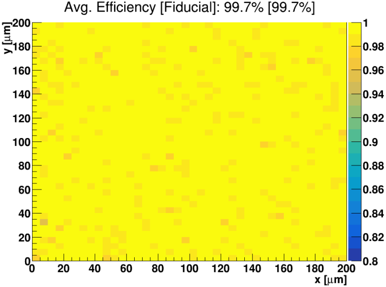


- Campaign split into runs, each reconstructed in parallel then analysis performed in parallel as well
- Parse output for entire campaign into single JSON file
- Plot results and comparisons using Streamlit web app
- Massive reduction in time and person-power requirements to process testbeam

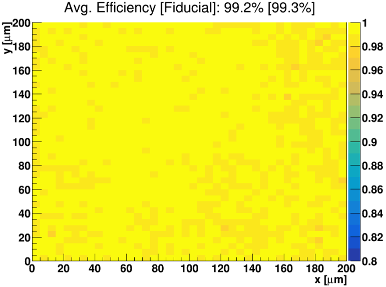


# Results

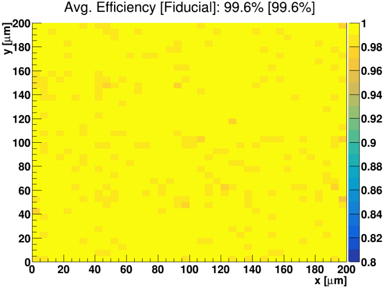
- For device w/o PTB, efficiency target comfortably met at $V_{\text{bias}} = 600$ V.
- Device passed criteria at both DESY and SPS campagns.




4 GeV electrons, no PTB, $V_{\text{bias}} = 600$ V, THL= 1027 $e$, linear FE.

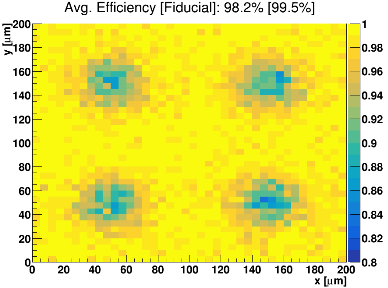



120 GeV pions, no PTB, $V_{\text{bias}} = 600$ V. ↑ - THL= 1200 $e$, differential FE. ↓ - THL= 1158 $e$, linear FE.

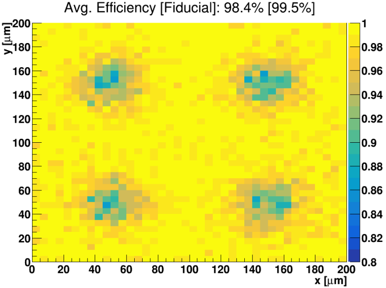


- Device with PTB tested at DESY campaign, using linear FE.

- Effect of PTB structure clear to see, but still pass 97% efficiency criteria relatively comfortably.



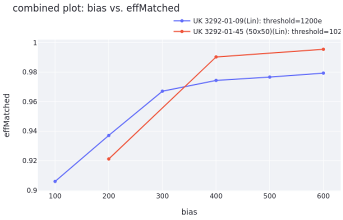

4 GeV electrons, PTB, $V_{\text{bias}} = 400$ V, THL= 1200 $e$.



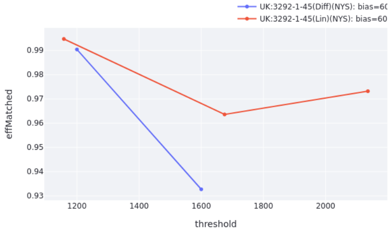

4 GeV electrons, PTB, $V_{\text{bias}} = 600$ V, THL= 1200 $e$.

- See similar behaviour in efficiency with threshold for both PTB and no PTB, but lower ceiling for the device with PTB.

- For device with no PTB, efficiency drops at high threshold. Likely eating into signal.




4 GeV electrons, with and without PTB, THL at 1200 and 1027 $e$, varied $V_{\text{bias}}$.




4 GeV electrons, without PTB, $V_{\text{bias}} = 600$ V, varied threshold. Differential and linear FE.

# Summary

- Testbeam measurements made of irradiated prototype ITk pixel modules using RD53a readout, with different PTB structures
- New framework use for reconstruction and analysis
- Clear to see local efficiency impact of the PTB structure on the in-pixel efficiency maps
- Regardless, modules with and without PTB achieve a global efficiency comfortably above the 97% required level
- Similar behaviour for both devices across $V_{\text{bias}}$ and threshold scans