Reconstruction and analysis of test-beam data from ATLAS ITk pixel modules with the Corryvreckan package

9th Beam Telescopes and Test Beams Workshop
8 - 11 February 2021
Lecce, Italy

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ATLAS EXPERIMENT

Upgrade of the ATLAS experiment

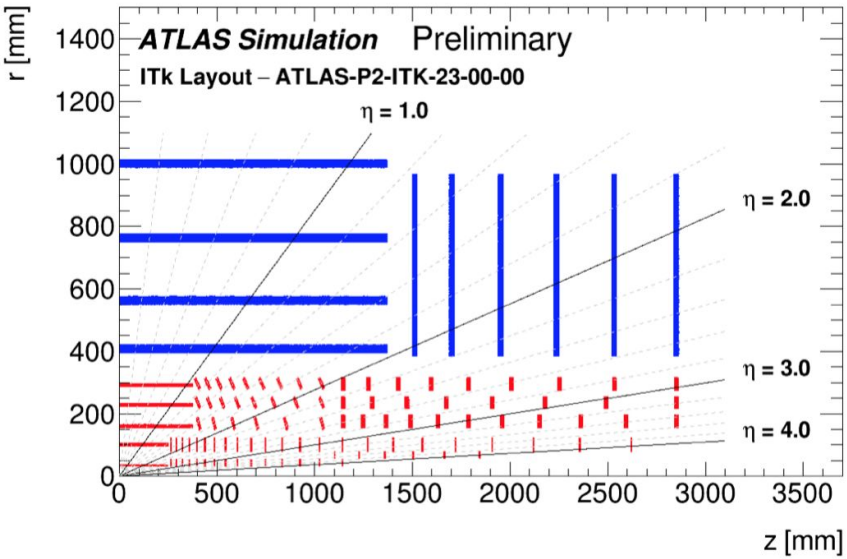
The High-Luminosity LHC (HL-LHC) requires an upgrade of all detector systems of the ATLAS Experiment to withstand the challenging environment.

The current Inner Detector will be replaced with the **Inner Tracker (ITk)** consisting of silicon strip and pixel modules.

The ITk Pixel detector will include:

- single-chip 3D sensors in the L0
  - 2x2 mm^2 size;
- quad planar sensors in L1-L4
  - 4x4 mm^2 size.

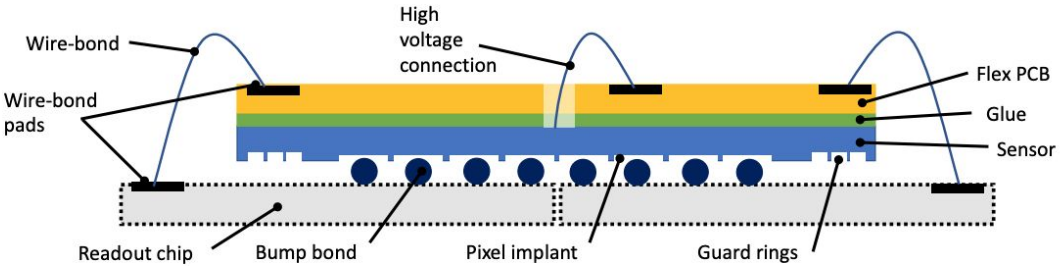
The schematic view of the ITk Layout



ATLAS ITk pixel modules assembly and testing

The ITk pixel modules are assembled in two steps:

- **bump-bonding**, where readout chips are attached to the sensor → bare module;
- **module assembly**, where a bare module is connected to the hybrid (flex PCB).



Beyer (2019)

The performance of assembled modules is evaluated in laboratory and test-beam measurements.

Test-beam data reconstruction and analysis

The ATLAS ITk Pixel test-beam data have been processed so far using two softwares:

- EUTelescope for the reconstruction;
- TBmon2 for the analysis.

The support for the EUTelescope package has been discontinued and it is being replaced by Corryvreckan (arXiv:2011.12730)

The Corryvreckan framework allows:

- an offline event building to combine detectors with different readout schemes;
- a use of the hit timing information for clustering and tracking step.

The framework is accompanied by a comprehensive user manual and is continuously extended with new features.

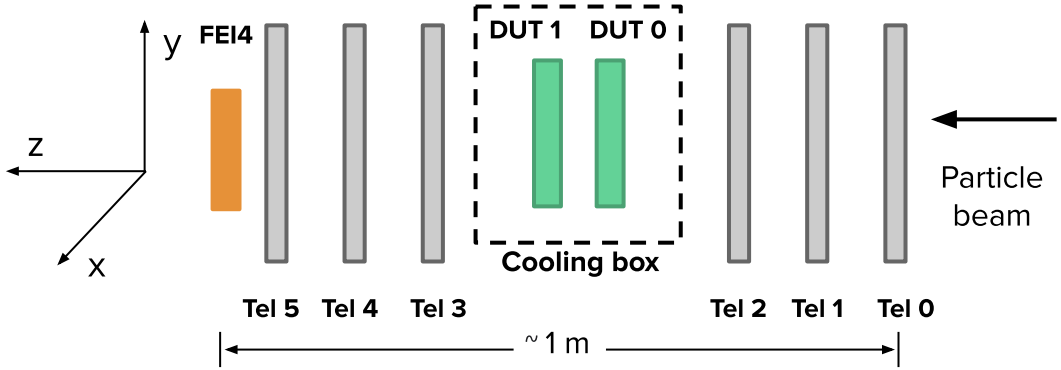
The ATLAS ITk Pixel test-beam group will move to the Corryvreckan software once fully validated.

Experimental setup

- The dataset analysed is recorded at **DESY II Test Beam Facility**, with $E_{electron}$ up to 5.6 GeV
- **EUDAQ1** framework is used for the data aquisition.

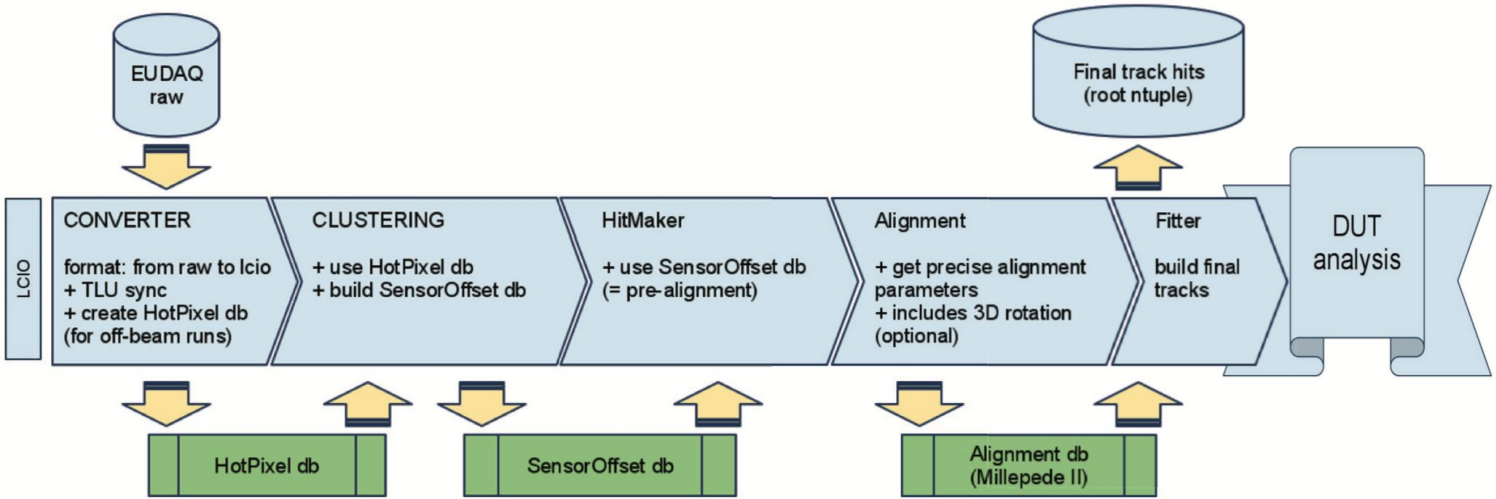
The experimental setup consists of:

- six **Mimosa26 modules**
  - 50 μm thick sensors
  - 18.4x18.4 μm^2 pixel size
- one **ATLAS FEI4 module**
  - 250x50μm^2 pixel size
  - timing reference
- two **RD53A ATLAS ITk pixel modules**
  - 100 μm or 150 μm thick sensors
  - 50x50 μm^2 or 100x25 μm^2 pixel size



Reconstruction and analysis steps

Many of the Corryvreckan modules have the same functionality as EUTelescope processors.



I. Rubinskiy, An EUDET/AIDA Pixel Beam Telescope for Detector Development, Physics Procedia, Volume 37, 2012, Pages 923-931

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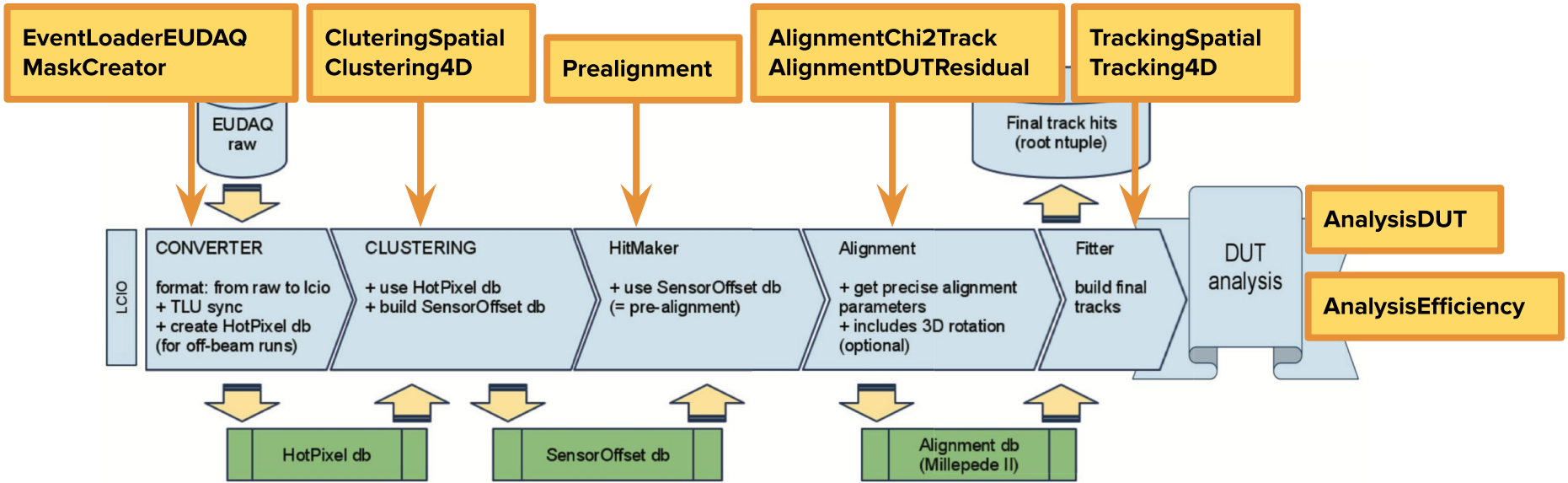

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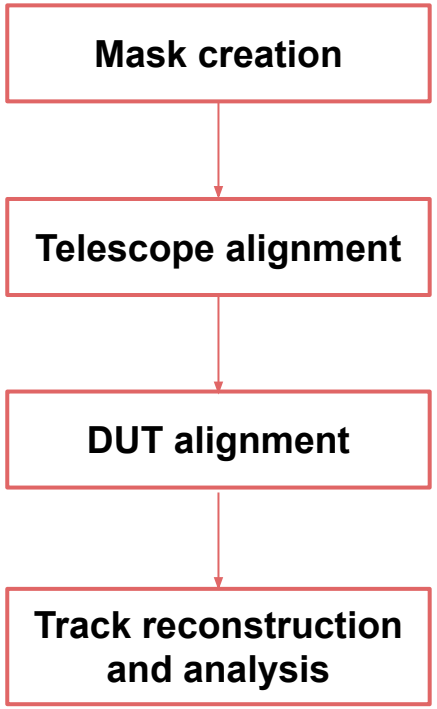
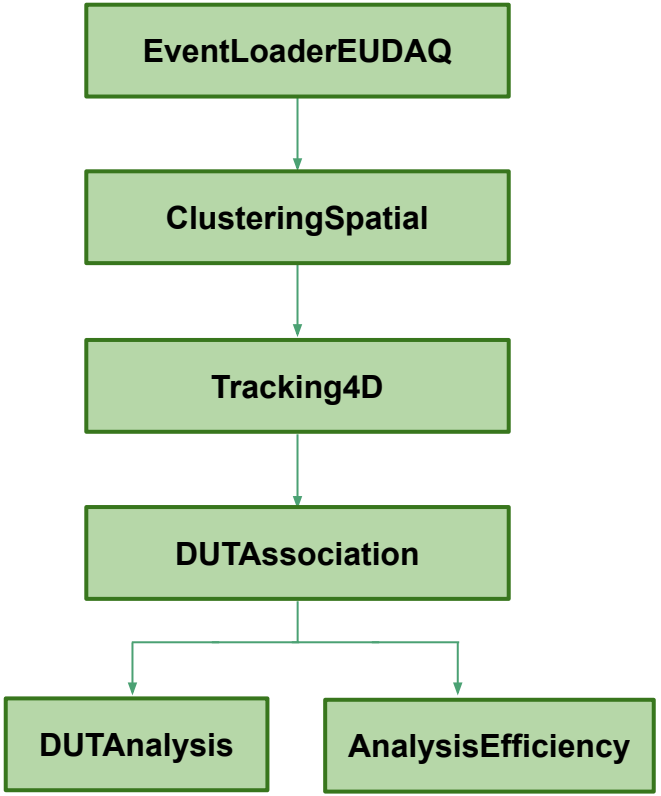
Reconstruction and analysis steps

Dataset is reconstructed and analysed in the following steps:



An example of a reconstruction and analysis chain



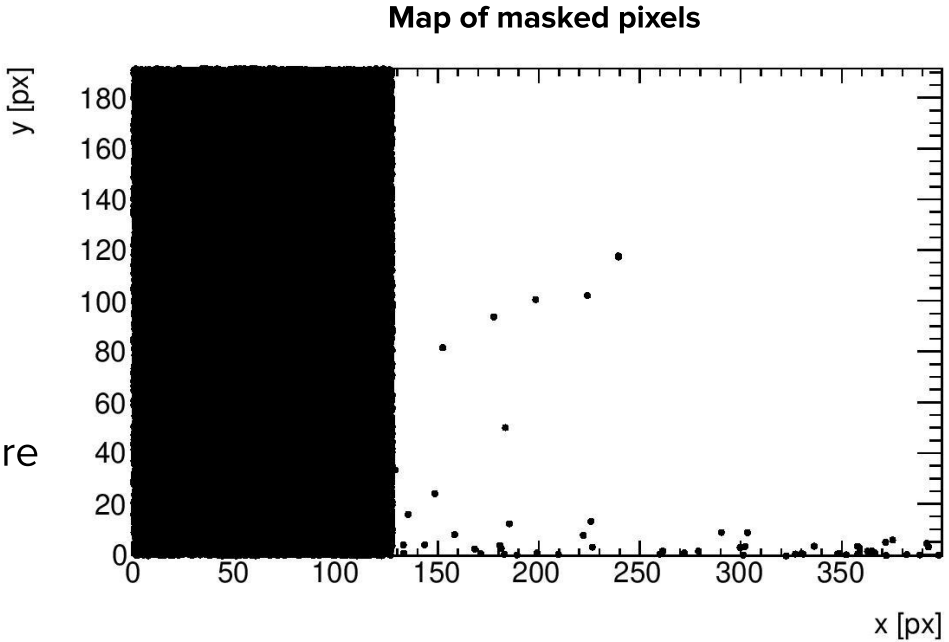
Mask creation

Noisy pixels

- The **MaskCreator** module masks pixels based on their firing frequency.

Pixels masked during the tuning

- The used **RD53A** chip contains three different readout concepts, but only two are used for the data taking.
- Pixels masked during the chip tuning are found as pixels without a hit over the entire run and are added to the masking file.

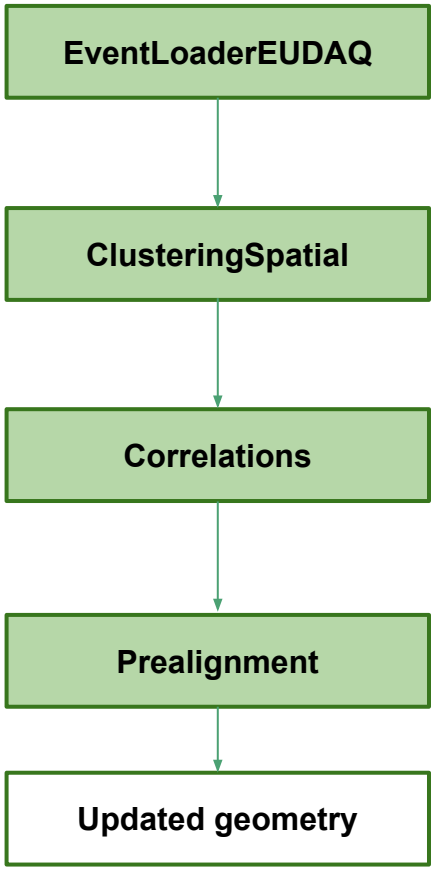


Telescope alignment

The alignment is performed in two steps.

Prealignment

Performs the adjustment of the recorded module locations transverse to the beam.



Telescope alignment

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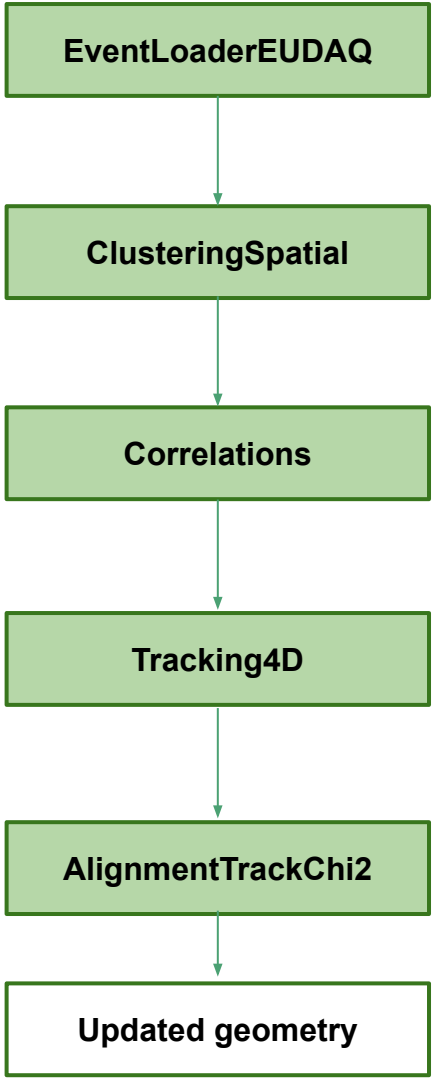
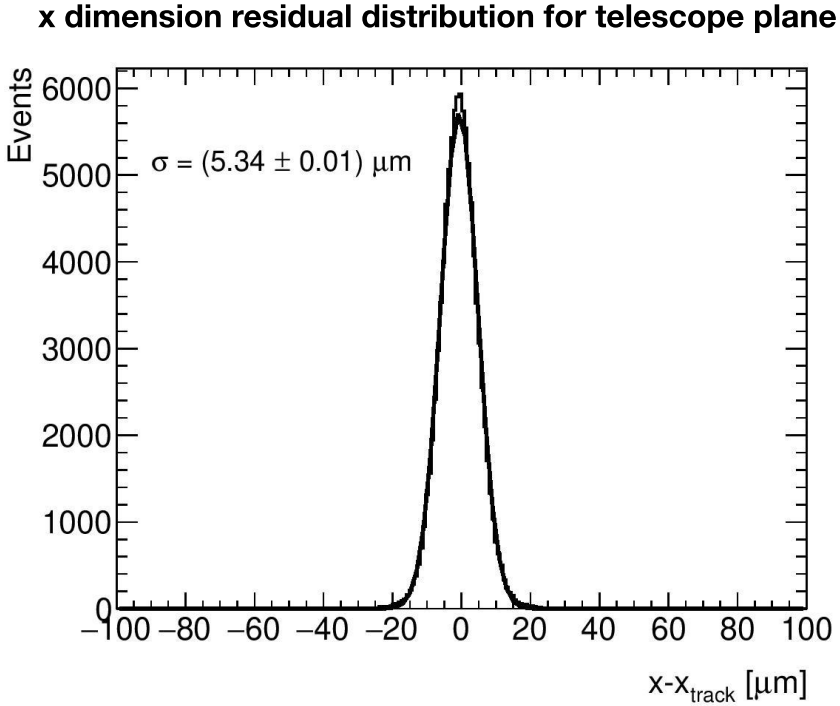
AlignmentTrackChi2

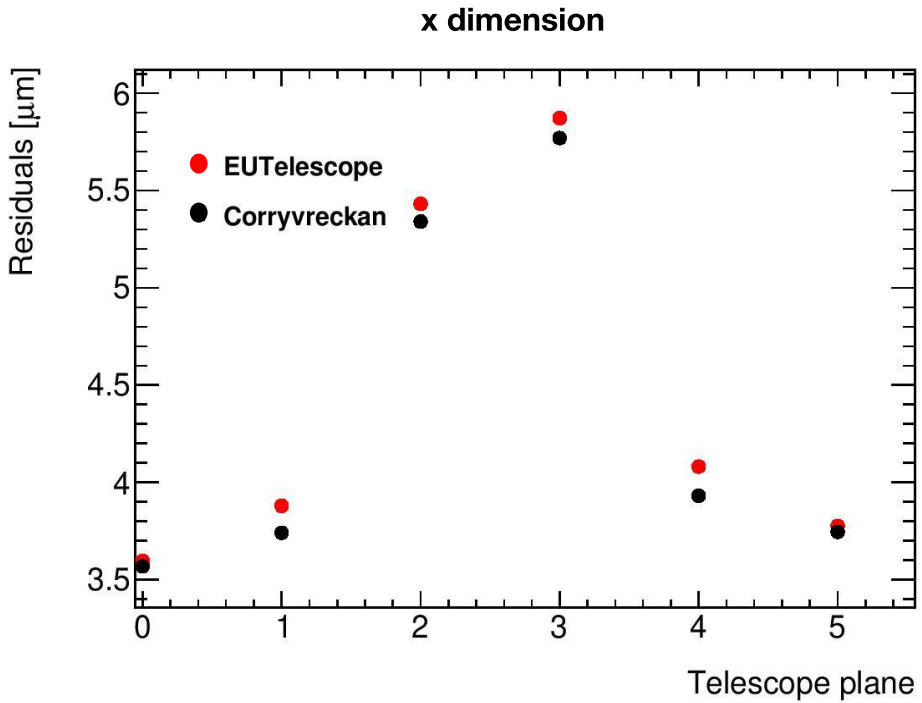
Refines the prealignment including the rotations.

- The z positions of all modules are fixed to the geometrical survey of the setup.
- General Broken Line used as a track model.



Telescope alignment - results





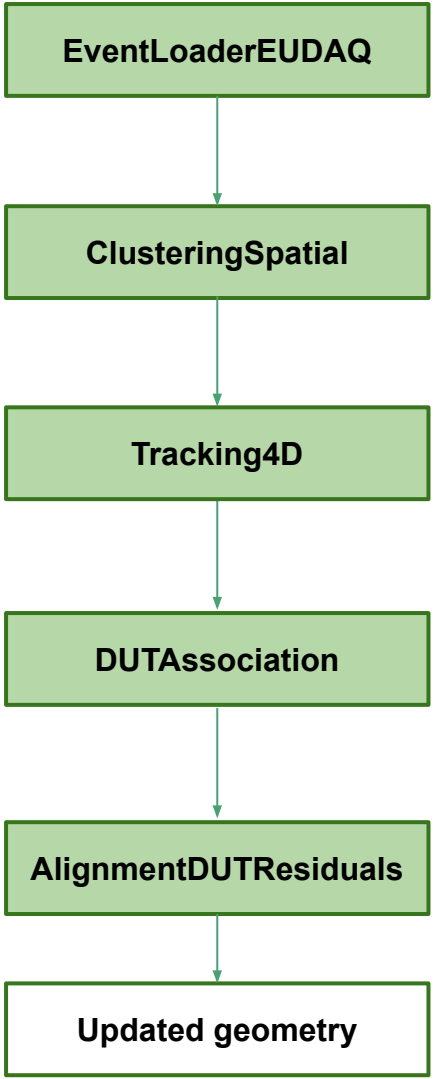
Expected width of residual distribution: 18.4 µm/sqrt(12) = 5.3 µm

Similar results are observed for the y dimension.

DUT alignment

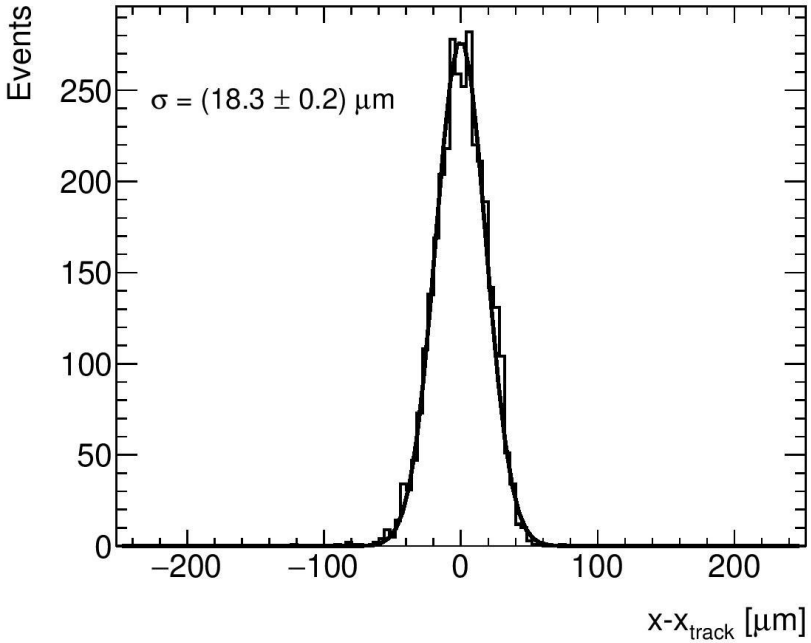
DUTAssociation
Assigns clusters on the DUTs to the telescope tracks.

AlignmentDUTResiduals
Varies the positions and rotations of the DUTs for centering the residuals in x and y around zero and minimising their width.



DUT alignment - results

x dimension residual for 50x50 µm² sensor



Two 50x50 µm² pixel

		Corryvreckan	EUTelescope
DUT0	x residuals [µm]	18.3 ± 0.2	17.9 ± 0.2
	y residuals [µm]	18. 2± 0.2	17.9 ± 0.2
	Associated tracks	3243	3300
DUT1	x residuals [µm]	17.8 ± 0.2	16.4 ± 0.2
	y residuals [µm]	17.8 ± 0.2	16.6 ± 0.2
	Associated tracks	3313	3357

Expected width of residual distribution for perfect beam: 50.0 µm/sqrt(12) = 14.4 µm

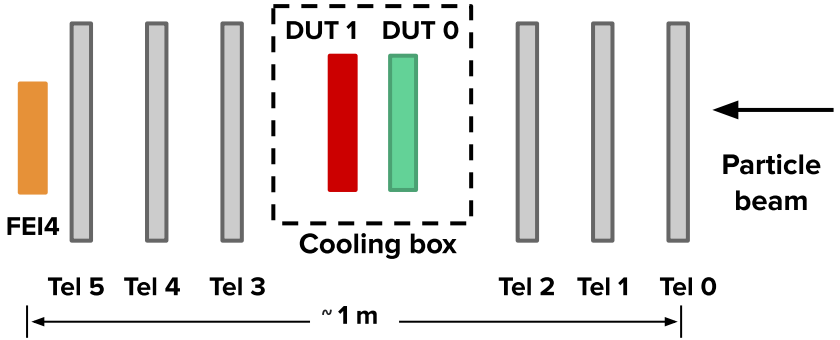
Track reconstruction

EUTelescope track reconstruction:

- General Broken Line algorithm;
- two partial tracks reconstructed, one for the **upstream telescope triplet** and one for the **downstream triplet**;
- a full track formed if partial tracks meet in the middle within a specified distance.

TBmon2 analysis:

- telescope tracks with a matching hit on **the reference DUT** accepted;
- timing information used.



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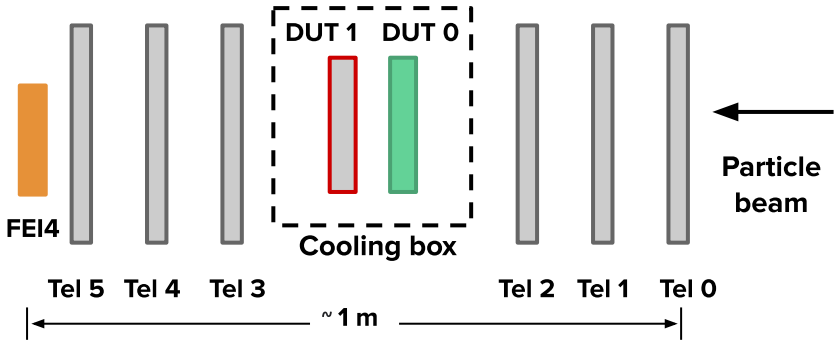
TBmon2 analysis:

- telescope tracks with a matching hit on **the reference DUT** accepted;
- timing information used.

Corryvreckan track reconstruction and analysis:

- General Broken Line algorithm;
- two telescope planes used to build a track candidate;
- clusters from further planes added if they fulfil spatial requirements;
- **the reference DUT** included in the tracking;
  - only tracks with a hit on this plane are accepted;
- timing information not yet used.



Hit Efficiency Determination

DUTAssociation

DUT clusters are assigned to the reconstructed tracks with maximum matching distance of two times the pixel pitch.

AnalysisEfficiency

Measures the efficiency of the DUT by comparing its cluster position with the interpolated track position at the DUT:

$$\text{Efficiency} = \frac{\text{Number of tracks with an associated cluster on the DUT}}{\text{Number of tracks intersecting the DUT}}$$

The number of tracks intersecting the DUT does not include:

- tracks that intersect pixels neighbouring masked pixels;
- tracks with χ^2 /ndof > 6.

Hit Efficiency

Pixel area [μm^2]	Thickness [μm]	Punch-through bias	Fluence [10^{15} n_{eq}/cm^2]	$\varepsilon_{Corryvreckan}$ [%]	ε_{TBmon2} [%]
50x50	100	no	0	99.11 ± 0.03	99.02 ± 0.05
50x50	100	no	0	99.44 ± 0.02	99.44 ± 0.03
50x50	100	yes	5	98.63 ± 0.06	98.75 ± 0.08
50x50	150	no	5	99.77 ± 0.02	99.65 ± 0.04

Without including systematic uncertainties, very similar efficiencies are observed with both frameworks.

Summary

- The Corryvreckan software is used for the first time to reconstruct and analyse ITk Pixel test-beam data.
- The datasets analysed include non-irradiated and irradiated samples.
- The alignment of the telescope planes and DUTs is successful. The results are similar to what has been achieved with the EUTelescope software.
- The results of hit efficiency measurement with the Corryvreckan software are consistent with those obtained using the TBmon2 software. They mostly agree within the statistical uncertainty.

Further steps:

- Improving the masking to be able to specify in more detail why certain pixels are masked;
- Implementing the use of the timing information in the analysis.

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).