New results on performance studies of the 3D modules in tests beam for the ATLAS ITk detector

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ATLAS ITk Pixel Innermost layer modules: the Triplet modules

First test beam results of irradiated ITkPix Triplet

First test beam results on the charge collected with ITkPix v2 chip

Towards the HL-LHC era: the all-new ATLAS ITk

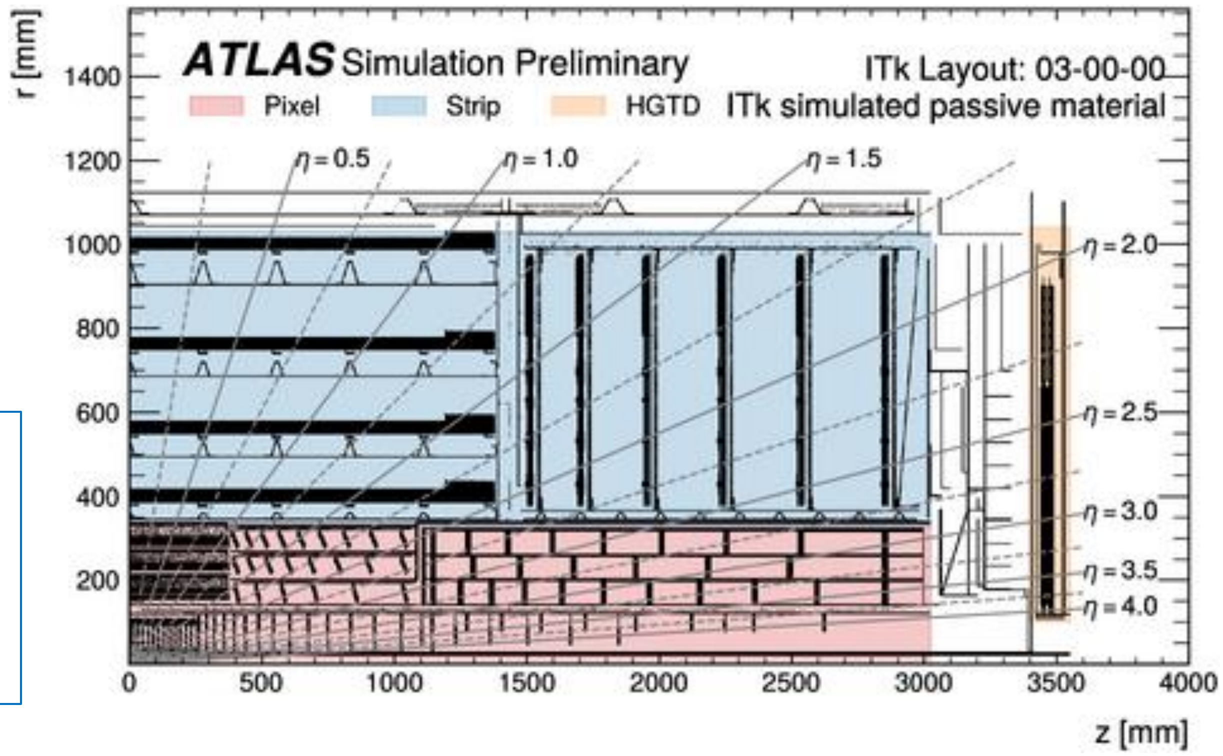
New all-silicon ATLAS Inner Tracker (ITk)

- ATLAS Inner Tracker to be replaced during LS3 of LHC for the HL-LHC
- **Strip sub-system** covering up to |η| < 2.7
- ***Pixel sub-system*** covering up to |η| < 4.0
    - Organised in ***5 concentric layers***

Instantaneous/integrated ***luminosity*** *will blow up*
Severe detector requirements

- Higher hit-rate capability
- Increased granularity
- Higher radiation tolerance
- Lighter detectors

ITK-2023-001



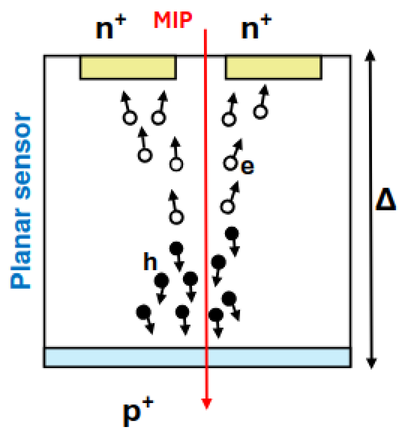
The ***ITk Pixel Detector*** plays a ***key role in vertexing and tracking*** and must face hard conditions in terms of ***radiation hardness and readout rate***

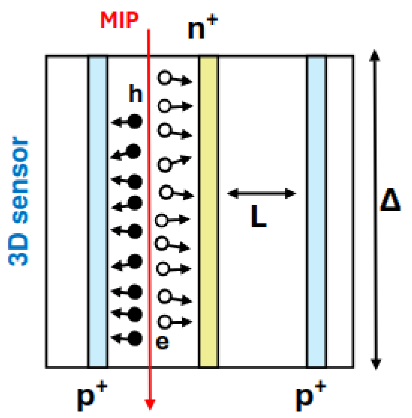
→ *Hybrid Pixel detectors*

ATLAS ITk Pixel – Hybrid pixel detectors

Pixel Sensors

- Fluence collected in each layer drives the tecnology
- ***Planar sensors everywhere, but in the innermost layer***
- ***Innermost layer is the most critical:***
  - **Fluence up to 1.7e16 n_{eq}/cm^2** (1.5 safety factor)
  - **Choice: High radiation hard 3D pixel sensors**
  - Single tiles ~2x2 cm^2 by two vendors: ***FBK* & SINTEF*****
  - Two pixel layout ***50x50 / 100x25 μm² pixel size*** (Endcaps / Barrel)
  - 150 μm thickness – Active material + 100 μm support wafer





Single Tile
3D sensor + ITkPix FE

2 cm
2 cm

Front-End (FE) Chip

ITkPix readout chip (***65 nm CMOS***)

- Delivered by ***RD53 Collaboration***
- Common effort for ATLAS & CMS

Two main versions tested:

- ***ITkPix v1.1 - Preproduction chip***
  - ***Bug: Not able to readout the Time over Threshold***
- ***ITkPix v2 – Production chip***
  - ***ToT can be readout in 4 bits***

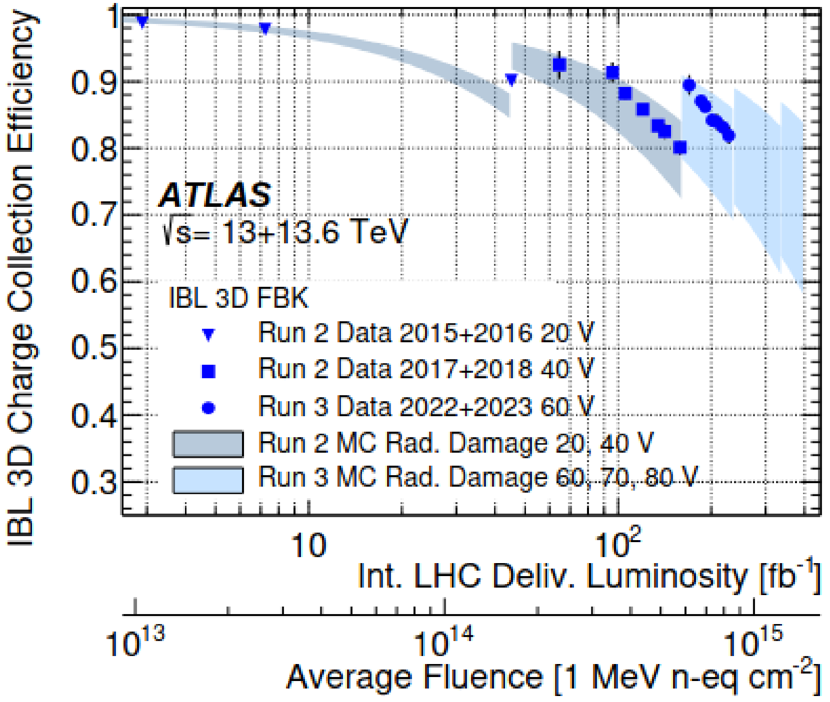
*FBK: Fondazione Bruno Kessler (Italy)
**SINTEF: Stiftelsen for industriell og teknisk forskning (Norway)

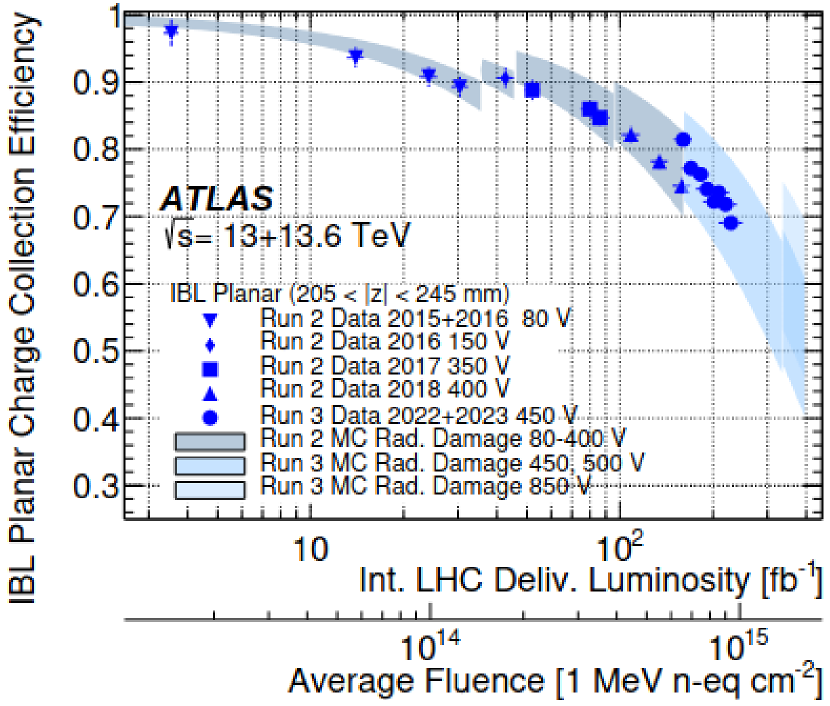
Radiation hardness of 3D pixel sensors

The ***radiation hardness of 3D pixel sensors already exploited in the ATLAS IBL***

- Insertable B-layer, innermost layer of the current ATLAS Pixel Detector
- Both *planars* (200 µm thick) and *3D pixels sensors* (230 µm thick)
- Already collected ***~ 1e15 n_{eq} / cm^2:***
  - *IBL **Planars charge collection efficiency is reduced by ~ 50%** while **only 30% in 3D** pixel sensors*

- We ***may expect that at the ITk innermost layers fluence (> 1e16 n_{eq} / cm^2) also the charge collection efficiency in ITk 3D pixels will be severely reduced***





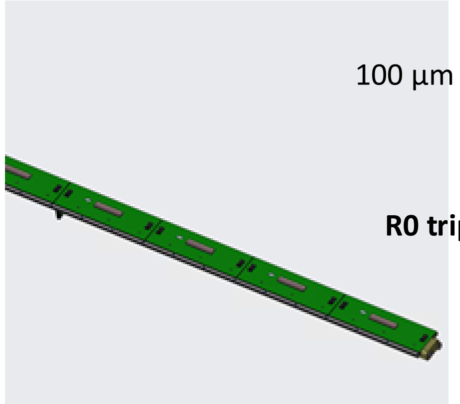
https://arxiv.org/pdf/2407.05716

ATLAS ITk Triplet Modules for the innermost layer

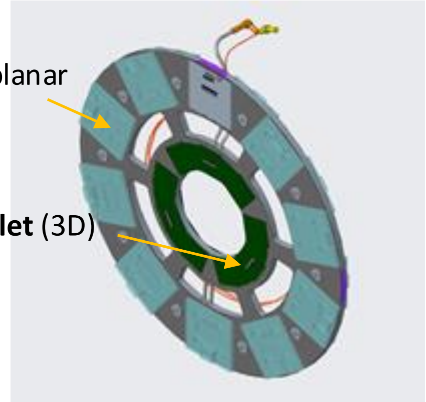
THE TRIPLET MODULE

- **3 single bare modules (3D sensor + ITkPix FE)** will be placed **on a common flexible PCB** for powering and readout forming a module
    - *Three module layouts to optimize the design*

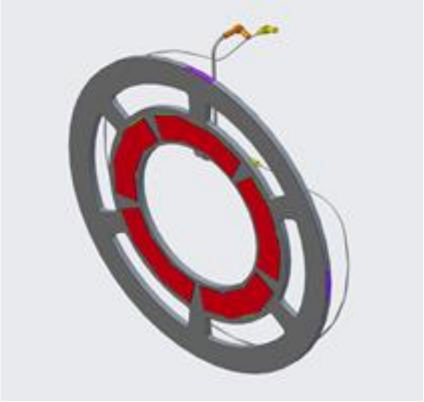
Layer 0 – Barrel stave

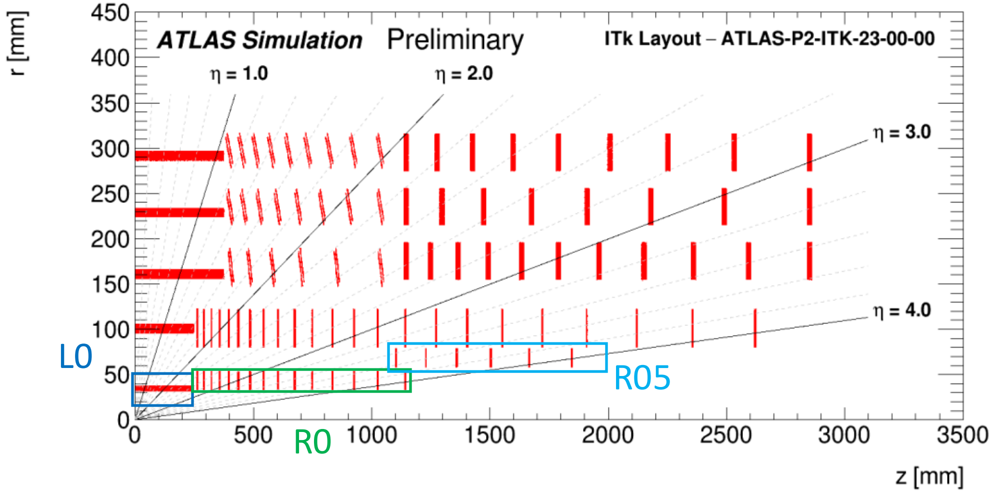


Layer 0 – Coupled Ring 0

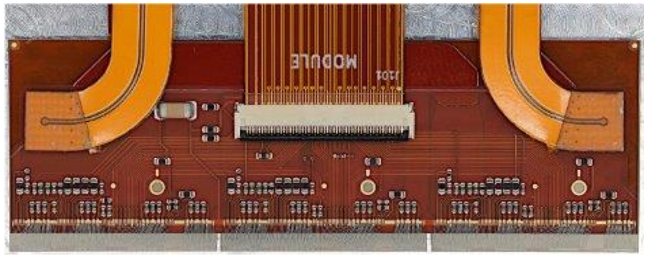


Layer 0 – Endcap Ring 0.5





Barrel linear module



Endcap ring module R05

A global effort towards the Innermost layer

- Italy, Spain and Norway building triplet modules
- ***Up to 400*** (+ yield) ***working modules to build!***
- SLAC (USA) to load the triplet modules on the carbon fiber supports

ATLAS ITk Pixel Innermost layer modules: the Triplet modules

First test beam results of irradiated ITkPix Triplet module

First test beam results on the charge collected with ITkPix v2 chip

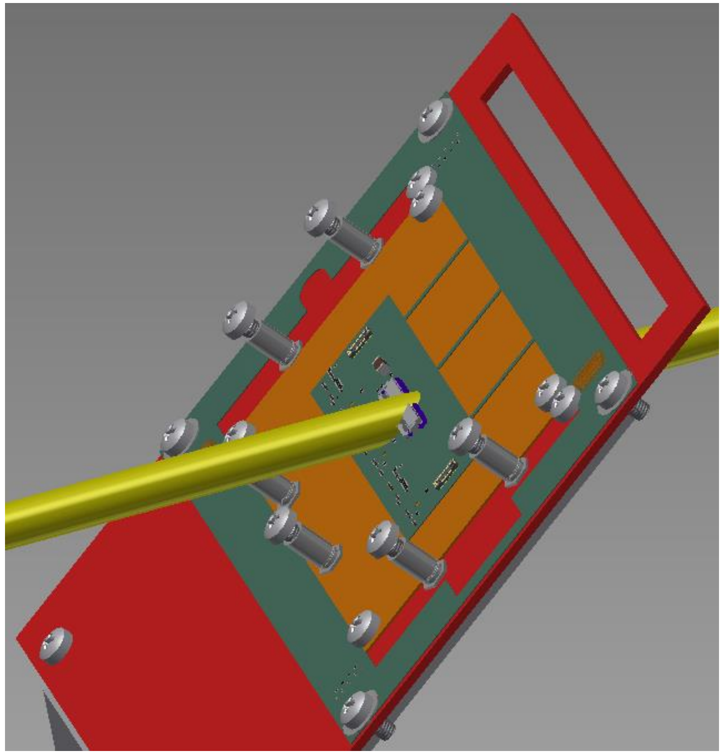
Irradiation of ITkPix Linear Triplet modules in 2025

Full validation of ITk 3D sensors completed in 2021-2024... Now it's time to test real modules!

First time in the project a ***linear triplet module is irradiated and tested on the beam***

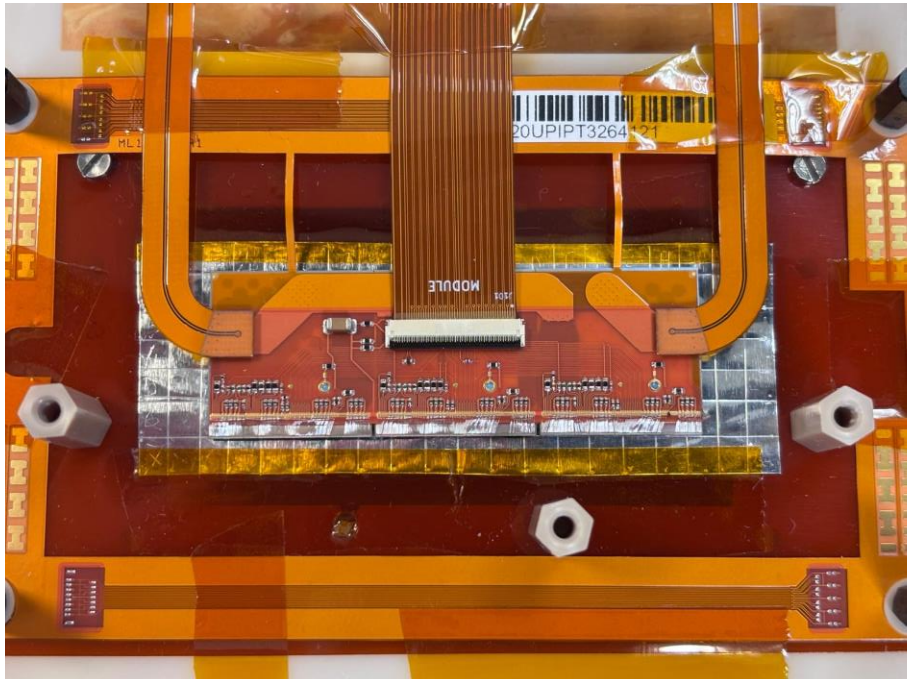
- ***One module (ITkPix v1.1 chip) irradiated in Japan at RaRis*** – Uniform fluence of ***1.0e16 n_{eq} / cm^2***
- ***One module (ITkPix v1.1 chip) irradiated at CERN in IRRAD*** – ***Average fluence 0.5e16 n_{eq} / cm^2*** *(Not uniform)*
- Two modules (ITkPix v1.1 + ***ITkPix v2***) still in IRRAD – ***Ready to be tested on the beam!***

CAD – Triplet holder for irradiation in IRRAD



Triplet module mounted in IRRAD

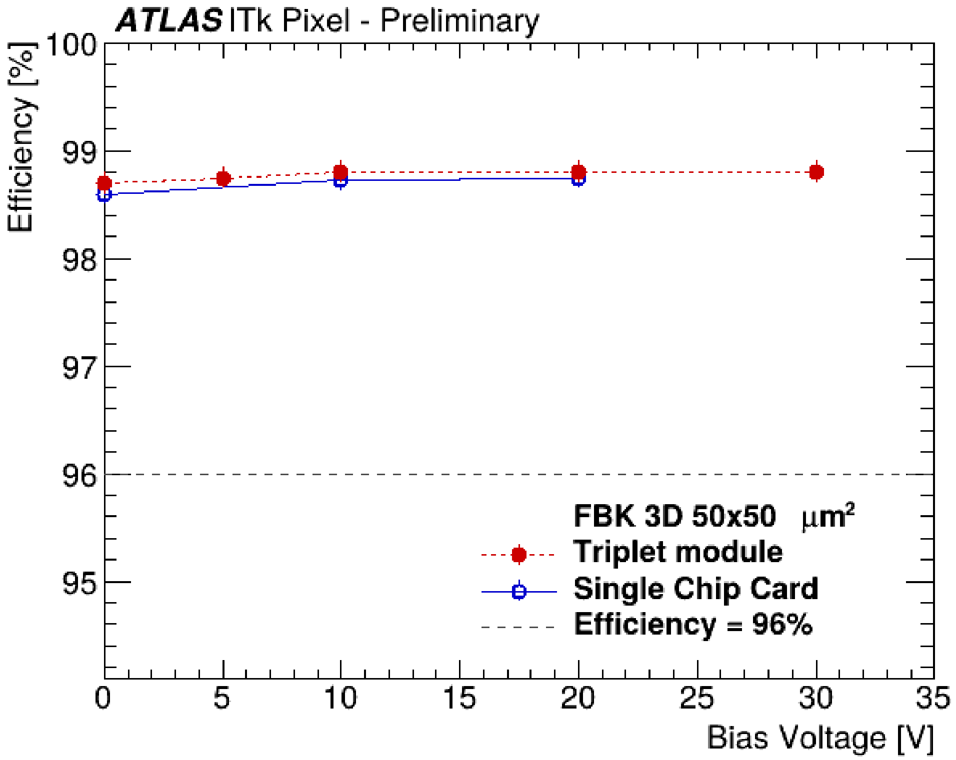
Triplet module with Al dosimeter

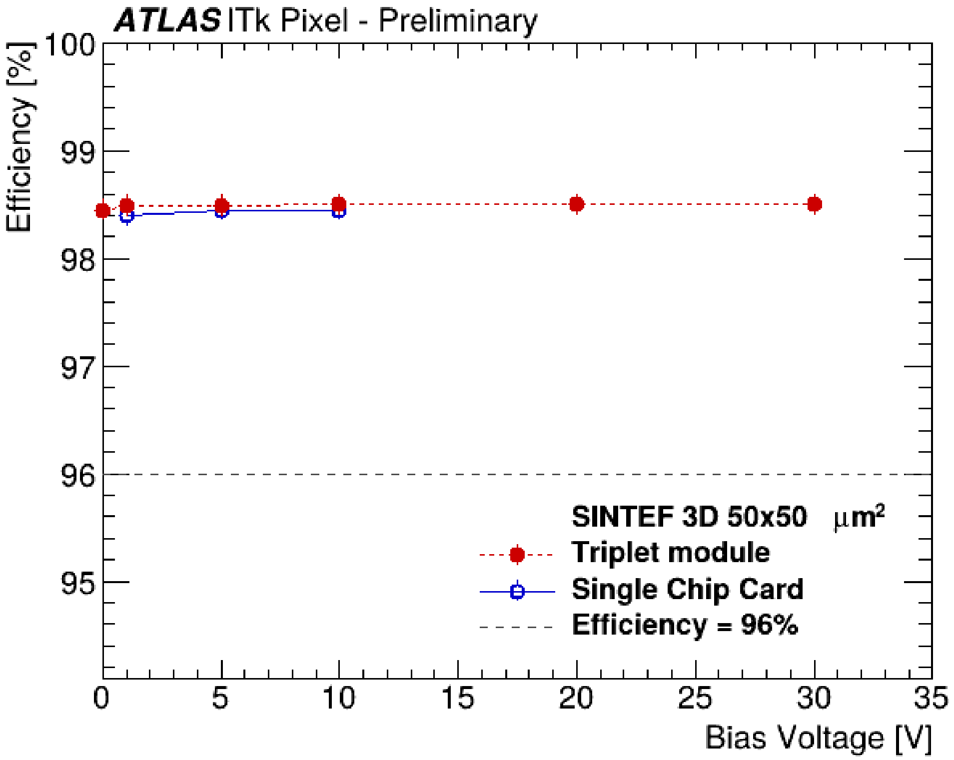


First beam test of unirradiated Triplet module - RaRis

Linear Triplet modules tested for the first time on the CERN SPS 120 GeV pion beam in May 2025

- The 3D sensors ***efficiency performance*** has been measured
  - ***For both vendors (FBK & SINTEF) the efficiency measurements at Triplet module level agree with the measurements obtained in the past on single bare 3D modules (Sensor + FE) mounted on Single Chip Cards***



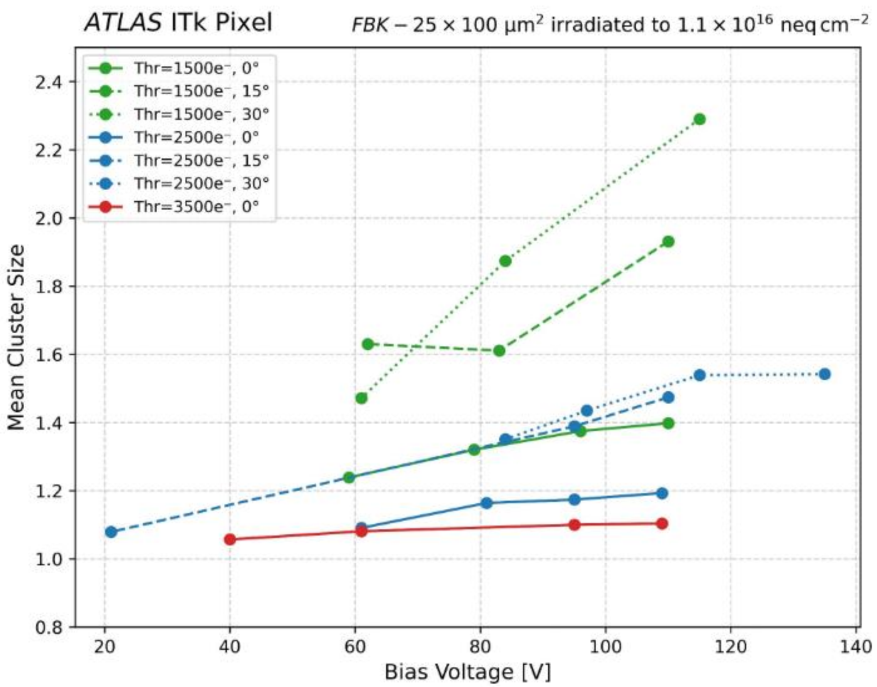


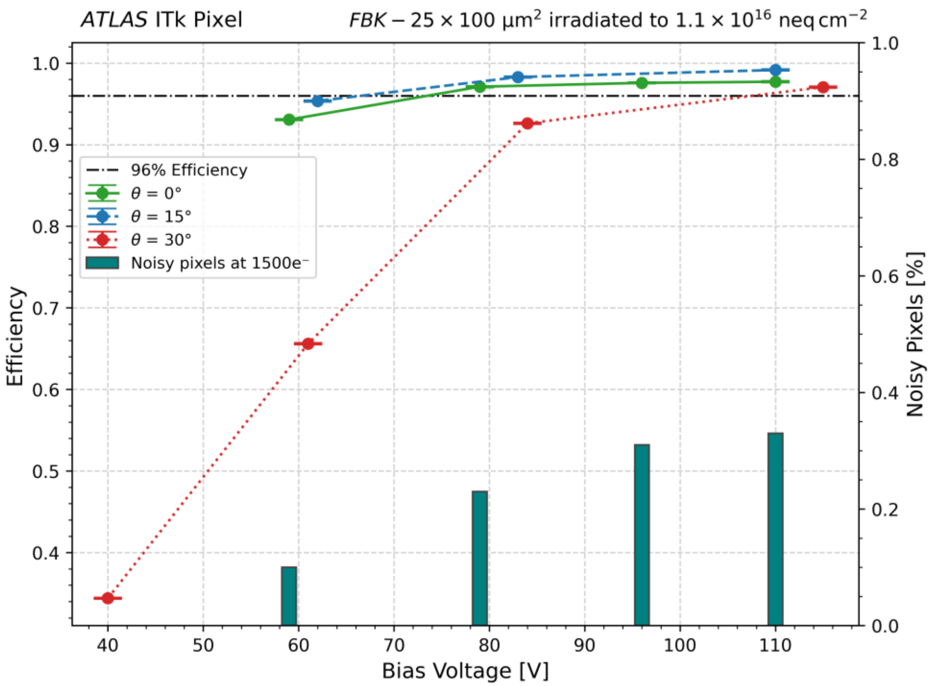
First beam test of irradiated Triplet modules - RaRis

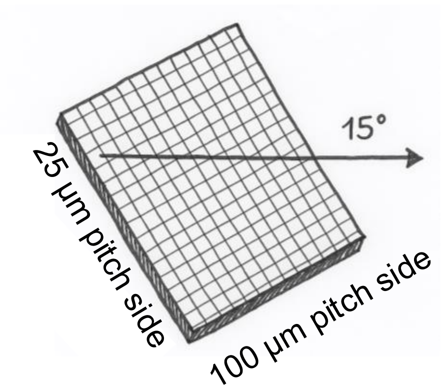
Uniformly irradiated Linear Triplet Module tested on the beam in July 2025 at CERN SPS

- ITkPix v1.1 + 3D sensor FBK (100x25 μm^2 pixel size)
- **Uniform irradiation in RaRis (Japan) at 1.0e16 n_{eq} / cm^2**

- Three configurations: inclinded ***0°, 15° & 30° with respect to the beam incidence + 1500e Threshold***
  - **Reduction of charge collection** *(Slide 5) and* ***larger clusters can justify the lower efficiency at 30°***
  - ***High bias voltage helps with charge collection and recover ~ 96% also at 30***







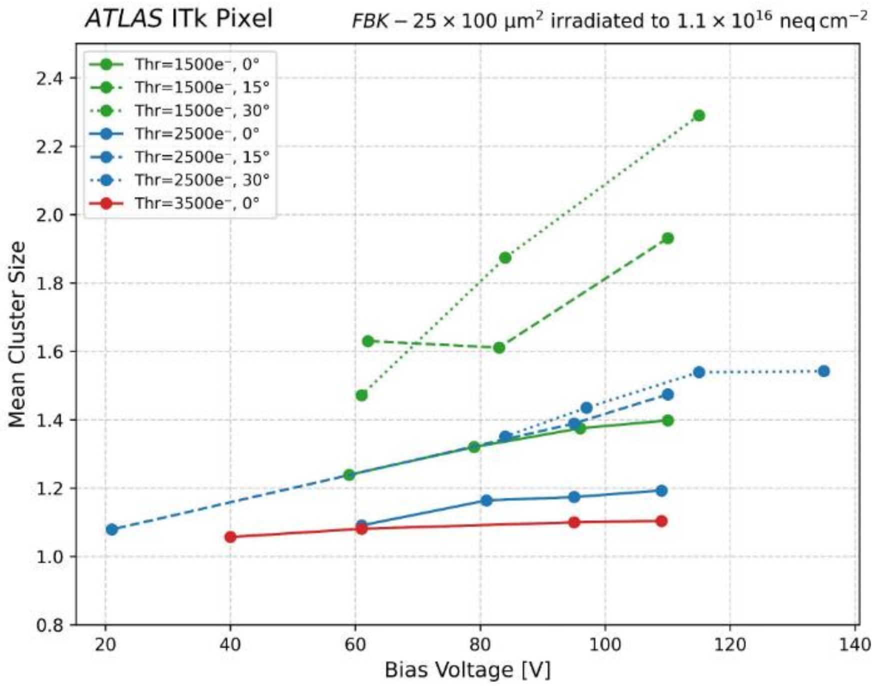
First beam test of irradiated Triplet modules - RaRis

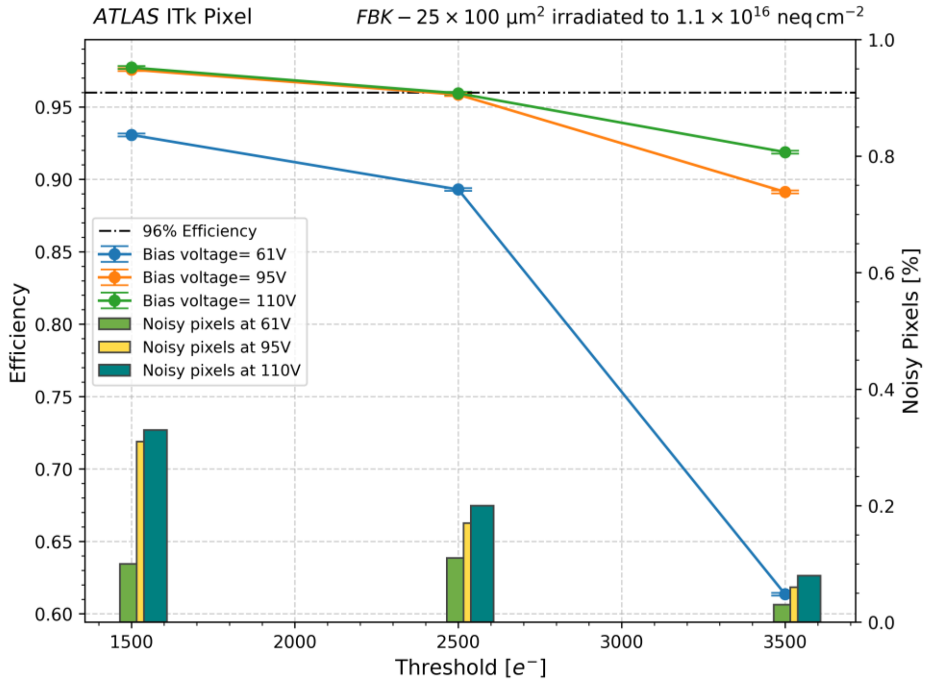
Triplet module tested also with three different thresholds: 1500e, 2500e and 3500e

The same considerations on charge collection apply as in the slide before

- *Before irradiation*: 150 µm x ~80 e/µm → *Expected charge released ~ 12ke*
- ***After irradiation*, assuming ~50% reduction in charge collection → *Expected ~6ke***

- ***Good efficiency at 3500e is hard to achieve every time the charge is shared on more than one pixel***
- ***Good results up to 2500e threshold configuration and 110V bias voltage***

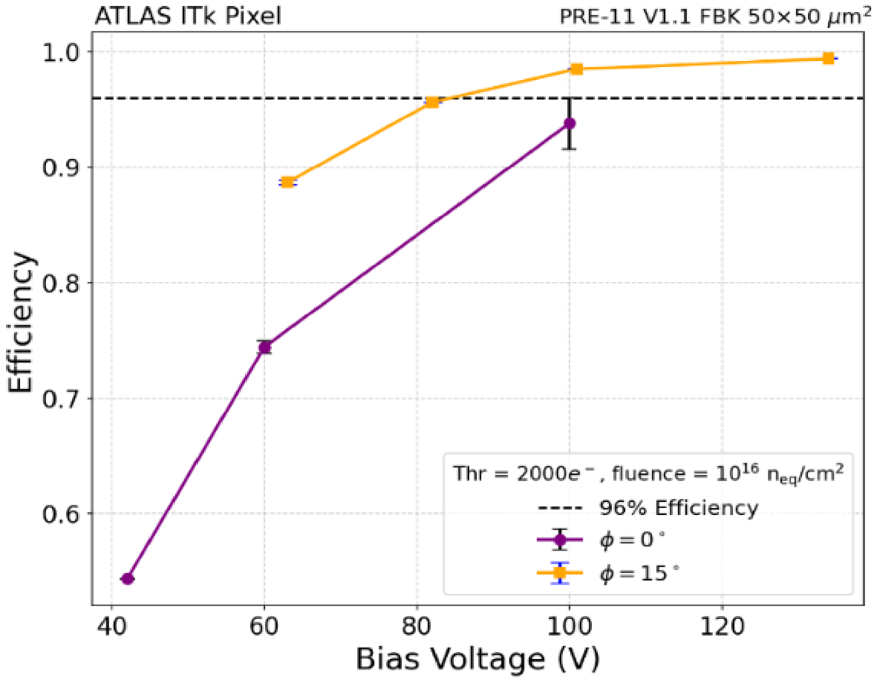




First beam test of irradiated Triplet modules - IRRAD

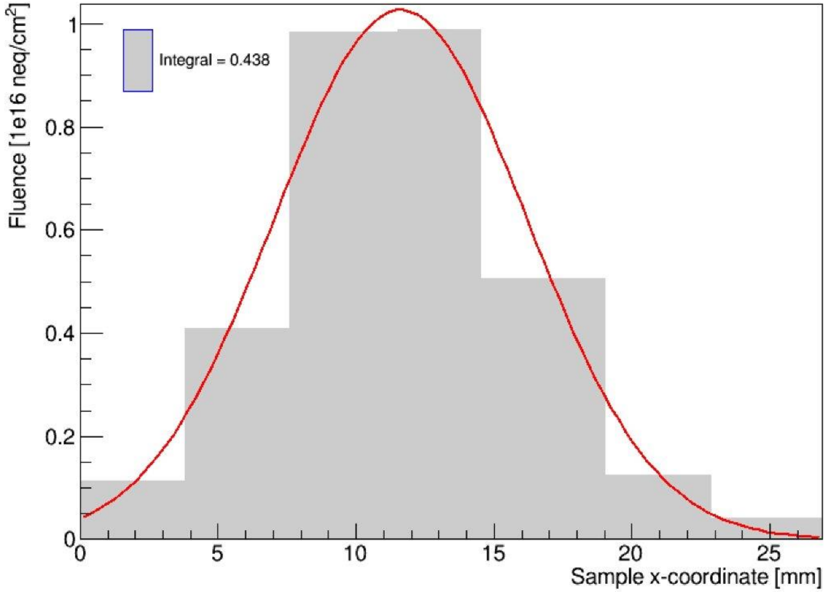
NOT uniformly irradiated Linear Triplet Module tested on the beam in July 2025 at CERN SPS

- ITkPix v1.1 + 3D sensor FBK (50x50 μm^2 pixel size)
- ***Irradiation in IRRAD (CERN) average fluence 0.5e16 n_{eq} / cm^2***
- **Peak fluence 1.0e16 n_{eq} / cm^2 → *Area where the efficiency is measured***
- Two different geometrical configurations: inclinded ***0°, 15° with respect to the beam incidence***
- Reaches the ***96% efficiency*** target set by the detector requirements ***at 100 V and 15***
  - ***Similar performance of the RaRis Triplet module irradiated at similar fluence*** (Previous slide)



Sample x-coordinate

Profile of the integrated fluence collected by the Al dosimeter strips along the sample x-coordinate



ATLAS ITk Pixel Innermost layer modules: the Triplet modules

First test beam results of irradiated ITkPix Triplet module

First test beam results on the charge collected with ITkPix v2 chip

ToT Calibration – ITkPix v2 chip – – Before Irraddiation

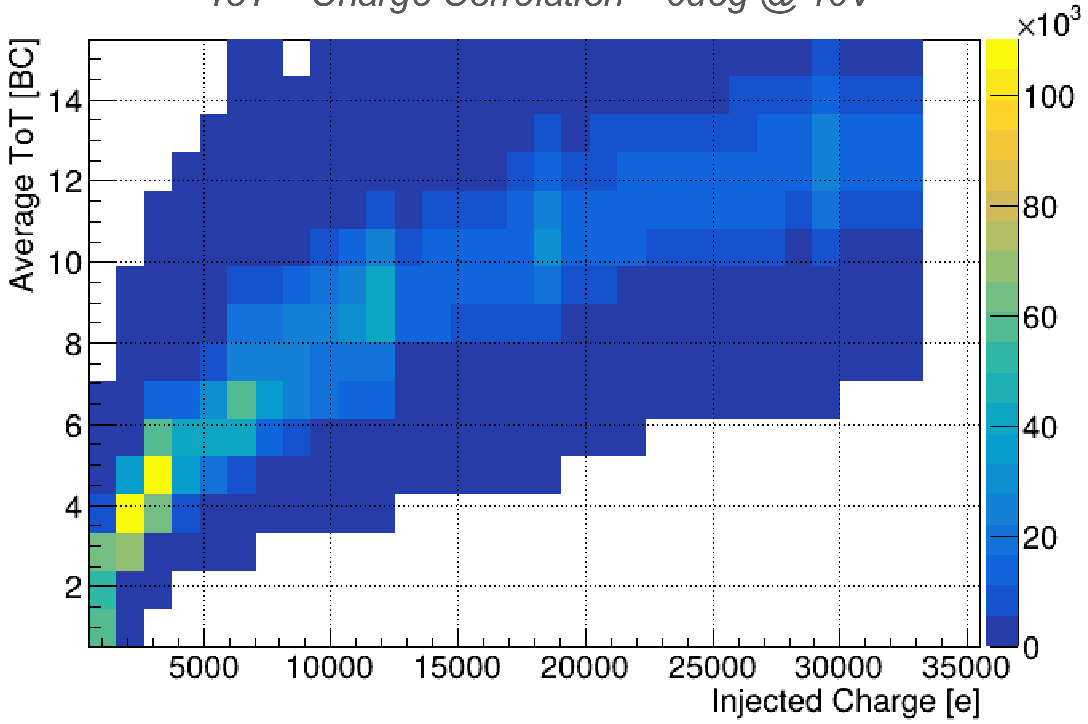
In May 2025 an ITkPix v2 + 3D sensor (FBK) on Single Chip Card tested for the first time on the SPS beam!

Large spread in the ToT-Charge Calibration

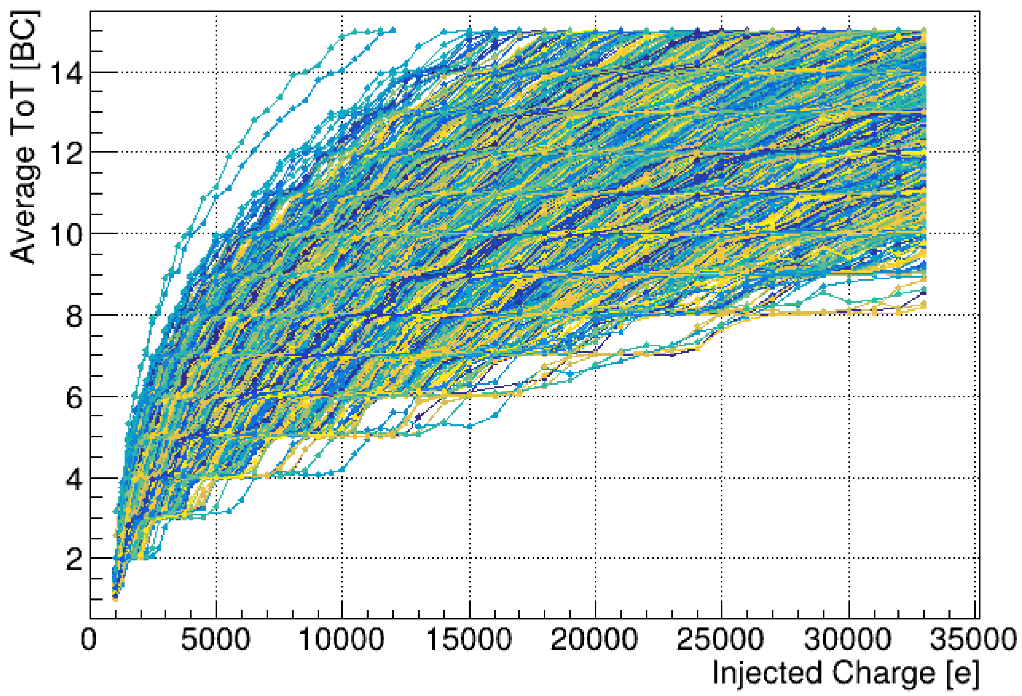
Even if it is not feasible to save a calibration curve per each pixel for the entire ITk

- We can make this exercise → ***Save a calibration curve per each pixel in a Tree***
- Reconstruct the charge with a different calibration curve per each pixel

ToT – Charge Correlation – 0deg @ 10V



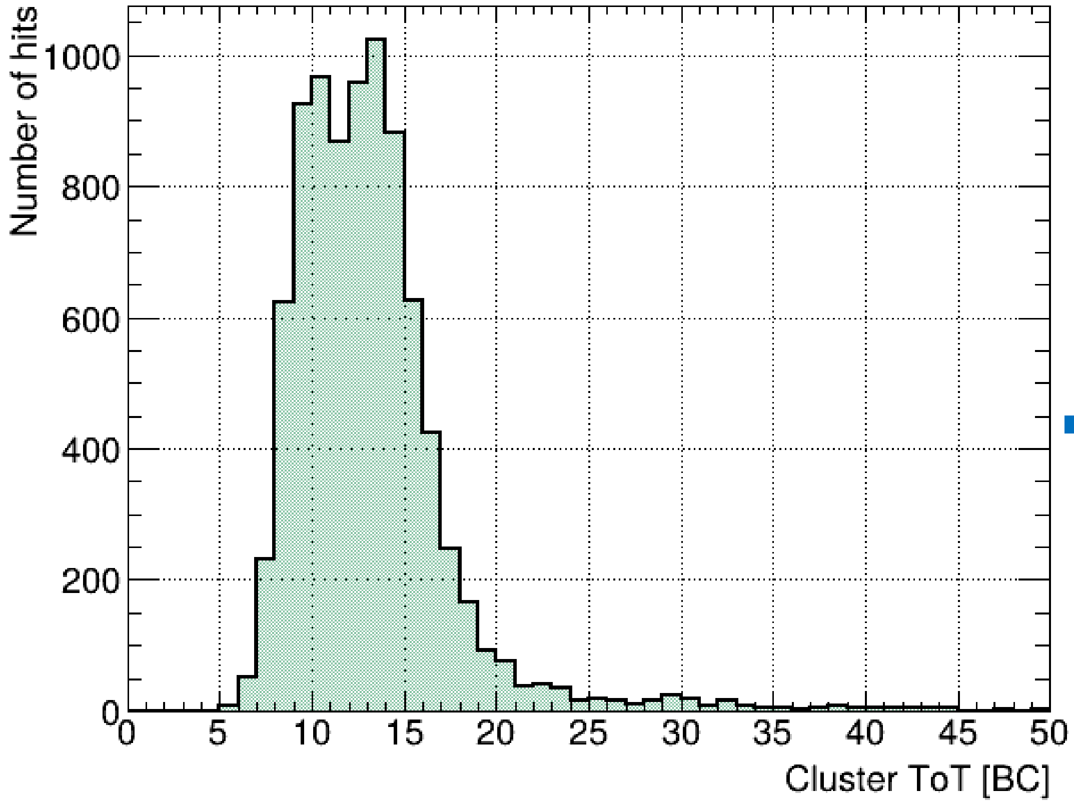
Several calib. Curves pixel-level – 0deg @ 10V



ToT to Charge – ITkPix v2 chip – Before Irraddiation

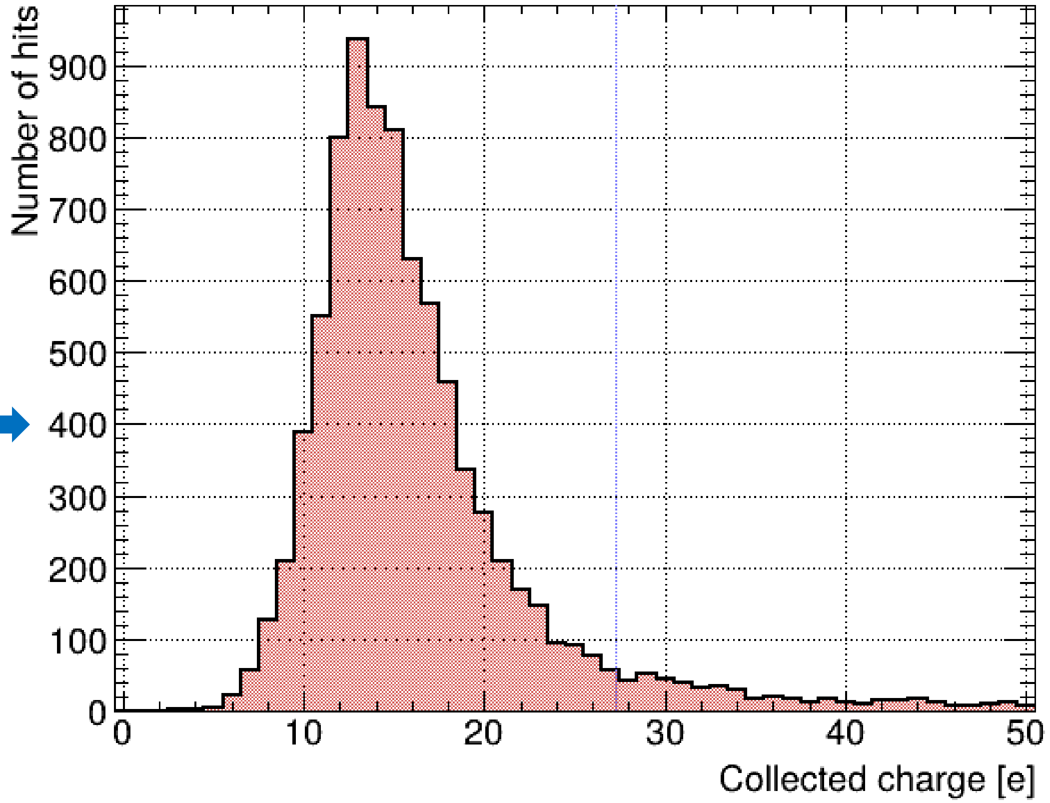
The pixel-by-pixel calibration helps in recovering some granularity in the reconstruction of the charge

ToT Distribution – May Test Beam – 0deg @ 10V



LUT Tree

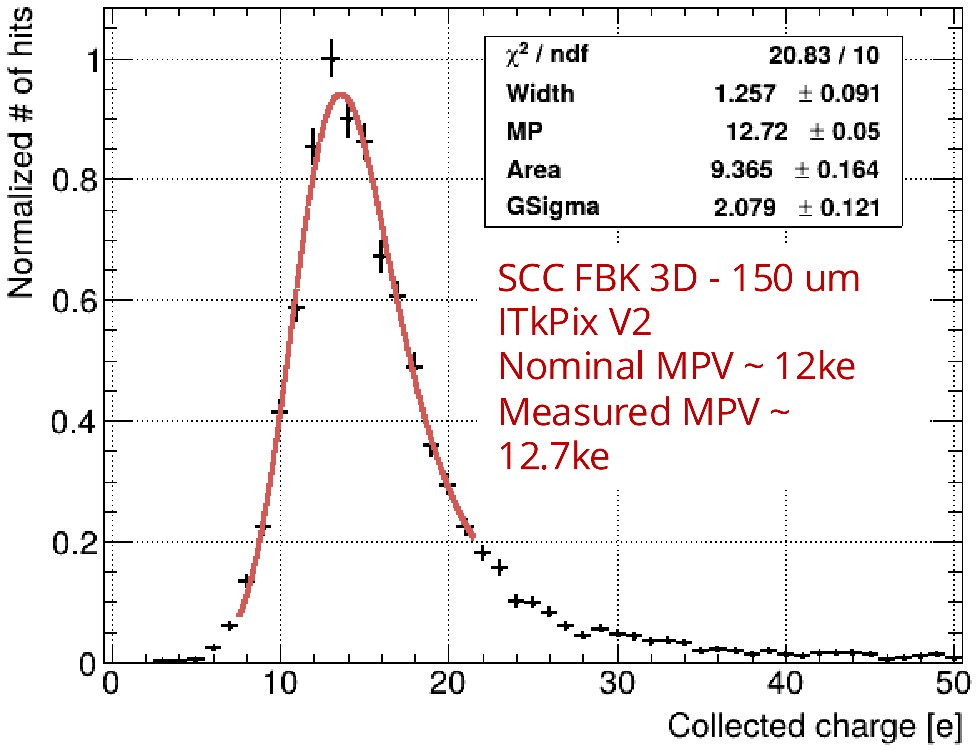
Charge Distribution – May Test Beam – 0deg @ 10V



Charge collected in FBK 3D – Before Irraddiation

Evaluate the charge released and collected by two samples available in the May test beam

- ***Evaluate the MPV using a Langaus distribution*** (Landau convoluted to a Gaus distribution)
  - *Residual error on the digitisation of the ToT, even if we use a pixel-by-pixel calibration curve*
  - *Residual error due to the uncertainty of the injected charge – Planned to be checked with sources*
  - *Up to now we may guess a ~ 10% uncertainty on the MPV*



Test beam on irradiated FBK 3D + ITkPix v2

FBK 3D 50x50 μm + ITkPix V2 on Single Chip Card irradiated in IRRAD in July and tested for the first time on the beam in August

- ***Average fluence of ~1.3e16 n_{eq} /cm²***
- IRRAD ***irradiation very uniform***, even if the device is tilted and scanned along the horizontal direction
- ***Peak fluence close to 2e16 n_{eq}/cm²***

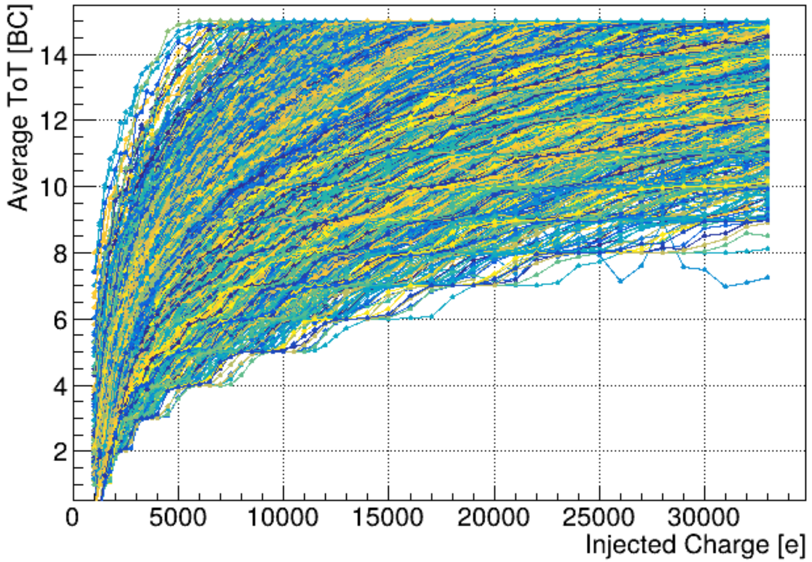
Experienced early **ToT saturation** (15BC @ 7ke) at the nominal working point ***7BC @ 6ke*** (Before irradiation)

Moved the working point at ***5BC @ 6ke can decrease the number of pixels saturating the ToT earlier***

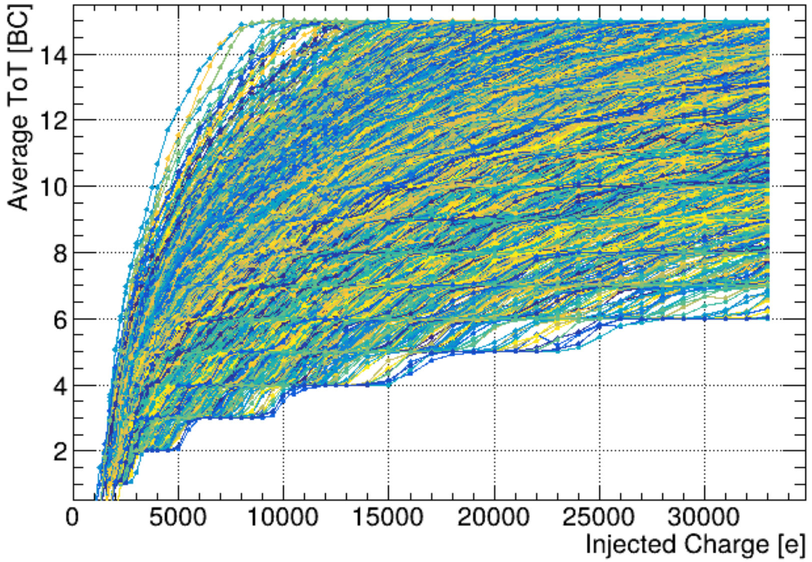
Data collected in September 2025

Sample	*Threshold*	*Working Point*
SCC 46 FBK 3D ITkPix V2	1500	7BC @ 6ke
	1500	5BC @ 6ke
	2500	5BC @ 6ke

Working point 7BC @ 6ke – *1500e Threshold*



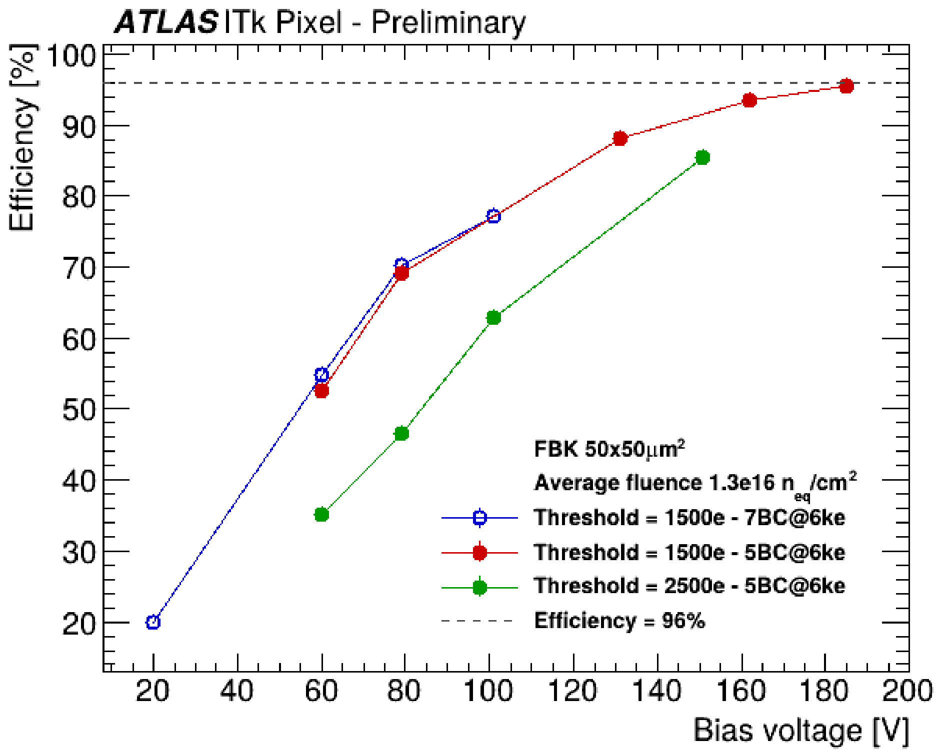
Working point 5BC @ 6ke – *1500e Threshold*

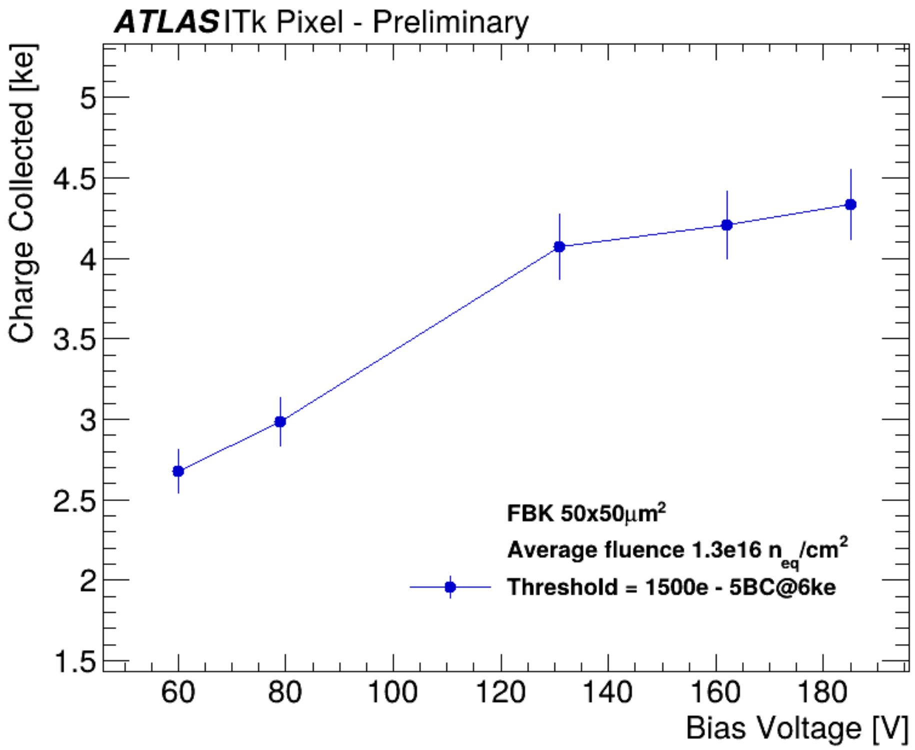


Charge collected in FBK 3D – Irraddiated

The module has been tested on the beam in the area of higher irradiation (~ 2e16 n_{eq} / cm^2)

- ***Can reach 96% target efficiency at 185V***, close to breakdown voltage
  - With ***only 2% of noisy pixels***
  - The *number of noisy pixels is much higher for bias voltage higher than 185V*
- ***Charge collected*** increases with the bias voltage
  - Reach kind of a ***plateu once the sensor is fully depleted at around 4k electrons***
  - Charge collection is ***reduce by ~ 60%*** with respect to the value before irradiation





To take over…

Conclusions and Outlooks

To be ready for the HL-LHC, **ATLAS** will replace its Inner tracking system with an **all new all-silicon tracker**

- **The Inner Tracker, ITk**

Considering the extremely high fluence collected by the innermost layers during HL (~ 1.7e16 n_{eq}/cm^2)

- 3D pixel sensors hybridized to 65 nm readout chip (ITkPix) has been chosen
- Three hybrid tiles arranged in three modules geometries to optimize the performance: the ***Triplet modules***

Triplet modules have been irradiated in two facilities (IRRAD, CERN & RaRis, Japan) and ***tested on the CERN SPS 120 GeV pion beam***

- The modules shows similar perfomance of bare 3D hybrid modules mounted on SCCs
- ***Can be operated up to 2500e threshold and 1e16 n_{eq}/cm^2***

The first ***3D FBK + ITkPix v2 chip has been tested on the beam and irradiated***

- Uniform irradiation up to an ***average fluence of 1.3e16 n_{eq}/cm^2*** (Peak fluence ~ 2e16 n_{eq}/cm^2)
- Can operate the module up to a bias voltage of ***185V with 96% efficiency and 2% of noisy pixels***
- ***Charge collection***, measured for the first time with v2 chip, ***is severly reduce down to 60% of the initial value***

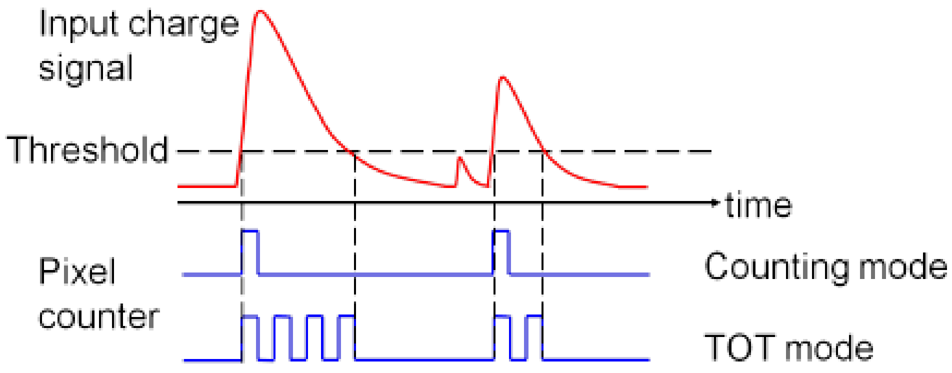
Ongoing... Last step of 2025... Test an irradiated ITkPix v2 Triplet module on the test beam facility at SPS

Backup

ToT Calibration of ITkPix v2 chip

In May 2025 an ITkPix v2 + 3D sensor (FBK) on Single Chip Card tested for the first time on the SPS beam!

ITk Pixel FEs ITkPix V2 able to measure of Time-over-Threshold (ToT)
- Time that the signal generated by the crossing charged particle hang above the discriminator threshold



The relation between charge released by the crossing particle and ToT can be calibrated

ToT-Charge tuning pixel-by-pixel
- Global register
- No single pixel registers – Large dispersion over pix. matrix
- Working point 7 BC @ 6000e

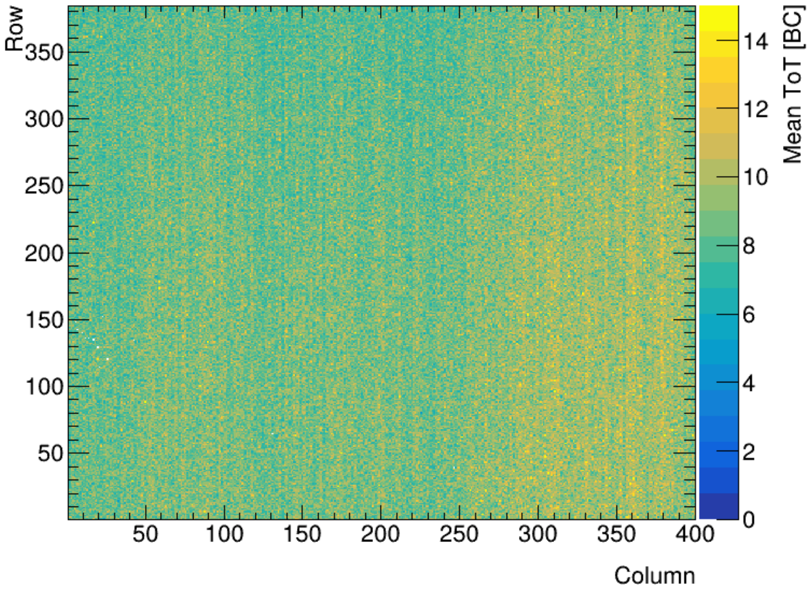
BEFORE DATA TAKING		DATA TAKING	DATA PROCESSING (OFFLINE)	
ToT-Charge Calibration via injection circuit	Calibration saved	***ToT is readout*** in the data stream **4 bits per pixel hit**	***ToT-to-Charge conversion*** via the previous calib.	Charge can be used for clustering or other task

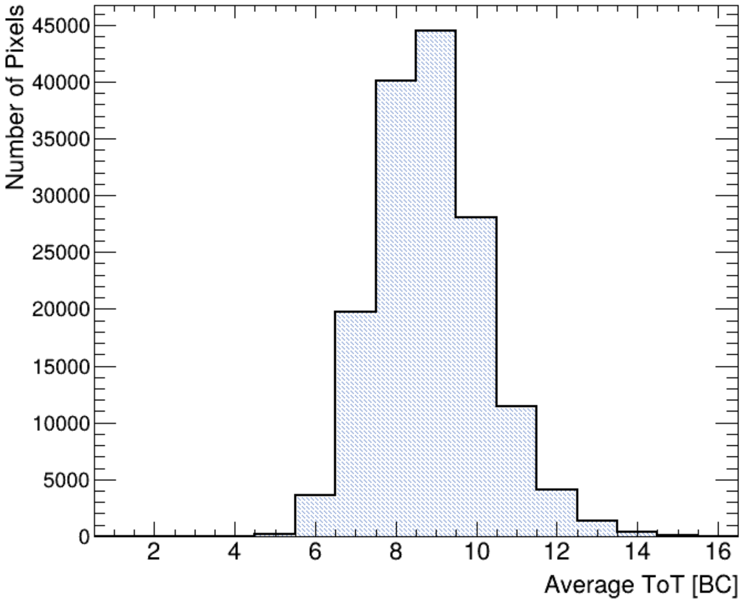
ToT Calibration of ITkPix v2 chip

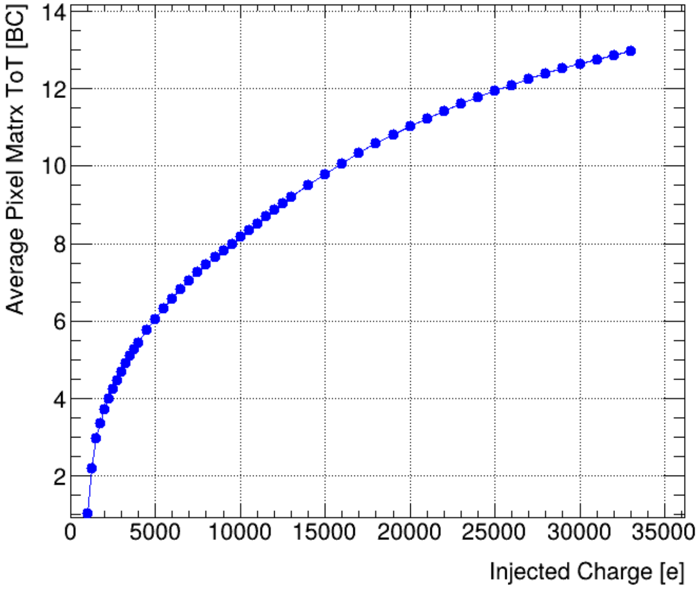
Device is tuned 7BC @ 6000e

The tuning can be checked measuring the ToT at different injected charges via std_totscan.json

- Performing *std_totscan.json with increasing injected charges from 1ke up to 33ke*
  - Each pixel is injected 50 times with the same value of charge
- Plot the Mean ToT map → Get the Mean ToT distribution of the chip matrix
- Plot the *Mean ToT value of the chip matrix VS the injected charge* → ***Calibration curve!***







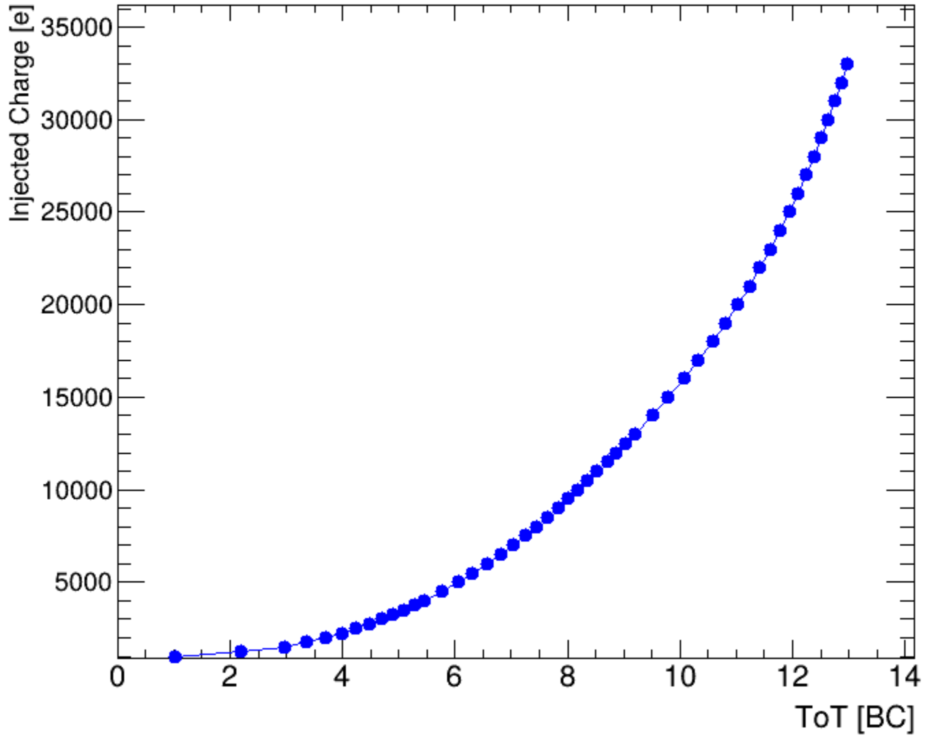
ToT Calibration of ITkPix v2 chip - Offline

The *calibration curve can be saved for offline* reconstruction of the charge

- ***Build a Look Up Table (LUT) ToT-to-Charge*** with the values of the calibration
- Once you have the ToT in your data you can retreive the charge
  - *Linear interpolation of the charge value between the two closest points in the LUT*

- ***NOTE: The calibration is NOT linear*** → *Need first to convert ToT-to-Charge per each pixel*
- *Once you have the pixel charge you can reconstruct the cluster charge (Charge released by the MIP)*
- ***Implemented the ToT-to-Charge conversion in the reco software Corryvreckan***

ToT-to-Charge – Look Up Table



Linear interpolation of ToT = 10