ATLAS ITk FBK 3D sensors 50x50 μm^2

In-Pixel local efficiency after irradiation up to 1.9 x 10^{16} n_{eq} / cm^2

G. Calderini, F. Crescioli, G.-F. Dalla Betta, G. Gariano, C. Gemme, S. Hadzic, T. Heim, **S. Ravera**, M. Ressegotti, A. Rummler, Md. A. A. Samy, D M S Sultan, L. Vannoli

TREDI 2023

18th Trento workshop on Advance Silicon Radiator Detectors

Trento, 28 February - 2 March 2023

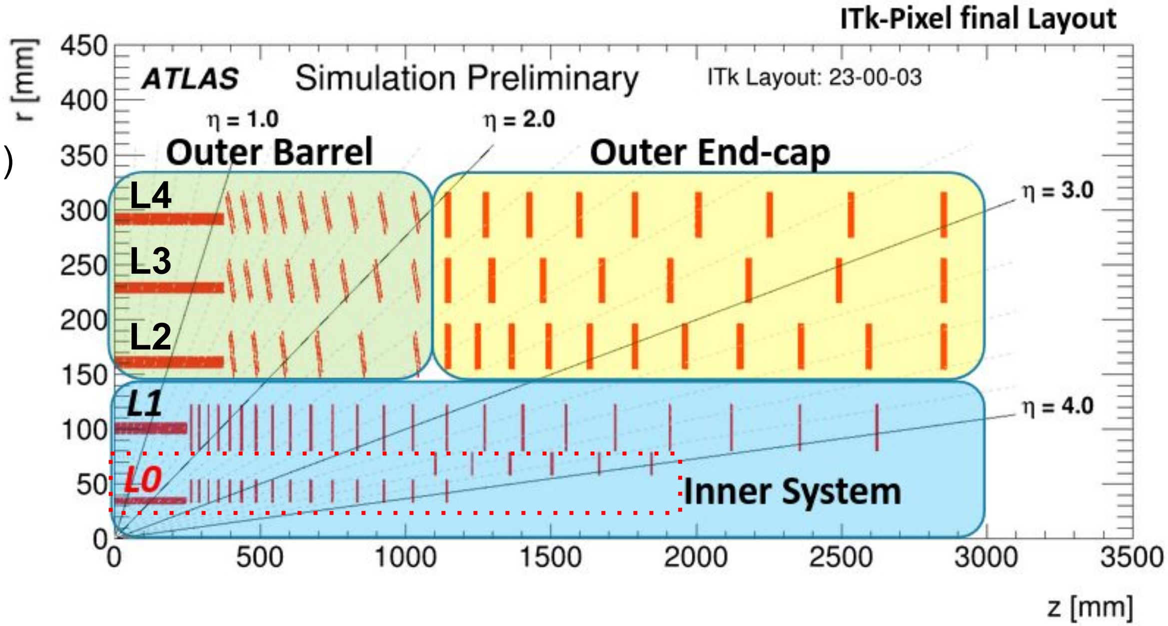
ATLAS Inner tracker towards HL-LHC → The ITk

With the HL-LHC program starting in 2026 the **luminosity will ramp up to 5-7.5 10^{34} cm^{-2} s^{-1}**

- the ATLAS Inner tracker will be completely replaced with a new **all-silicon** (pixel+strip) tracking detector → **The ITk**

The ITk Pixel detector:

- 5 layers of Pixel detectors:
  - **L2-L3-L4**: Planar sensors (150 μm)
  - **L1**: Planar sensors (100 μm)
  - **L0: 3D sensors**
- Pixel Inner System will be replaced after 2000 fb^{-1} (1.5 safety factor on max fluence)
  - **Fluence of about 2e16 n_{eq}/cm^2**
  - **TID up to 1 Grad**



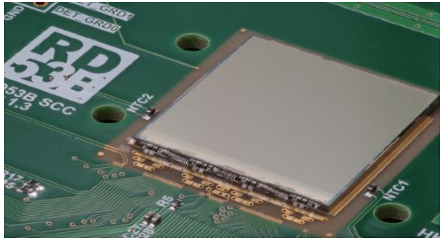
ITk_Final_Layout

The ITk Pixel FE Chip: The ITkPix

The ITkPix FE Chip will be will be used for all ITk modules

- **Delivered by the RD53 Collaboration**, using the same "library" to finalize the ATLAS and CMS read-out chips
- **ITkPixV1.1** chip: patch fixed high current (**ToT still not usable**)
- **ITkPixV2** chip to be submitted **in Spring 2023** (final simulation ongoing)

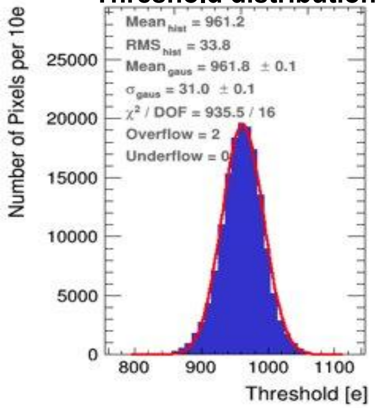
ITkPix FE Chip on SCC



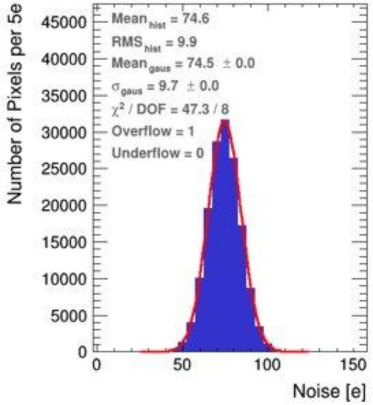
Main ITkPixV1 features:

- 65 nm CMOS, 2x2 cm^2 area
- 384 x 400 pixels (50x50 μm^2)
- Power consumption: 0.56 W/cm^2
- **Radiation hardness > 1 Grad**
- **Standard threshold: 1000*e*** (30e dispersion)
- **Mean Noise: 40*e* (FE only) → 80*e* after sensor bump-bonding**

Threshold distribution



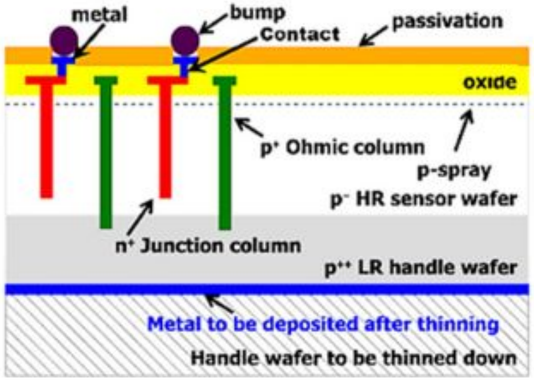
Noise distribution



Inner System 3D pixel sensor

ATLAS ITk will use **3D pixels in the Inner System** L0 with 2 different pixel cell dimensions (2x2 cm^2 tiles):

- 25x100 μm^2 in the barrel
- 50x50 μm^2 in the endcaps



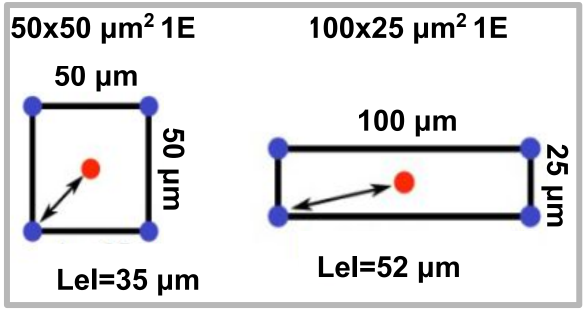
ATLAS Production is split between:

- CNM (25x100 μm^2, backup FBK)
- FBK and SINTEF (50x50 μm^2)

Pre-production almost completed

- by **FBK in Summer 2021** (50x50 μm^2) → **Production**
- by FBK in Summer 2022 (25x100 μm^2)
- by SINTEF in February 2022 (50x50 μm^2)

- CNM expected delivery: March 2023 (25x100 μm^2)



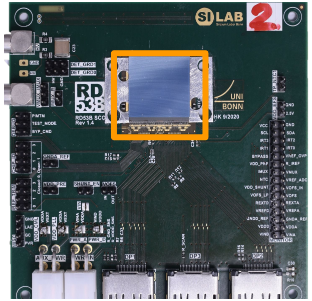
See also J. Carlotto's talk

Assembly of 3D FBK+ITkPix v1.1 on SCC in Genova

Eight 3D + ITkPixV1.1 single-chip modules assembled in Genova on Single Chip Cards (SCCs)

- Bump-bonded at IZM
- Radiation hardness and performance qualification of single chips

Module on SCC

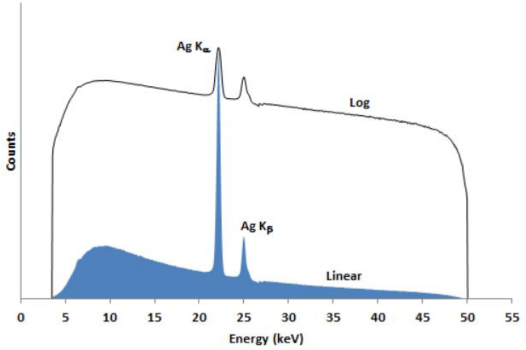


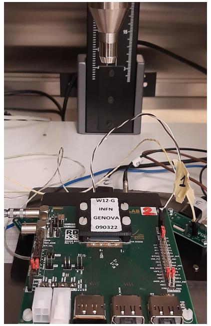
Sensor #	TB before irradiation	Irradiation	Fluence	TB after irradiation	Notes
W12-G	CERN PS & SPS	IRRAD	up to 1.7 x 10^{16} n_{eq}/cm^2		Magnet issue at IRRAD → Not able to test after irradiation
W12-M		Bonn + IRRAD	**up to 1.9 x 10^{16} n_{eq}/cm^2**	SPS	
W12-N	CERN PS & SPS				Used as timing reference plane at TBs
W12-J		Bonn + IRRAD	**up to 1.9 x 10^{16} n_{eq}/cm^2**	SPS	
W12-L		CYRIC	1.5 x 10^{16} n_{eq}/cm^2		Irradiation finished on February 2023
W14-K		IRRAD	up to 1.7 x 10^{16} n_{eq}/cm^2		Magnet issue at IRRAD → Not able to test after irradiation
W14-H					Serious BB issue
W14-M		CYRIC	1.5 x 10^{16} n_{eq}/cm^2		Irradiation finished on February 2023

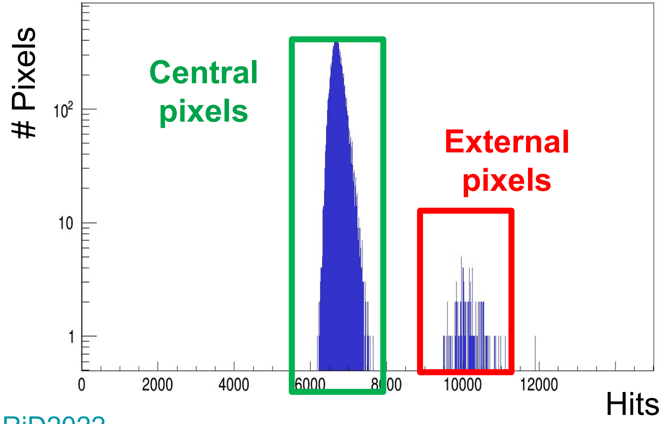
In the following
W12-M → SCC3
W12-J → SCC5

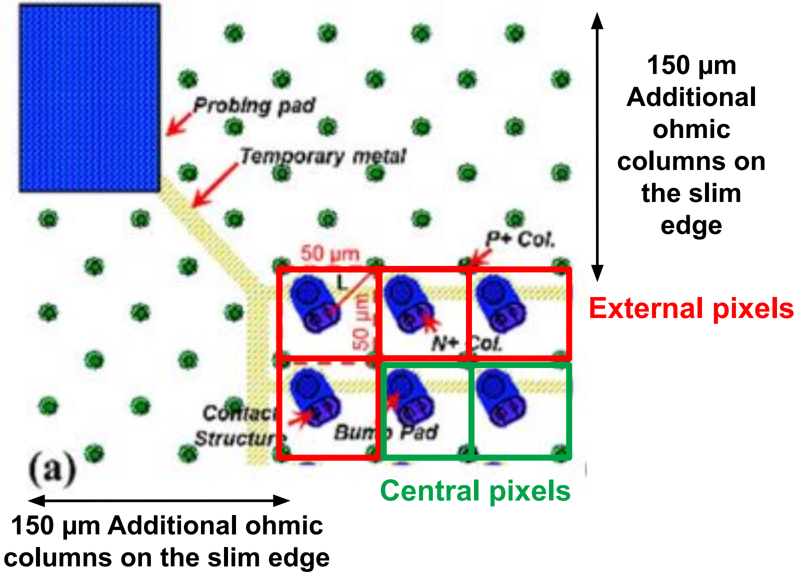
Laboratory characterisation

- Source: X-ray tube (Amptek Mini-X2), with Ag anode









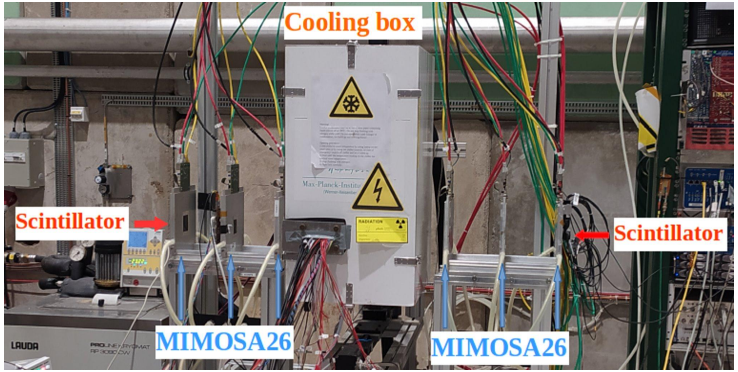
More info here iWoRiD2022

- Scans are run in Self-Trigger mode(HitOR)
  - **30% more hits in the external pixels** on the slim edge due to extension of the electric field

CERN PS & SPS Beam tests setup and data analysis

Several TBs 2022 Campaigns

- Proton Synchrotron (PS): April 2022
- Super Proton Synchrotron (SPS): May-July-November 2022

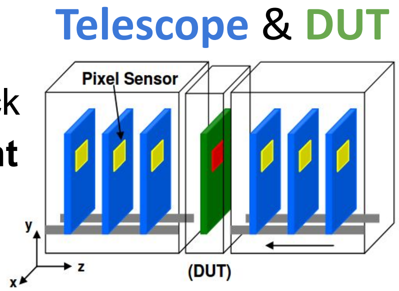


- Data analysed with the C++ based framework Corryvreckan

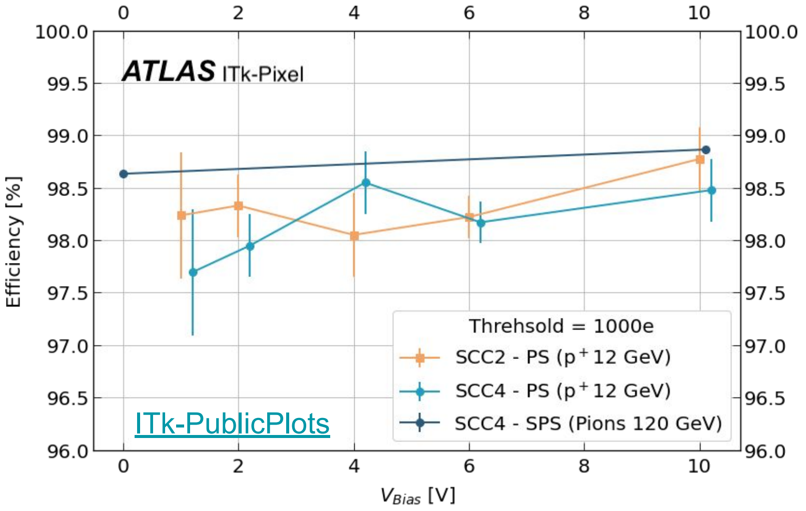
- A 6-plane telescope [MIMOSA26] alignment with track χ^2 minimization → ~3 µm resolution on track reconstruction

The efficiency is calculated

- with tracks on DUT that **meets spatial and time** cuts w.r.t. reconstructed track
- **disabled, masked pixels and neighbouring ones are not taken in account**
- the resulting efficiency is valid for pixels that are not masked or disabled

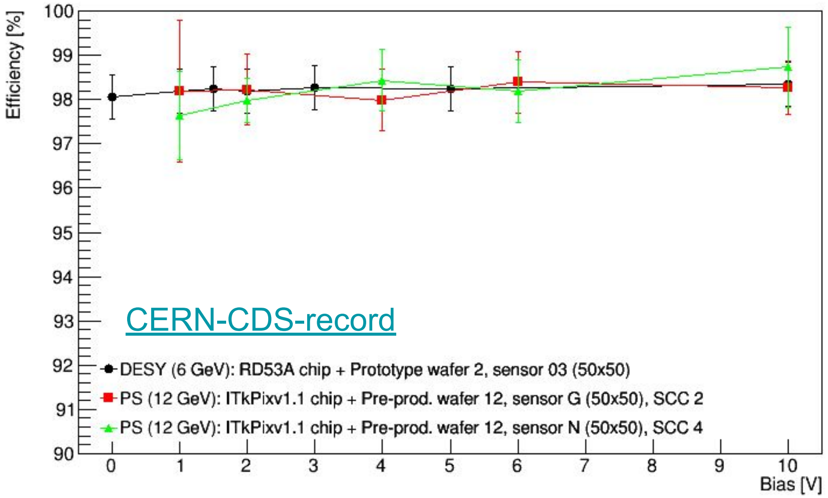


Efficiency of unirradiated 3D modules



Unirradiated modules tested at PS and SPS perpendicular to the beam

- **Efficiency > 98% already at 0 V bias (unirradiated)**
- PS [12 GeV protons] 1-10 V bias, low statistics, not optimal DAQ
- SPS [120 GeV pions] 0 and 10 V bias, high statistics



SPS proton beam perpendicular to DUT

Sensor average efficiency

- **0 V : 98.7 ± 0.1 %**
- **10 V: 98.9 ± 0.1 %**

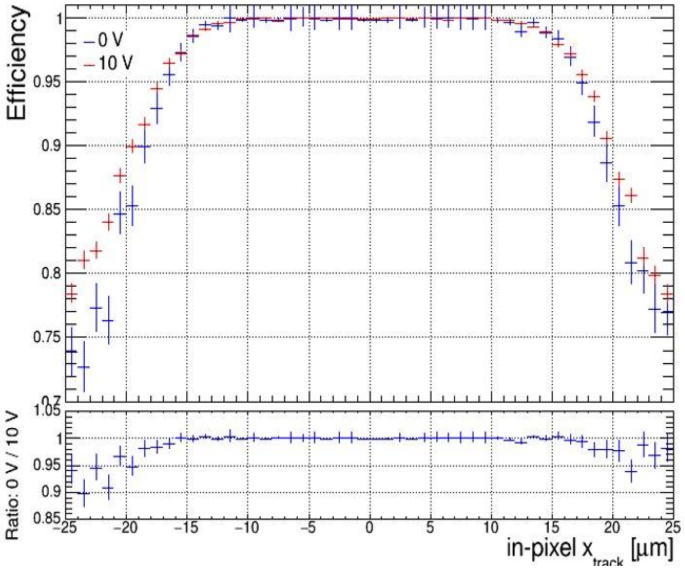
Results compatible with 50x50 μm^2 prototype (RD53A chip + FBK 3D sensor) previously tested at DESY (6 GeV electrons)

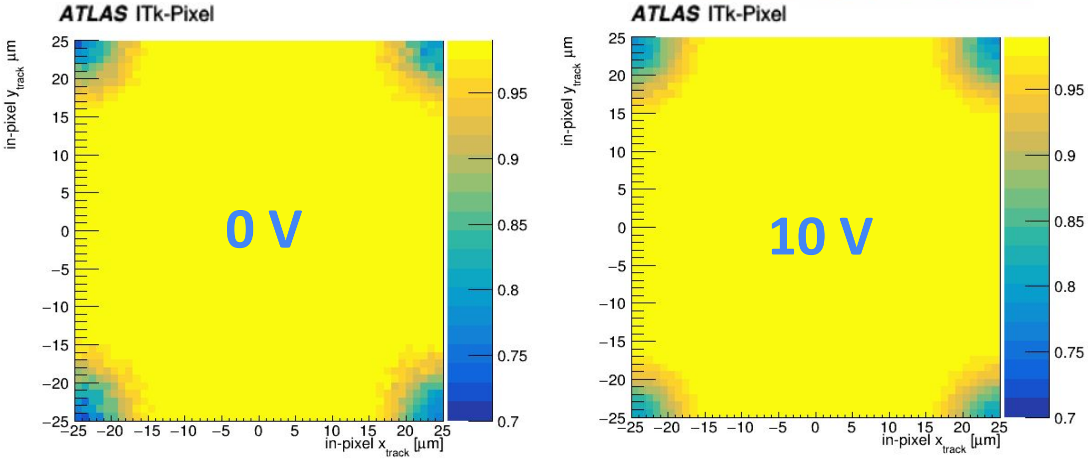
3D Pixel cell local efficiency before irradiation

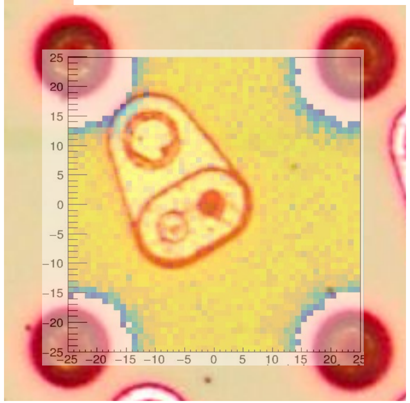
Pixel cell local efficiency map **(normal incidence)**

- **Central area**: higher than **99% efficiency**
- n^+-columns are formed at a safety distance of 25 µm from the handle wafer
  - **~99% efficiency at the N^+ column**

Projection of the top row of the maps



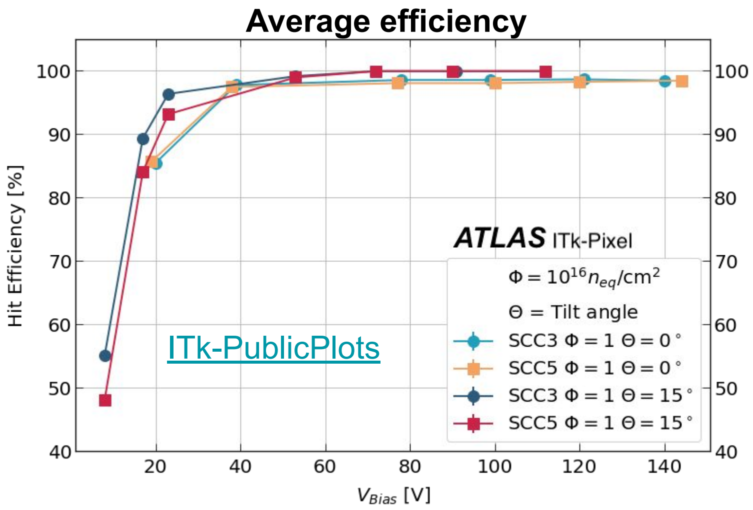




- **Lower efficiency zones visible in corners:**
  - Effect (75% – 99%) radius: 10 µm
  - p^+ **columns** max radius: 4 µm

iWoRiD2022 & ITk-PublicPlots

Beam Tests after 1st irradiation

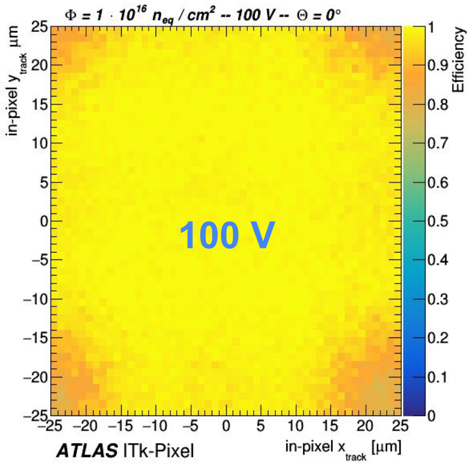


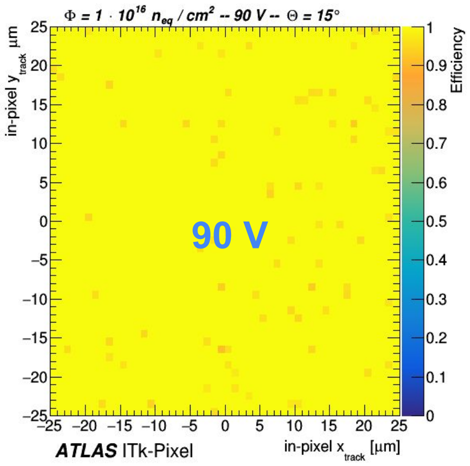
Two modules irradiated in Bonn

- **Uniform fluence Φ of 1 x 10^{16} n_{eq}/cm^2**
- **Tested perpendicular** (θ=0°) **and tilted** (θ=15°) w.r.t. the beam axis
- Average **efficiency > 97% @ 40V bias**
- FE average **threshold of 1000 *e***

Pixel cell local efficiency maps

- For **θ = 0°** results are similar to the one obtained before irradiation with **lower efficiency zones of radius ~ 10 μm at the corner** of the pixel cell
- For **θ = 15° lower efficiency areas are no longer visible in the local efficiency map** → higher mean efficiency



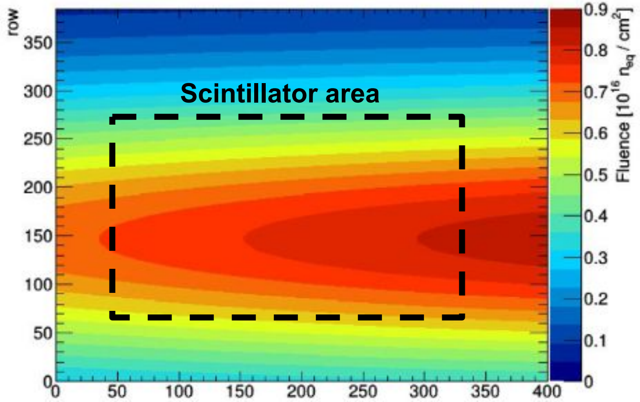


Beam tests after 2nd irradiation

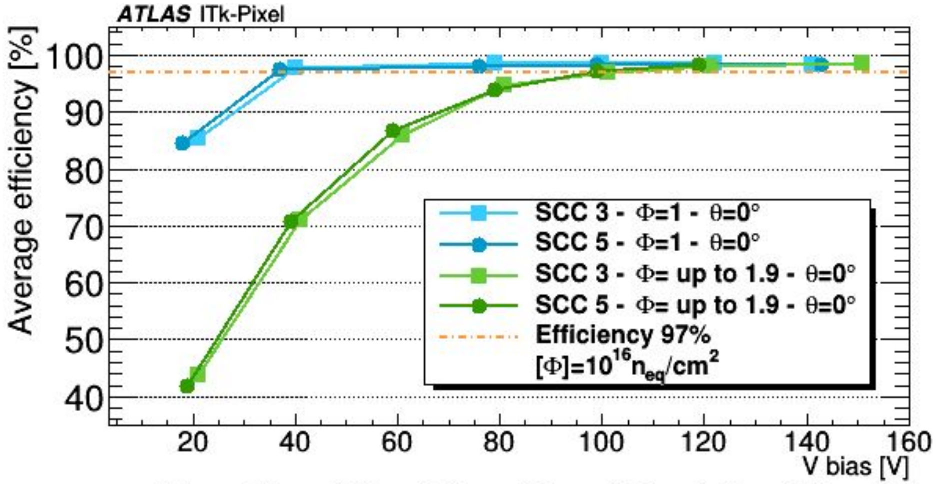
Second irradiation at CERN IRRAD facility for the two modules irradiated in Bonn

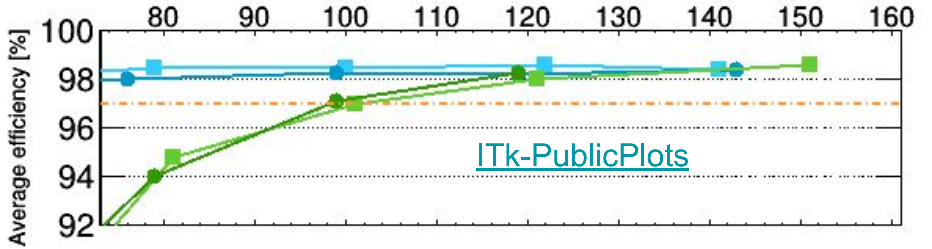
- **Not uniform fluence Φ up to 1.9 x 10^{16} n_{eq}/cm^2**
  - Over the TB scintillator area the **mean fluence is 1.71 x 10^{16} n_{eq}/cm^2** with a 3% uncertainty
- Tested perpendicular (θ=0°)
- Average **efficiency ~97% @ 100V bias**
- FE average **threshold of 1000 e**

IRRAD Reconstructed fluence map



More info in backup and here





ITk-PublicPlots

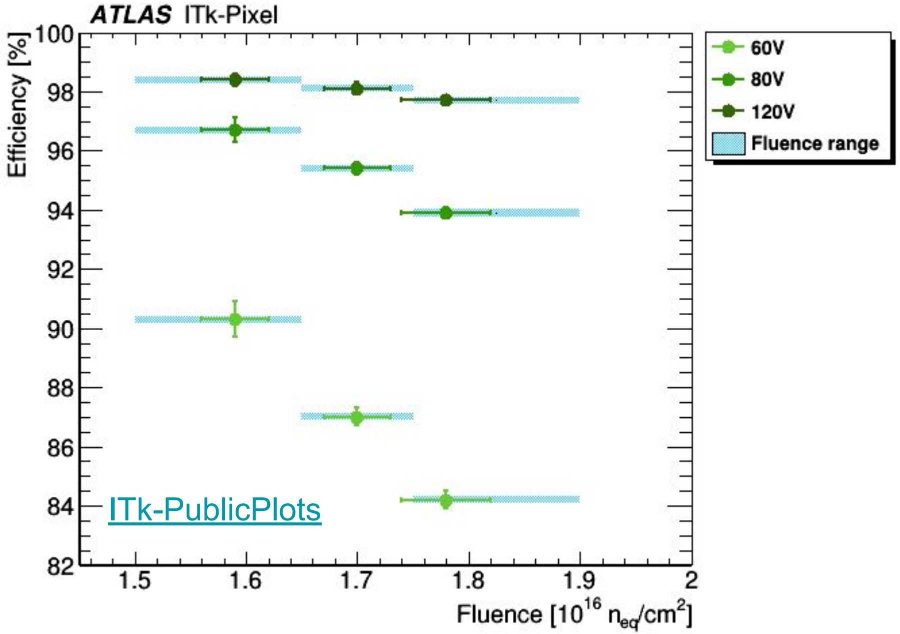
Average efficiency over the area covered by the TB scintillators

Efficiency vs Fluence (2nd irradiation)

Using the reconstructed fluence map of slide11

- Able to **assign a received fluence value to each pixel**
- Pixels are grouped in three fluence ranges (light blue boxes) according to the fluence Φ received
- **For each fluence range the average fluence** is calculated (3% uncertainty)
- **Lower efficiency at same bias voltage with increasing fluence**, as expected

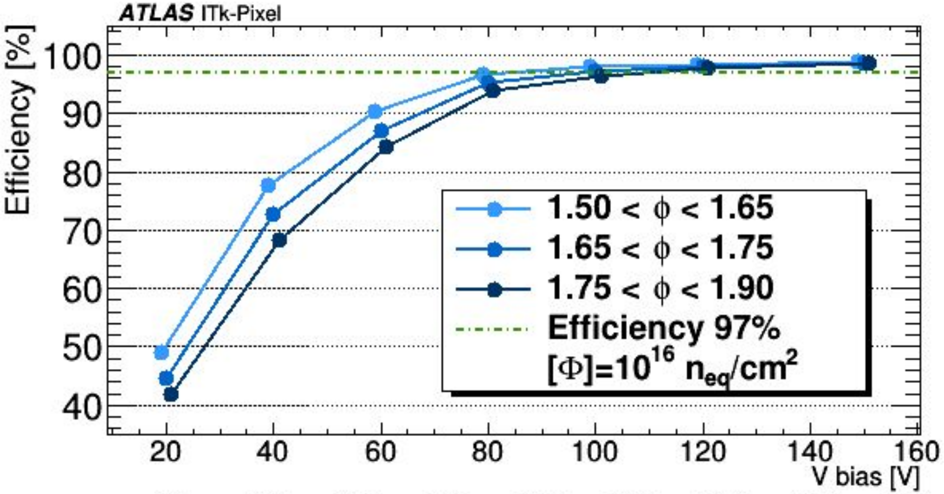
Fluence range [10^{16} n_{eq}/cm^2]	**Average fluence** [10^{16} n_{eq}/cm^2]
1.5 < Φ < 1.65	**1.59**
1.65 < Φ < 1.75	**1.70**
1.75 < Φ < 1.9	**1.78**

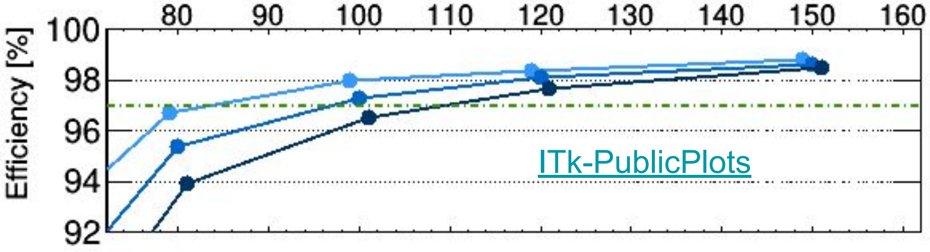


Efficiency vs Fluence (2nd irradiation)

- In the three different fluence range **efficiency > 97%** is reached
  - at **~ 80 V for <Φ> ≈ 1.59**
  - **at ~ 100 V for <Φ> ≈ 1.70**
  - **at ~ 110 V for <Φ> ≈ 1.78**

Fluence range [10^{16} n_{eq}/cm^2]	**Average fluence** [10^{16} n_{eq}/cm^2]
1.5 < Φ < 1.65	**1.59**
1.65 < Φ < 1.75	**1.70**
1.75 < Φ < 1.9	**1.78**





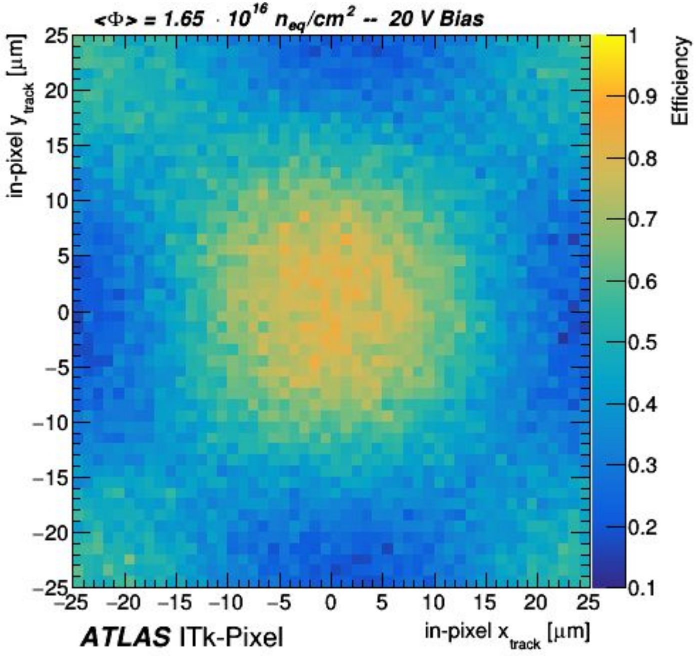
ITk-PublicPlots

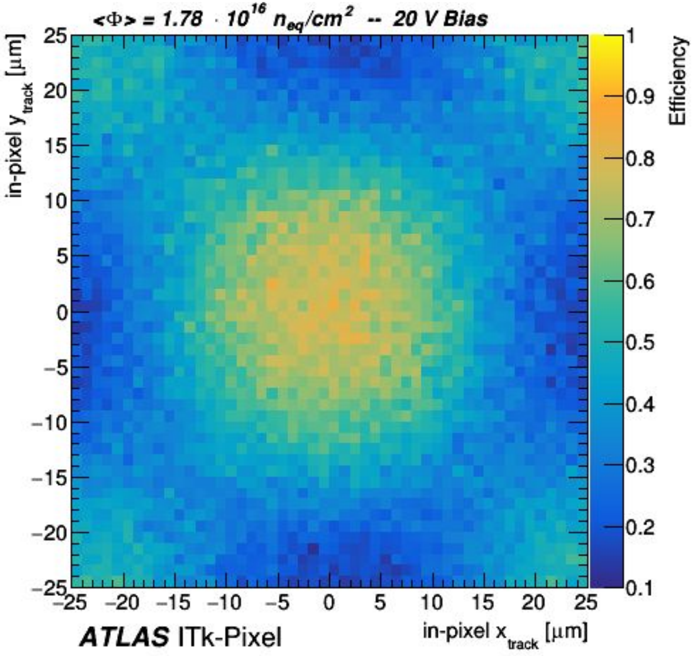
3D Pixel local efficiency after 2nd irradiation - 20V

At this stage pixels were grouped in two intervals based on the fluence received to increase statistics

Fluence range [10^{16} n_{eq}/cm^2]	**Average fluence**
$1.5 < \Phi < 1.75$	**1.65×10^{16} n_{eq}/cm^2**
$1.75 < \Phi < 1.9$	**1.78×10^{16} n_{eq}/cm^2**

Normal incidence





Lower efficiency areas

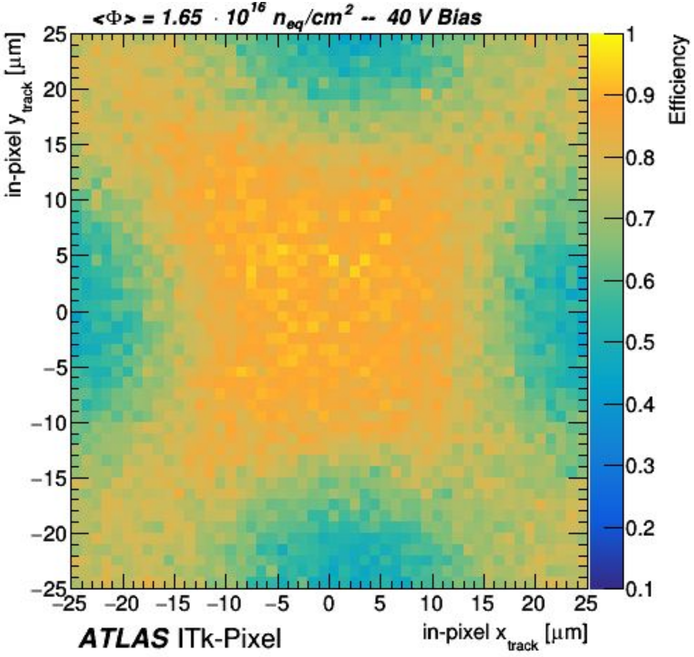
- Region with low electric field (simulation in backup)
- Areas were the electrodes are implanted

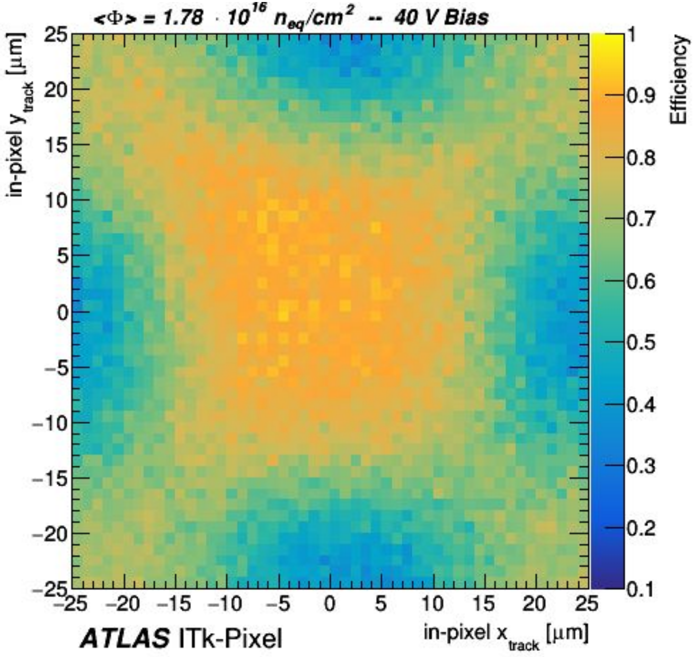
3D Pixel local efficiency after 2nd irradiation - 40V

At this stage pixels were grouped in two intervals based on the fluence received to increase statistics

Fluence range [10^{16} n_{eq}/cm^2]	Average fluence
1.5 < Φ < 1.75	**1.65 x 10^{16} n_{eq}/cm^2**
1.75 < Φ < 1.9	**1.78 x 10^{16} n_{eq}/cm^2**

Normal incidence





Lower efficiency areas

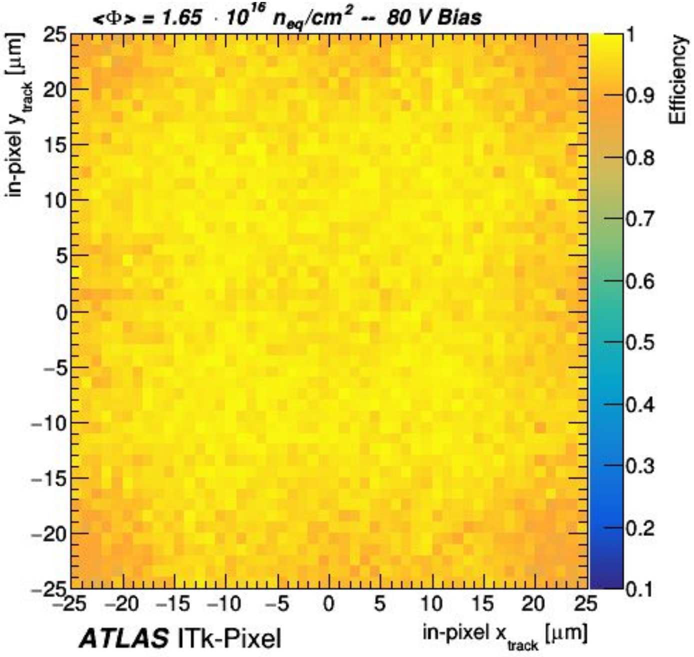
- Region with low electric field (simulation in backup)
- Areas were the electrodes are implanted

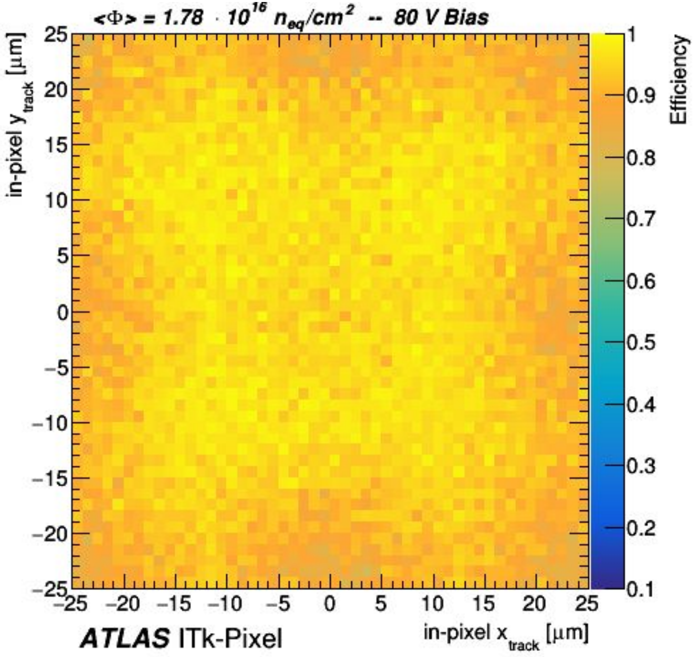
3D Pixel local efficiency after 2nd irradiation - 80V

At this stage pixels were grouped in two intervals based on the fluence received to increase statistics

Fluence range [10^{16} n_{eq}/cm^2]	Average fluence
$1.5 < \Phi < 1.75$	**1.65×10^{16} n_{eq}/cm^2**
$1.75 < \Phi < 1.9$	**1.78×10^{16} n_{eq}/cm^2**

Normal incidence





Lower efficiency areas

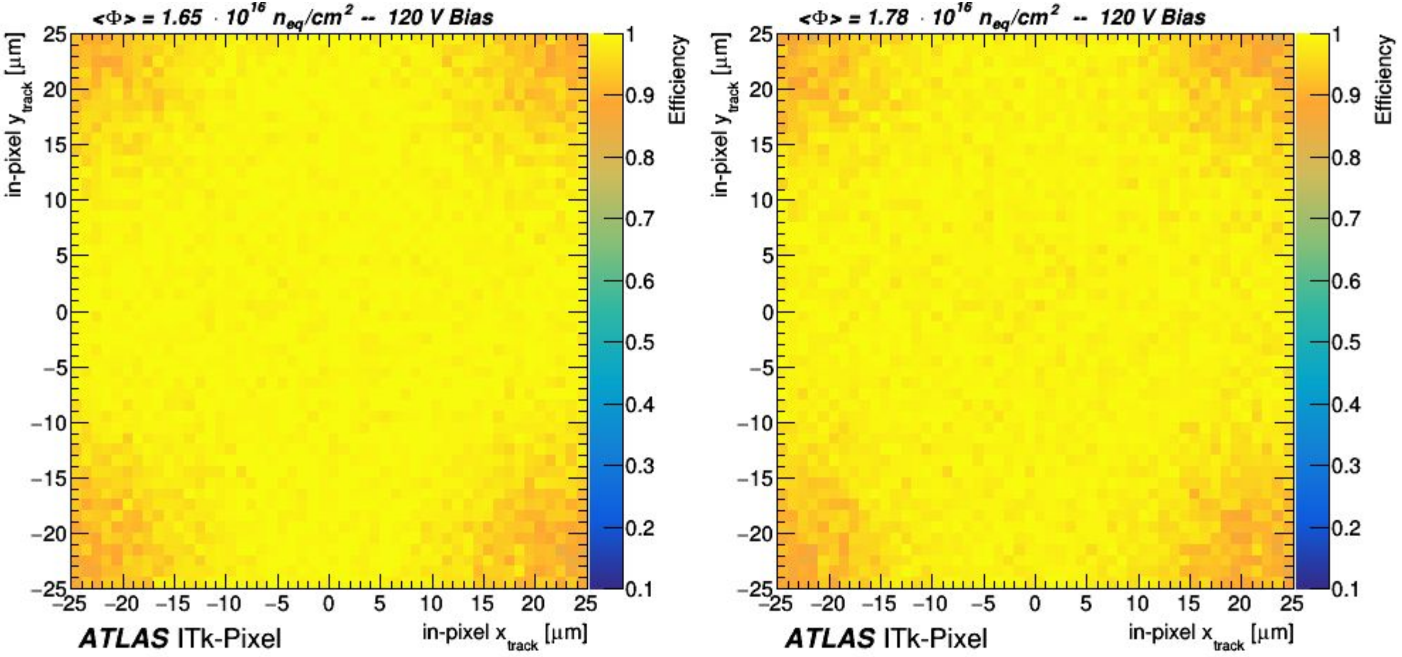
- Region with low electric field (simulation in backup)
- Areas were the electrodes are implanted

3D Pixel local efficiency after 2nd irradiation - 120V

At this stage pixels were grouped in two intervals based on the fluence received to increase statistics

Fluence range [10^{16} n_{eq}/cm^2]	**Average fluence**
$1.5 < \Phi < 1.75$	**1.65×10^{16} n_{eq}/cm^2**
$1.75 < \Phi < 1.9$	**1.78×10^{16} n_{eq}/cm^2**

Normal incidence



Lower efficiency areas

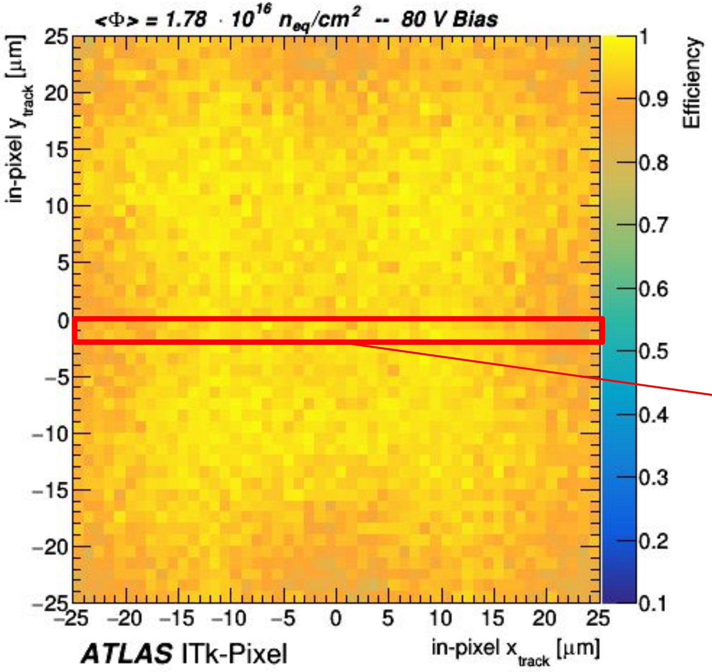
- Region with low electric field (simulation in backup)
- Areas were the electrodes are implanted

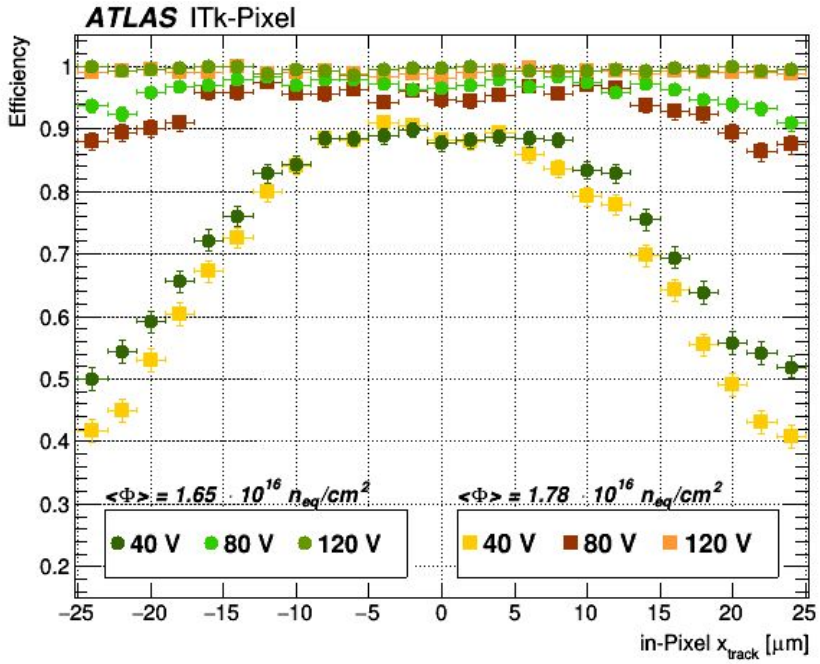
Irradiated 3D pixel cell efficiency projections

Projection of the central row of the local efficiency map for different bias Voltages and fluences

- **Efficiency is lower for pixels which received higher fluence**
- **At 120V Bias no significant differences** between the to fluence ranges
- **At low bias** (< 120 V) **partial inefficiency in the middle of the cell** (n^+ column)

Normal incidence



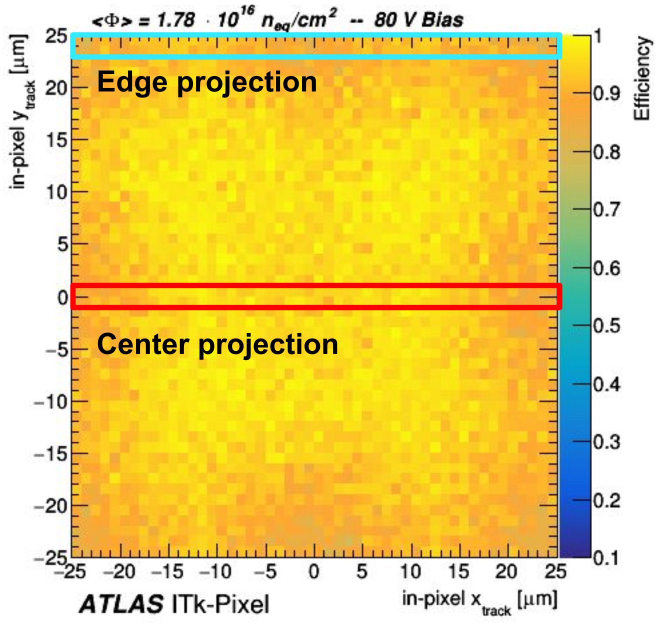


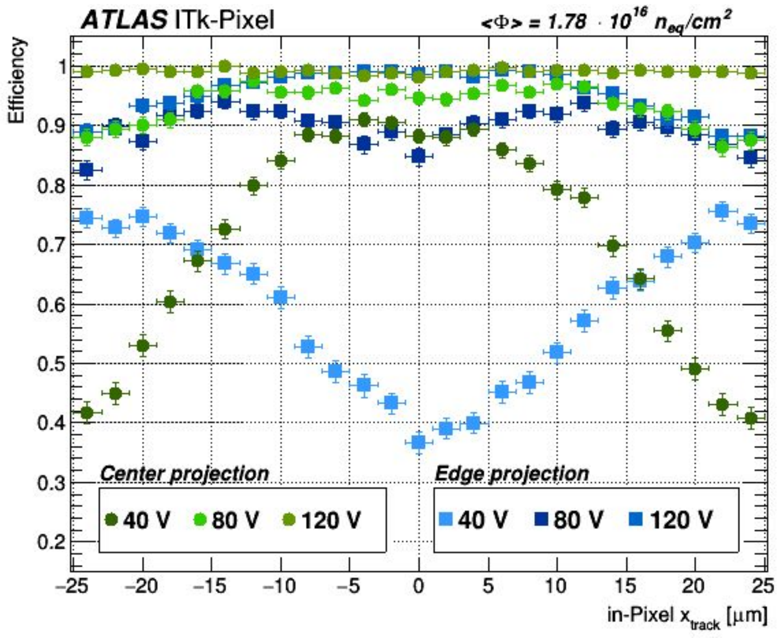
Irradiated 3D pixel cell efficiency projections

Projection of the central and top rows of the local efficiency map for different bias Voltages

- In the edge projection **lower efficiency areas are visible in corners** (p^+ columns) also at 120 V
- At **120 V Bias** the **central region** is **fully depleted**
- The **lower efficiency in the middle of the edge** is related to a **lower electric field** in this region

Normal incidence





Conclusions & Summary

The ATLAS ITk detector will be equipped with 3D sensor modules in the innermost layer (33-34 mm from collisions)

- Max fluence = 1.9 10^{16} n_{eq}/cm^2 (1.5 safety factor)
- Max TID = 1 Grad

3D modules (ITkPixV1.1 + 3D FBK 50x50 um^2) assembled in Genova presented

- Tested unirradiated in laboratory (X-rays) and in test beams (CERN PS and SPS)
  - Efficiency > 98% already at 0 V bias
  - In-pixel efficiency in central area >99% efficiency
  - Lower in-pixel efficiency zones visible in corners
- Irradiated **up to 1.9 x 10^{16} n_{eq}/cm^2** (not uniform, @Bonn and IRRAD) and tested in test beams (CERN SPS)
  - Average efficiency >97% reached at ~80 V, ~100 V, ~110 V for average fluence ≈ 1.59 Φ, 1.70 Φ, 1.78 Φ resp.
  - Visible effect of p^+ columns: lower in-pixel efficiency in corners → no longer visible if DUTs are tilted w.r.t the beam direction
  - The pixell cell is fully depleted with a bias voltage of about 150 V

Outlooks

- Studies ongoing to investigate pixels that became noisy during data taking in these sensors

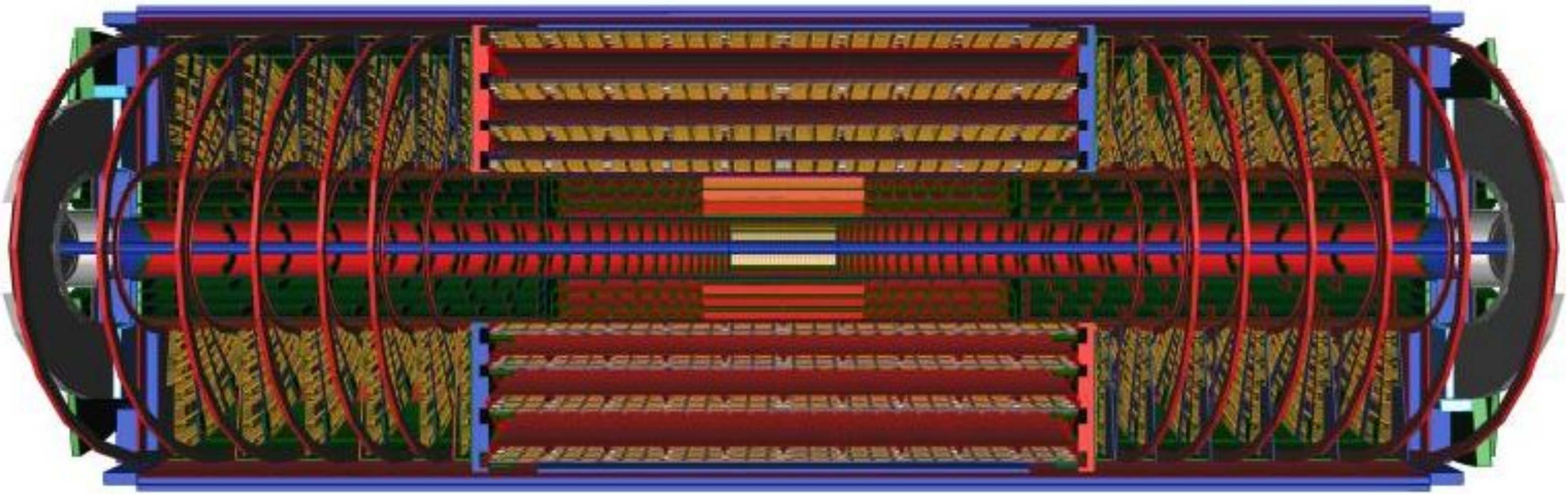
Thank you for the attention !

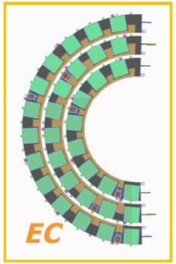
Acknowledgements to:

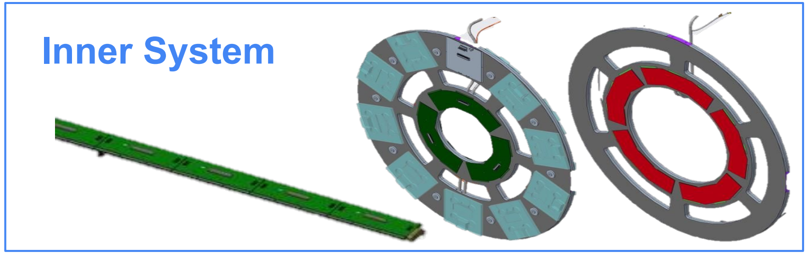
M.Bomben, T.I.Carcone, P.M.Chabrillat, A.Cordeiro, Y.A.R. Khwaira, C.Krause, K.Nakkalil, A.R.Petri, A.Skaf, S.Terzo, Y.Tian , P.Wolf, H.Ye and G.Pezzullo, F.Ravotti, M.Jaekel

Backup

ITk Pixel layout

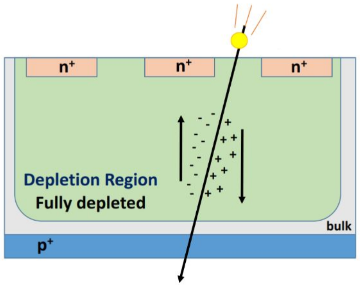


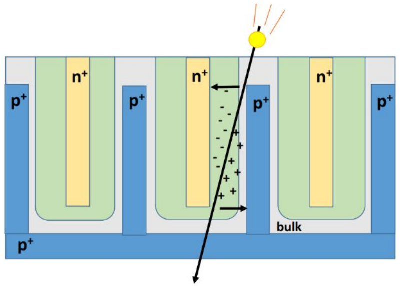




ITk Pixel Modules

- **Planar sensor**: standard pixel technology, n+ implants on p bulk surface
- **3D sensor**: n+ and p+ columns implanted vertically in p bulk substrate
  - Reduced distance between electrodes Shorter path of e/h
    - Lower impact of charge trapping along charge carrier path
    - Improved radiation hardness: perfectly OK @ 1e16 n_{eq}/cm^2 NIEL
  - Lower depletion voltage Lower power dissipation after irradiation



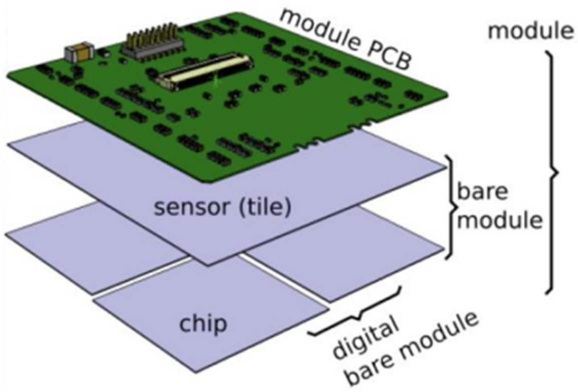


Planar sensors arranged in quad-modules: 1 bare module (4 chips + 1 planar sensor) + 1 flexible PCB

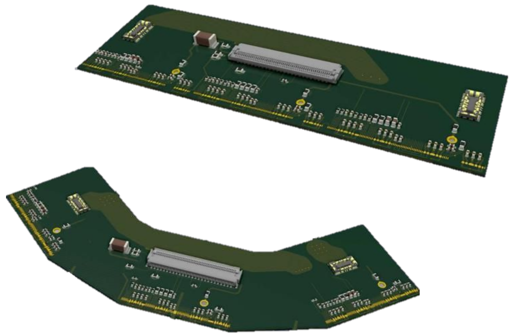
3D sensors arranged in triplet modules: 3 bare modules (1 chip + **3D sensor**) + 1 flexible PCB

- Both ring and barrel triplet assembly exercised with RD53A prototypes

Quad-module stack-up



Ring and barrel triplet module flexible PCB

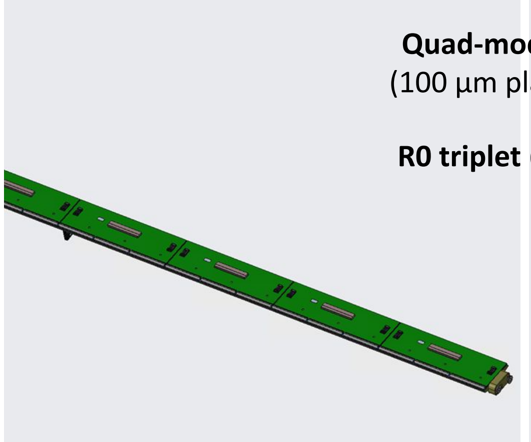


ITk Pixel modules: Triplets

Barrel (stave)

L0: 96 triplets

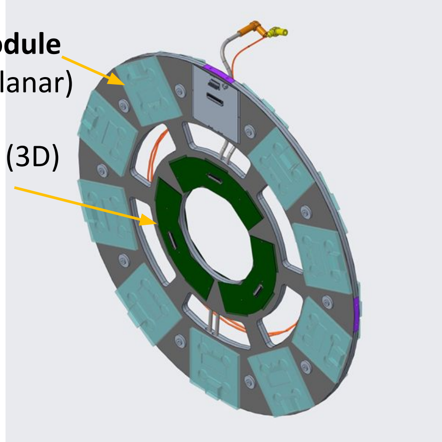
12 staves x 8 triplets



Endcap (rings)

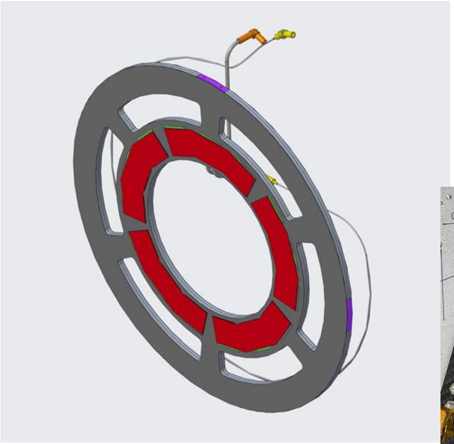
R0: 180 triplets

30 rings x 6 triplets



R0.5: 120 triplets

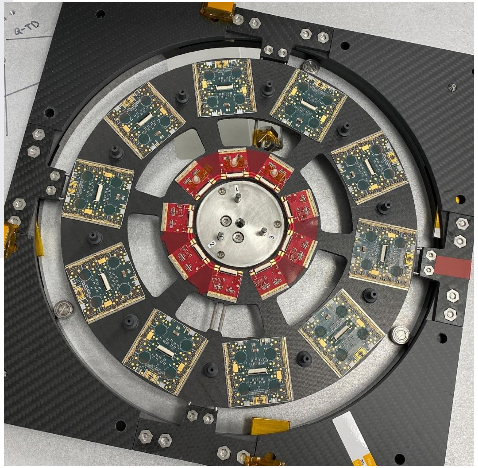
12 rings x 10 triplets



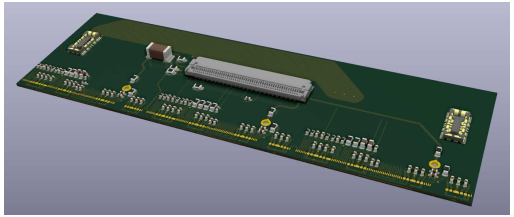
Prototype of ITk R0 ring with RD53A modules:

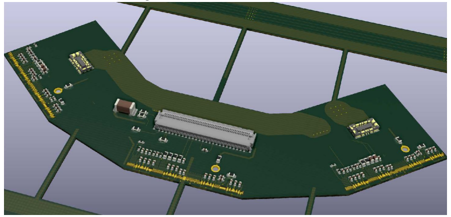
10 quad-modules

3 R0 triplets



- 3D sensors will be assembled in triplet modules (1 flex + 3 bare modules)

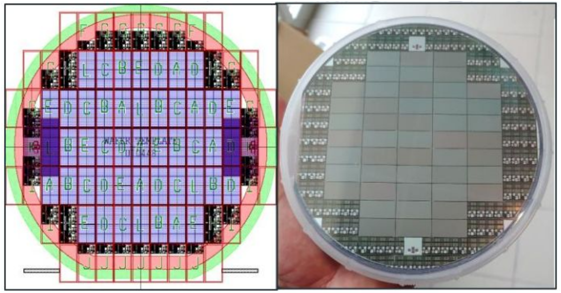




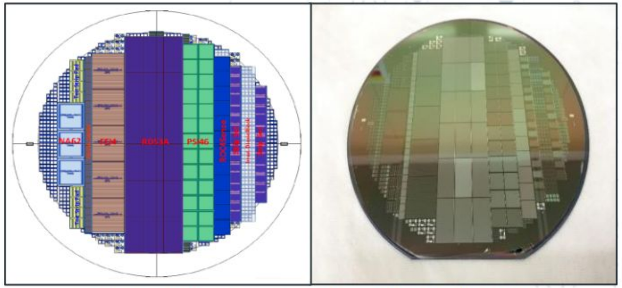
R&D 3D program with RD53A FE

- 2 different pixel cell dimensions for the 3D sensors (2x2 cm^2 pieces):
  - 25x100 μm^2 in the barrel triplet modules (288 sensors needed)
  - 50x50 μm^2 in the endcap triplet modules (900 sensors needed)

- In the last years, several R&D production of wafers by FBK:
  - Sensors 1x2 cm^2 compatible with the RD53A chip
    - Batch 2: Mask aligner, 130 µm active thickness
    - Batch 3: Stepper, 150 µm active thickness
    - Details at: <u>*S. Terzo et al* 2021 Front. Phys. 9:624668</u>
  - Bare modules (3D sensor + RD53A chip) assembled on card (SCC)
    - Tested before and after irradiation at DESY, up to 1e16 n_{eq}/cm^2
    - Details at: <u>*Md.A.A. Samy et al 2021 JINST 16 C12028*</u>



3rd 3D-SS batch also "New RD53A" ROCs
With Stepper Lithography Technique

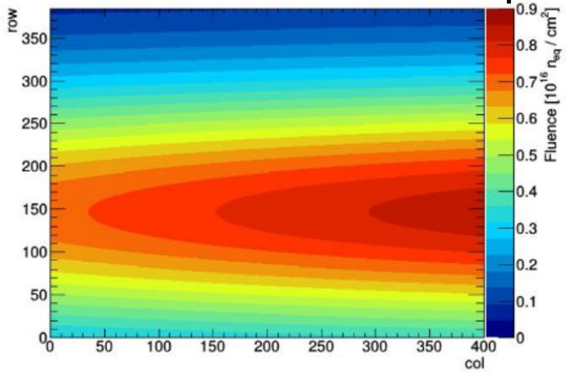


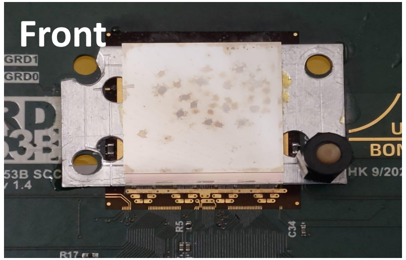
2nd 3D-SS batch also "New RD53A" ROCs
With Mask Aligner Lithography Technique

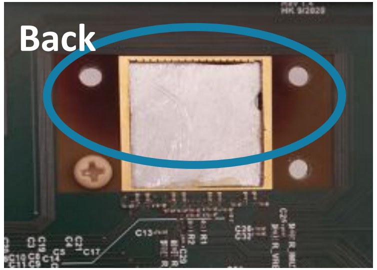
Modules 2nd irradiations at IRRAD

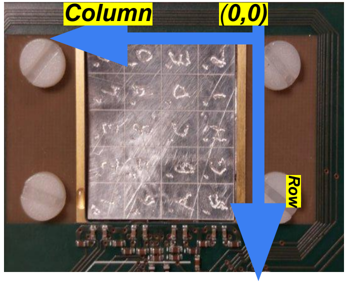
- at IRRAD (CERN, 7-27 September 2022) to add to fluence (not uniform)
  0.9 x 10^{16} n_{eq}/cm^2 (peak), 0.5 x 10^{16} n_{eq}/cm^2 average
- devices inclined to increase irradiated area, scanning horizontally
  □ quite uniform irradiation along x, gaussian along y (beam profile)
- Visual inspection: visibile dark shape in a ~1x2 cm^2 area, not vertically centered, dots on the sensor surface
- Received fluence (local and average) measured from the activation of Al dosimeters placed on the back of sensor

IRRAD Reconstructed fluence map

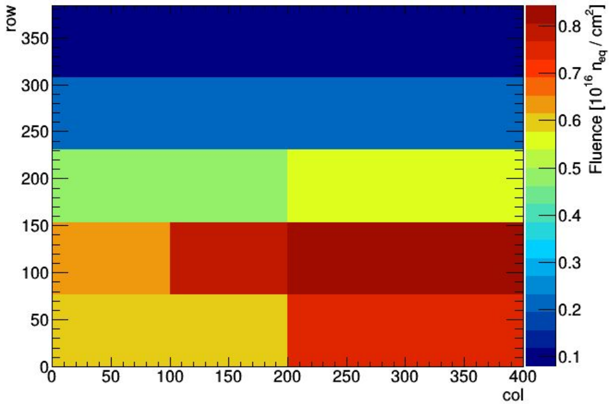




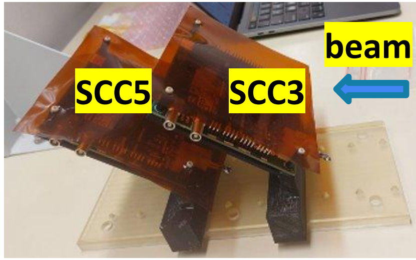




IRRAD measured fluence map with Al foil



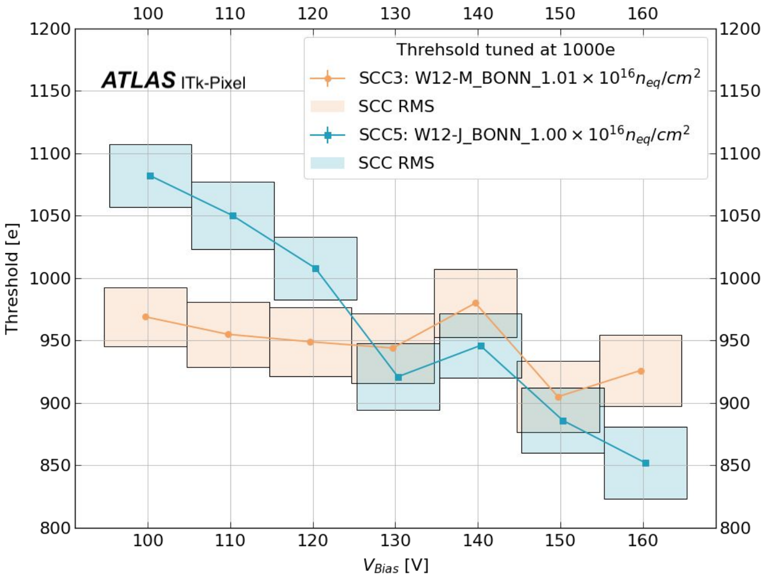
Total integrated fluence:
- **1.9 x 10^{16} n_{eq}/cm^2 (peak)**
- **1.5 x 10^{16} n_{eq}/cm^2 average**
- Not uniform fluence used to **map efficiency** measurements **to different fluence values**

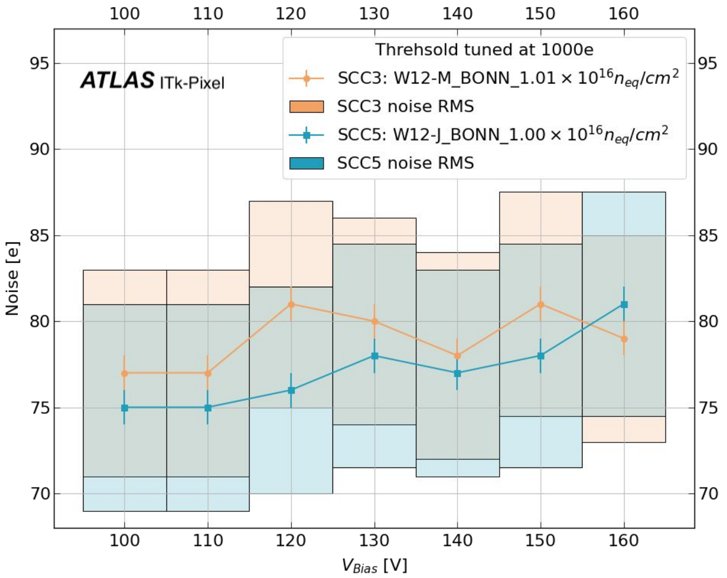


Tuning strategy and stability at TBs

- SCCs studied in test beams at CERN SPS after each irradiation
  - Strategy: tuned with target 1000e at 100V bias, same tuning used for all V_{bias}
  - Threshold and Noise distributions verified to be reasonably stable over a large V_{bias} range

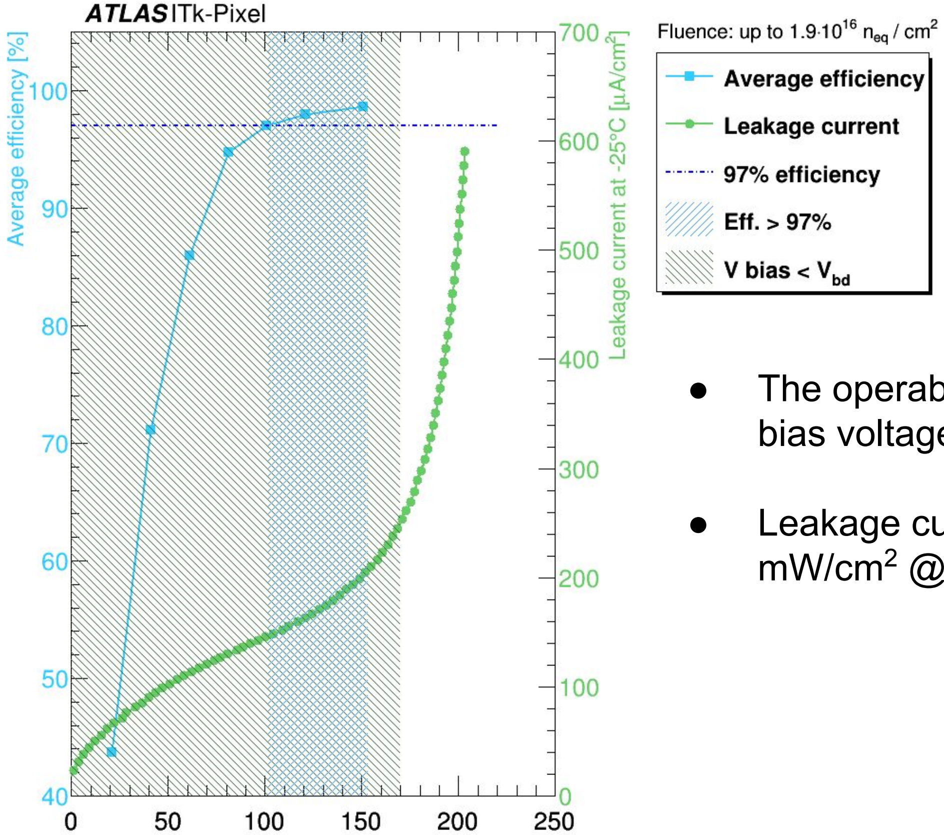
ITk-PublicPlots





(Error bars are the distribution mean error, columns are the distribution standard deviation)
Plots with modules irradiated at 10^{16} n_{eq}/cm^2, similar results after second irradiation

Operability window

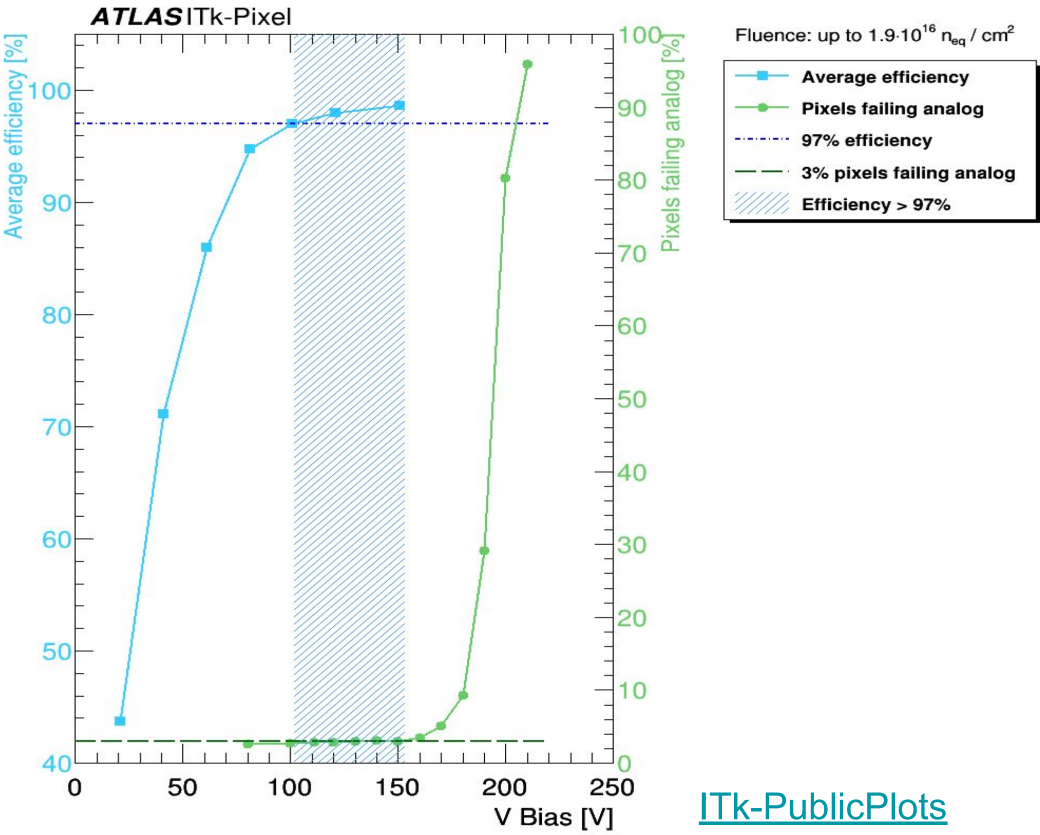


ITk-PublicPlots

- The operability window is defined by high efficiency (>97%) and bias voltage below the breakdown: ~100V to ~170V bias
- Leakage current I ~ 150 µA/cm2 and power dissipation 15 mW/cm^2 @ 100 V bias (scaled at -25°C) for SCC3

Operability window

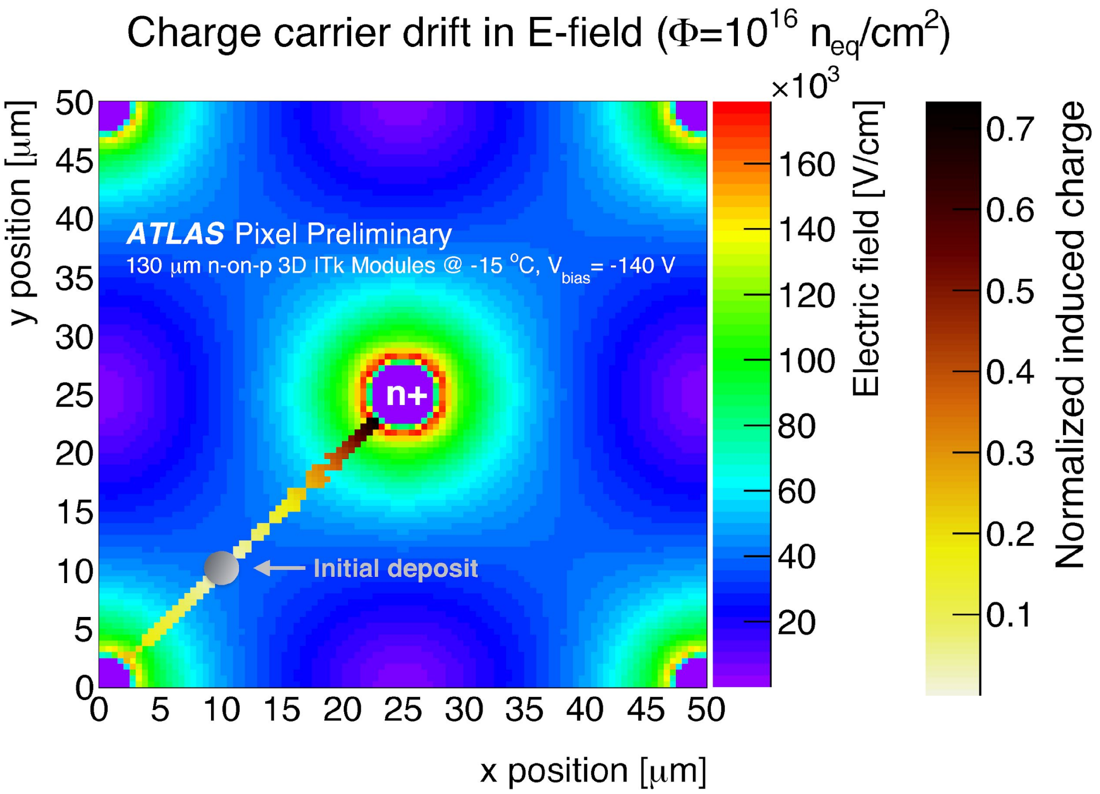
- Observed number of noisy / disabled pixels increasing at high voltages (>120V bias)
  - same tuning (1000e @ 100V bias) used for all V_{bias} may be reduced by tuning at each voltage under investigation
- performed **analog** scan vs V_{bias} to study the effect systematically
  - Slow increase at around ~3% failing pixels up to about ~150V bias
  - Faster rise next to breakdown voltage
  - Possibility to improve the 3% failing plateau under investigation
- The operability window is reasonably the overlap between the region at high efficiency and the region with low fraction of failing pixels: ~100V to ~160V bias in this example



ITk-PublicPlots

Operability window

Simulated electric field after irradiation [more info: (ITk_Public_Plots)]



In the plot represented field at V =-140V, after 1x10e16 neq/cm2

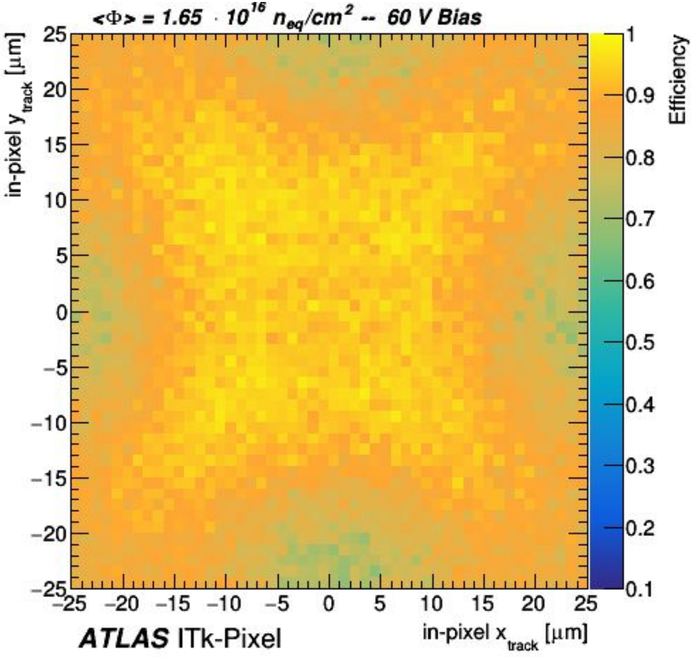
Lower electric field may be associated with lower efficiency areas, at least at low Voltage Bias ?

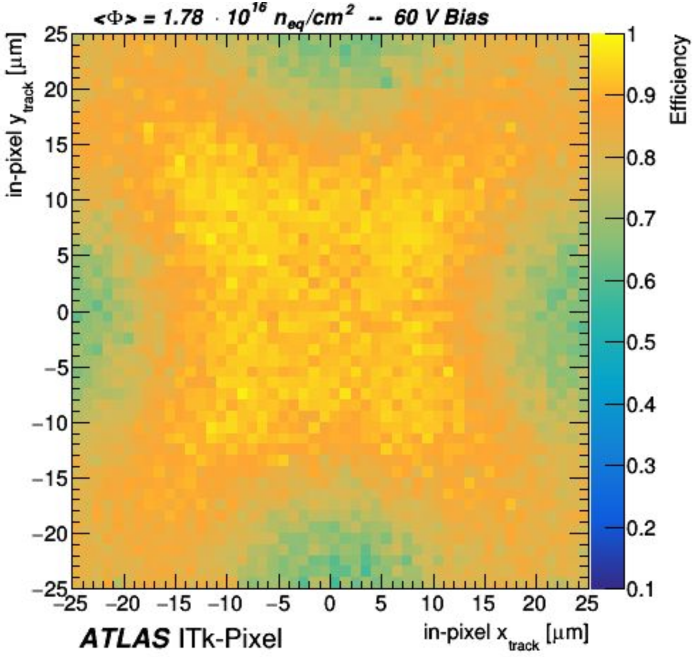
3D Pixel local efficiency after 2nd irradiation - 60V

At this stage pixels were grouped in two intervals based on the fluence received to increase statistics

Fluence range [10^{16} n_{eq}/cm^2]	**Average fluence**
$1.5 < \Phi < 1.75$	**1.65×10^{16} n_{eq}/cm^2**
$1.75 < \Phi < 1.9$	**1.78×10^{16} n_{eq}/cm^2**

Normal incidence





Lower efficiency areas

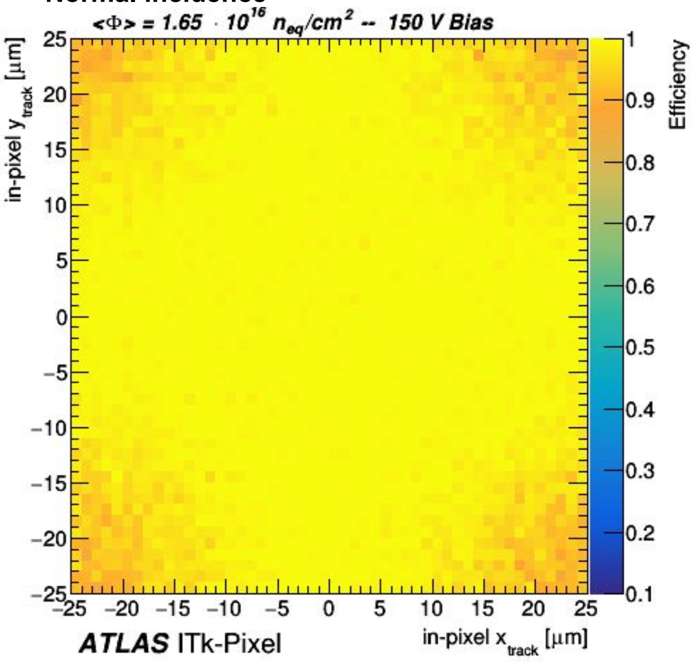
- Region with low electric field (simulation in backup)
- Areas were the electrodes are implanted

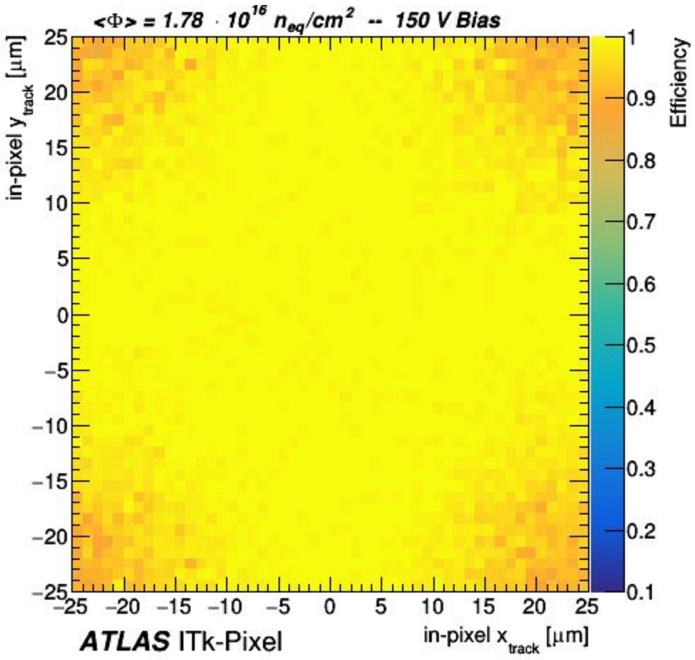
3D Pixel local efficiency after 2nd irradiation - 150V

At this stage pixels were grouped in two intervals based on the fluence received to increase statistics

Fluence range $[10^{16}\ n_{eq}/cm^2]$	Average fluence
$1.5 < \Phi < 1.75$	**$1.65 \times 10^{16}\ n_{eq}/cm^2$**
$1.75 < \Phi < 1.9$	**$1.78 \times 10^{16}\ n_{eq}/cm^2$**

Normal incidence





Lower efficiency areas

- Region with low electric field (simulation in backup)
- Areas were the electrodes are implanted