Towards the production of the 3D pixel detectors for the upgrade of the ATLAS Inner Detector

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on behalf of the ATLAS ITk Pixel Collaboration

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19th TREDI Workshop on Advanced Silicon Radiation Detectors

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Introduction

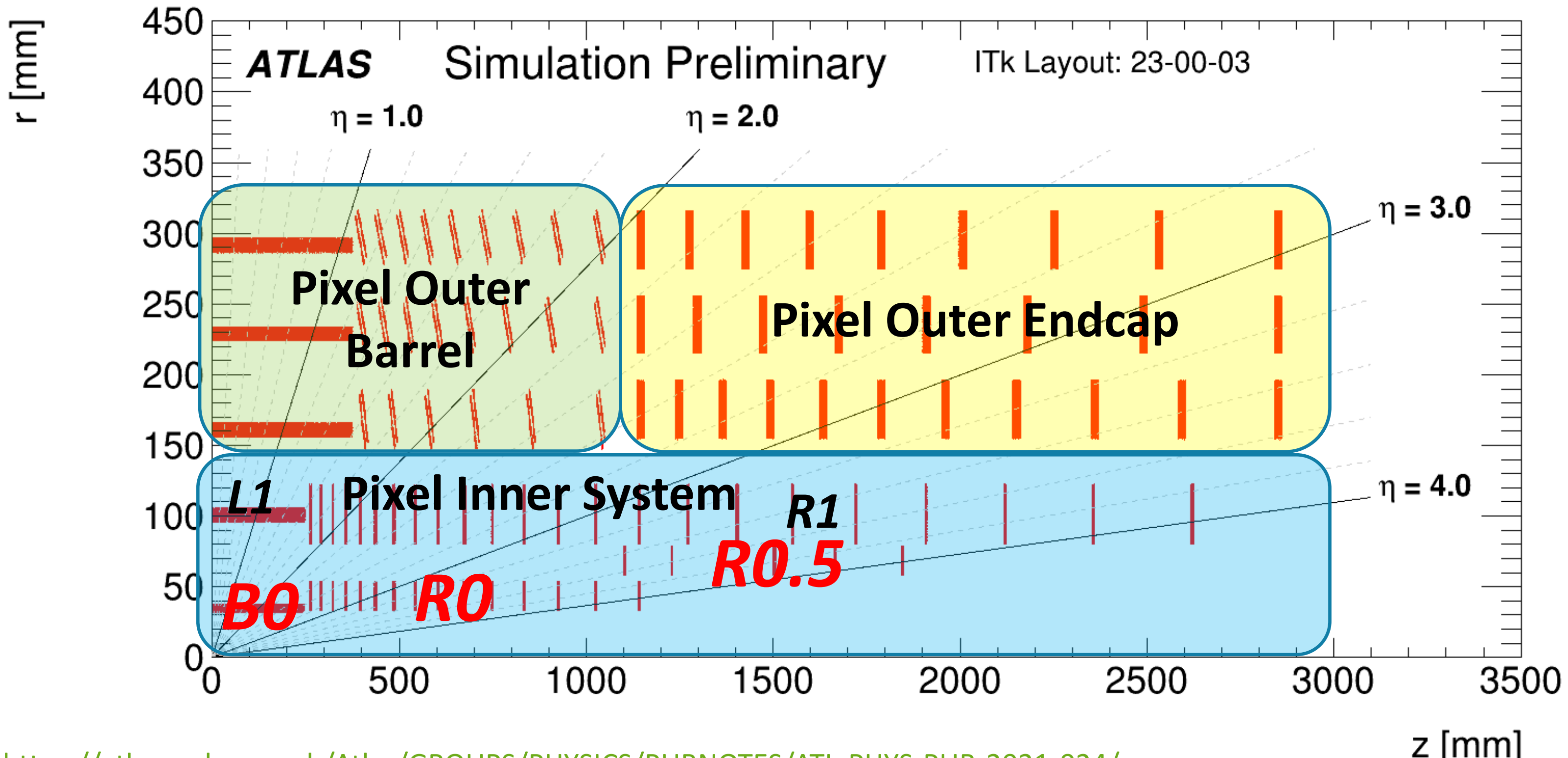
The HL-LHC and the Inner Tracker (ITk)

HL-LHC: after 2026 luminosity up to 5-7.5 10^{34} cm^{-2} s^{-1}

- 4000 fb^{-1} int. luminosity in 10 years : more statistics to study rare physics processes
- Harsher operational conditions for the detectors:
  - Pile-up collisions increase from 20-50 to 150-200 → challenging for tracking
  - Higher radiation environment → radiation-hard detectors

→ Impossible to operate the current ATLAS tracking system (ID) during HL-LHC

→ **will be completley replaced with the ATLAS Inner tracker (ITk):**



ITk Pixel detector: see S.Mobius's talk

- Innermost part of ITk
- 5 layers of pixel detectors
- Planar sensors in the 4 outer layers (100 µm and 150 µm active thickness)
- Inner System to be replaced after 2000 fb^{-1} (1.5 safety factor on max fluence):
  - **Fluence up to 1.9e16 n_{eq}/cm^2**
  - **TID up to 1 Grad**
  - **3D sensors in the innermost layer L0 (B0, R0, R0.5)**

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/

3D pixel sensors in ITk

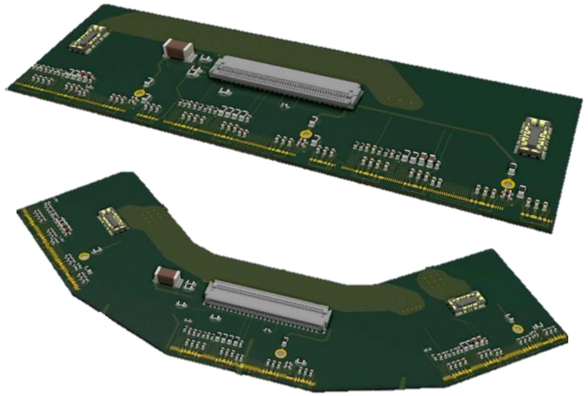
3D sensors in the innermost layer L0:

- Barrel at 34 mm from collisions
- Endcap rings down to 33.2 mm from beam

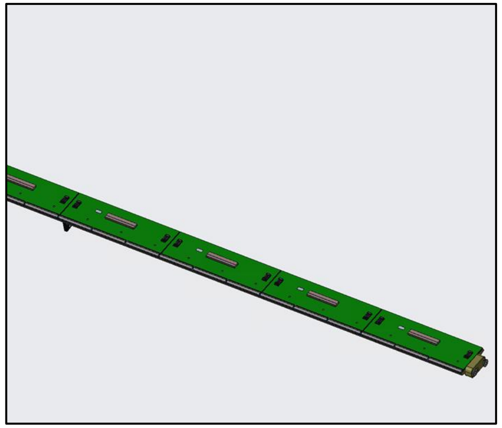
- Single bare modules (1 sensor tile to 1 readout ASIC) of size 2x2 cm^2 arranged in triplets
- Thickness: **150 µm active** + 100 µm support
- **Two pixel cell sizes:**
  - **50x50 µm²** (endcap rings R0 & R0.5, 900 sensors)
  - **25x100 µm²** (barrel flat stave B0, 288 sensors)

- Total:
  - **1188 modules (installed)**
  - 210 pre-production
  - To be produced including yield (~1.6): **0.80 m², ~2000 sensors**

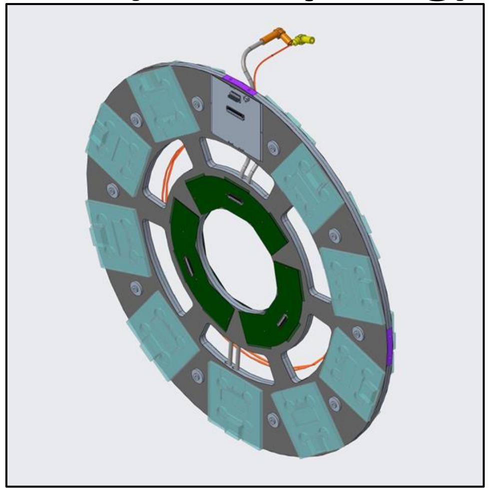
Ring and barrel triplet module flexible PCB



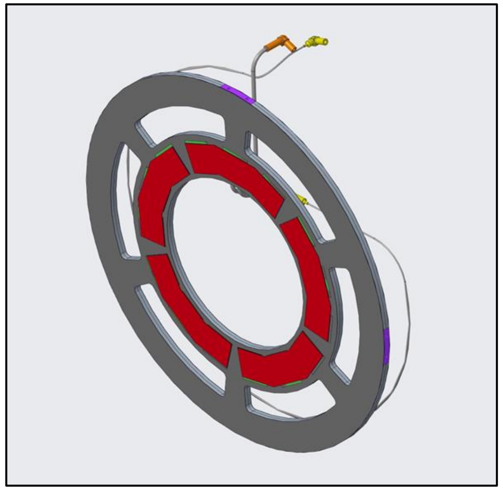
L0 (barrel stave)



R0 (endcap ring)



R0.5 (endcap ring)



3D sensors pre-production flow

ATLAS ITk

Sensor vendors:
- **FBK** (25x100 μm^2 and 50x50 μm^2)
- **SINTEF** (50x50 μm^2)

Quality Control (QC):
- IV (all sensors)
- IV and CV (sub-sample)

→ See also S.Ronchin's talk

CERN

Hybridization:
- IZM (Fraunhofer)
- LEONARDO

(Thinning) + dicing

a few sensors are not flip-chipped and sent to ITk institutes for QA

ITk requirements (after irradiation at final fluence):
- **>96% (97%) efficiency** for normal (tilted 15°) incidence
- with **<3% masked pixels**
- Operating at $\mathbf{V_{bias}}$ **<250 V**
- Power dissipation **<40 mW/cm²**

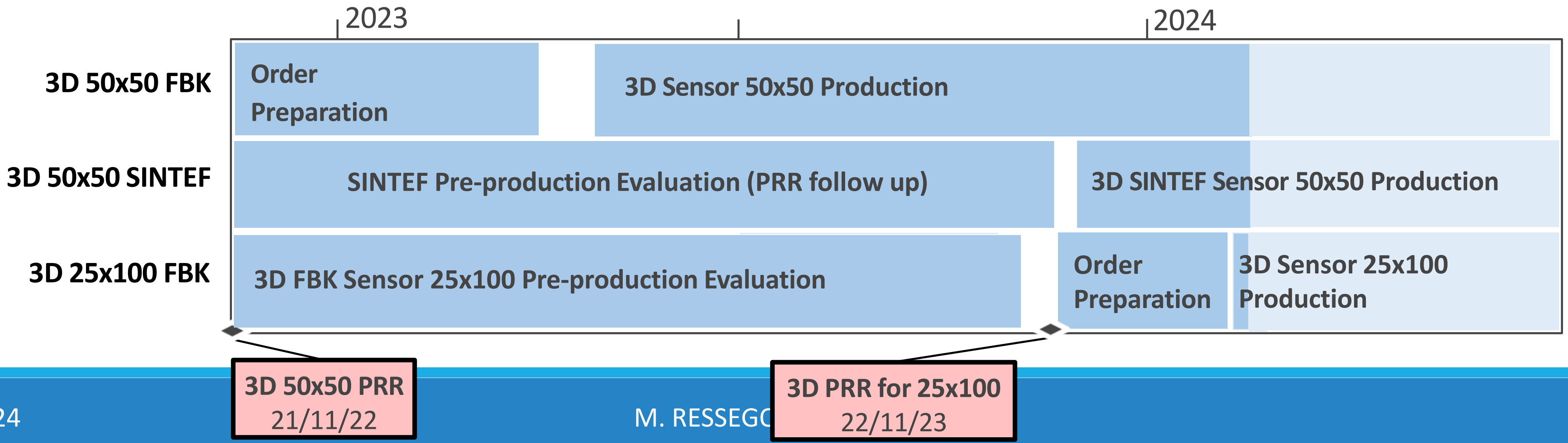
ITK institutes:
- University of Trento
- University of Bergen
- University of Oslo
- IFAE

Quality assurance (QA)
- Electrical tests
- Irradiations of bare sensors and test structures (diodes, strips, ….)

3D sensors production schedule

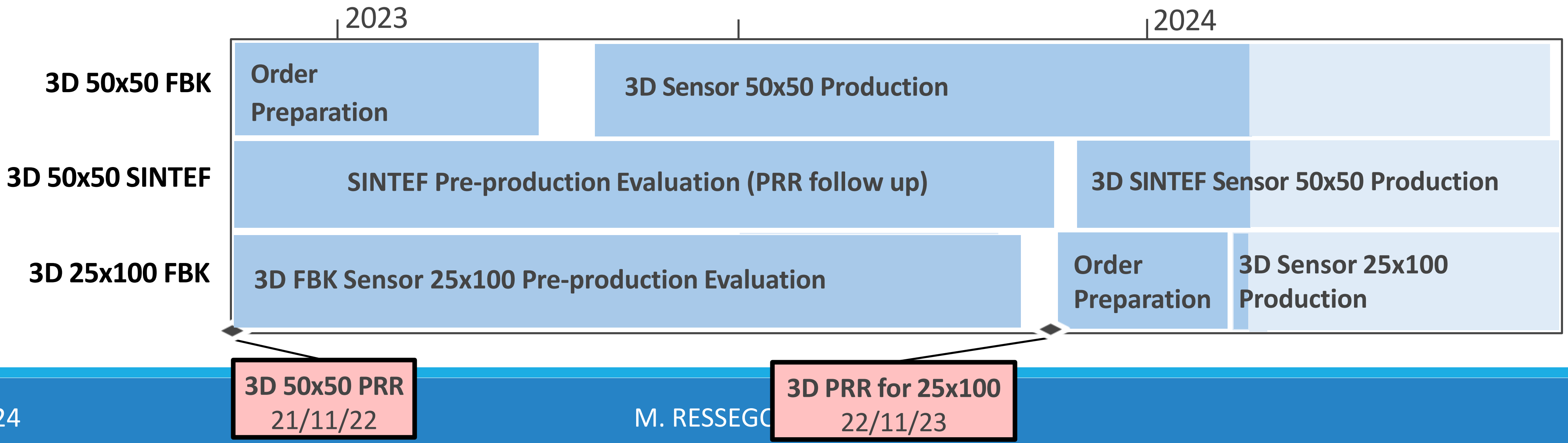
- **Pre-production (completed):**
  - **FBK completed and Production Readiness Review passed** in November 2022 (50x50) and November 2023 (25x100)
  - **SINTEF (50x50) still under review** due to sensor bow out of specs after back-thinning, problematic for flip-chipping at IZM. Different path investigations ongoing (encouraging results): 1) changing the passivation at SINTEF, 2) Hybridization at Leonardo (indium bumps), 3) Flip-chipping at IZM with glass support

- **Pre-production sensors assembled with ITkPixV1.1 chip (RD53B)**
  - **TimeOverThreshold (ToT) not usable**
  - ITkPixV2 chip (final version) submitted at the end of 2023, qualification measurements recently finished, production officially started



3D sensors production schedule

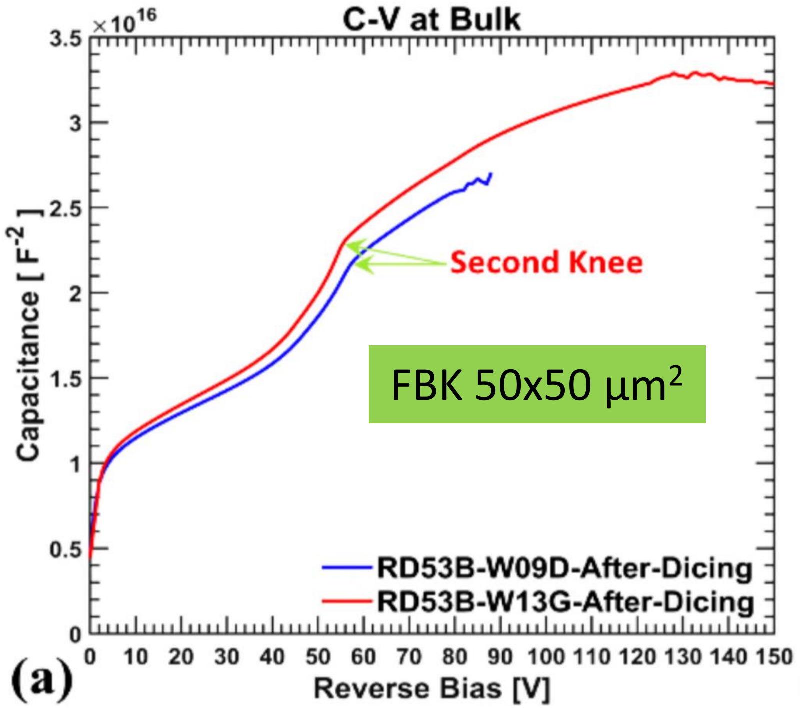
- **Production (ongoing):**
  - FBK 50x50 production started May 2023 until end mid-2024
  - SINTEF (50x50) in-kind production started November 2023 until end 2024
  - FBK 25x100 production starting in February until end 2024



Results before irradiation

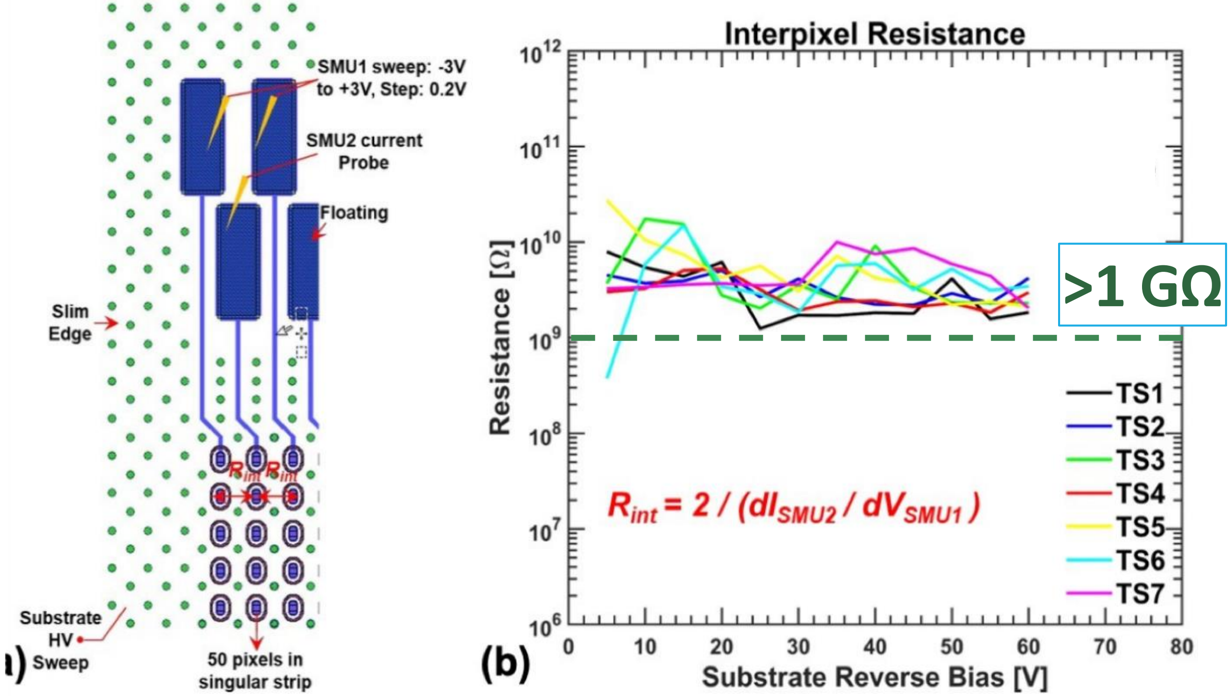
Sensor QC/QA

See also S.Ronchin's talk



- **Depletion voltage**
  - from capacitance vs voltage curves
  - on a sub-sample of diodes out of each wafer
  - QC measurements values show **depletion voltage <5 V**

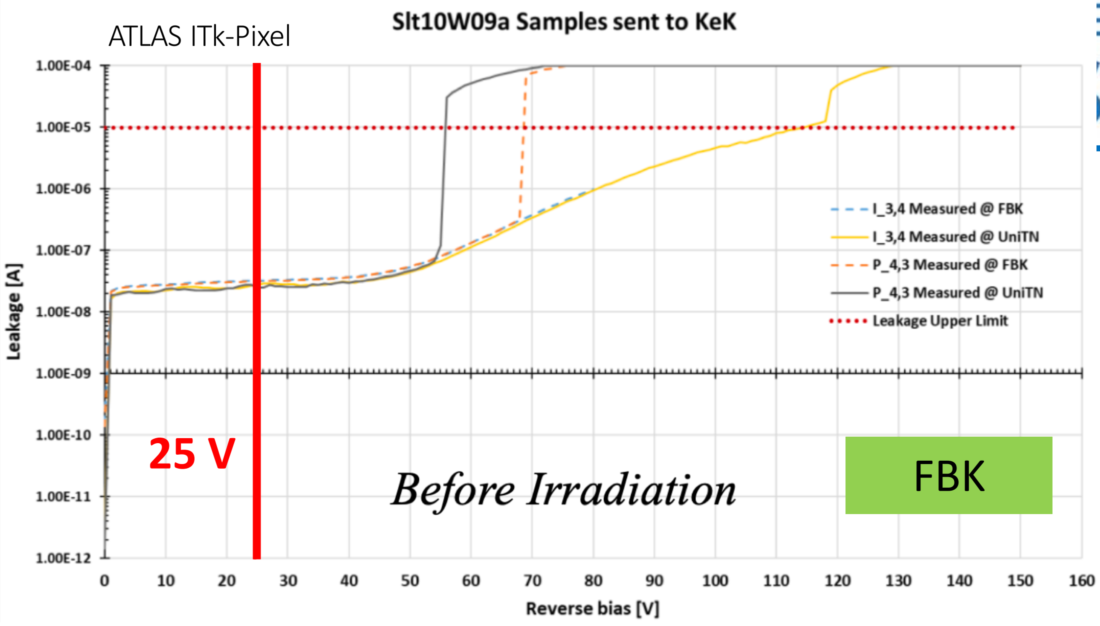
- **Inter-pixel resistance**
  - with special "strip" test structures that short together pixel structures, then result scaled by number of pixels in a strip
  - 3D sensors must have R_{int} > 1 GΩ



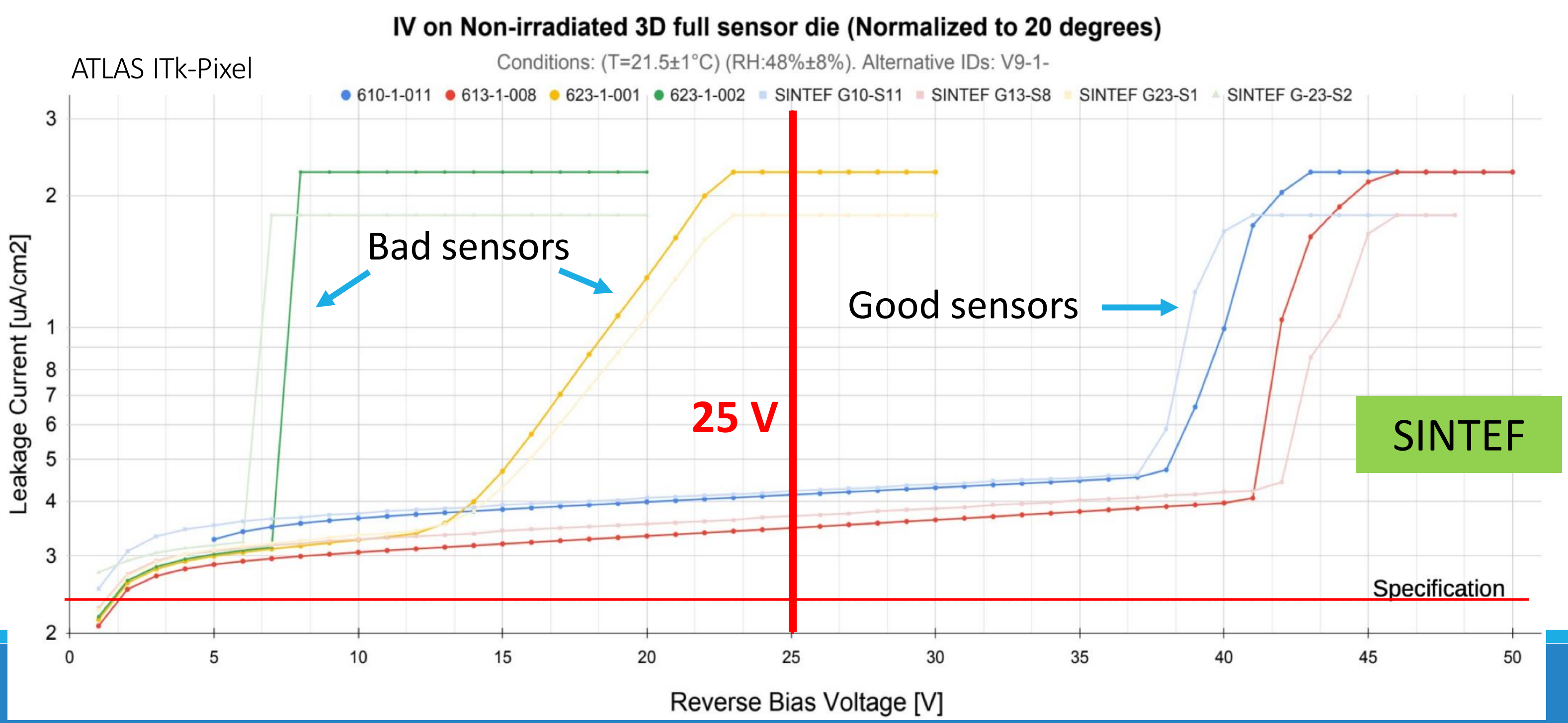
Leakage current

See also S.Ronchin's talk

- **ITk requirements:**
  - Breakdown voltage > 25V
  - Leakage current < 2.5 µA/cm²

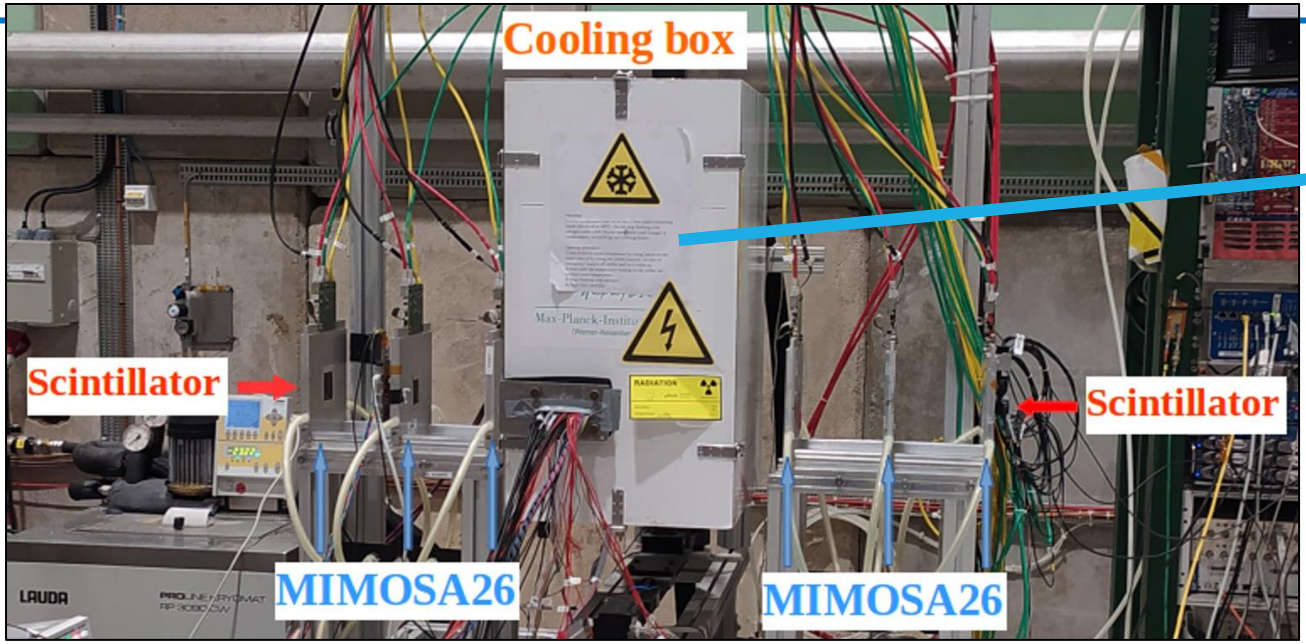


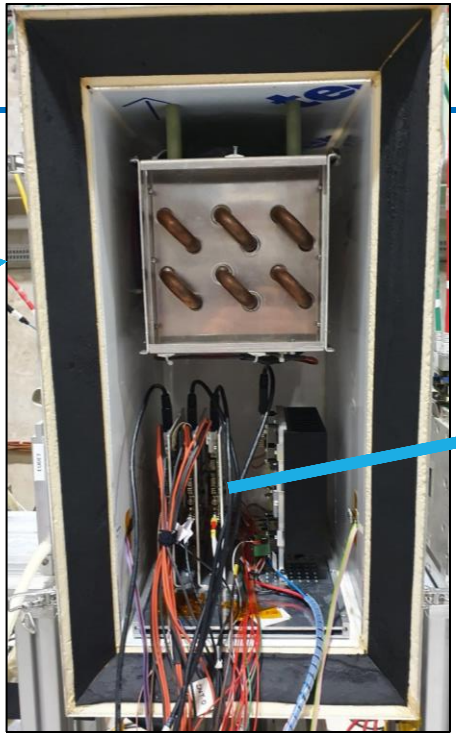
- **Measurements on wafer:**
  - FBK within specs
  - SINTEF leakage current higher than specs, but excellent yield based on breakdown
  - ITk considering to relax leakage current specs

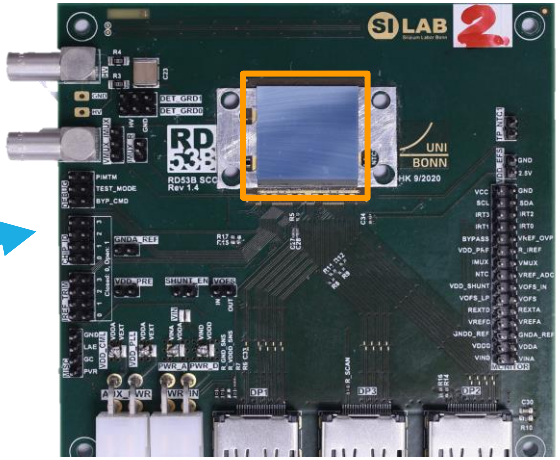


https://indico.tlabs.ac.za/event/112/contributions/3146/

Test beam setup

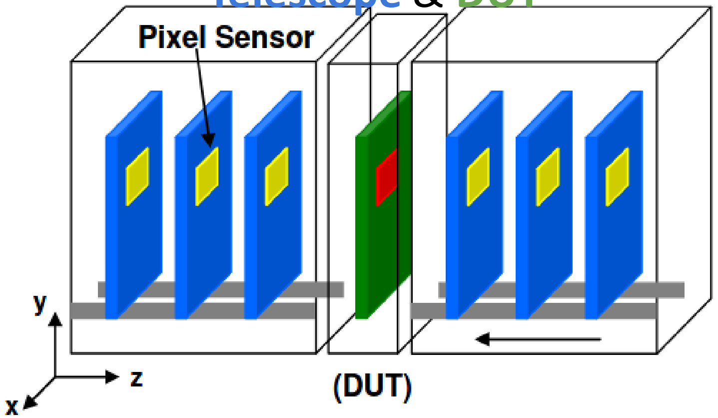






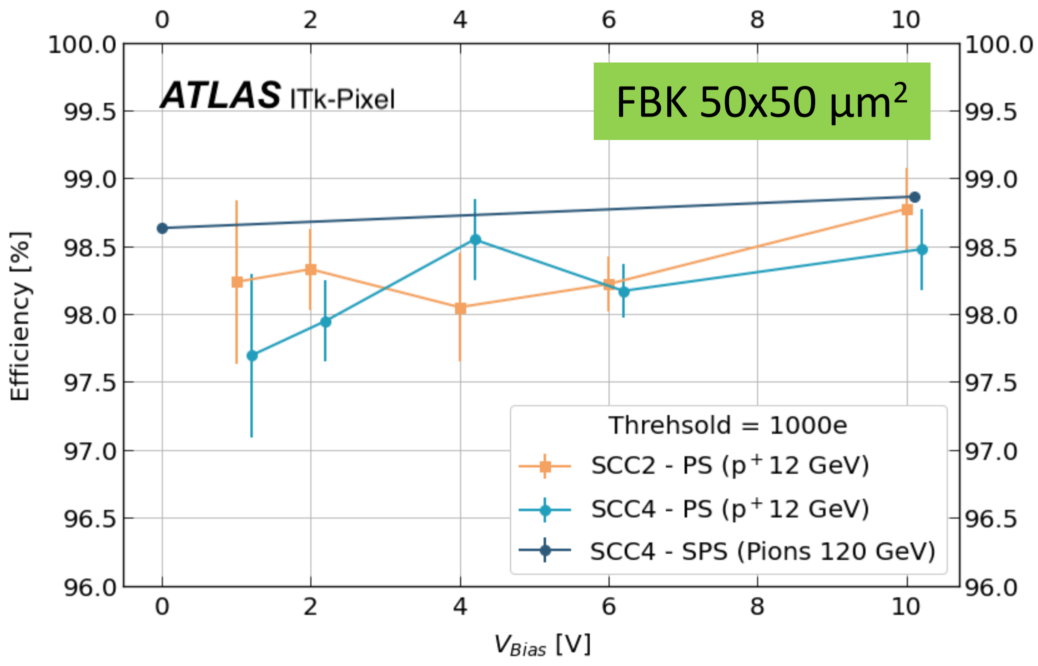
Module on SCC

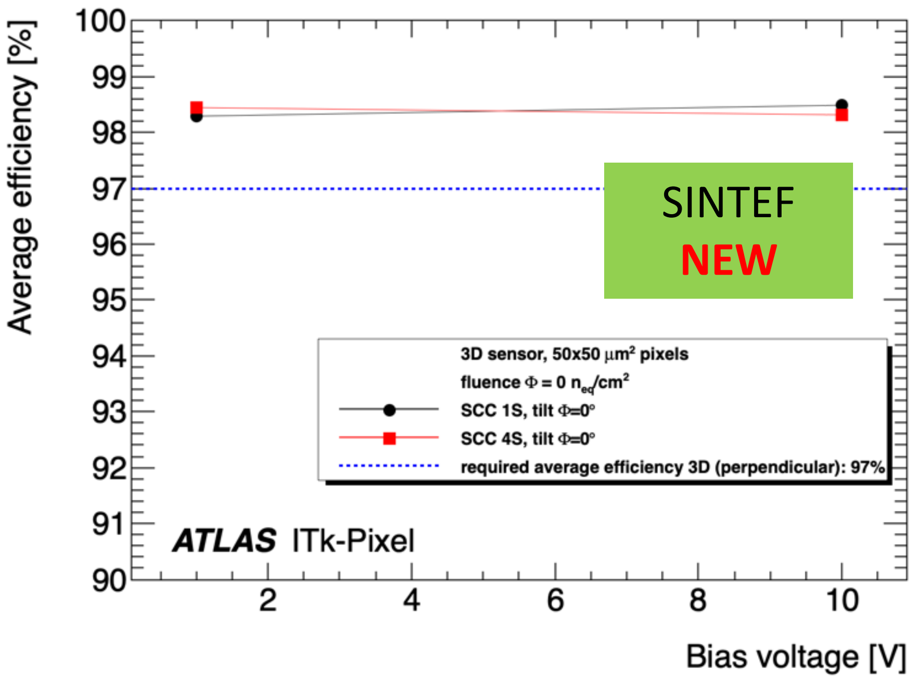
Telescope & DUT



- 3D with ITkPixV1.1 tested on **Single Chip Cards** (SCCs): dedicated PCBs hosting a single module
- Test beams at CERN (PS (12 GeV p) and mainly) SPS (120 GeV pions)
- Efficiency calculation:
  - with tracks on DUTs that **meet spatial and time** cuts w.r.t. reconstructed track
  - **disabled, masked pixels and neighbouring ones are not taken into account**

Efficiency vs V bias (unirradiated): 0 – 10 V





- Unirradiated modules tested at PS (12 GeV protons) and SPS (120 GeV pions), perpendicular to beam:
  → **Average Efficiency 97.5%-99%**
  → **Meets the ITk requirement >96%** for normal incidence (already **at few volts** bias unirradiated)

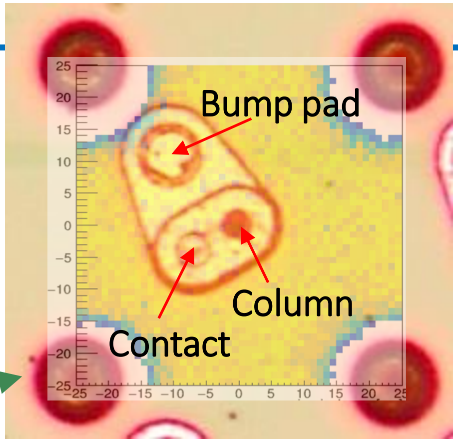
- Results compatible with 50x50 µm² prototype (RD53A chip + FBK 3D sensor) previously tested at DESY (6 GeV electrons) [reported in https://cds.cern.ch/record/2815570]

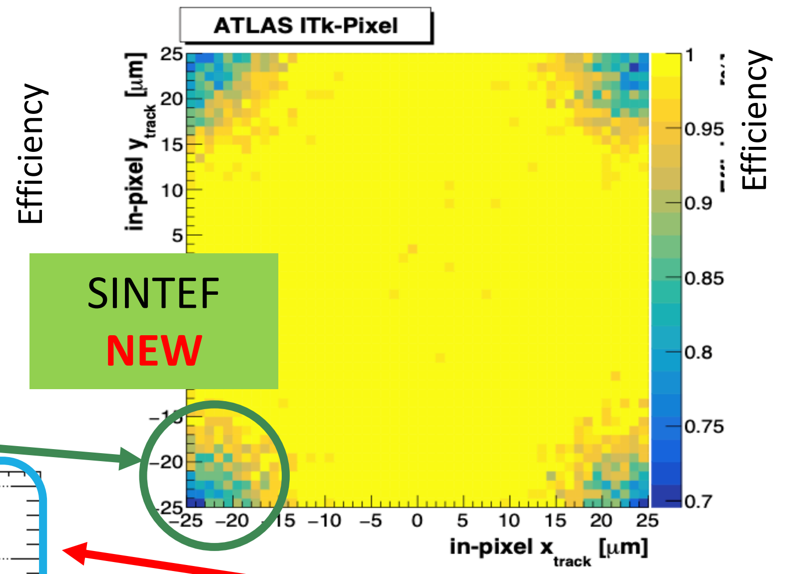
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2022-004/
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2023-004/

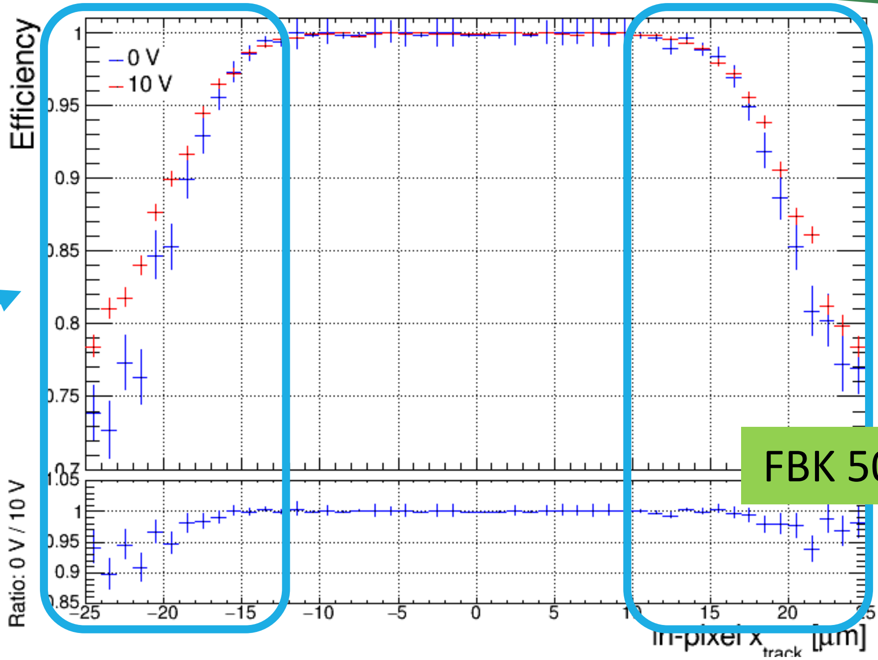
In-Pixel efficiency map (unirradiated): 0 – 10 V

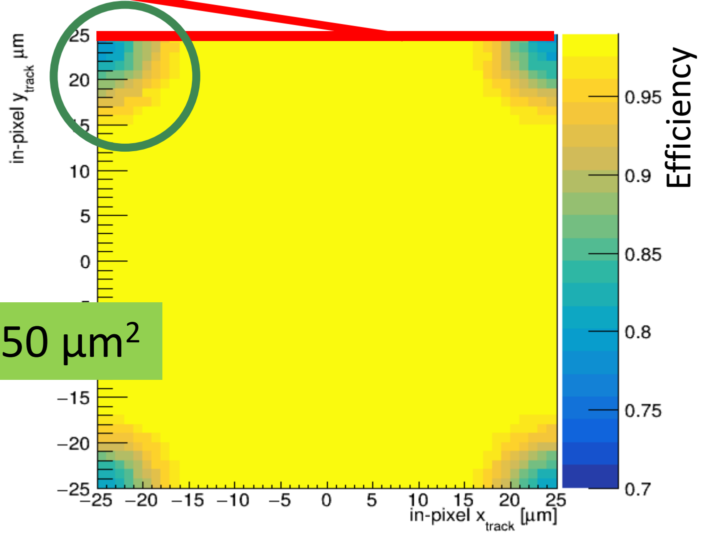
- **Similar results by FBK and SINTEF**
- **Average in-pixel efficiency > 99%** for normal incidence for both vendors at full depletion
- **Central area: higher than 99%** efficiency

- **Lower efficiency zones visible in corners** for normal incidence:
  - Effect (75% – 99%) radius: 10 μm
  - p^+ columns max radius: 4 μm
- No other structure visible (e.g. polySilicon cap)









- No evident differences between 10 V and 0 V bias in terms of the extension of the low efficiency zone

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Results after irradiation

NEW RESULTS from 2023 TB campaign data:

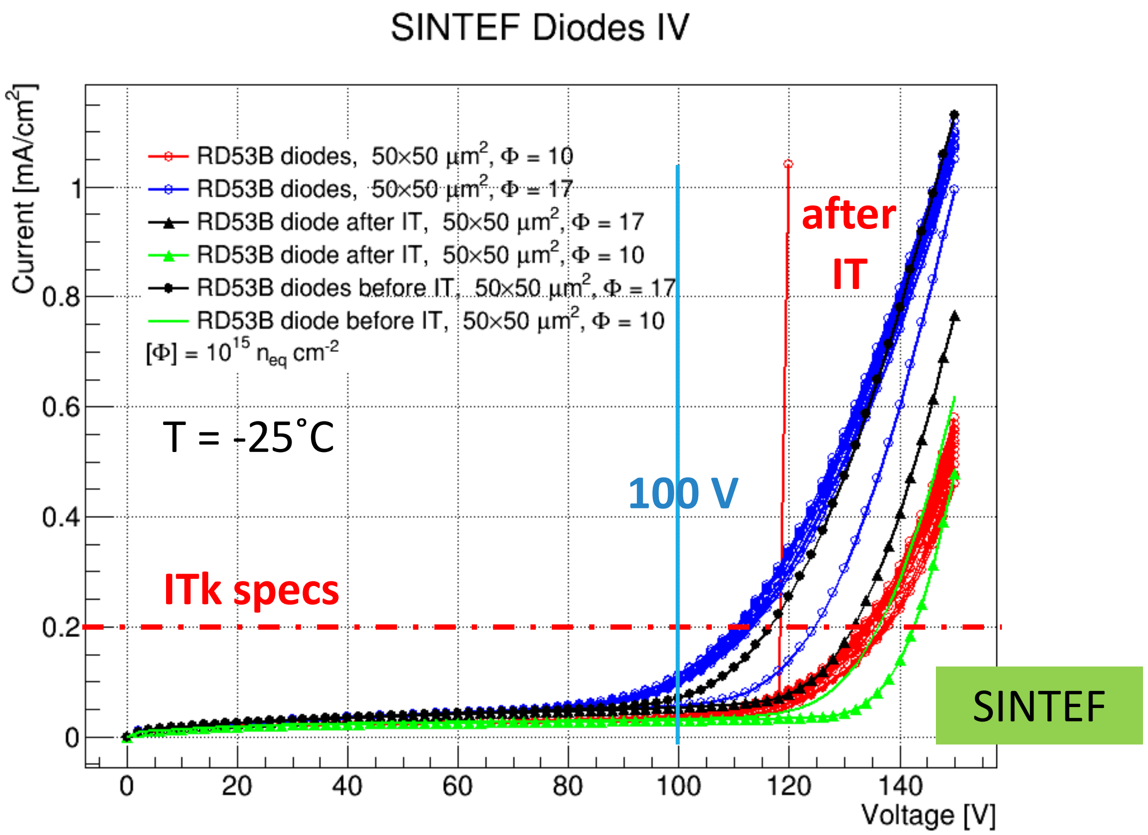
- **SINTEF**
- **FBK 25x100 μm^2 pixel cell**

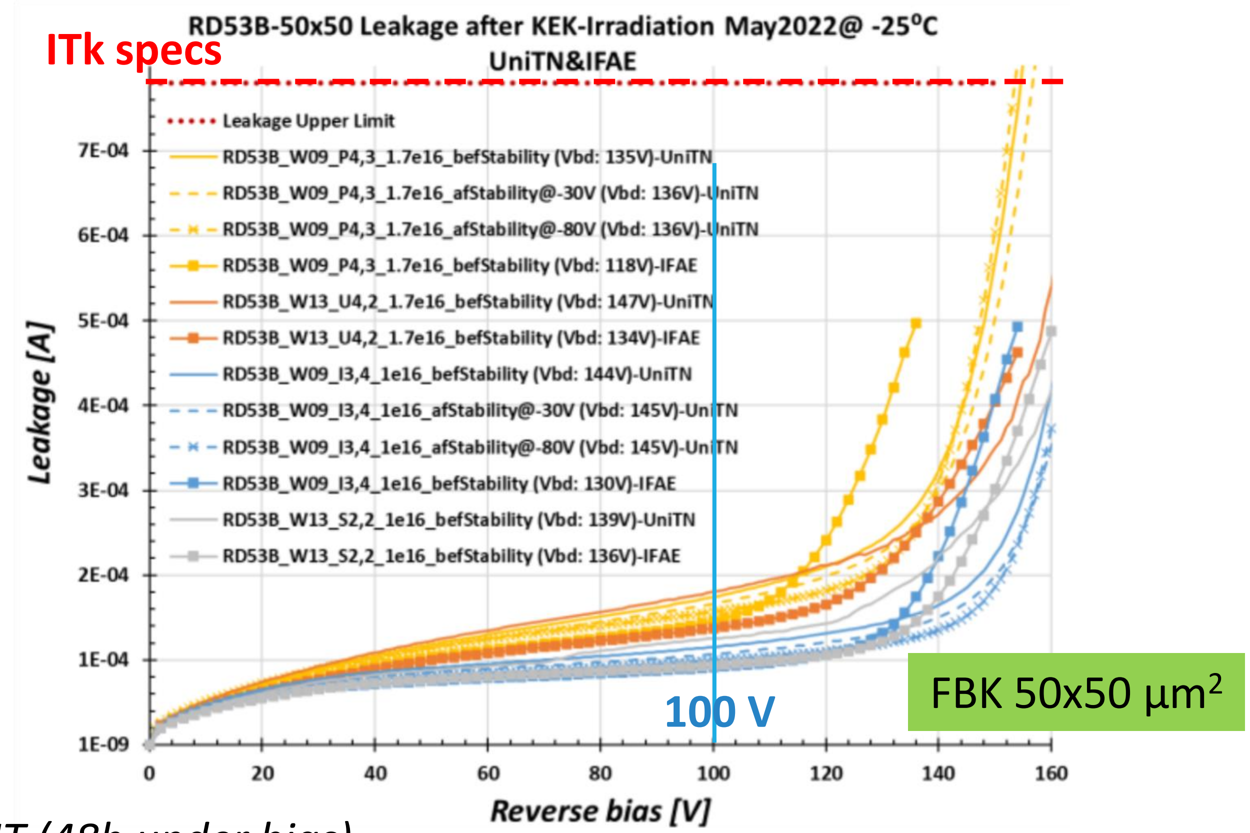
for previous results see also:

- S.Ravera, Qualification of irradiated 3D pixel sensors produced by FBK for the pre-production of the ATLAS ITk detector , VERTEX 2023
- S.Hellesund, Qualification of irradiated 3D pixel sensors produced by Sintef for the pre-production of the ATLAS ITk detector, VERTEX 2023
- S.Ravera, Pixel cell local efficiency of FBK 3D pre-production pixel sensors after irradiation up to 1.9 10^{16} n_{eq}/cm^2, TREDI 2023
- M.Ressegotti, Qualification of the first preproduction 3D FBK sensors with ITkPixV1, PIXEL 2022
- A.Lapertosa, Test of ITk 3D sensor pre-production modules with ITkPixv1.1 chip, iWoRiD 2022
- A.Lapertosa, Performance of irradiated FBK 3D sensors for the ATLAS ITk pixel detector, TREDI 2021

Leakage current

- 3D diodes and bare sensors with temporary metal **irradiated to 1 x10^{16} and 1.7 x10^{16} n_{eq}/cm^2** at CYRIC (protons)
  - **Breakdown >100 V**
  - Breakdown **shifts** towards higher voltage **after annealing and/or stability tests** (IT - 48h under bias)

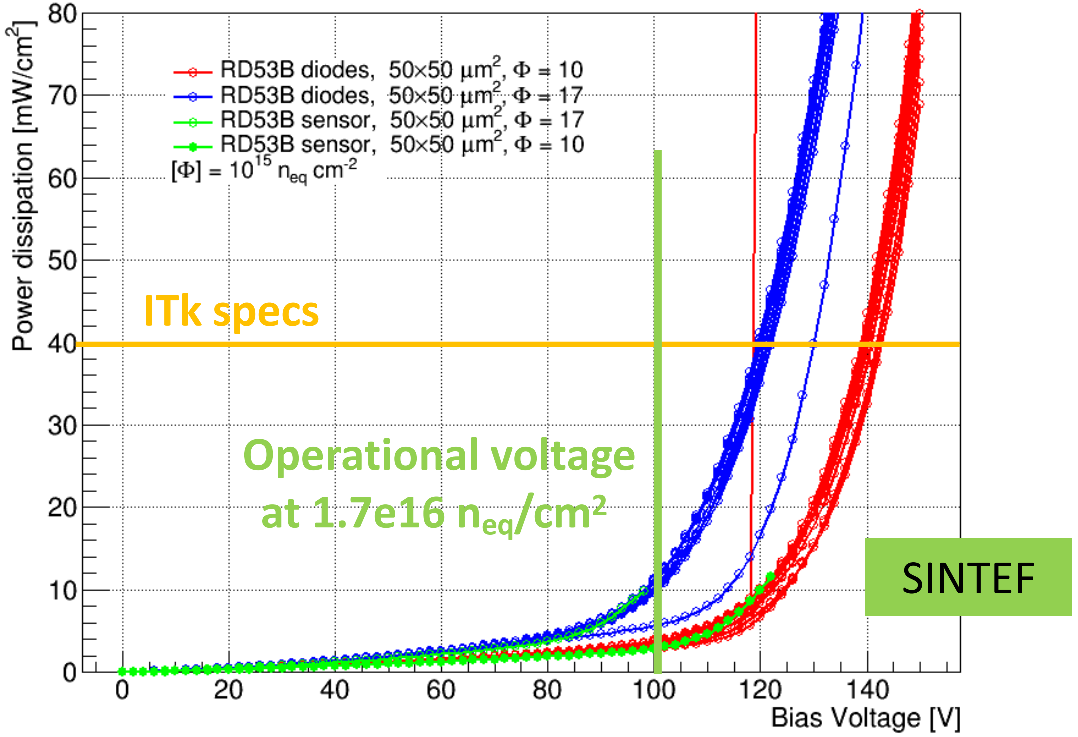


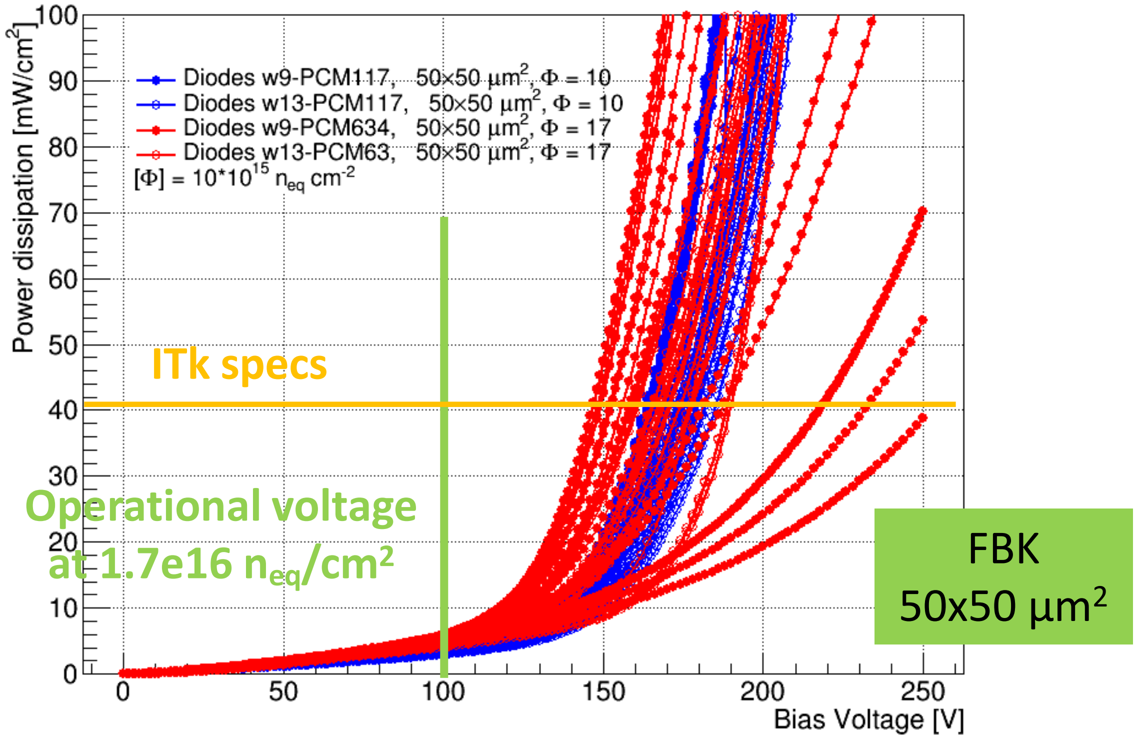


IV curves before/after IT (48h under bias)

Power dissipation

- ITk requirement: <40 mW/cm² at the operational voltage (efficiency >96-97%)
  - power dissipation (at operational voltage) **<10 mW/cm² at -25˚C up to 1.7e16 n_{eq}/cm²**



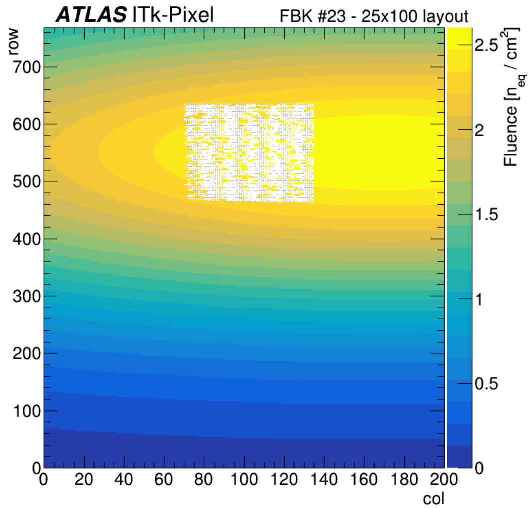


SCCs irradiations summary

- Modules irradiated with protons of different energy at different facilities (Bonn, KIT, IRRAD) to **different fluences**
- Some of them irradiated two times to accumulate higher fluence gradually, studied after each irradiation
- **Some irradiations (at CERN IRRAD) are not uniform**

Module	Irradiation facility	Fluence
FBK 50x50 μm^2	Bonn (14 MeV protons)	**$0.6 \cdot 10^{16}$** n_{eq}/cm^2 uniform
	Bonn (14 MeV protons) + IRRAD (12 GeV protons)	**$1.9\ 10^{16}$** n_{eq}/cm^2 (peak) not uniform
SINTEF 50x50 μm^2	KIT (23 MeV protons)	**$1 \cdot 10^{16}$** n_{eq}/cm^2 uniform
	KIT (23 MeV protons) + IRRAD (12 GeV protons)	**$1.8\ 10^{16}$** n_{eq}/cm^2 (peak) not uniform
FBK 25x100 μm^2	KIT (23 MeV protons)	**$1 \cdot 10^{16}$** n_{eq}/cm^2 uniform
	IRRAD (12 GeV protons)	**$2.4\ 10^{16}$** n_{eq}/cm^2 (peak) not uniform

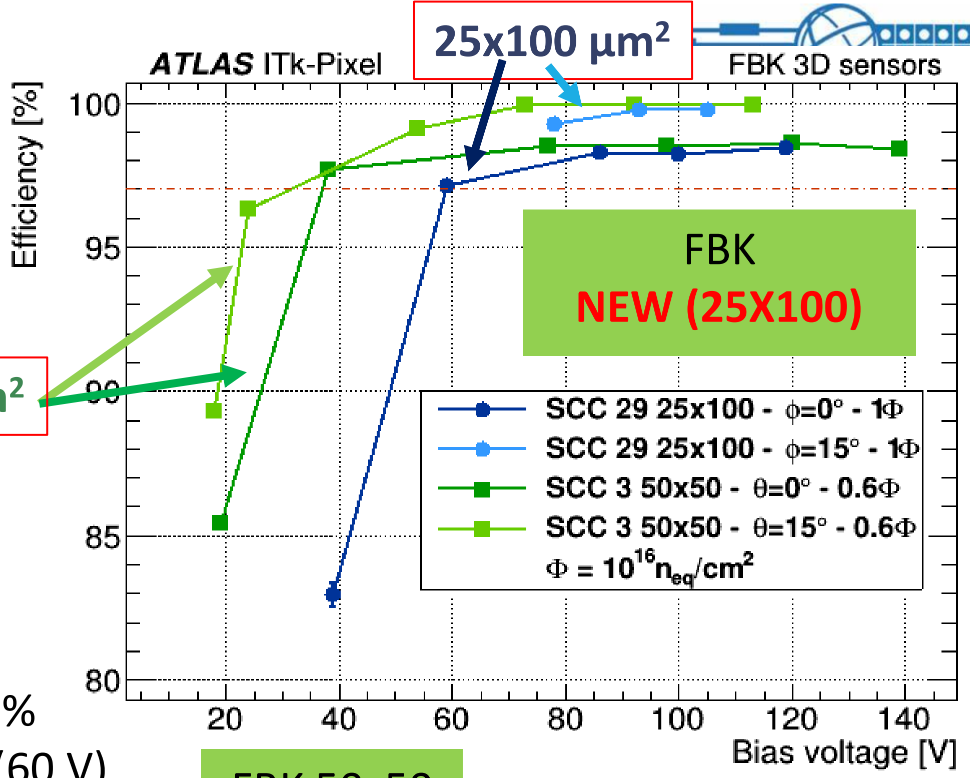
- Not uniform irradiations:
  - Note that the average and peak fluence are provided together with the results
  - Not uniform fluence used to map efficiency measurements to different fluence values → **results at different fluence values with the same module**



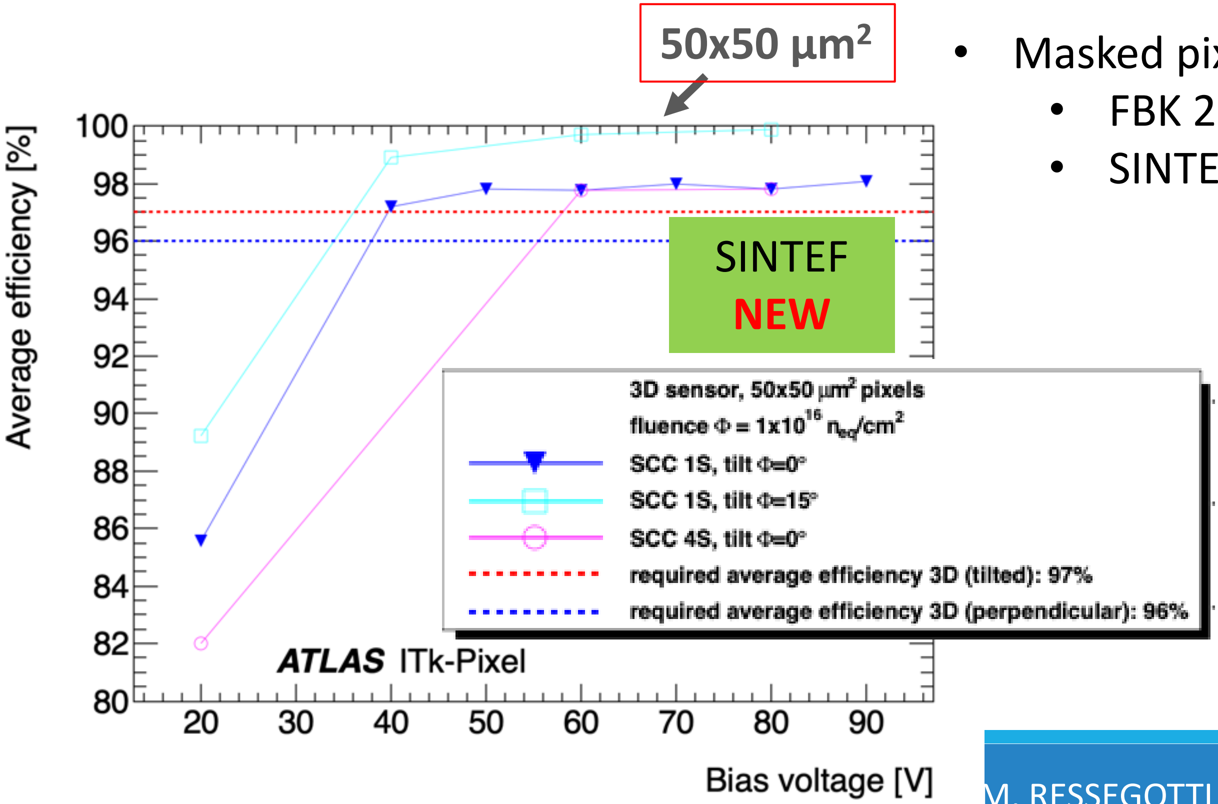
Example of reconstructed **fluence map** (from Al dosimeter foil activation matched to efficiency map)

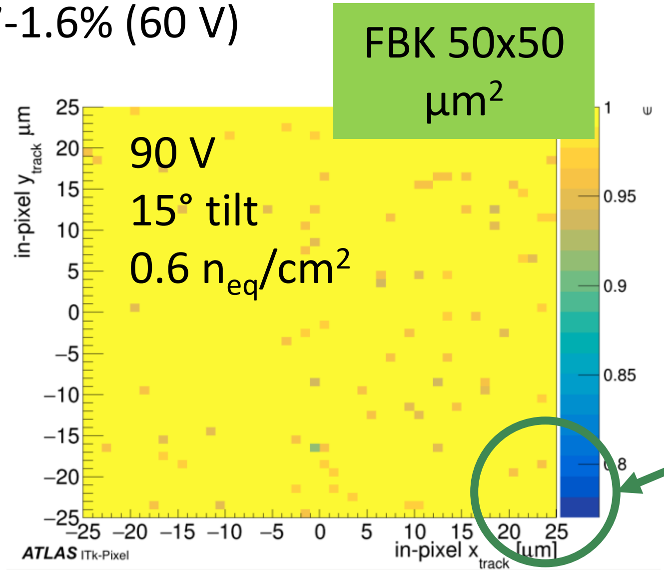
Fluence up to 10^{16} n_{eq}/cm^2

- Sensors with **25x100 µm² pixel cell depleted at higher V_{bias}** wrt 50x50 µm²
- **No evident difference between FBK and SINTEF** for same pixel cell and similar fluence
- Maximum efficiency is higher for **15° tilt** angle w.r.t. beam
  → saturation value of 99.9% reached
  → confirmed by in-pixel efficiency
- All results with modules uniformly irradiated



- Masked pixels:
  - FBK 25x100: ~10^{-2}%
  - SINTEF: 0.7-1.6% (60 V)

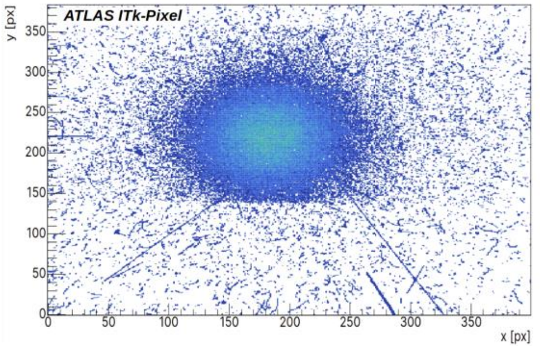


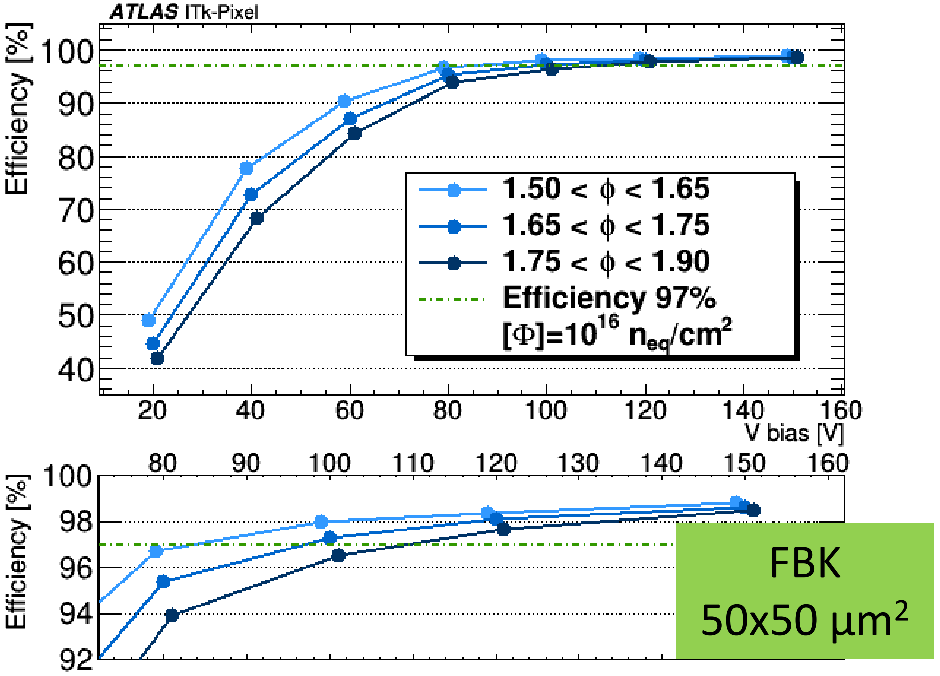


- Efficiency drop in corners of in-pixel efficiency disappears for 15° tilt angle (as expected)

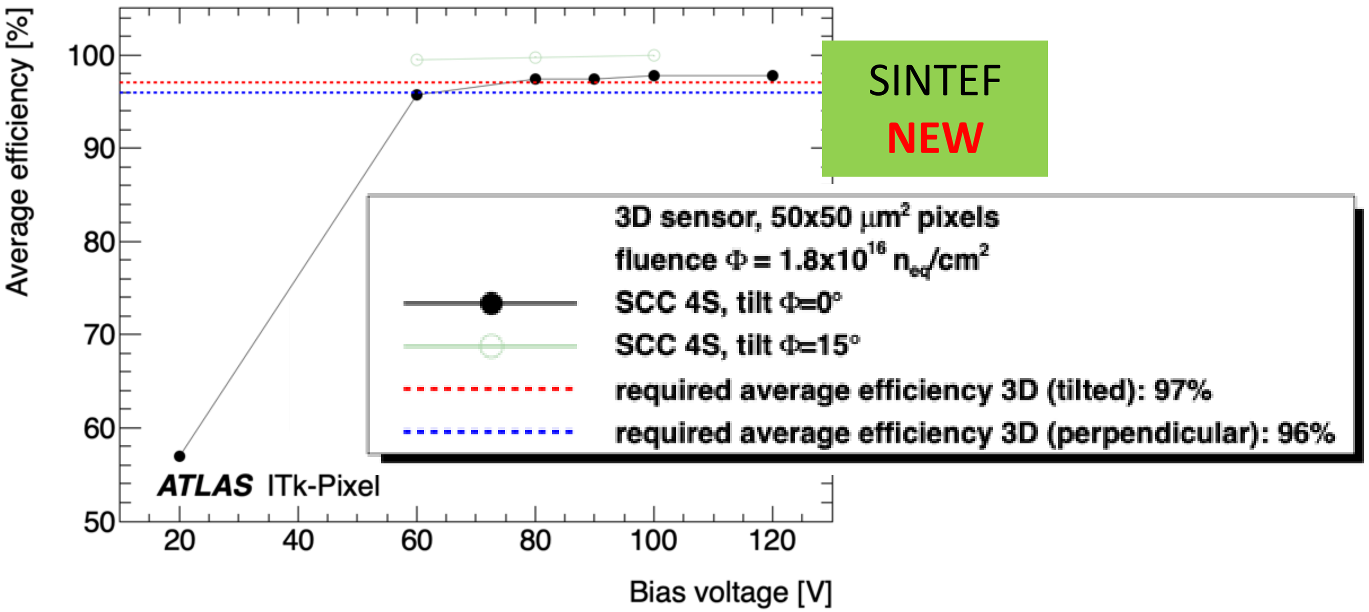
Fluence up to 1.9 10^{16} n_{eq}/cm^2

- Fluences studied **closest to end-of-life fluence** (1.9 10^{16} n_{eq}/cm^2 with 1.5 safety factor)
- **Depletion at ~100 V_{bias}** (within ITk specs)
- Confirmed depletion obtained at increasing V_{bias} for increasing fluence and efficiency is higher for 15° tilt angle
- Results with modules NOT uniformly irradiated





- Efficiency in different fluent ranges from **reconstruction of fluence map**



- **Average efficiency in the area hit by beam (no fluence map)**
- Fluence: 1.8 10^{16} n_{eq}/cm^2 (peak), 1.5 10^{16} n_{eq}/cm^2 (average)
- Masked pixels: 0.7% (80 V) at 1.8 10^{16} n_{eq}/cm^2

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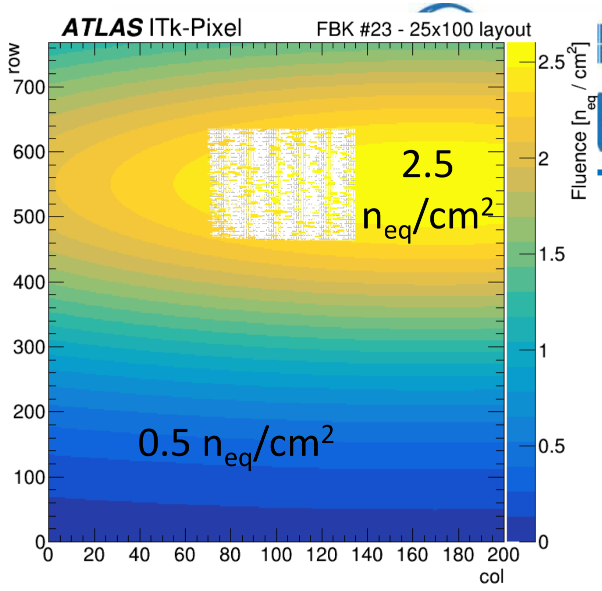
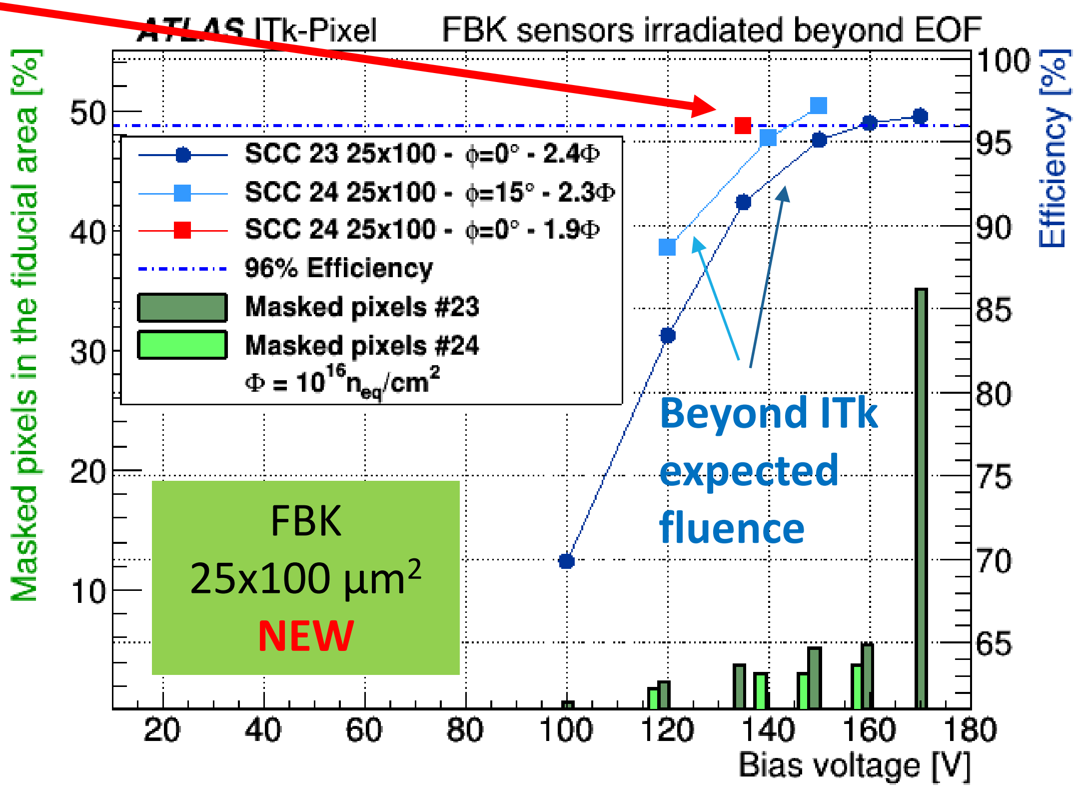
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2023-004/

Beyond end-of-life fluence

- Results with fluence at **end-of-life with safety factor** (1.9 n_{eq}/cm^2) and beyond (up to 2.4 10^{16} n_{eq}/cm^2)
- On same modules NOT uniformly irradiated, with test beam hitting in different zones
  - **at 1.9 10^{16} n_{eq}/cm^2 (EOL with 1.5 safety factor):** only **one point taken, at the efficiency requirement (96%)**
  - **at 2.4 10^{16} n_{eq}/cm^2 (beyond EOL):** still operable in a small V_{bias} range where efficient with ~4-6% masked pixels (average)
    - **Number of noisy pixels rapidly increases at higher V_{bias}**
- Show that sensors are operable up **to very high fluences, but next to the limit** of the voltage range in which nr. of noisy pixels rapidly increases
- Difficult to precisely evaluate with not uniform irradiations → **further uniform irradiation planned to clarify**



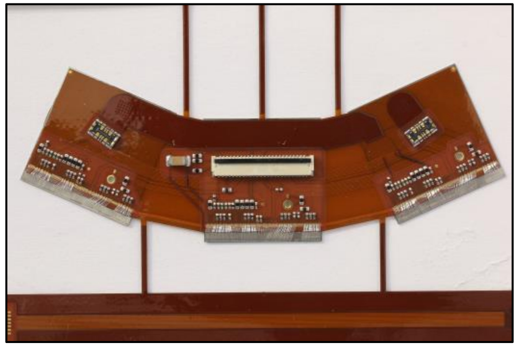
ITk end-of-life fluence with SF



Summary & Outlook

- **Sensor Production Readiness Review (PRRs)** in November 2022 and November 2023
  - FBK passed PRR, SINTEF follow-up working on bow issue
  - Production for FBK and SINTEF (SINTEF in-kind, hybridization to be verified) ongoing
  - First pre-production triplets with 3D modules are being produced

- 3D modules **from pre-production evaluation**:
  - **Efficiency and power dissipation** requirements at fluences up to the expected end-of-life **meet the ITk requirements**
    - More **uniform irradiations planned** to confirm results
    - Studies on stability of noisy pixels also ongoing
  - Considering to **relax specs on breakdown voltage** (improved after annealing and/or stability tests)
  - Further studies with **ITkPixV2 FE chip** including ToT when modules available
  - Working on follow-up of SINTEF issues for the PRR



First assembled triplet for R0.5 with sensor and FE (assembled in Genoa)

Thank you for the attention!

Special acknowledgements to:

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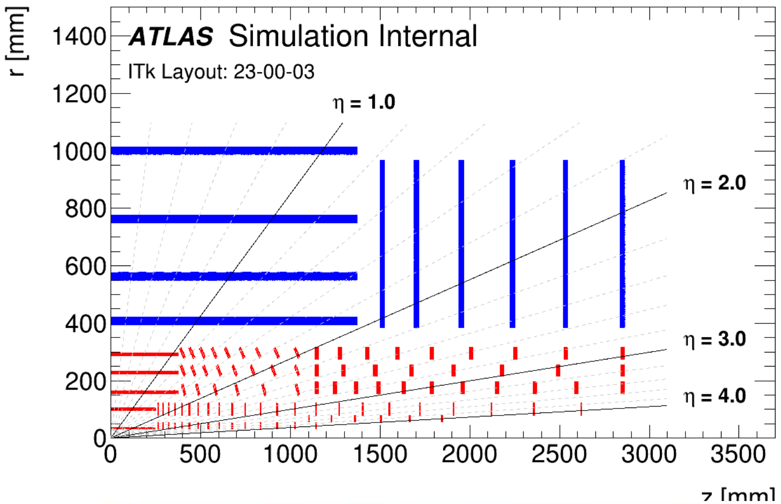
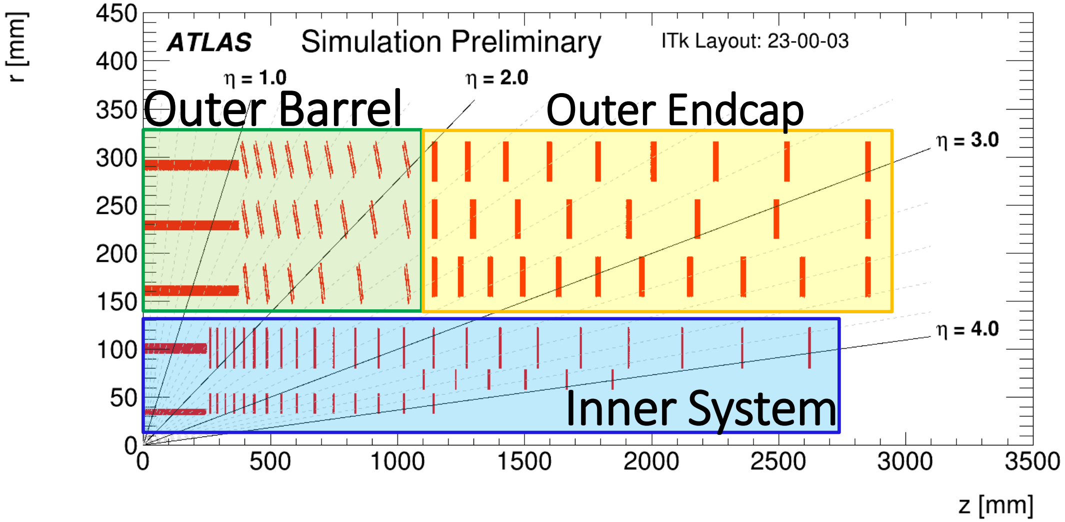
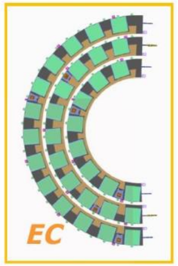
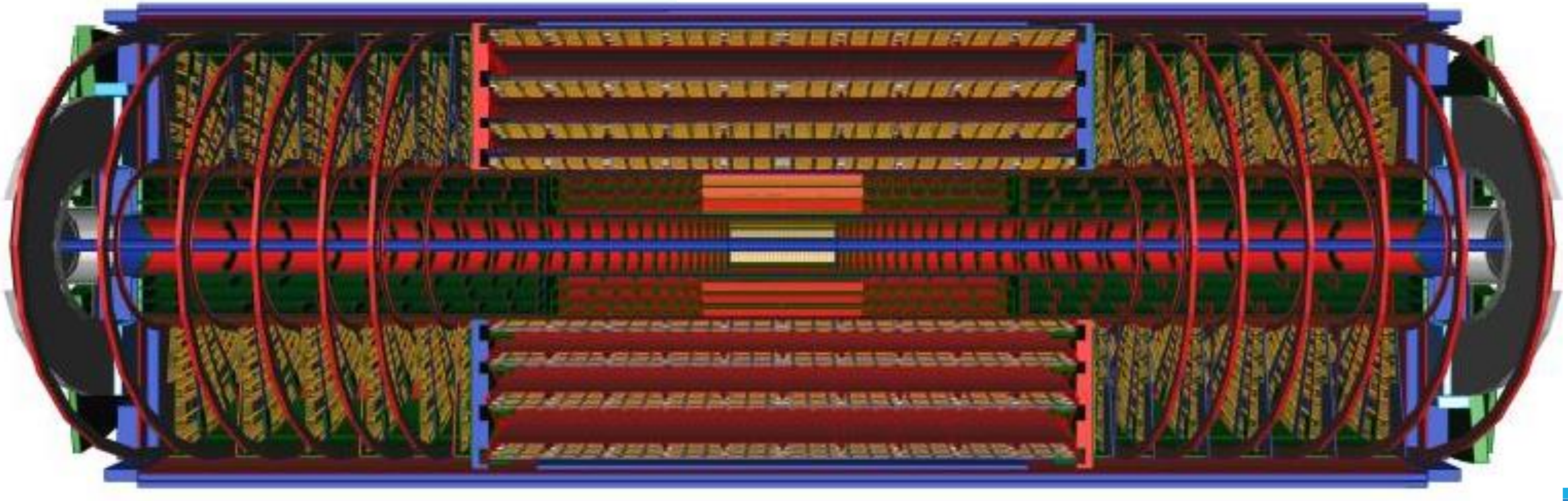
Backup

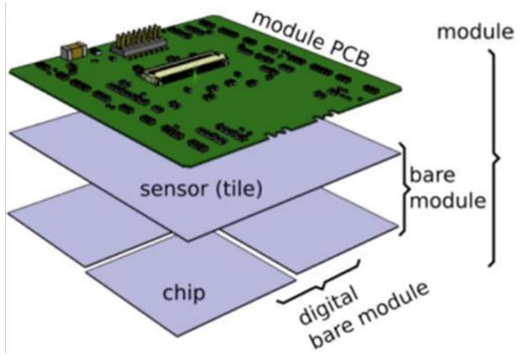
Inner Tracker layout

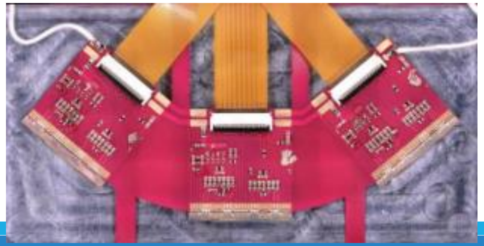






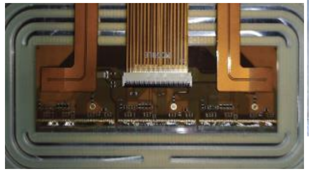


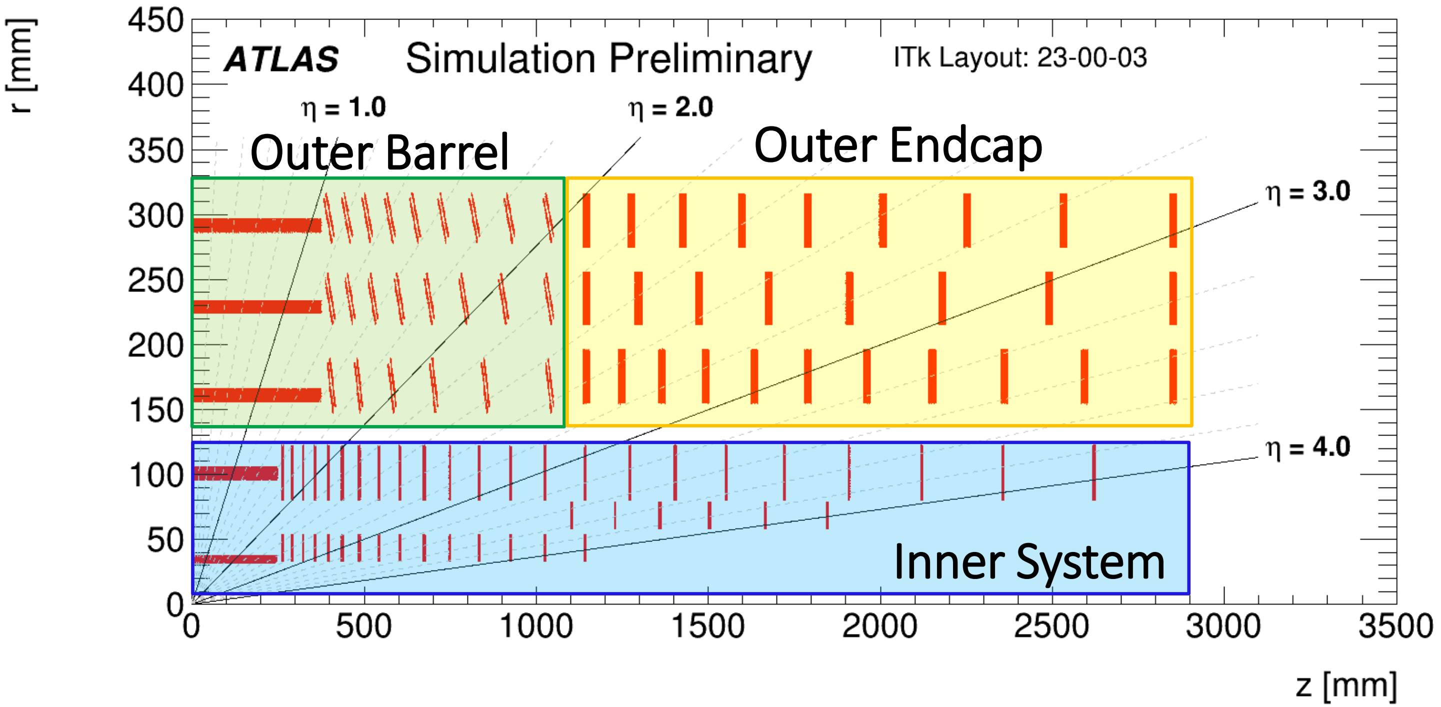


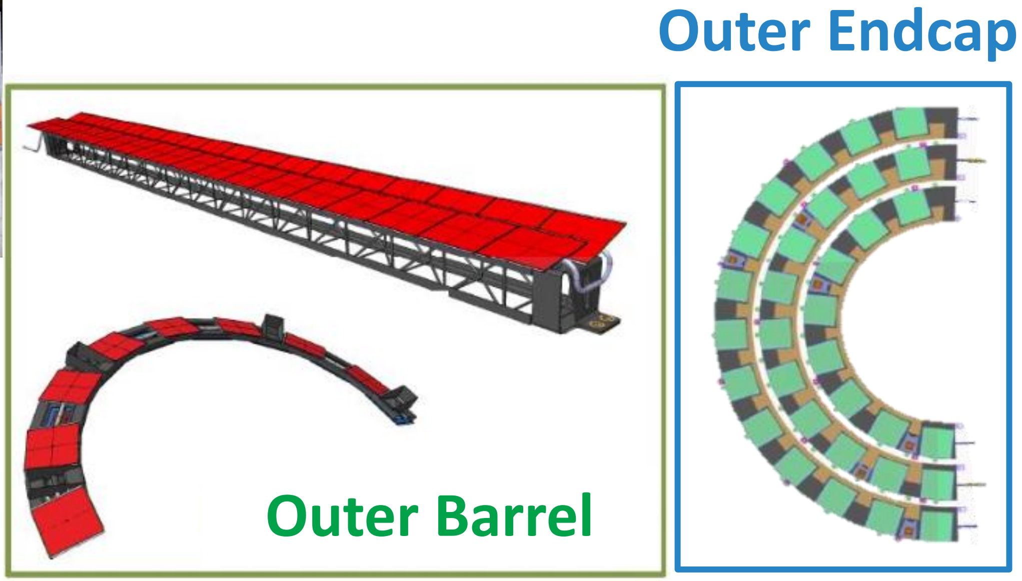


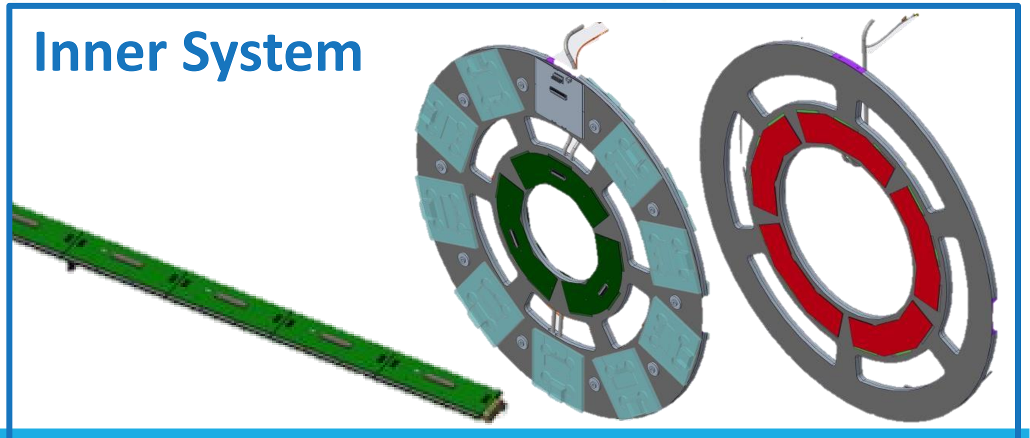
Pixel: detector structure and modules

- Design: completed! → Prototypes: done! → Pre-production: ongoing!
- Pixel detector made up by 3 main parts: **Outer Barrel**, **Outer Endcap**, **Inner System**
- Two different module concepts:
  - All the external layers (L1-4): Quad-module →
  - Innermost layer (L0): Triplet mod. →
- Modules glued to carbon structures
- Titanium pipes for CO_2 cooling







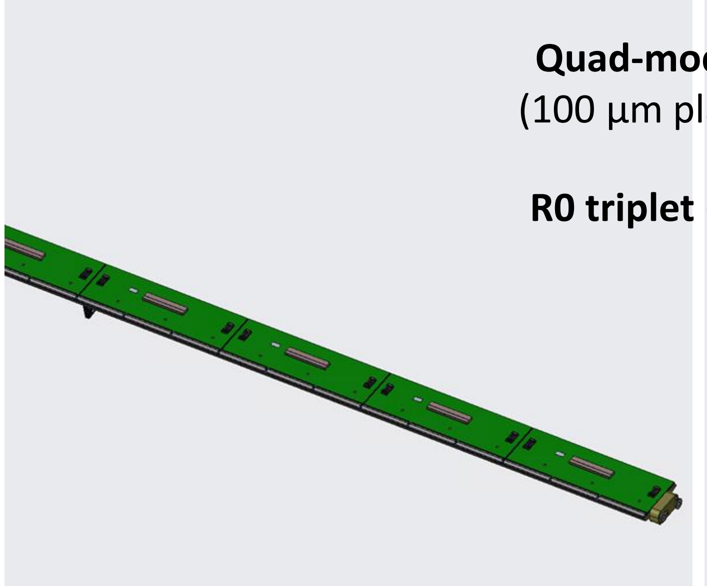


ITk pixel: triplet modules

Barrel (stave)

L0: 96 triplets

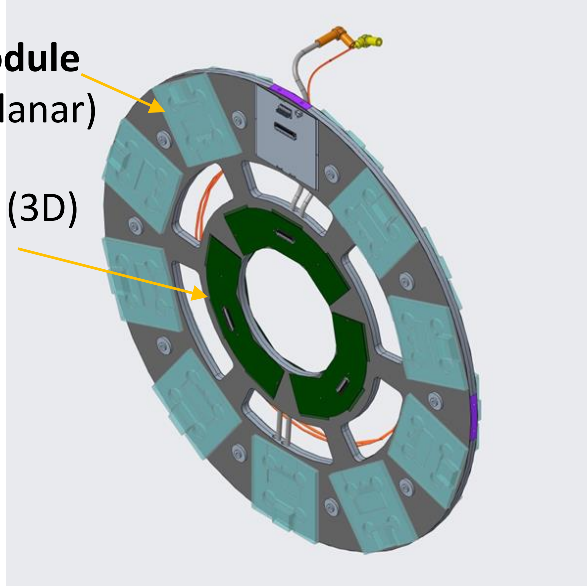
12 staves x 8 triplets



Endcap (rings)

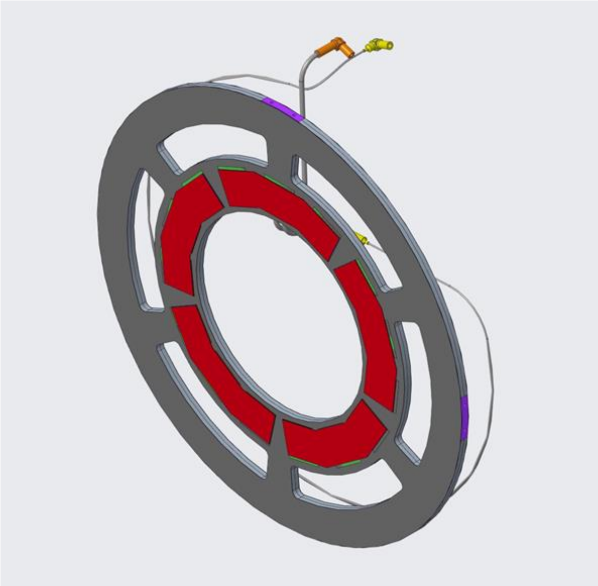
R0: 180 triplets

30 rings x 6 triplets



R0.5: 120 triplets

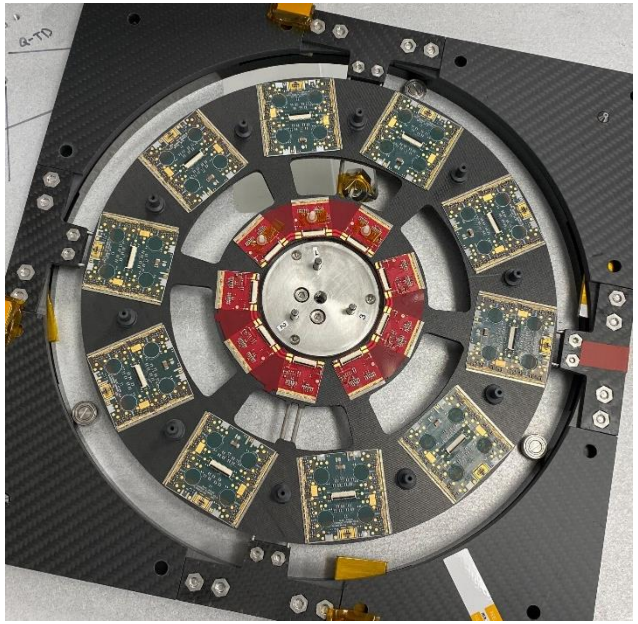
12 rings x 10 triplets



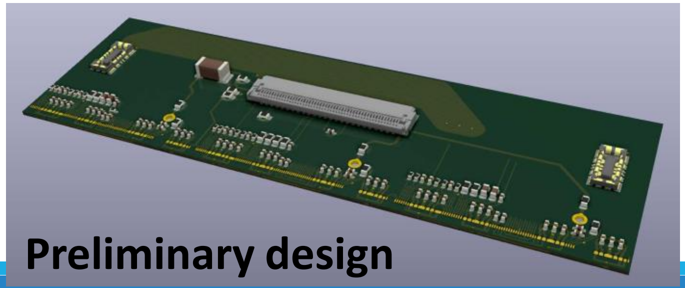
Prototype of ITk R0 ring with RD53A modules:

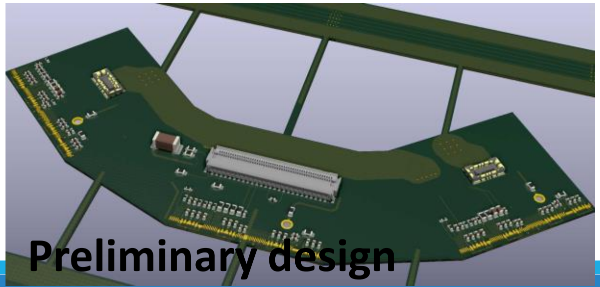
10 quad-modules

3 R0 triplets



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





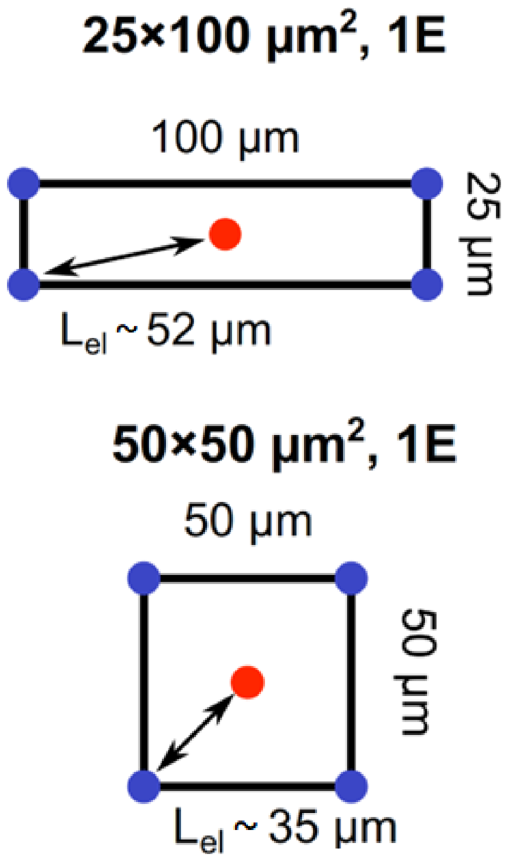
Design ongoing

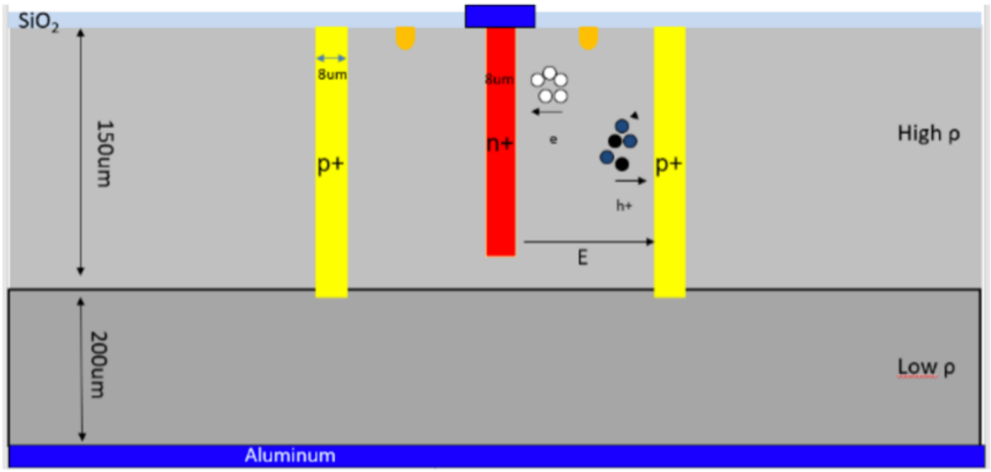
3D sensor technology

- ATLAS ITk will use 3D technology in L0 with 2 different pixel cell dimensions
  - 25x100 μm^2 in the barrel triplet modules (B0, 288 sensors)
  - 50x50 μm^2 in the endcap triplet modules (R0 & R0.5, 900 sensors)

- **Pros**: low depletion voltage, fast response rise, less trapping probability
  → **RAD-HARDNESS**

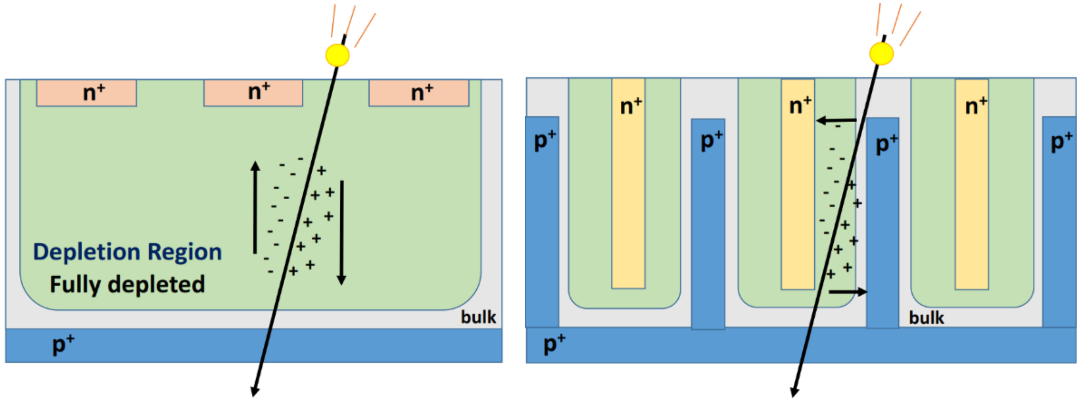
- **Cons**: iniform spatial response, higher capacitance w.r.t. to planar, cost, yield





ITk Pixel: sensor arrangement

- **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

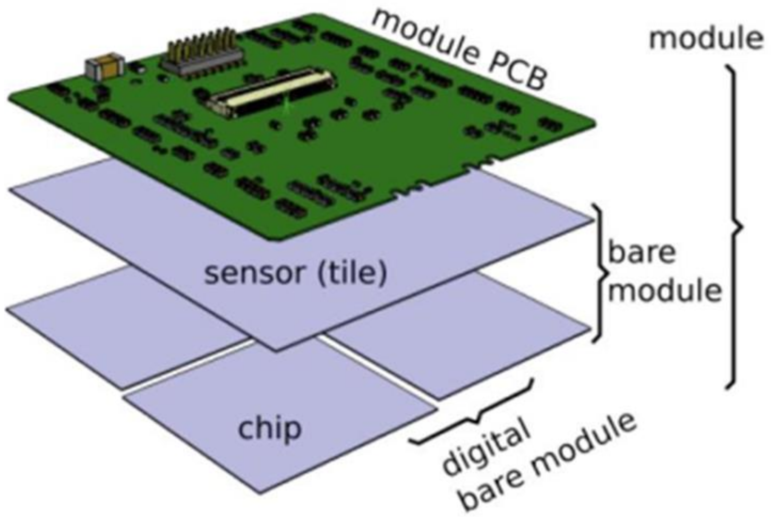


Planar sensors arranged in quad-modules: 1 bare module (4 chips + 1 planar sensor) + 1 flexible PCB

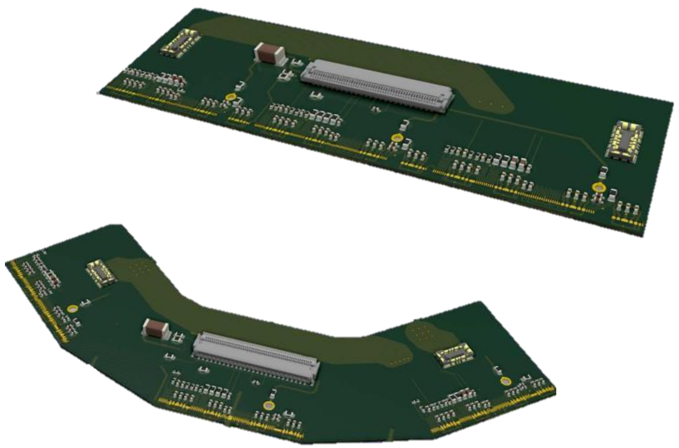
3D sensors arranged in triplet modules: 3 bare modules (1 chip + **3D sensor**) + 1 flexible PCB

- Both ring and barrel triplet assembly exercised with RD53A prototypes

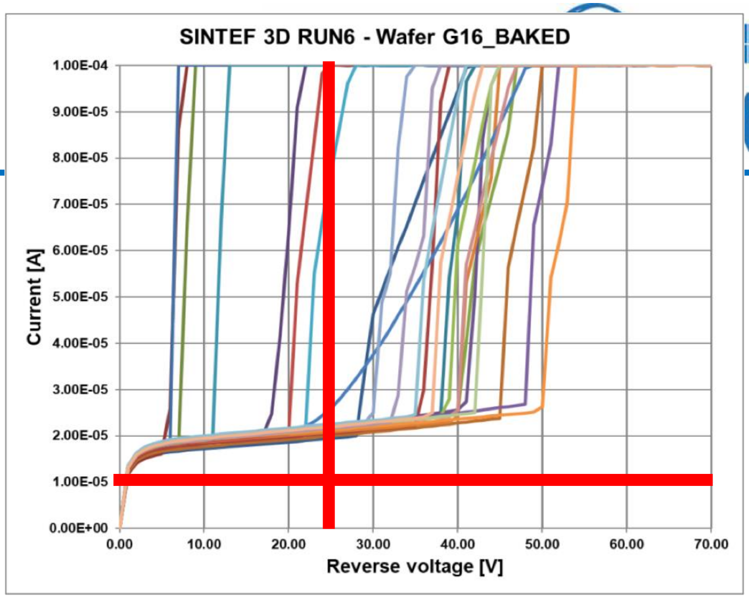
Quad-module stack-up



Ring and barrel
triplet module flexible PCB



SINTEF PRR follow up issues



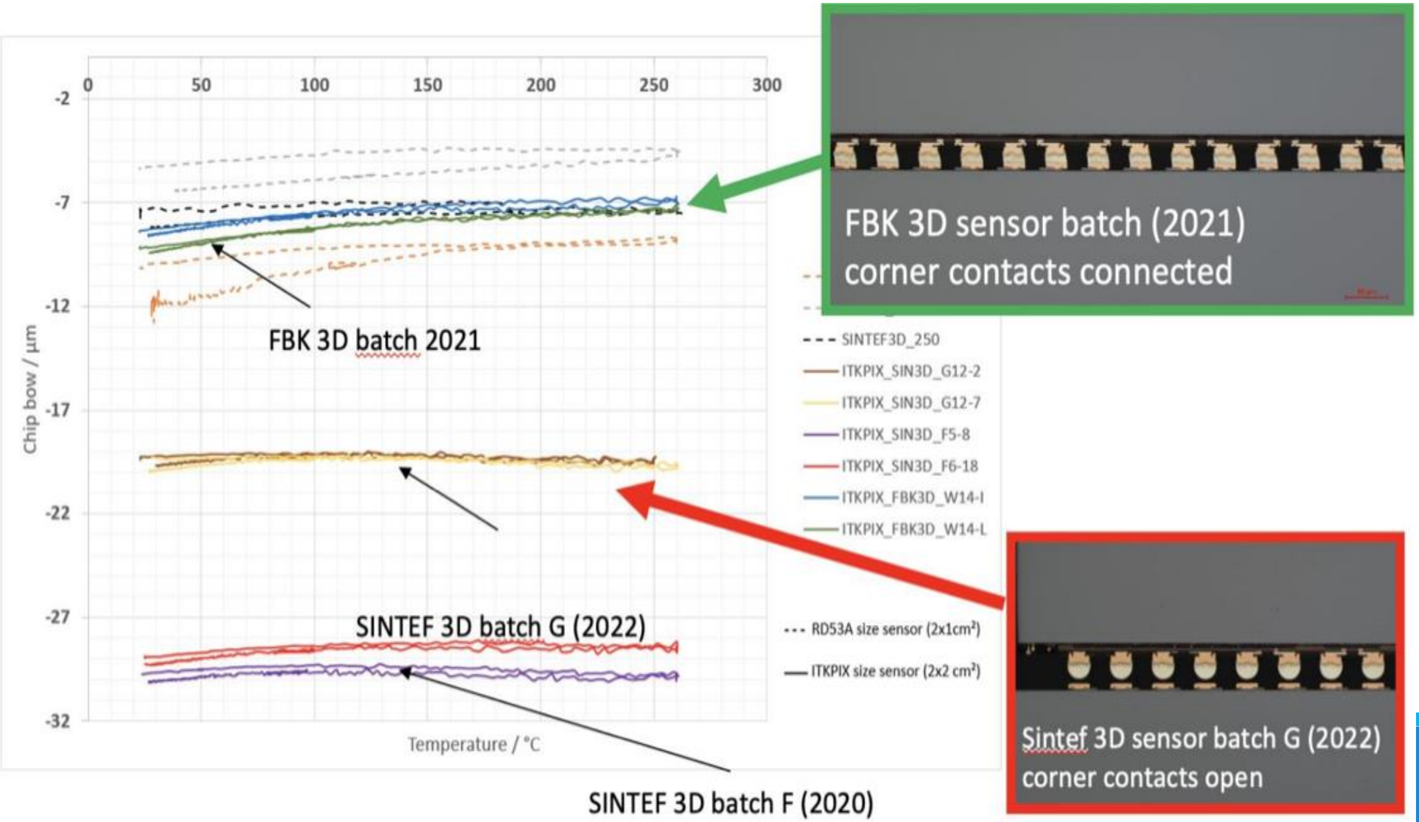
SINTEF high leakage current

- Leakage current of SINTEF sensors before irradiation outside specs (~2 times over the limit)
- Leakage current within specs after irradiation
- Plan to relax the specifications for this production

SINTEF large bow after back-thinning

- After back-thinning the sensor bow is out of specs
  - Problematic for flip-chipping at IZM
- Possible solutions under investigation
  1. Changing the passivation at SINTEF
     - A few wafers have been reworked, two wafers sent to IZM to hybridize
  2. Hybridization at Leonardo (indium bumps):
     - First results expected soon (bare modules in institutes for module assembly)
  3. Flip-chipping at IZM with glass support
     - Few modules produced, being assembled in modules, results very encouraging.

Sensor in-kind started: acceptance will be considered based on the results



ITk Pixel: FE chip from RD53A to ITkPixV2

- RD53A chip (by RD53A collaboration) largely used to build module prototypes before 2022
- ITkPixV1.x chip (RD53B): **ToT not usable**
  → Most of results shown done with ITkPixV1.1
  → ITkPixV1.1: noise of bare FE ~40e (~10e dispersion)

- **ITkPixV2** chip submitted at the **end of 2023**
  → qualification measurements recently finished
  → production officially started

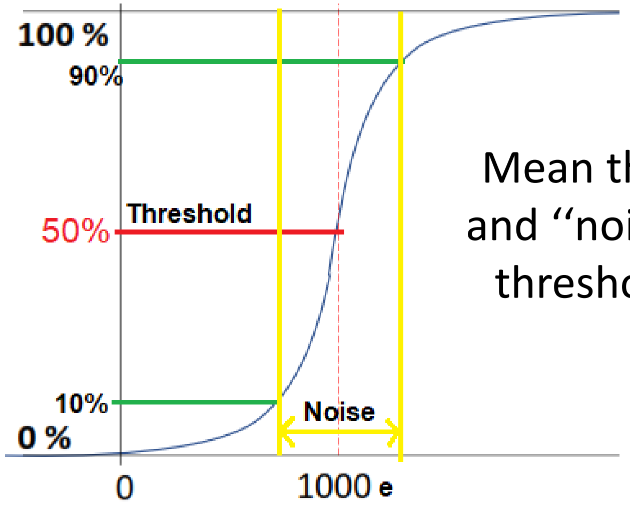
- Main ITkPix features:
  - 65 nm CMOS, 2x2 cm^2 area
  - 384 x 400 pixels (50x50 μm^2)
  - Differential Analog FE
  - Power consumption: 0.56 W/cm^2
  - Shunt Low Drop Output regulators (I const.)
  - Timewalk < 25 ns (charge > 1000 e)
  - **Radiation hardness > 1 Grad**
  - **Standard threshold: 1000e** (30e dispersion)

Summary of the 3D FBK 50x50 μm^2 assembled modules (+2 bare chip)

- Threshold tuning to 1000e → Threshold dispersion: 30e
- Mean ''noise'' from S-curve: (decreasing with V bias)
  - Bare chip (no sensor) → Average: 40 ± 7 e
  - Module (10 V bias) → Average: 70 ± 10 e

SCC	Bare chip	Mean Threshold	Sigma Threshold	Mean Noise	Sigma Noise
A	ITkPixV1.1	969	31	39	7
B	ITkPixV1.1	961	29	41	7

SCC	Module	Mean Threshold	Sigma Threshold	Mean Noise	Sigma Noise
2	3D + ITkPixV1.1	974	28	71	10
3	3D + ITkPixV1.1	979	31	67	9
4	3D + ITkPixV1.1	971	31	70	9
5	3D + ITkPixV1.1	969	31	73	10
6	3D + ITkPixV1.1	973	29	70	10
8	3D + ITkPixV1.1	962	31	75	10



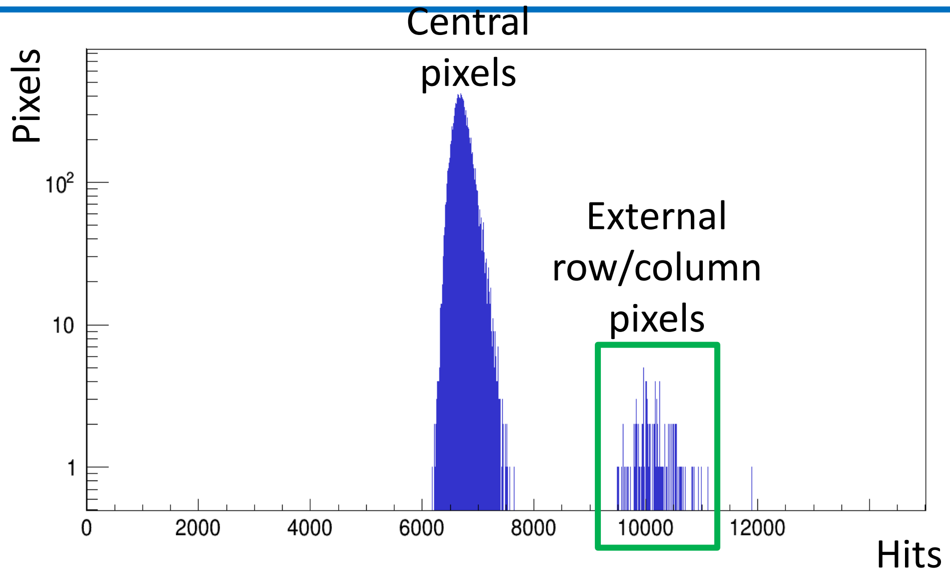
Mean threshold and ''noise'' from threshold scan

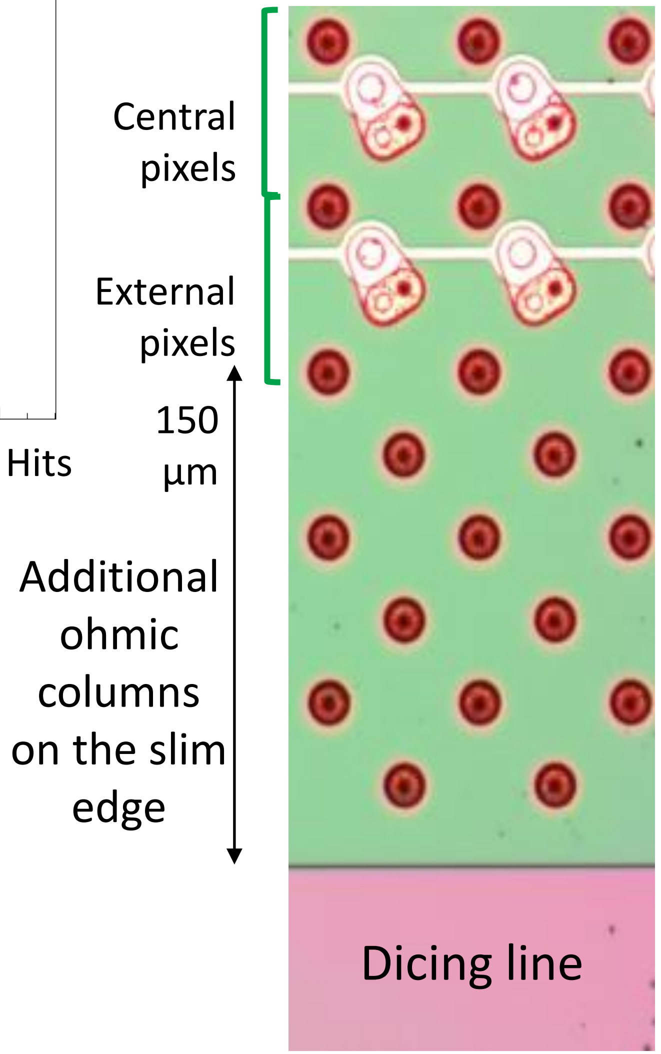
- Leakage current:
  - at sensor level (on wafer): < 1 µA (3.84 cm²) up to 80 V
  - on bare module (on SCC): < 0.2 µA/cm² (compatible)
- Breakdown voltage V_{bd}:
  - V_{bd} > 80 V (requirement: V_{bd} > 25 V @ V_{depl} + 20 V)

X-ray scan

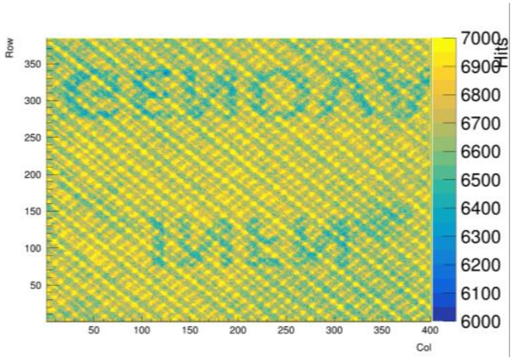
- Source: X-ray tube (Amptek Mini-X2), with Ag anode

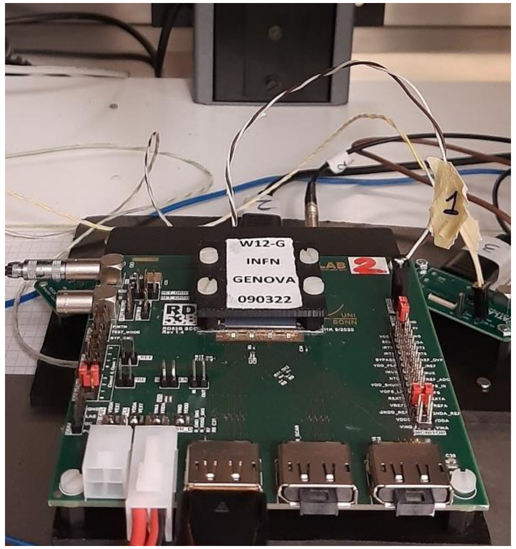
- Masking noisy pixel (X-rays OFF): 60 seconds random trigger scan (40 kHz)
- Data taking (X-rays ON): 60 seconds self-trigger scan (HitOR)
  - Central pixels: 6700 hits/pixel in 60 s (110 Hz)
  - **Edge pixels: 10000 hits/pixel in 60 s**
    - ***30% more hits due to extension of the electric field***





- 3D printed plastic cover between X-ray tube and the sensor
  - Visible pattern of the 3D printed filament
  - Visible pattern of the ink on printed label INFN Genova





Test beam data analysis

- Data analysed with the C++ based framework Corryvreckan

- Procedure:
  1. Telescope (6 planes) alignment with track χ2 minimization → stops when telescope residuals comparable to plane resolution (~5 µm)
  2. DUTs alignment with track χ2 minimization → stops when the DUTs residuals are of the order of the device resolution (~14 µm)
  3. The efficiency is calculated
     - with tracks on DUT that **meets spatial and time** cuts w.r.t. reconstructed track
     - <u>disabled, masked pixels and neighbouring ones are not taken in account</u>

→ the resulting efficiency is valid for pixels that are not masked or disabled

FBK Irradiations in 2022 details

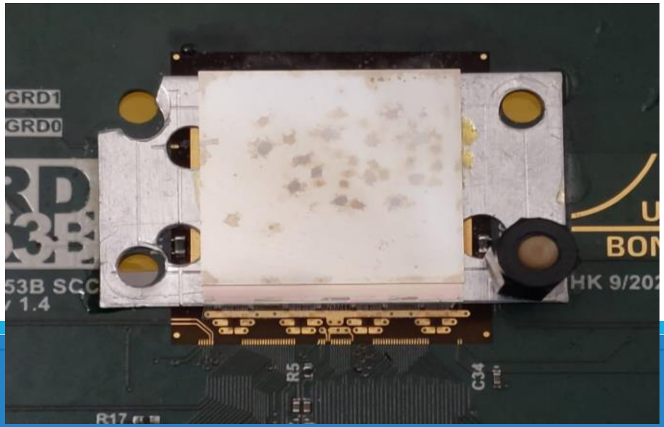
Two ITkPixV1.1 + 3D FBK 50x50 μm² have been irradiated at two different facilities in 2023:

- **First irradiation:**
  - in Bonn (May-June 2022) to uniform fluence (uniform) **1×10^{16} n_{eq}/cm^2**
  - 14 MeV protons beam, 1 Grad
- **Second irradiation:**
  - at IRRAD (CERN, 7-27 September 2022) to add to fluence (not uniform) **0.9×10^{16} n_{eq}/cm^2 (peak), 0.5×10^{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 cm² 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 the sensor

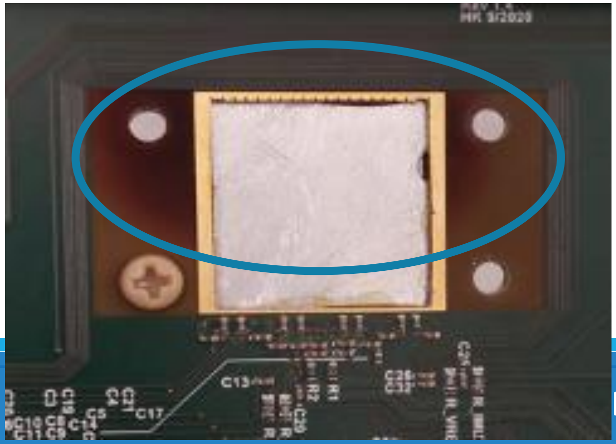
Total integrated fluence:

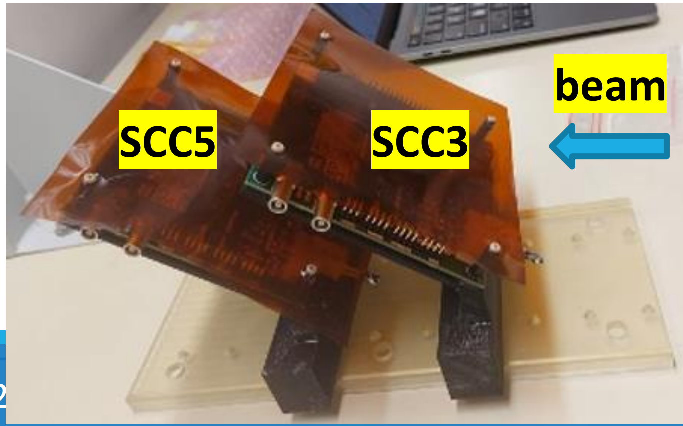
- **1.9×10^{16} n_{eq}/cm^2 (peak), 1.5×10^{16} n_{eq}/cm^2 average**
- Not uniform fluence used to **map efficiency** measurements **to different fluence values**

Front



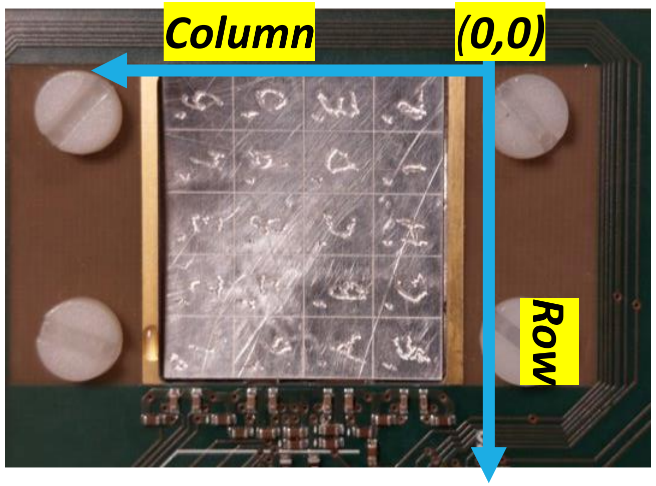
Back

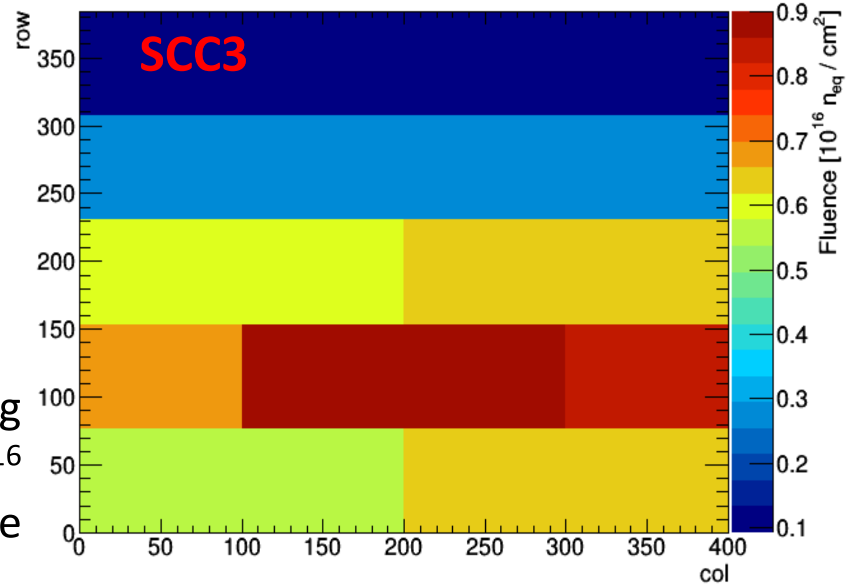




Evaluation of local fluence

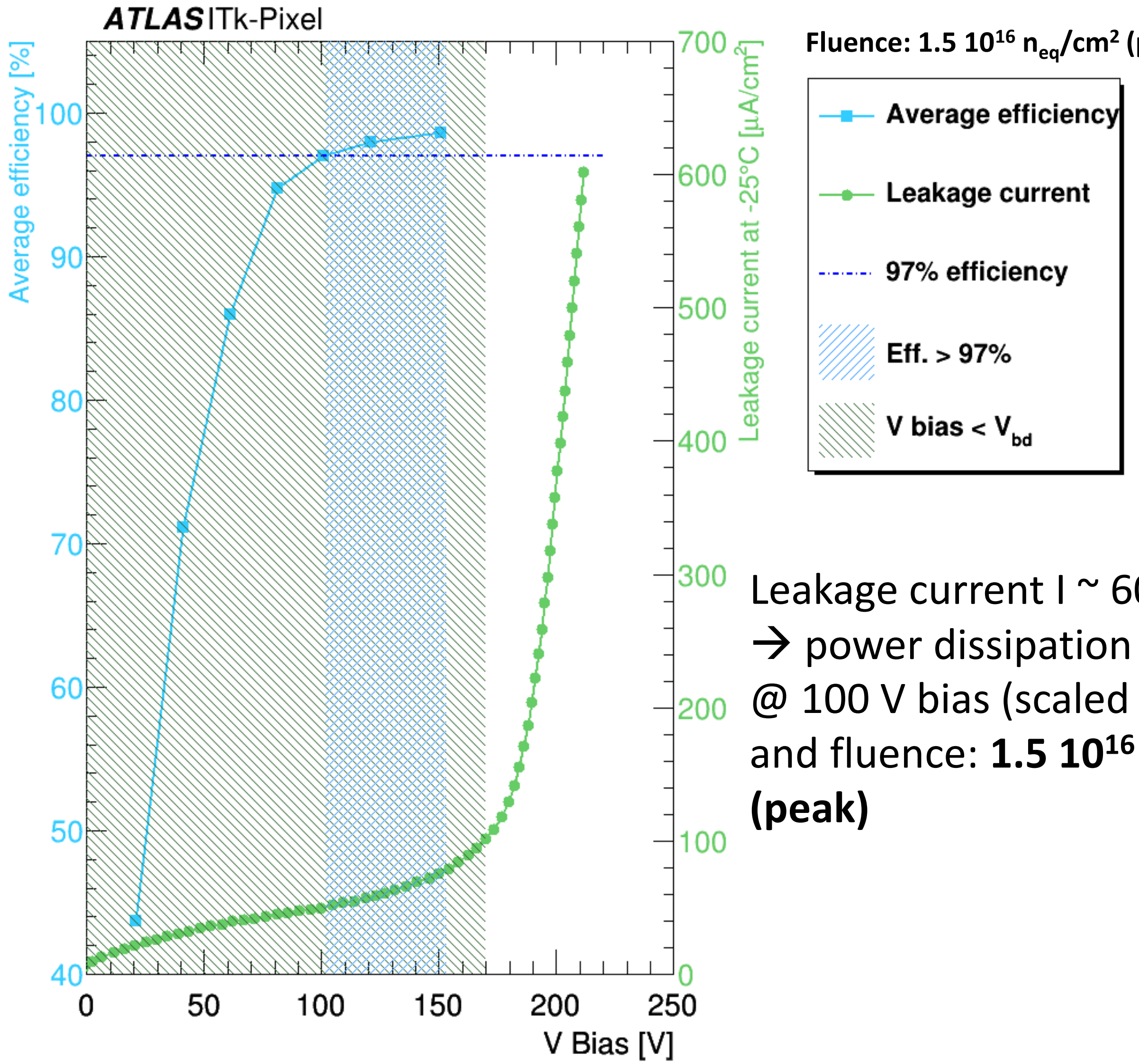
- Aluminium dosimeters were placed on the back of the sensors during irradiaton
- After irradiation, dosimeters are cut in smaller pieces
  - Measured activity of Na-22 with Ge detector, from which the fluence is calculated
  - → a map of local measured fluence is obtained with granularity of squares / strips
- Fit the 2D map with a 2D gaussian distribution to obtain a map of fluence vs individual pixel
- Improve the map by correlating it to the noise map or efficiency map



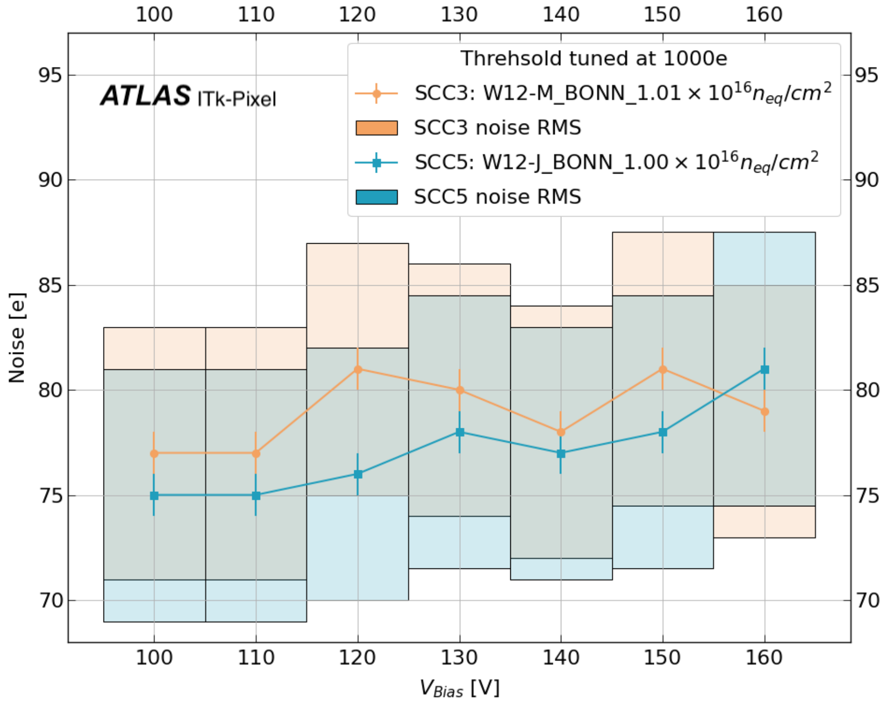


Fluence accumulated during second irradiation, add 10^{16} n_{eq}/cm^2 for total fluence

IV curve and noise



Leakage current I ~ 60 μA/cm²
→ power dissipation 6 mW/cm²
@ 100 V bias (scaled at -25°C)
and fluence: **1.5 10^{16} n_{eq}/cm^2 (peak)**



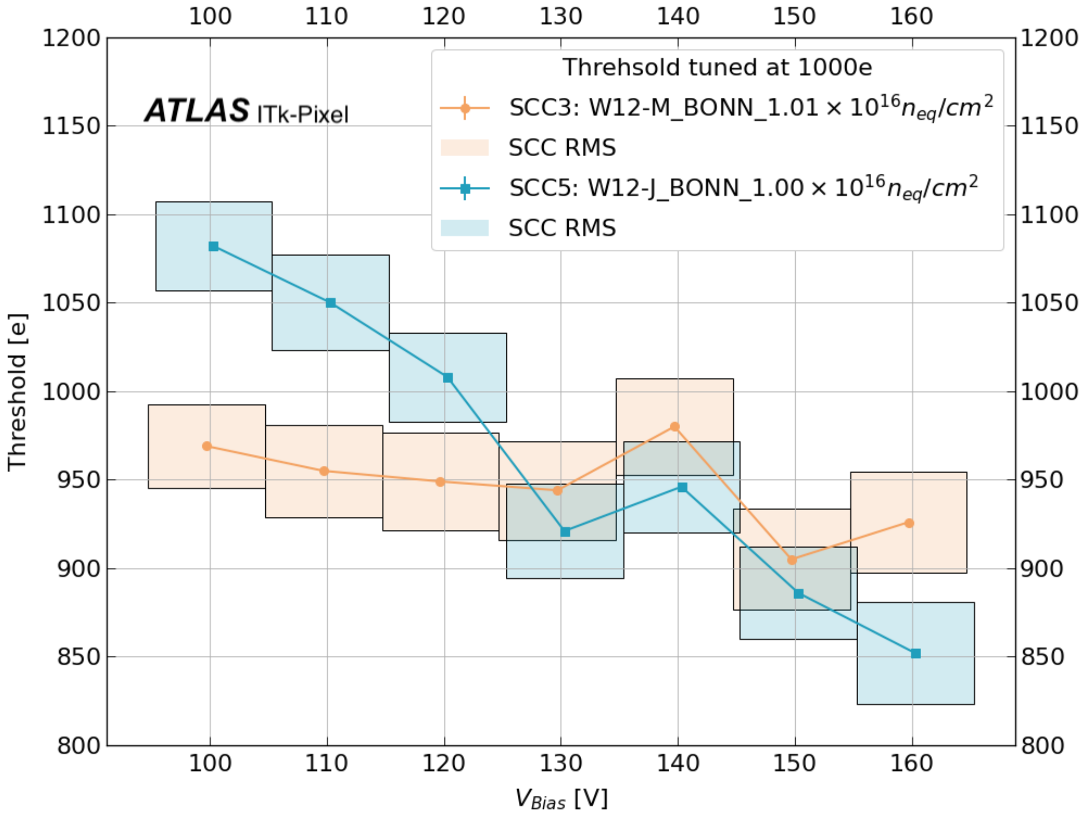
Sensor noise at fluence **10^{16} n_{eq}/cm^2** stable over the entire V_{bias} range used in datataking at **~80e** (same tuning done at 100V used for all V_{bias} values)

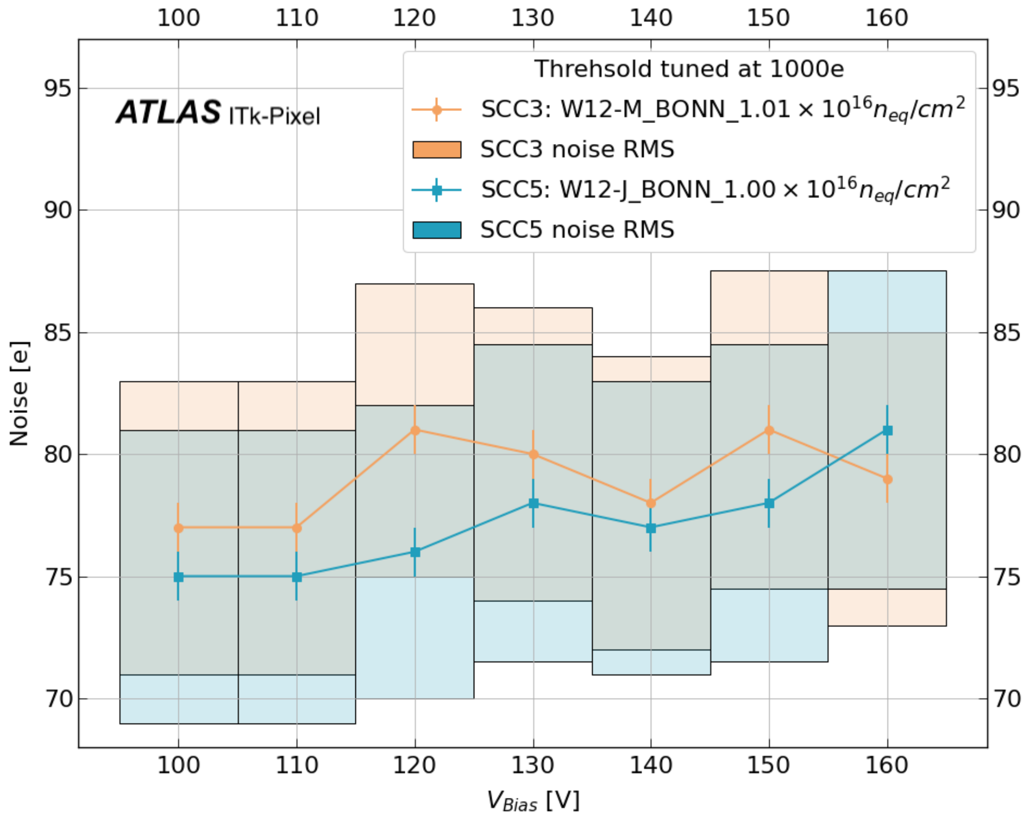
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2022-004/

Tuning strategy and stability at test beams in 2022

SCCs studied in test beams at CERN SPS after each irradiation

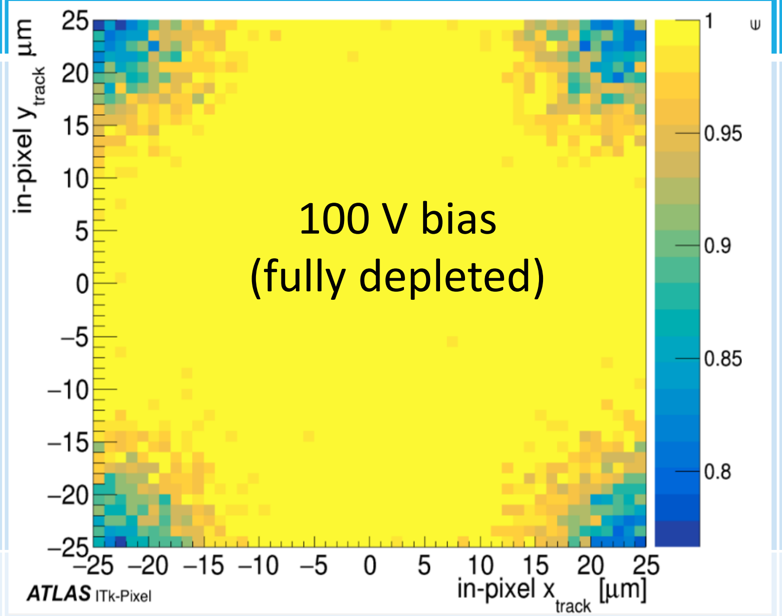
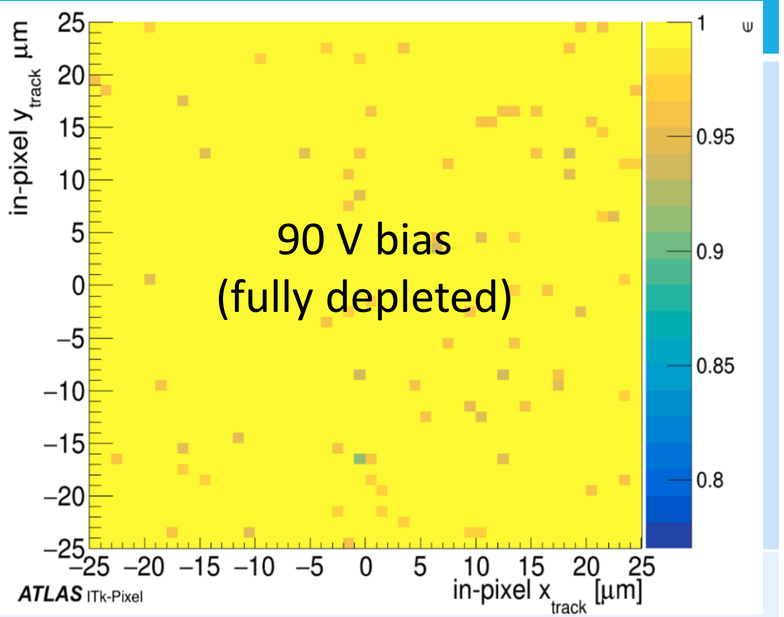
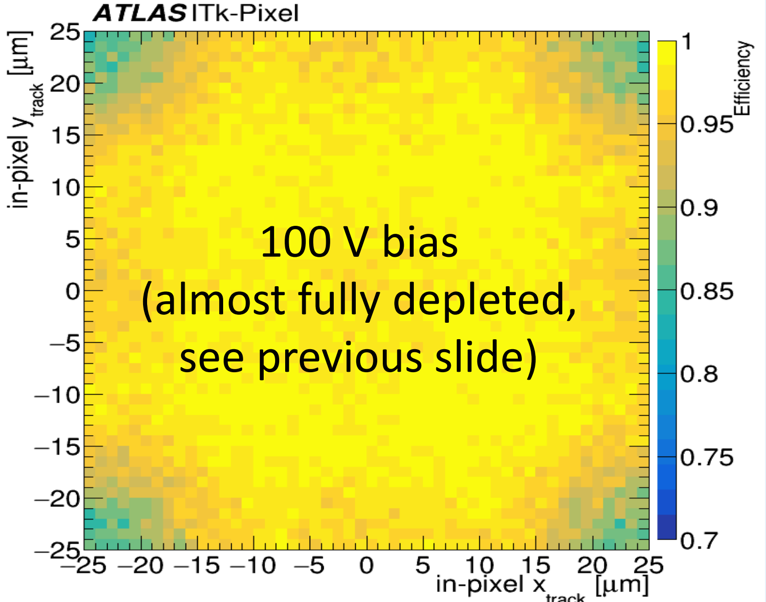
- Strategy (2022 TB campaign): tuned with target 1000e at 100V bias, same tuning used for all V bias
- Threshold and Noise distributions verified to be reasonably stable over a large V bias range





Plots with modules irradiated at 10^{16} n_{eq}/cm^2, similar results after second irradiation

In-pixel efficiency after irradiation

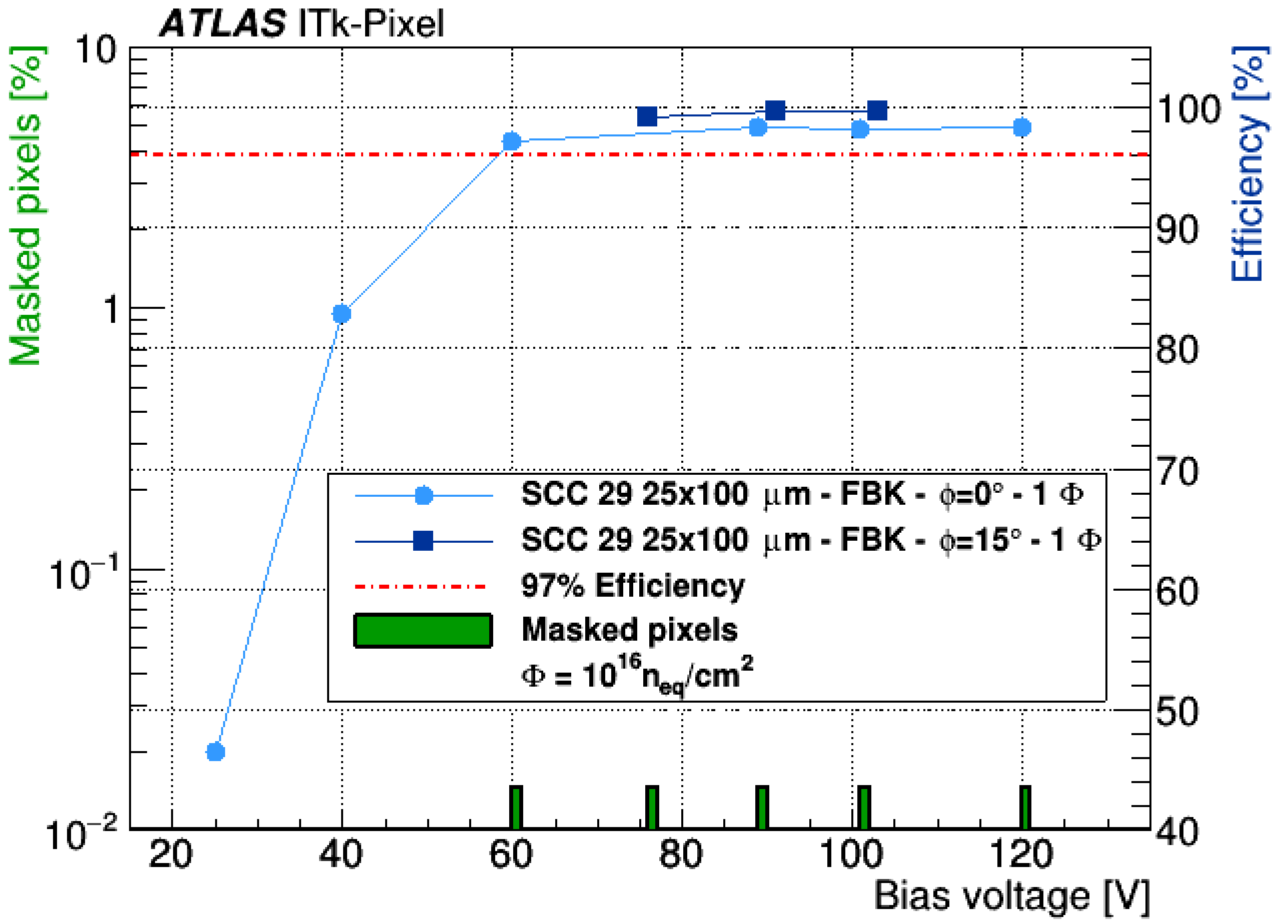
Fluence [$\phi=10^{16}\ n_{eq}/cm^2$]	Tilt ϴ=0° w.r.t. beam direction	Tilt ϴ=15° w.r.t. beam direction
Φ = 1		
Φ = up to 1.9 (Average Φ≈1.6-1.7)		

- Effect of p^+ columns confirmed in perpendicular configuration
- Effect of p^+ columns not visible in tilted configuration as expected
- Comparable max efficiency in central area

https://atlas.web.cern.ch/Atlas/GROUPS
OTS/ITK-2022-004/

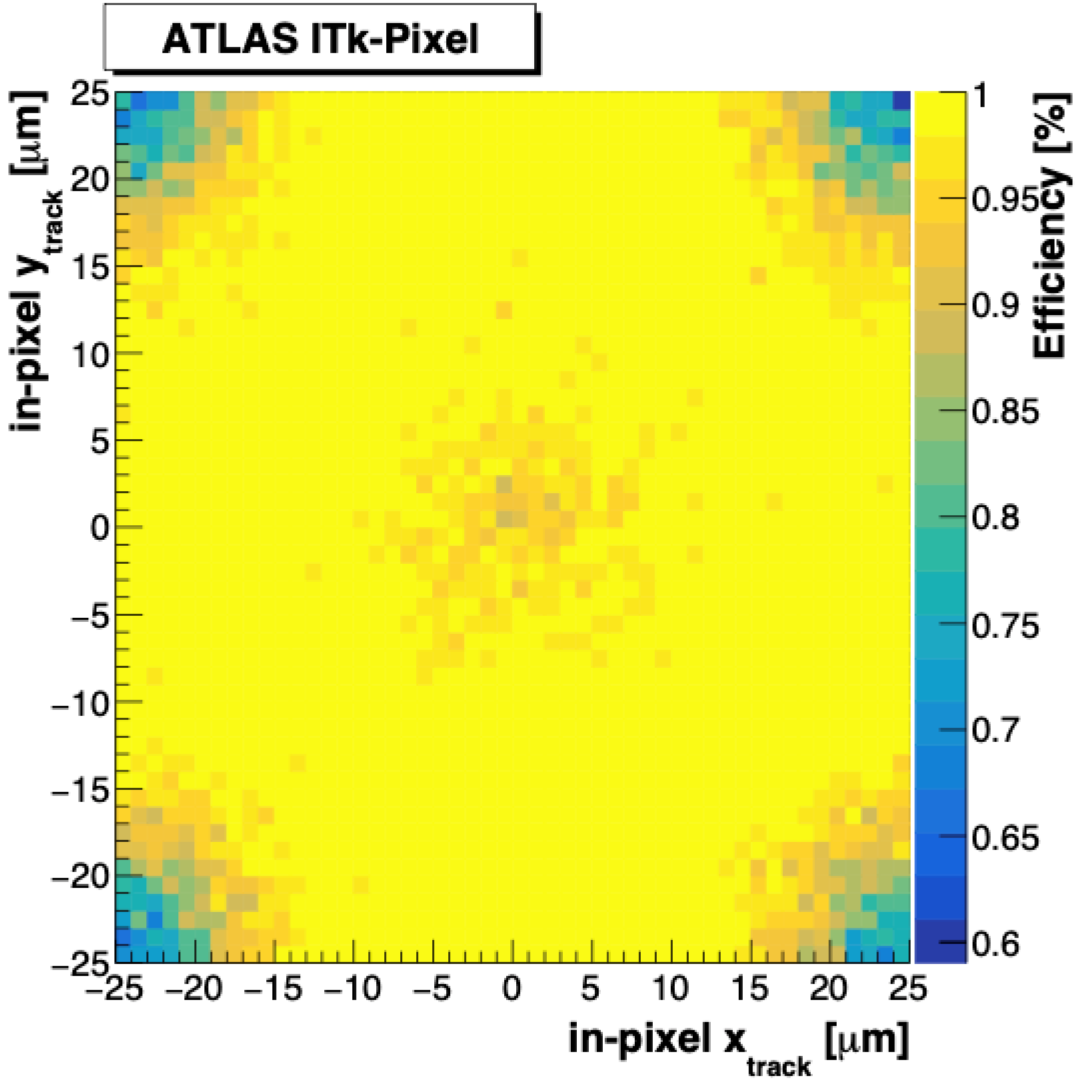
Efficiency and masked pixels

Efficiency of FBK 25x100 with fraction of masked pixels



SINTEF irradiated in-pixel efficiency

SINTEF at 10^{16} n_{eq}/cm^2



Irradiated 3D pixel cell efficiency projections

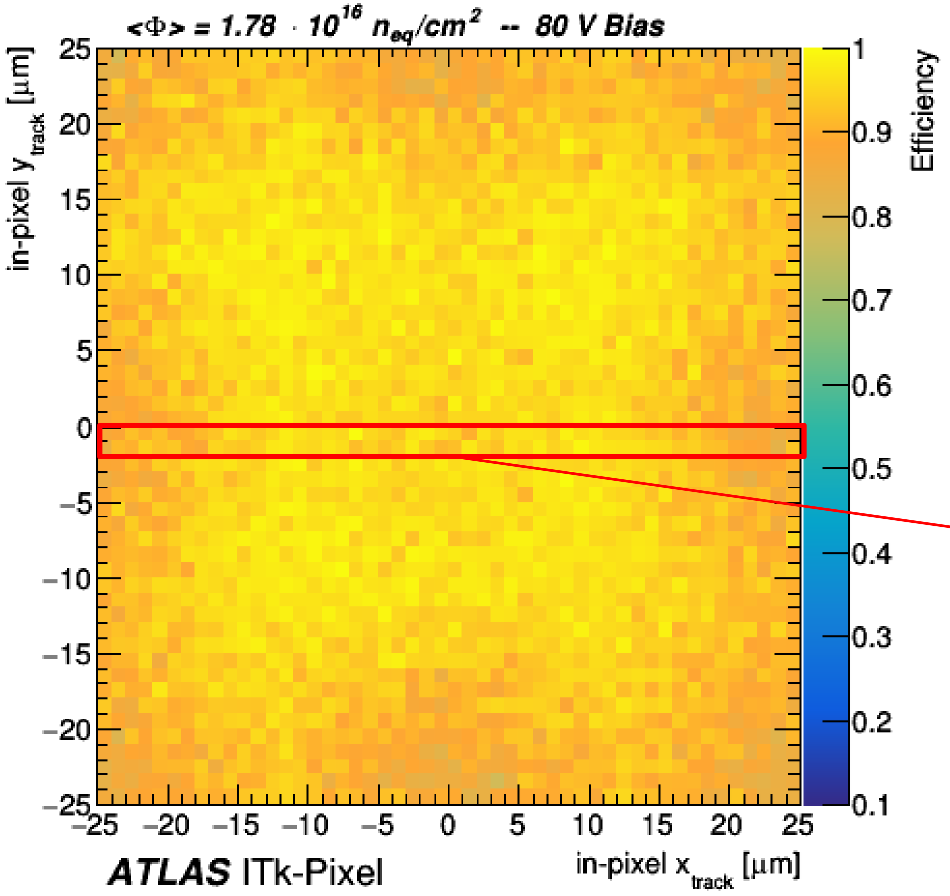
FBK 50x50 μm²

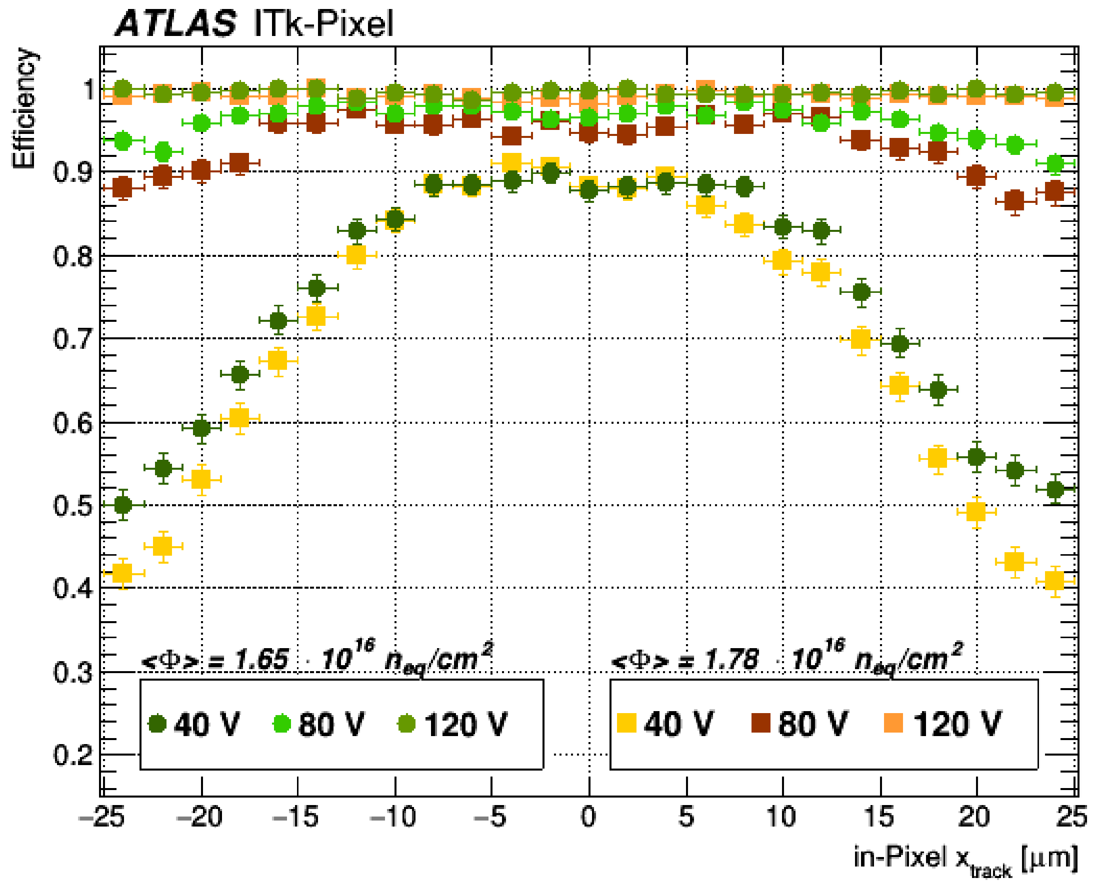
https://indico.cern.ch/event/1223972/contributions/5262028/

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

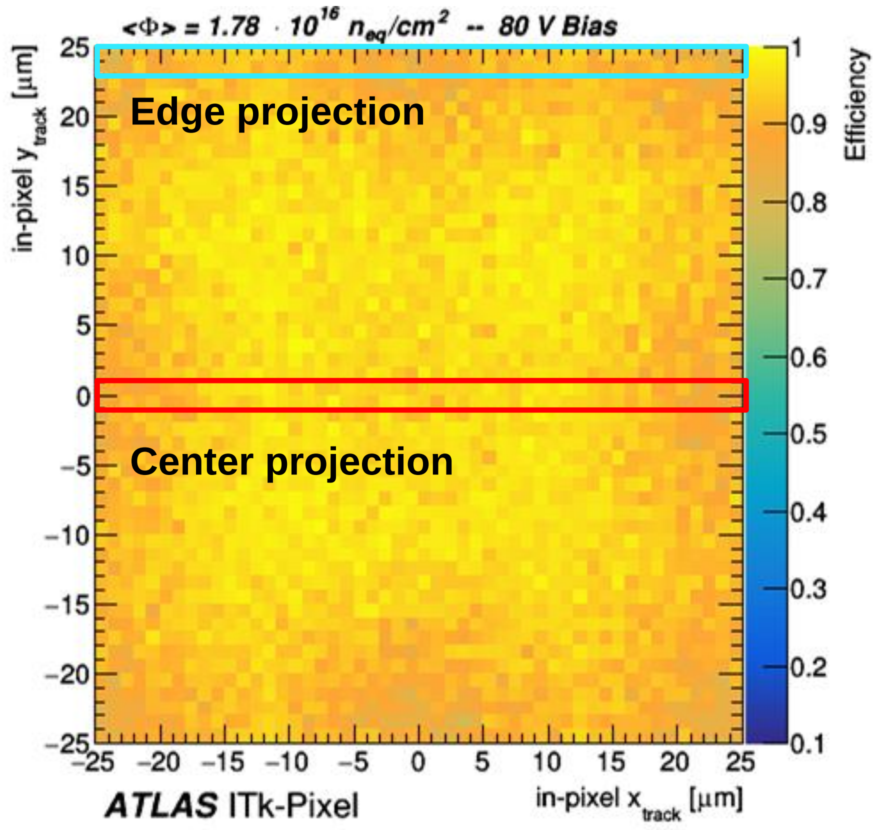
FBK 50x50 μm²

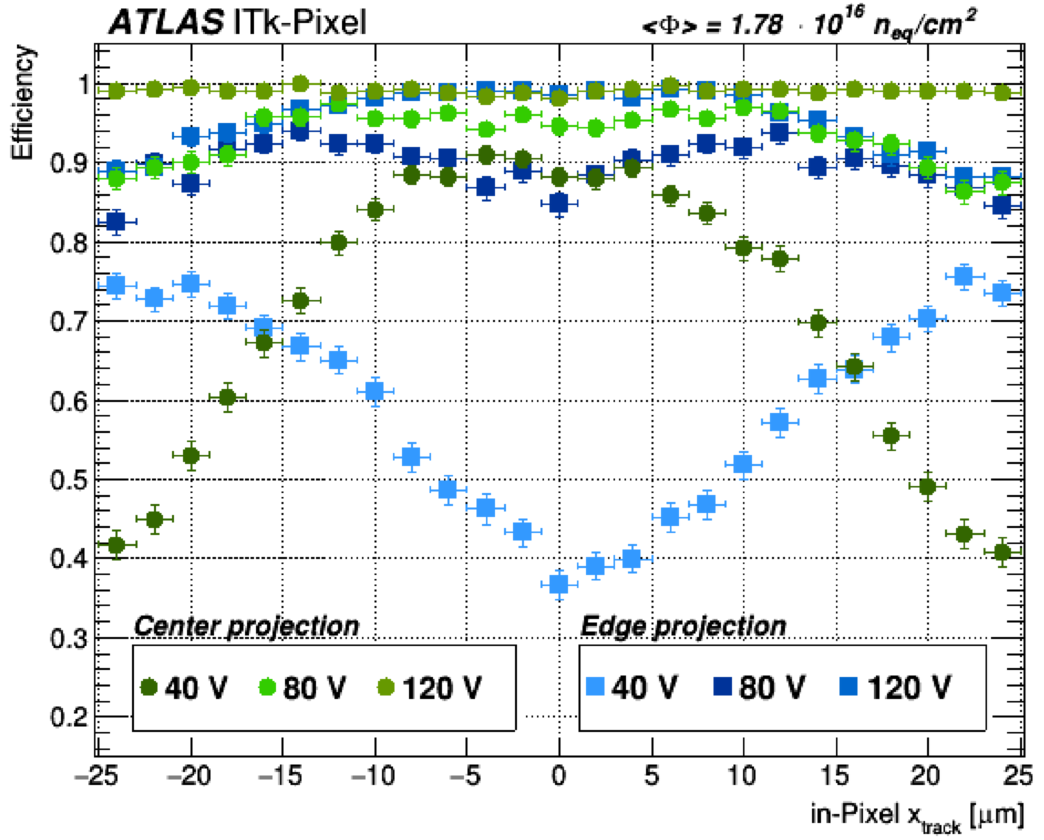
https://indico.cern.ch/event/1223972/contributions/5262028/

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

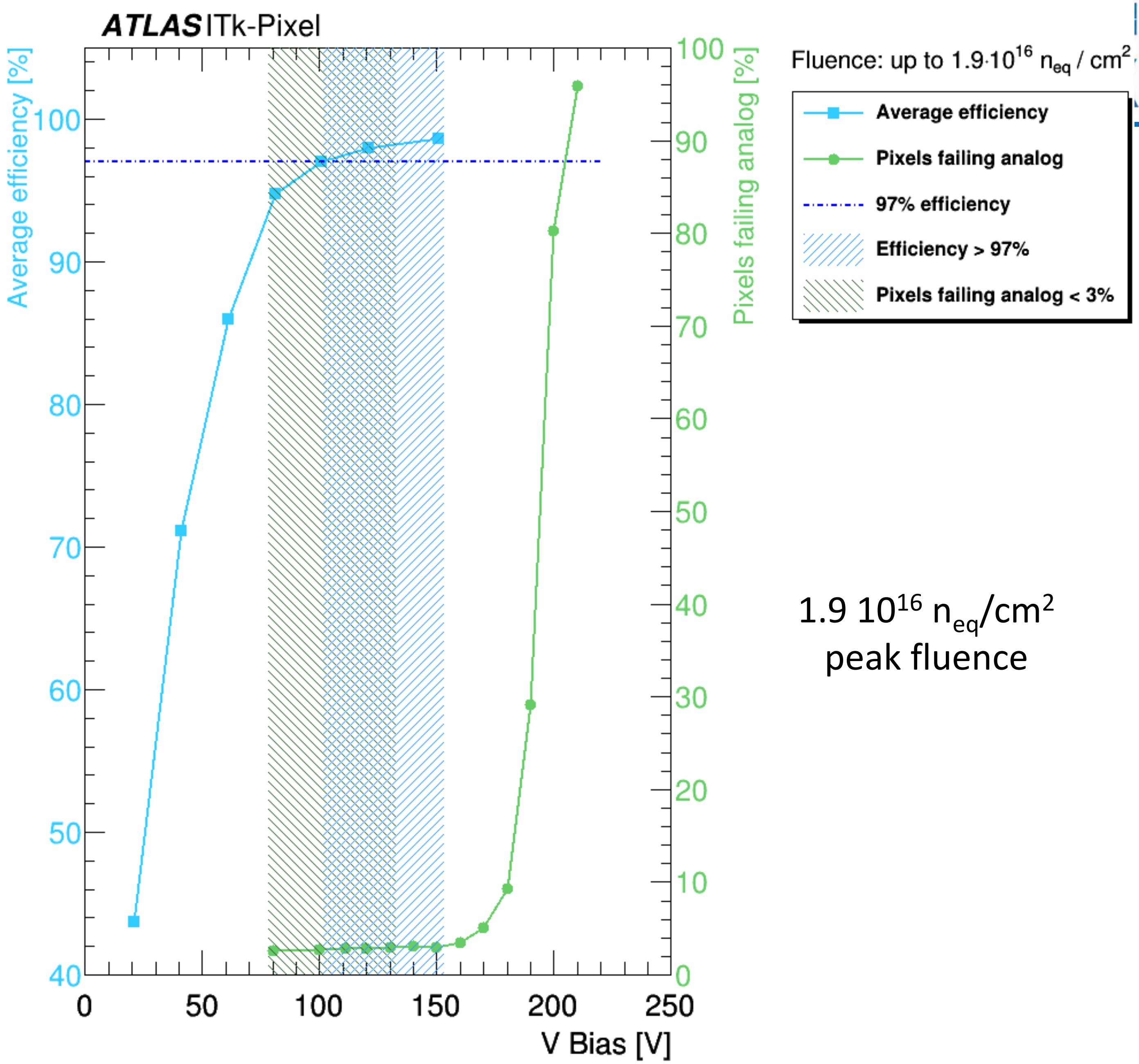
Normal incidence





Operability window

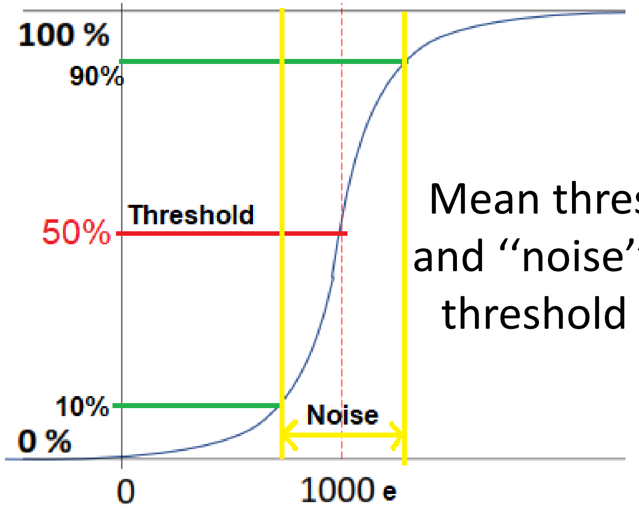
- Observed number of noisy / disabled pixels increasing at high voltages (>120V bias)
  - same tuning (1000e @ 100V bias) used for all V bias → may be reduced by tuning at each voltage → <u>under investigation</u>
- performed **analog** scan vs V bias to study the effect systematically
  - Slow increase at around ~3% failing pixels up to about ~150V bias
  - Faster rise next to breakdown voltage
  - Possibility to improve the 3% failing plateau <u>under investigation</u>
- 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



$1.9\ 10^{16}\ n_{eq}/cm^2$
peak fluence

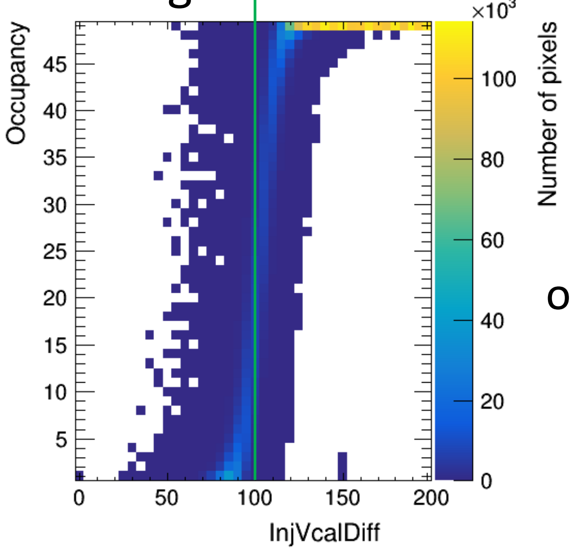
ITkPixV1.1 chip: threshold tuning

- Test with YARR DAQ @ 640 Mbps
- Threshold tuned to 1000 e
- Homogeneus distribution
  - ITkPixV1.1 cell: 50x50 μm^2
  - Matrix: 384x400 pixels



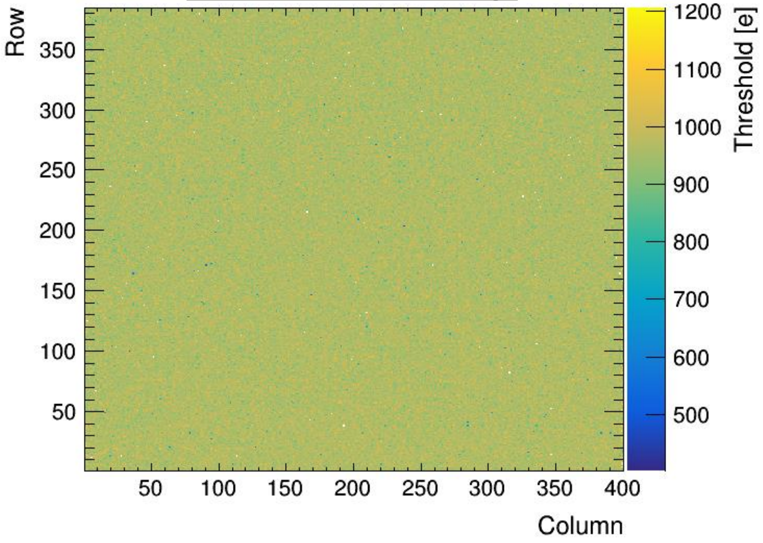
Mean threshold and ‘‘noise’’ from threshold scan

Target: 1000 e

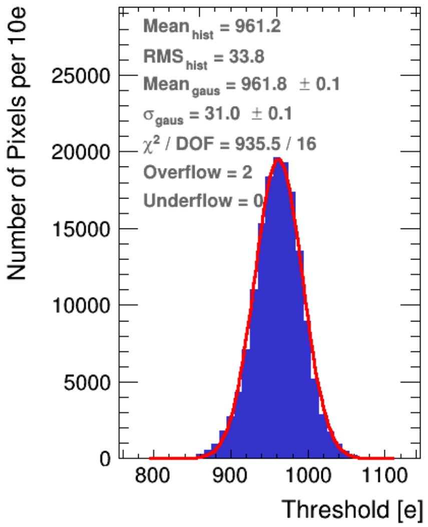


S-curve from threshold scan on 3D+ITkPixV1.1

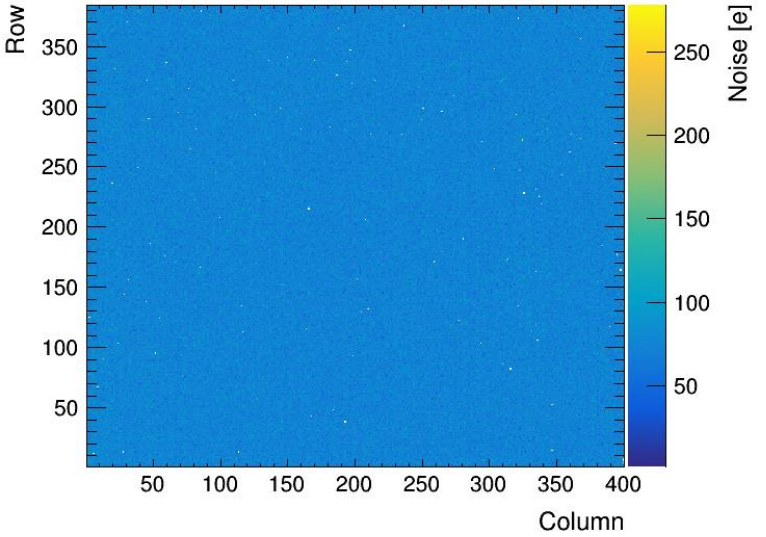
Threshold map



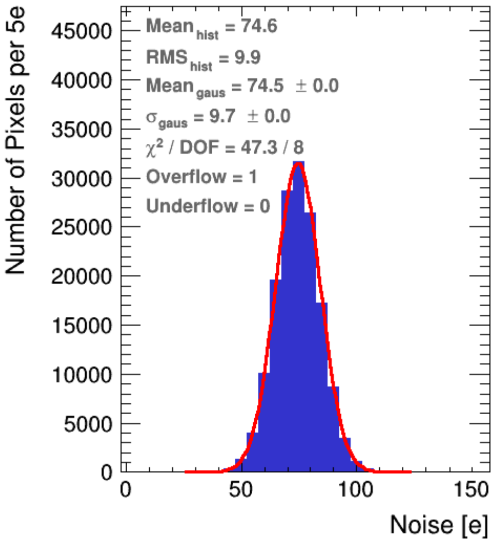
Distribution



Noise map



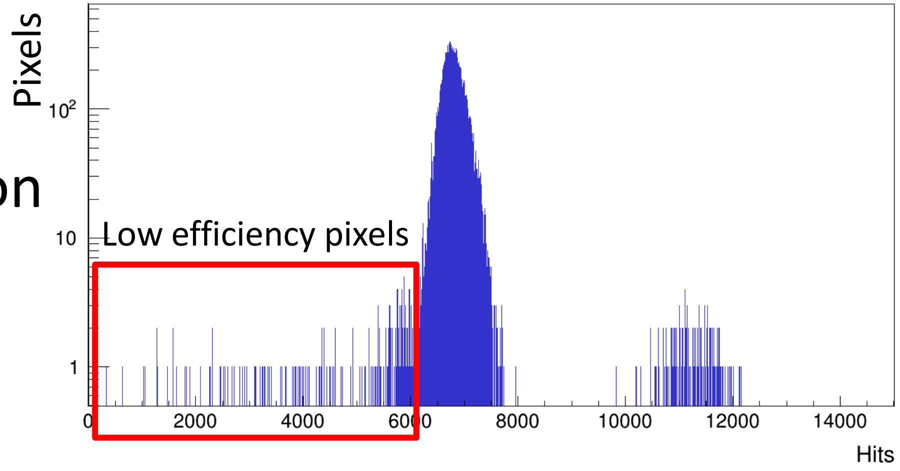
Distribution



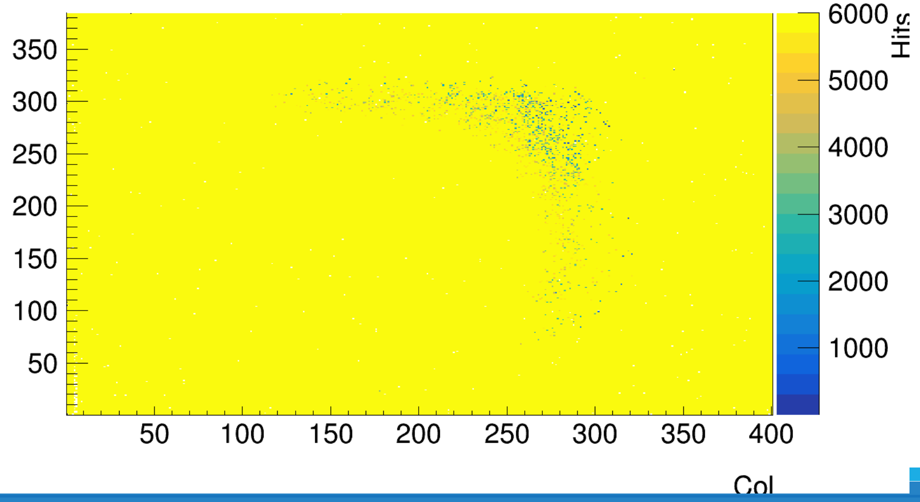
X-ray scan results: issues on SCC 5 and 6

- Bump disconnection area in the center
  - Due to damage to bump structures by handling during hybridization (?)
  - 1000 pixels record lower amount of hits (not noisy pixels)

SCC 5:
hit distribution

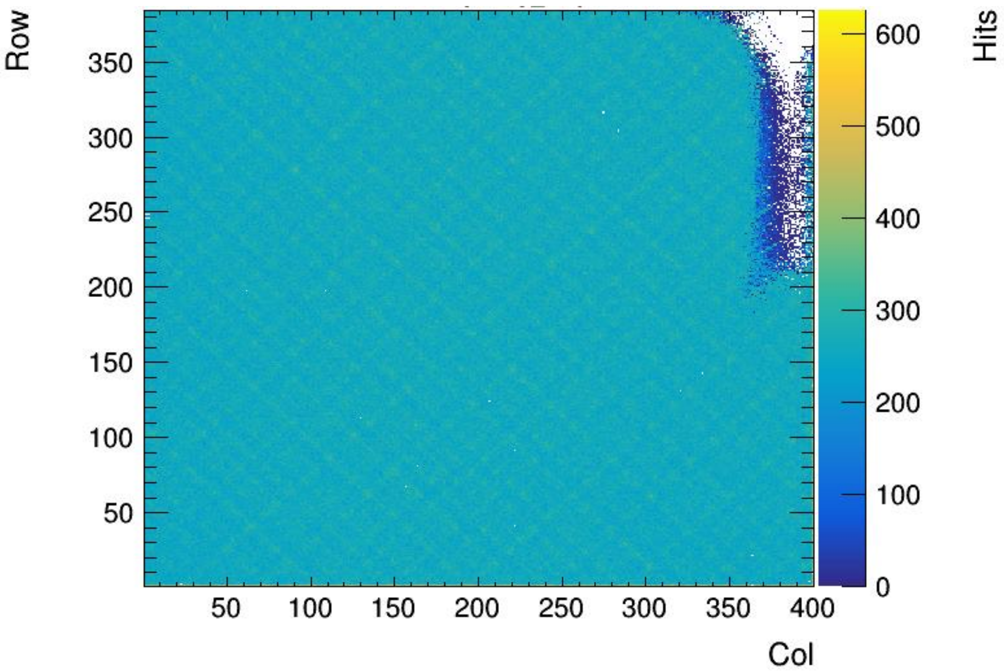


SCC 5:
About 1000
low
efficiency
pixels
(< 6000 hits)



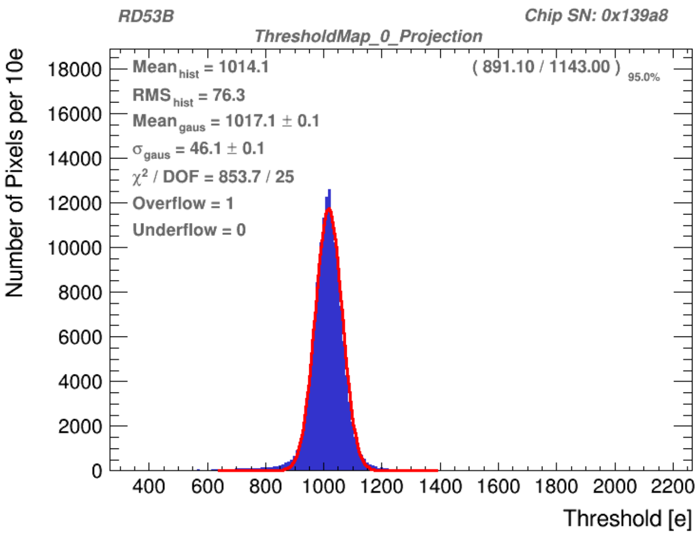
- Large bump disconnection area in the corner

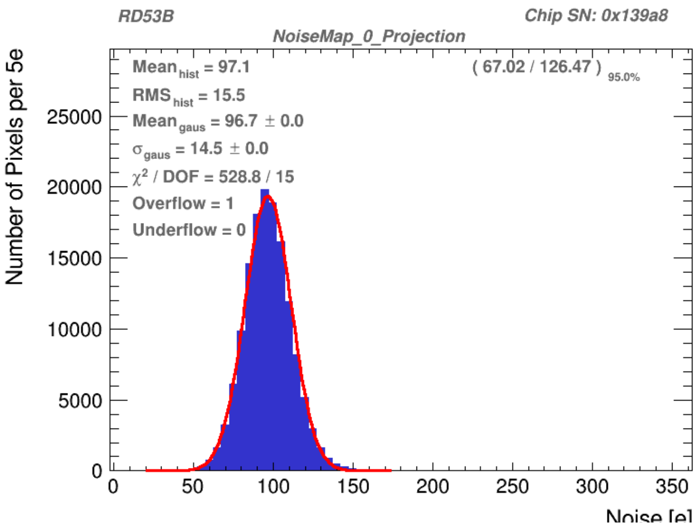
SCC 6: hit map



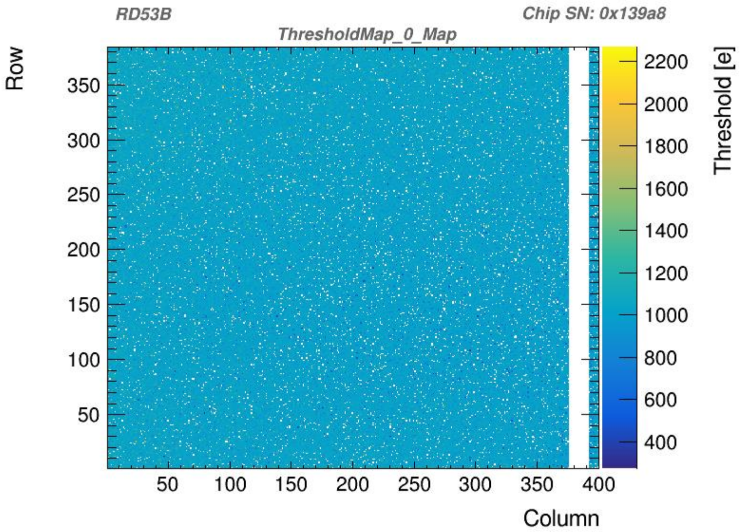
SCC 3: irradiated 1e16 (Bonn) + up to 0.9e16 (IRRAD)

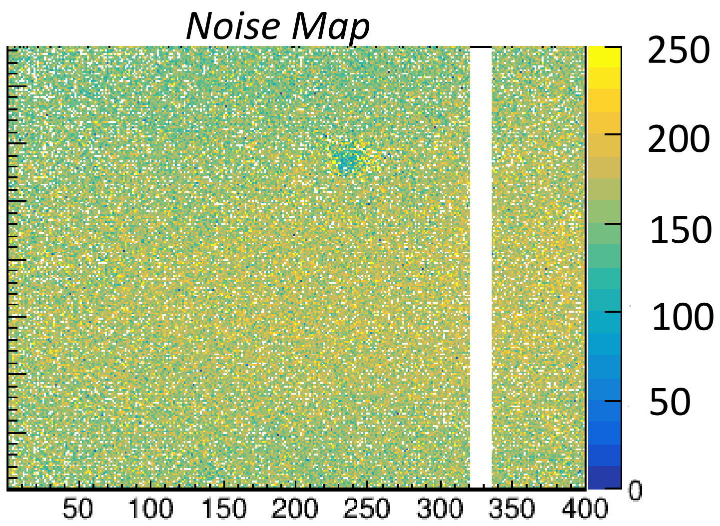
- 100 V bias → Threshold scan after tuning to 1000 e → 2 disabled core columns

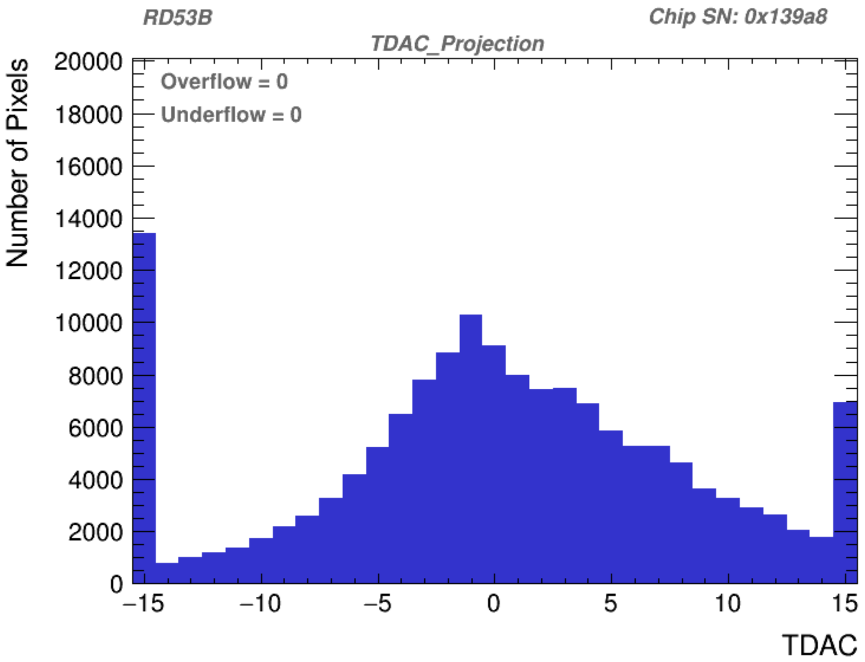




Visible irradiation profile --> to be fitted to improve the fluence map

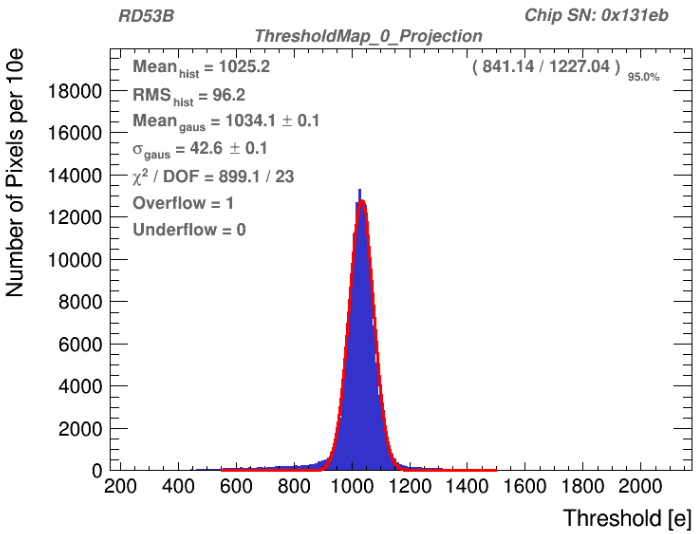


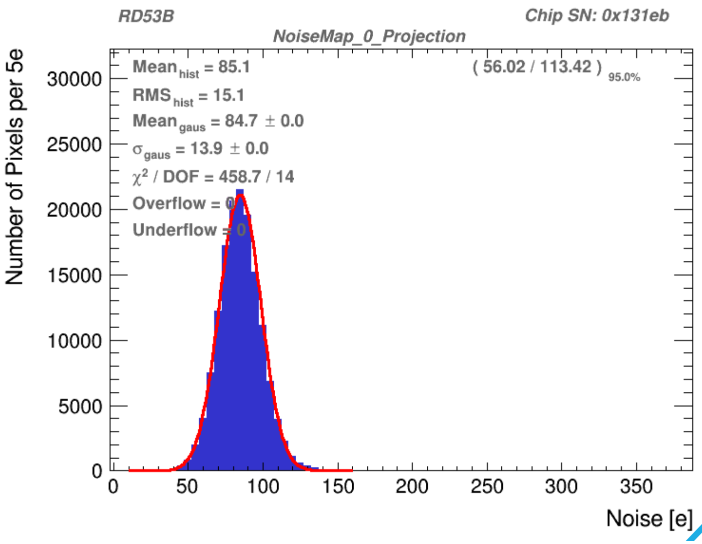




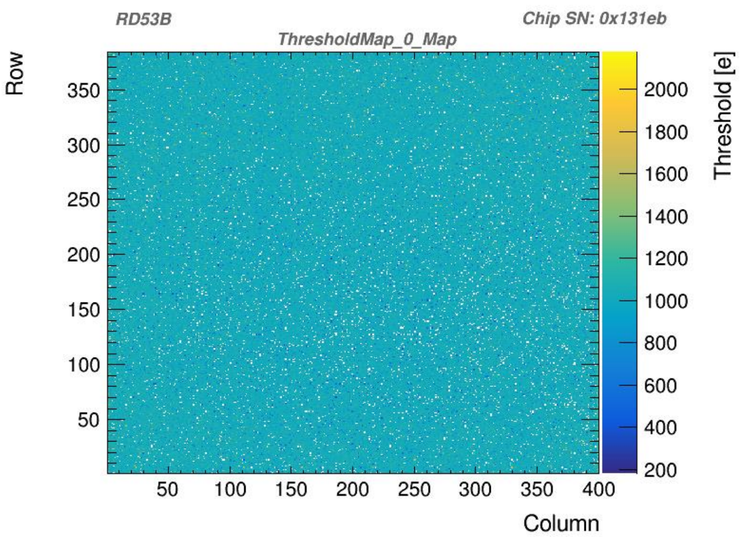
SCC 5: irradiated 1e16 (Bonn) + up to 0.9e16 (IRRAD)

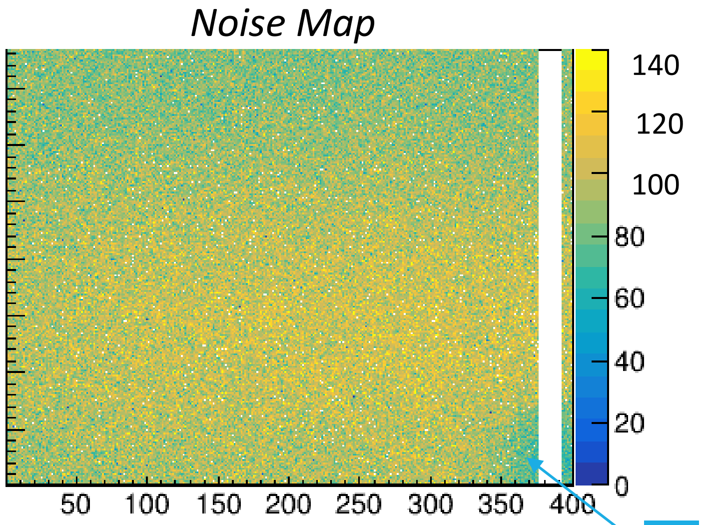
- 100 V bias → Threshold scan after tuning to 1000 e

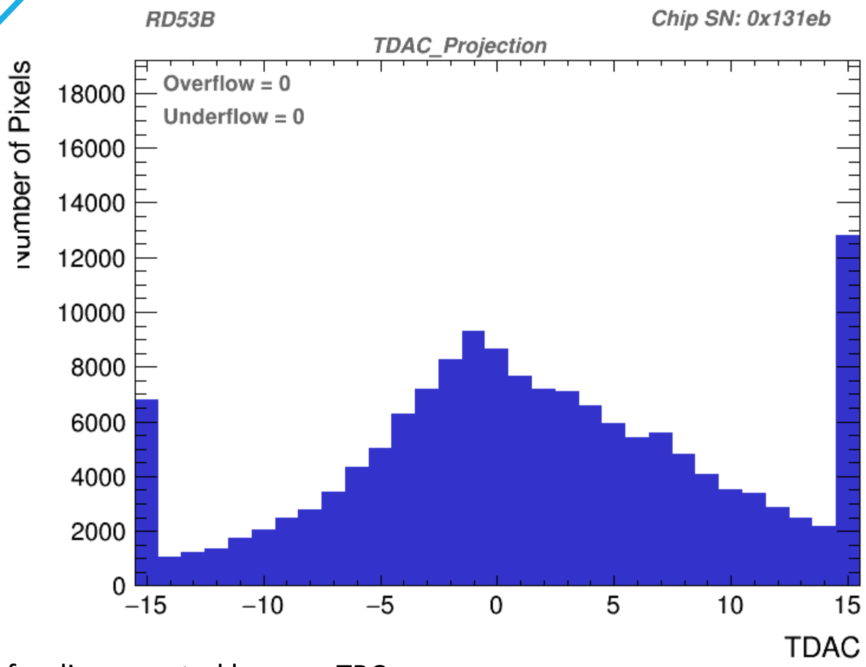




Visible irradiation profile --> to be fitted to improve the fluence map

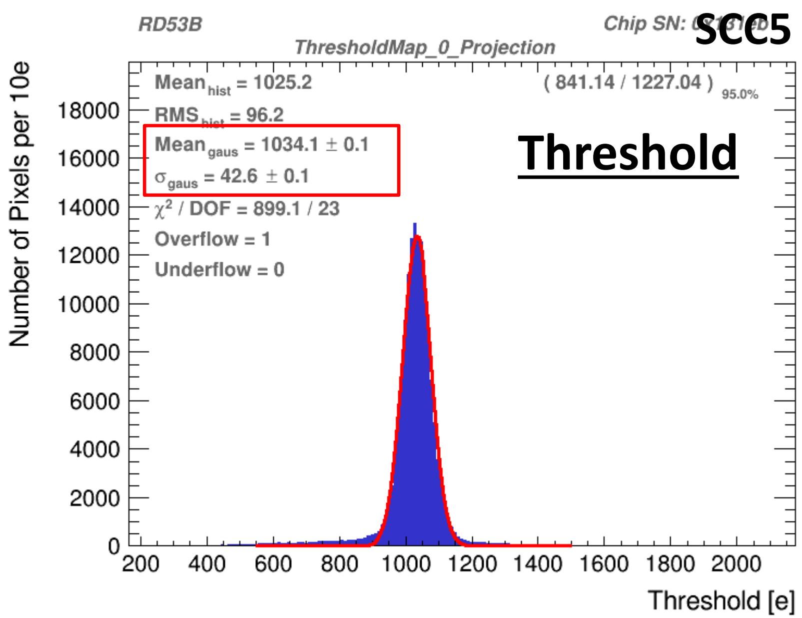


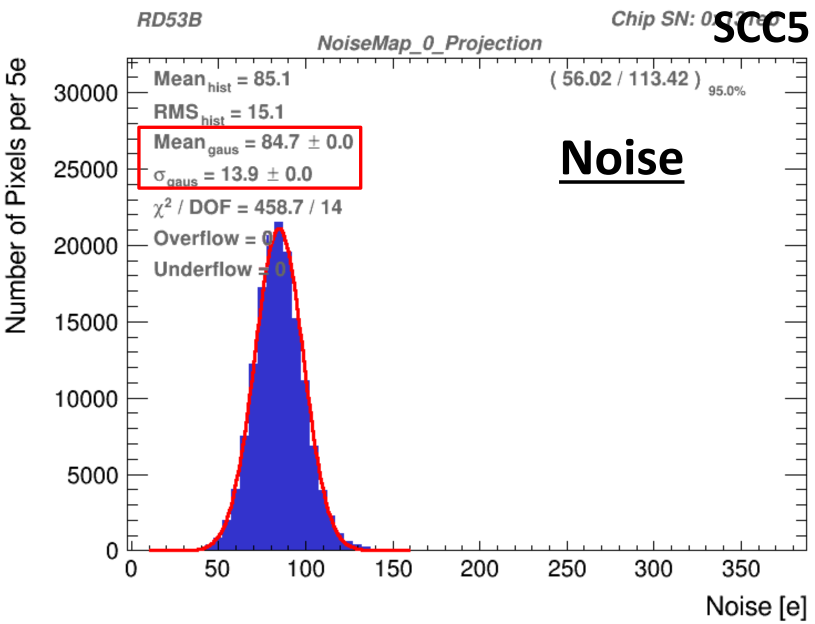


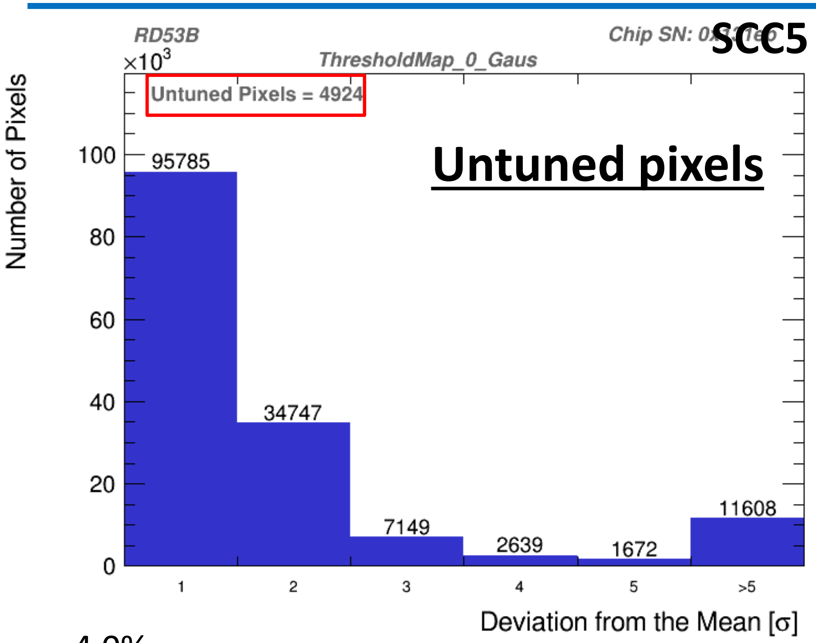


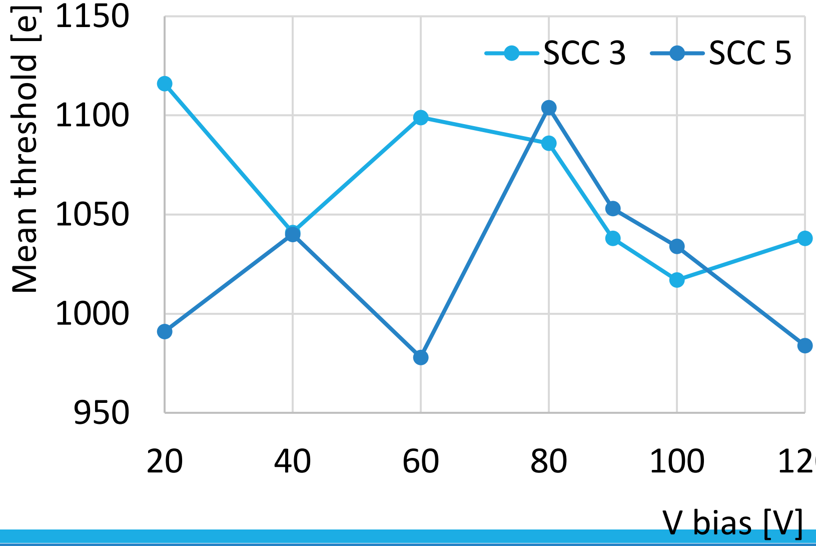
Hint for disconnected bumps- TBC

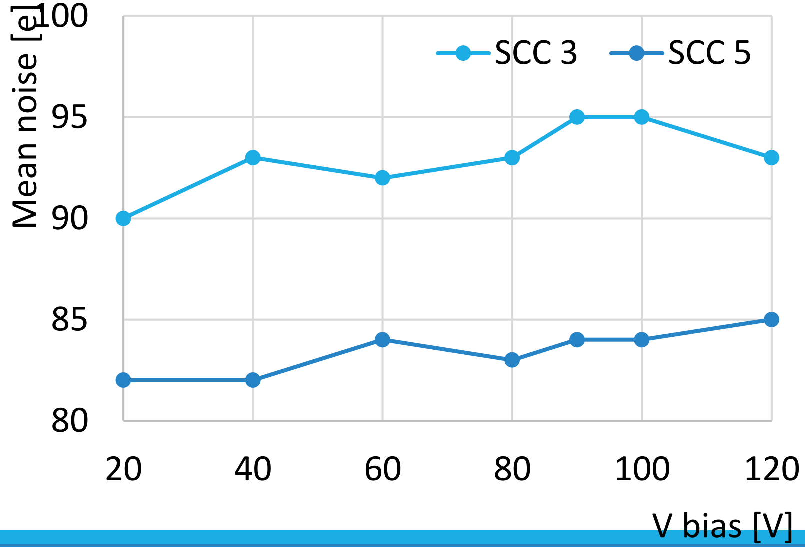
Tuning stability vs Vbias: thresh., noise, untuned pix.

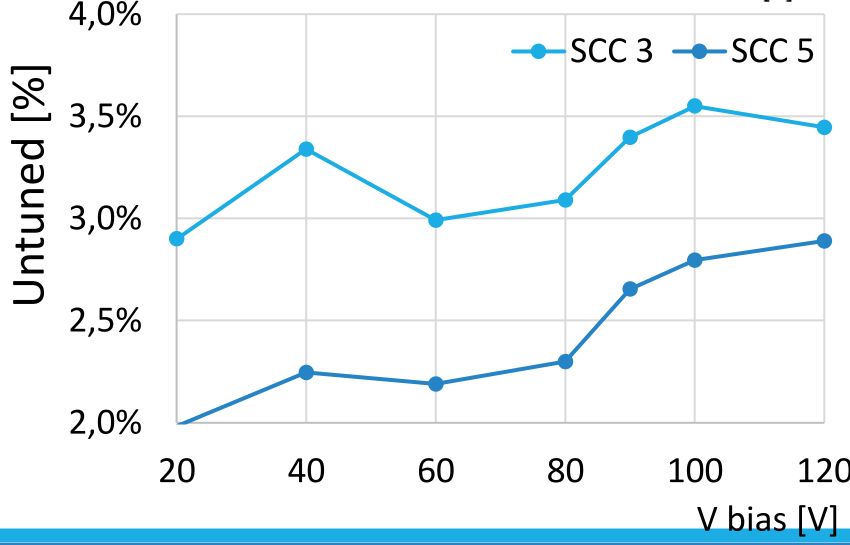






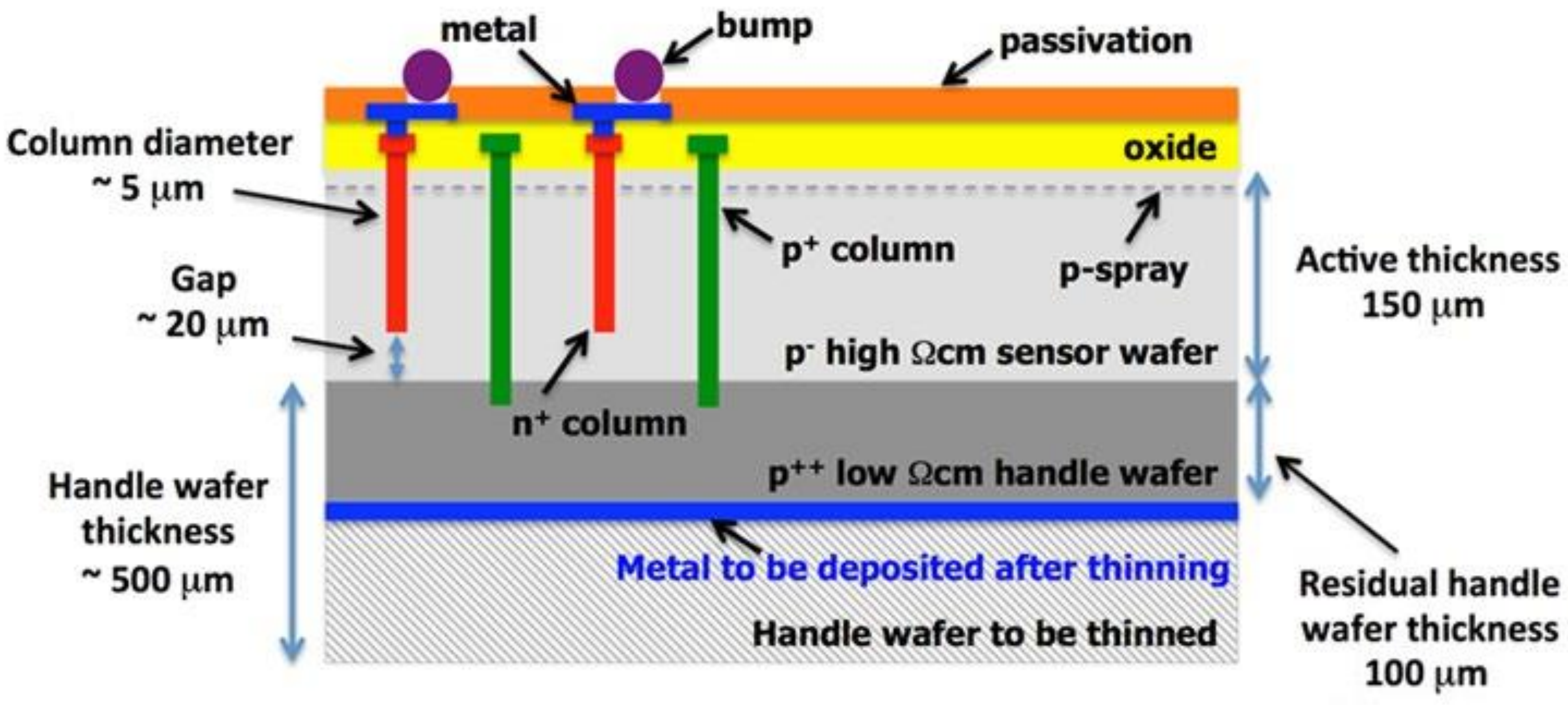




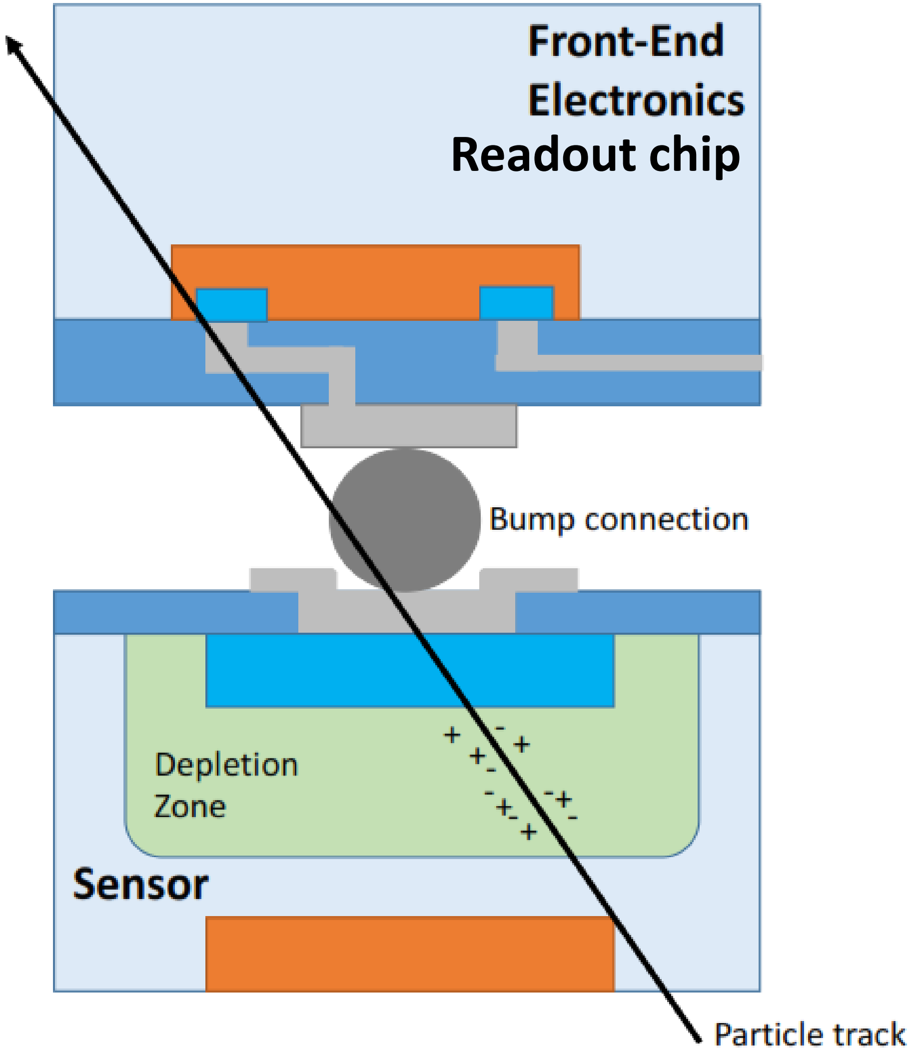


3D sensor detail – Bare module assembly

3D Sensor

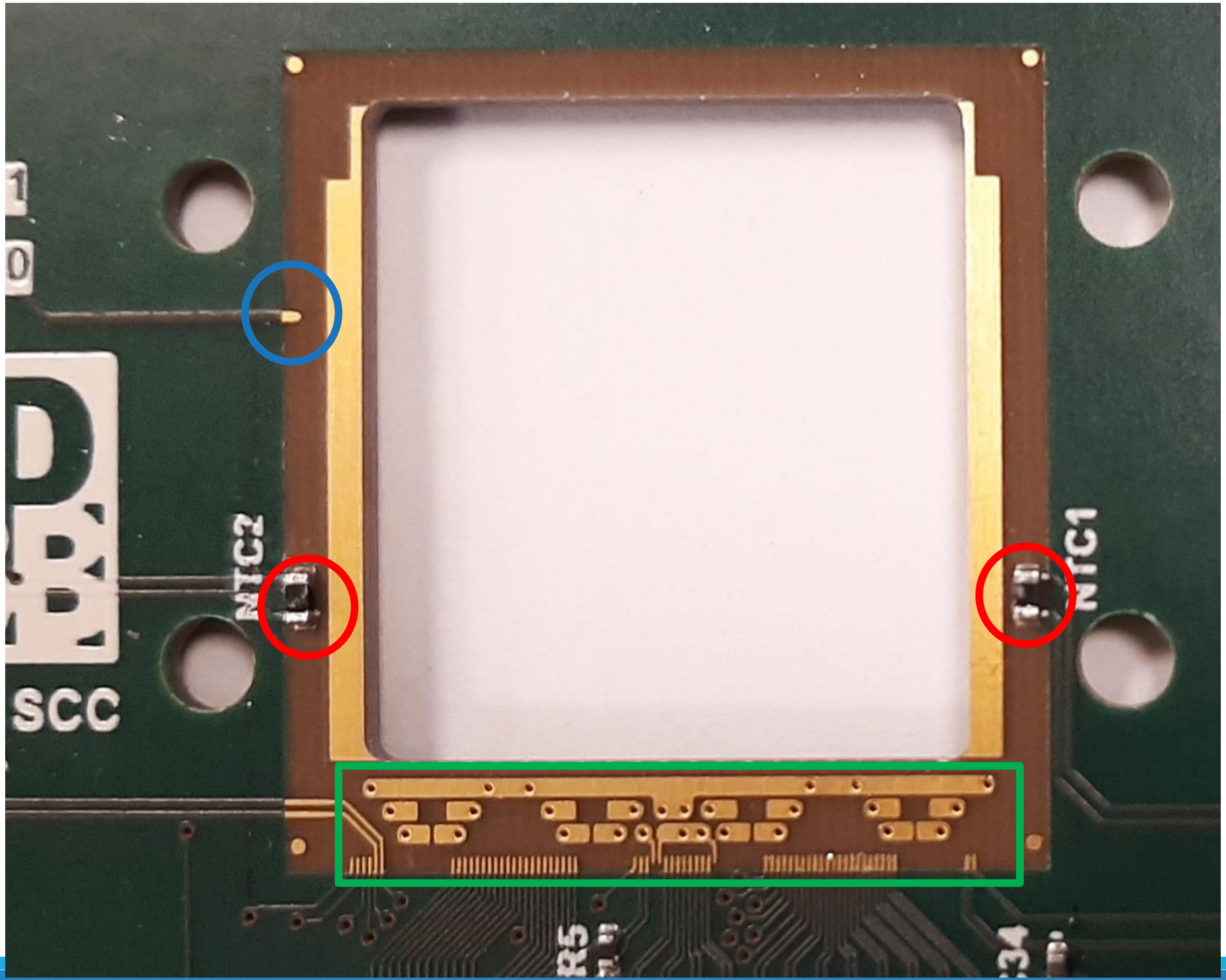


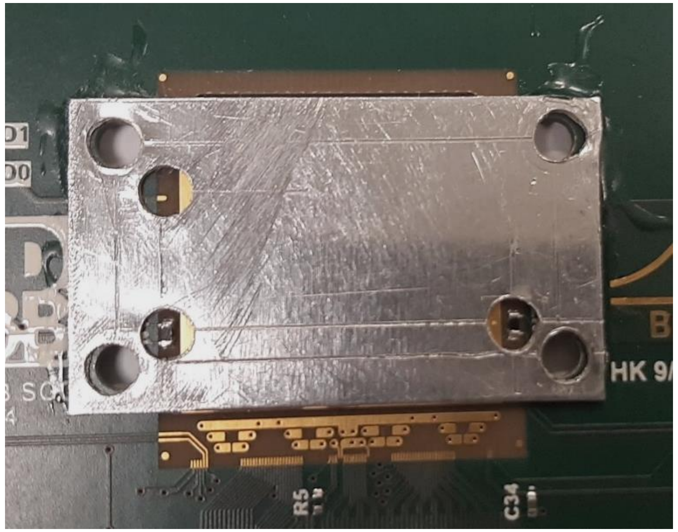
Bare module



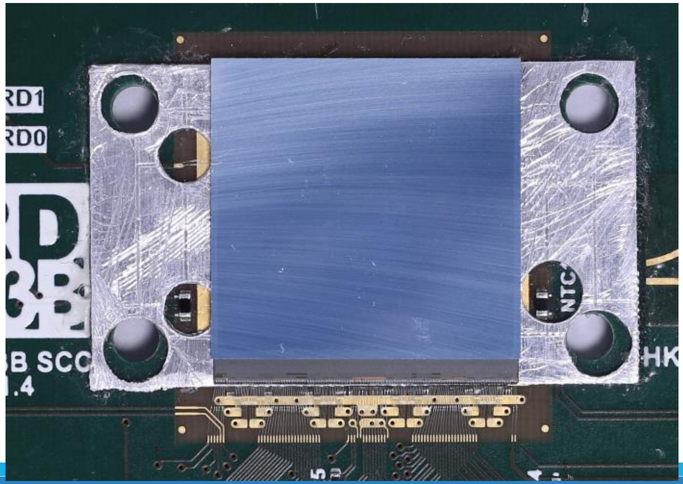
Preparation of the SCC for the assembly

- SCC have been prepared in Genova for irradiation → removed material behind bare module
- SCC v1.4: NTCs, HV bond pad, WB pads





- Thin (0.5 mm) Aluminum plate glued with Araldite 2011



- Bare module glued with Araldite 2011 and wirebonded