Novel pixel sensors for the Inner Tracker upgrade of the ATLAS experiment

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on behalf of the ATLAS ITk Collaboration

Institut de Física d'Altes Energies

Barcelona Institute of Science and Technology

Technology in Instrumentation & Particle Physics Conference

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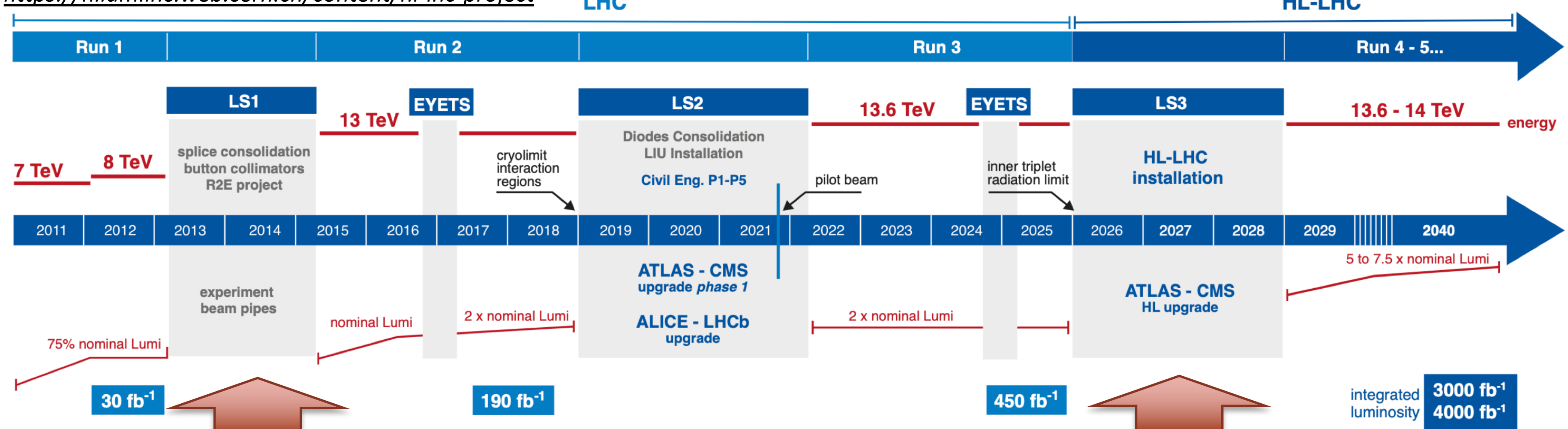
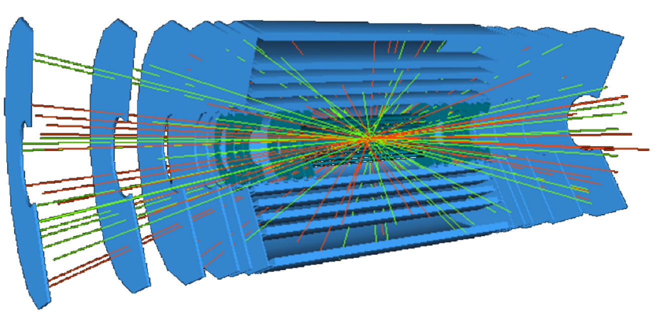
LHC upgrade

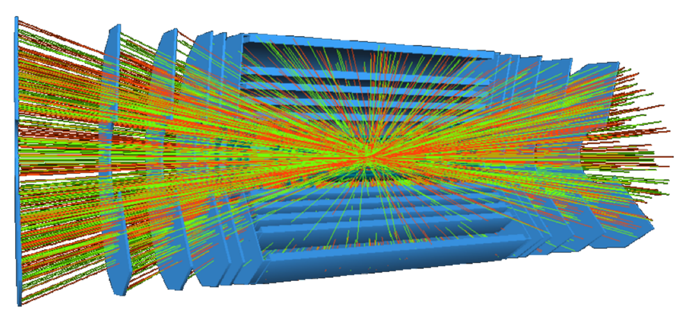
https://hilumilhc.web.cern.ch/content/hl-lhc-project



Inner Detector: TRT (gas detector) + Strips + Pixels (with new Insertable B-Layer, IBL)

Phase 2: all-silicon detector (Strips + Pixels)



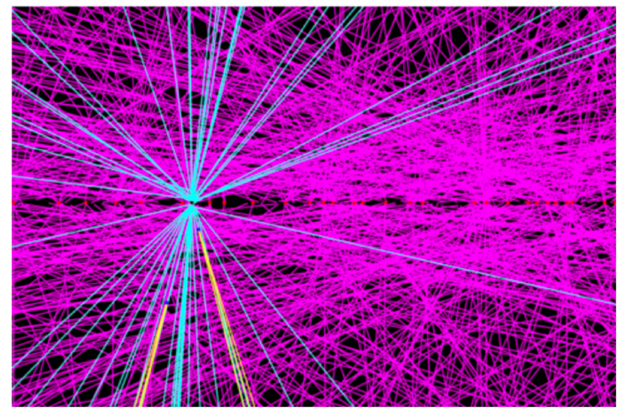


- **LHC**
  - 19 -> 55 Pile-up events
- **High Luminosity LHC (HL-LHC)**
  - 140-200 Pile-up events

Phase-2 challenges

- **Present Inner Detector pixel technology** will **not be able to cope** with the challenges of the HL-LHC

$t\bar{t}$ event @ 140 avg. pileup



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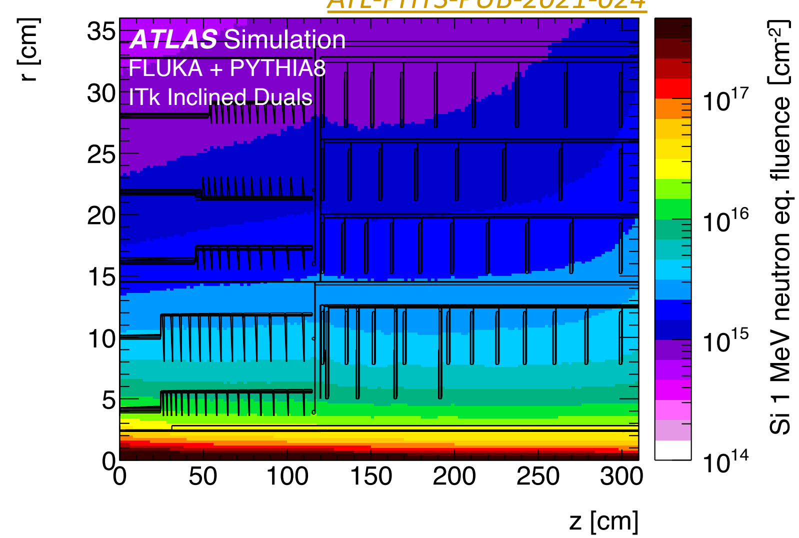

- **Particle multiplicity**
  - About 10 times more track density
    - Needs better tracking granularity
    - Bandwidth saturated

- **Radiation damage**
  - Radiation dose becomes critical closer to the beam line
    - Total Ionizing Dose (TID) up to 10 MGy
    - Particle fluence up to 2 x 10^{16} $n_{eq}cm^{-2}$ in the pixel region

A new Inner Tracker (ITk) is necessary!

The ITk pixel detector

- New layout with ***5 pixel barrel layers*** & large η coverage

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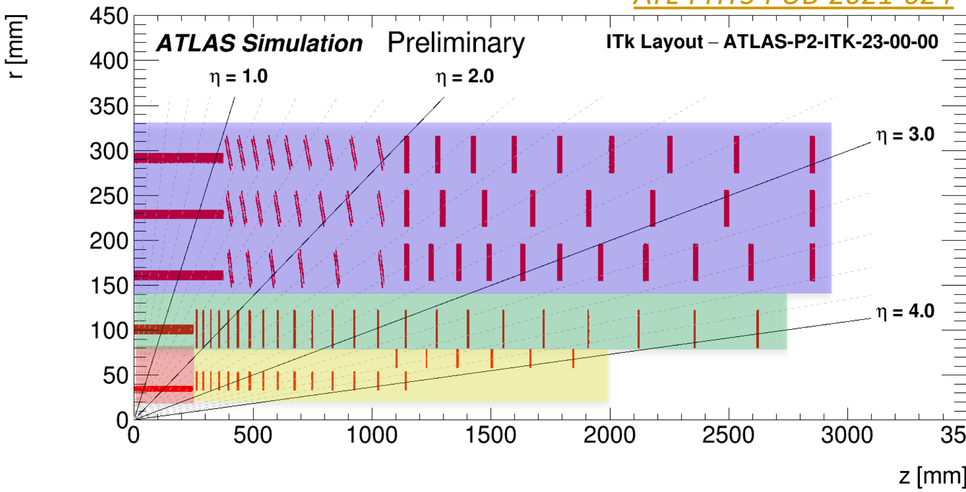
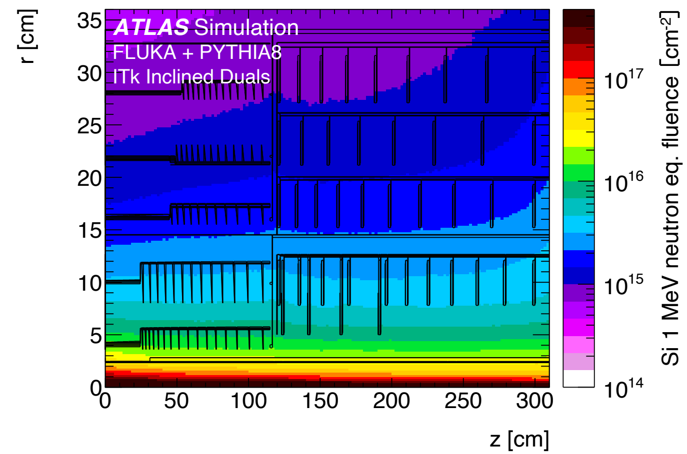
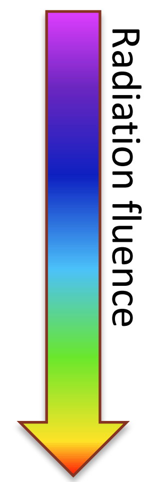


Extended tracking coverage at large eta



- **Sensor technologies:**
  - **Outer pixel layers** (3 layers)
    - n-in-p planar silicon sensors (150 μm thick)
  - **Inner pixel layers** (2 replaceable layers)
    - Thin n-in-p planar silicon sensors (100 μm thick)
    - 3D silicon sensors
      - Endcap Rings: 25x100 μm^2
      - Barrel: 50x50 μm^2

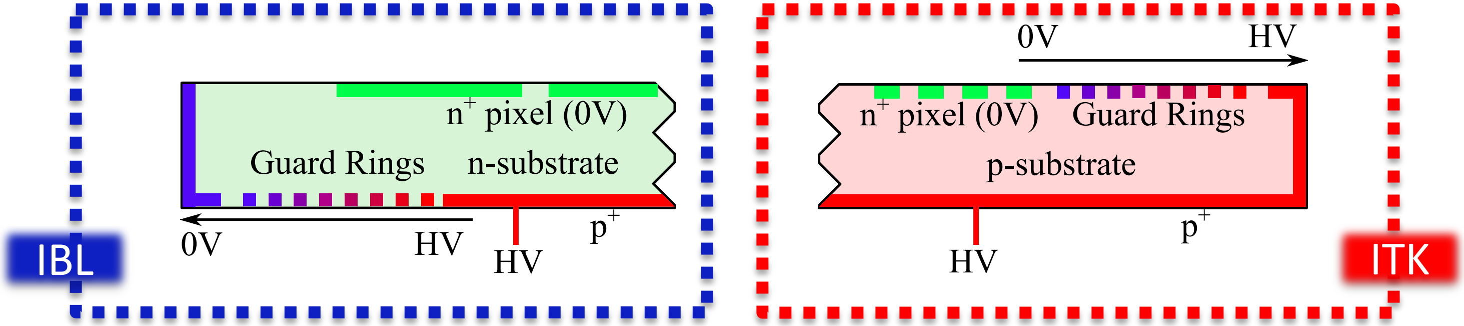


1e15 n_{eq}/cm^2

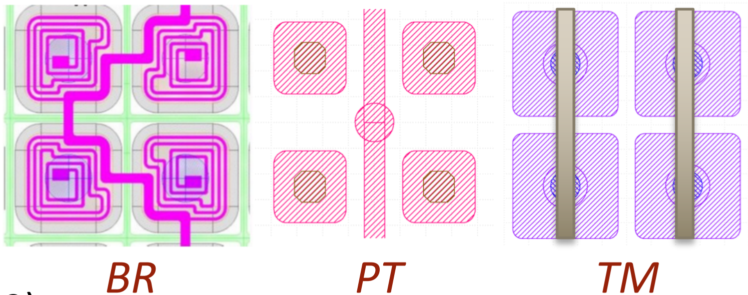
~2x16 n_{eq}/cm^2

Planar sensors in ITk

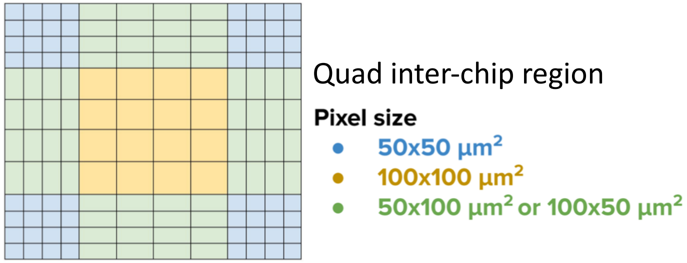
- **Thin n-in-p planar sensors**
  - **IBL** is presently using 200 µm thick n-in-n planar sensors with 50x250 µm^2 pixel cells
  - **ITk** will use 150 (100) µm thick n-in-p technology (single-side process) with 50x50 µm^2 pixel cells

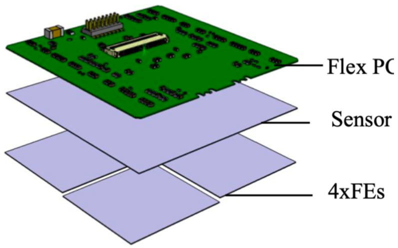


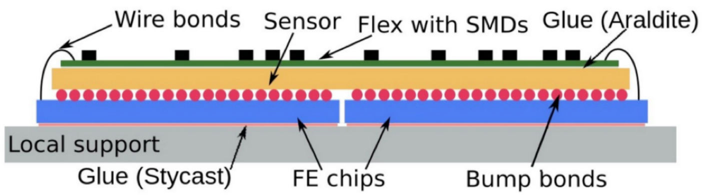
- **Different testing solution employed**
  - Punch Through (**PT**)
  - Bias rail and Bias Resistor (**BR**)
  - Temporary Metal (**TM**)



- **Quad modules**
  - 4 chips connected to 1 large sensor (4x4 cm2)
  - Inter-pixel region covered with larger pixels

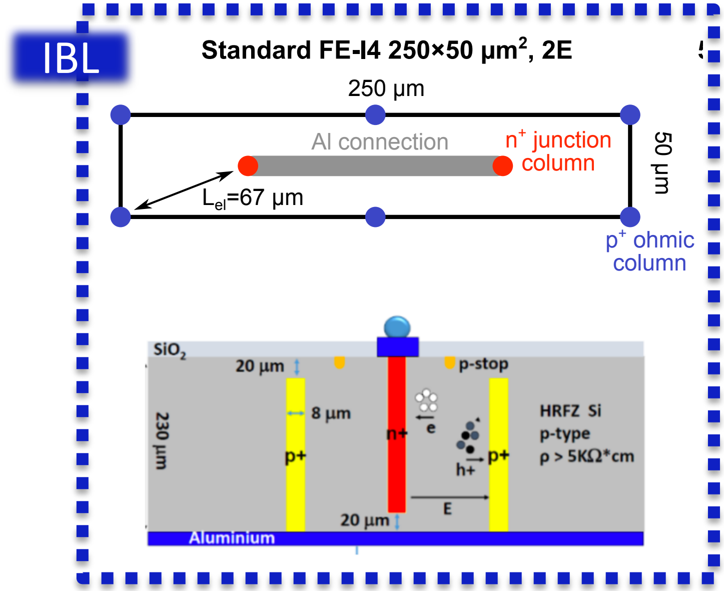


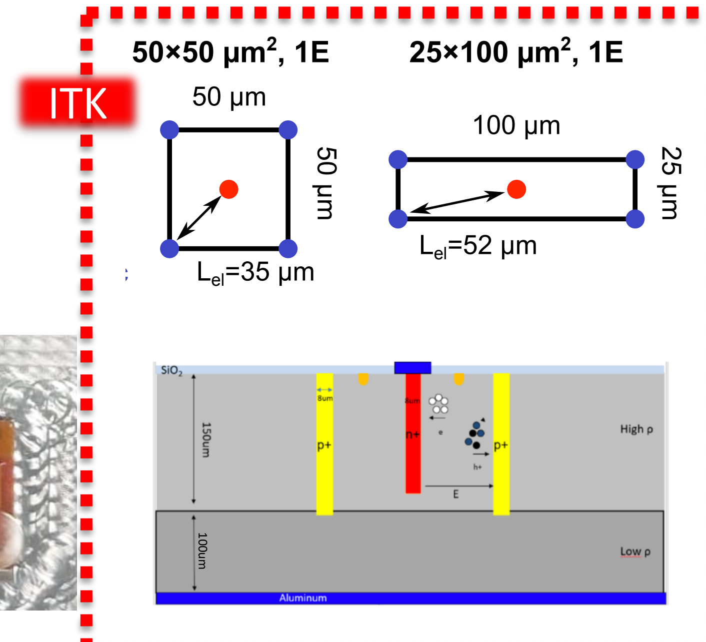


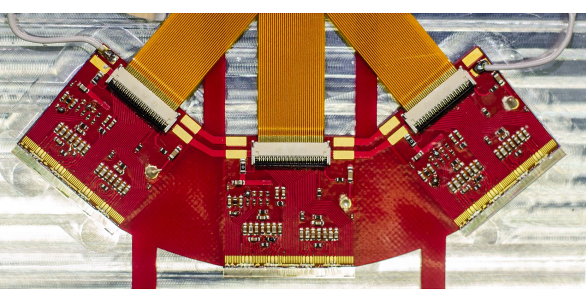


3D sensors in ITk

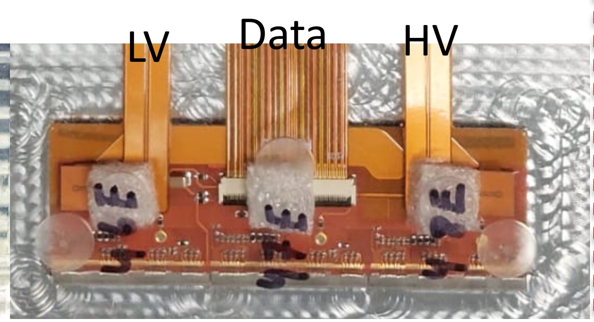
- **New single-side technology**
  - Conductive support wafer (Si-Si)
  - Both electrodes etched from the same side
- **Thin active substrates (150 µm)**
  - Reduce cluster size and data rates
- **Small pixels (high occupancy + resolution)**
  - Rings: 50x50 µm^2
  - Flat barrel: 25x100 µm^2
    - For improved impact parameter resolution
- **Triplet modules**
  - Three single-chip bare modules (sensor + chip) connected to the same flex PCB
    - Common voltages
    - A single pigtail for data transmission







Ring design (prototype)



Barrel design (final)

Sensor pre-production evaluation

Sensor producers

- Micron
- HAMAMATSU (HPK)
- FBK – Fondazione Bruno Kessler
- SINTEF
- CNM – Centro Nacional de Microelectrónica, IMB

Quality Control (QC):

- IV on all sensors
- IV and CV on a sub-sample of diodes

CERN

Hybridization

- ADVACAM – Imaging the Unseen
- Fraunhofer IZM
- LEONARDO

(Thinning) + Dicing

A few sensors are spare from flip-chipping and sent to ITk institutes for QA evaluation

ITk institutes

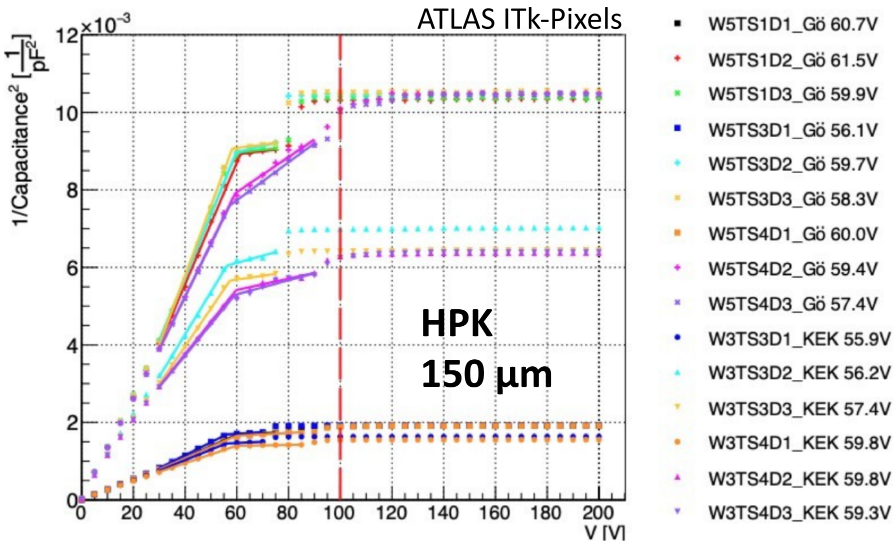
- IJCLab – Irène Joliot-Curie, Laboratoire de Physique des 2 Infinis
- Georg-August-Universität Göttingen
- IFAE
- Universitas Bergensis
- UiO – University of Oslo
- LPNHE Paris
- technische universität dortmund
- KEK
- Università di Trento
- TIFPA – Trento Institute for Fundamental Physics and Applications
- Lancaster University
- Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

Quality Assurance (QA):

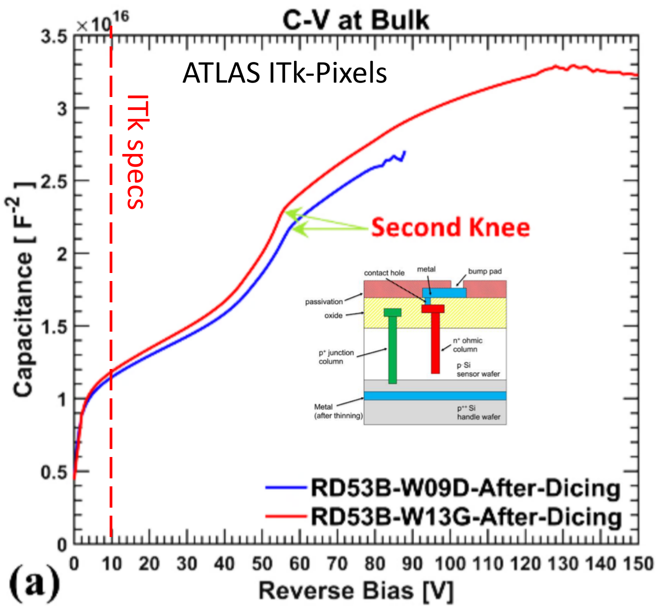
- Electrical tests and Irradiations of bare-sensors and test structures (diodes, strips, …)

Depletion voltage

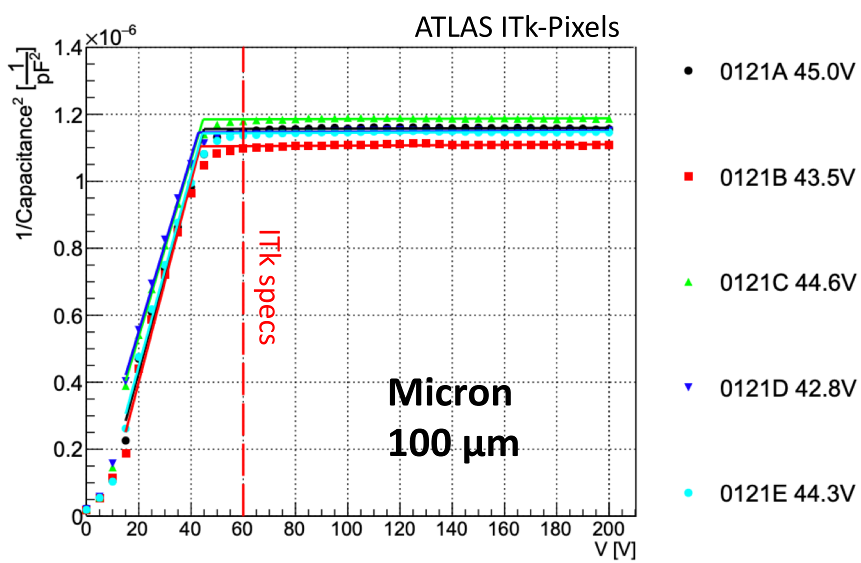
HPK diodes (un-irradiated)



- **Depletion voltage:**
  - Extracted from Capacitance vs Voltage curves on a sub-sample of diodes out of each wafer
- **Typical pre-production values**
  - Planar sensors 150 µm thick: ~60 V
  - Planar sensors 100 µm thick: 40-50V
  - 3D sensors: < 5V



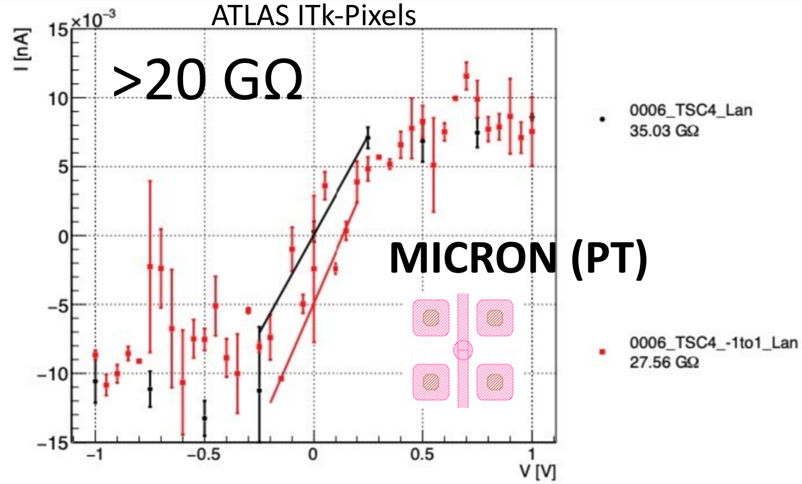
FBK 3D sensors
50x50 µm²

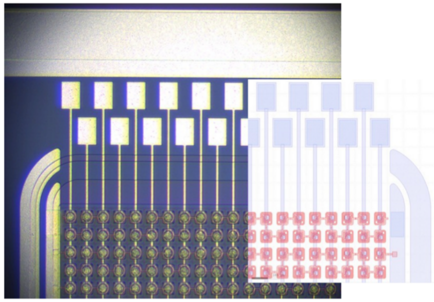


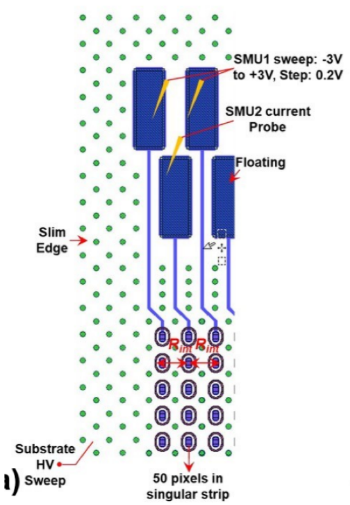
Inter-pixel resistance

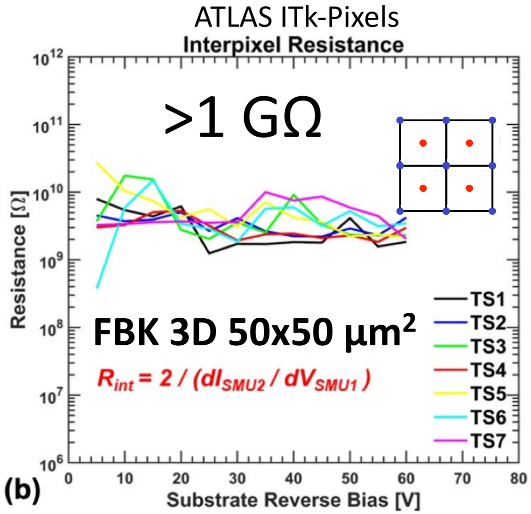
- **Inter-pixel resistance measured with special "strip" test structures**
  - Same pixel structures as in the main sensors but shorted together in strips
  - The inter-pixel resistance is obtained by scaling the result by the number of pixels in one strip

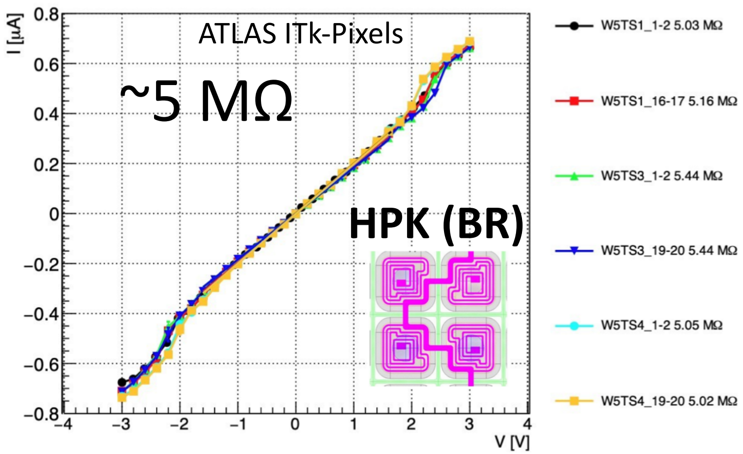
- **Results for different sensor types:**
  - **3D** sensors and **Planar** sensors with **PT** structures must have R_{int} > 1 GΩ
  - Planar sensors with **BR** must have R_{int} > 1 MΩ











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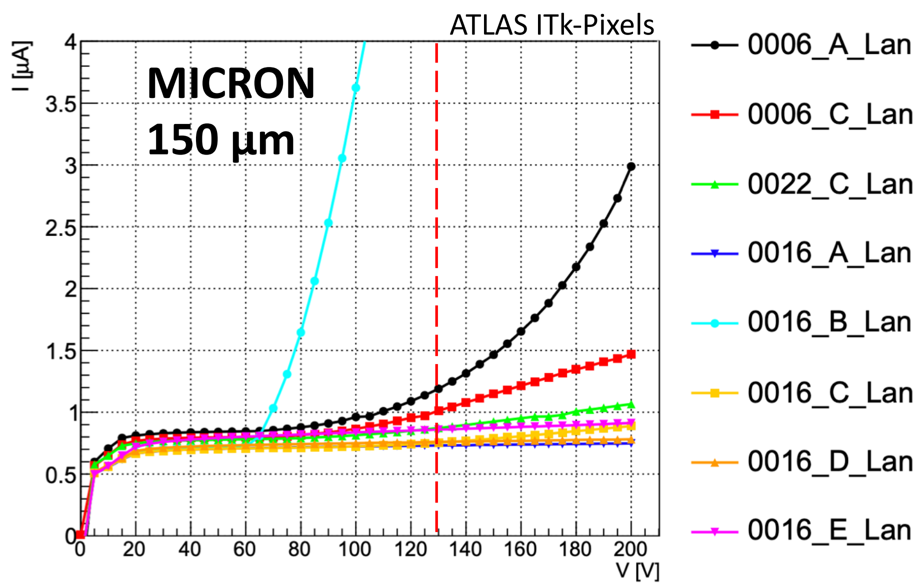
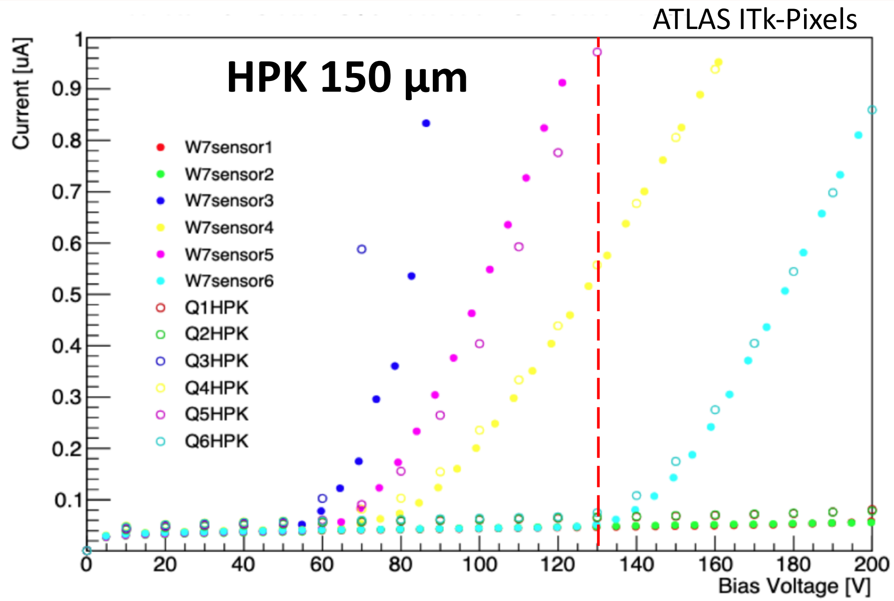
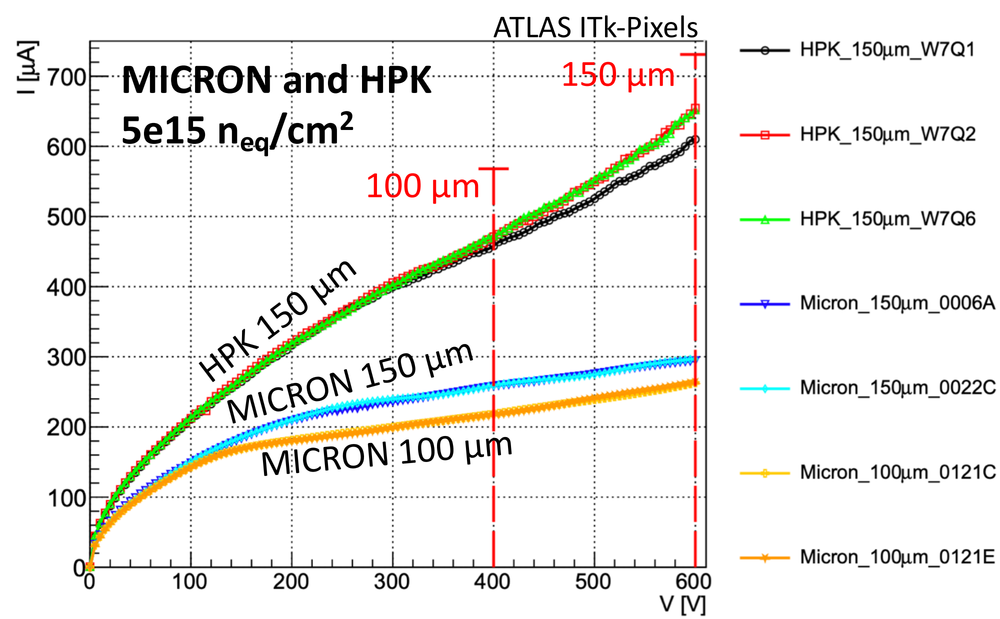
Leakage current: Planars 150 µm





- **Before irradiation:**
  - Good sensors need to have a breakdown >130V
  - Most of the sensors have a larger breakdown >200V
  - Results mostly in agreement with vendor measurements on wafer



- **After irradiation with protons up to 5e15 n_{eq}/cm^2**
  - No breakdown observed up to 600V
  - Leakage current within specifications

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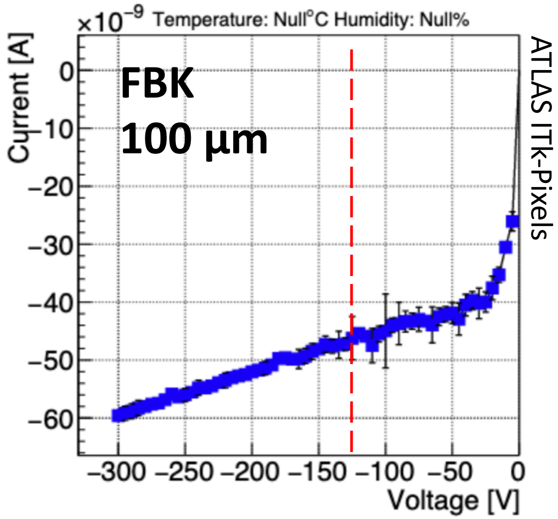
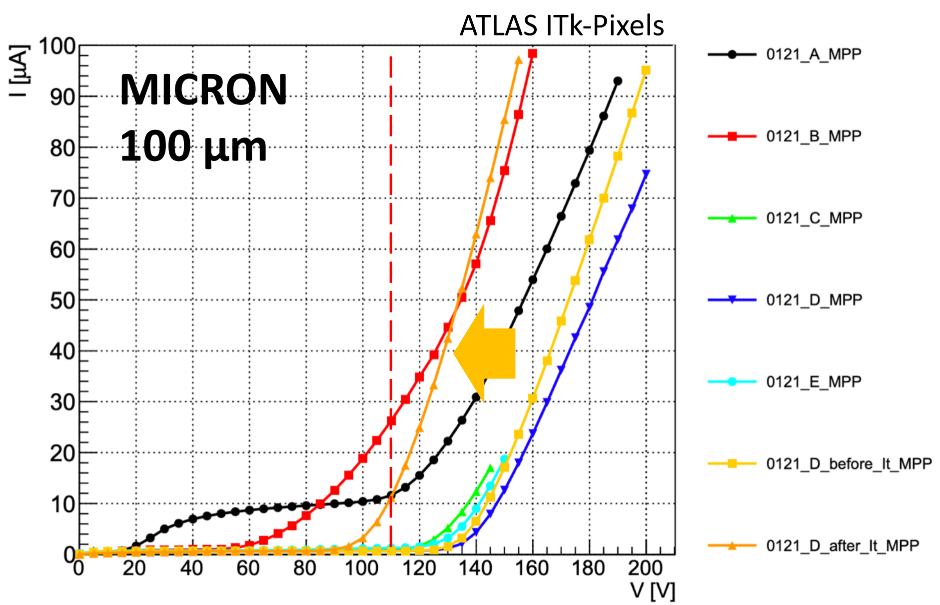
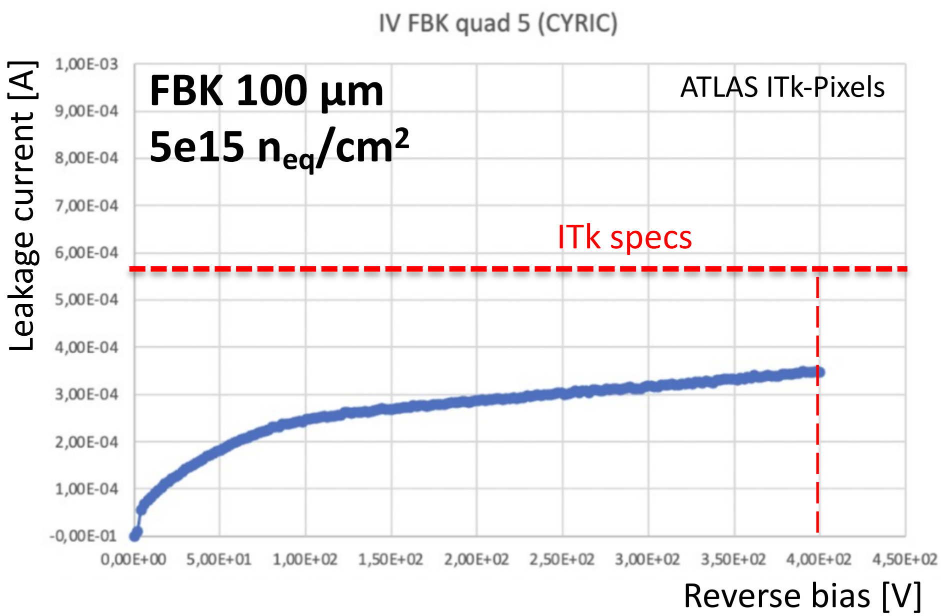
Leakage current: Planars 100 µm





- **Before irradiation**
  - Good sensors need to have a breakdown >110-120V
  - Degradation of the breakdown has been observed on MICRON sensors after leakage current stability test (It)

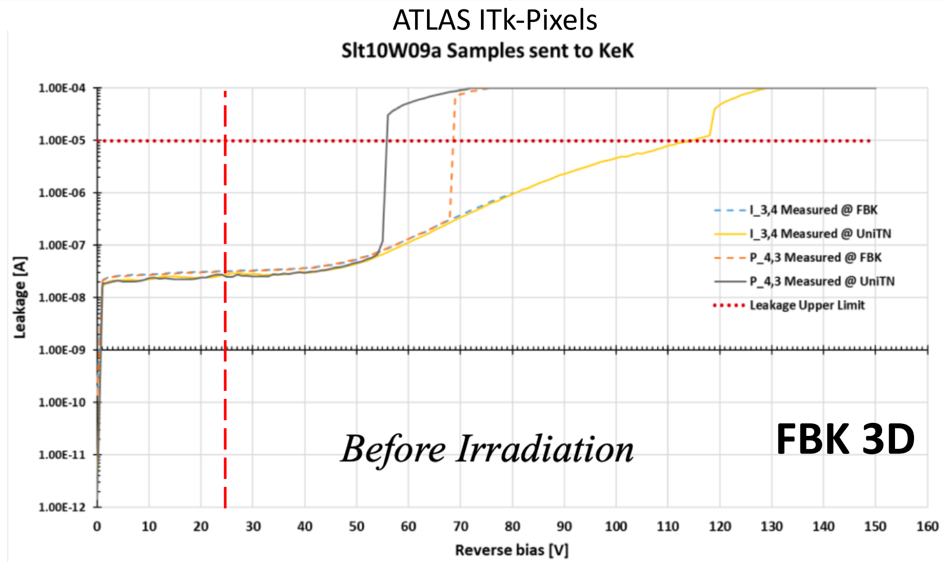


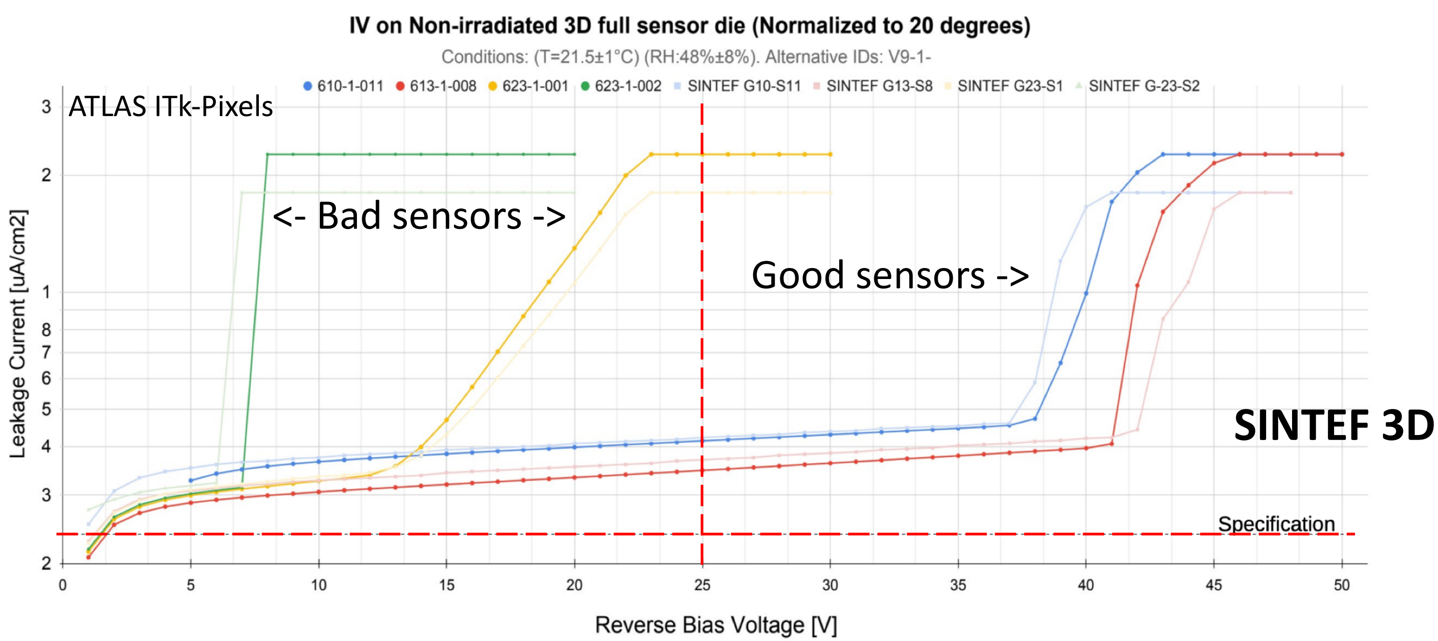
- **After irradiation with protons up to 5e15 n_{eq}/cm^2**
  - No breakdown observed up to 600V
  - Leakage current within specifications

Leakage current: 3D before irradiation

- **Leakage current measured as a function of the reverse bias voltage (IV) for FBK sensors is within specs:**
  - Breakdown > 25V
  - Leakage current < 2.5 µA/cm^2

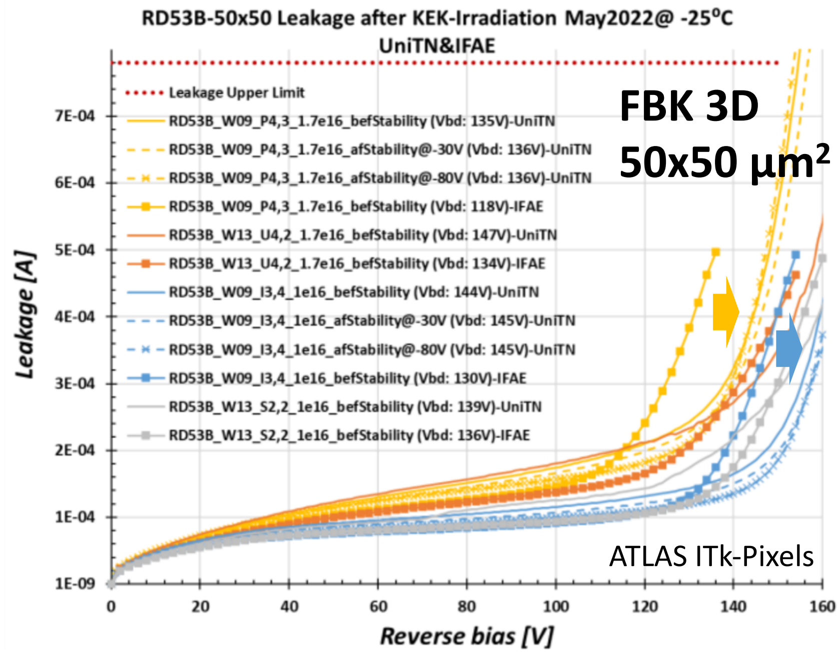
- **Leakage current of SINTEF sensors is higher than in the ITk specs (<2.5 µA/cm^2)**
  - Nevertheless, yield based on breakdown is excellent
  - Considering to relax leakage current specs

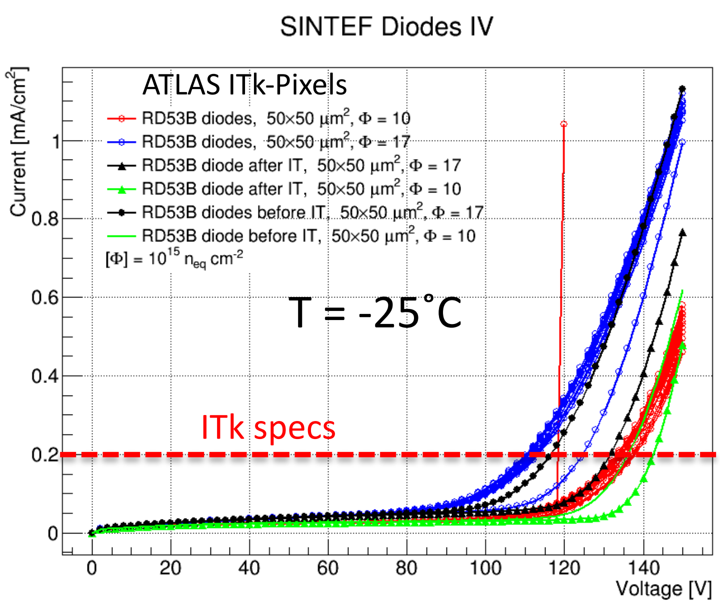


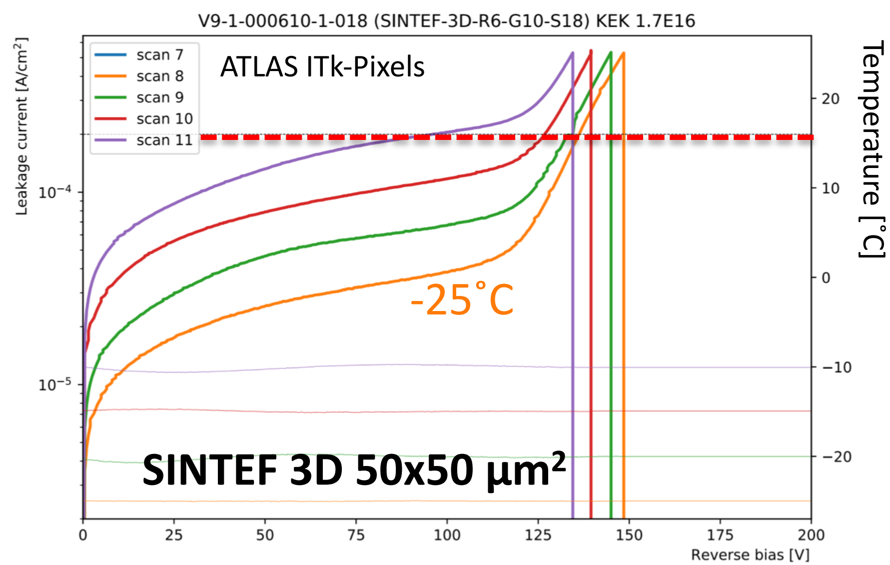


Leakage current: 3D after irradiation

- **3D diodes and bare sensors with TM irradiated to 1e16 and 1.7e16 n_{eq}/cm^2**
  - SINTEF and FBK sensors irradiated with protons in CYRIC
  - Soft breakdown >100 V
  - Breakdown shifts towards higher voltage after annealing and/or stability tests (IT - 48h under bias)

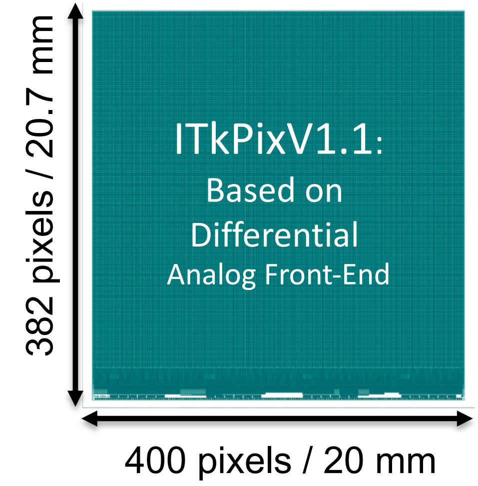






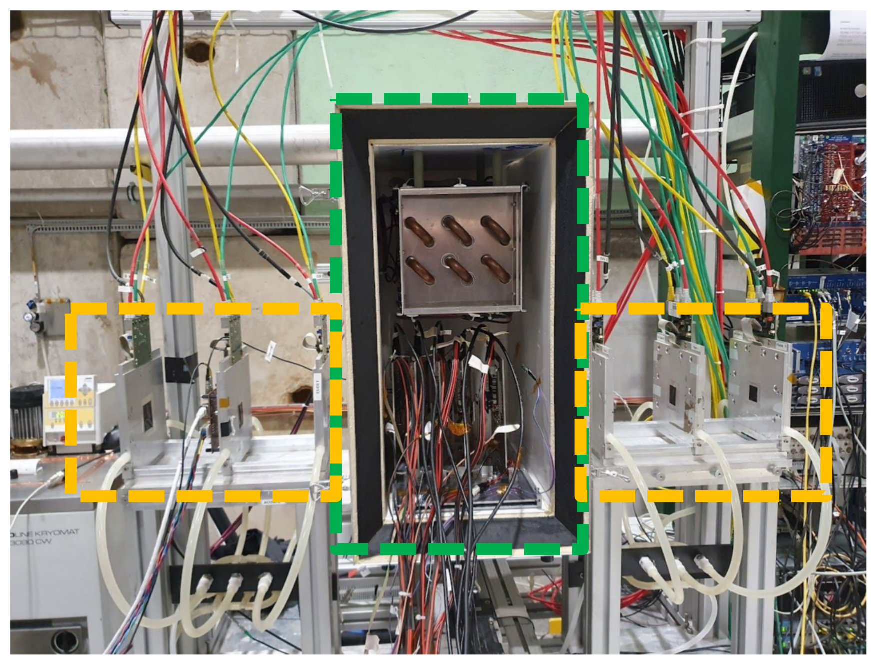
Modules and test beam

- **First modules assembled with full size chips ITkPixV1.1**
  - 3D single-chip bare-modules assembled on testing PCBs



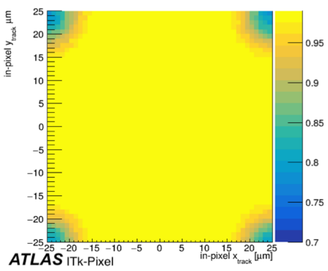
- **Irradiations**
  - FBK 3D single chip modules irradiated with protons in two steps:
    - At Bonn to 1e16 n_{eq}/cm^2 (uniform)
    - At CERN PS for a total fluence up to 1.9e16 n_{eq}/cm^2 (+0.5 average, non-uniform)

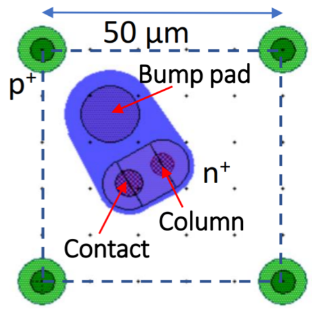
- **Several test beam campaigns at CERN SPS (~120 GeV pion beam)**
  - EUDET telescope:
    - 6 MIMOSA26 tracking planes
    - Up to 2 µm pointing resolution
  - MPP cooling box:
    - Chiller based: down to -50˚C
    - Dry environment: Nitrogen flushing

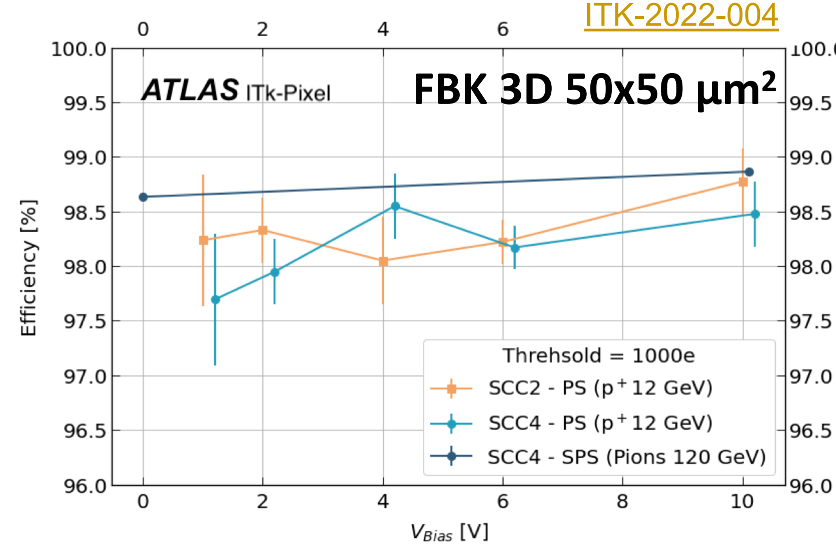


Test beam results: 3D sensors

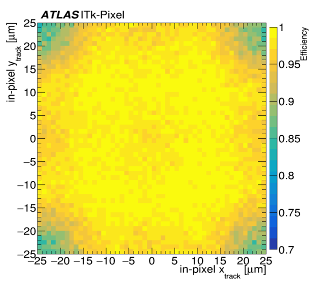
- **Before irradiation**
  - >97% hit efficiency with just a few volts
  - Inefficiency localised in the fully passing p-columns

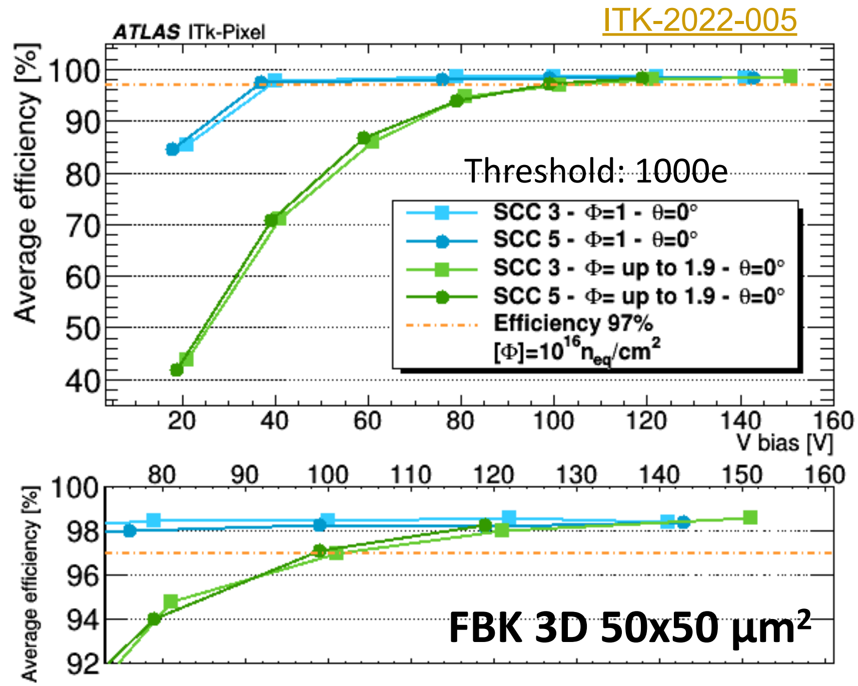






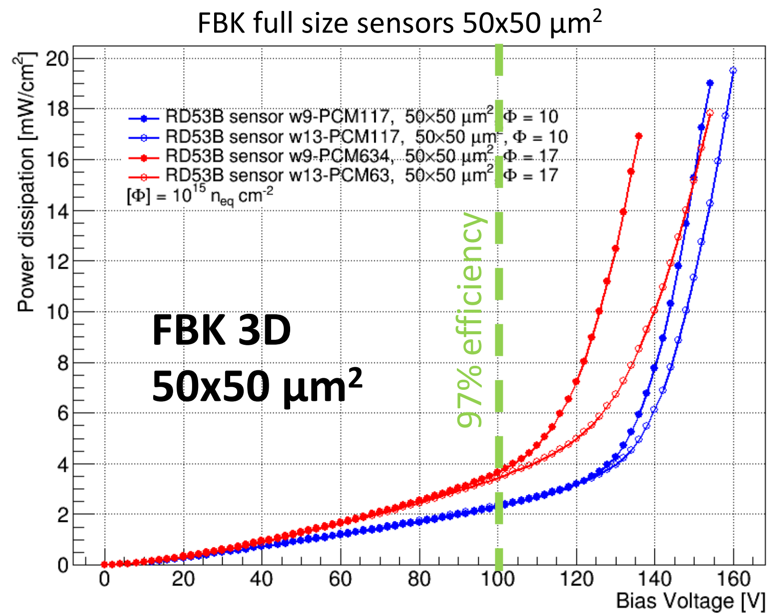
- **After irradiation**
  - **Fluence 1e16 n_{eq}/cm^2**
    - >97% hit efficiency with just 40 V
  - **Fluence ~2e16 n_{eq}/cm^2**
    - ~97% hit efficiency with just 100 V

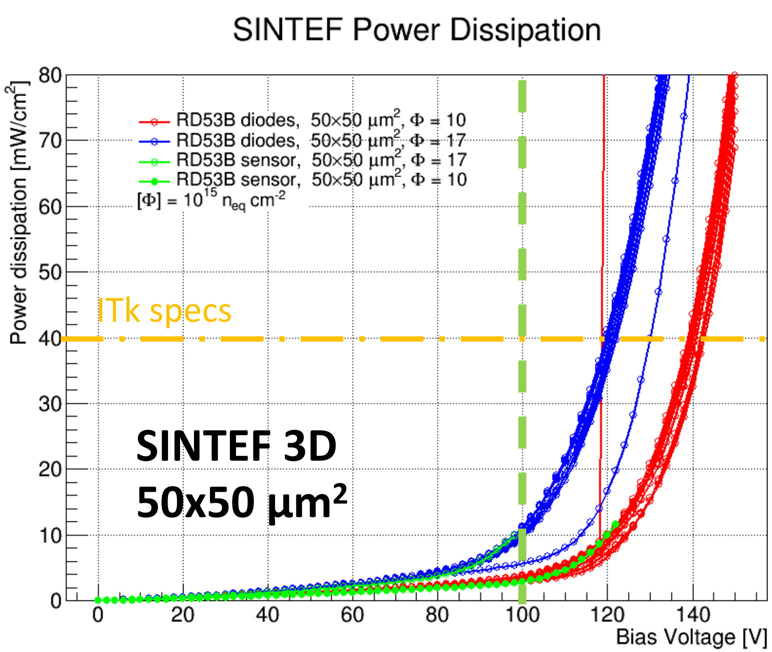


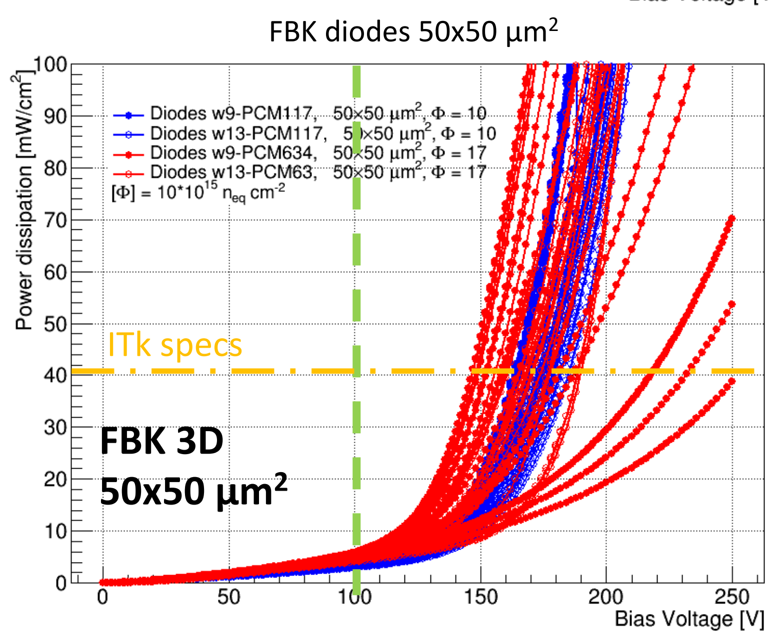


Power dissipation: 3D sensors

- **Power dissipation is critical especially for the innermost pixel layer**
  - At the operational voltage (i.e. efficiency >96-97%) the sensor power must be less than 40 mW/cm^2
  - Sensors and diodes can be operated within these limits after irradiation up to 1.7e16 n_{eq}/cm^2
  - The power dissipation at the operational voltage can be kept below 10 mW/cm^2 at -25˚C







Summary

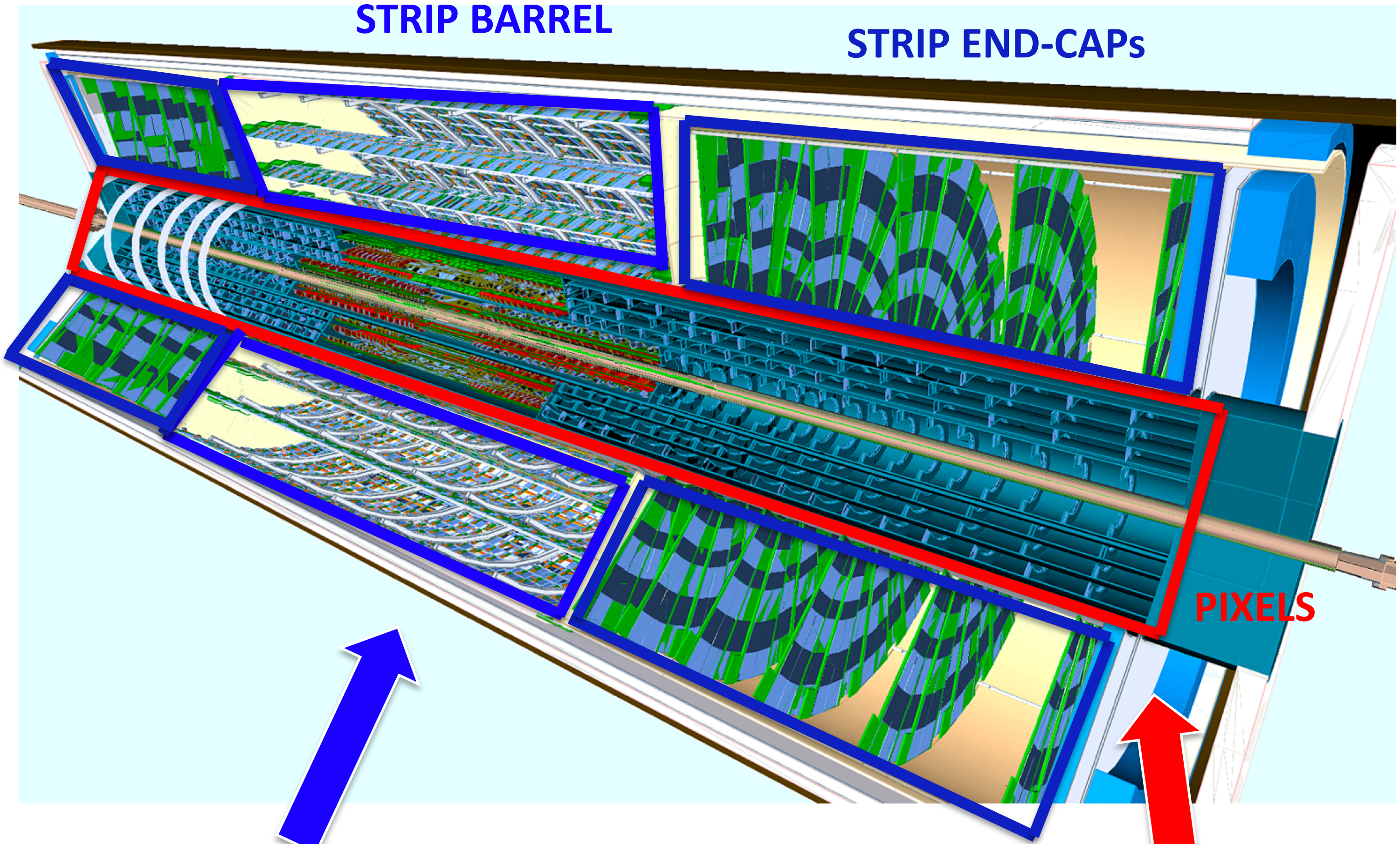
- **Pre-production of pixel sensors for ATLAS ITk is completed**
  - First evaluation of the sensors has been performed by the ITk institutes
    - 3 sensor types (FBK 3D 50x50 μm^2, FBK Planar 100 µm and HPK Planar 150 µm) have been successfully evaluated
    - The evaluation of the sensors from the remaining vendors will be completed soon

- **Evaluation of modules with the full-size chip (ITkPixV1.1)**
  - Modules with 3D single-chip- and planar quad sensors are being measured in test beam experiments
    - First measurements on 3D modules reveal excellent results, even after irradiation to ultimate particle fluence expected at the HL-LHC
    - Planar quad modules and 25x100 μm^2 3D modules have been measured in more recent testbeams (One more testbeam campaign planned at CERN for this year)

- **Moving from sensor pre-production to production**
  - First production orders have been issued (HPK 150 µm and FBK 3D 50x50 μm^2) and more will be issued before the end of 2023
  - A Quality Assurance (QA) program, including IV, CV and irradiations of a sub-sample of sensors and test structures, will be carried on during production

BACKUP

The new Inner Tracker: ITk



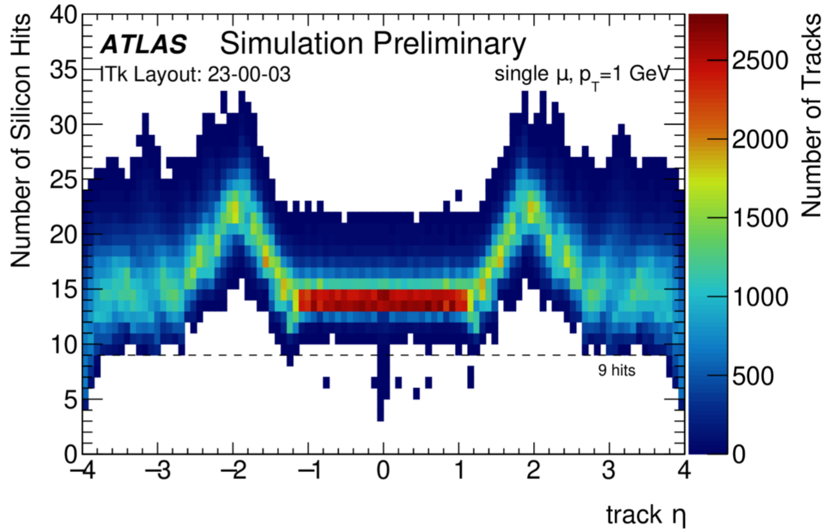
CERN-LHCC-2017-021

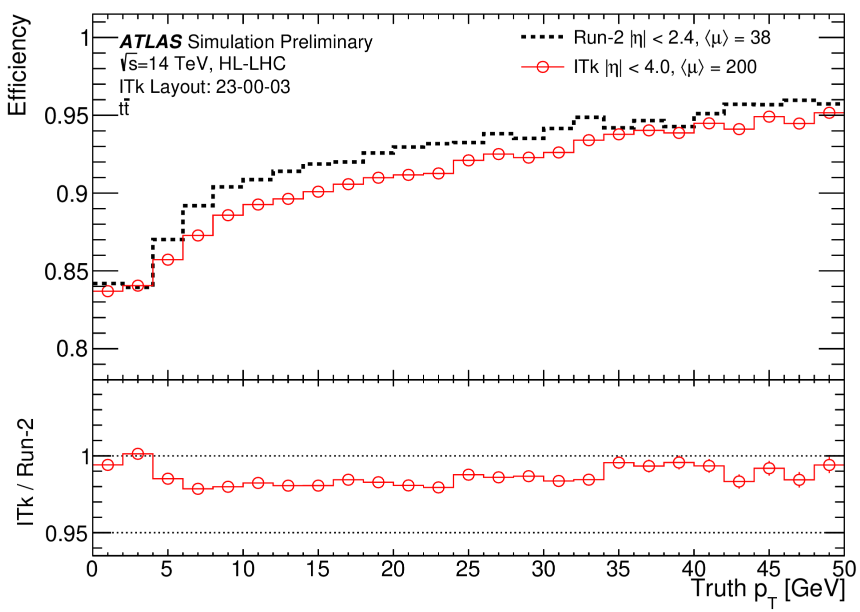
New Strip system
~165 m^2 of silicon
17 888 modules
~60 Mega-channels

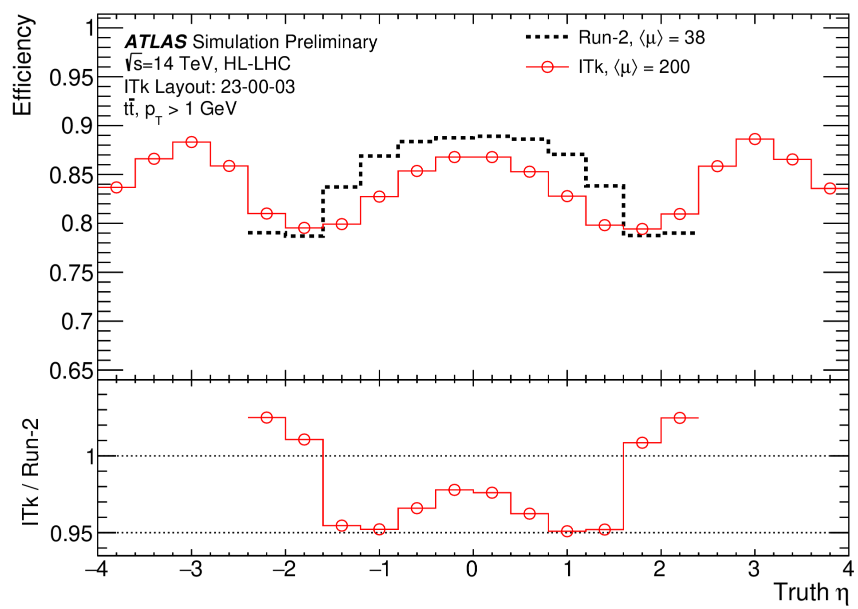
New Pixel system
~13 m^2 of active area
9 400 modules
1.4 Giga-pixels

Tracking performance

- **Tracking efficiency at 200 pileup (5x compared to Run-2)**
  - Similar performance to Run-2 in the barrel
  - Improved efficiency (over 85%) at high-eta
  - Improved **fake rate** even considering the increased in pile-up







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The ITk pixel detector

- New layout with *5 pixel barrel layers* & large η coverage

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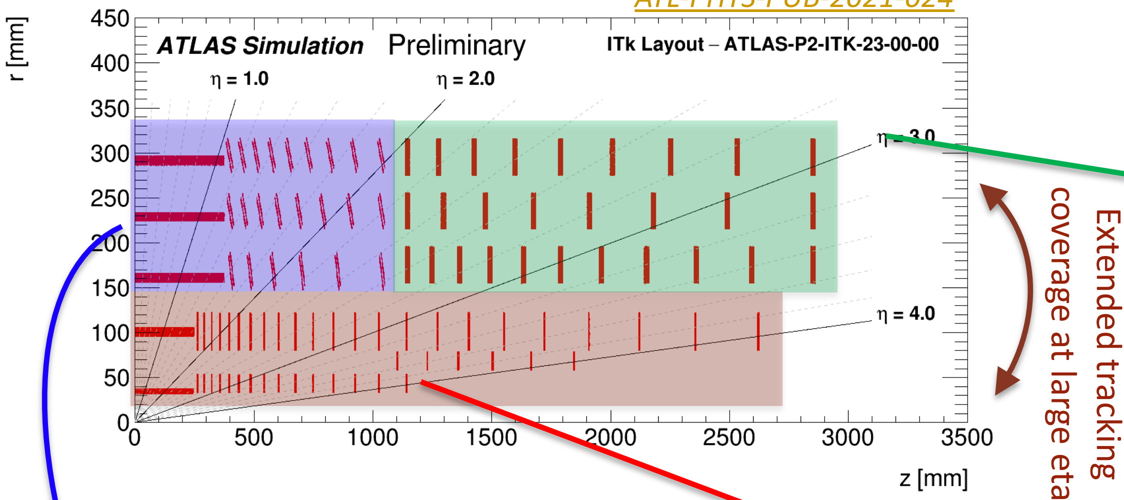
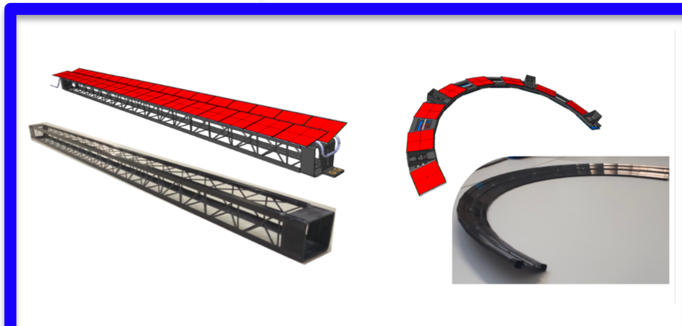


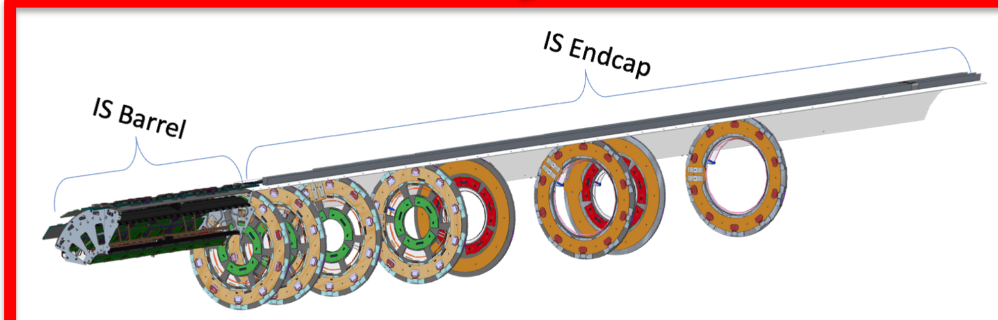
Outer Endcap (OE)

Ring structures



Outer Barrel (OB)

Flat staves + inclined rings

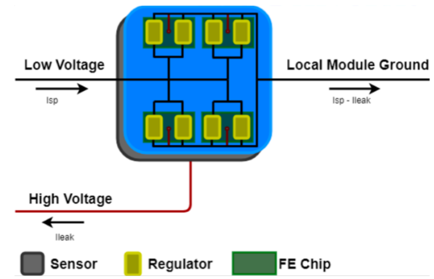


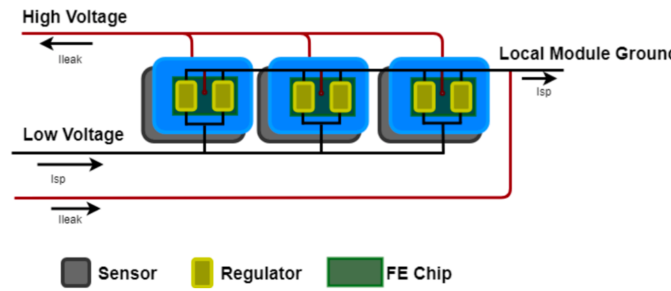
Inner System (IS)

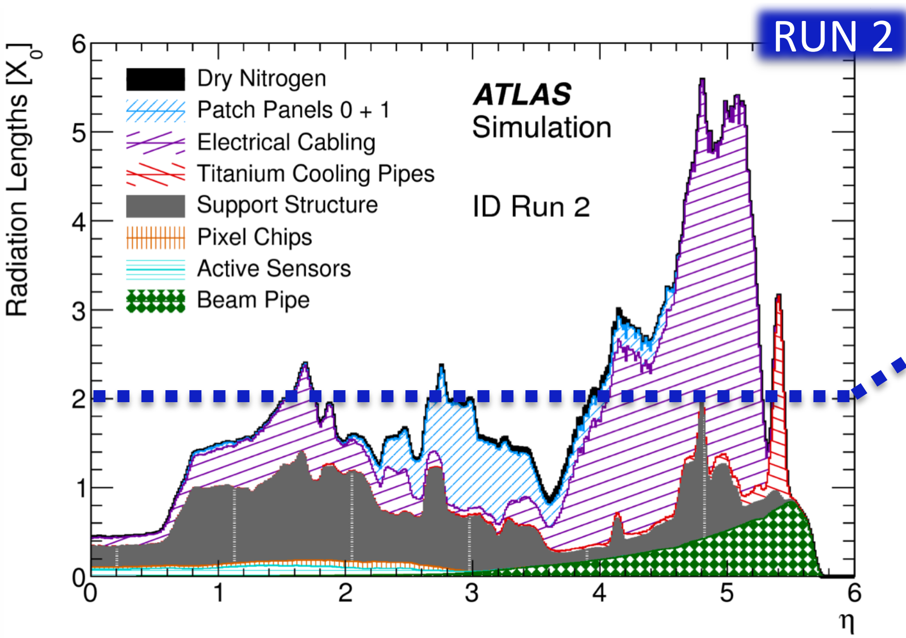
Ring and couple ring structures

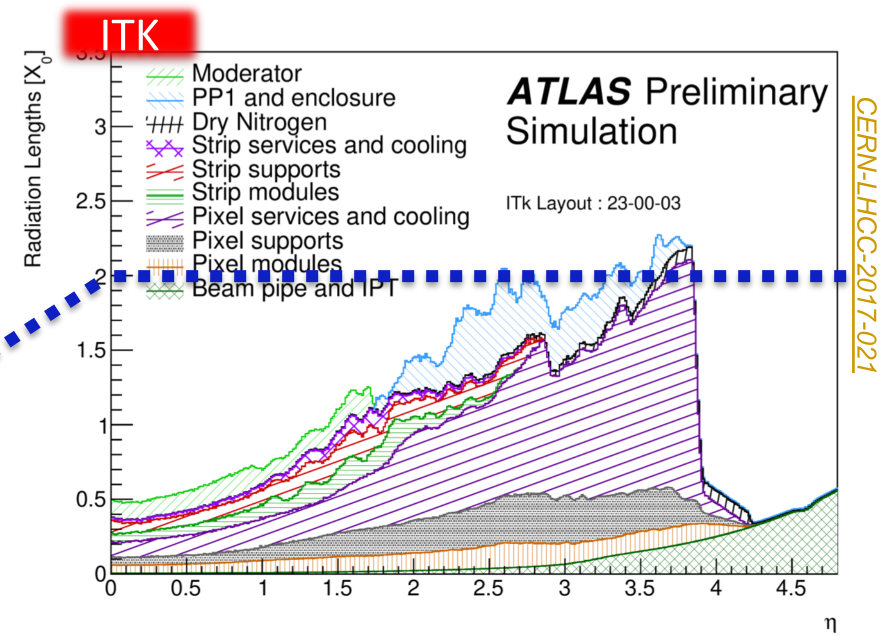
Material budget

- **Reduced material with respect to Run-2 thanks to:**
  - Evaporative CO_2 cooling system with titanium pipes
  - Carbon structures for mechanical stability and mounting
  - Optimised number of readout cables using link sharing
  - Innovative **Serial Powering (SP)** scheme in the pixels









Serial Powering

- **Innovative Serial Powering (SP) scheme**
  - Readout chips on a triplet or quad module are powered in parallel using up to 8W of power
  - ShuntLDO allow voltage regulation of the frontend chip with constant current and redundant power budget from the external power source
  - By powering **up to 14 modules** in series in a chain, the amount of required cables is reduced and thus material budget in the detector
  - Average chain of about 10 modules
    - LV inside the module distributed in parallel
    - Several HV channel for serial powering chain

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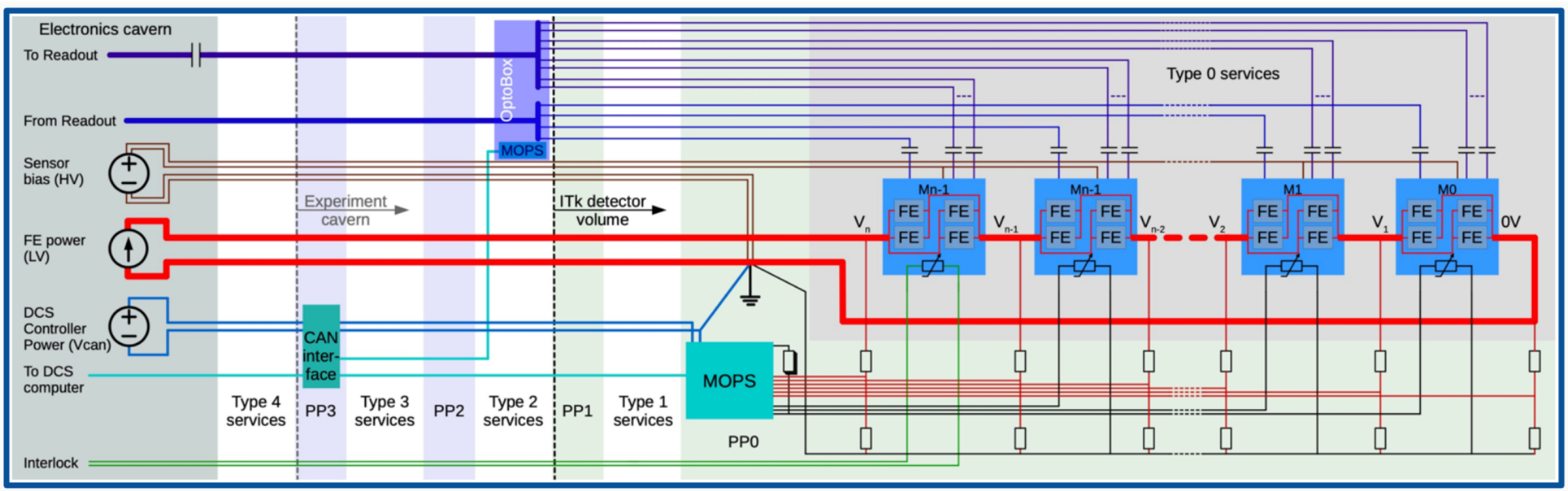
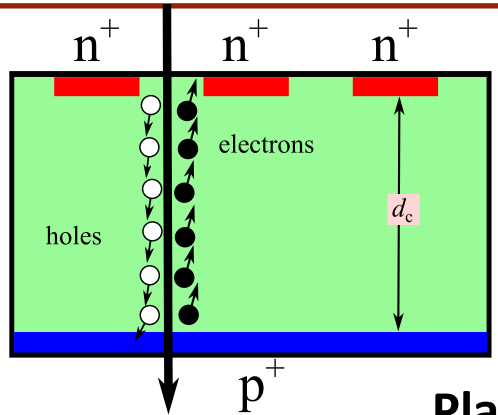
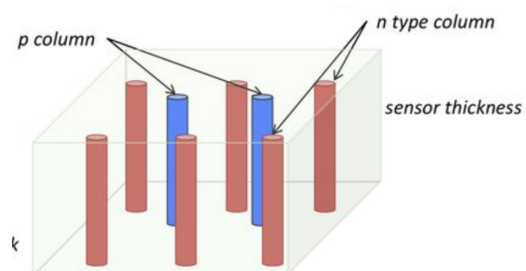


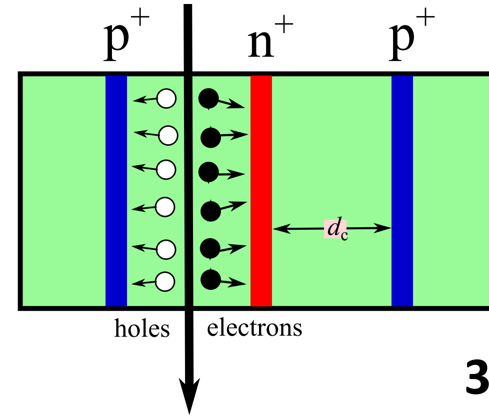
S. Terzo (IFAE, Barcelona) - TIPP 2023

3D sensors vs Planar sensors



Planar





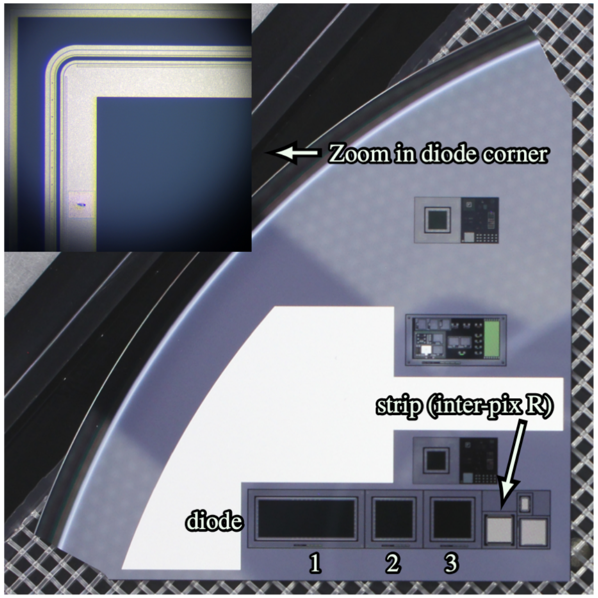
3D

- **Advantages of 3D**
  - Collection distance (d_c) disentangled from active thickness
  - Large signal with short collection distance
    - Less charge trapping
    - Fast charge collection
    - **Radiation hardness**
  - Very low full depletion voltage
    - **Low power dissipation**

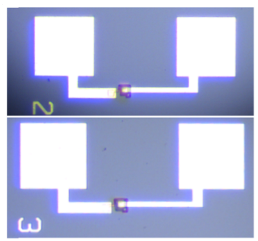
- **Drawbacks of 3D**
  - Complex fabrication
    - Lower yield than Planars
    - Longer production times
    - More expensive
  - Higher capacitance (noise)
    - Depending on the design:
      - Column distance, thickness, column width…
  - Non uniform electric and weighting fields

Test structures

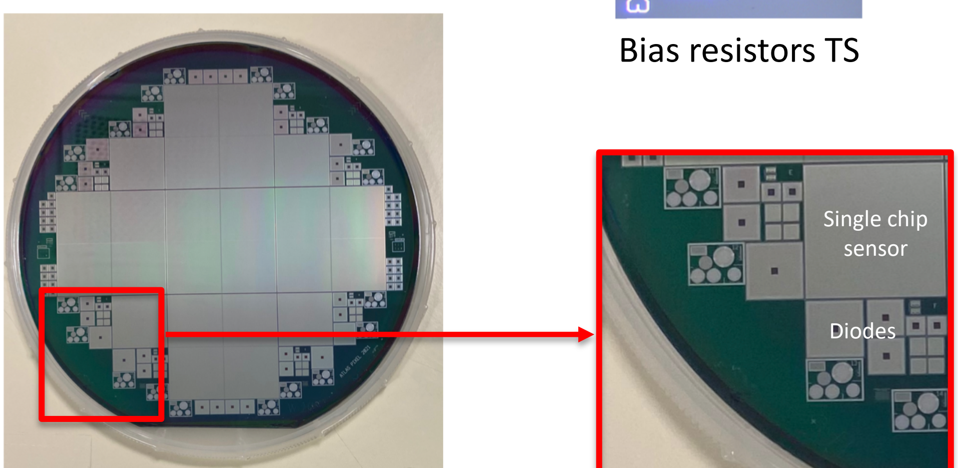
- **Diced half moons containing test structures (TS)**
  - Diodes of different dimensions
  - Strips (pixels shorted in columns by metal lines)
  - Bias Resistors (only for HPK)
  - Special structures for measuring inter-pixel capacitance (only implemented in Planar sensors)
  - Vendor specific structures (ex. MOS capacitors)



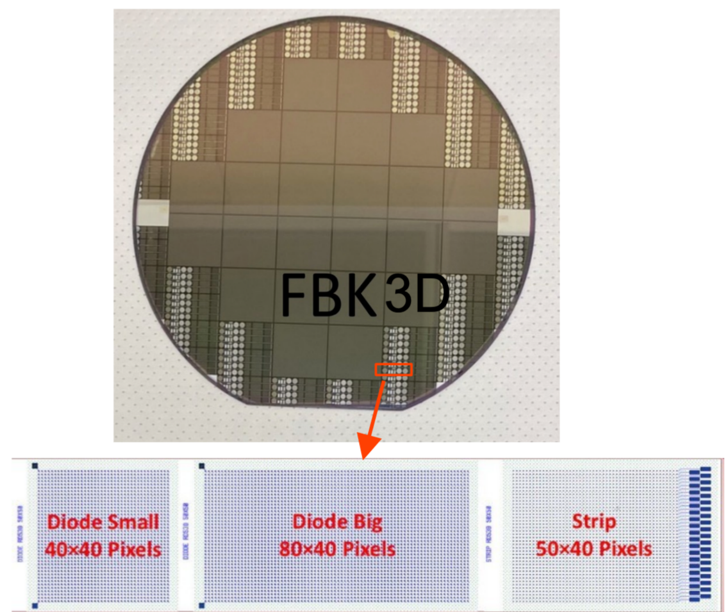
Example: HPK half moon with TS



Bias resistors TS



FBK Planar sensors 100µm



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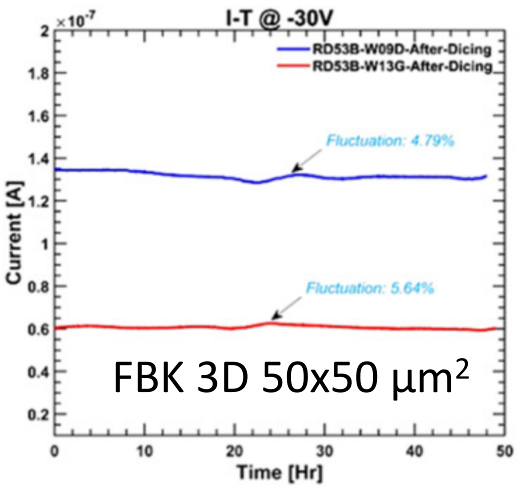
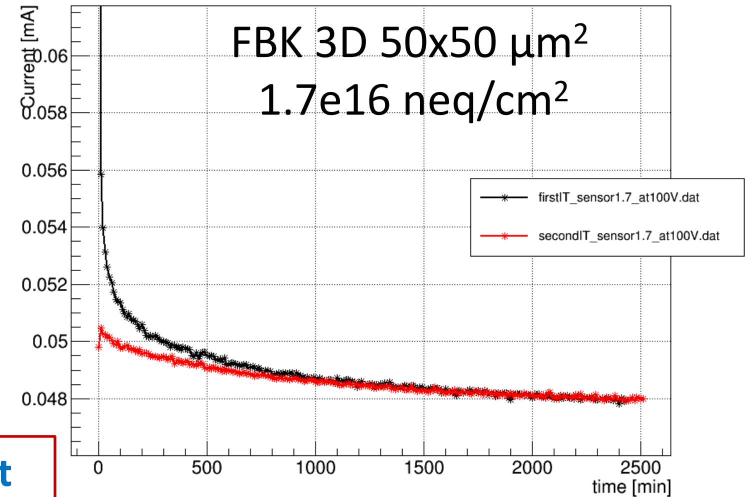
Leakage current stability (3D)

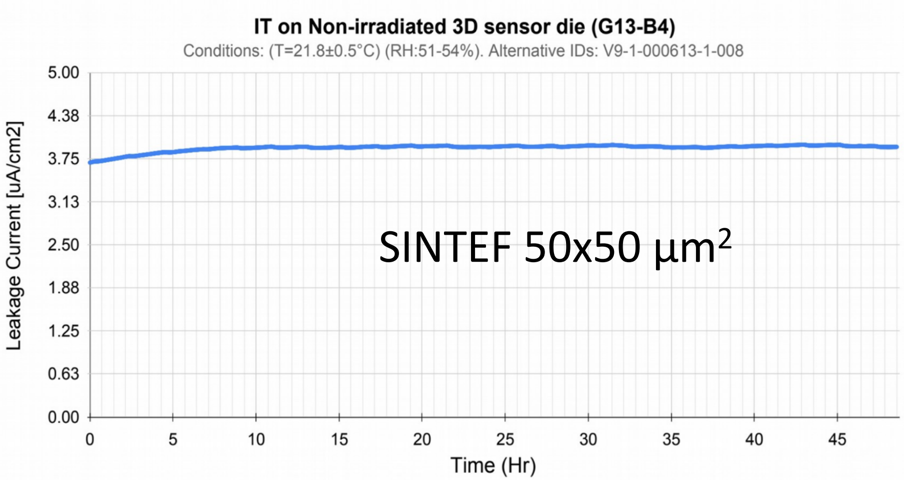


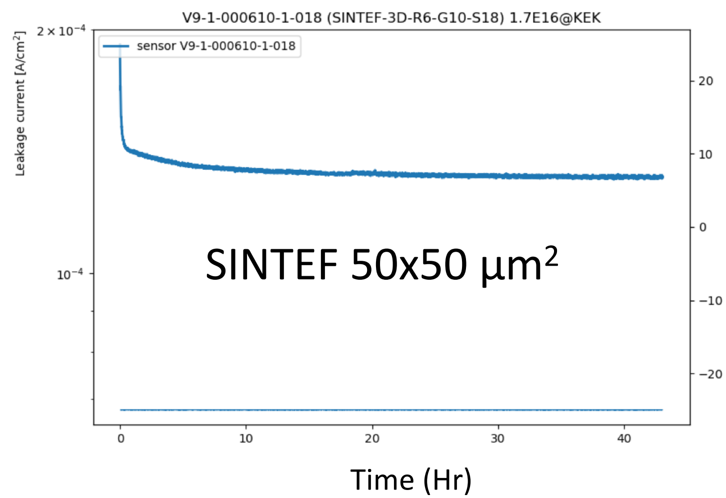
Before irradiation



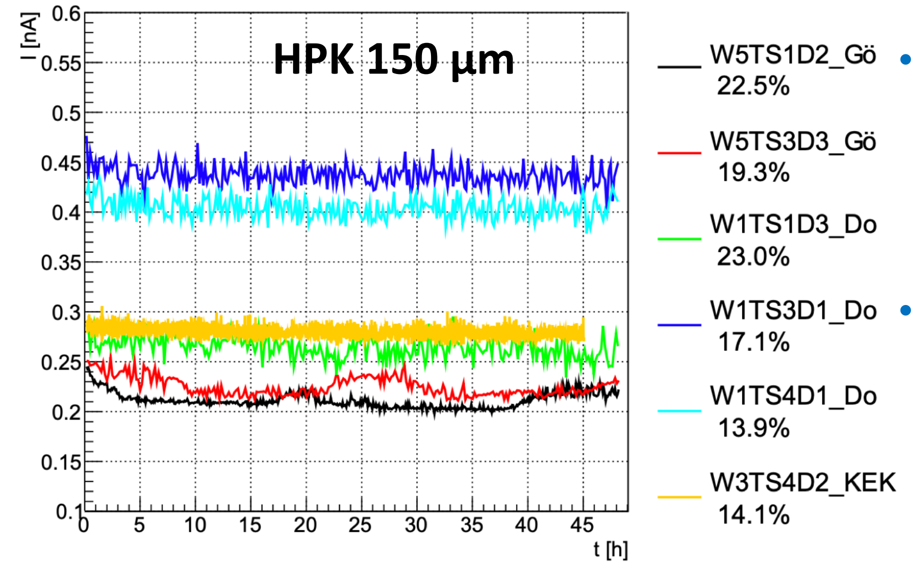
After irradiation

Stable leakage current before/after irradiation for both FBK and SINTEF sensors (< 25% fluctuation)



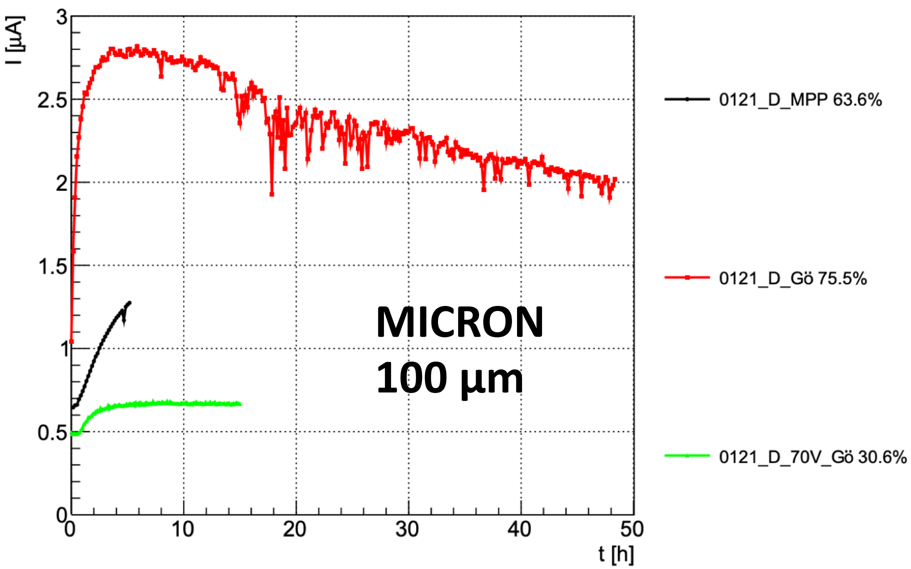


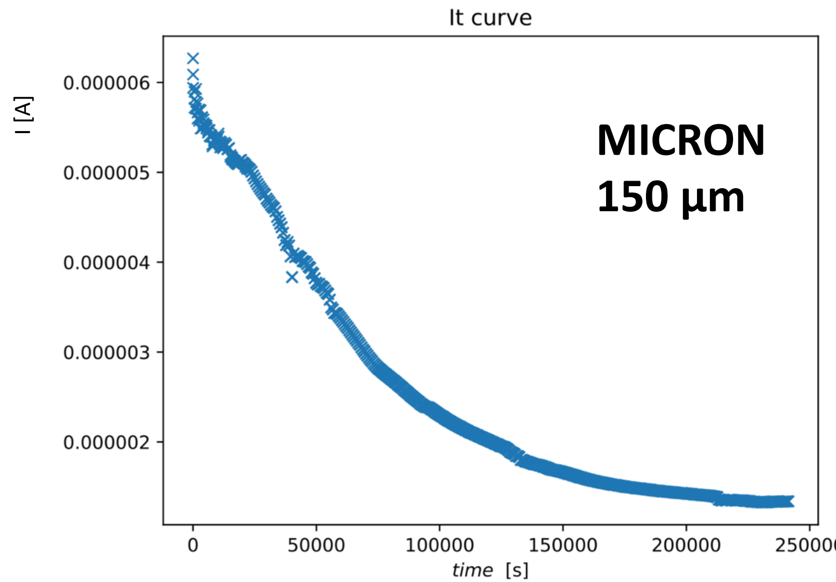
Leakage current stability (Planars)



- **We require the leakage current before and after irradiation to be stable:**
  - Less than 25% deviation from the average over 48 hours
- **MICRON sensors before irradiation**
  - Large drift of the current observed over several hours for both 100 µm and 150 µm thick sensors
  - Breakdown shifts towards lower voltage

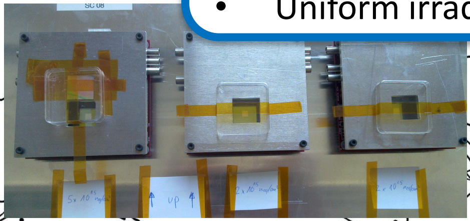
Before irradiation



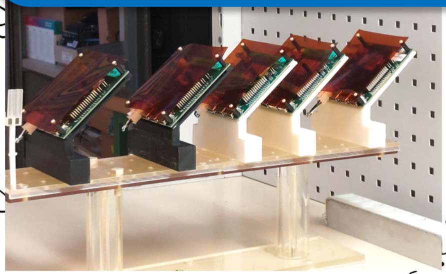


Irradiation sites

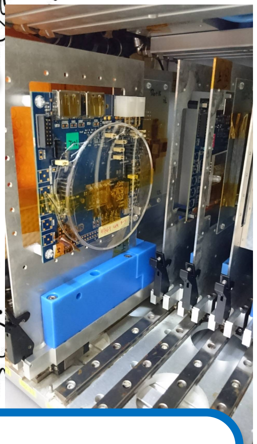
KIT, Germany
- 23 MeV protons
- Large TID: ~750 Mrad for 5e15 n_{eq}/cm^2
- Uniform irradiation at T<0˚C



CERN PS, Switzerland
- 23 GeV protons
- Realistic TID: ~220 Mrad for 5e15 n_{eq}/cm^2
- Non-uniform irradiation at room temp.



Bonn, Germany
- 18 MeV protons
- Large TID: >800 Mrad for 5e15 n_{eq}/cm^2
- Uniform irradiation at T<0˚C



CYRIC, Japan
- 70 MeV protons
- Realistic TID: ~350 Mrad for 5e15 n_{eq}/cm^2
- Uniform irradiation at T<0˚C

TRIGA reactor at JSI, Slovenia
- Reactor neutrons
- Negligible TID
- Uniform irradiation
- Not suited for modules due to activation

Thanks to: Koji Nakamura, Vladimir Cintro, Igor Mandic, Alexander Dierlamm, Giuseppe Pezzullo, Federico Ravotti and Pascal Wolf

Test beam results

ITK-2022-005