Test of ITk 3D sensor pre-production modules with ITkPixV1.1 chip

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Università
di Genova

Inner Tracker (ITk) for High Luminosity (HL-LHC)

- Inner Tracker (ITk): a new silicon tracking detector in preparation for the ATLAS upgrade at the HiLumi-LHC
- Details of the latest design version: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/
- ITk Pixel detector status: prototypes assembled and tested → improved designs → pre-production phase
- Nice overview talk about ITk detector by A. L. Heggelund: https://indico.cern.ch/event/1120714/timetable/?view=standard#127-atlas-itk-pixel-detector-o

- 5 layers of pixel:
  - **L4**: Planar sensors (150 µm)
  - **L3**: Planar sensors (150 µm)
  - **L2**: Planar sensors (150 µm)
  - **L1, R1**: Planar sensors (100 µm)
  - **L0, R0, R0.5**: 3D sensors
- Inner System will be replaced
- HL-LHC @ 2000 fb^{-1} (1.5 safety factor):
  - Fluence up to 1.9e16 n_{eq}/cm^2
  - TID up to 1 Grad
- Barrel at 34 mm from collisions
- Endcap rings down to 33.2 mm

ATLAS Simulation Preliminary
ITk Layout: 23-00-03
η = 1.0
η = 2.0
η = 3.0
η = 4.0
r [mm]
z [mm]
L0
R0
R0.5
Inner System
Barrel (stave) **Endcap (rings)**

Inner Tracker (ITk) triplet modules

ATLAS ITk

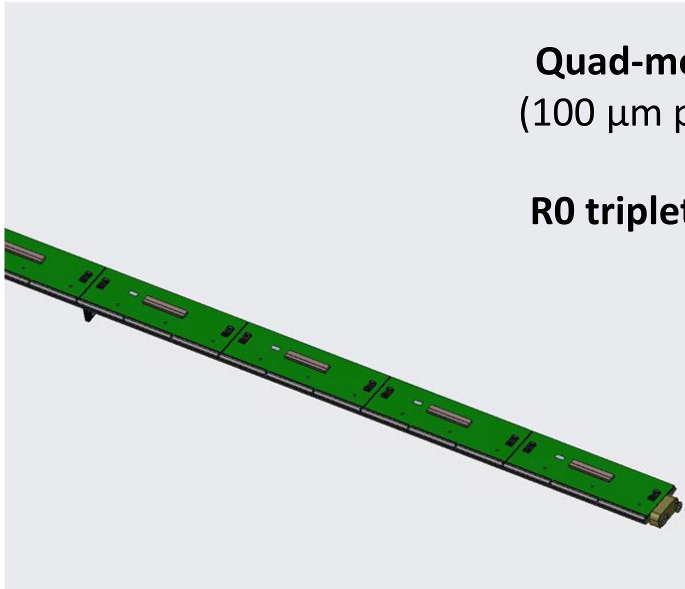
Barrel (stave)

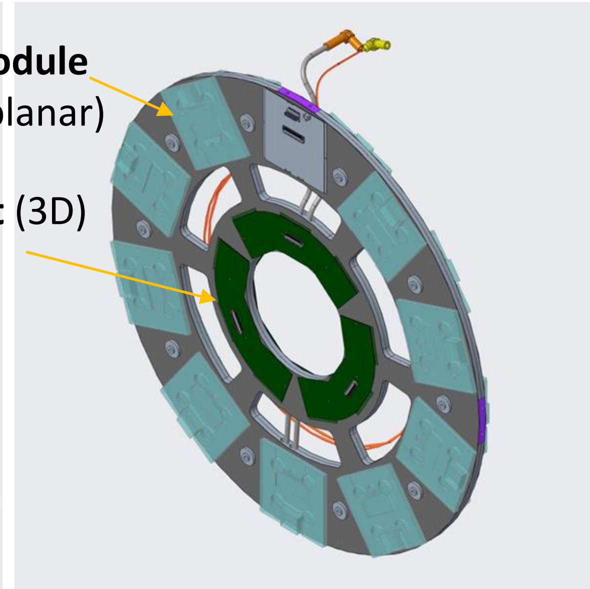
L0: 96 triplets
12 staves x 8 triplets

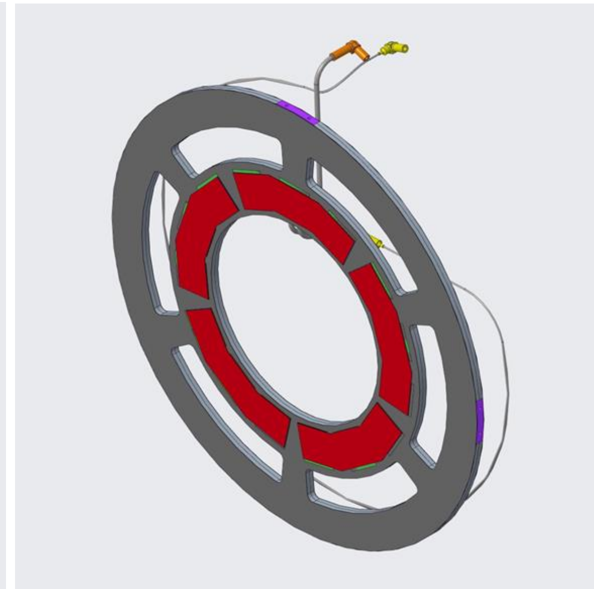
Endcap (rings)

R0: 180 triplets
30 rings x 6 triplets

R0.5: 120 triplets
12 rings x 10 triplets

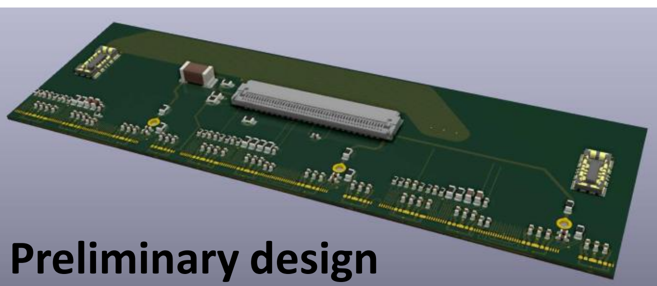


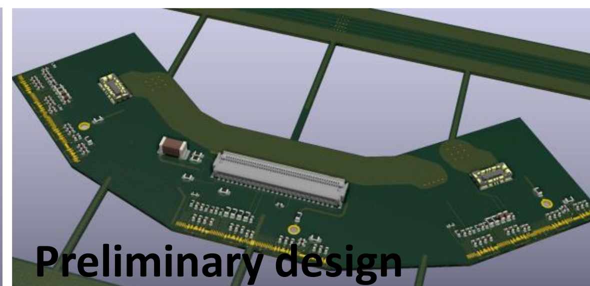




Prototype of ITk R0 ring with RD53A modules:
10 quad-modules
3 R0 triplets

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

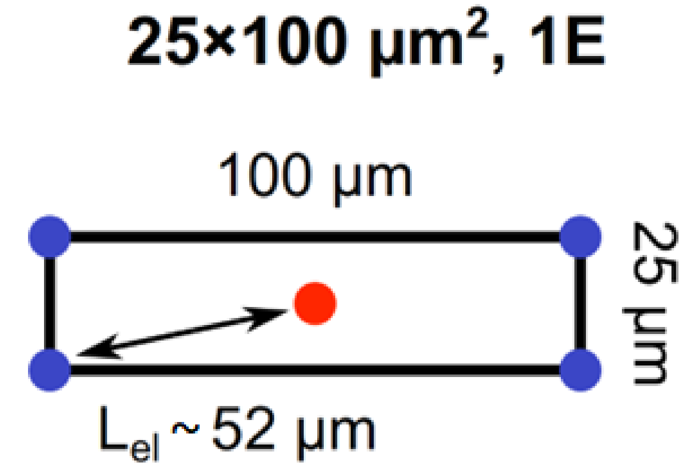


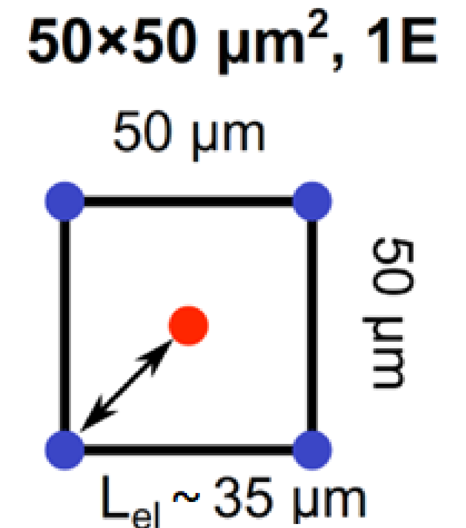


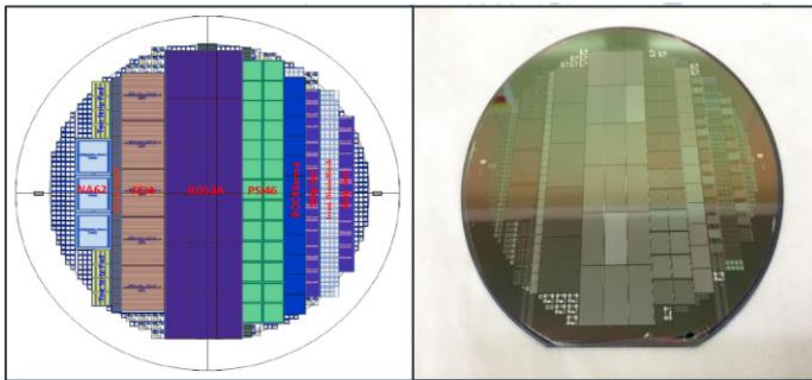
Design ongoing

Sensor wafer: R&D prototypes

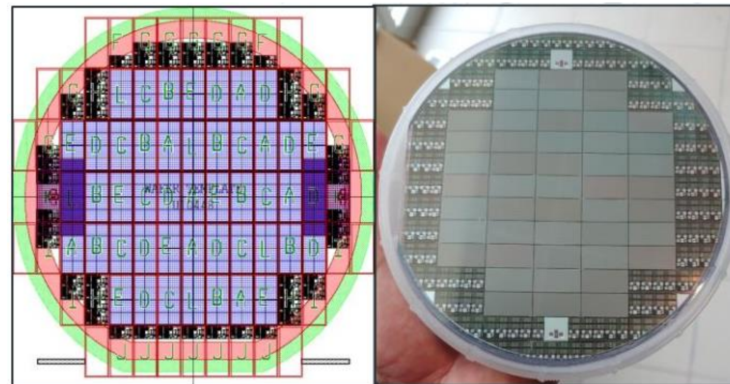
- 2 different pixel cell dimensions for the 3D sensors (2x2 cm^2 pieces):
  - 25x100 μm^2 in the barrel triplet modules (288 sensors needed)
  - 50x50 μm^2 in the endcap triplet modules (900 sensors needed)
- In the last years, several R&D production of wafers by FBK:
  - Sensors 1x2 cm^2 compatible with the RD53A chip
    - Batch 2: Mask aligner, 130 μm active thickness
    - Batch 3: Stepper, 150 μm active thickness
    - Details at: *S. Terzo et al* 2021 Front. Phys. 9:624668
  - 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: *Md.A.A. Samy et al 2021 JINST 16 C12028*





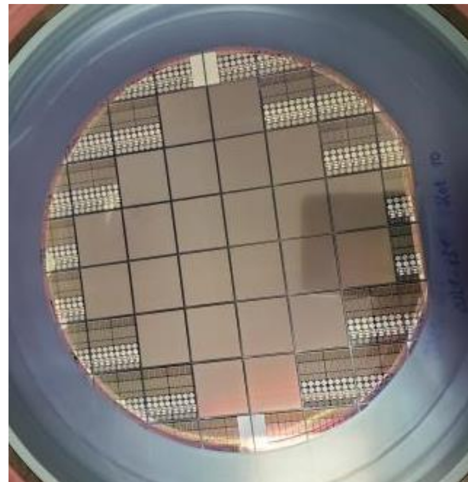


2nd 3D-SS batch also "New RD53A" ROCs
With Mask Aligner Lithography Technique

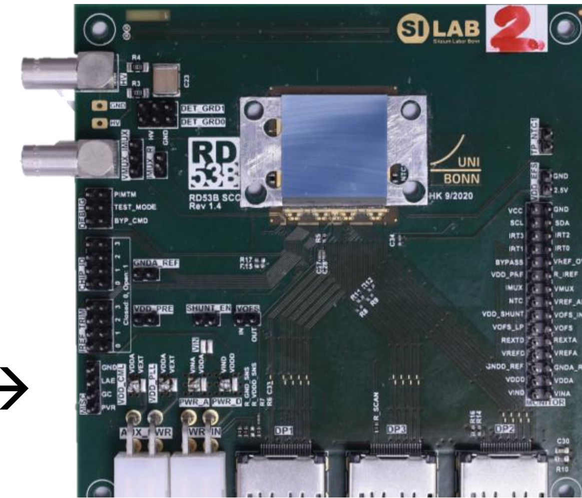


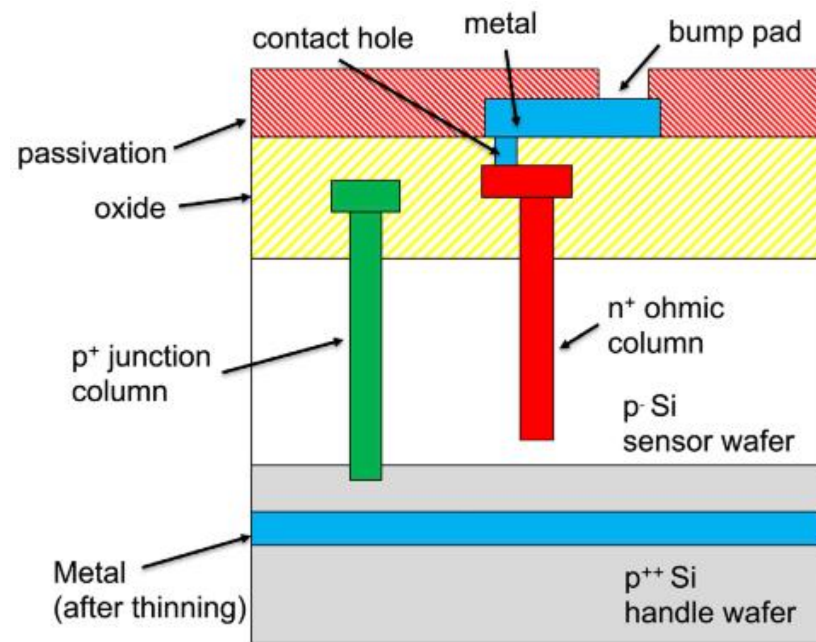
3rd 3D-SS batch also "New RD53A" ROCs
With Stepper Lithography Technique

Sensor wafer: pre-production



- FBK pre-production wafers
  - 24 sensors per wafer + several test structures
  - 7 wafers delivered to CERN (5 + 2 with temp. metal)
    - 20 sensor tiles bonded at IZM to ITkPixV1.1 chips
      - 10 received in Genova
      - 6 assembled on Bonn Single Chip Card (SCC) →
      - https://twiki.cern.ch/twiki/bin/viewauth/RD53/RD53BTesting#RD53B_Bonn_Single_Chip_Card_SCC

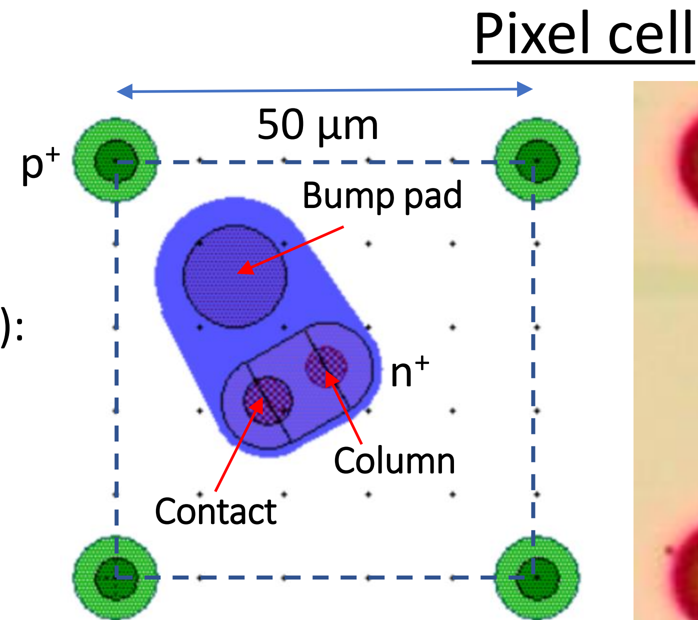


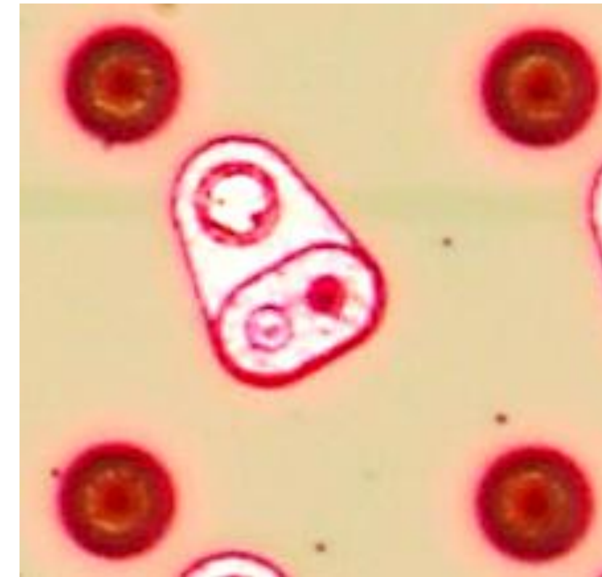


3D sensor thickness (after backside thinning):

- Total: 250 µm
- Active: 150 µm
- Support: 100 µm

Pixel cell



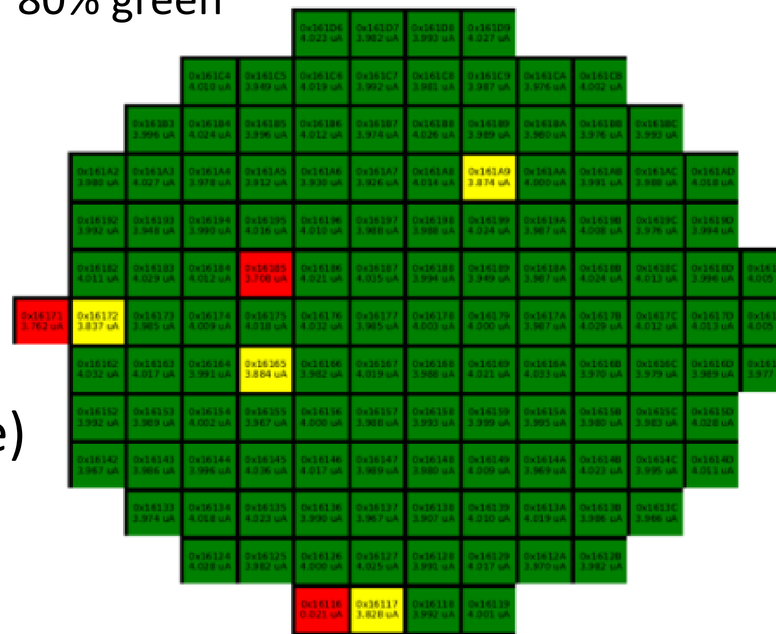


Chip wafer: ITkPixV1 (RD53B)

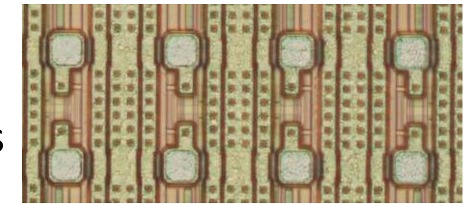
- ITkPixV1.0 chip: bug in ToT memories → induces high digital current (not possible to use ToT)
    - ITkPixV1.1 chip: patch fixed high current (ToT still not usable)
    - Several wafers produced, probed, thinned (150 μm) and diced → 80% green yield (wafer)
    - Summary of chip studies: H. Yang TIPP 21 https://indico.cern.ch/event/981823/contributions/4295325/attachments/2250597/3817670/ITkPixV1_analog_FE_testing_Hongtao_Yang.pdf

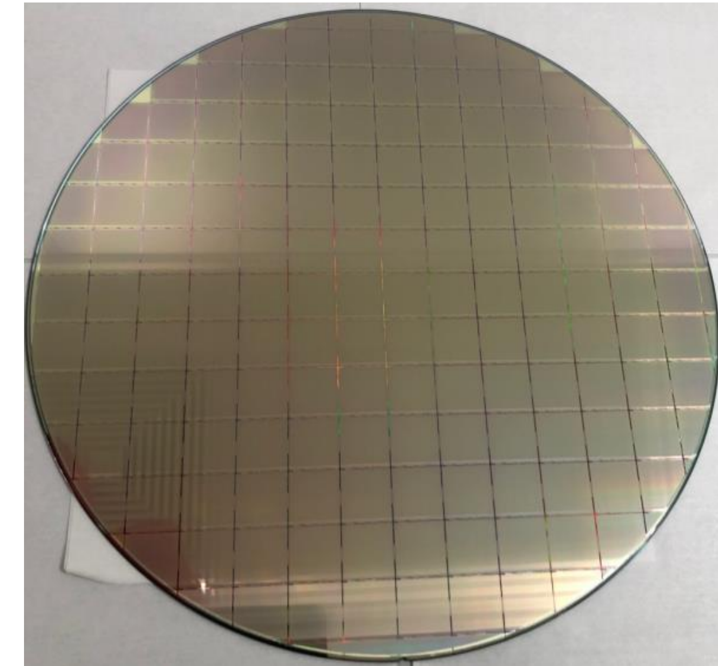
- Main features:
    - About 2x2 cm^2 area
    - 384 x 400 pixels (50x50 μm^2)
    - Differential Analog FE
    - Power < 1 W/cm^2
    - Standard threshold: 1000 e
        - No noisy pixels @ 600 e
        - 1% noisy pixels @ 400 e
    - Timewalk < 25 ns (charge > 1000 e)
    - Radiation hardness > 1 Grad

V1.1 good yield
80% green



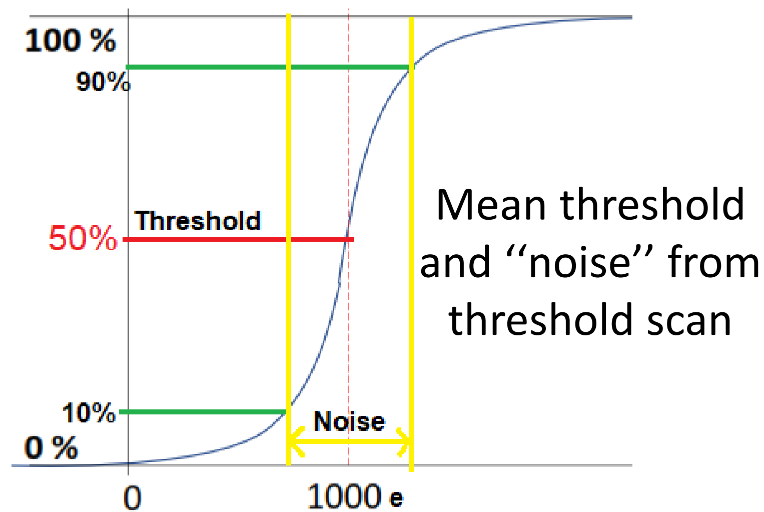
ITkPixV1
bump pads





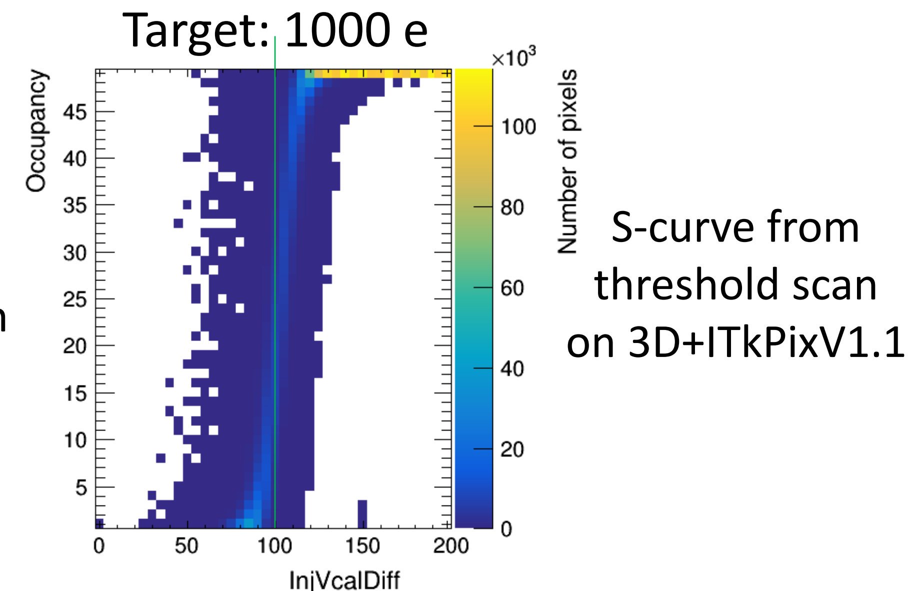
ITkPixV1.1 chip: threshold tuning

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



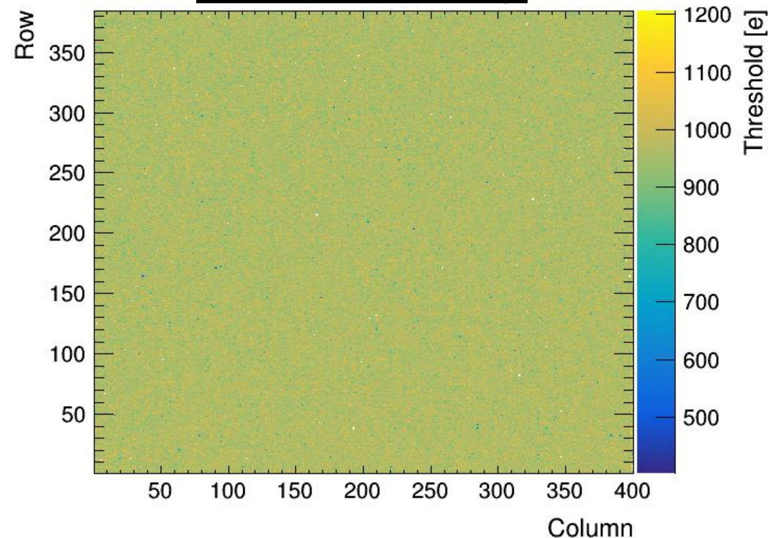
Mean threshold and "noise" from threshold scan

Target: 1000 e

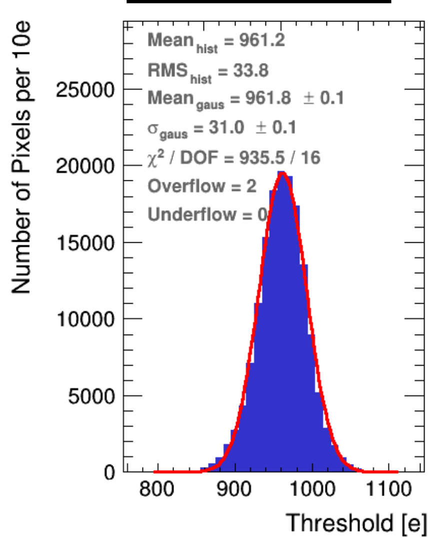


S-curve from threshold scan on 3D+ITkPixV1.1

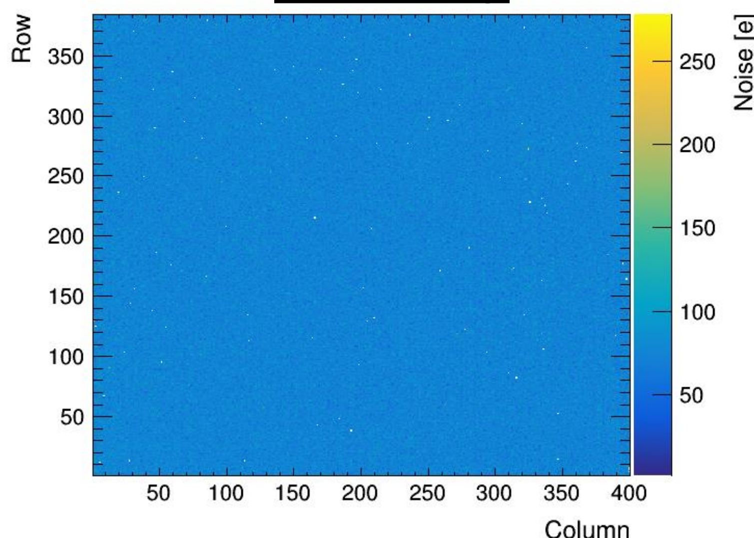
Threshold map



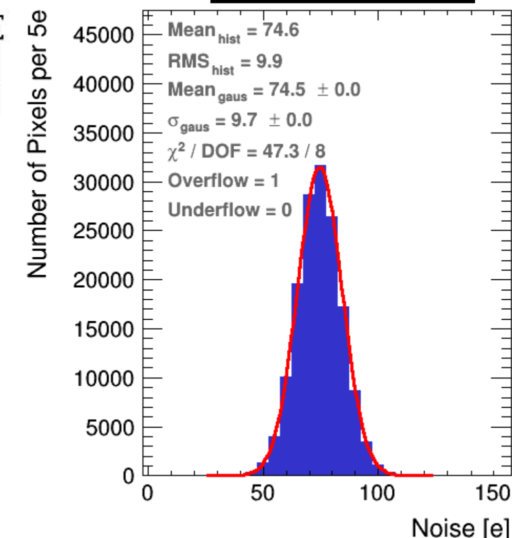
Distribution



Noise map



Distribution

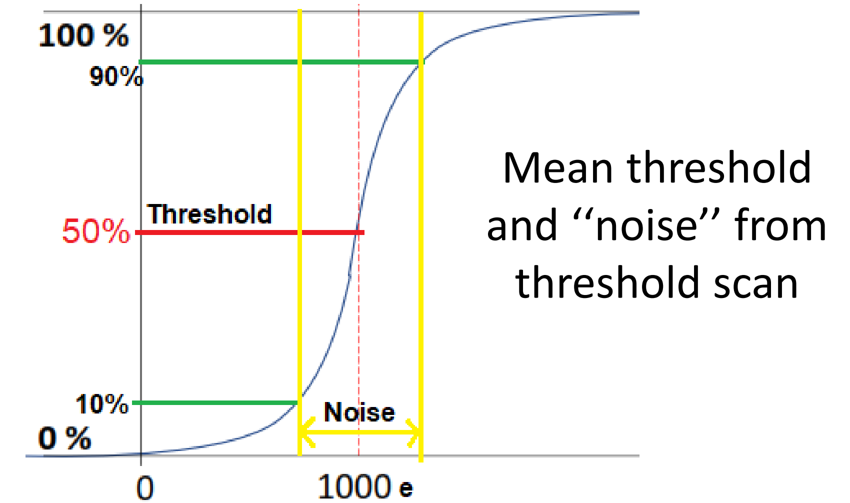


Summary of the 6 assembled modules (+2 bare chip)

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

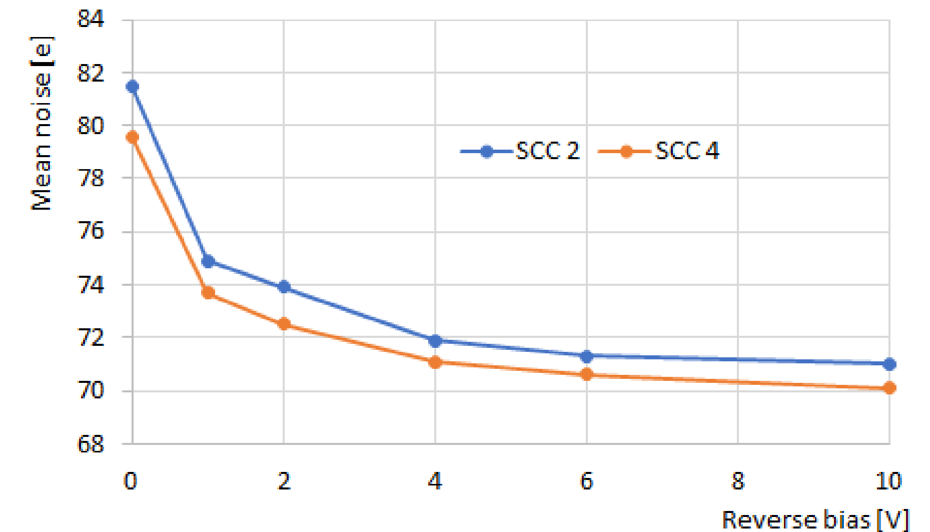
SCC	Bare chip	Mean Threshold	Sigma Threshold	Mean Noise	Sigma Noise
A	ITkPixV1.1	969	31	39	7
B	ITkPixV1.1	961	29	41	7

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

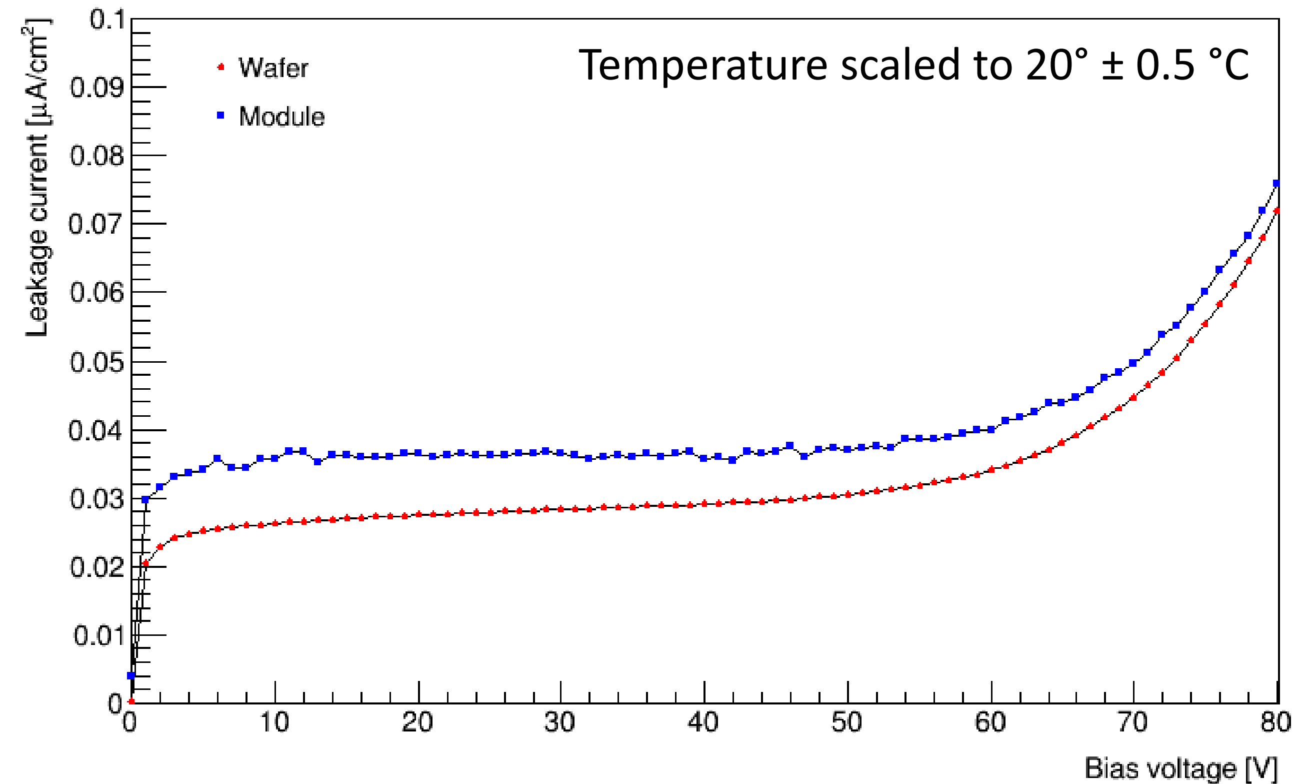
Mean "noise" decreasing with V bias



IV: wafer and bare module measurements

- IV measured up to 80 V at sensor level (on wafer) in Trento
  - Leakage current always below 1 µA (3.84 cm^2)
- Measured again on bare module (assembled on SCC) in Genova
  - Compatible current, below 0.2 $\mu A/cm^2$
  - Sligth increase at bare module level, not worrisome

- ''Green'' sensors used in these bare modules:
  - Breakdown voltage V_{bd}:
    - Defined as V bias at which:
      $I_{leak}(V + 10\ V) / I_{leak}(V + 5\ V) < 2$
    - Requirement: $V_{bd} > 25$ V (V_{depl} + 20 V)
    - These sensors: $V_{bd} > 80$ V
  - Leakage current I_{leak}:
    - Requirement: $I_{leak}(V_{depl}+20V) < 2.5\ \mu A/cm^2$
    - These sensors: $I_{leak}(25\ V) < 0.05\ \mu A/cm^2$



X-ray scan: setup and data acquisition

- X-ray tube (Amptek Mini-X2) used as source https://www.amptek.com/products/mini-x2-x-ray-tube

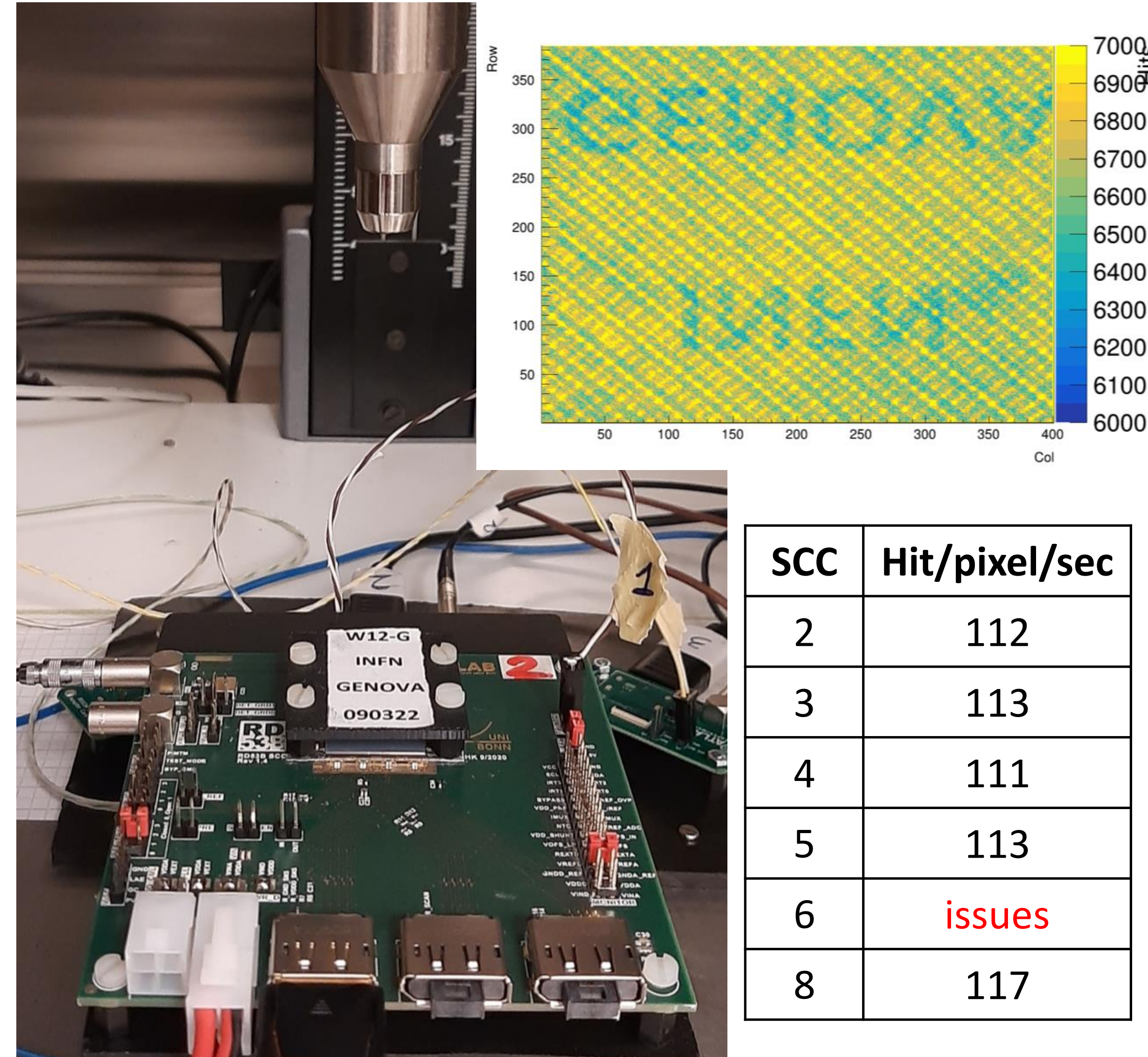
- Anode: Ag
- Operating point: 50 kV, 80 µA (4W, max energy)
- Distance: about 15 cm

- Masking noisy pixel (X-rays OFF):
  - 60 seconds random trigger scan (40 kHz)

- Data taking (X-rays ON):
  - 60 seconds self-trigger scan (HitOR)

- In these conditions: 6700 hits/pixel in 60 seconds (110/sec)

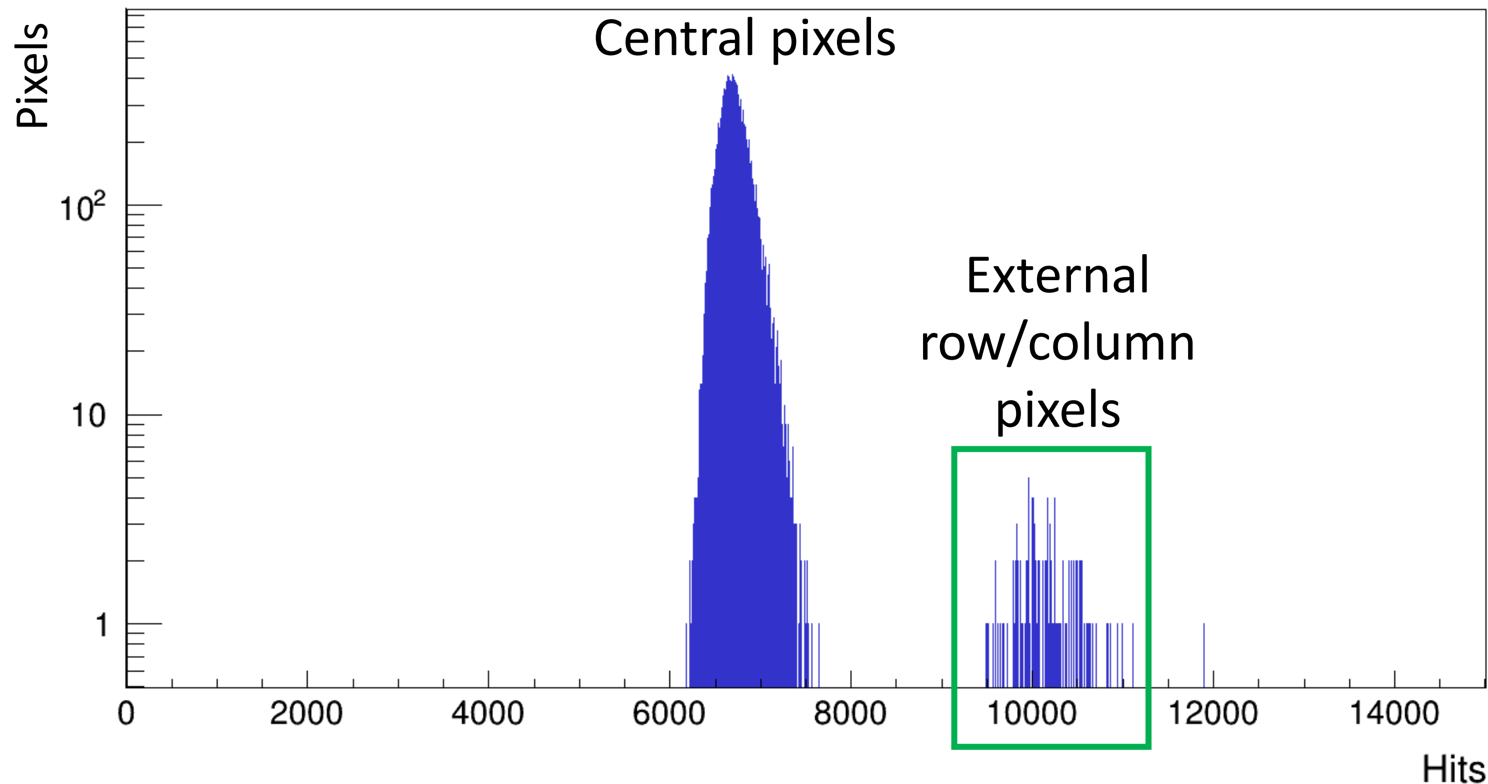
- 3D printed plastic cover between X-ray tube and the sensor
  - Visible pattern of the 3D printed filament
  - Visible pattern of the ink on printed label INFN Genova

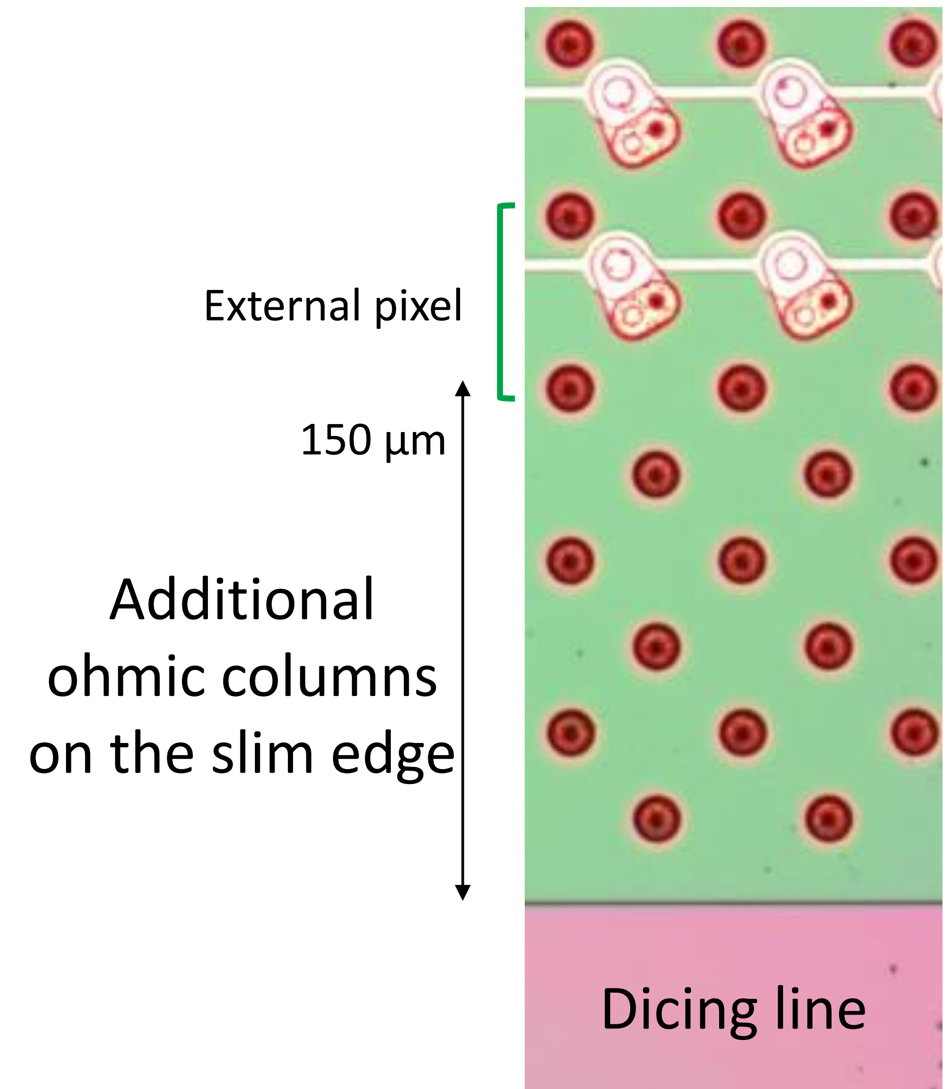


SCC	Hit/pixel/sec
2	112
3	113
4	111
5	113
6	issues
8	117

Hit collection: central and edge pixels

- Hit distribution (60 seconds acquisition):
  - Central pixels: 6700 hits/pixel
  - Edge pixels: 10000 hits/pixel
    - 30% more hits due to extension of the electric field

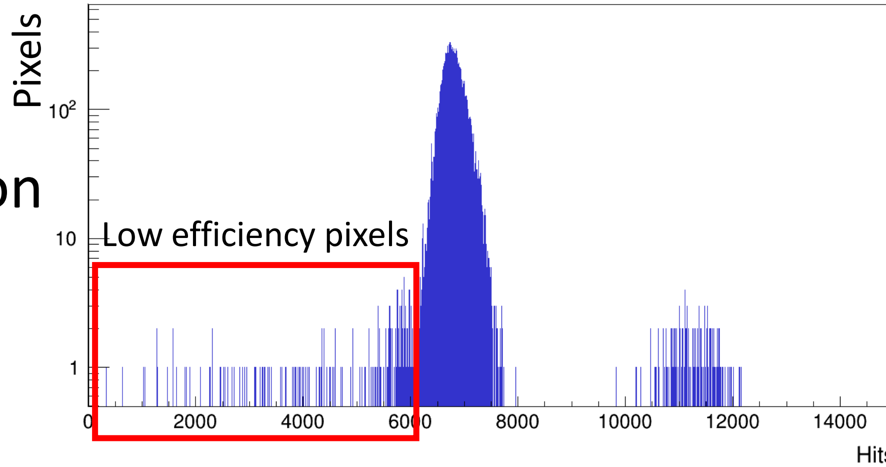




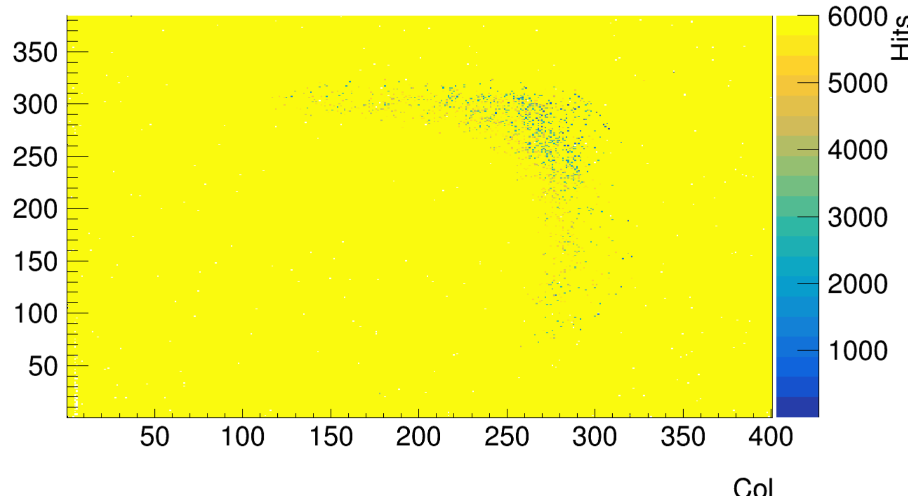
X-ray scan results: issues on SCC 5 and 6

- 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

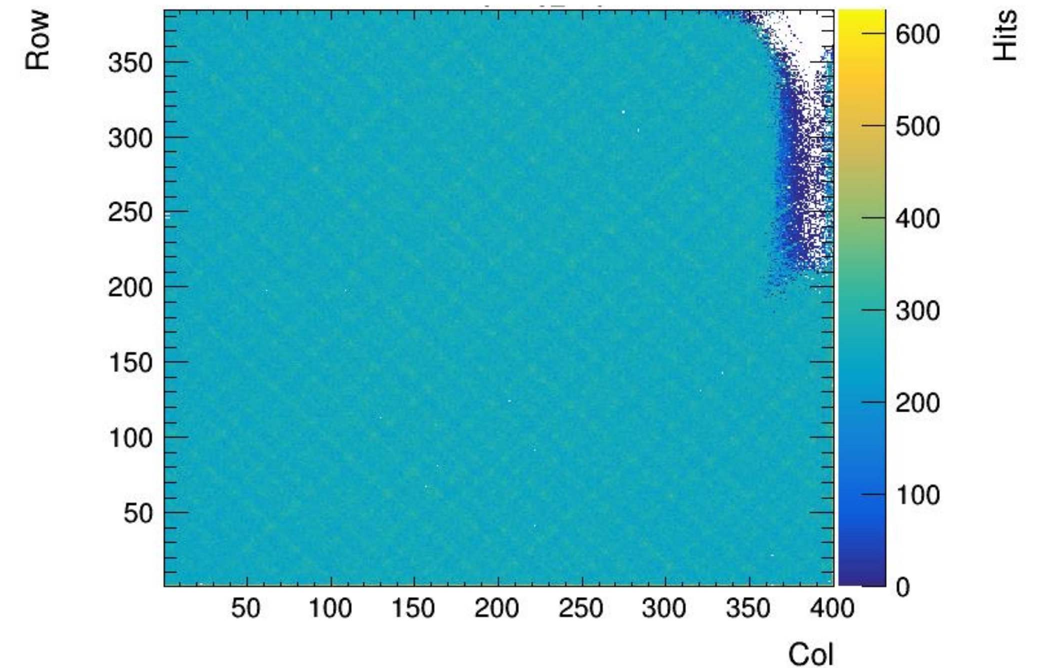


SCC 5: About 1000 low efficiency pixels (< 6000 hits)



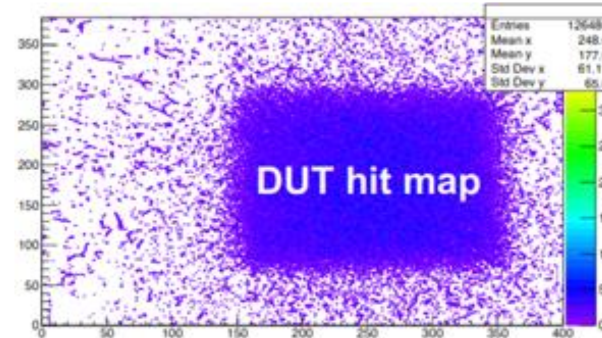
- Large bump disconnection area in the corner

SCC 6: hit map

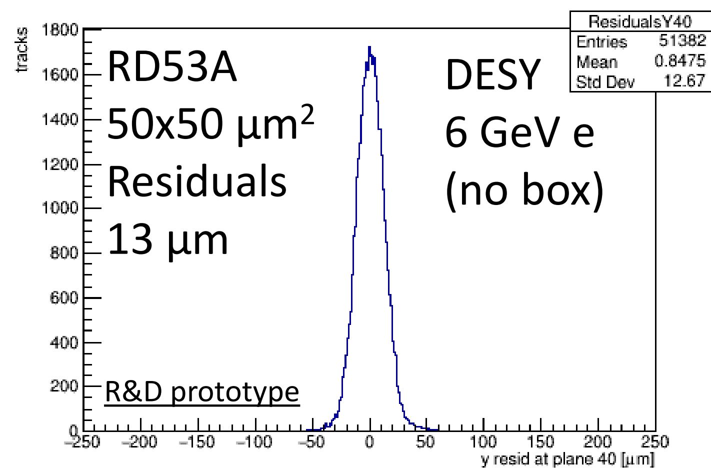


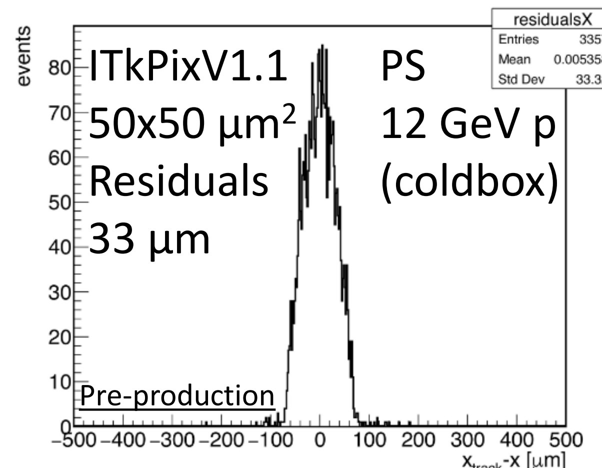
First ITkPixV1.1 testbeam results @ PS and SPS

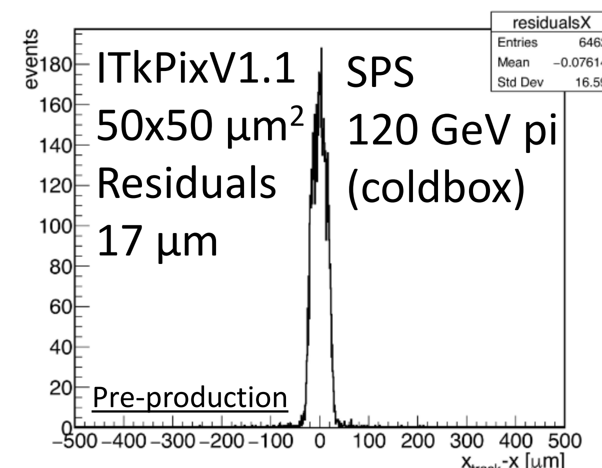
- SCC 2 and 4 tested at CERN beamlines → Work of many people along several weeks! Huge Thanks!!!
- First ITkPixV1.1 testbeam, a lot of debug of YARR DAQ
- During development, profited of beam to take data:
  - PS (12 GeV protons): 1, 2, 4, 6, 10 V bias
  - SPS (~120 GeV pions): 0, 10 V bias
- Pixel cell 50x50 μm^2:
  - Expected resolution (no ToT): 50 µm/sqrt(12) = 14 µm
  - PS: DUT residuals higher (33 µm) than expected (14 µm)
    - Probably due to multiple scattering (lower beam energy)
  - SPS data (higher energy) confirms expected residuals (17 µm)



Scintillators used for the trigger





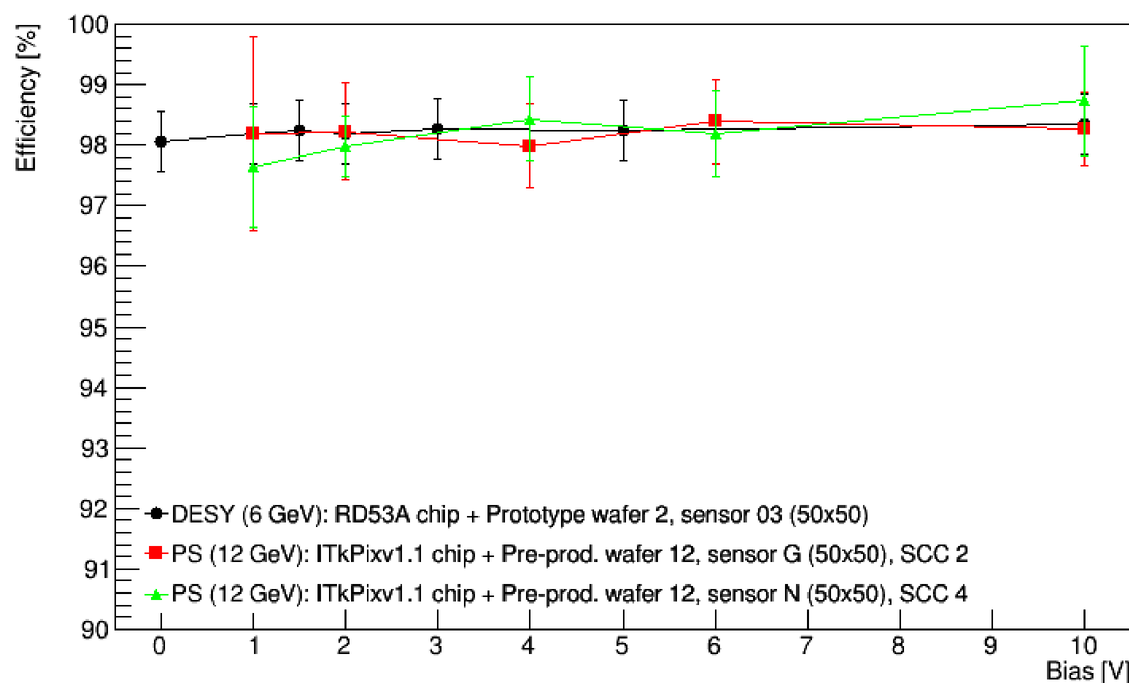


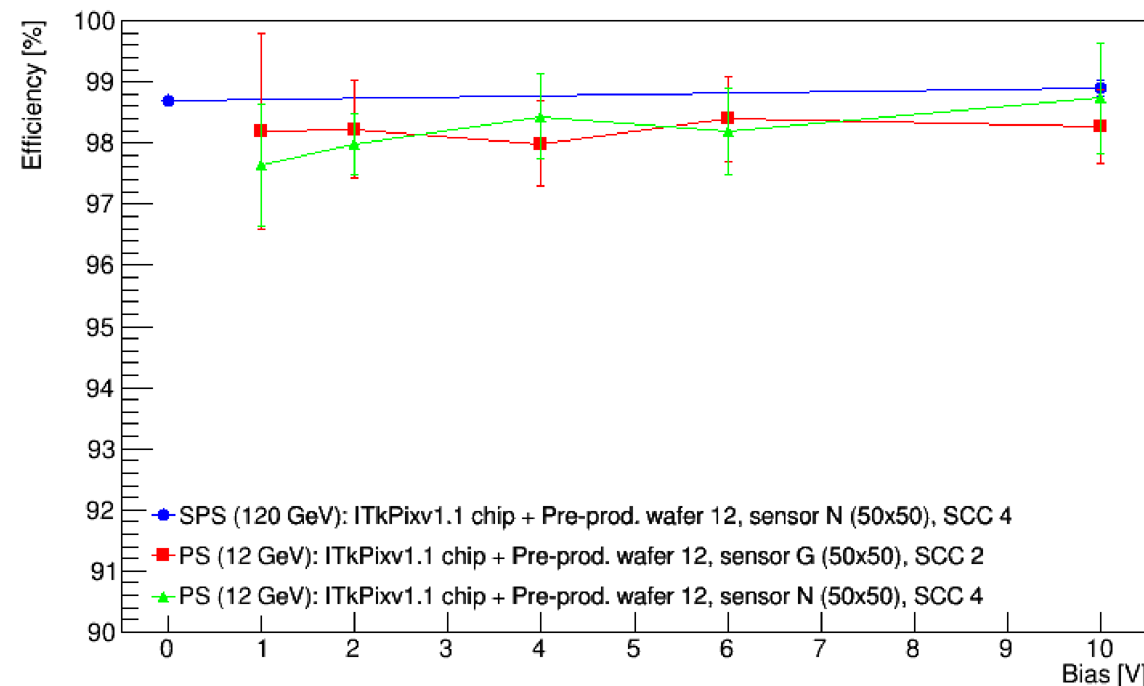
<u>Constant Temp: 15°C</u>

Modules were kept in Aluminum coldbox with plastic windows (chiller for cooling)

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

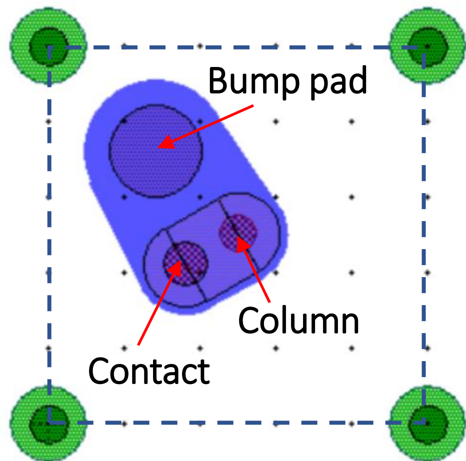
- Unirradiated modules tested at PS and SPS → Efficiency > 97.5 % already at 0 V bias
  - Uncertainty evaluated as variation among different data taking runs
- Results compatible with 50x50 μm^2 prototype (RD53A chip + FBK 3D sensor) previously tested at DESY:
  - **DESY** (6 GeV electrons) : 0, 1, 1.5, 2, 3, 5, 10 V bias
  - **PS** (12 GeV protons): 1, 2, 4, 6, 10 V bias
  - **SPS** (~120 GeV pions): 0, 10 V bias
    - Higher efficiency, DAQ software and firmware optimized with respect to PS datataking

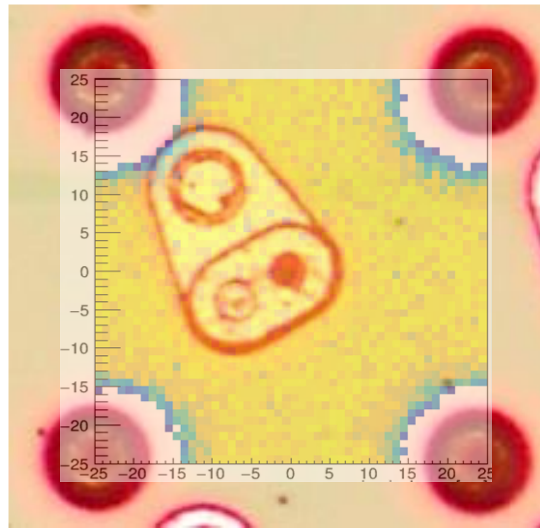




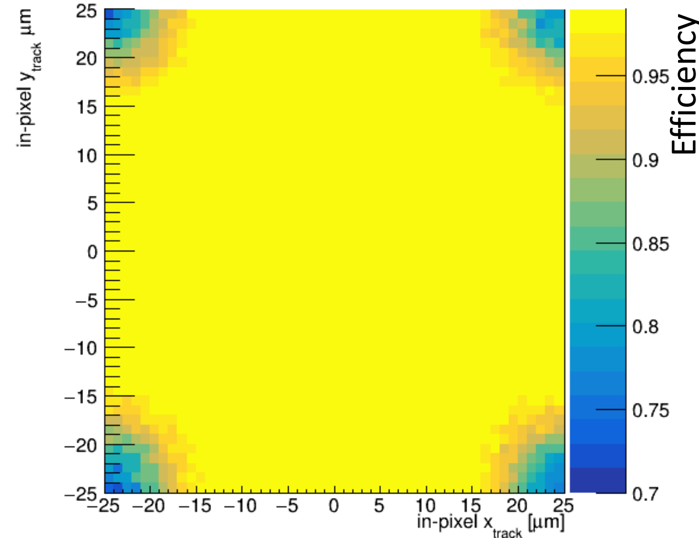
Pixel efficiency map: 0 V vs 10 V bias

- SPS proton beam perpendicular to DUT:
  - 0 V : 98.7 ± 0.1 %
  - 10 V: 98.9 ± 0.1 %
- Central area: higher than 99% efficiency
- Lower efficiency zones visible in corners:
  - Effect (75% – 99%) radius: 10 μm
  - p^+ columns max radius: 4 μm
- Surface: polySilicon cap visible (no effect)
- No other structure visible

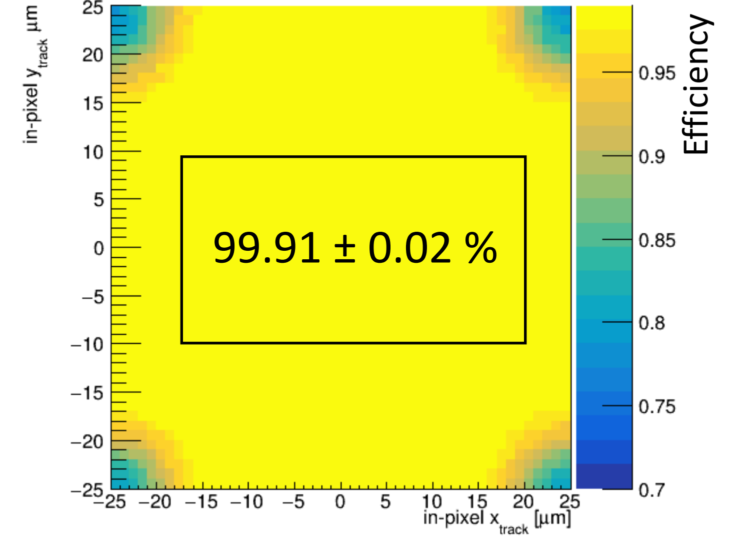


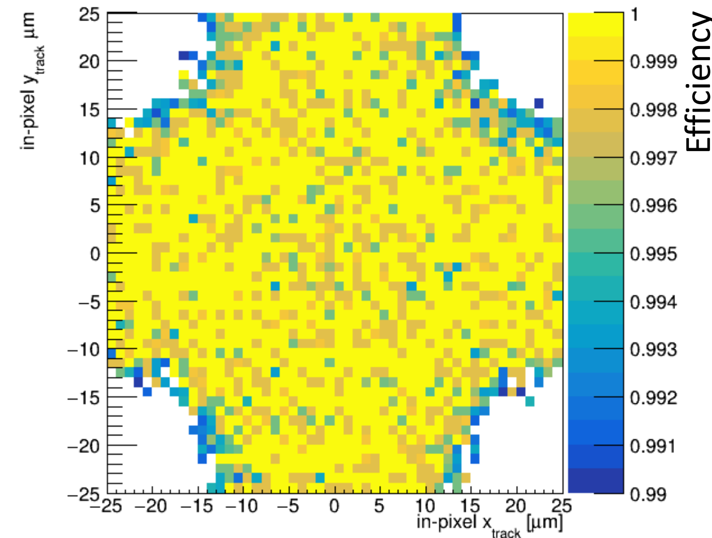


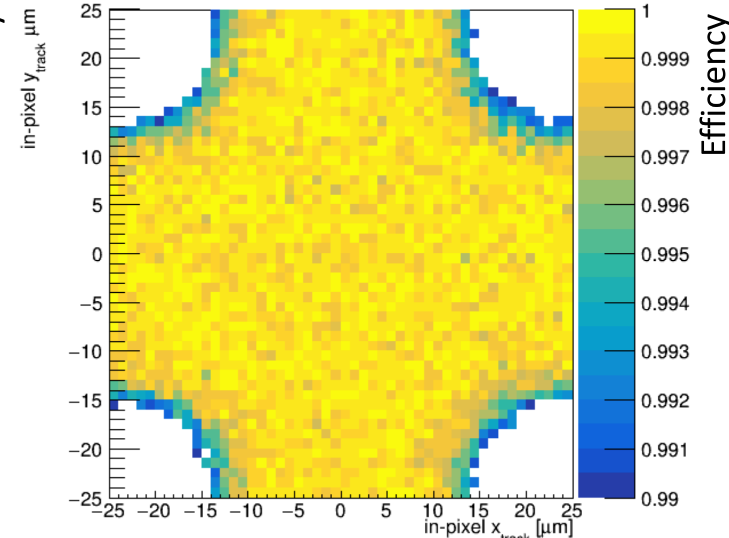
0 V



10 V

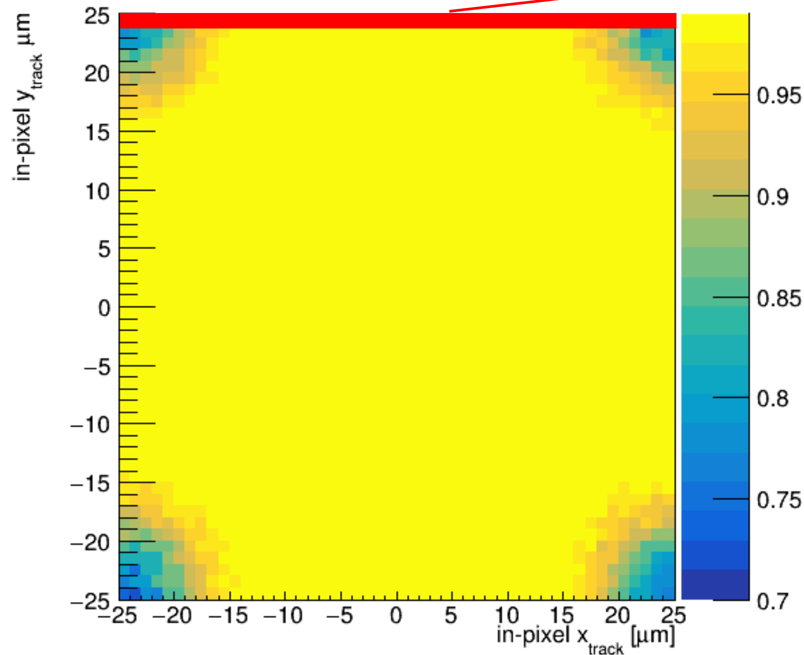






Projection of first row: 0 V vs 10 V bias

- 3D sensor is already efficient at 0 V bias
- Not evident differences between 10 V and 0 V bias in terms of the extension of the low efficiency zone



Efficiency: Projection of the first row of the pixel cell

Efficiency

— 0 V

— 10 V

Ratio: 0 V / 10 V

in-pixel x_{track} [µm]

- From sensor CV measurements:
  - Lateral (col. sides) depletion at ~3 V bias
  - Complete depletion under n+ col at ~60 V bias

Summary: ITkPixV1.1 chip + FBK 3D sensor

ATLAS ITk

- ITk detector will be equipped with 3D sensor modules in the innermost layer (33-34 mm from collisions)
  - Expected radiation at HL-LHC after 2000 fb^{-1}, including 1.5 safety factor:
    - Max fluence = 1.9e16 n_{eq}/cm^2
    - Max TID = 1 Grad

- 8 SCC assembled in Genova: 2 bare chip (ITkPixV1.1) + 6 modules (ITkPixV1.1 + FBK 3D sensor)
  - Chips are responding properly, tuned to 1000 e threshold: 70 ± 10 e mean noise @ 10 V bias
  - Sensors IV are compatible with wafer level measurements: leakage current < 0.05 $\mu A/cm^2$ @ 25 V bias

- Testbeam data with proton beam perpendicular to SCC, unirradiated devices:
  - PS (1, 2, 4, 6, 10 V bias): efficiency > 97.5 %
  - SPS (0, 10 V bias): efficiency = 98.9 ± 0.1 % @ 10 V bias
    - Central area: efficiency = 99.91 ± 0.02 % @ 10 V bias
    - Lower efficiency zones visible in corners (75% – 99%): 10 µm radius (4 µm p^+ columns)

- Irradiation ongoing (SPS testbeam expected in summer)
  - 2 SCC to 1e16 n_{eq}/cm^2 (Bonn, 14 MeV protons)
  - 2 SCC to 1.7e16 n_{eq}/cm^2 (IRRAD, 24 GeV protons)

Acknowledgements

ATLAS ITk

Thank you for the attention!

Posters:

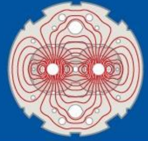
D M S Sultan et al. *“Quality Control of FBK 3D Si Sensors from the ATLAS ITk Preproduction”*
Md Arif Abdulla Samy et al. *“Cold Temperature characterization of Ring Triplets based on RD53A readout chip”*

Credits:

T. Heim, H. Yang: *Chip operations with YARR SW & FW*
https://gitlab.cern.ch/YARR/YARR
S. Hadžić, Y. Tian: *Testbeam data analysis with Corrywreckan*
https://gitlab.cern.ch/corryvreckan/corryvreckan
A. Rummler, F. Guescini: *Testbeam coordination*

High Luminosity timeline

ATLAS ITk



LHC / HL-LHC Plan

LHC

HL-LHC

Run 1 | Run 2 | Run 3 | Run 4 - 5...

7 TeV

8 TeV

LS1

splice consolidation
button collimators
R2E project

13 TeV

EYETS

cryolimit
interaction
regions

LS2

Diodes Consolidation
LIU Installation

Civil Eng. P1-P5

pilot beam

13.6 TeV

EYETS

inner triplet
radiation limit

LS3

HL-LHC
installation

13.6 - 14 TeV

energy

2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2040

75% nominal Lumi

experiment
beam pipes

nominal Lumi

2 x nominal Lumi

ATLAS - CMS
upgrade *phase 1*

ALICE - LHCb
upgrade

2 x nominal Lumi

ATLAS - CMS
HL upgrade

5 to 7.5 x nominal Lumi

$30\ fb^{-1}$

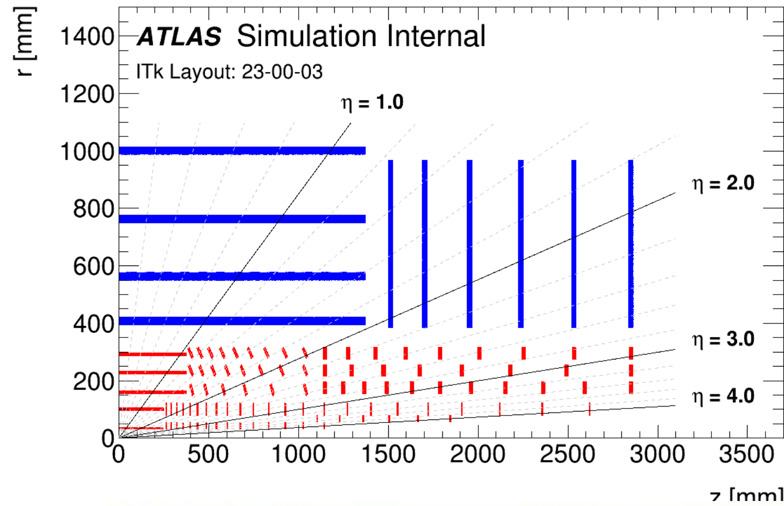
$190\ fb^{-1}$

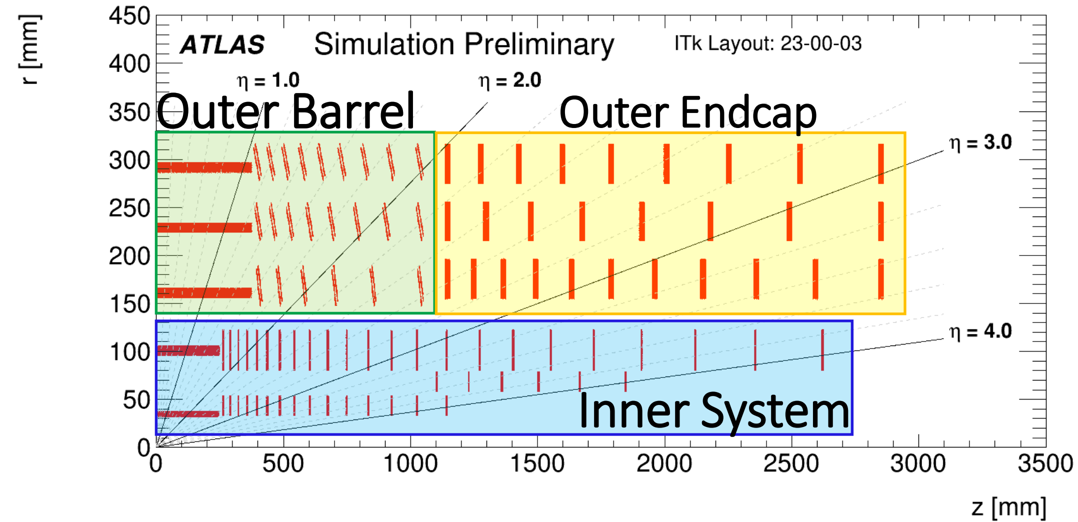
$450\ fb^{-1}$

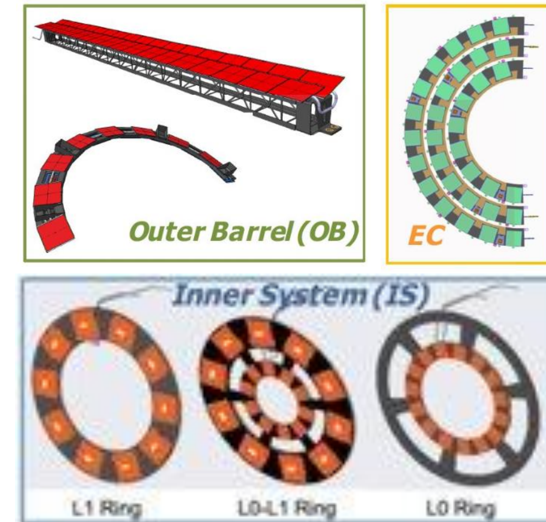
integrated
luminosity

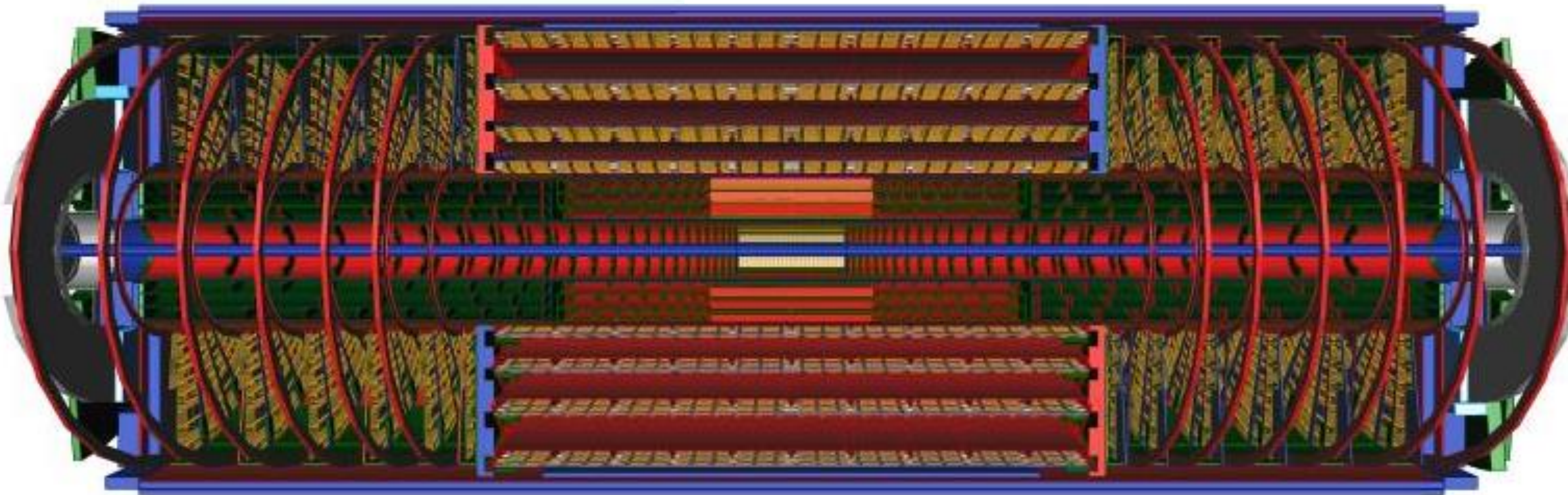
$3000\ fb^{-1}$
$4000\ fb^{-1}$

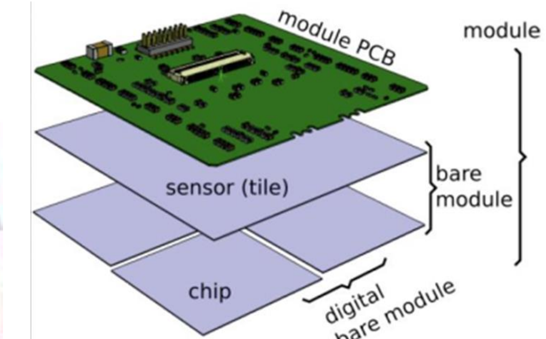
Inner Tracker layout





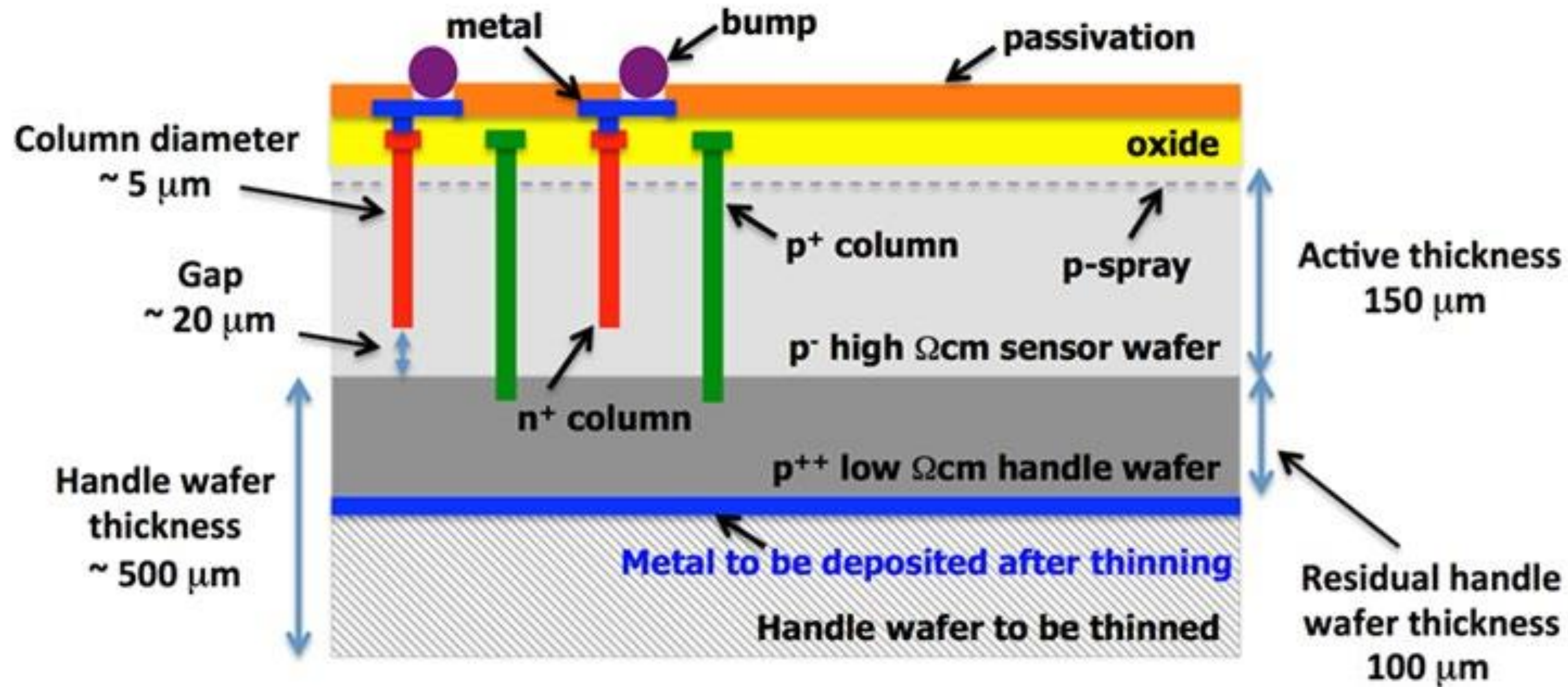






3D sensor detail – Bare module assembly

3D Sensor



Bare module