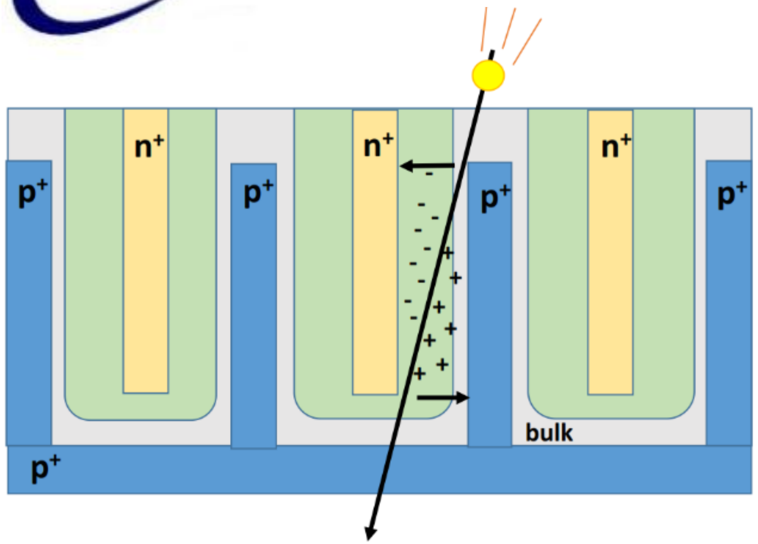
16th “Trento” Workshop on Advanced Silicon Radiation Detectors

16-18 February 2021



Performance of irradiated FBK 3D sensors for the ATLAS ITk pixel detector

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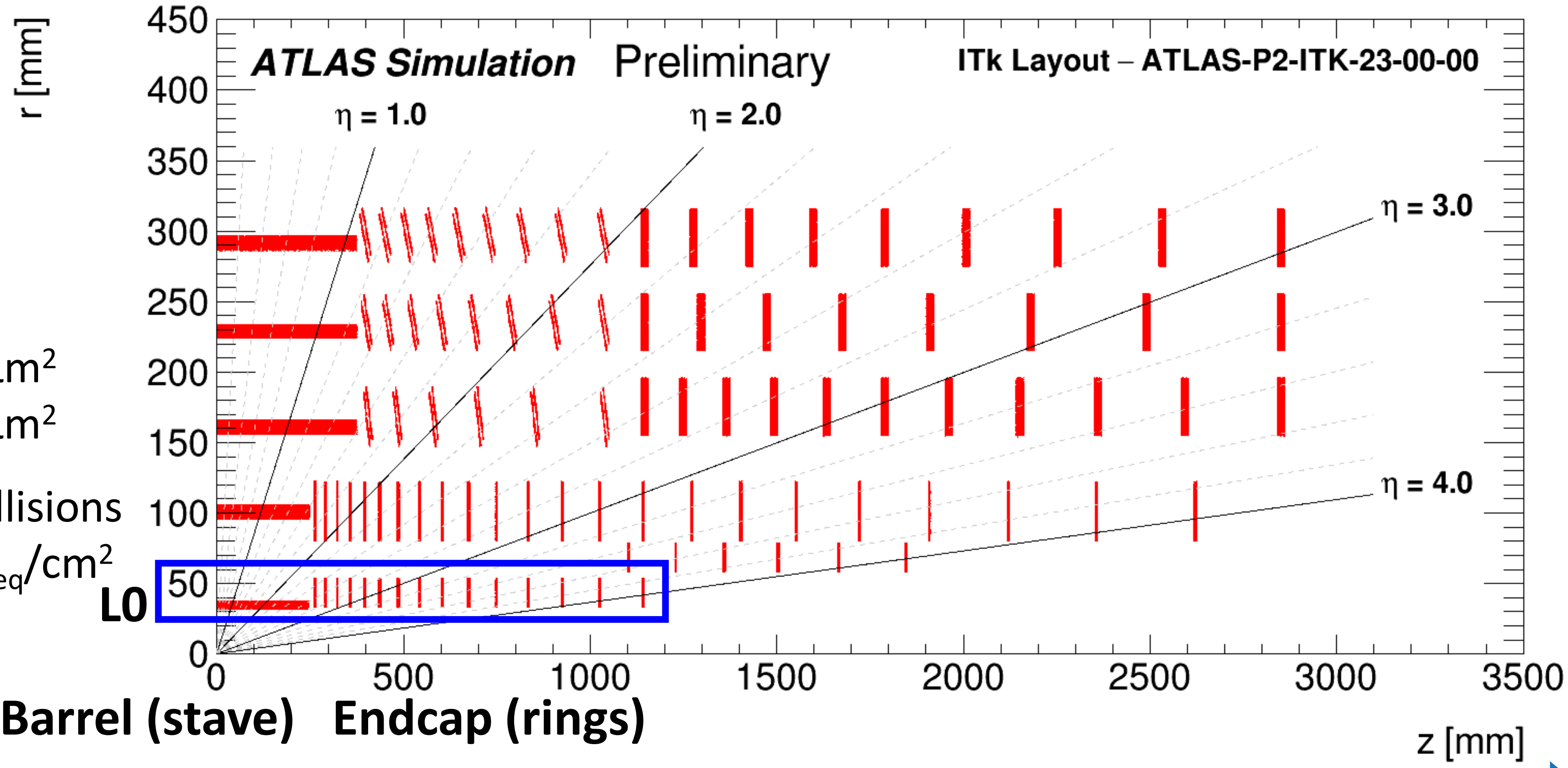
FONDAZIONE BRUNO KESSLER

Introduction

- Inner Tracker (ITk): a new silicon tracking detector in preparation for the ATLAS upgrade at the HiLumi-LHC
- Pixel: R&D phase to find the best solution, as a compromise between radiation tolerance and performance
- Details of the latest design version: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2020-002/

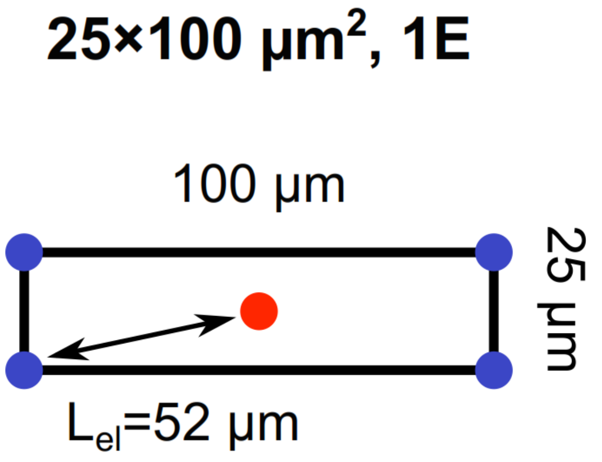
- 5 layer of pixels:
  - **L4**: Planar sensors
  - **L3**: Planar sensors
  - **L2**: Planar sensors
  - **L1**: Planar sensors
  - **L0**: 3D sensors
    - Barrel: 25x100 μm^2
    - Endcap: 50x50 μm^2
- Barrel at 34 mm from collisions
  - Dose up to 1.8e16 n_{eq}/cm^2
- L0 triplet modules
  - barrel: 288
  - endcap: 900



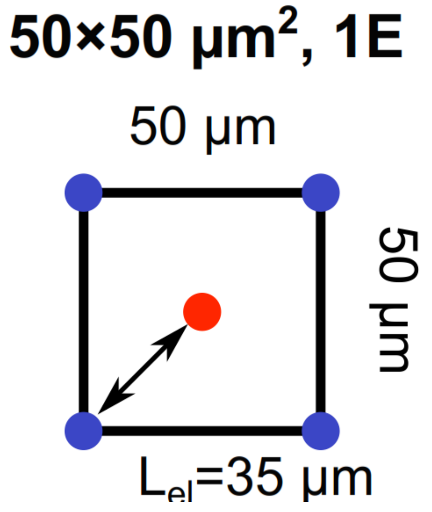
FBK pixel 3D sensors for ITk L0

- L0 of the ITk Pixel detector will be equipped with 3D sensors
  - 25x100 μm^2 in the barrel → linear triplet modules to be placed on stave
  - 50x50 μm^2 in the endcap → curved triplet modules to be placed on ring
- In the last years, several R&D production of wafers by FBK
  - Batch 2: Mask aligner, 130 µm active thickness
    - 5 wafers: 2 to Leonardo and 3 to IZM
  - Batch 3: Stepper, 150 µm active thickness
    - 11 wafers: 2 to Leonardo and 2 to IZM
  - Sensors 1x2 cm^2 compatible with the RD53A chip
  - Assembled in modules (3D sensor + RD53A chip) on card (SCC)

- In this talk, a summary of results from FBK 3D sensor irradiated modules
  - Moreover, also diodes test structures irradiated and tested
- Meanwhile FBK, CNM and SINTEF foundries are preparing for pre-production
- ATLAS institutes are preparing for ITk module assembly and test
  - Briefly introducing the triplet module and an assembly method (Genoa)



L0 barrel



L0 rings

6 modules irrad. to 1e16 n_{eq}/cm^2

- Recent results from 6 RD53A modules built from batch 3 sensors (150 µm active thickness)
  - Irradiated uniformly at CYRIC (70 MeV protons)
  - Fluence: 1.0e16 n_{eq}/cm^2
  - TID: 700 Mrad

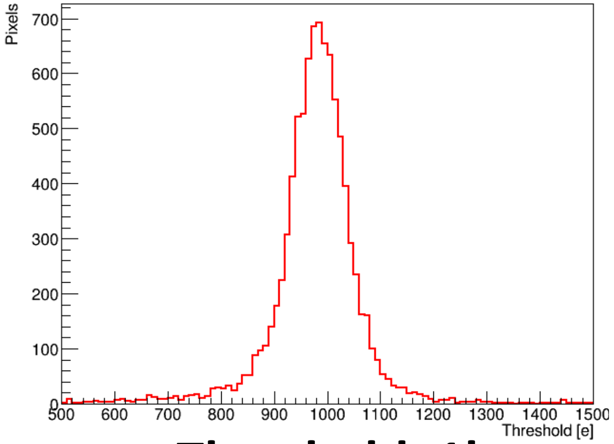
- 2 sensors from wafer 27 (thinned)
  - F03_27_25x100-1E_**D4.1** → damages to chip WBs → in lab, measured IV
  - F03_27_50x50-1E_**E6.5** → damages to chip WBs → in lab, measured IV
- 2 sensors from wafer 27 (thinned)
  - F03_27_25x100-1E_**D10.4** → sensor OK, but problematic chip → only IV
  - F03_27_25x100-1E_**D11.2** → sensor high current, while chip OK → only IV
- 2 sensors from wafer 30 (not thinned)
  - F03_30_50x50-1E_**E3.3** → sensor and chip OK → IV and testbeam data →
  - F03_30_25x100-1E_**D9.5** → sensor and chip OK → IV and testbeam data →

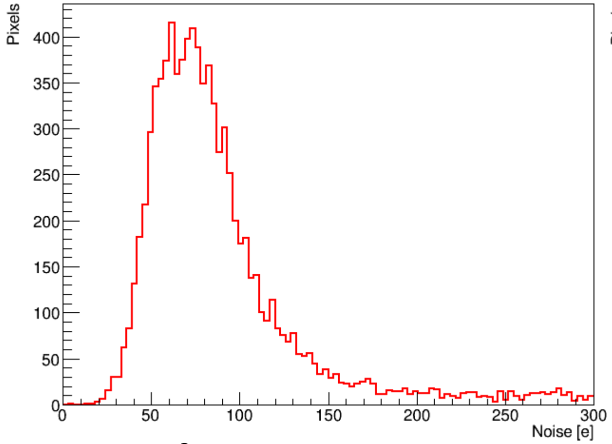
- Testbeam data results shown today for E3.3 and D9.5
  - Data taking at DESY in October 2020

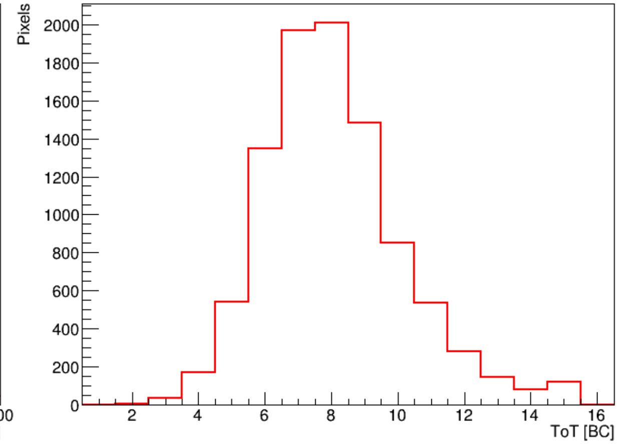
Tuning

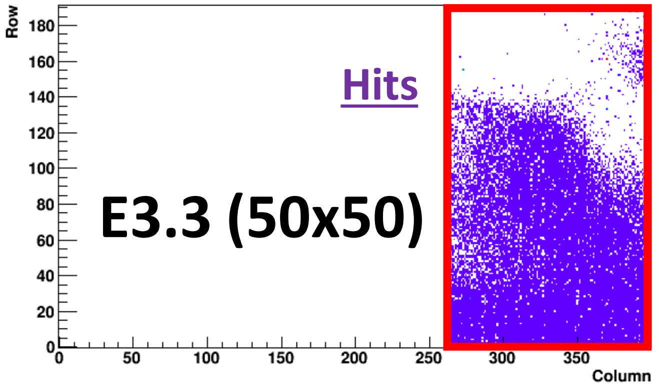
- Data taking at DESY II 6 GeV electron beam
- Chip tuning: Differential Front End
- Top right corner: bumps damaged → no hits recorded there

RD53A Differential Front End

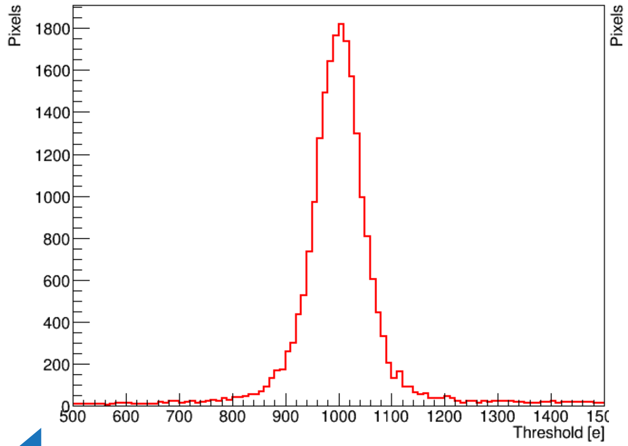


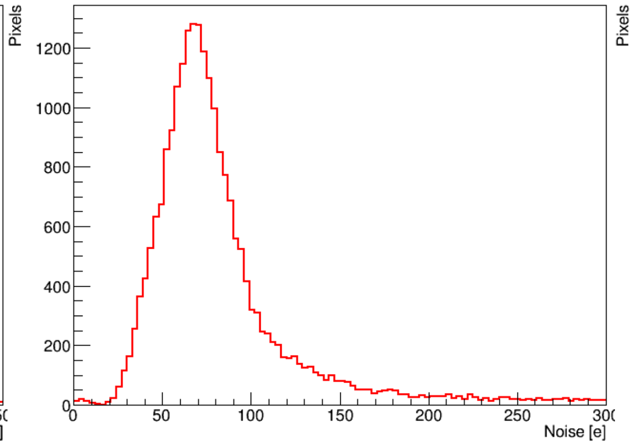


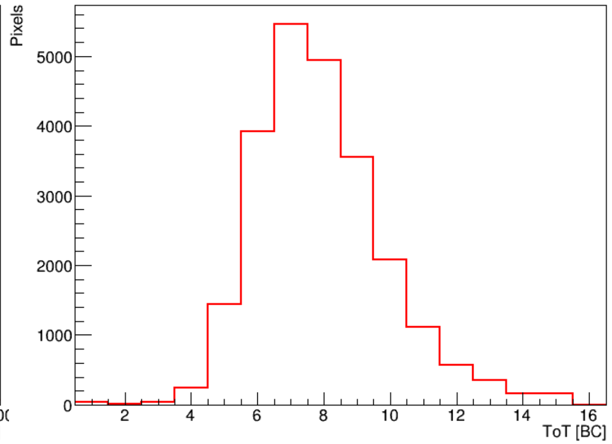


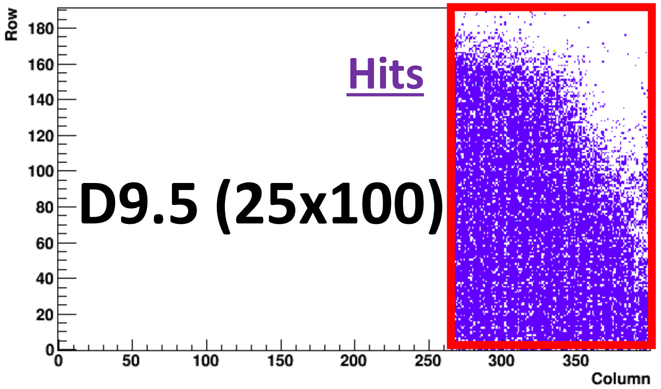


Threshold: 1ke **Noise: ~70e** **ToT: 10ke @ 7 BC** **Data taking**





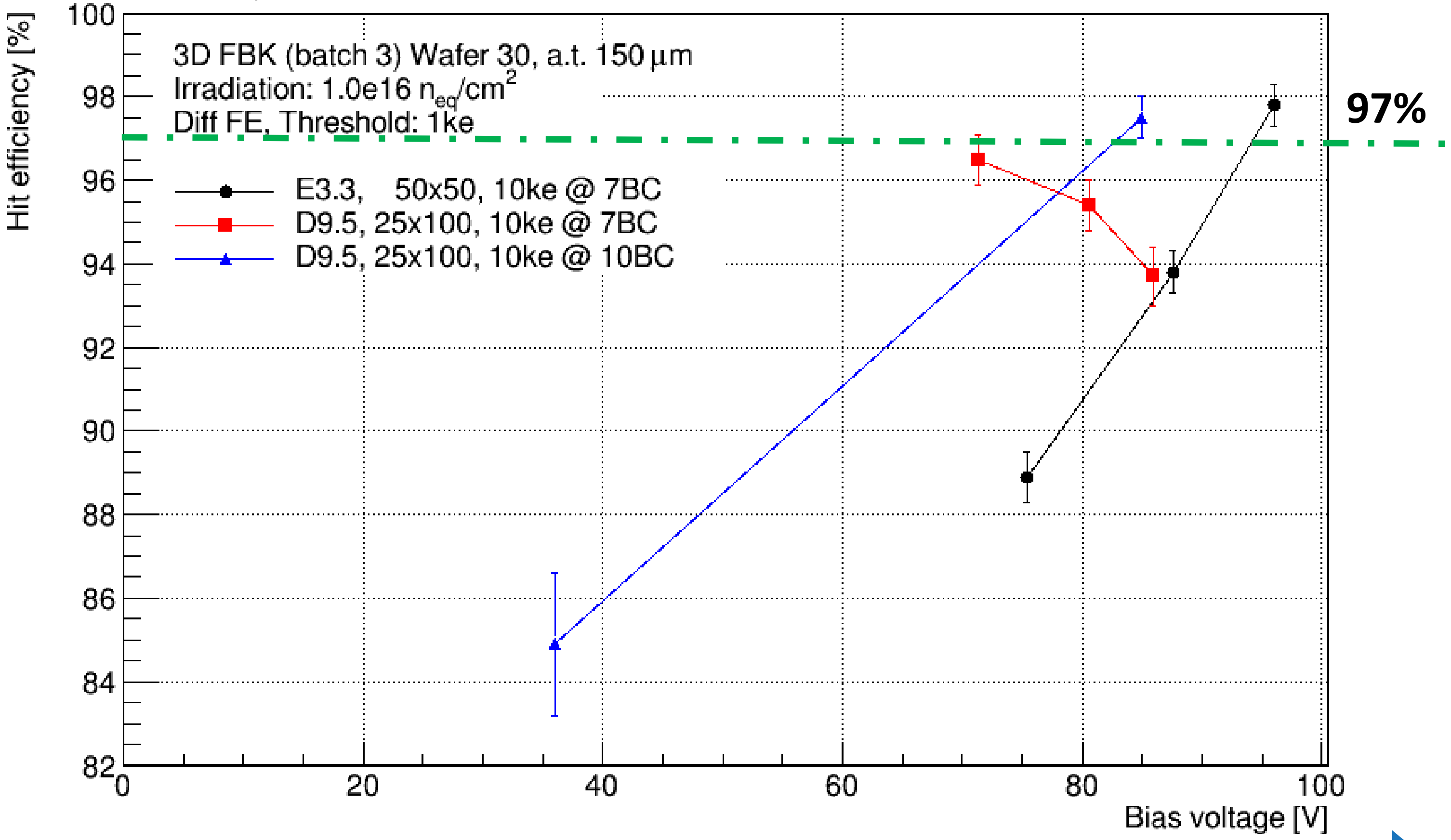




Efficiency

- Hit detection efficiency higher than 97% above 90 V bias
  - Confirmation of many experimental results from other pixel modules irradiated to 1.0e16 n_{eq}/cm^2
  - Testing modules irradiated to 1.0e16 n_{eq}/cm^2 has become a routine
  - Planning an irradiation campaign up to 2.0e16 n_{eq}/cm^2 at Los Alamos in June 2021

- Unexpected behaviour of D9.5
  - Decreasing efficiency at higher V_{eff}
- Let's take a look at the charge collection!

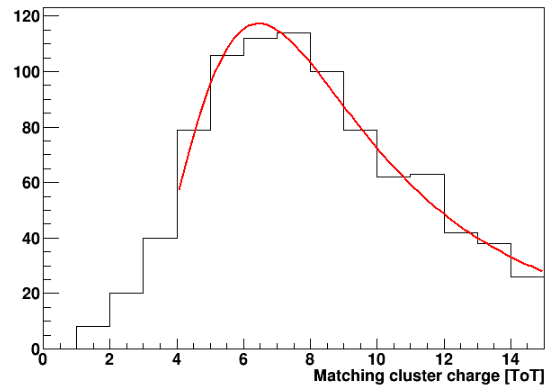


D9.5 ToT tuning 10ke @ 10BC

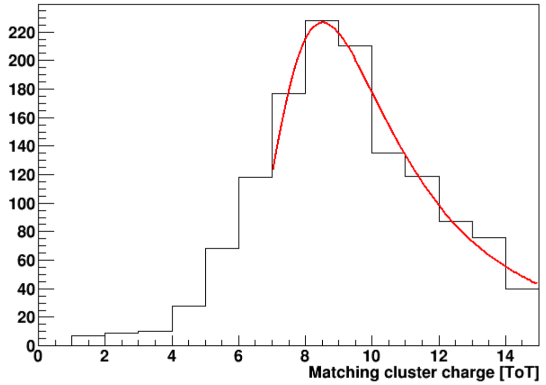
- D9.5 (25x100 μm^2) module, ToT tuning: 10ke @ 10BC
- ToT vs charge calibration extrapolated by injecting 3-to-10ke charge
- Cluster ToT converted in charge exploiting the calibration
- Higher V bias → cluster ToT → collected charge → efficiency
  - At 97% efficiency, collected 8.5 ke charge (75% of 11ke expected)

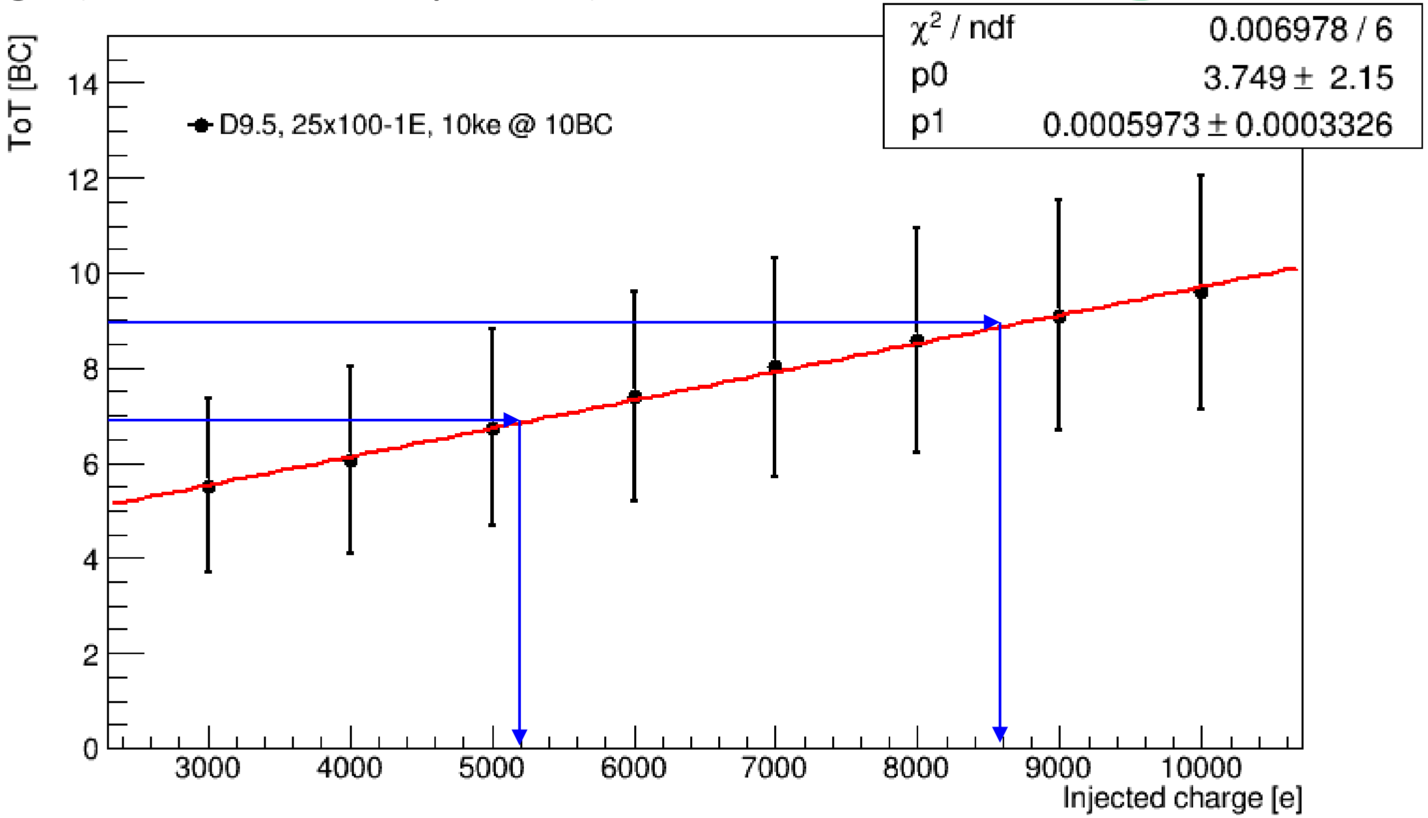
V_{eff} [V]	Cluster ToT MPV	Charge [ke]	Eff [%]
36.0	6.8	5.2	84.9
85.0	8.8	8.6	97.5

V_{eff} = 36 V
Eff = 84.9 %



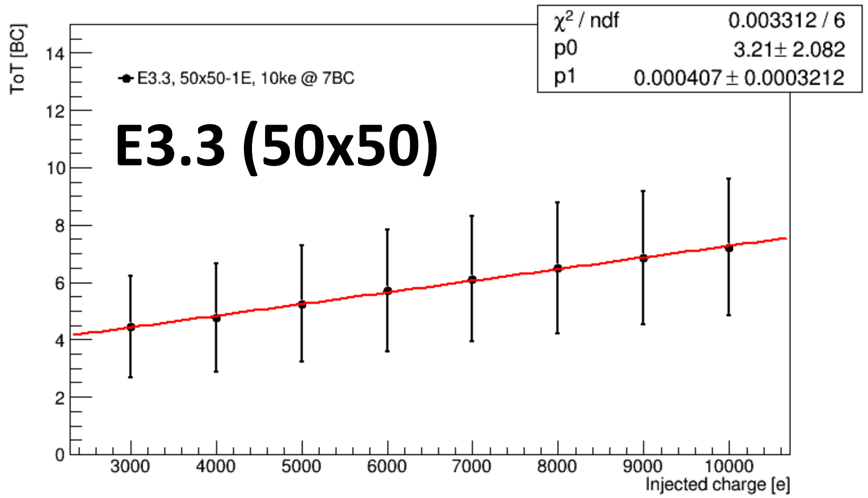
V_{eff} = 85 V
Eff = 97.5 %

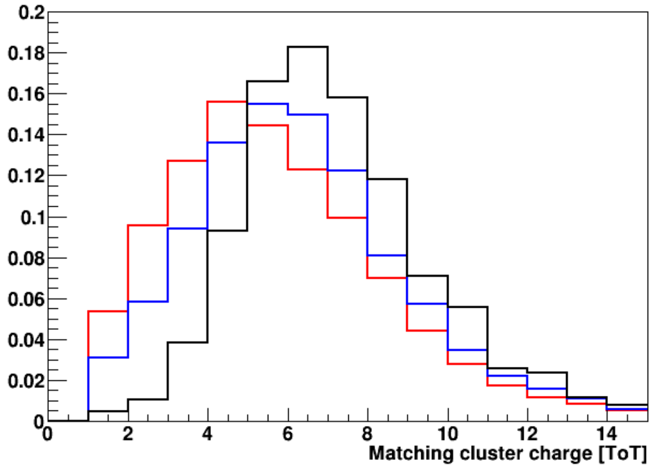




E3.3 - D9.5 ToT tuning: 10ke @ 7BC

- Again, exploiting the calibration curve, the collected charge was extrapolated from the cluster ToT
- Tuning of D9.5 was not effective: ToT & charge decreased when increasing V bias → could explain eff. drop

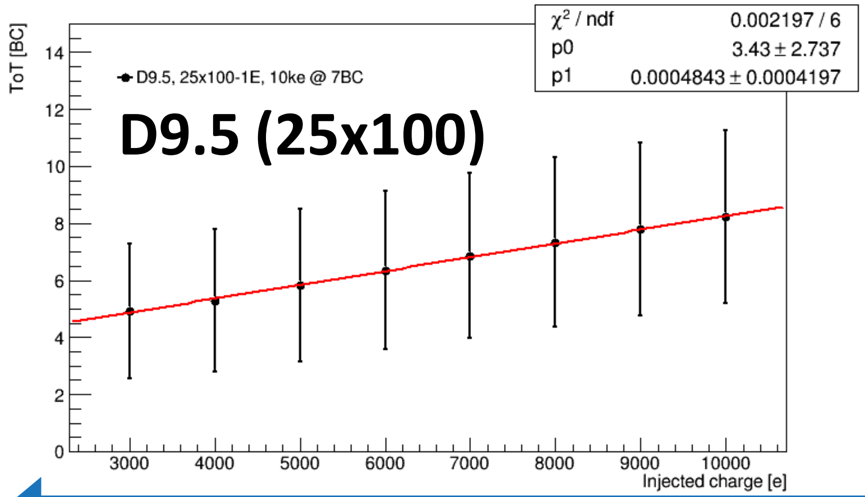


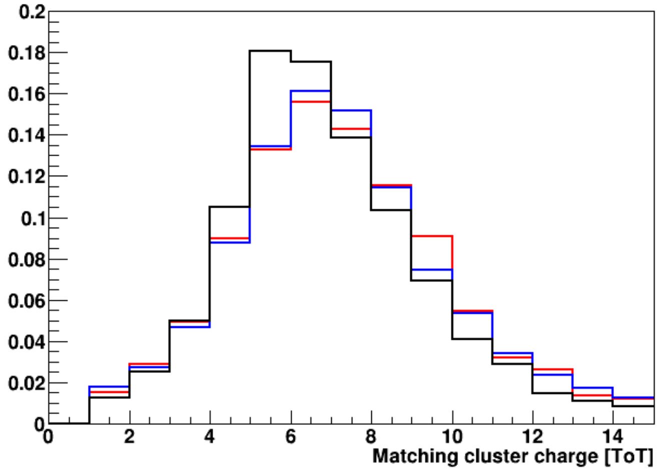


V_{eff} [V]	Cluster ToT MPV	Charge [ke]	Eff [%]
75.4	4.8	4.2	88.9
87.6	5.7	6.1	93.8
96.0	6.4	7.5	97.8

Eff. ↑

(70% of 11ke expected in 150 μm)



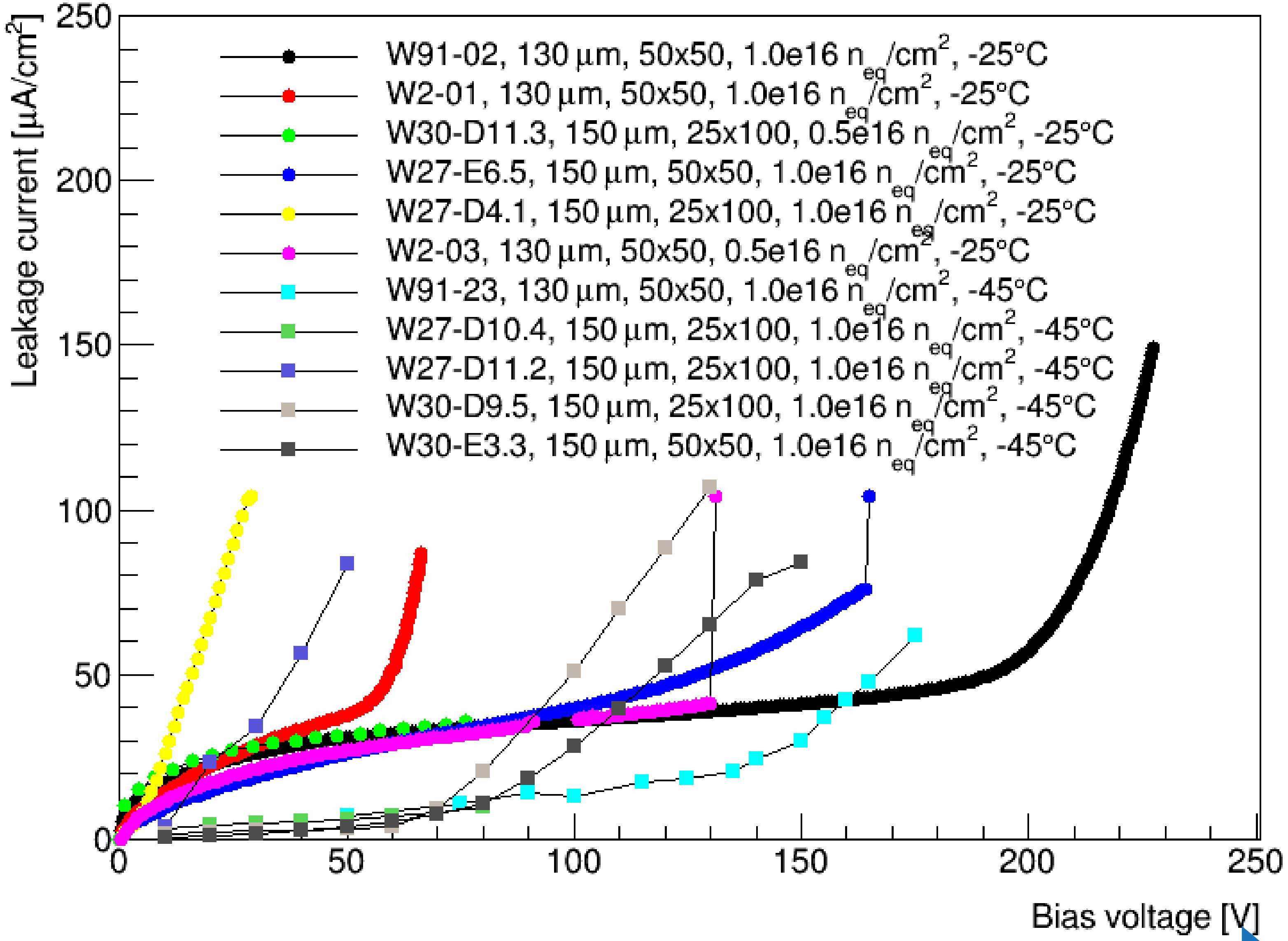


V_{eff} [V]	Cluster ToT MPV	Charge [ke]	Eff [%]
71.4	6.7	6.8	96.5
80.6	6.6	6.8	95.4
86.0	6.0	5.2	93.7

Eff. ↓

IV of irradiated 1x2 cm^2 sensors

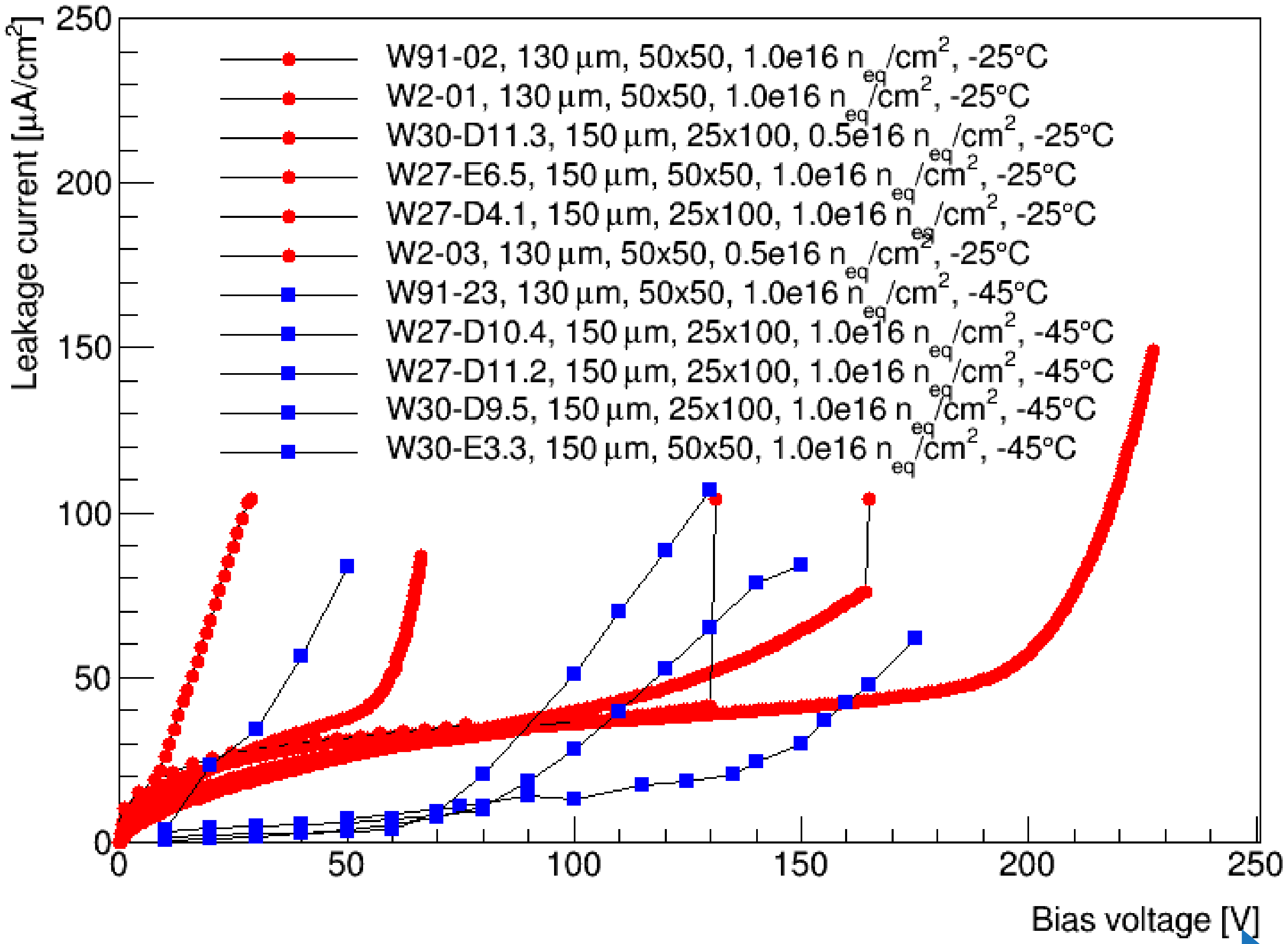
- 3D sensor + RD53A chip modules
- Irradiated at different facilities
- Different annealing times



IV of irradiated 1x2 cm² sensors

- 3D sensor + RD53A chip modules
- Irradiated at different facilities
- Different annealing times

- IV measured in different conditions:
  - **Dots: in lab, -25°C**
  - **Squares: at testbeam, -45°C**



IV of irradiated 1x2 cm² sensors

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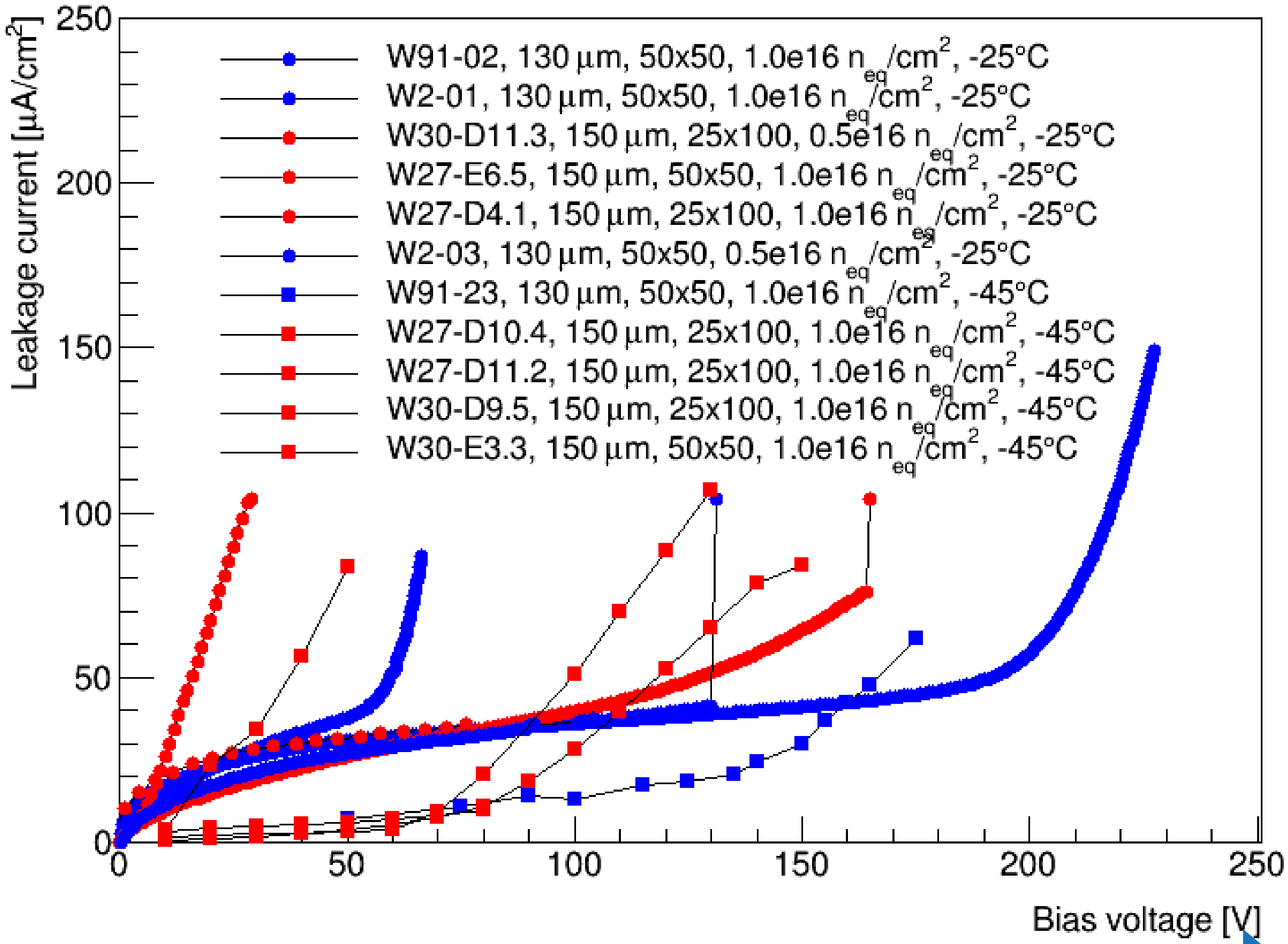
- IV measured in different conditions:
  - Dots: in lab, -25°C
  - Squares: at testbeam, -45°C

- Not visible effect of active thickness:
  - **Blue: Batch 2, 130 μm a.t.**
  - **Red: Batch 3, 150 μm a.t.**



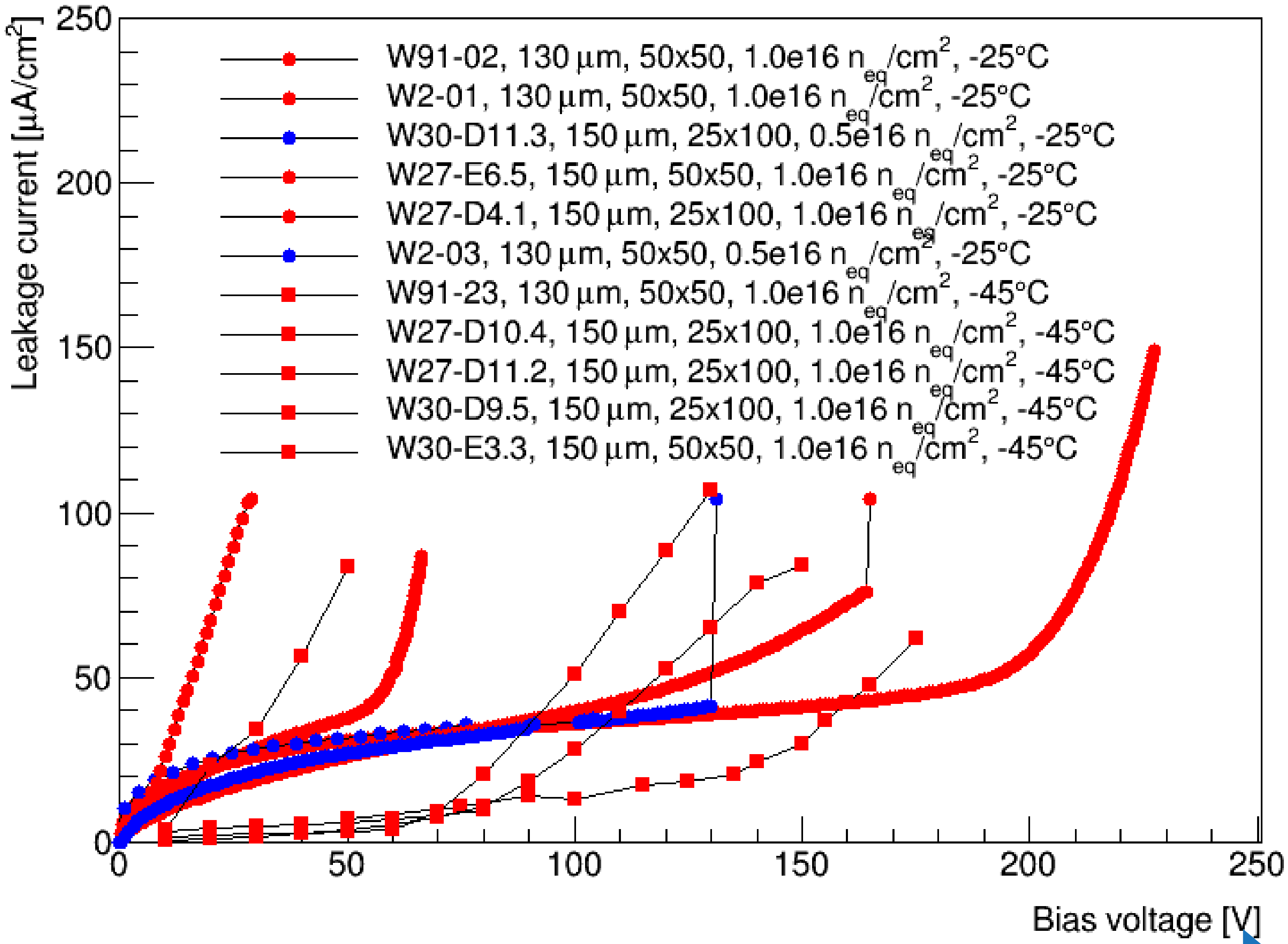
IV of irradiated 1x2 cm² sensors

- 3D sensor + RD53A chip modules
- Irradiated at different facilities
- Different annealing times

- IV measured in different conditions:
  - Dots: in lab, -25°C
  - Squares: at testbeam, -45°C

- Not visible effect of active thickness

- Negligible effect of additional dose:
  - **Blue: 0.5e16 n_{eq}/cm^2**
  - **Red: 1.0e16 n_{eq}/cm^2**



IV of irradiated 1x2 cm^2 sensors

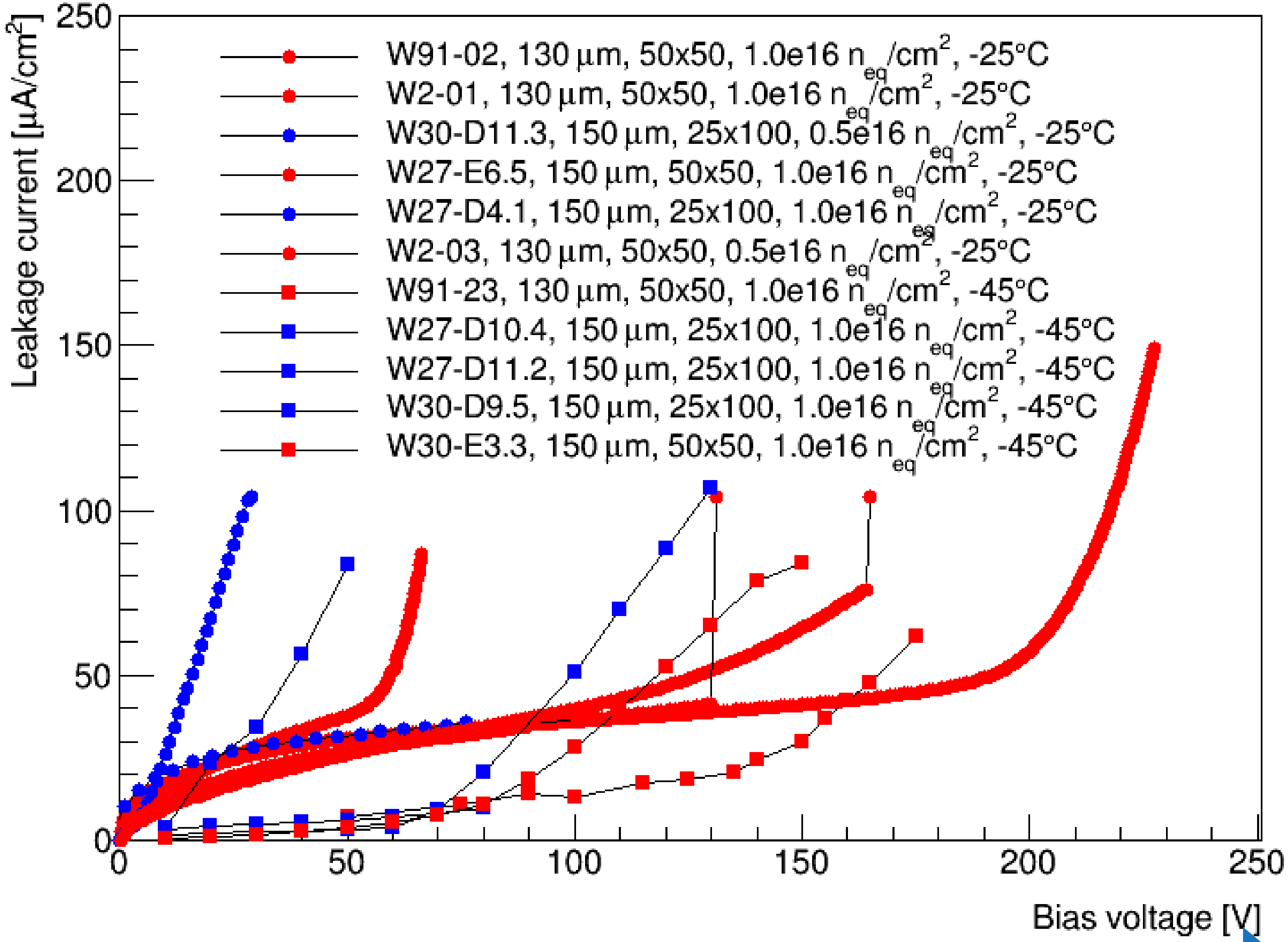
- 3D sensor + RD53A chip modules
- Irradiated at different facilities
- Different annealing times

- IV measured in different conditions:
  - Dots: in lab, -25°C
  - Squares: at testbeam, -45°C

- Not visible effect of active thickness

- Negligible effect of different dose

- Not significant effect of pixel size:
  - **Blue: 25x100**
  - **Red: 50x50**

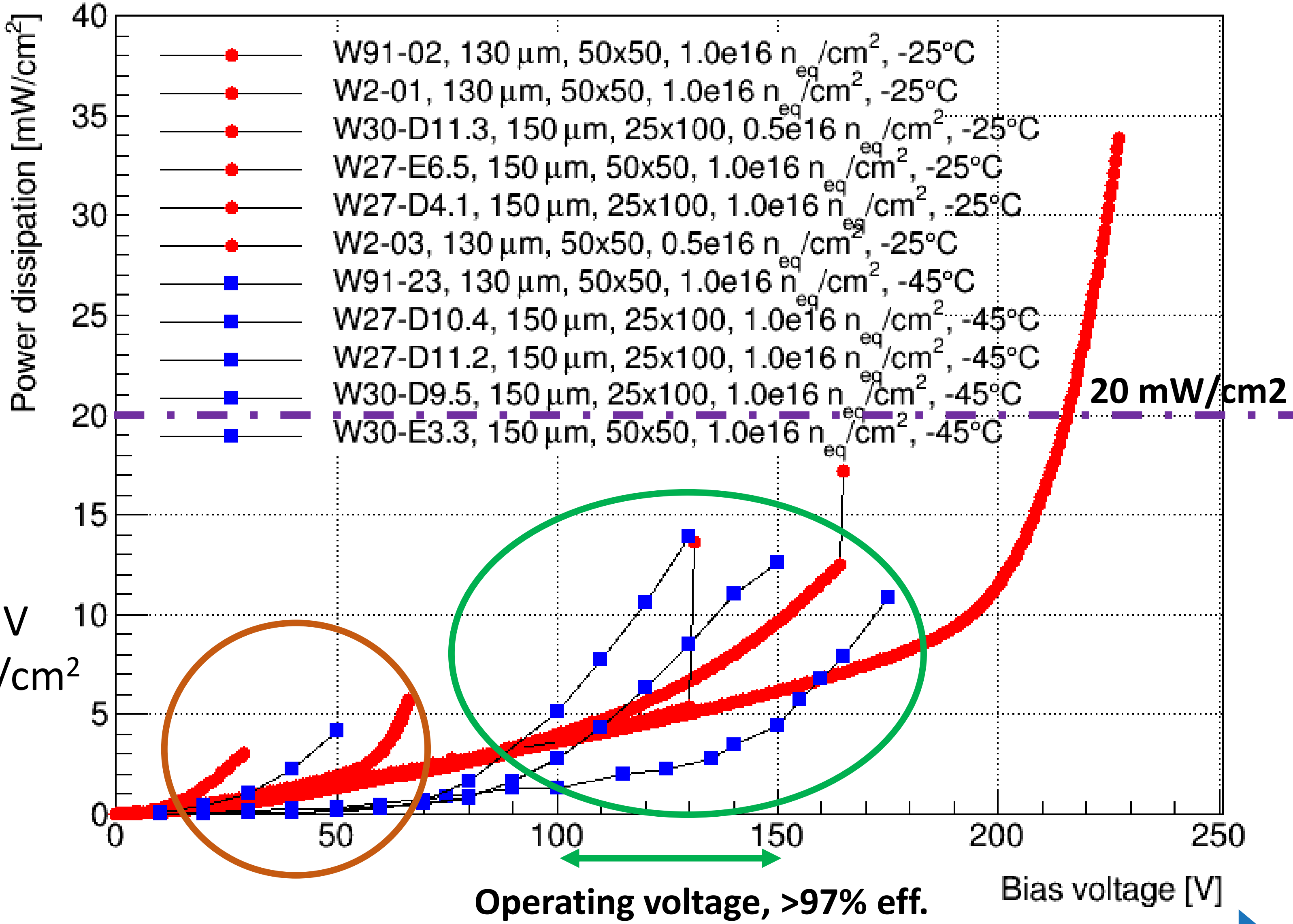


Power dissipation of irr. sensors

- 3D sensor + RD53A chip modules
- Irradiated at different facilities
- Different annealing times

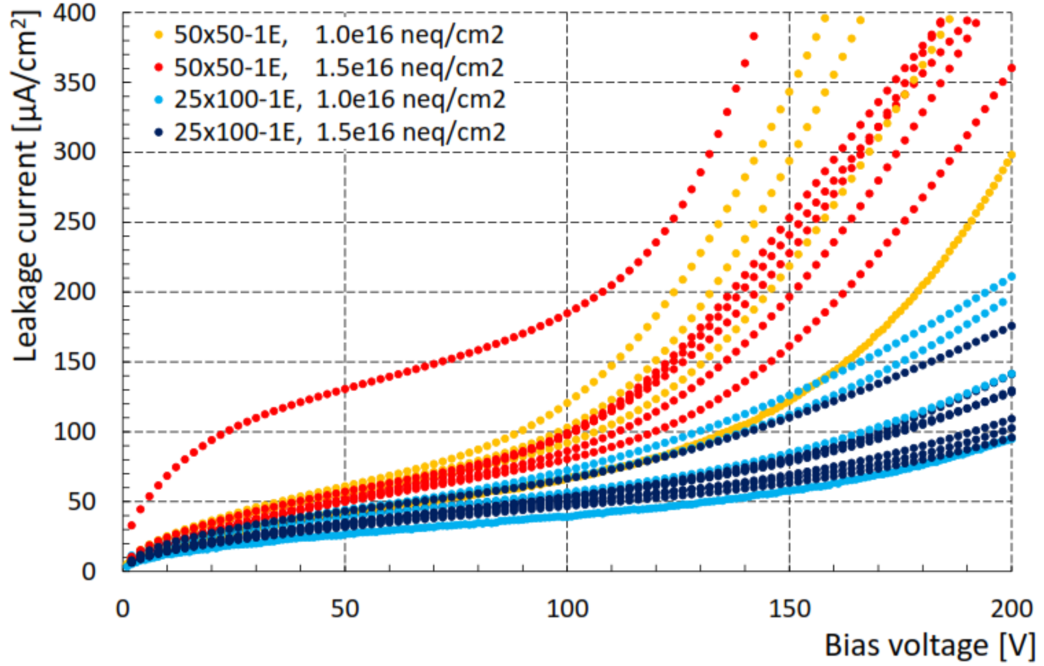
- IV measured in different conditions:
  - **Red dots: in lab, -25°C**
  - **Blue squares: at testbeam, -45°C**

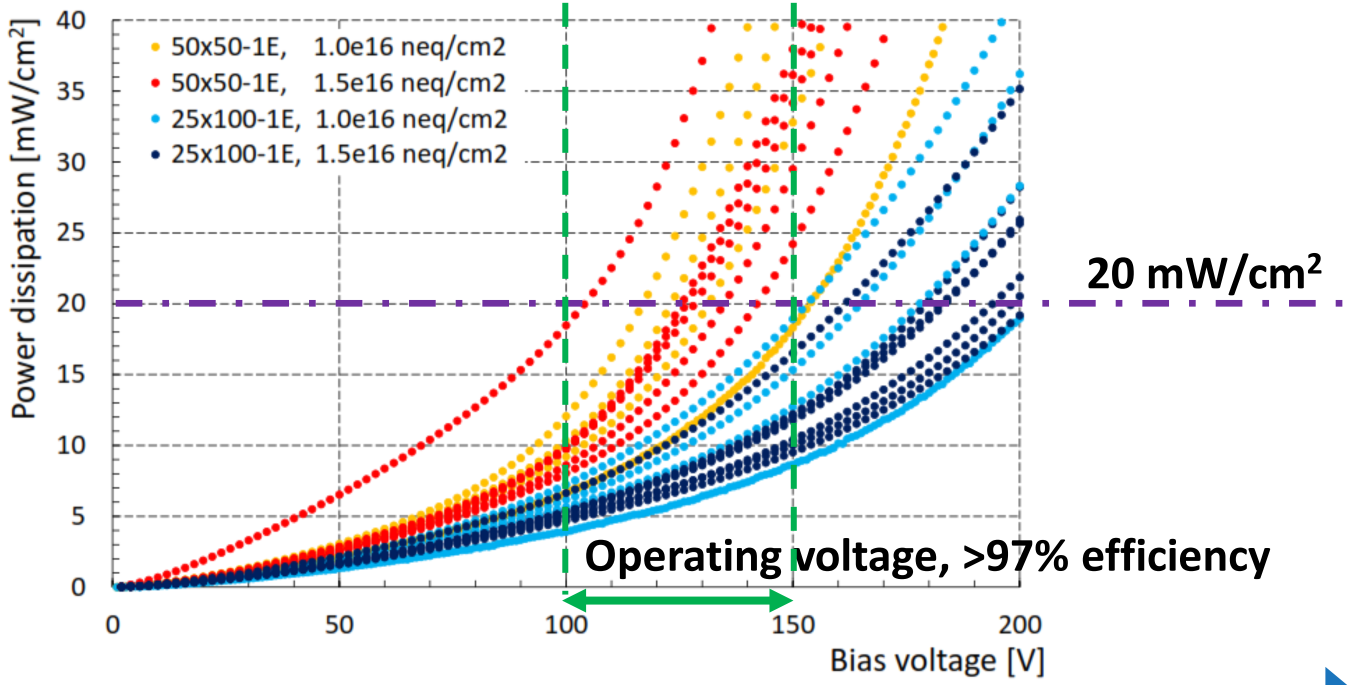
- **Power dissipation:**
  - Not possible to disentangle effects
  - Some early breakdowns → avoid!
  - Most IVs increase around 100-150 V
    - Power diss. still below 20 mW/cm²



Diodes: IV and power dissipation

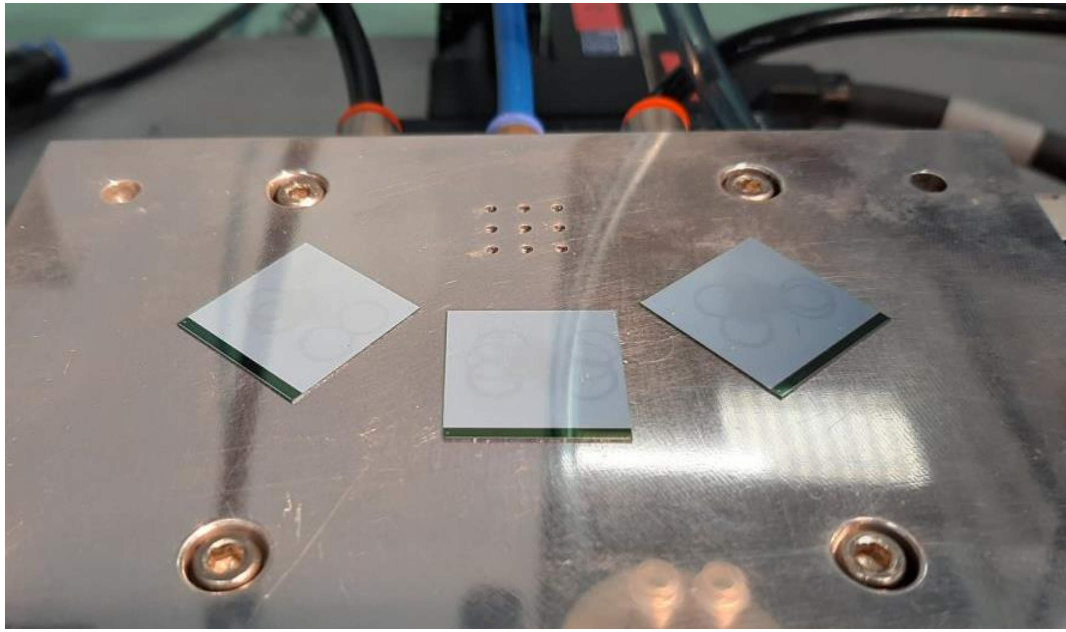
- 2 mm^2 diodes (n^+ columns shorted together) were produced together with modules inside FBK wafers
  - Irradiated to 1.0 and 1.5e16 n_{eq}/cm^2 with neutrons at JSI reactor, Lubiana
  - IV measured at -25°C (ITk operation temperature) in climate chamber
  - Spread between different diodes higher than the effect of higher dose (1.0 to 1.5e16 n_{eq}/cm^2)
  - 25x100 μm^2 performs better with respect to 50x50 μm^2 (lower current → lower power dissipation)
  - Power dissipation around 20 mW/cm^2 in the range 100-150 V of bias voltage (> 97% effic. since 80-90 V)
  - Small size diodes, contribution of the edges → 20 mW/cm^2 limit is therefore conservative

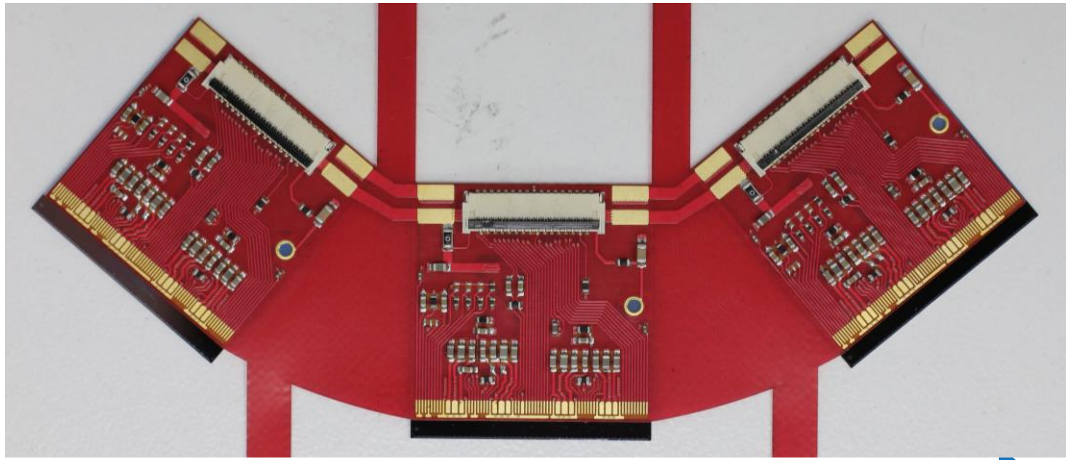


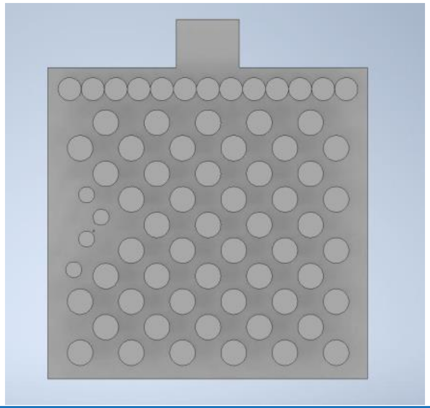


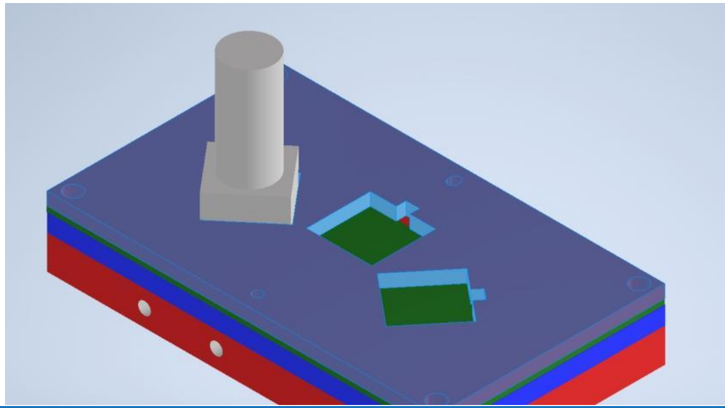
Triplet module assembly in Genoa

- While FBK, CNM and SINTEF produce pre-production sensors
- ITk institutes involved in the R&D on module assembly & test
- 6 teams: Genoa, Milan, Trento, Barcelona, Oslo, Bergen
- Assembly is done by gluing 3 bare modules to a flexible PCB
  - High precision in the bare module placement: ~50 µm
  - Uniform layer of Araldite 2011
    - Achieved by stamping the glue on the flexible PCB
  - Flexible PCB is placed on top of the 3 bare modules
- As soon as the assembly procedure is verified
  - First production of triplet modules (sensor + RD53A)
  - Then, modules with 3D sensor + ITkPixV1 chip will follow









Summary

- In the last years, several 3D sensor wafers were produced by FBK for R&D towards HiLumi-LHC application
- 1x2 cm^2 sensors bonded to RD53A chips were irradiated and tested
- Both 25x100 and 50x50 μm^2 sensors irradiated to 1.0e16 n_{eq}/cm^2 reach 97% detection efficienct at ~90V
- 97% efficiency is reached when the sensor collect at least ~8ke
  - This corresponds to a charge collection efficiency of the 70% (11ke deposited in 150 µm a.t. sensor)
- Leakage current very similar between 0.5 and 1.0e16 n_{eq}/cm^2
  - Seen also in diodes irradiated to 1.0 and 1.5e16 n_{eq}/cm^2 (spread larger than effect of the radiation)
- At 1.0e16 n_{eq}/cm^2, operating voltage would be around 100-150 V
  - At this voltage, power dissipation below 20 mW/cm^2
  - More systematical study with diodes (small area 2x2 mm^2)
    - Clearly visible that 25x100 dissipate less than 50x50 μm^2
- INFN Genoa started R&D for assembling triplet modules
- In the next months few triplet prototypes will be assembled
- Then, the pre-production of ITkPixV1 chip modules will follow
  - Ongoing pre-production of 2x2 cm^2 3D sensors
    - FBK and SINTEF focusing on 50x50 μm^2
    - CNM focusing on 25x100 μm^2

Some of these results in a summary paper just accepted:
https://www.frontiersin.org/articles/10.3389/fphy.2021.624668/abstract frontiers

Novel 3D pixel sensors for the upgrade of the ATLAS Inner Tracker

Stefano Terzo[1,*], Maurizio Boscardin[2], Juan Carlotto[1], Gian-Franco Dalla Betta[3,4], Giovanni Darbo[5], Ole Dorholt[6], Francesco Ficorella[2], Giuseppe Gariano[5], Claudia Gemme[5], Giulia Giannini[1], Sebastian Grinstein[1,7], Andreas Heggelund[6], Simon Huiberts[8], Angela Kok[9], Ozhan Koybasi[9], Alessandro Lapertosa[5,10], Magne Elk Lauritzen[8], Maria Manna[11], Roberto Mendicino[2,3,4], Hideyuki Oide[5], Giulio Pellegrini[11], Marco Povoli[9], David Quirion[11], Ole Myren Rohne[6], Sabina Ronchin[2], Heidi Sandaker[6], Md. Arif Abdulla Samy[3,4], Bjarne Stugu[8], and Leonardo Vannoli,[5,10]