

# Performance of radiation hard 3D pixel sensors for the upgrade of the ATLAS Inner Tracker

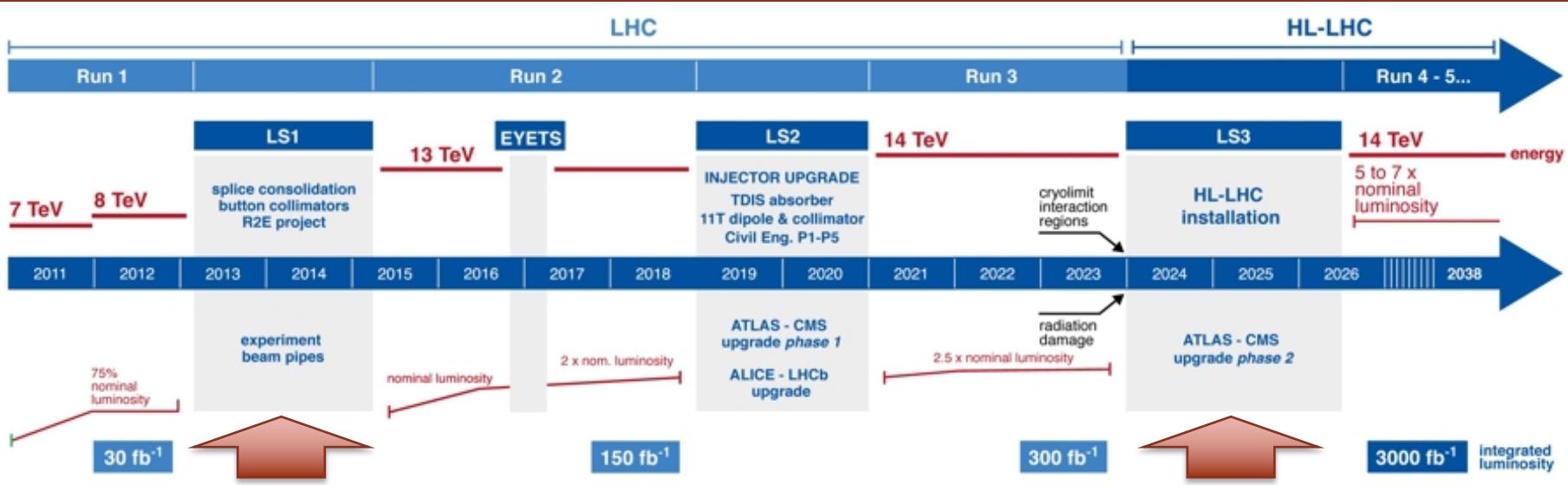
Stefano Terzo, Juan Carlotto, Sebastian Grinstein



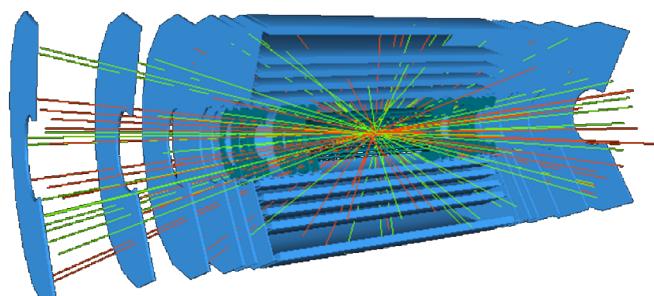
Maria Manna, Giulio Pellegrini, David Quirion



# ATLAS upgrade for HL-LHC

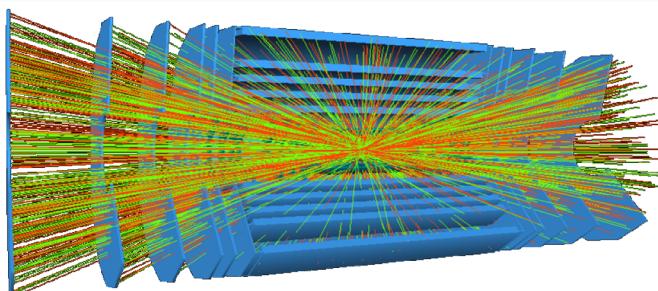


**Insertable B-Layer (IBL):** forth pixel layer at 3.2 cm from the beam line



- **LHC**
  - 19 Pile-up events

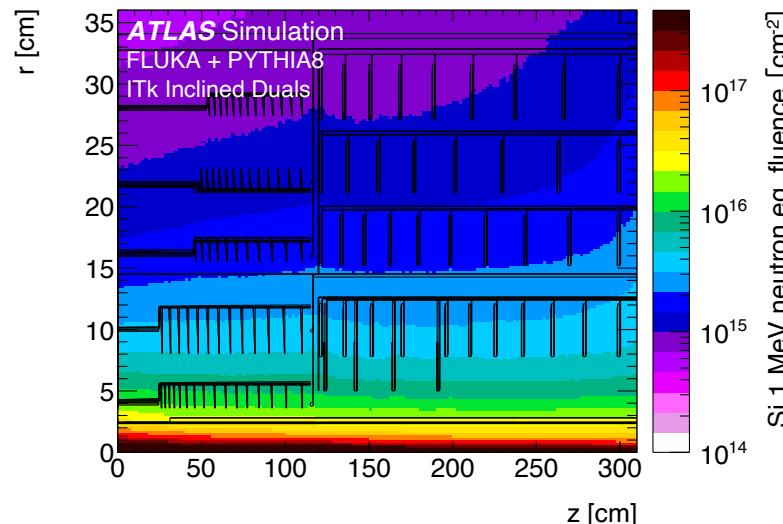
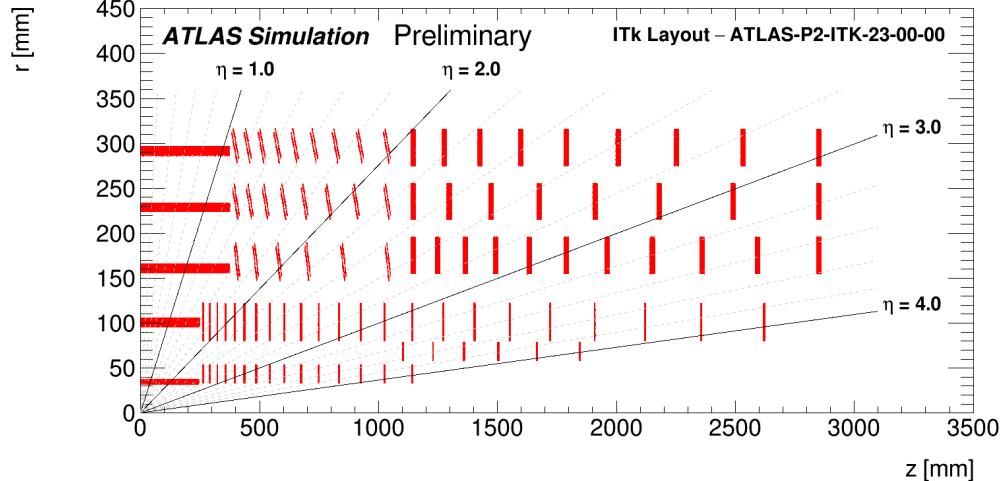
**“Phase II”:** full inner detector replacement (5 pixel layers)



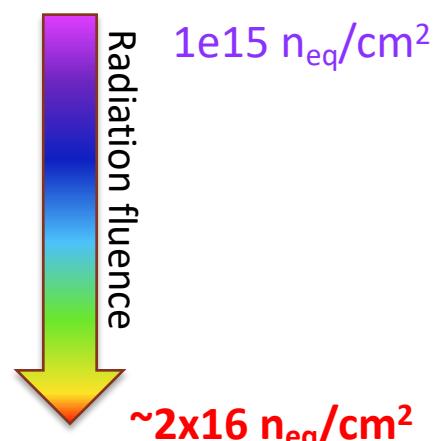
- **HL-LHC**
  - 140-200 Pile-up events
    - High particle multiplicity
    - Critical radiation damage

# The new Inner Traker (ITk)

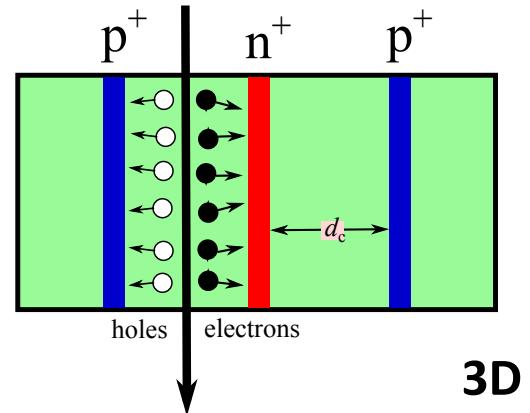
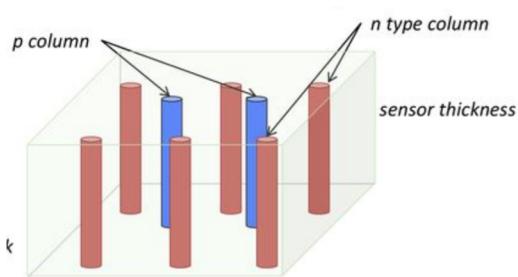
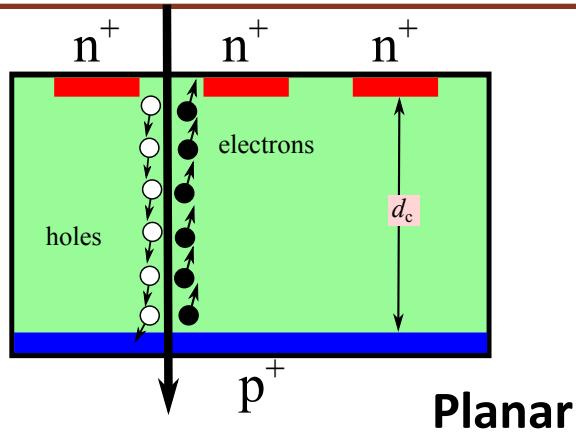
Replace the whole ATLAS Inner Detector with a new full-silicon Inner Tracker (ITk)



- New layout with *5 pixel barrel layers* & large  $\eta$  coverage
- **Sensor technologies:**
  - Outer pixel layers (3 layers)
    - n-in-p planar silicon sensors (150  $\mu\text{m}$  thick)
  - Inner pixel layers (2 replaceable layers)
    - Thin n-in-p planar silicon sensors (100  $\mu\text{m}$  thick)
    - **3D silicon sensors (Chosen for the innermost layer)**
      - **Barrel: pixel cell 25x100  $\mu\text{m}^2$**
      - **Rings: pixel cell 50x50  $\mu\text{m}^2$**



# 3D sensors vs Planar sensors



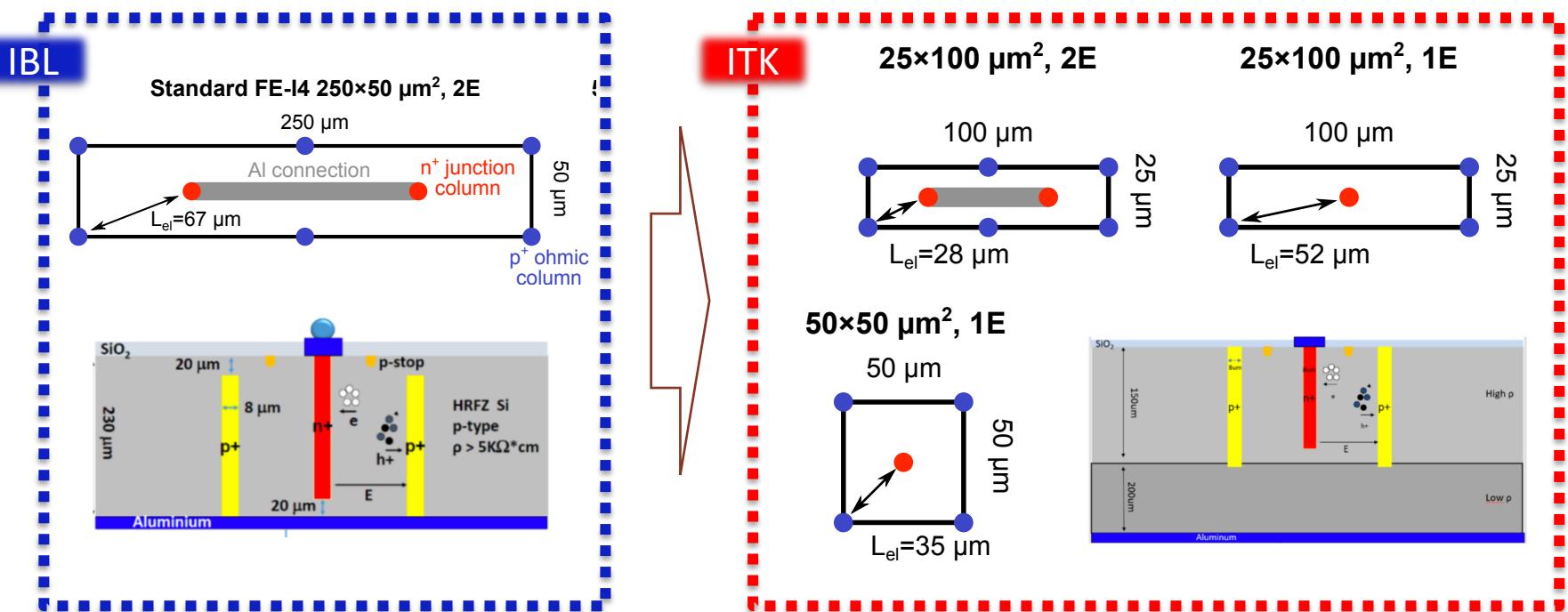
- **Advantages of 3D**

- 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**

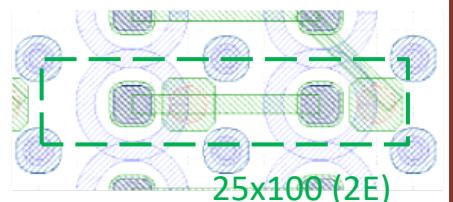
- Complex fabrication
  - Lower yield than Planars
  - Longer production times
  - More expensive
- Higher capacitance (noise)
  - Depending on the design:
    - Column distance, thickness, column width...
- Non uniform electric and weighting fields

# 3D pixel developments for ITk



- Small pixel cells, thin active substrates (150  $\mu\text{m}$  active thickness)**

- 50x50  $\mu\text{m}^2$  (1E) -> Rings
- 25x100  $\mu\text{m}^2$  (1E) -> Barrel
- 25x100  $\mu\text{m}^2$  (2E) -> Excluded due to problematic production yield
  - Critical lithography due to proximity of the bump-pad to the p-columns



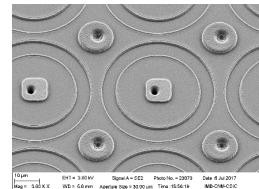
- Two important challenges for ITk sensors at very high radiation levels**

- Hit efficiency
- Power dissipation: Leakage current + operational voltage

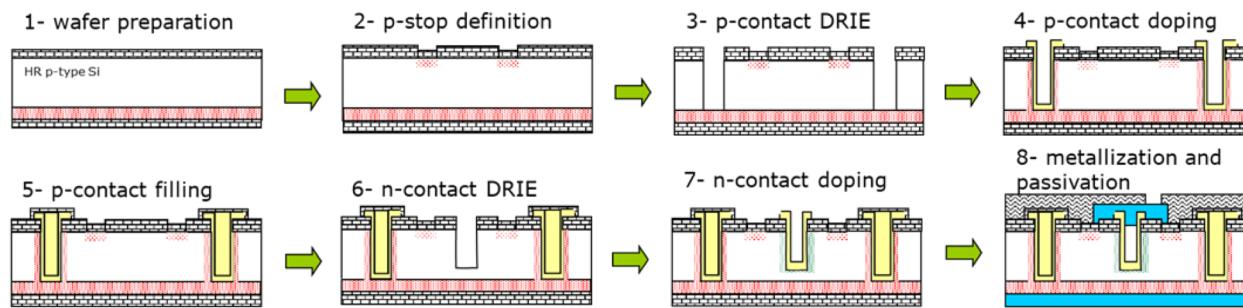
# 3D sensor production at CNM

- **Single-side 3D process at CNM, Barcelona**

- Both column types etched from the front side
  - Fully passing **p+ columns** and partially passing **n+ columns**
  - 130  $\mu\text{m}$  n-column depth, 8  $\mu\text{m}$  column diameter
- P-stop insulation



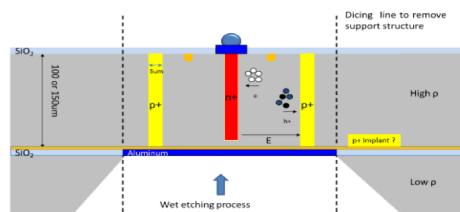
Picture from CNM Run9052



- **Two R&D runs with 3D sensors compatible to the RD53A prototype chip for ATLAS, and 3D diodes**
- **Run9761: Silicon-on-Insulator (SOI)**

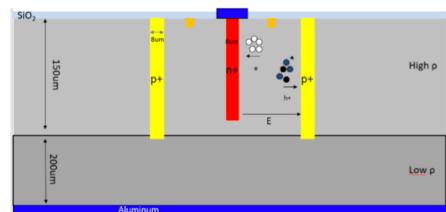
- Needs removal of the handle wafer for back-bias

SOI

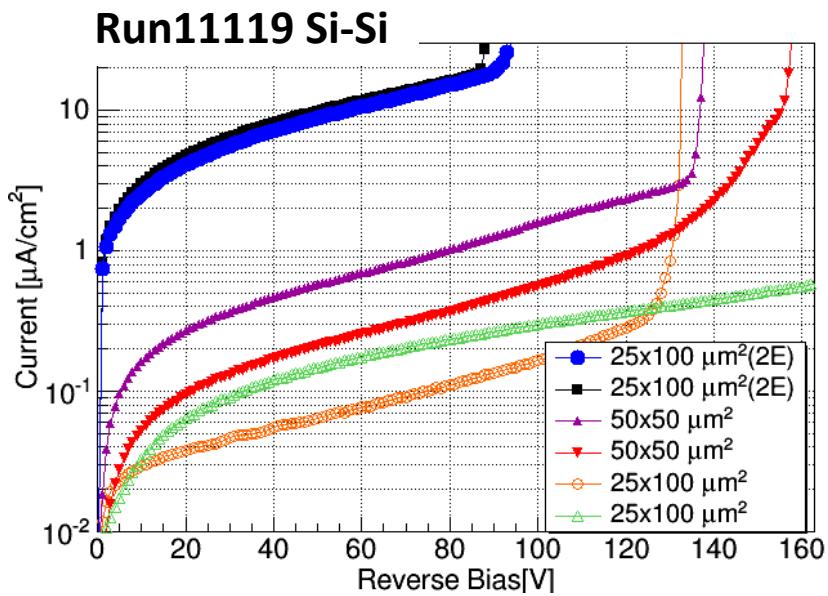
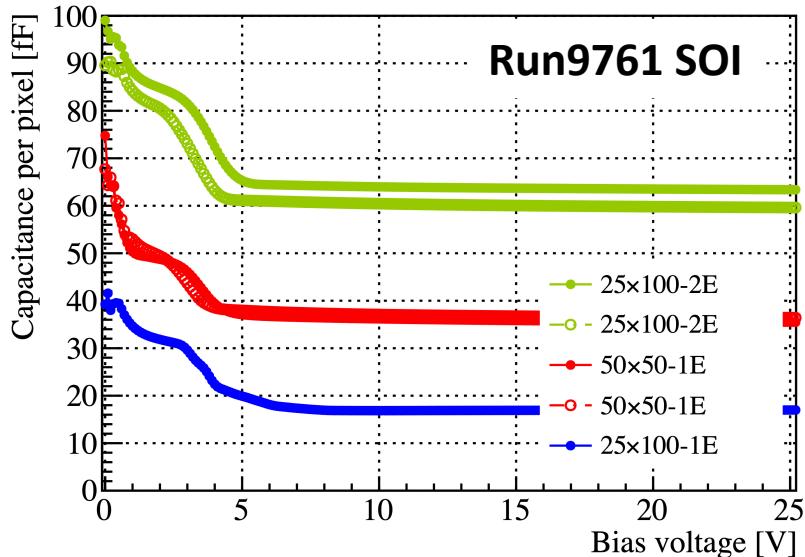
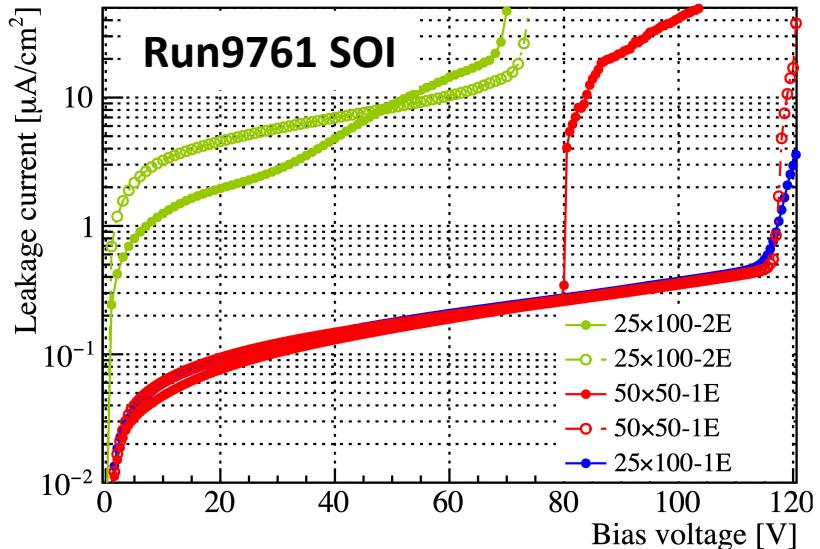
- **Run11119: Silicon-on-Silicon (SiSi)**

- Uses low resistivity handle wafer
  - No need for handle wafer removal for back-bias

SiSi



# Electrical characteristics (diodes)



- Very low depletion voltage: < 5V
- Good sensors have breakdown over 25 V and up to more than 100 V
- **25x100-1E** design has smaller current than the **50x50-1E** design
- **25x100-2E** design has the largest leakage current of all design and in general breaks at lower voltages

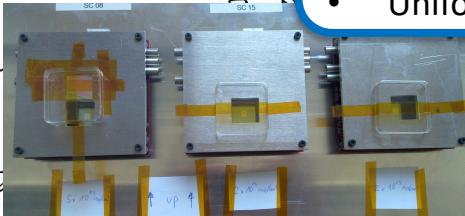
# Irradiations

**KIT, Germany**



This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

 AIDA<sup>2020</sup>



**RD53A**

- 23 MeV protons
- Large TID:  $\sim 750$  Mrad for  $5e15 n_{eq}/cm^2$
- Uniform irradiation at  $T < 0^\circ C$

**Birmingham, UK**

**RD53A**

- 27 MeV (up to 37 MeV) protons
- Large TID:  $\sim 650$  Mrad for  $5e15 n_{eq}/cm^2$
- Uniform irradiation at  $T < 0^\circ C$



**RD53A**

**CYRIC, Japan**

- 70 MeV protons
- Large TID:  $\sim 350$  Mrad for  $5e15 n_{eq}/cm^2$
- Uniform irradiation at  $T < 0^\circ C$

**TRIGA reactor at JSI, Slovenia** **Diodes**

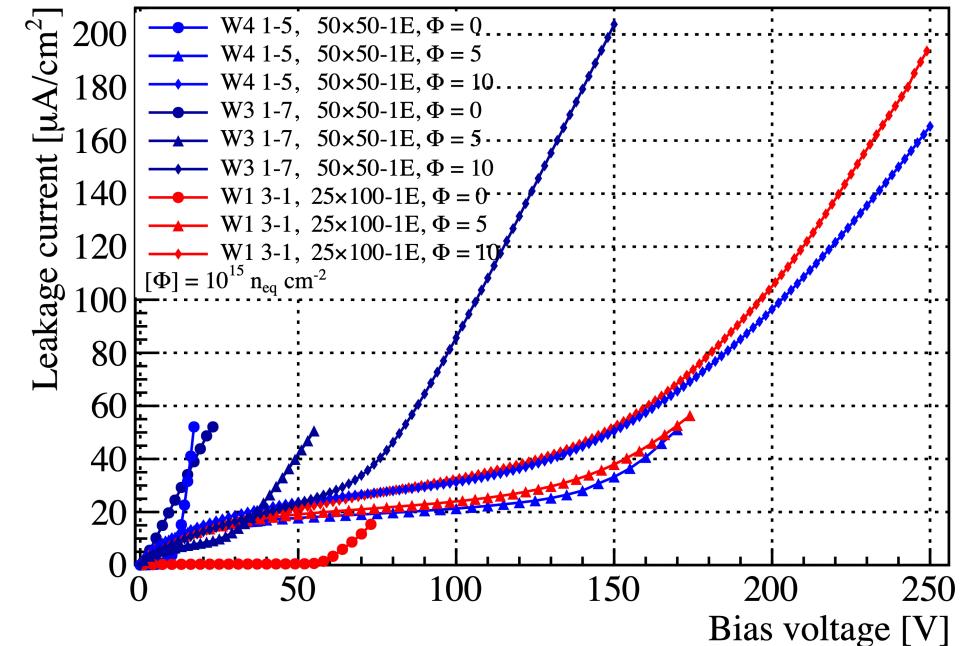


- Reactor neutrons
- Negligible TID
- Uniform irradiation
- Tantalum in the RD53A gets activated

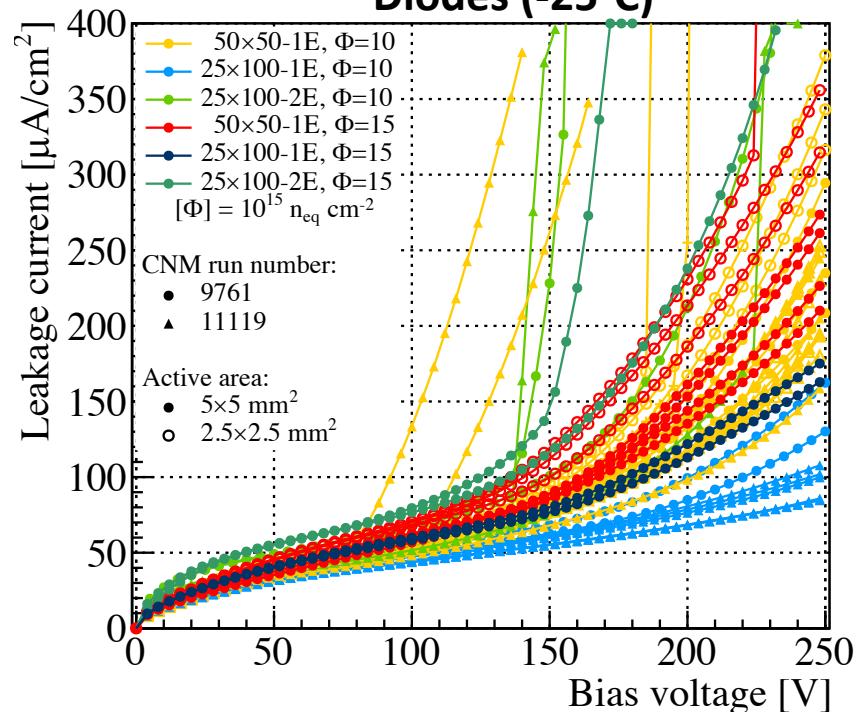
**Thanks to:** Koji Nakamura, Vladimir Cintro, Laura Gonella & Amelia Hunter, Felix Bögelspacher & Alexander Dierlamm

# Leakage current up to $1\text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$

**RD53A sensors (-25°C)**



**Diodes (-25°C)**



- **IV current after irradiation to  $5\text{e}15$  and  $1\text{e}16$  and  $1.5\text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$**

- Some RD53A sensors show early breakdown before irradiation and in same case a failure is observed after flip-chipping (under investigation)
  - After irradiation IV shape tend to uniform
- Slightly larger current for diodes wrt. RD53A sensors
  - Different contribution of the edge current (larger edge fraction in smaller sensors)
  - Overall consistent results

# Beam test campaigns

- **Beam tests at SPS CERN 2018**

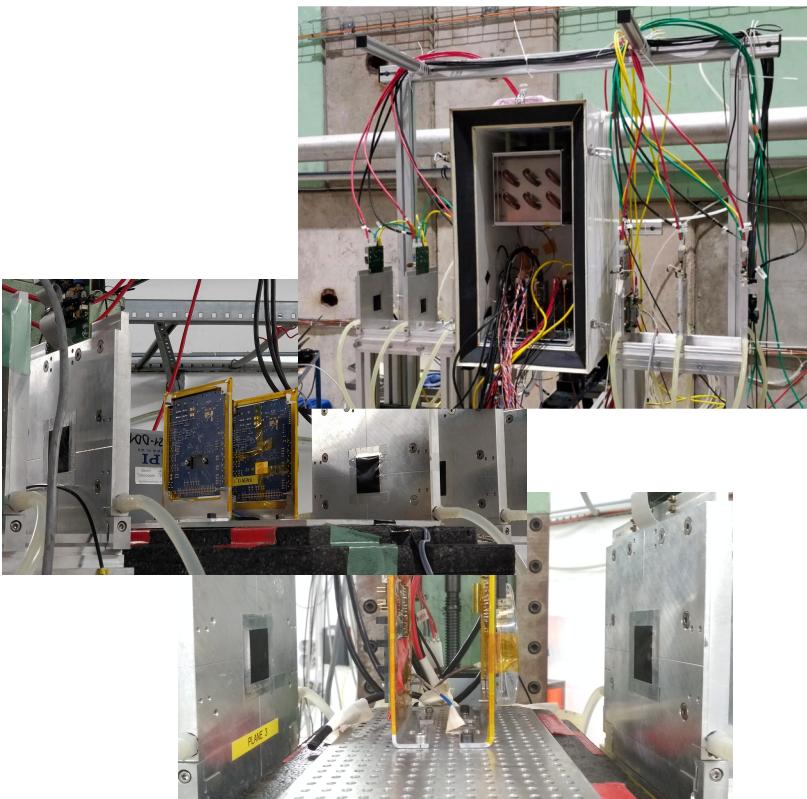
- RD53A modules with SOI sensors
- 50x50 and 25x100  $\mu\text{m}^2$  (1E) sensors
- Before and after irradiation to  $5\text{e}15 \text{n}_{\text{eq}}/\text{cm}^2$

- **Beam tests at DESY 2019**

- RD53A modules with SOI and Si-Si sensors
- 50x50 and 25x100  $\mu\text{m}^2$  (1E)
- Before and after irradiation up to  $1\text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$

- **Beam tests at DESY 2020**

- RD53A modules with SOI and Si-Si sensors
- 25x100  $\mu\text{m}^2$  (1E) up to  $1\text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$
- 50x50  $\mu\text{m}^2$  irradiated up to  $1.6\text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$



**SETUP**

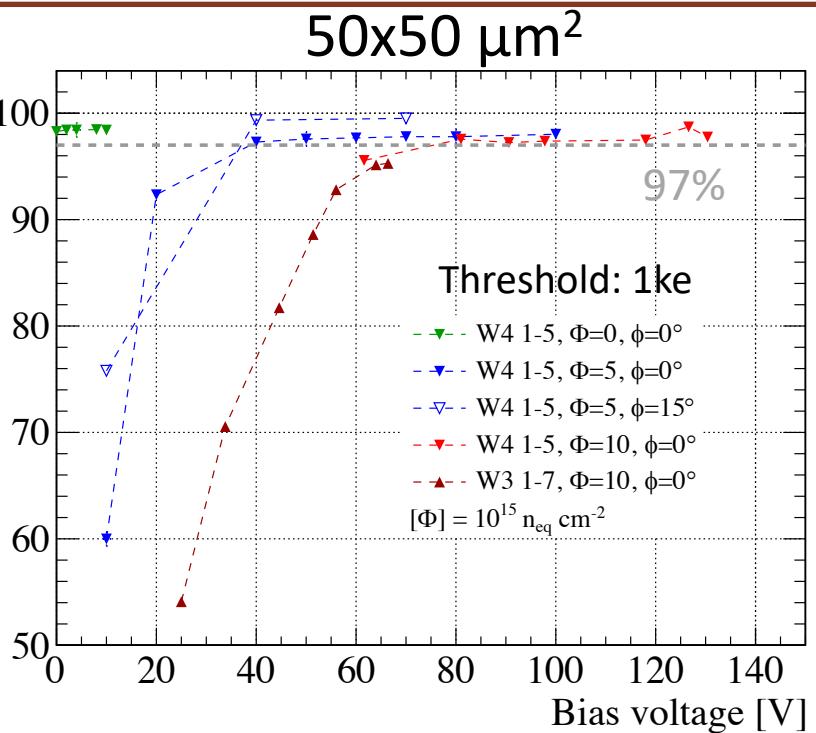
- EUDET telescope + ATLAS FE-I4 module as time reference (25 ns precision)
- RD53A readout with BDAQ (DOI: [10.1016/j.nima.2020.164721](https://doi.org/10.1016/j.nima.2020.164721)) and YARR (DOI: [10.1088/1742-6596/898/3/032053](https://doi.org/10.1088/1742-6596/898/3/032053))
- @CERN:
  - 120 GeV pions
  - Controlled temperature in the MPI cooling box (Non-irradiated at 20°C, irradiated at -50°C)
- @DESY:
  - 4-6 GeV electrons
  - Modules cooled with Dry Ice within a Styrofoam box (Temperature between -25°C and -50°C)

# Efficiency up to $1\text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$

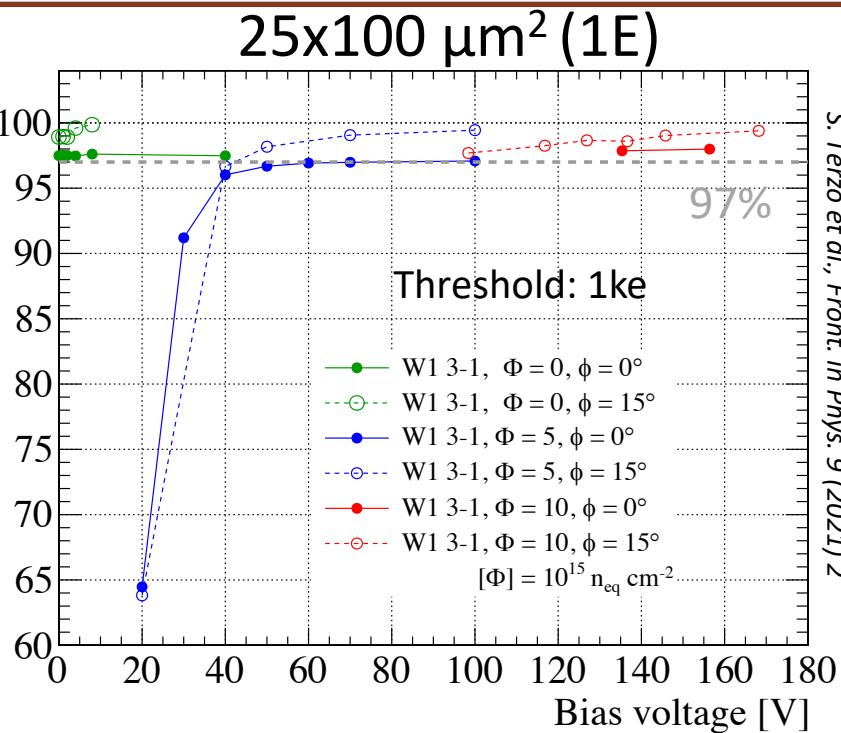
S. Terzo et al., *Front. in Phys.* 9 (2021) 2

S. Terzo (IFAE, Barcelona) - TIPP 2021

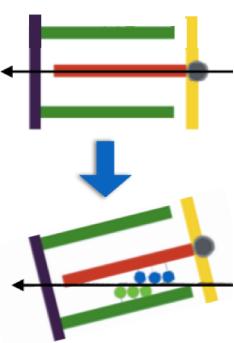
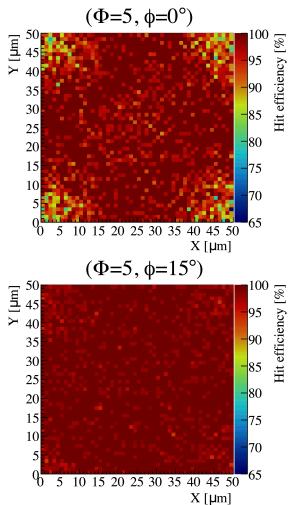
Hit efficiency [%]



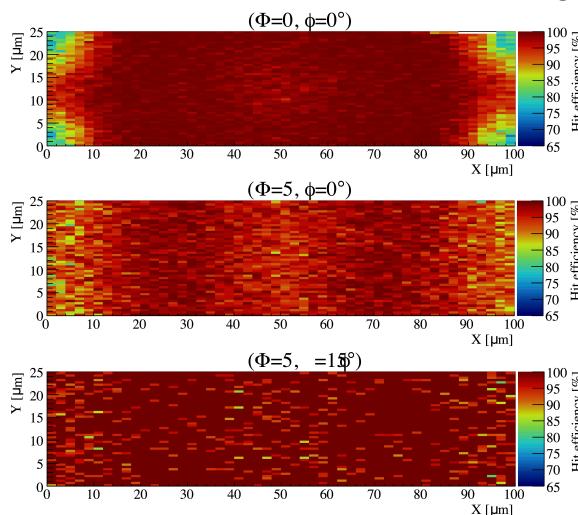
Hit efficiency [%]



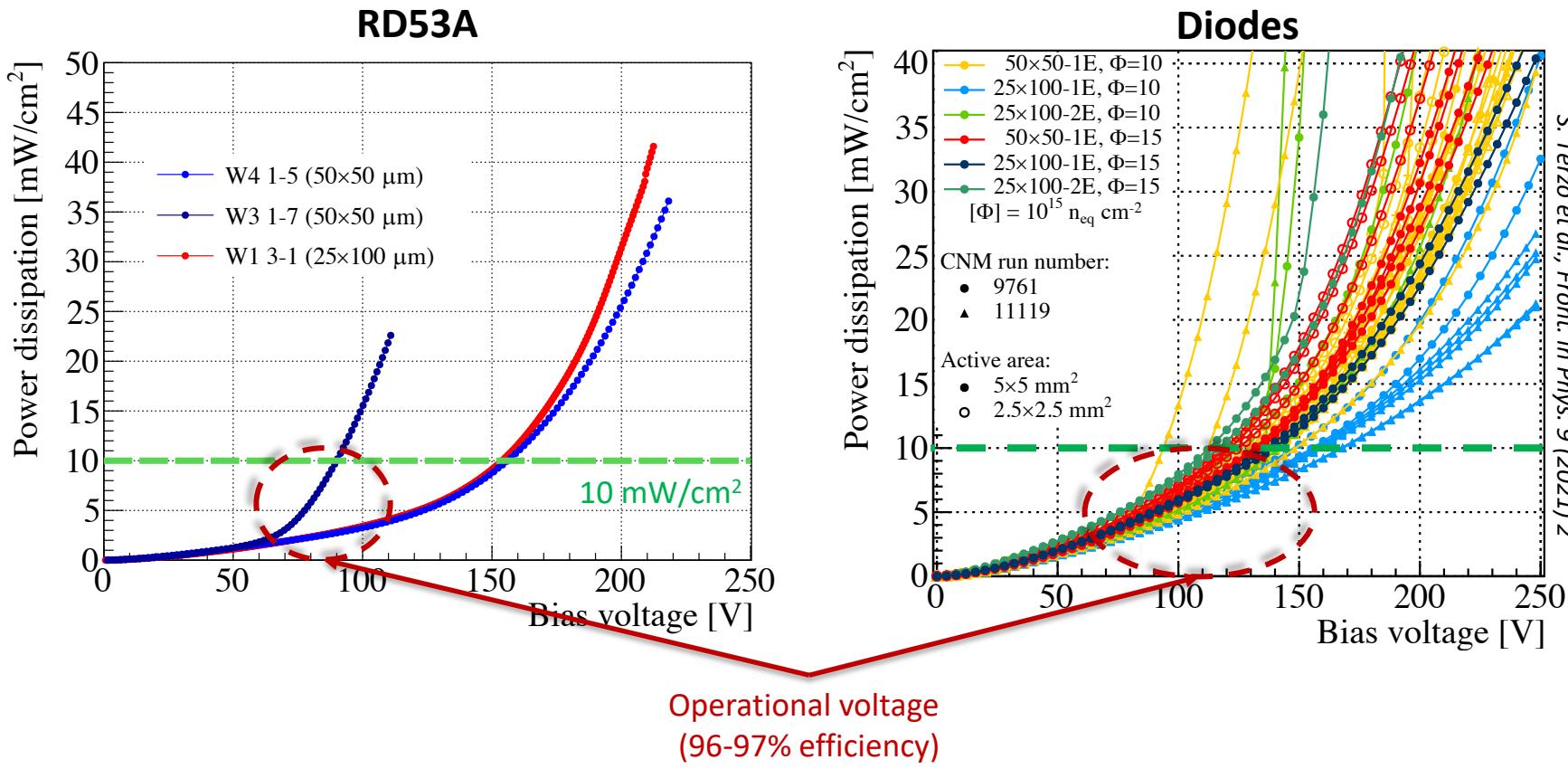
Perpendicular beam



15° tilted

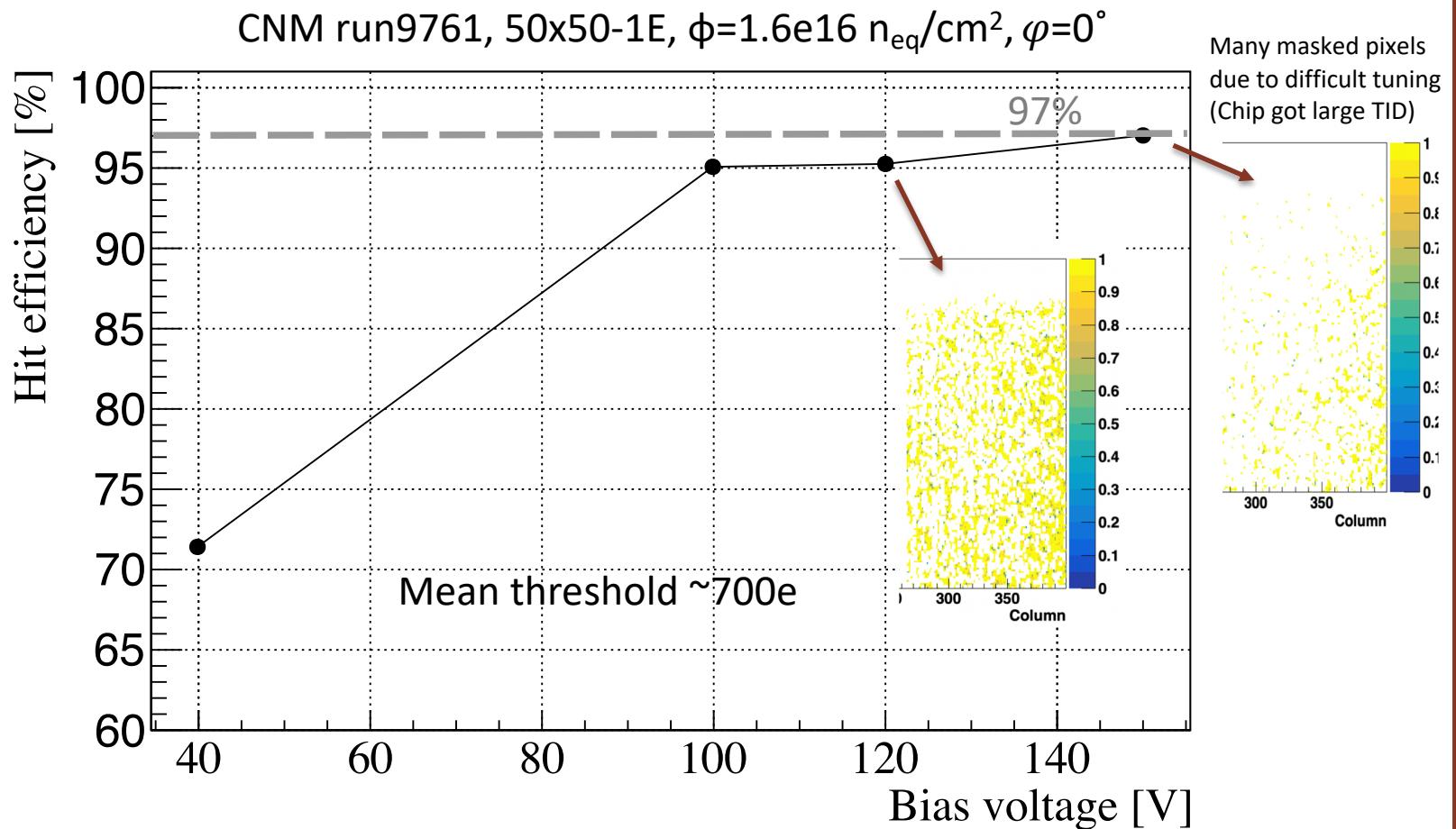


# Power dissipation up to $1\text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$



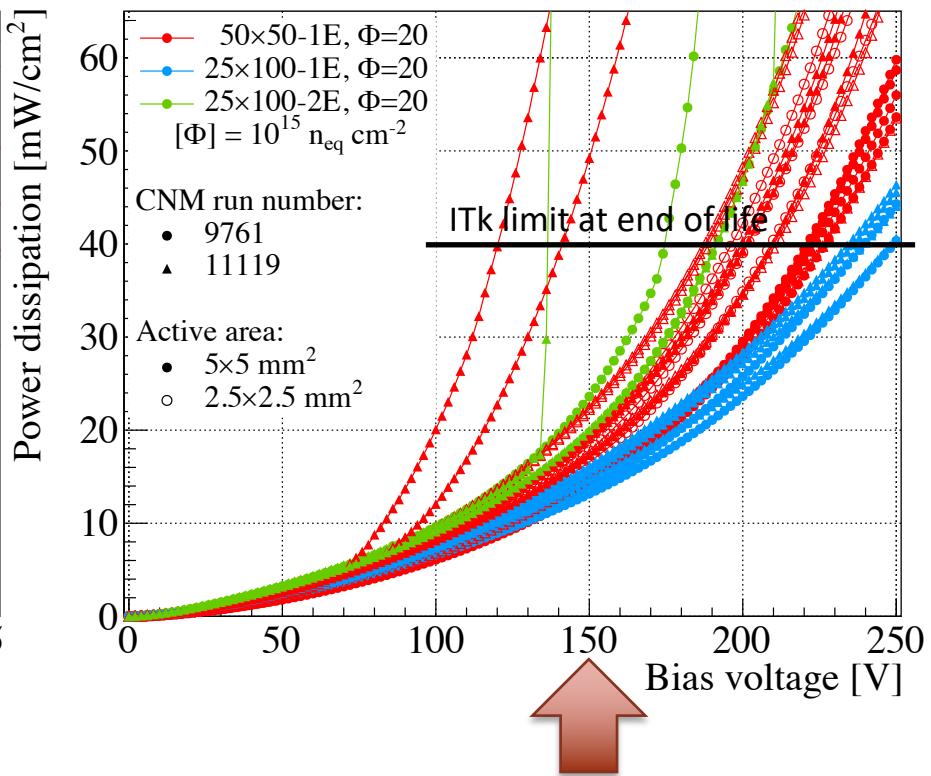
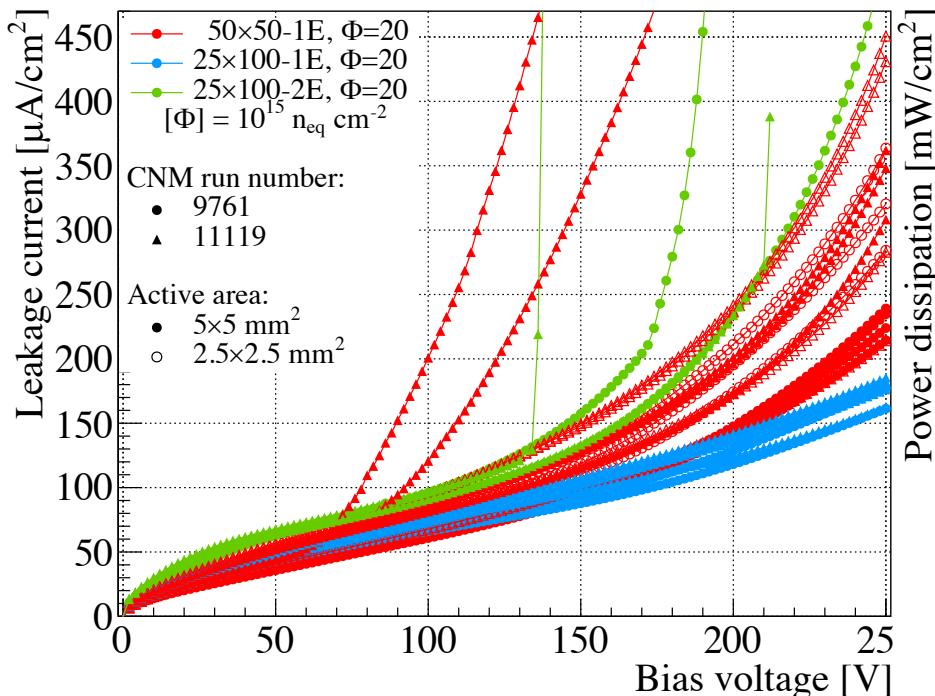
- **Power dissipation below  $10 \text{ mW}/\text{cm}^2$  at the operational voltage for  $1\text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$** 
  - All measurements at the reference temperature of  $-25^\circ\text{C}$
  - Sensors can be operated at  $\sim 97\%$  hit efficiency with less than 150V
  - Power consumption is well within the ITk limits ( $40 \text{ mW}/\text{cm}^2$ )
  - Acceptable even for sensors with early breakdown (96% efficiency at  $\sim 60\text{V}$ )

# Efficiency at $1.6\text{e}16 \text{ n}_{\text{eq}}/\text{cm}^2$



- **97% hit efficiency reached with 150V**
  - Perpendicular incident beam (better performance foreseen with tilted devices)
  - >95% efficiency already at 100V
- **Further measurements foreseen at next test beams**

# Power dissipation at $2\text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$



- **Diodes further irradiated with reactor neutrons in Ljubljana to  $2\text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$** 
  - 25x100-1E 3D sensors can be operated up to 250V with a power dissipation lower than  $40 \text{ mW}/\text{cm}^2$  (ITk requirement)
- **Further irradiations to be performed with Gammas**
  - TID effects expected to be negligible

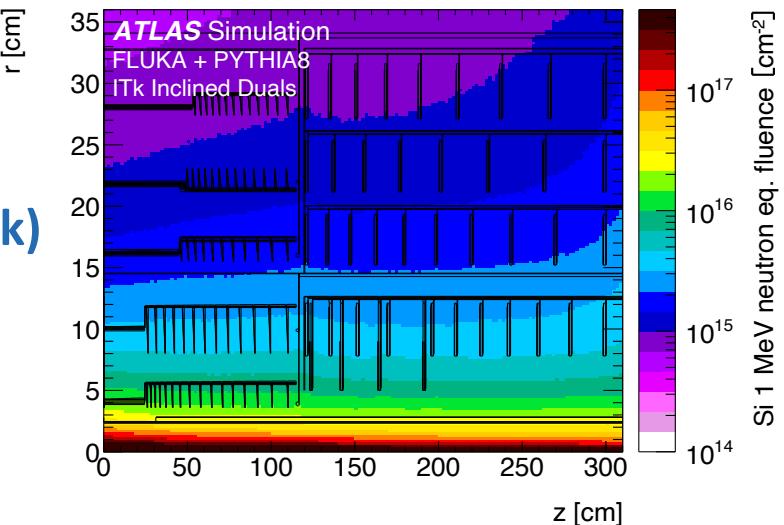
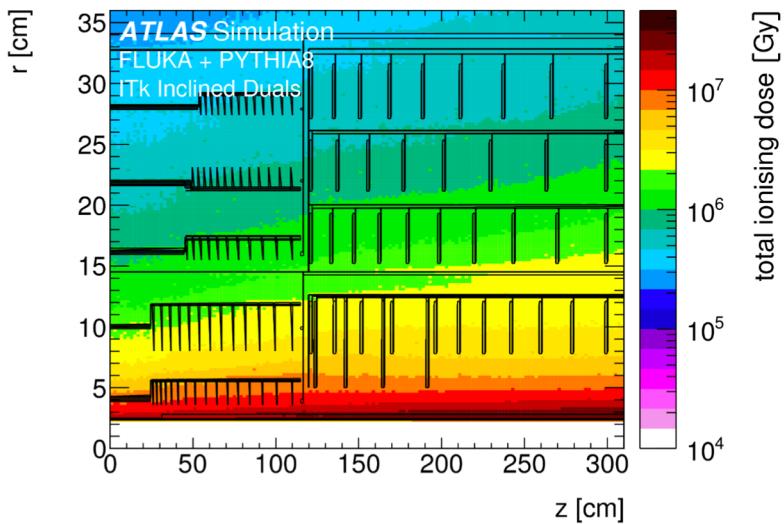
# Conclusions and outlook

- Two R&D runs of 3D pixel sensors for ATLAS ITk have been produced at CNM
  - Single side approach with 150 µm thick active substrates
  - Both on SOI and Si-Si (ITk final design)
  - Including different designs of small pixel cells
- Good hit efficiency measured on RD53A modules up to  $1.6 \text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$ 
  - 97% hit efficiency at 150V for 50x50-1E sensors after irradiation to  $1.6 \text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$
  - >97% hit efficiency with <100V for both 50x50-1E and 25x100-1E up to  $1 \text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$
- Power dissipation studied with diodes up to  $2 \text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$ 
  - Within ATLAS specs up to 250V for 25x100-1E design
  - Within ATLAS specs up to 150V-200V for 50x50-1E design
- Future irradiations of RD53A modules to  $2 \text{e}16 \text{n}_{\text{eq}}/\text{cm}^2$  in Los Alamos
  - High proton energy (120 GeV) -> Low TID
  - Possible to reach high irradiation fluences without huge damage to the chip
    - Similar to the final experimental conditions in ATLAS

# BACKUP

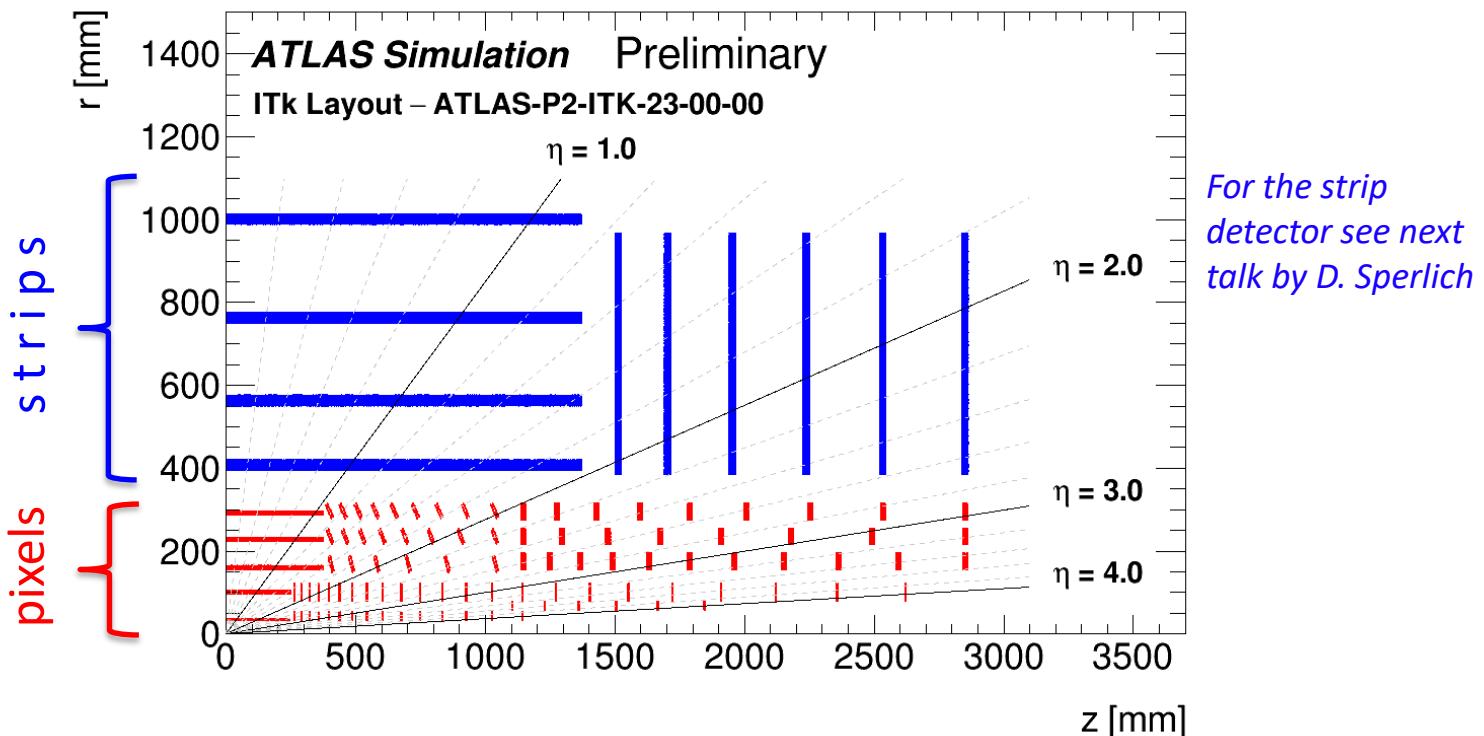
# Phase-2 challenges

- **Particle multiplicity**
  - About 10 times more track density
    - Needs better tracking granularity
    - Cope with increased readout rates
- **Radiation damage**
  - Radiation dose becomes critical closer to the beam line
    - Total Ionizing Dose (TID) up to 10 MGy
    - Particle fluence up to  $2 \times 10^{16} n_{eq} cm^{-2}$  in the pixel region
- **Present Inner Detector system will be replaced with a full silicon Inner Tracker (ITk)**
  - Maintain/improve the present tracking performance in the HL-LHC environment
    - Occupancy < 1%
    - Minimize material
    - Radiation hardness



# The new ITk detector

- 4 strip and 5 pixel barrel layers + 2x6 strip disks and pixel ring layers
  - Coverage up to 4 eta with at least 9 space point per track
  - Possibility to replace the two innermost pixel layers (reduce radiation damage)



## Current pixel system

~1.9 m<sup>2</sup> of active area  
 2000 modules  
 92 Mega-pixels

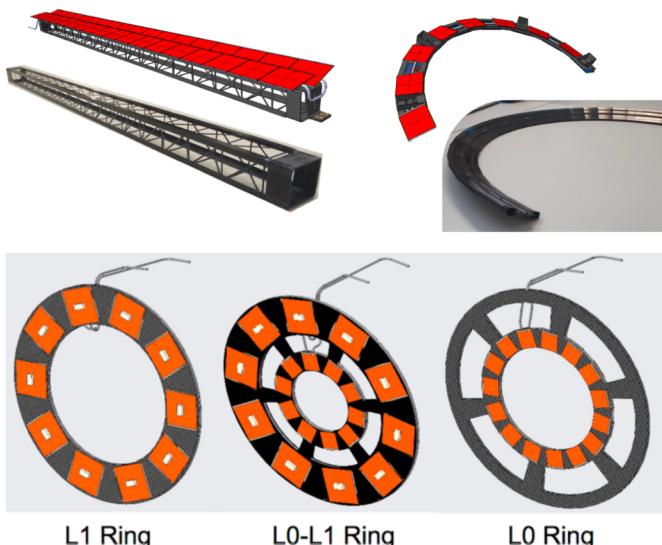
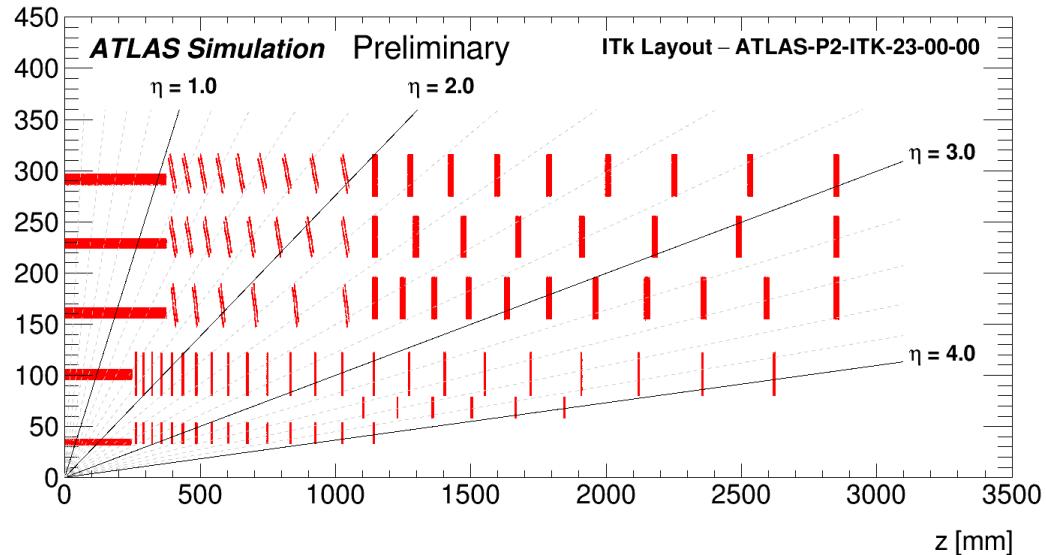


## New ITk pixel system

~13 m<sup>2</sup> of active area  
 9400 modules  
 1.4 Giga-pixels

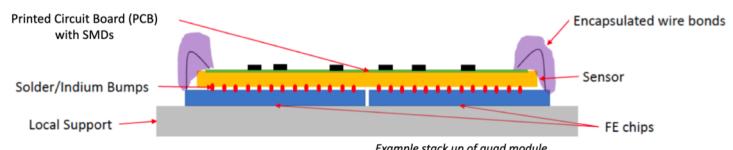
# ITk pixel layout

[ $\omega_{\eta}$ ]  $\eta$



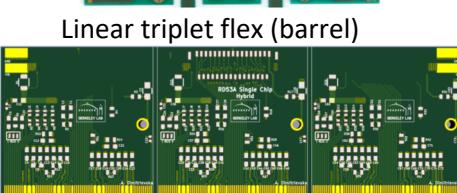
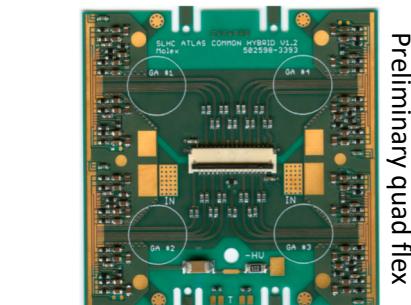
## • Outer Barrel and forward pixels

- n-in-p planar silicon sensors (150  $\mu\text{m}$  thick)
- Quad modules: 4472 (barrel) + 2344 (rings)



## • Inner pixel layers (replaceable)

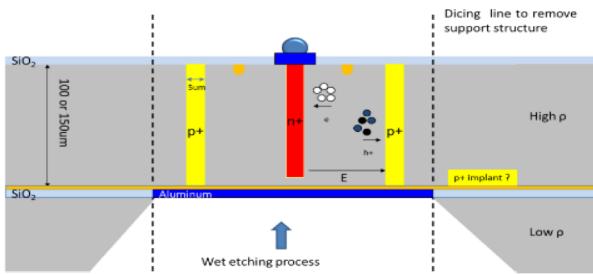
- Thin n-in-p planar silicon sensors (100  $\mu\text{m}$  thick)
  - Quad modules: 240 (barrel) + 920 (rings)
- 3D silicon sensors
  - “Pseudo” Triplets modules
    - Single sensors: 288 (barrel) + 900 (rings)
    - 34 mm from the beam line



# First RD53A run at CNM (SOI)

- First CNM run with 3D sensors compatible with the RD53A chip

- Single sided process
  - Both p- and n-columns etched from the front
  - p-stop insulation
- SOI wafers 150  $\mu\text{m}$  active thickness with 300 $\mu\text{m}$  handle wafer

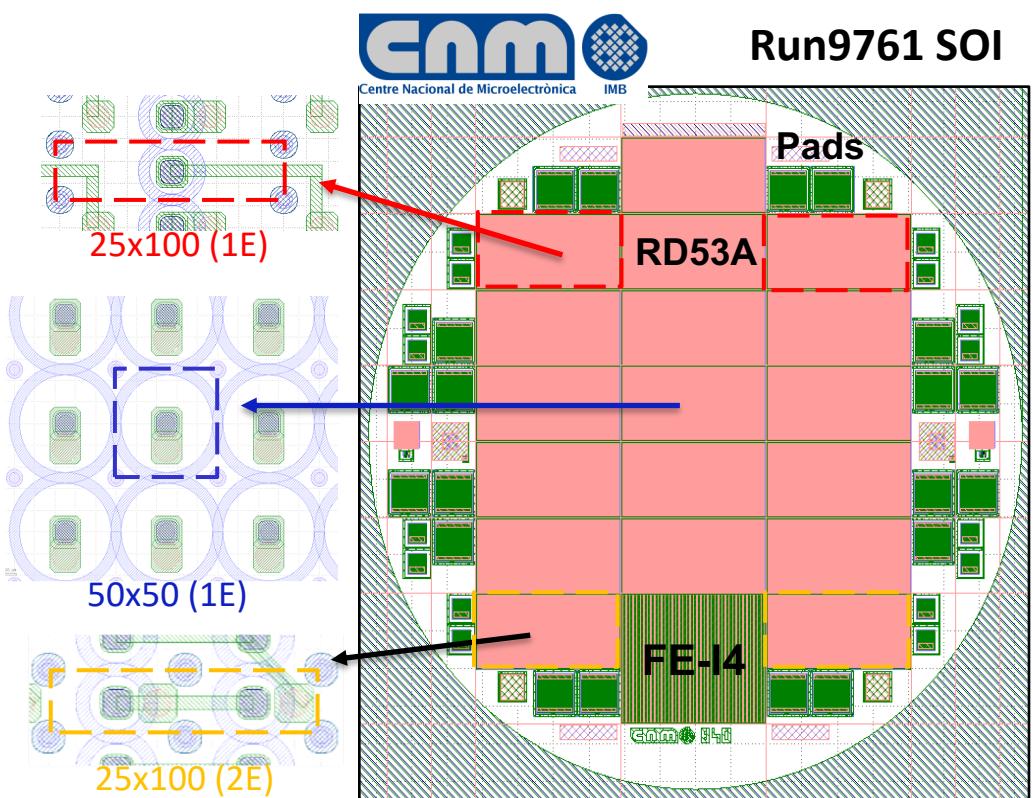


- The mask includes:

- 14x RD53A 50x50  $\mu\text{m}$  1E
- 2x RD53A 25x100  $\mu\text{m}$  1E
- 2x RD53A 25x100  $\mu\text{m}$  2E
- 1x FE-I4 50x50  $\mu\text{m}$  1E
- Pad diodes of 50x50  $\mu\text{m}^2$
- Pad diodes 25x100  $\mu\text{m}^2$

- 7 wafers produced

- Biasing from the backside through holes in the support wafer
- Very low yield for 25x100-2E design of R53A sensors due to bump pad proximity to the p-columns

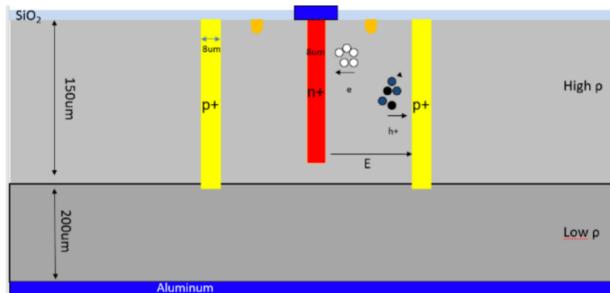


# Second RD53A run at CNM (Si-Si)

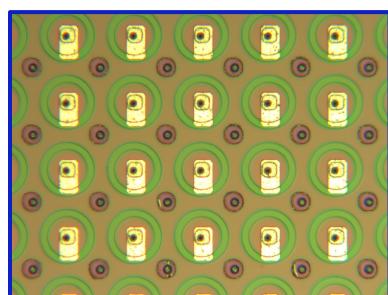
- New CNM run with 3D sensors compatible with the RD53A chip

- Single side process
  - Both p- and n-columns etched from the front
  - p-stop insulation
  - 130  $\mu\text{m}$  n-column depth, 8  $\mu\text{m}$  column diameter
- 8x Si-Si wafers (shared with CMS)
  - No need of removing handle wafer for bias: (handle wafer is conductive)
- 150  $\mu\text{m}$  active thickness with 200  $\mu\text{m}$  handle wafer

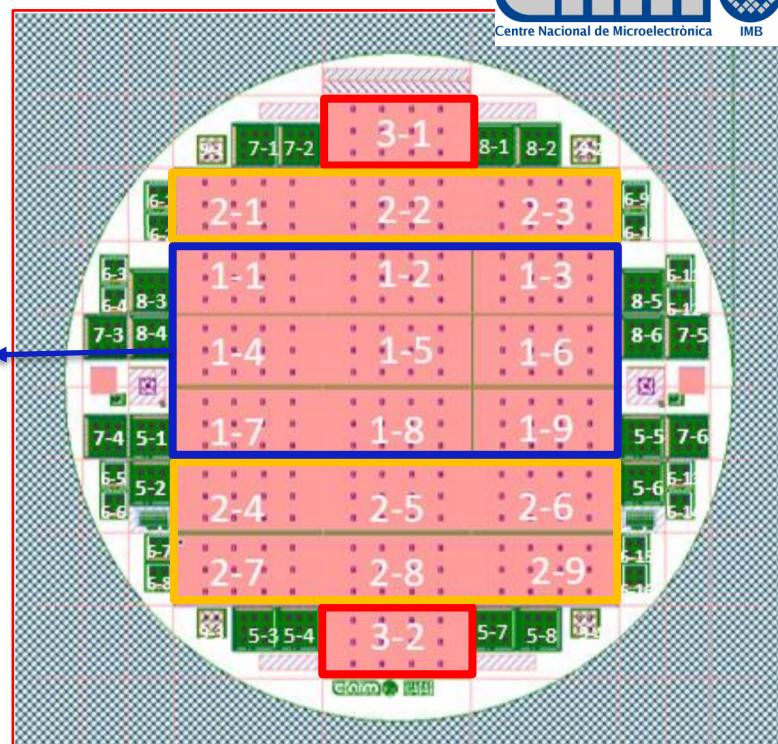
AIDA<sup>2020</sup>



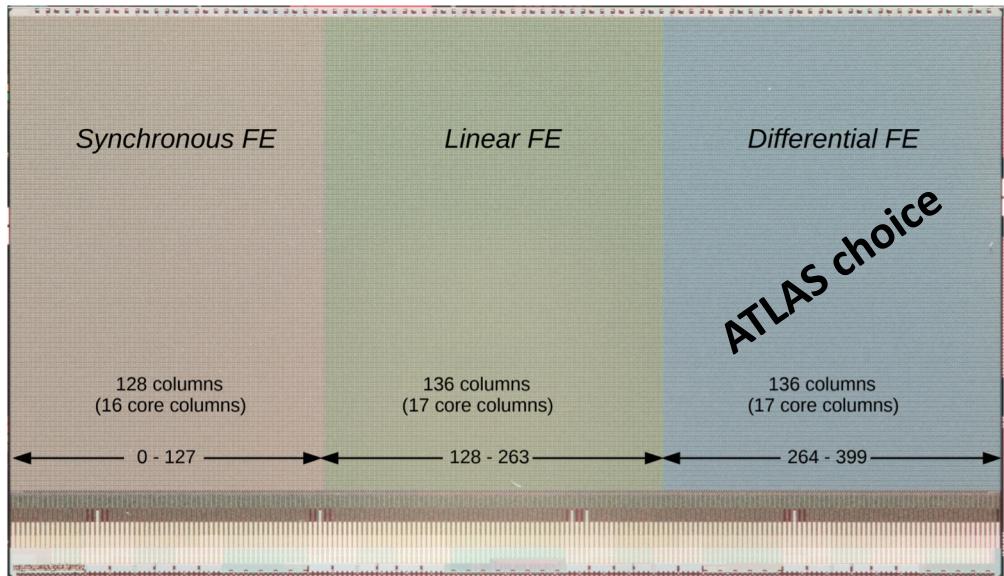
Run11119 Si-Si



All RD53A sensors up to the specifications of the ITk baseline



# RD53A and readout systems

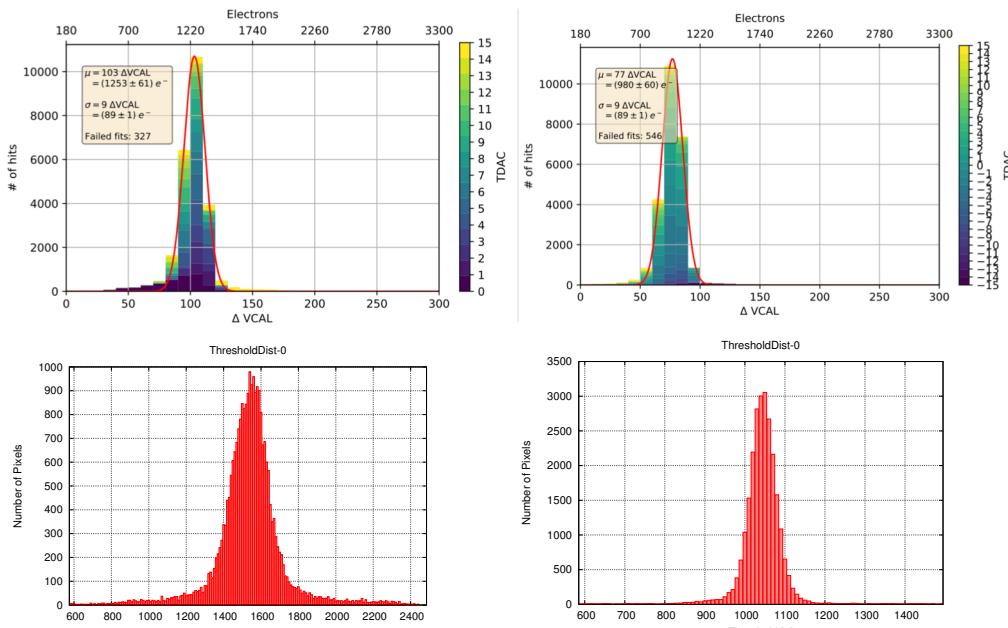


- The RD53A chip is divided in 3 different FE
  - All results presented are obtained with either **Linear FE** or **Differential FE**
  - The **Differential FE** architecture has been chosen for the ATLAS final chip

- Two readout systems employed **BDAQ\*** and **YARR†**
  - Different tuning algorithms
  - Mostly consistent results
  - They use different calibration for the threshold

\*<https://gitlab.cern.ch/silab/bdaq53>

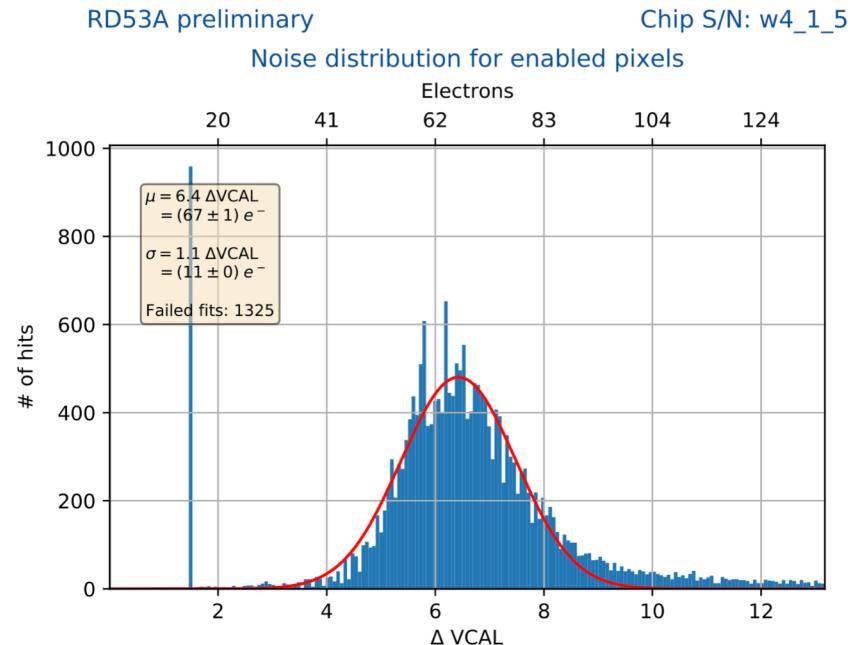
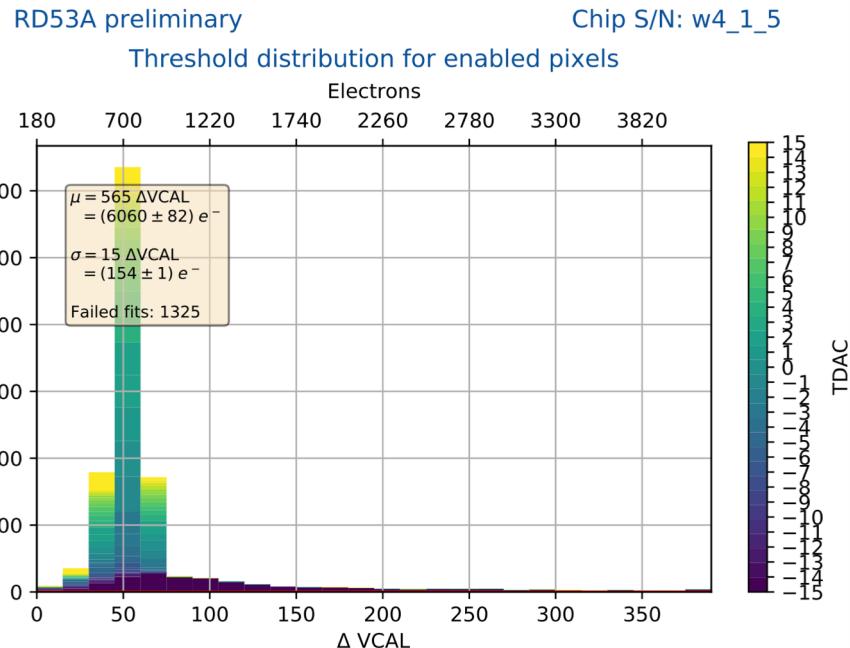
†<https://yarr.readthedocs.io/>



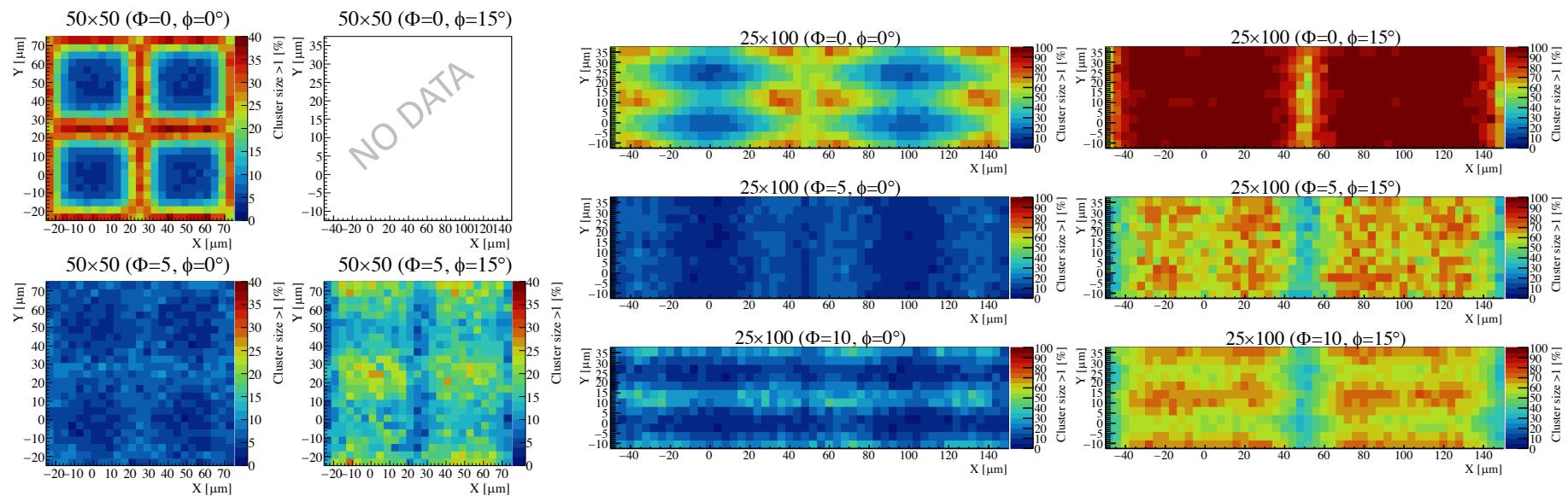
# Tuning at $1.6 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$

- SOI  $50 \times 50 \mu\text{m}^2$  RD53A module irradiated in different steps:

- KIT @  $5 \times 10^{15}$  + CYRIC @  $5 \times 10^{15}$  + CYRIC @  $6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$
- Very large total TID ( $\sim 1.5$  Grad)
- Very difficult and long chip tuning (thanks to Yannik Dieter for the great help with BDAQ)
  - Only differential front-end measured
  - Finally achieved **threshold  $\sim 700e$**  (target tuning was  $1000e$ )
  - But many noisy pixels
    - Masked during data-taking
    - 8x more masked pixels in the analysis to avoid pointing resolution effects



# Charge sharing



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- Before irradiation:**

- Significantly larger charge sharing with  $25 \times 100 \mu\text{m}^2$ 
  - ~2 times more cluster size 2

- After irradiation:**

- Charge sharing is suppressed due to trapping
- $25 \times 100\text{-1E}$  and  $50 \times 50\text{-1E}$  show similar results
  - < 10% difference in cluster size 1 and 2

Cluster size > 1	$\Phi = 0$ $\phi: 0^\circ$	$\Phi = 5$ $\phi: 0^\circ$	$\Phi = 0$ $\phi: 15^\circ$	$\Phi = 5$ $\phi: 15^\circ$
$25 \times 100\text{-1E}$	50%	15%	95%	70%
$50 \times 50$	20%	10%	No data	30%

