Pixel Modules for the ATLAS Inner Tracker Upgrade

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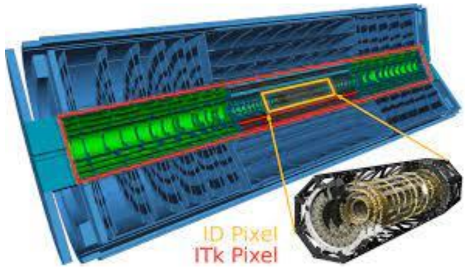
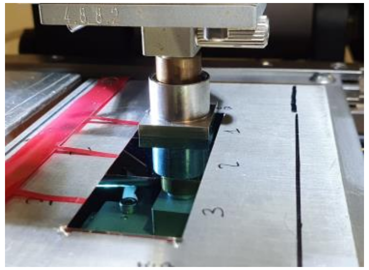
Juan Ignacio Carlotto
(IFAE-Barcelona)

Institut de Física d'Altes Energies

IFAE Pixel Group

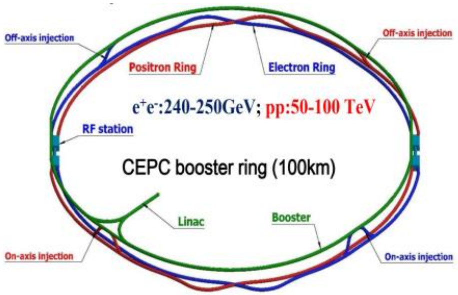


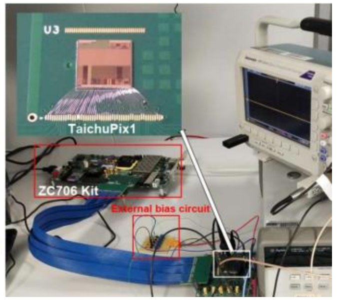


ATLAS Pixel Detector

Qualified 3D sensors from CNM

Fabricate modules for innermost layer



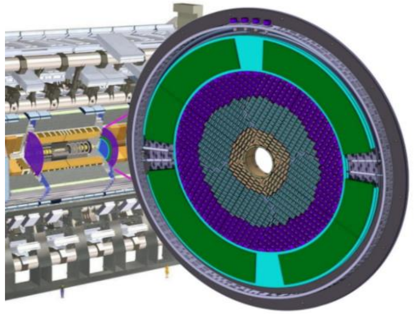


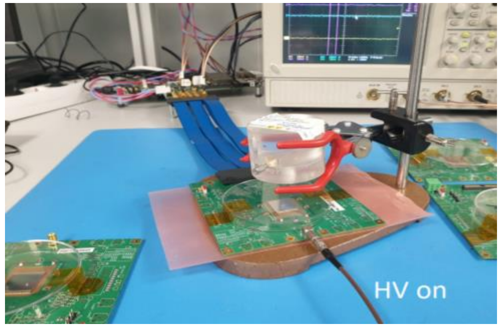
Future Accelerators

DMAPS for the CEPC

Timing with DMAPS

3D for ultra-rad hard and timing



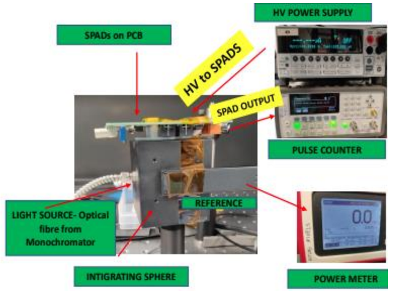


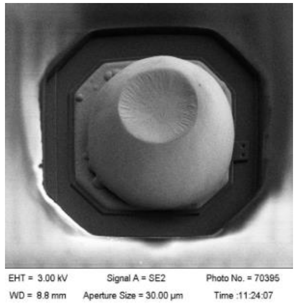
ATLAS Timing Detector

Qualified LGADs from CNM

Bump-bonding at IFAE

Fabricate modules





Other Applications and R&D

APDs for neuromonitoring

2D materials for MIP detection

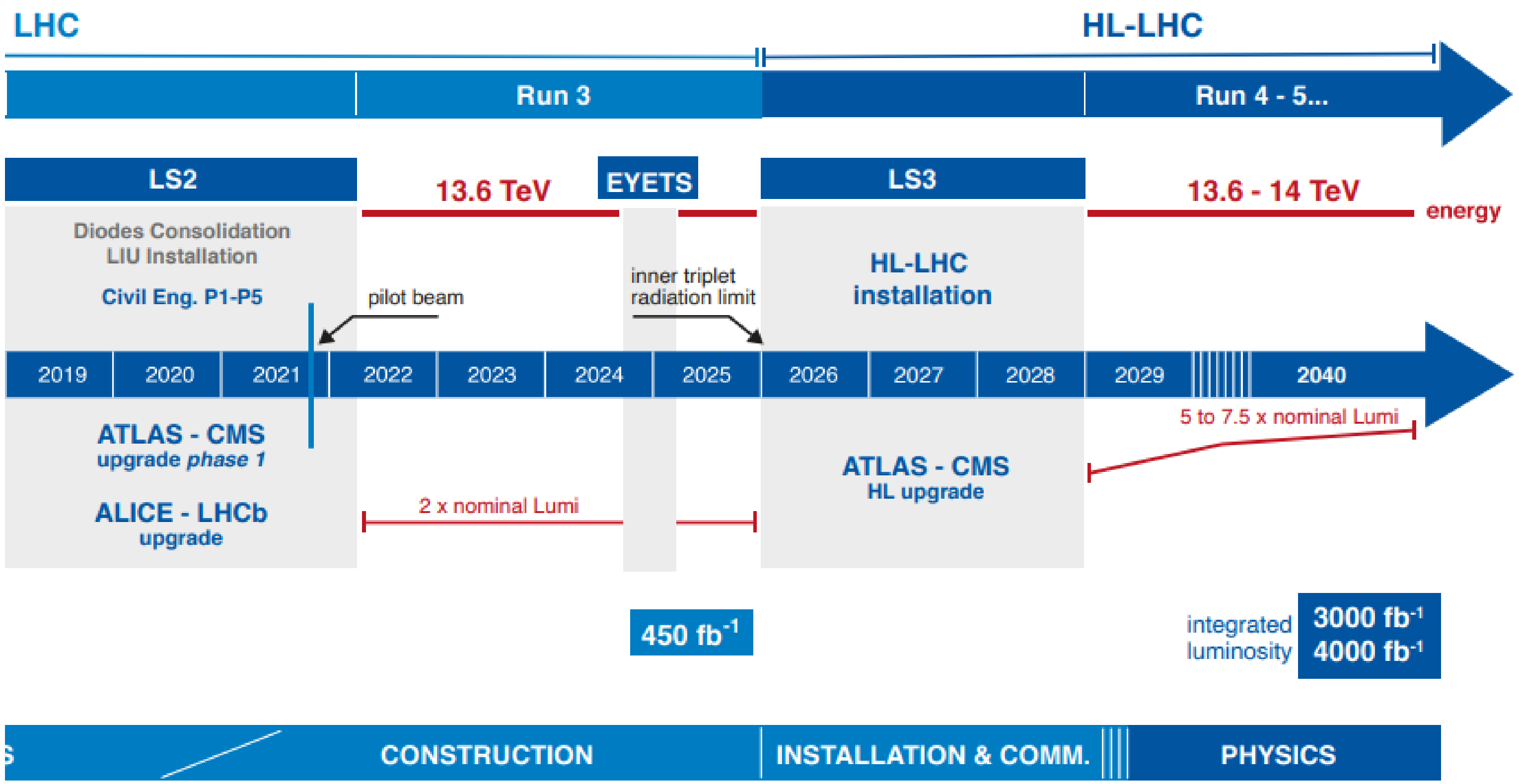
Bump-bonding process

Large Hadron Collider upgrade

The next LHC upgrade is the High-Luminosity LHC (HL-LHC) planned to start operation in 2029.

Increase of the luminosity → **4 times more p-p collisions** → **Detectors exposed to more than 3 times the present radiation dose**

<u>ATLAS will replace its current tracker with a full silicon system called ITk.</u>



ATLAS ITk upgrade

One of the most critical and demanding sub-detector systems of the ATLAS HL-LHC upgrade is the Pixel Detector of the Inner Tracker.

The total surface of the ITK Pixel system is ~13 m^2

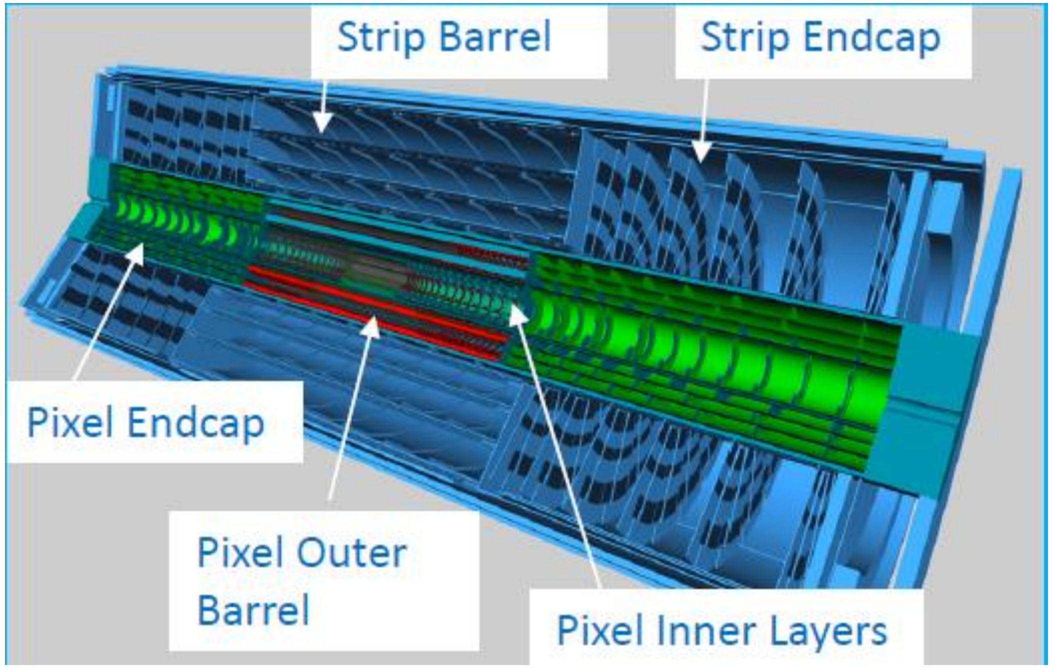
<u>ITk Pixel detector is critical for:</u>

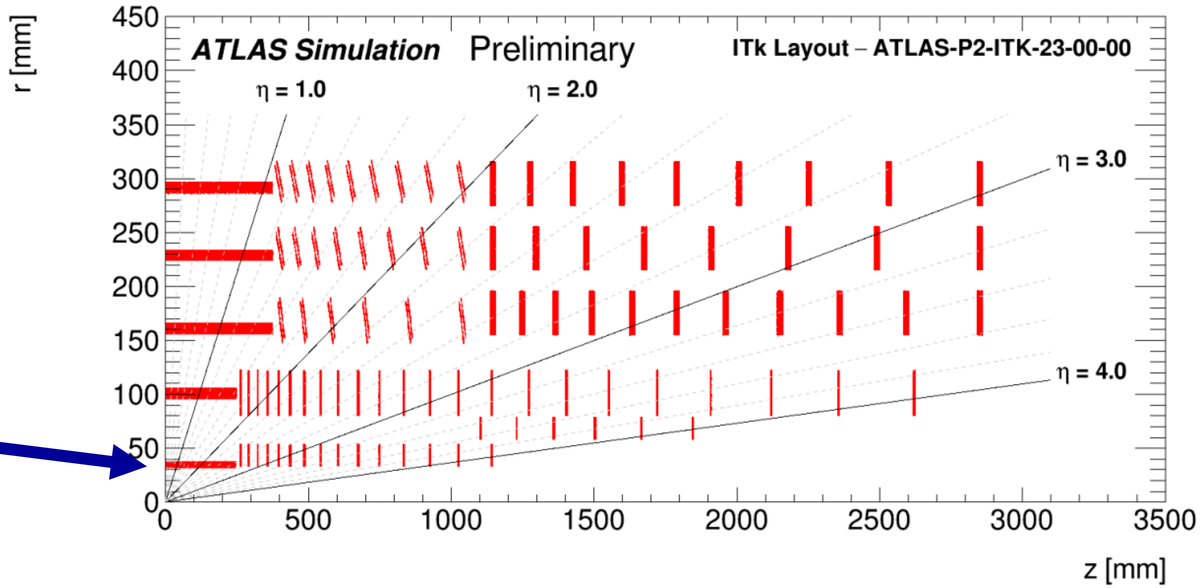
- Track and vertex reconstruction
- Track impact parameter resolution (b-tagging)

<u>Challenges:</u>

- **Radiation hardness**
    - The radiation dose is larger close to the interaction point.
- **Space constraints**
    - Limited space for detector modules, electrical services and cooling system results in very stringent mechanical constraints.

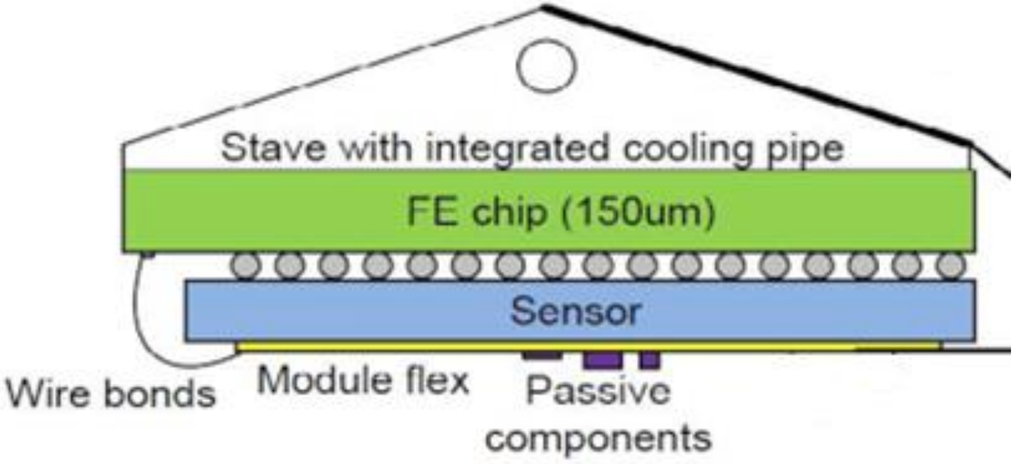
<u>IFAE will build modules for the innermost layer of the ITk Pixel system (the linear "triplet modules").</u>

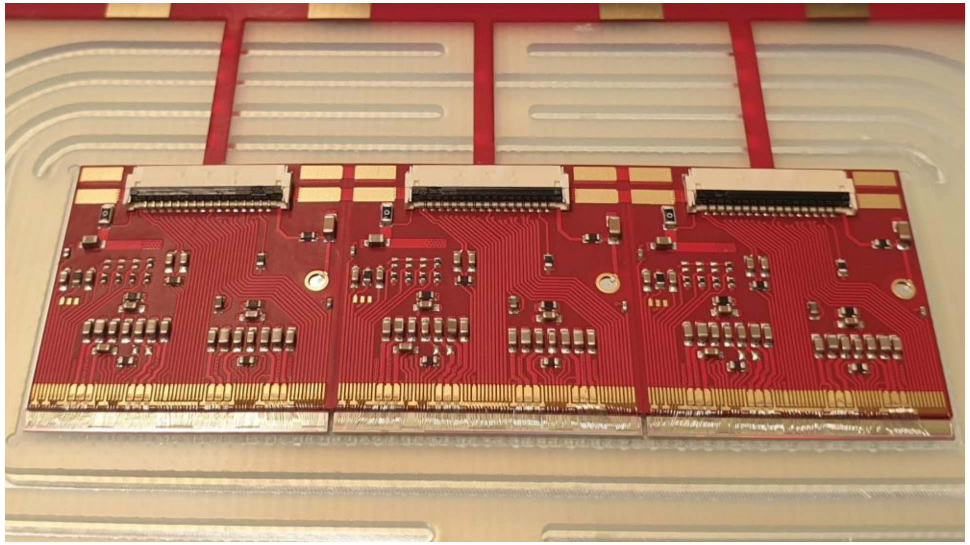




The ITk Pixel Triplet Module

- **The Front-End (FE) chip**
  - Amplify and discriminate the signal.
- **Sensor**
  - Where particles interact generating the signal.
  - 3D silicon pixel sensors (50x50 μm^2 cell).
- **Chip and sensor are attached pixel-by-pixel by a Bump-bonding process**
  - This is called bare-module.
- **Flexible PCB (flex):**
  - The chip is connected with micrometer wires to an electronic board.
  - Allows the communication with the chips.
- **A set of 3 bare-modules attached together in a flex created a Module.**
  - One flex handles communication for 3 chips reducing the number of cables.
- **Finally, the module is attached to a mechanical support for cooling.**



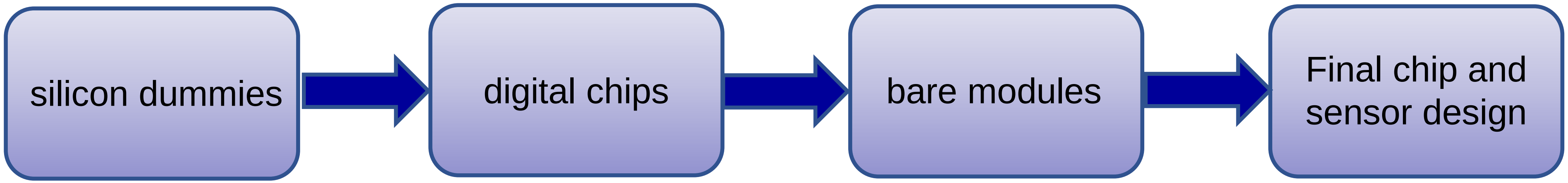


Triplet assembly at IFAE

<u>IFAE is responsible of the assembly of 120 functional linear triplet modules for ATLAS ITk in the layer L0:</u>

- **Developing the process and methodology of assembly**
- **Testing electrical performance.**

The qualification for the module assembly requires several steps:



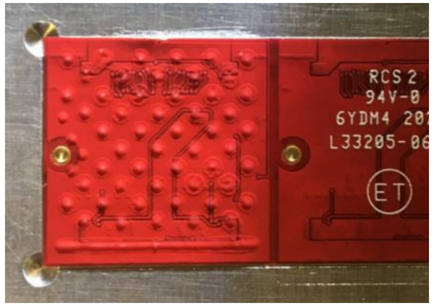
Assembly process

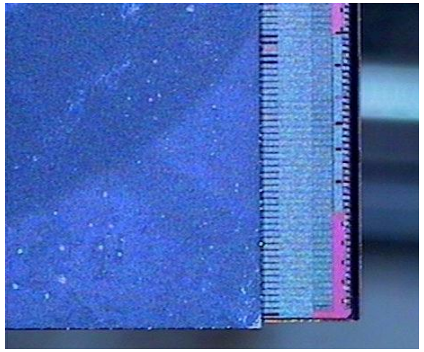
Glue is prepared and applied on the flex.

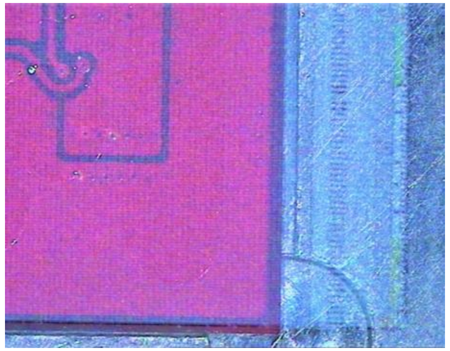
The chip is aligned with respect the flex in the correct position.

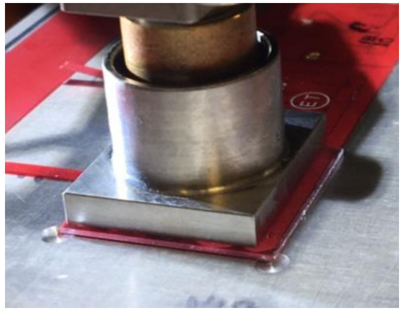
The chip is placed on the top of the flex, and it is necessary to wait until the glue is cured.

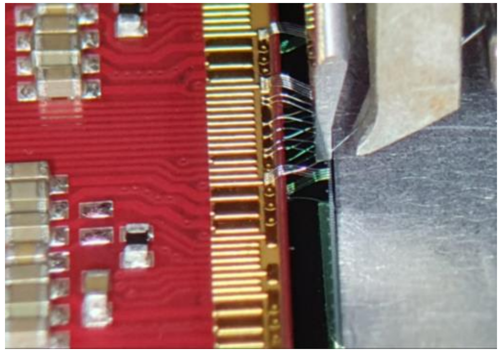
The connection between the chip and the flex is done by a wire-bonding process.











<u>Assembly process at IFAE achieved a 5μm precision in position.</u>

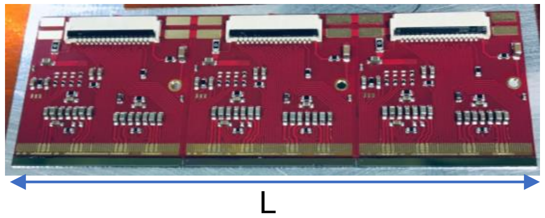
Mechanical tests

Modules that don't match mechanical specifications can not be loaded in the final detector.

Dimensions

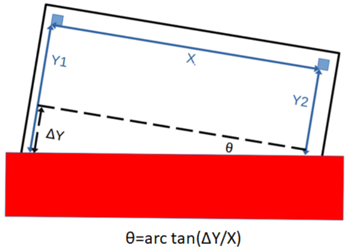
Full length (L)

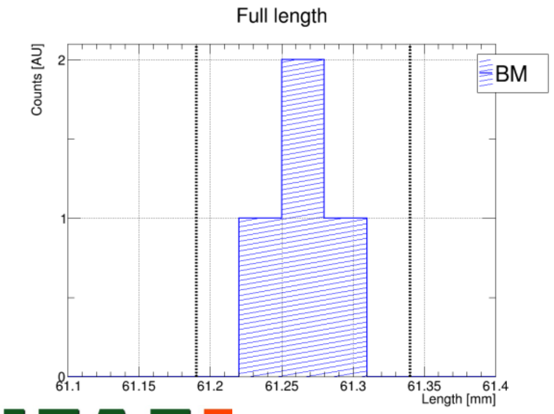
Between 61.26 +/- 0.075mm

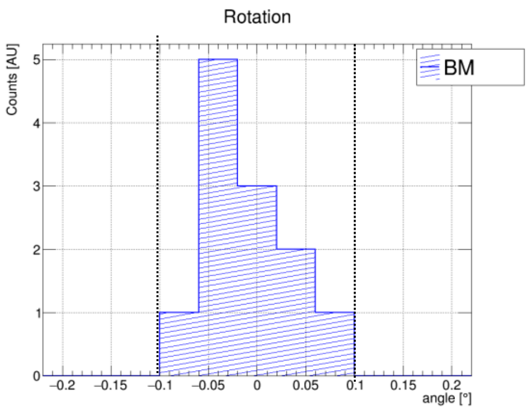


Rotation

Value should be smaller than 0.1 degrees.



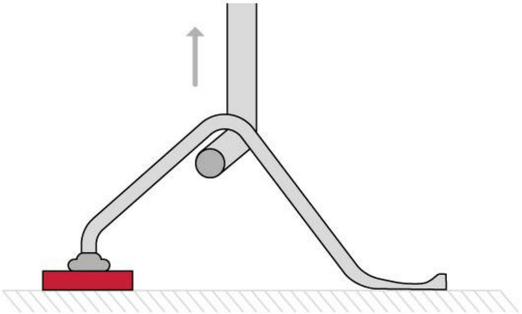




Wire bonding pull test

If wires are weak, they can break during shipping or loading in the mechanical support.

Pull test values should be higher than 5g.

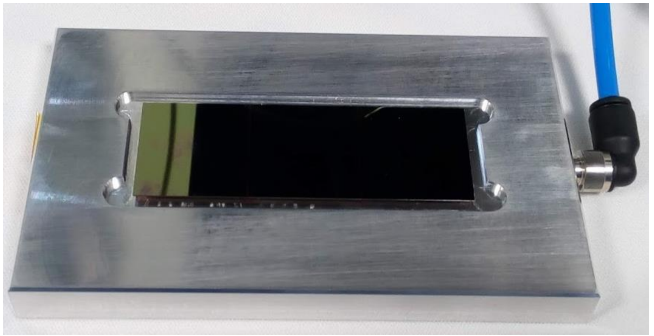


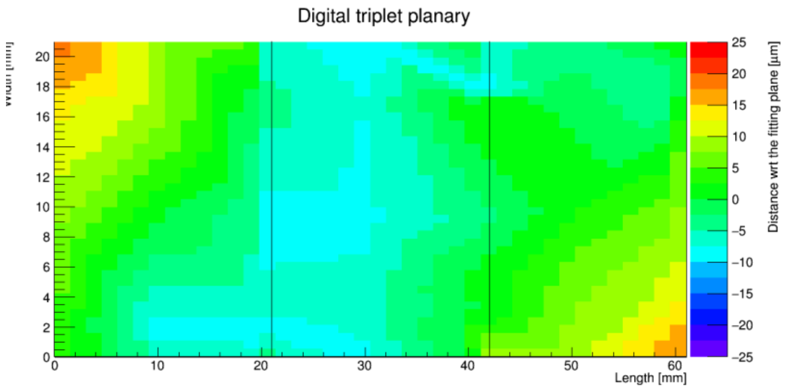
Mean value for triplets is 6.1g.

Flatness

Flatness measurements are performed to check the height alignment among the chips

The height between 2 points in the module should be lower than 50um.





DAQ system

After the assembly, the modules are ready for the electrical tests:

Readout system YARR:

- Communication with the module
- Configure chip parameters
    - Threshold
    - Voltage/current regulators

The setup also contain:

- Temperature meter (ntc)
- Low voltage sources (to power the chip)
- High voltage source (to bias the sensor)
- Digital multimeter (for multiple measurements)

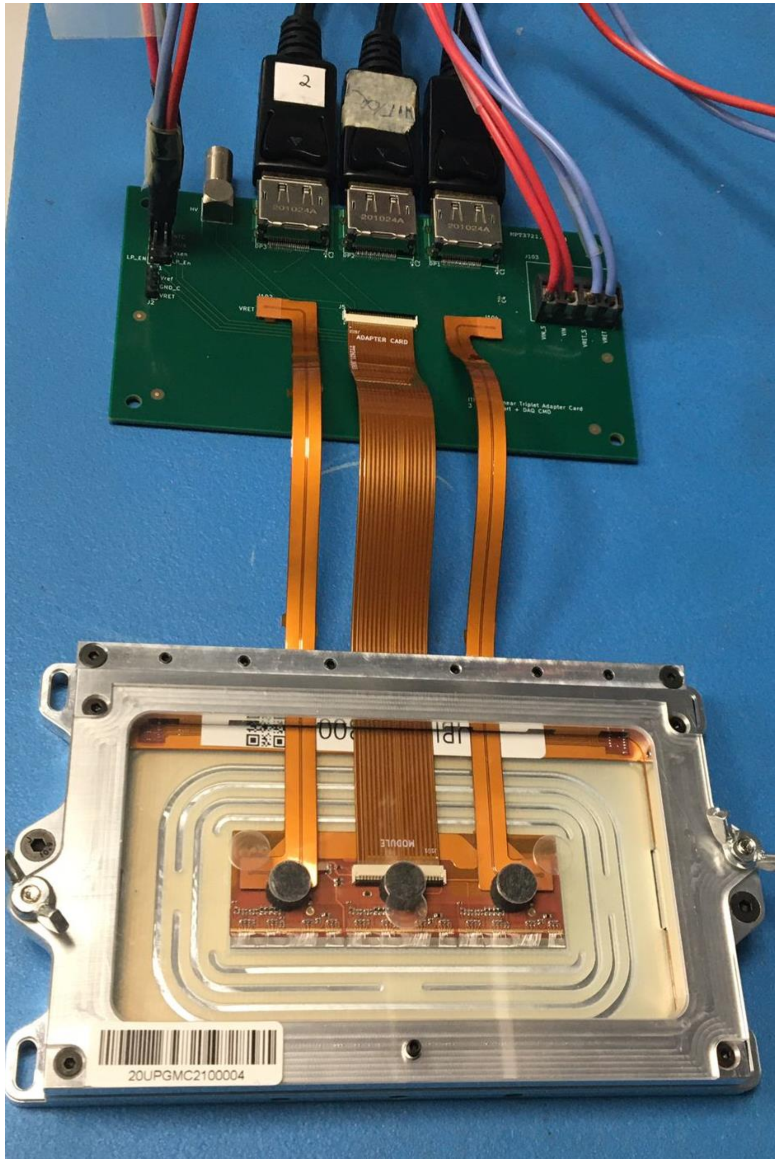
} Python (pyvisa) programs were developed at IFAE to control the instruments.

Modules are tested using a series of scripts: “Quality Control tool” scripts, developed by Berkeley lab

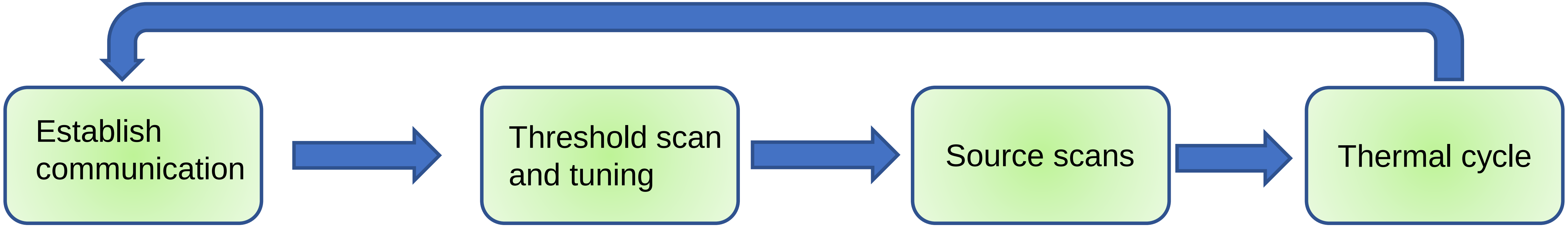
- Automation of the measurement process.
- Reduce human intervention.

Finally, mechanical and electrical tests results must be uploaded into a database.

During the module production, these tests will be used to discard malfunctioning modules.



Electrical test



Basic communication with the chip is established.

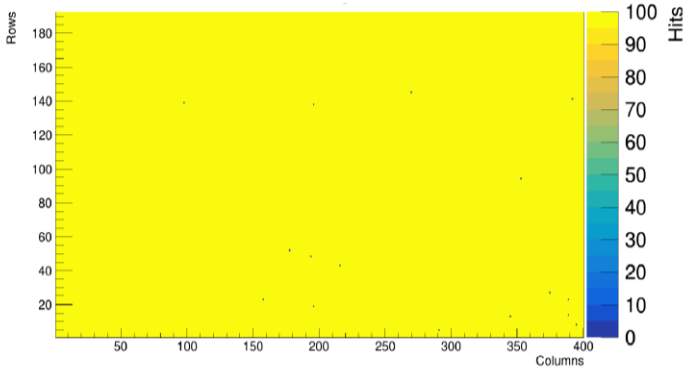
Threshold is measured in each pixel and tuned to the correct value.
Noise ~ 100e.

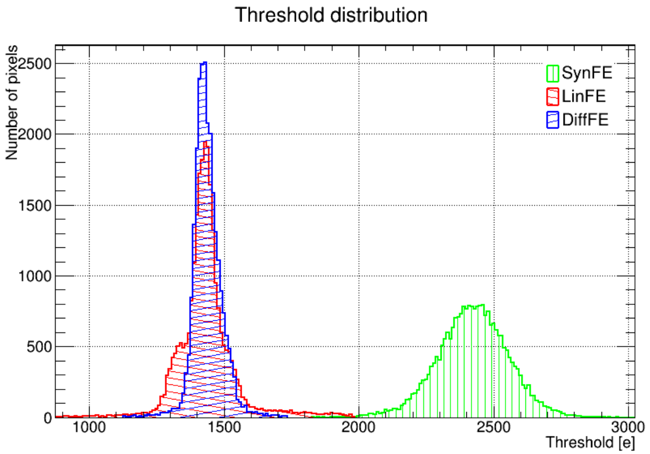
Using a radioactive source to measure the signal on each pixel.

Looking for not responding pixels due to a bad bump-bonding connection.
(See next slides)

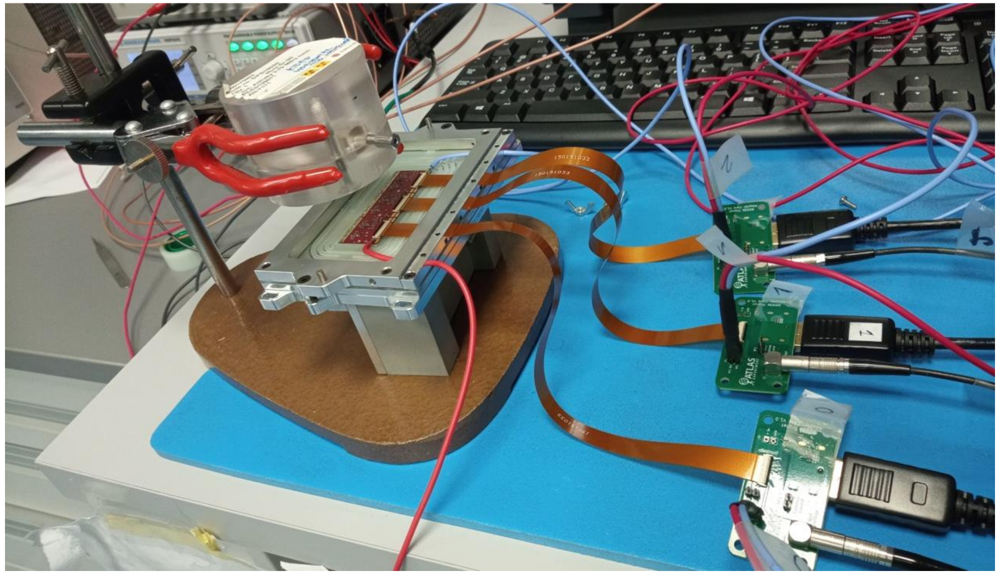
Thermal stress test to check the quality of the bump connections between chip and sensor.

After thermal cycling it is necessary to repeat the tests.



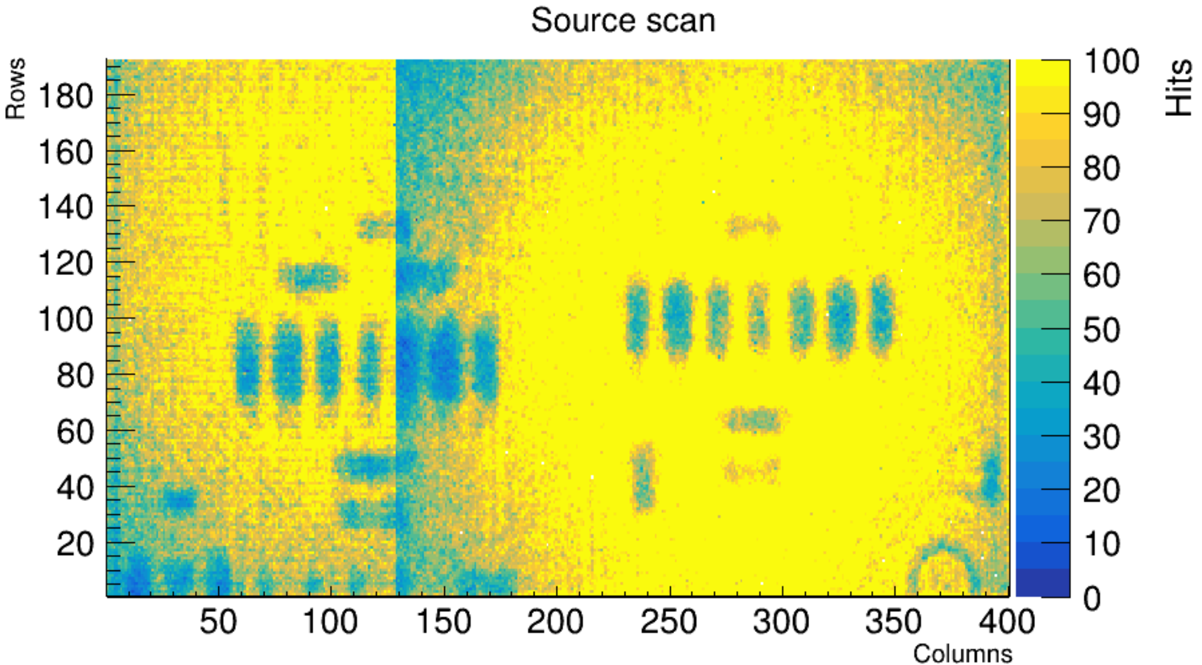


Electrical test - Source scan



The final test to study the performance of the triplet is the Source scan.

In this test we use a radioactive source to measure the signal on each pixel looking for not responding pixels due to a bad bump-bonding connection.



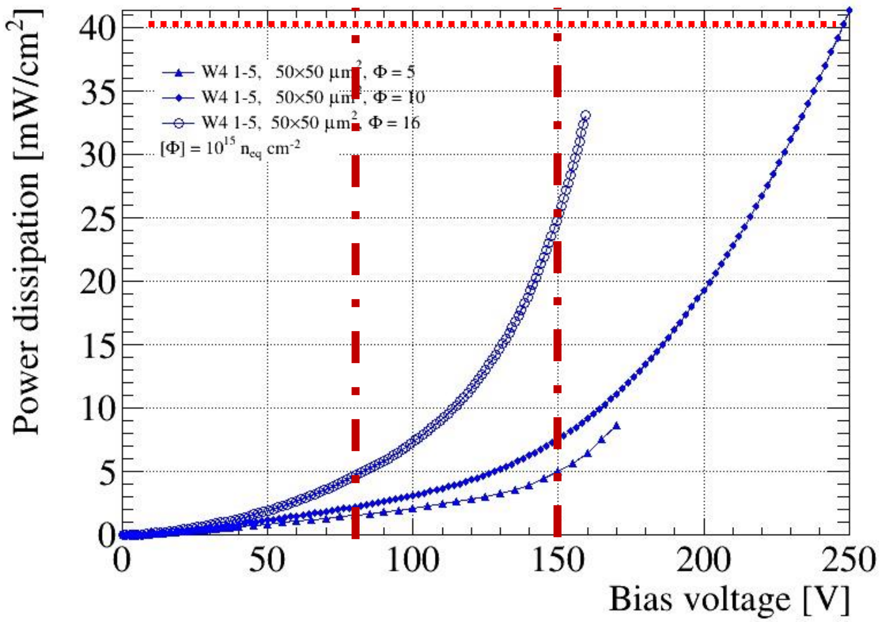
It can be seen that all the pixels respond.

So, there are no damage in the structure of the detector.

Performance after irradiation

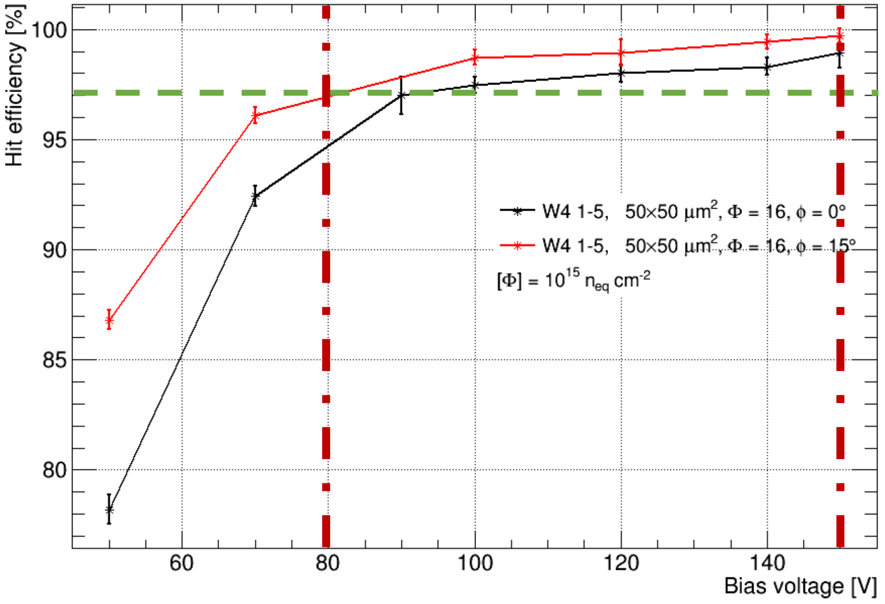
3D pixel sensors (manufactured at CNM and flip-chiped at IFAE) were tested after being irradiated to study its radiation tolerance.

- **<u>Power dissipation</u>**
  - **<u>Modules needs to be operated at low temperature to avoid a thermal runaway effect.</u>**
  - The power dissipation of the sensor is measured at different levels of bias voltage.
  - **For ATLAS specifications, Power Dissipation must be lower than 40 mW/cm².**



- **<u>Particle detection efficiency (Hit efficiency):</u>**
  - Using an electron accelerator beam to study the hit efficiency of the sensors.
  - **For ATLAS ITk it is necessary to reach an efficiency higher than the 97%.**

Efficiency curve



<u>Modules tested achieved the requirement for ATLAS in therms of power dissipation and particle detection efficiency.</u>

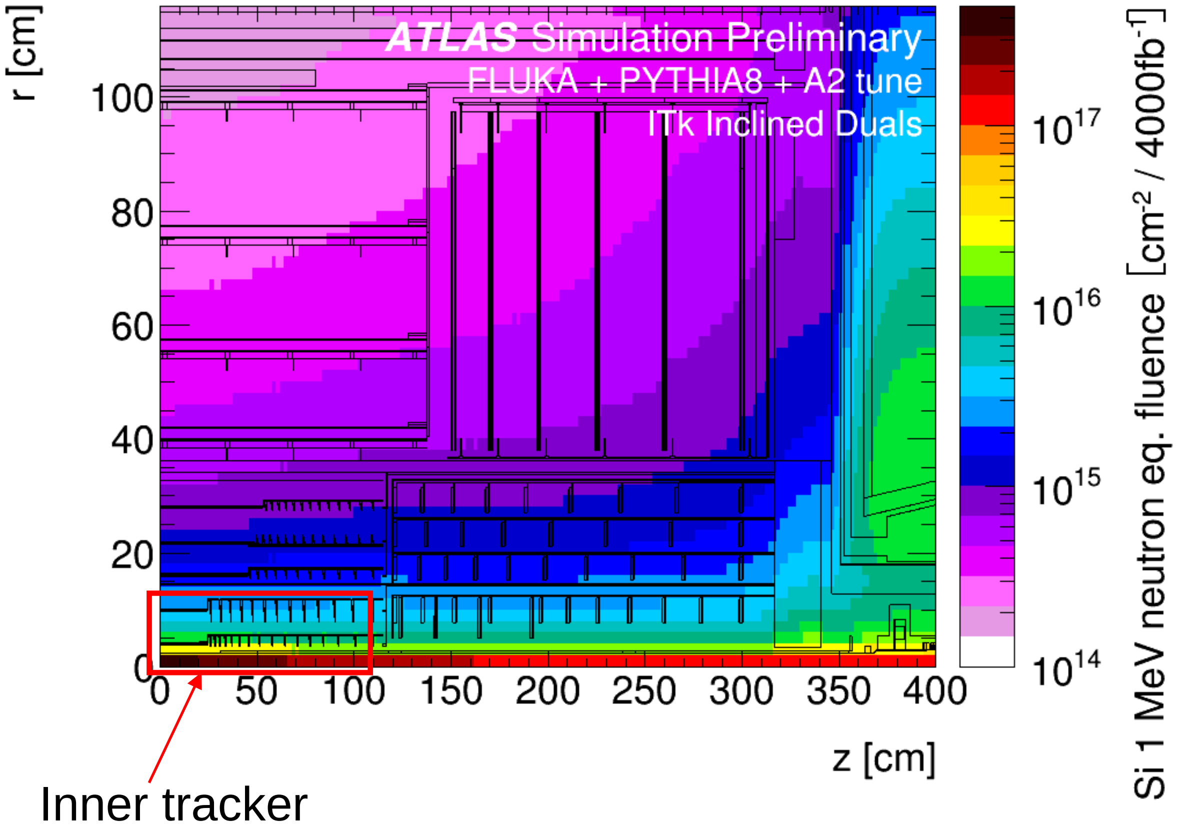
Conclusion

- IFAE is engaged in the production of modules for the innermost layer of the new ATLAS tracker for the HL-LHC era (which will start in ~2029)
- First prototype modules (RD53A) assembled at IFAE meet all the ATLAS specifications related to
  - Assembly process and electrical performance
- We are currently working on the next step of the site assembly qualification process, which is the production of ITkPixV1.1 triplet modules
  - We expect to start the pre-production on November of 2023.
- In parallel we are verifying the performance of the devices after irradiation:
  - 3D sensor produced at CNM and flip-chipped at IFAE was irradiated to full fluence
  - We confirmed excellent efficiency and power dissipation results

Thank you for your attention

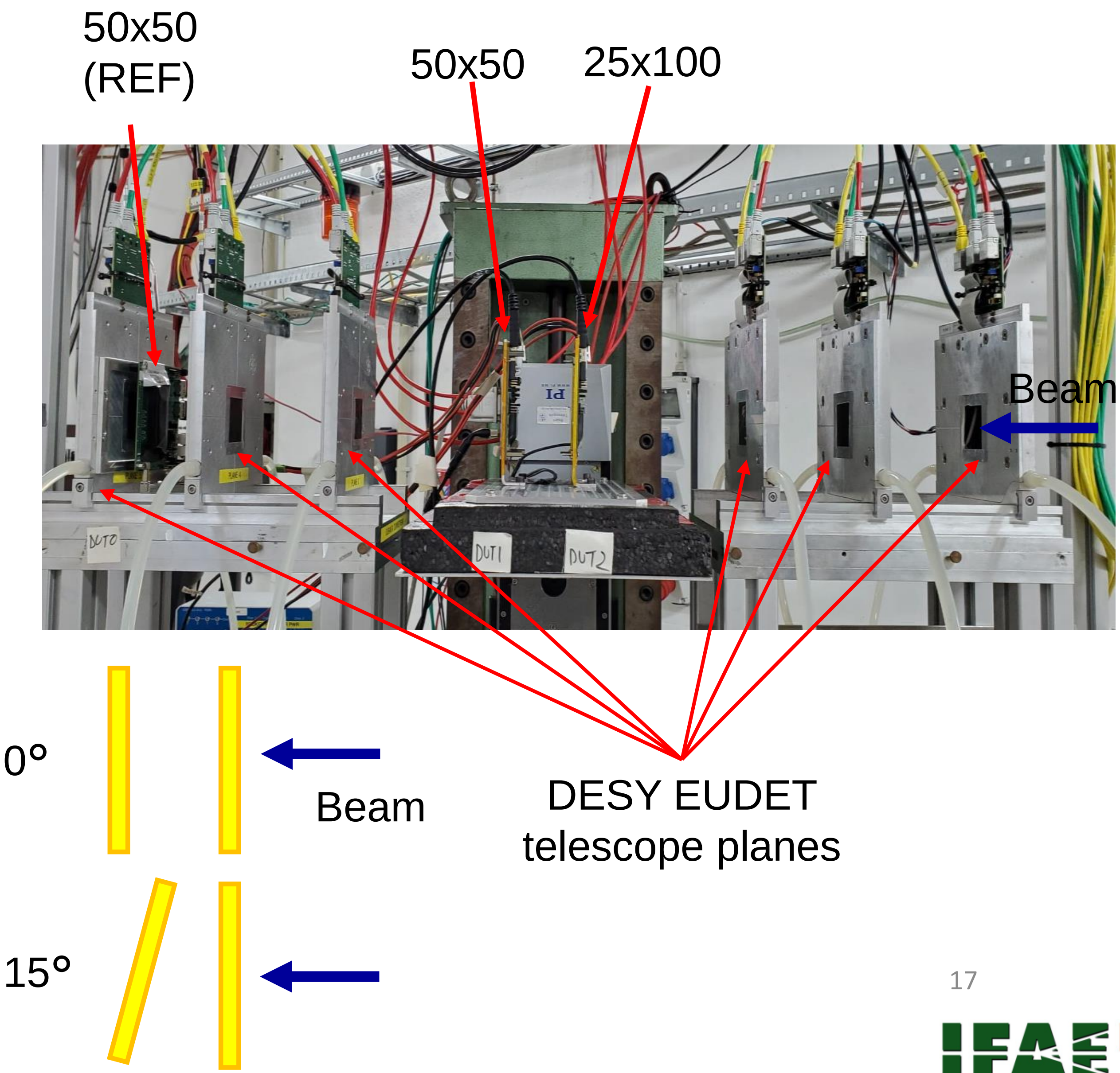
Backup slides

ATLAS – ITk radiation tose



DESY setup – December 2021

- EUDET telescope: 6 MIMOSA pixel detectors for tracking.
- We use a 50x50 non-irradiated RD53A planar sensor as timing reference.
- We use dry ice to reduce the leakage current on the modules.
    - Box temperature: -48ºC
- We used EUTELESCOPE to reconstruct the particle tracks and TBMon2 to calculated the efficiency.
- 50x50 was measured at 0º (normal to the incident beam direction) and at 15º
- 25x100 was measured only at 0°.

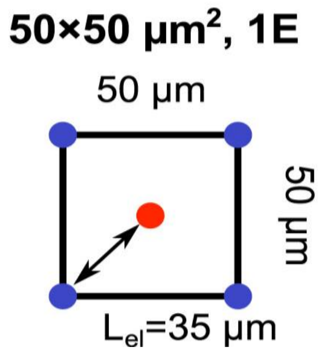


Efficiency pixel map 50x50 at 70V

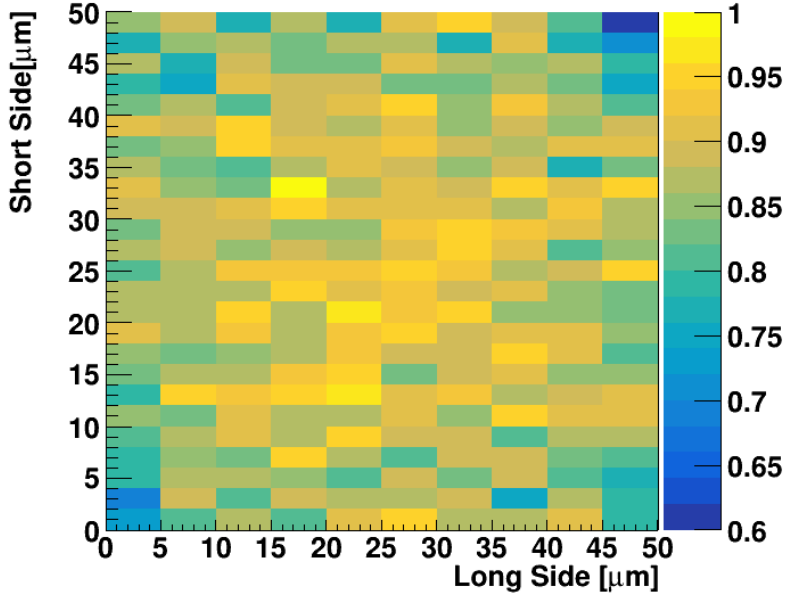
Efficiency pixel map for the same sensor (50x50) normal (left) and tilted 15º (right) at the same scale.

Efficiency in the corners for the tilted one is higher and uniform.

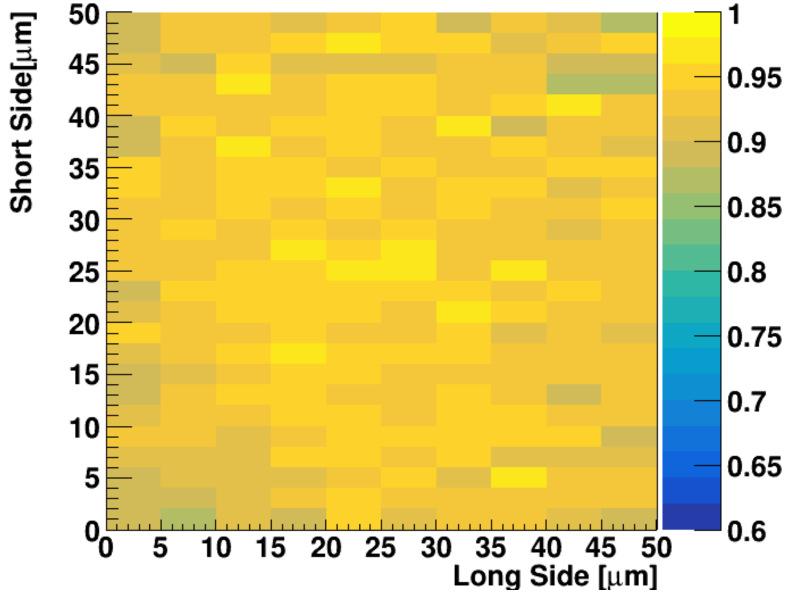
When an electron cross through a column it doesn't deposit charge, so the efficiency in the corners decrease.

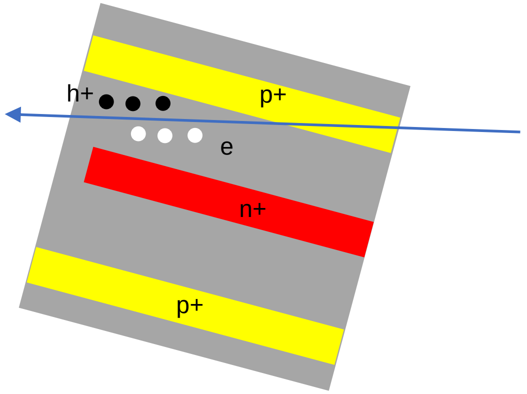


Not tilted



Tilted

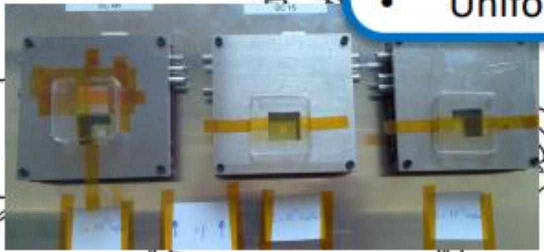


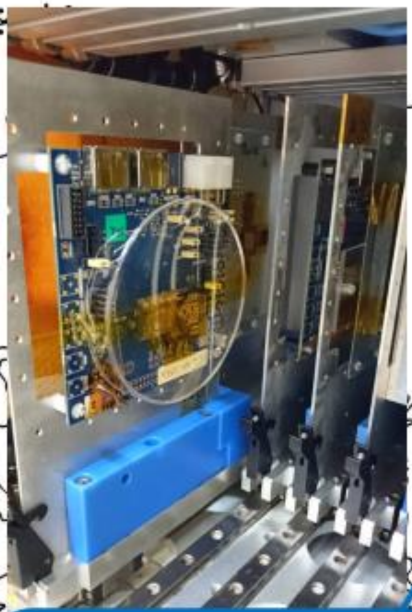


15º tilted scheme

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

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





Birmingham, UK
- 27 MeV (up to 37 MeV) protons
- Large TID: ~650 Mrad for 5e15 n_{eq}/cm^2
- Uniform irradiation at T<0˚C

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

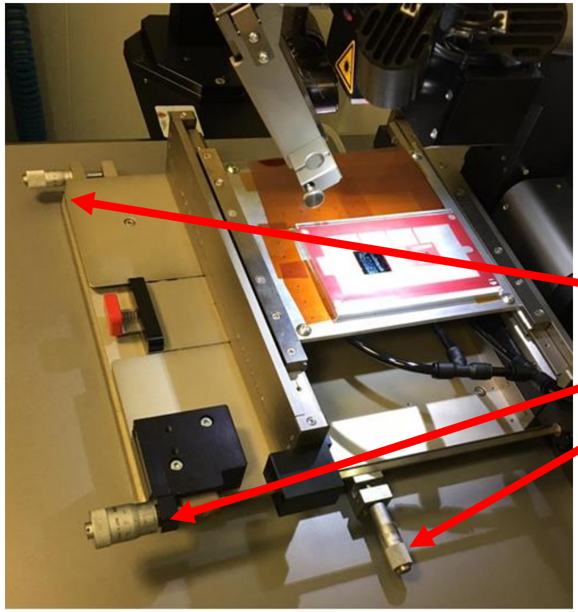
TRIGA reactor at JSI, Slovenia
- Reactor neutrons
- Negligible TID
- Uniform irradiation
- Tantalum in the chip gets activated

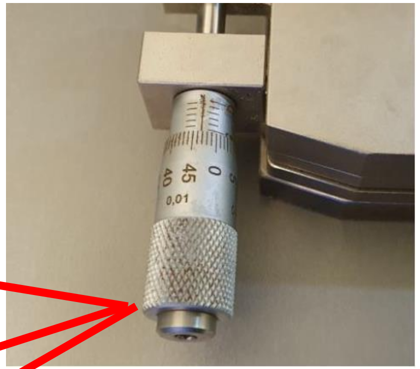
Thanks to: Koji Nakamura, Vladimir Cintro, Laura Gonella & Amelia Hunter, Felix Bögelspacher & Alexander Dierlamm

Triplet assembly - Pick and place

The main instrument for the assembly is the pick and place machine.

- It has a set of micrometers to move the base with a precision of 5 μm.
- An arm to set the applied strength from 1 N to 20 N (during the assembly we applied 7N)



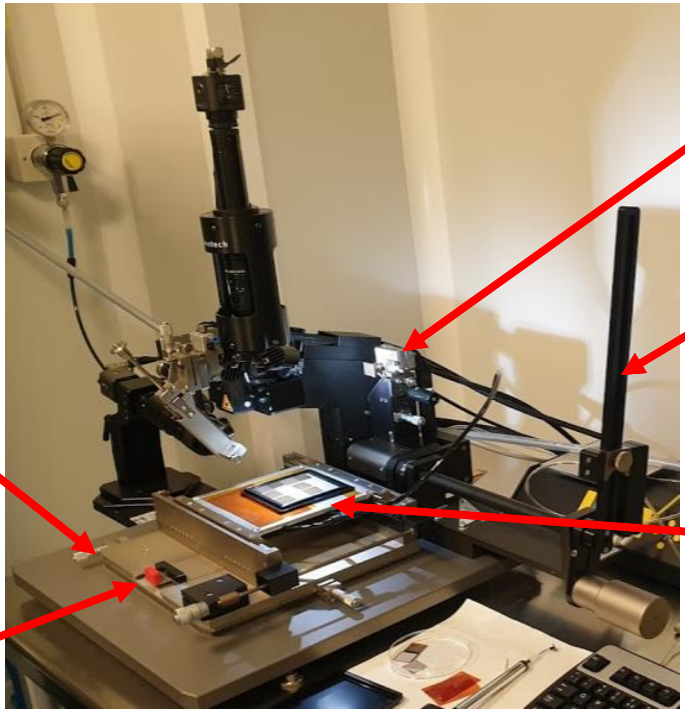


Set of micrometers:

- 3 in the base: up-down, left-right forth-back
- 1 in the holder: Rotation
- 5 μm precision

Set of micrometers

Mobile base

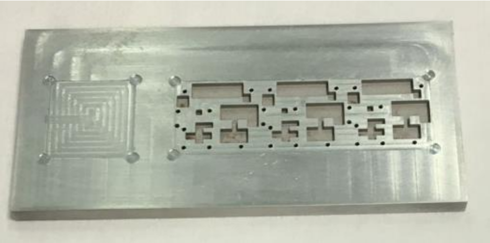


Holder

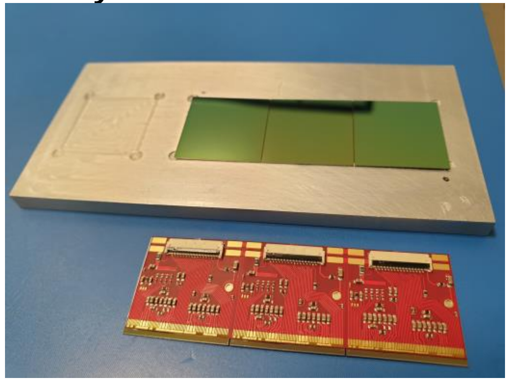
Pick and place arm

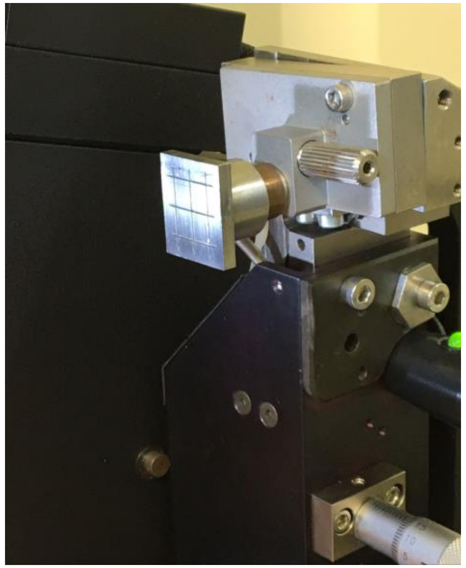
Vacuum system for chucks

Pick and place device



Chuck for triplets, it has a vacuum system in the bottom





Vacuum system on the holder to pick the dummies or glasses

3D sensor run at CNM

First 3D pixel sensor compatible with the RD53A chip manufactured at CNM.

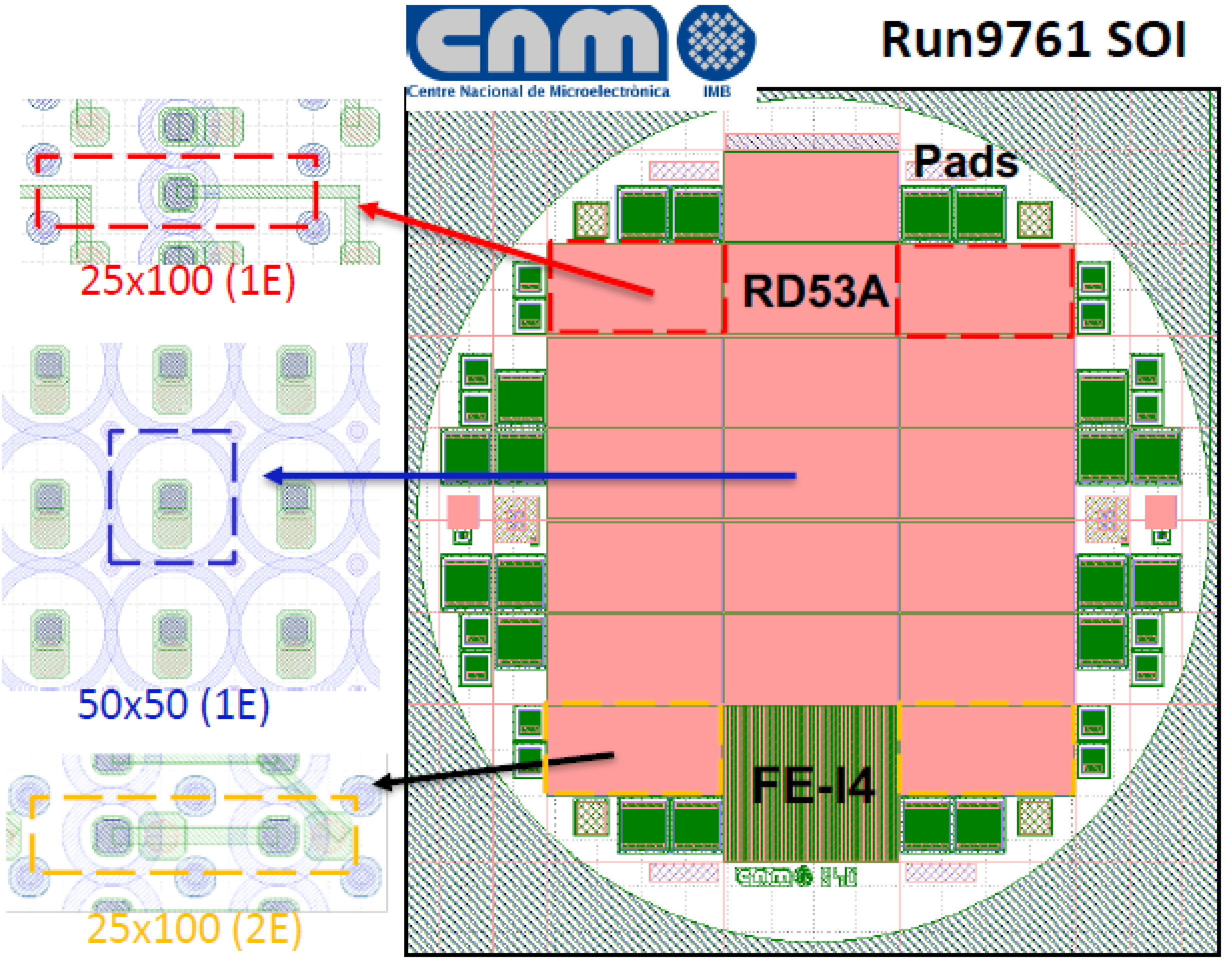
- Single sided process
  - Both p- and n-columns etched from the front
  - p-stop insulation
- Silicon on Insulator (SOI) wafers 150 µm active thickness with 300µm handle wafer
- Under-Bump Metallization (UBM) were performed at CNM and the **Flip-chip was carried out at IFAE**.

The mask includes:

- 14x RD53A 50x50 µm² 1E
- 2x RD53A 25x100 µm² 1E
- 2x RD53A 25x100 µm² 2E
- 1x FE-I4 50x50 µm 1E
- Pad diodes of 50x50 µm²
- Pad diodes 25x100 µm²

Sensors tested in this presentation are:

- 50x50 µm² 1E pixels



ATLAS – ITk sensors

The radiation damage in a sensor change some properties:

- The depleted zone change due to a change of a doping concentration in the structure. So, it is necessary to increase the voltage to fully depleted.
- The charge collected travel less distance (L), so the damage in the structure of the silicon affect less the signal.
- Finally, the broken structure creates free thermal electrons that increase the current in the sensor. For this reason, it is necessary to cold down during test after the irradiation.