# Towards the construction of the new ATLAS inner detector for the HL-LHC upgrade
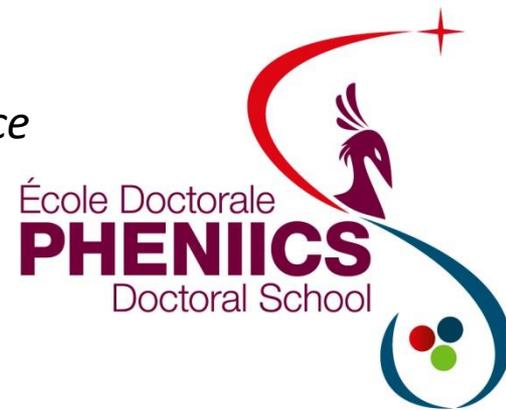
Dmytro HOHOV

*Laboratoire de L'accélérateur Linéaire, Orsay, France*

*Université Paris-SUD XI*

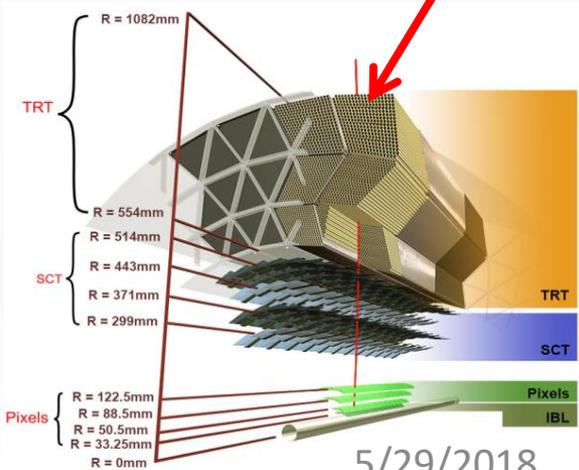PHENIICS Fest  -  28-29 mai 2018

# Outline

- **ATLAS project**
  - Structure of the ATLAS detector
  - ATLAS detector upgrade connected with HL-LHC project
- **Pixel detectors**
  - Working principle of pixel detectors
  - Current and future concepts of pixel detectors
- **Tests and characterization as an important stage in the pixel detector development**
  - Module characterization at test beam facilities
  - Characterization in the clean room
  - LAL participation in Demonstrator project
- **Conclusions**

# ATLAS detector



44 m long
25 m tall
7000 tons

**Toroid magnets** · **Muon Chambers** · **Inner Detector** · **Solenoid magnet** · **Calorimeters**
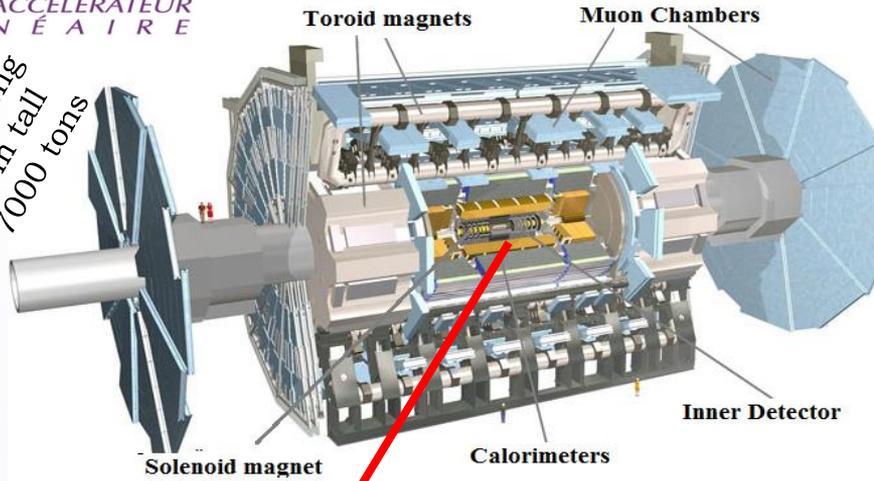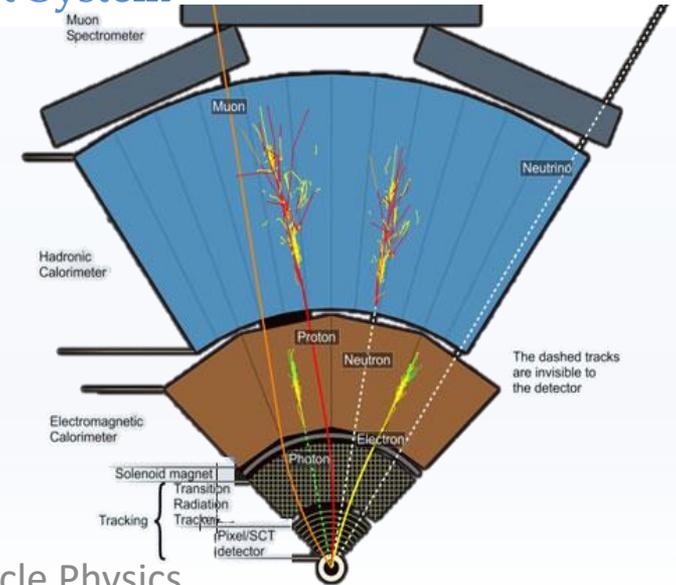
- **Inner Detector** (measures the momentum of charged particles)
- **Calorimeter** (measures the energies carried by particles)
- **Muon Spectrometer** (Identifies and measures muons)
- **Magnet System**



R = 1082mm
TRT
R = 554mm
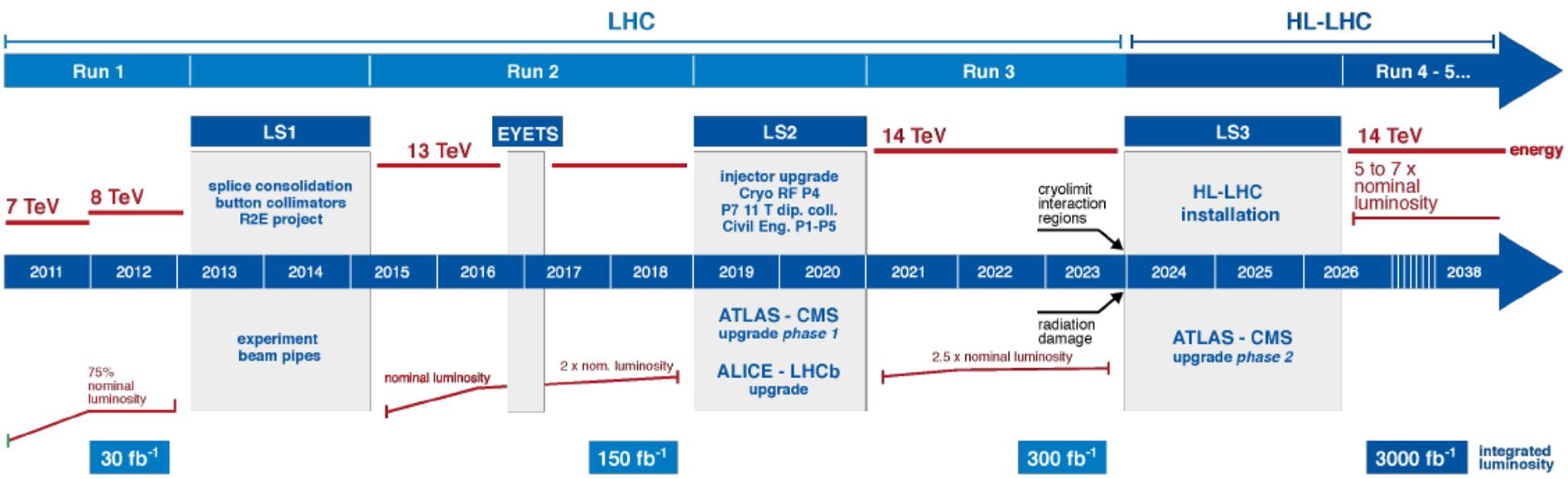R = 514mm
SCT
R = 443mm
R = 371mm
R = 299mm
Pixels
R = 122.5mm
R = 88.5mm
R = 50.5mm
R = 33.25mm
R = 0mm
TRT
SCT
Pixels
IBL

**Transition Radiation Tracker**

**Semi-Conductor Tracker**

**Pixel Detector**



Muon Spectrometer · Muon · Neutrino · Hadronic Calorimeter · Proton · Neutron · Electromagnetic Calorimeter · Photon · Electron · Solenoid magnet · Transition Radiation Tracker · Tracking · Pixel/SCT detector

The dashed tracks are invisible to the detector

# The (HL-)LHC Timeline

# Motivation for ATLAS Inner Detector upgrade

| Name of the upgrade | Date | Luminosity | Energy √s |
|---|---|---|---|
| LHC startup | 2009 | $6 \times 10^{33}$ cm$^{-2}$s$^{-1}$ | 7-8 TeV |
| Phase- 0 | 2014 | $1 \times 10^{34}$ cm$^{-2}$s$^{-1}$ | 13 TeV |
| Phase- 1 | 2018 | $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ | 13-14 TeV |
| Phase- 2 | 2023 | $7,5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ | 14 TeV |

Very severe pile-up conditions expected:

Corresponding num. of inelastic **pp** collisions per beam-crossing (25 ns) will increase : **25 -> 200**

## New Tracking detectors must fulfill the conditions:

- Fast (40MHz), high granularity & good pattern recognition capabilities ($10^3$ tracks/25 ns).

# **Motivation for ATLAS Inner Detector upgrade**

- Increased luminosity also leads to increasing of radiation load.
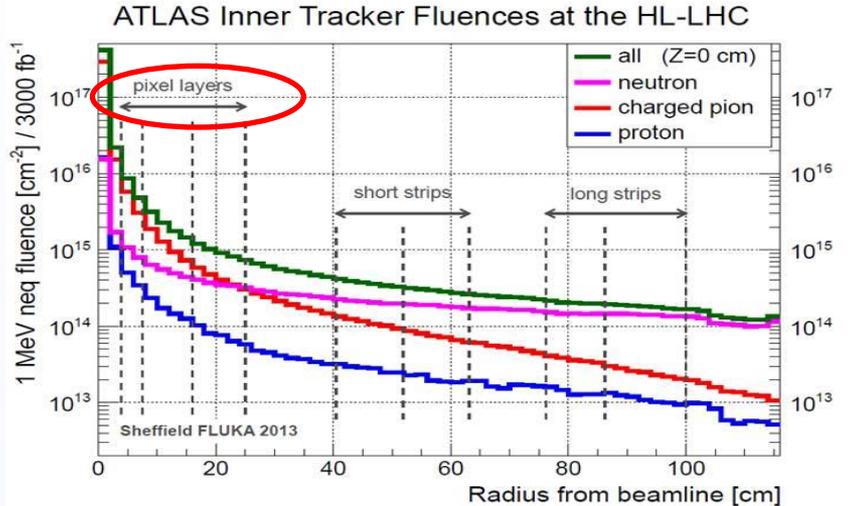


Aim is **3-4k fb$^{-1}$** integrated luminosity

ID (Inner Detector) has limited lifetime:

Expected:
$1.6 \cdot 10^{16}$ $n_{eq}$ cm$^{-2}$    ➡    **1.7 GRad**

Designed :
$10^{14}$ $n_{eq}$ cm$^{-2}$    estimated to correspond to **400 fb$^{-1}$**

**Radiation Effects:**

- Creation of lattice defects (loss in the charge collection due to charge capture).
- Change of depletion voltage (due to type inversion).
- Rise of leakage current (additional energy levels are being formed in the band gap region)

# Motivation for ATLAS Inner Detector upgrade

**The new <u>All Silicon</u> Inner Tracker (ITk), ~ 10 years operational, Strips and Pixels**



Layout for the Phase-II Inner Tracker (Apr 2017)
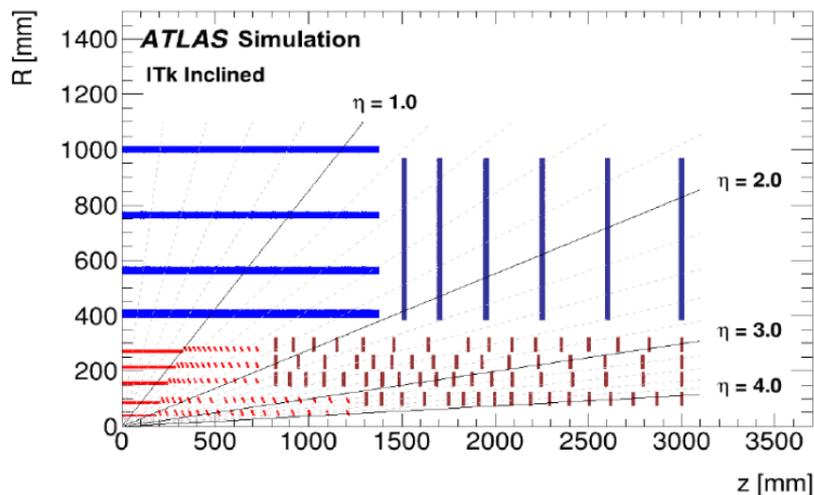
| | Silicon Area | Channels [$10^6$] |
|---|---|---|
| Pixel | ~13 m$^2$ | 580 |
| Strip | 160 m$^2$ | 50 |

- The target acceptance has been extended to ± 4 units of pseudorapidity
- Pixel system extending to roughly twice the radius and four times the length
- Reduced material budget before calorimeters

# Working principle of pixel detectors

## Hybrid planar pixel detector:



~20μm

Front-End readout

n⁺-type

n-type

Electrical field

Charge carriers

Sensor

p-type

Guard rings

Al



N-Type

Donor impurity contributes free electrons

Si

Si P Si

Si

Phosphorus added as impurity

P-Type

Acceptor impurity creates a hole

Si

Si B Si

Si

Boron added as impurity

Energy

| Intrinsic | n-type | p-type |
|---|---|---|
| Conduction Band | Conduction Band | Conduction Band |
| | electrons | Acceptor Level |
| | Donor Level | |
| Valence Band | Valence Band | Valence Band |

holes

To operate, the semiconductor (silicon) must be depleted:

Full charge collection only for
$(V_{bias} > V_{dep})$

reverse biased pn-junction



n-type | Depletion region | p-type



150 μm

sensor pixel

chip pixel unit cell

solder bump

silicon sensor

readout chip

250 μm

150 μm

data buffers
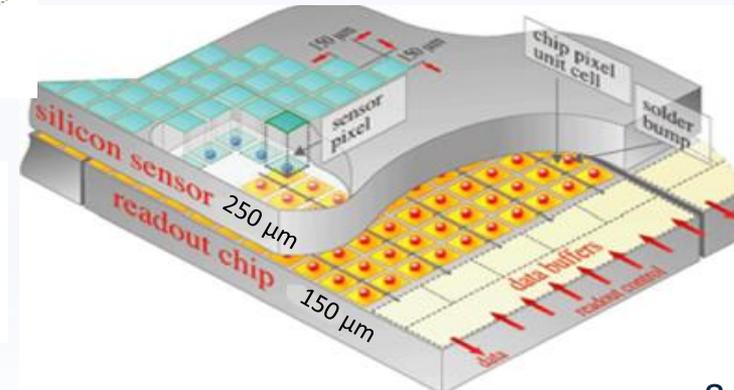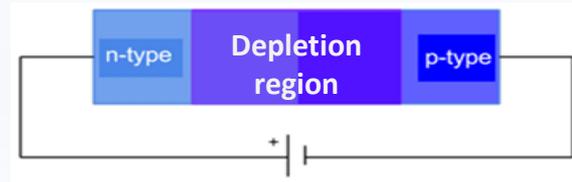
# Alternatives for Planar pixel technology

There are two planar sensor configurations that can be used for high particle fluences due to their fast charge collection : **n-in-n** and **n-in-p**.

## n-in-n



## n-in-p



## Type inversion effect



The change of the effective doping concentration due to irradiation
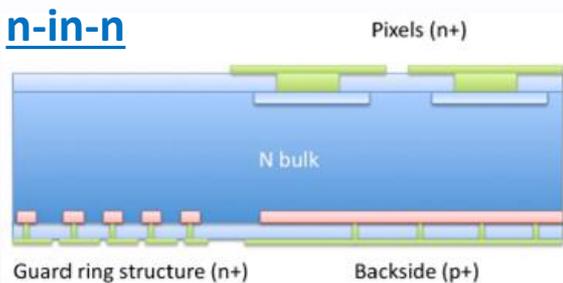
- Collect electrons (3 x faster than holes)
- Guard rings are not on front-end side
- Double-sided processing
- Type inversion of the n-doped silicon bulk
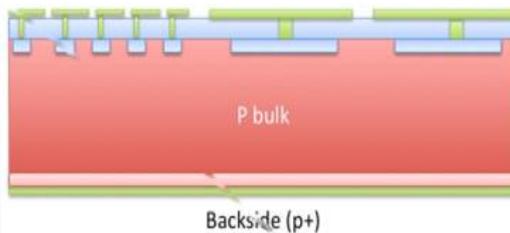
- Collect electrons (3 x faster than holes)
- No type inversion
- Can be operated partially depleted
- Single –sided processing
- Guard rings are on front-end side

# Alternatives for Planar pixel technology

- **Design parameters to improve:**

**Sensors:** the radiation resistance, reducing of non active area (efficiency), thinning, production cost

**Electronics:** processing speed (dead time), signal-to-noise ratio, reducing of power consumption (cooling), price

Achievements of the Phase 0 (Insertable B-layer) IBL Upgrade:

New Front-End readout chip, designed for the Phase 0



| | FE-I3 | FE-I4 | RD53 A |
|---|---|---|---|
| Pixel size | 50x400um$^2$ | 50x250um$^2$ | 50x50um$^2$ 25x100um$^2$ |
| Pixel matrix | 18x160 | 80x336 | |
| Chip size | 7,6x10,8 mm$^2$ | 20,0x18,6mm$^2$ | ~20x20 mm$^2$ |
| Technology | 250 nm | 130 nm | 65 nm |
| Active part | 74% | 89% | more |
| Analog current | 16 uA/pixel | 10 uA/pixel | less |
| Digital current | 10 uA/pixel | 10 uA/pixel | Less |
| Data rate | 40 Mb/s | 160 Mb/s | 2 Gb/s |
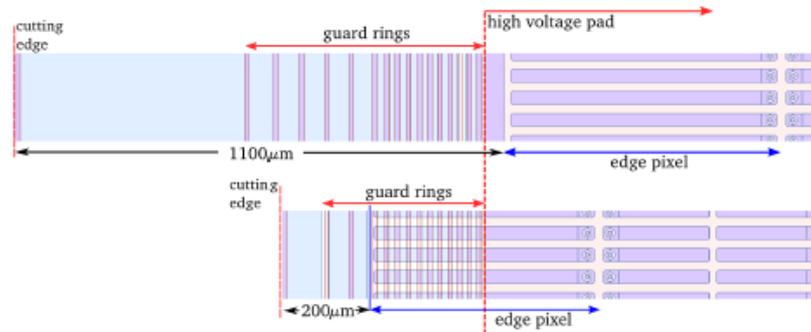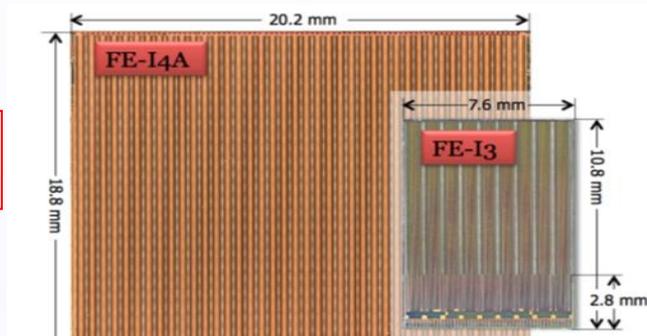
# Planar pixel sensors to test

**Samples to study:** FE-I4 compatible thin **n-in-p** planar pixel sensors with *the active and slim edge design* produced by ADVACAM.

- Radiation hard (no type inversion, thin);
- Single side processing;
- Thickness : 50 um, 100um, 150um;
- Maximized active area (Deep Reactive Ion Etching (DRIE));

**It is particularly interesting for the innermost layers where it is important to reduce geometrical inefficiencies.**

**Goal:**

➢ Study the overall and edge hit efficiency with normal and inclined tracks before and after irradiation;

## Active edge
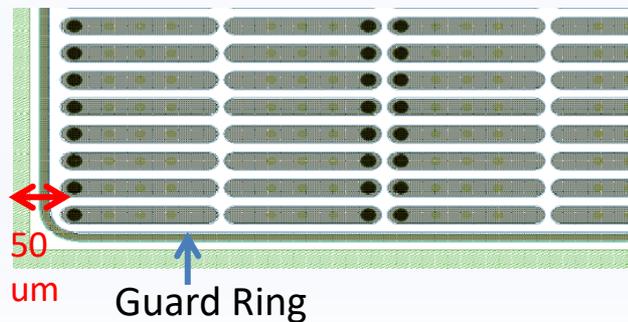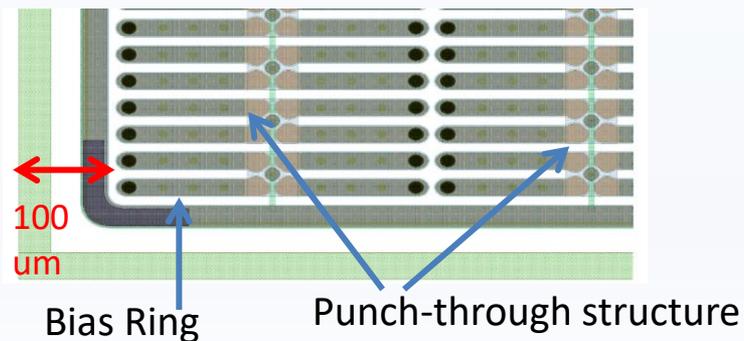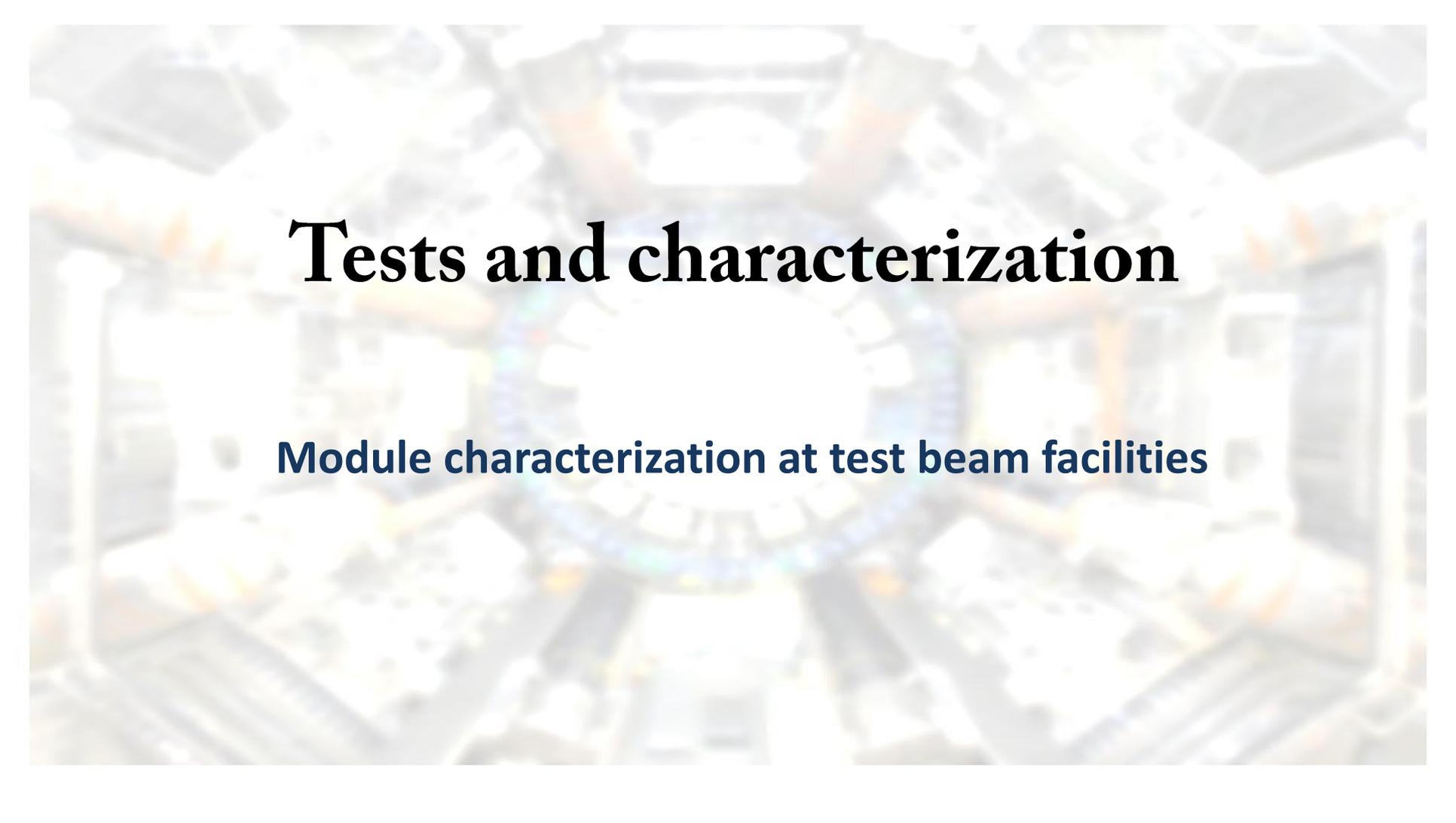


50 um

Guard Ring

## Slim edge



100 um

Bias Ring

Punch-through structure

# Tests and characterization

## Module characterization at test beam facilities

# Test beam characterization

**Test Beam telescope setup:**



EUDET telescope
ACONITE (H6A):

Scintillator

Beam

DUTs

Telescope planes
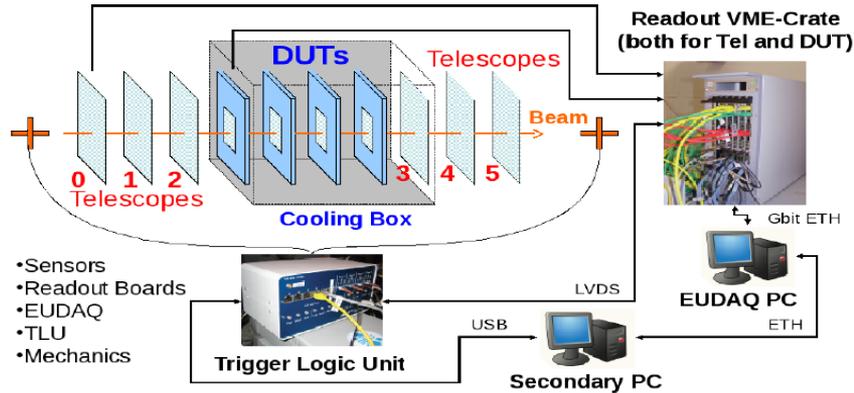
- ➢ Mimosa26 sensors (1152 x 576 ) with a pixel pitch of 18.4 μm,
- ➢ 50μm thick;
- ➢ Spatial resolution up to 2 um;
- ➢ Pixel read-out systems fully integrated into EUDAQ software framework;
- ➢ Multiple DAQ systems for lab tunings and measurements: USBPix, RCE, etc
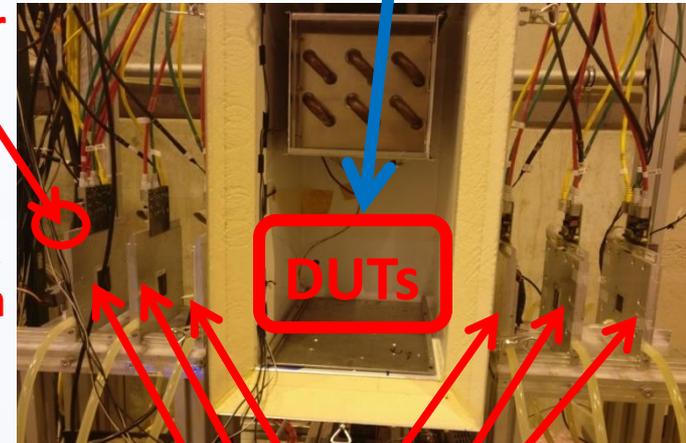
# Test beam characterization results

- Hit efficiency calculated as :

$$Efficiency = \frac{Number\ of\ Matched\ Tracks}{Number\ of\ Total\ Tracks}$$

**Overall efficiency**

Efficiency Map DUT 24

**94,73+0,24%**

**50V**

ADV-50-3-3A (slim edge)

Efficiency Map DUT 24

**97,21±0,05%**

**50V**

ADV-50-3-1D (active edge)
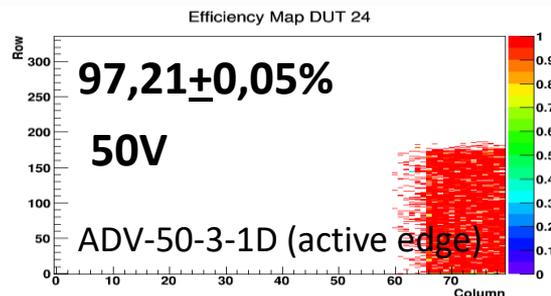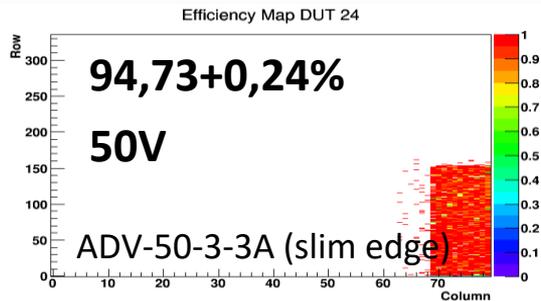
Non –irradiated and Irradiated, $1e15\ n_{eq}/cm^2$ ADVACAM sensors

Efficiency Pixel Map DUT 24 Geometry 0

**97,21±0,05%**

50V, **non-irrad.**

**In-pixel efficiency**

Efficiency Pixel Map DUT 24 Geometry 0

Efficiency Pixel Map DUT 24 Geometry 0

Efficiency Pixel Map DUT 24 Geometry 0

**81,92±0,07%**

50V, **irrad.**

Efficiency Pixel Map DUT 24 Geometry 0

**89,27±0,09%**

120V, **irrad.**
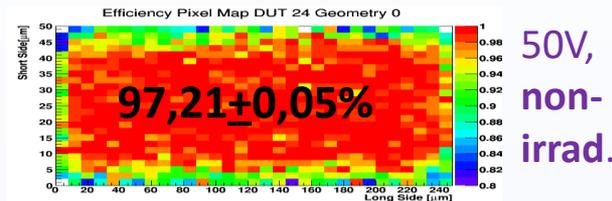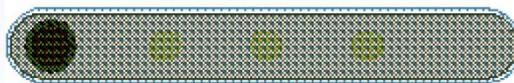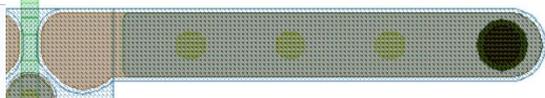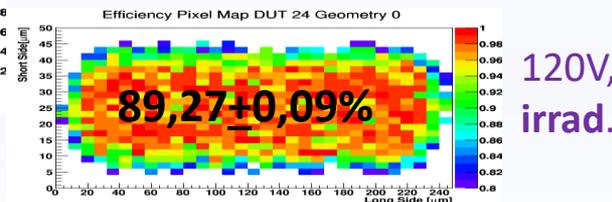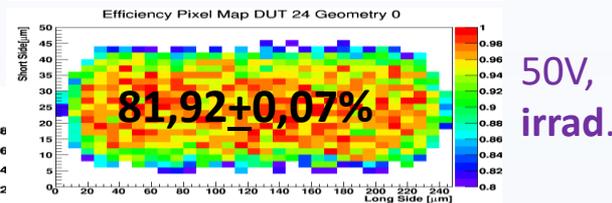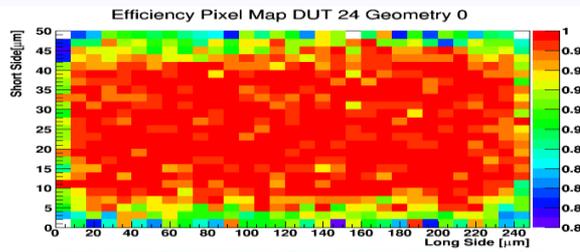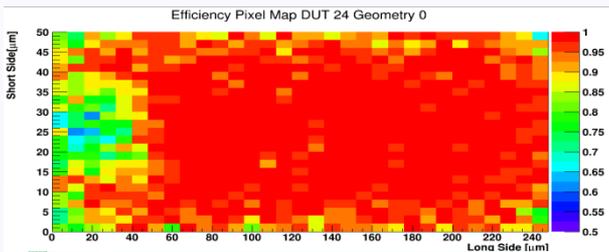
# Test beam characterization results

- Efficiency vs bias voltage: 1e15 $n_{eq}$/cm$^2$, tilted (45$^o$ and 27$^o$)
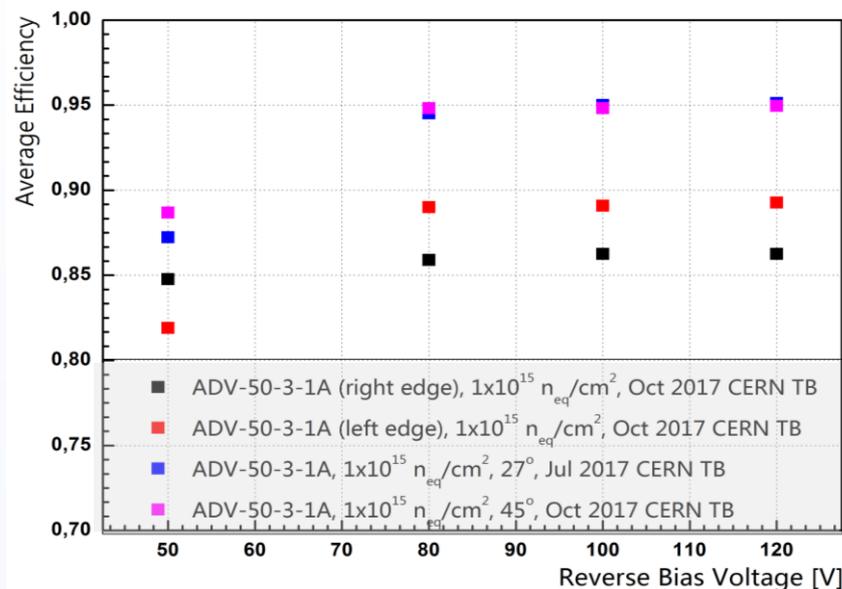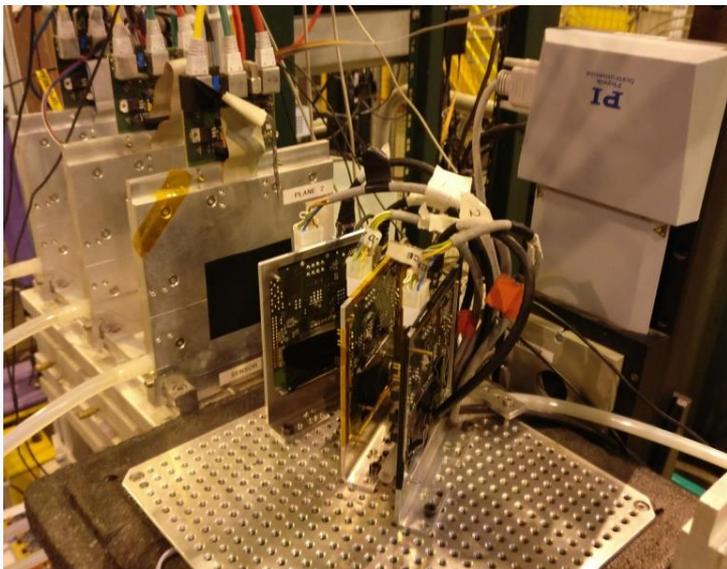




At a <u>tilted angle of 45˚, the efficiency performance improved</u>, reaching 95% at 80V bias voltage. The performance is very similar to the performance at 27˚ case (but with dry ice cooling).
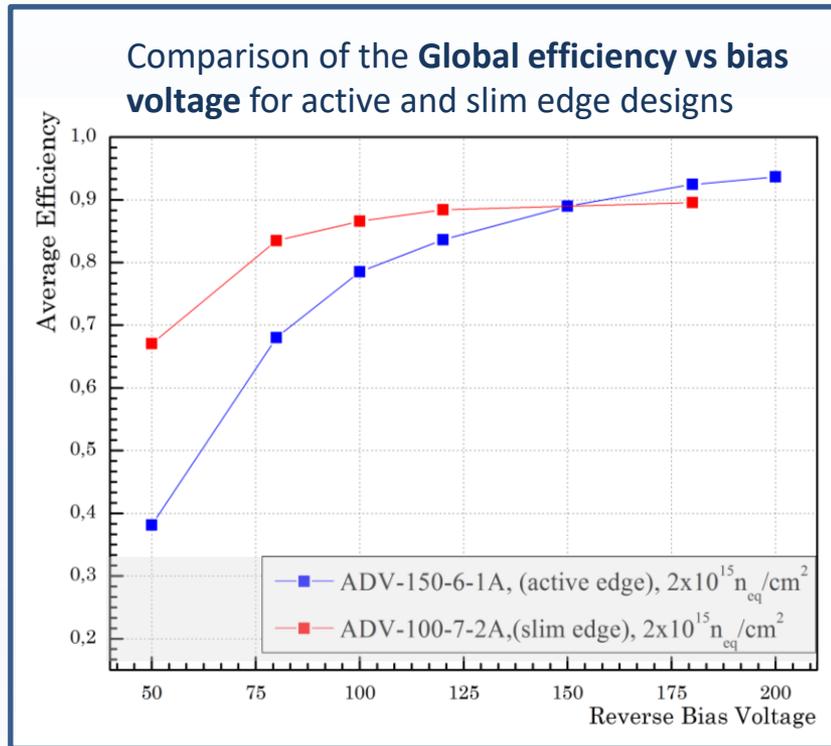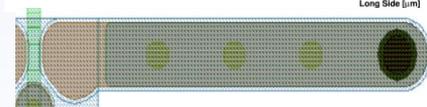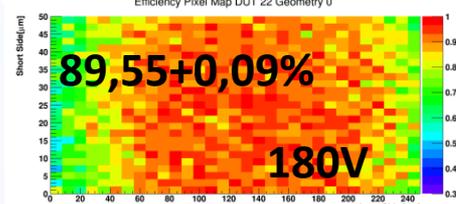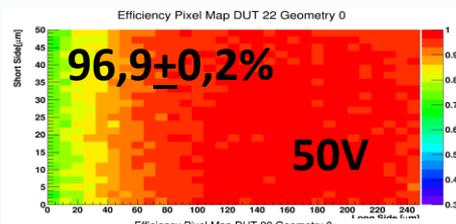
# Test beam characterization results

Efficiency performance for the **active edge (150 um )** and **slim edge (100 um)** after irradiation **$2\times10^{15}$ $n_{eq}/cm^2$** at different bias voltages.

- In-pixel efficiency maps

**Active edge**
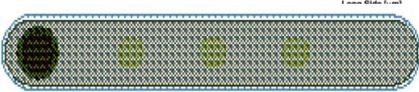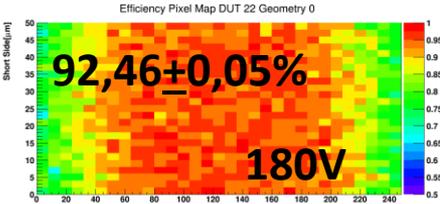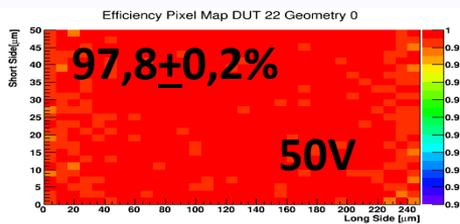


97,8±0,2%  50V

92,46±0,05%  180V

**Slim edge**



96,9±0,2%  50V

89,55+0,09%  180V

Comparison of the **Global efficiency vs bias voltage** for active and slim edge designs

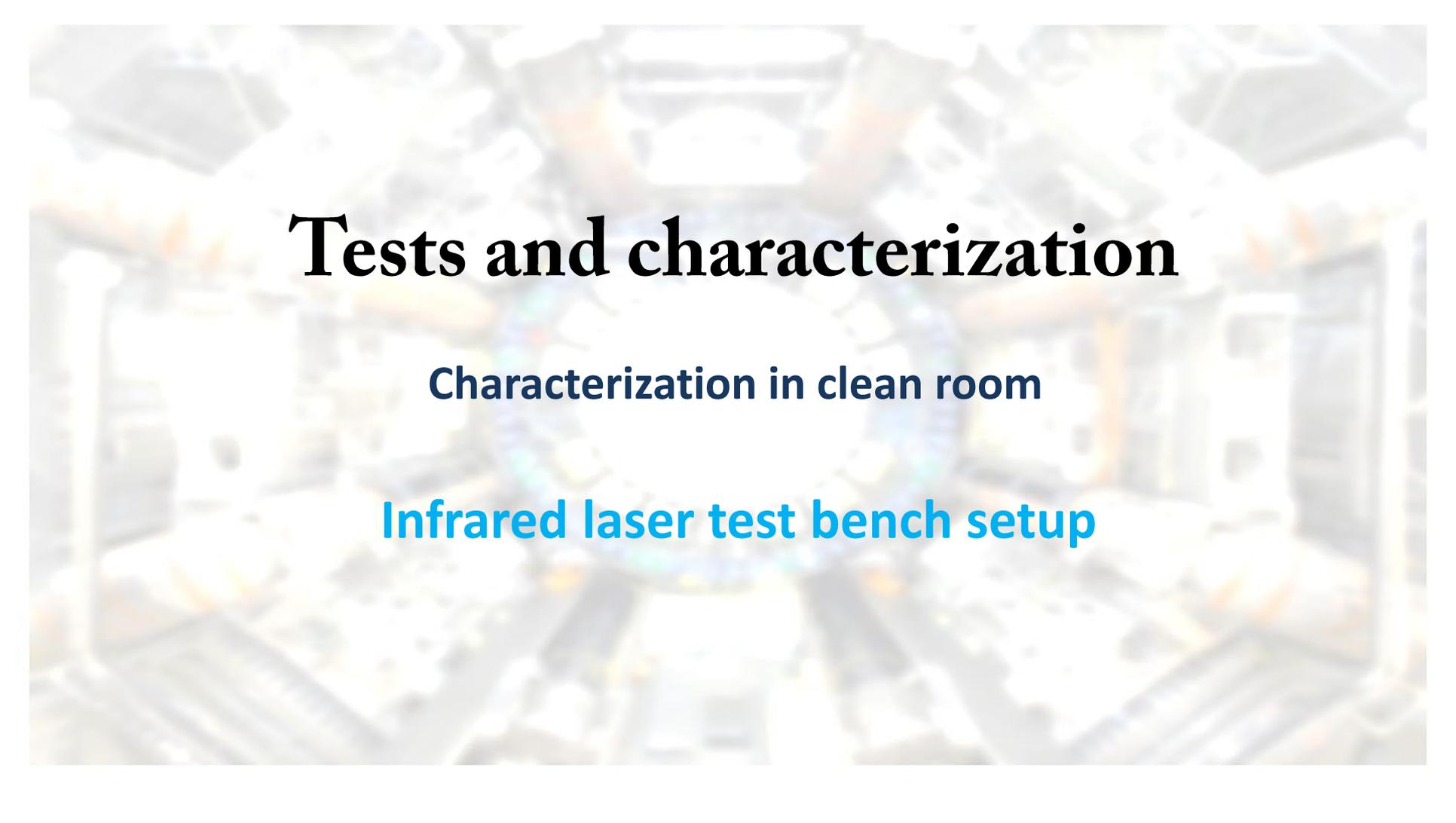# Test beam characterization results

Efficiency performance for the **active edge (150 um )** and **slim edge (100 um)**



ACTIVE EDGE

SLIM EDGE
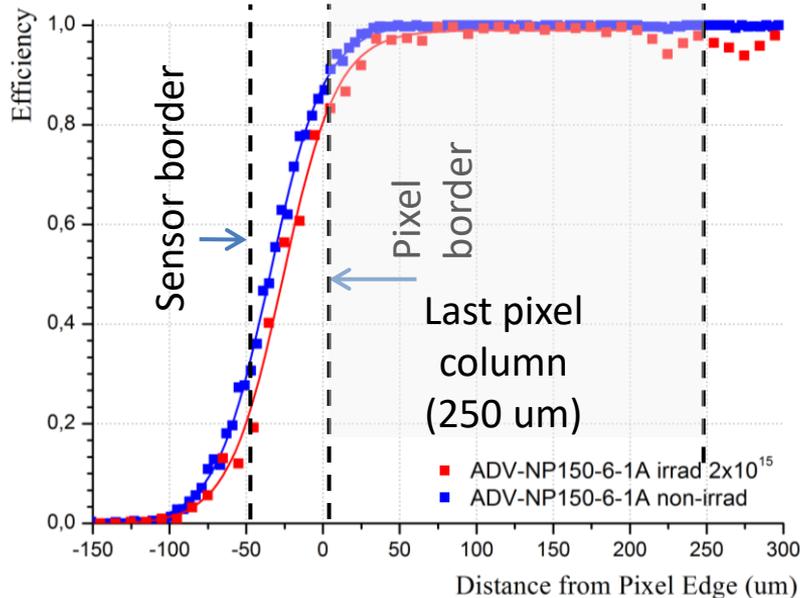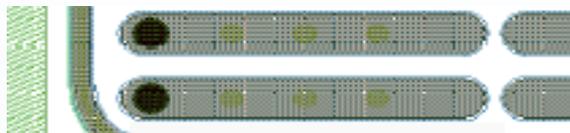
# Tests and characterization
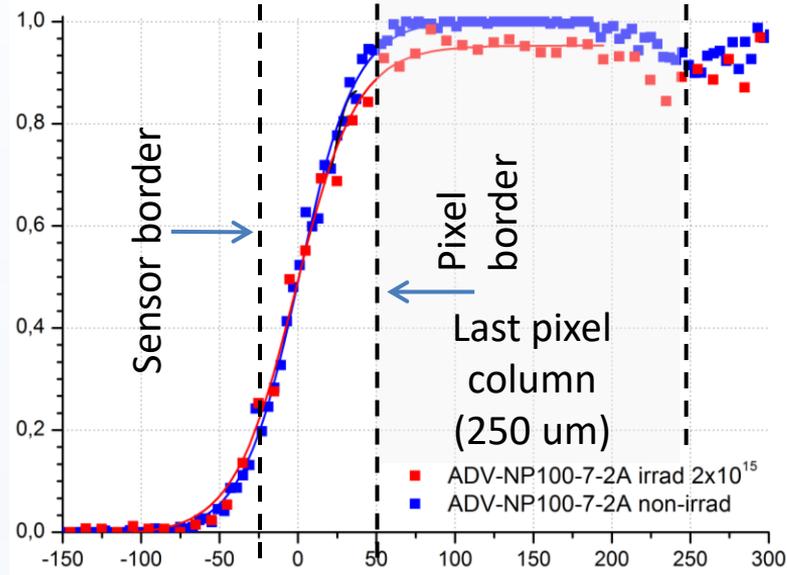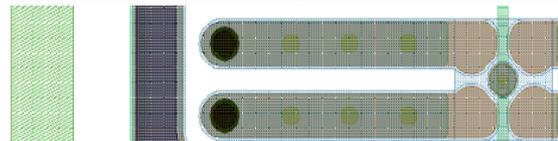
## Characterization in clean room

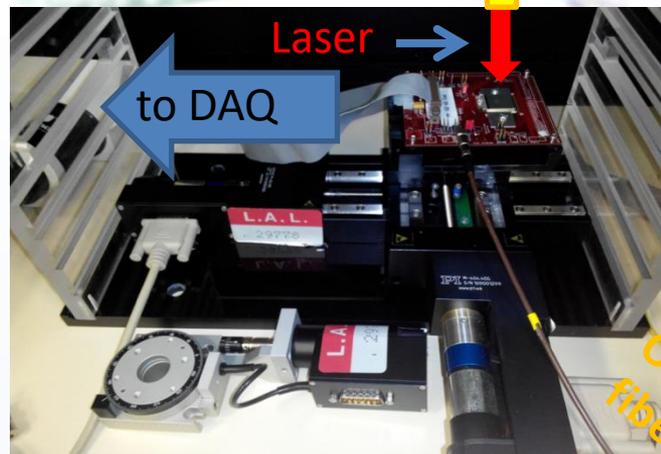## Infrared laser test bench setup

# Laser test bench setup

**<u>Purpose:</u>** To have a compact set-up to characterize silicon pixel modules and test their functionality in clean room before beam tests.

- ➢ charge collection efficiency (before and after irradiation, for the edges, scanning along an individual pixel);
- ➢ charge sharing between adjacent pixels;
- ➢ performance with inclined tracks;

## Our goals for this development:

- to have a setup based on infrared laser to mimic a MIP like charge generation;

- to have a possibility for micrometric positioning of the DUT in X-Y direction (so the interaction point determination without reconstruction);

- to be able to rotate a DUT to perform studies with inclined tracks;

- to adapt to new quad sensors and RD53-A readout electronics;

- have high rates (kHz), for high statistics in measurements;
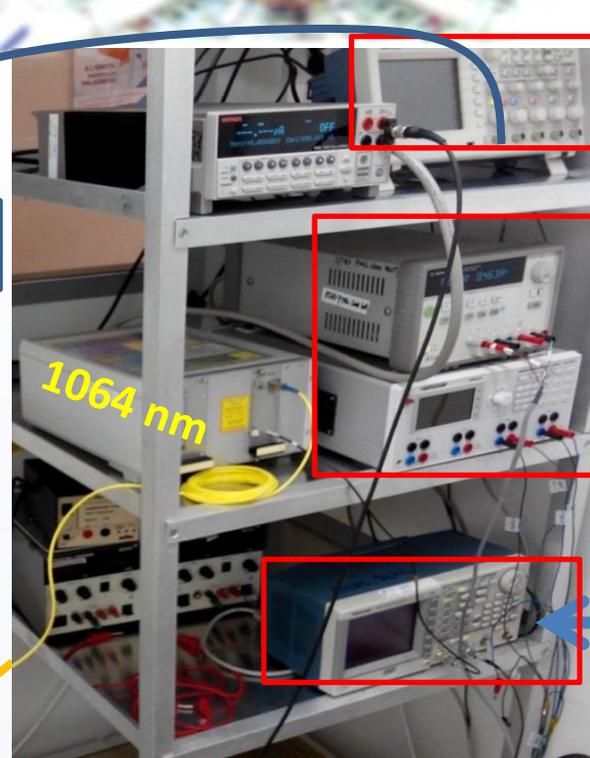
# Laser test bench setup



Laser → to DAQ

Scope

O/E converter

Optical fiber

1064 nm

25%
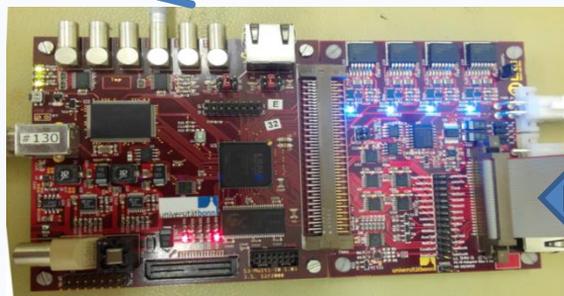
Module Front-End power suppliers

Trigger signal

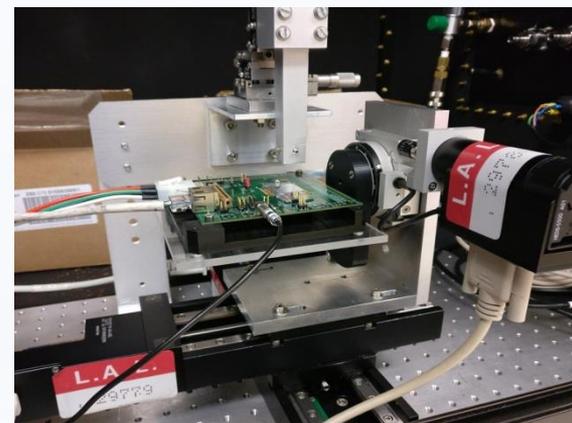Function generator

DAQ system

From Module

Bias HV for the module

# Laser test bench setup

LabVIEW software for the laser test bench controlling and parameters readout
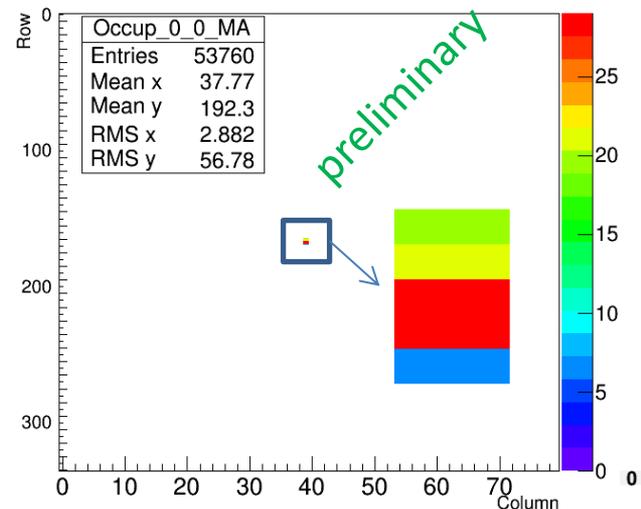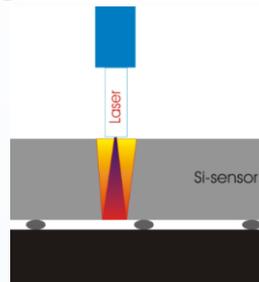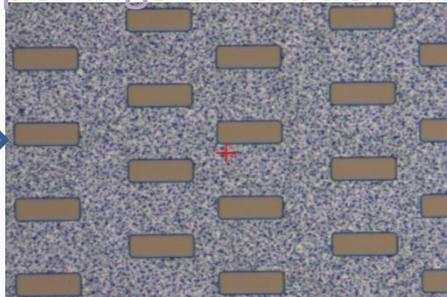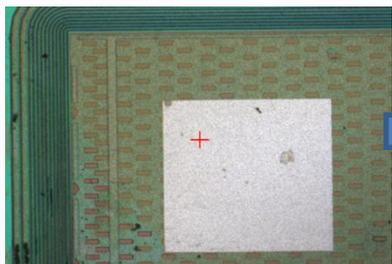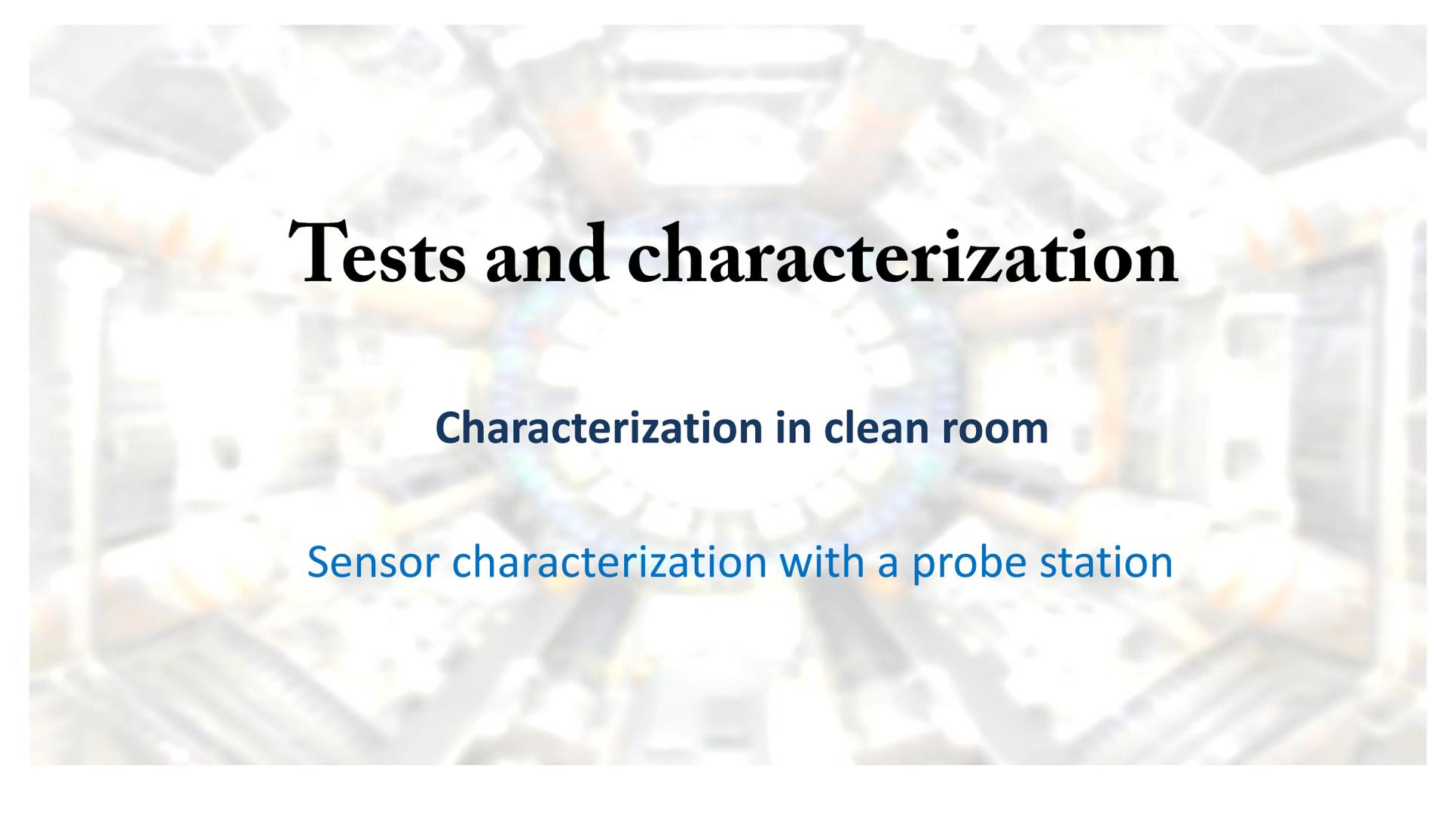
DUT support with rotating stage

# Laser test bench setup

Openings on a back side
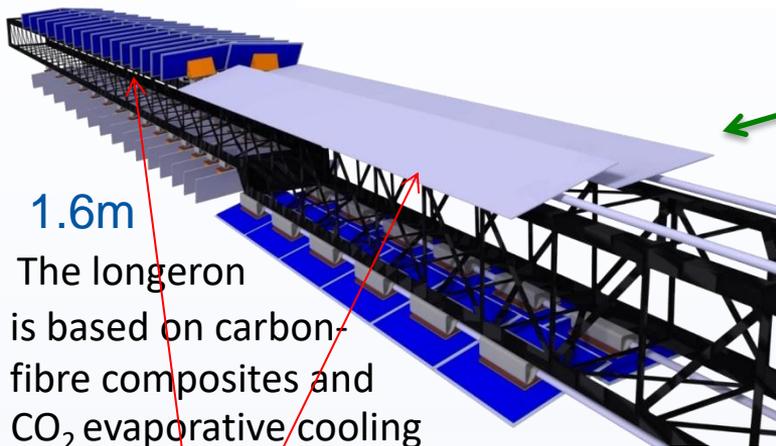


Hit map with the visible laser spot.
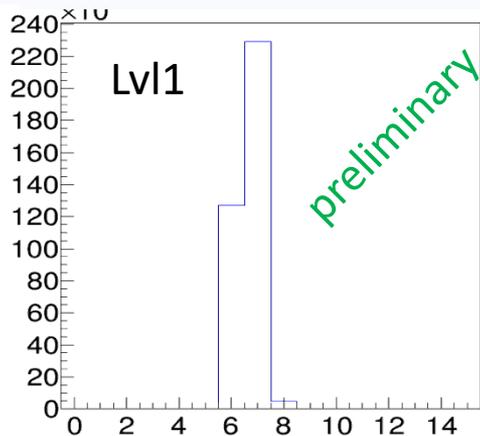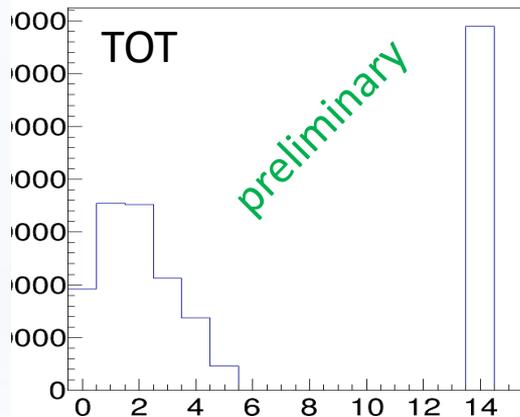
# Tests and characterization

**Characterization in clean room**

Sensor characterization with a probe station

# ITk Demonstrator project

The key goal is the demonstration of the system aspect of the complete and functional ITK pixel barrel stave.

This is the element which we propose to build as "Stave-0"
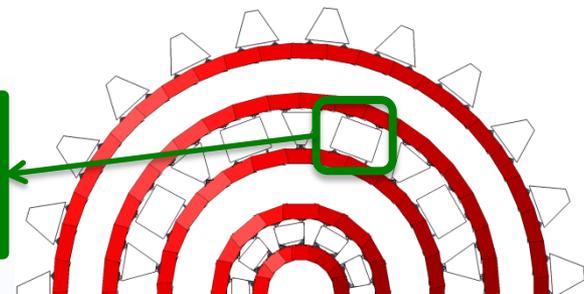
**1.6m**

The longeron is based on carbon-fibre composites and $CO_2$ evaporative cooling in titanium pipes.

Module Cells are built with quad M4 (flat) and double-chip M2 (inclined)

Build and test large scale, realistic prototype

Objectives:

- *Validate local support concept*
- *Validate integration and electrical services*
- *Validate procedure for loading and survey*
- *Study thermal performance*

Mockup heaters (minimum 48xM4 & 109xM2)
- Silicon heaters with embedded thermal sensors for thermal and thermo-mechanical testing
- Flexes to power the heaters & read the thermal sensors  (similar to the actual electrical)

# ITk Demonstrator project
## Thermal sensor characterization as a function of temperature
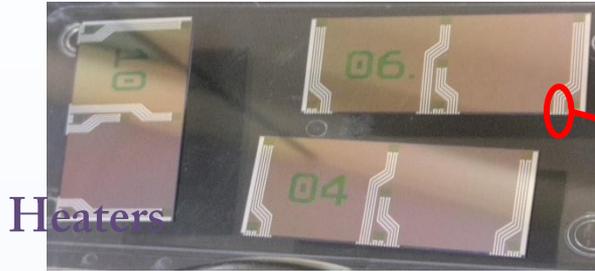


Heaters

**Four-terminal (Kelvin sensing)**



Sense High

Sense Low

GND

HV
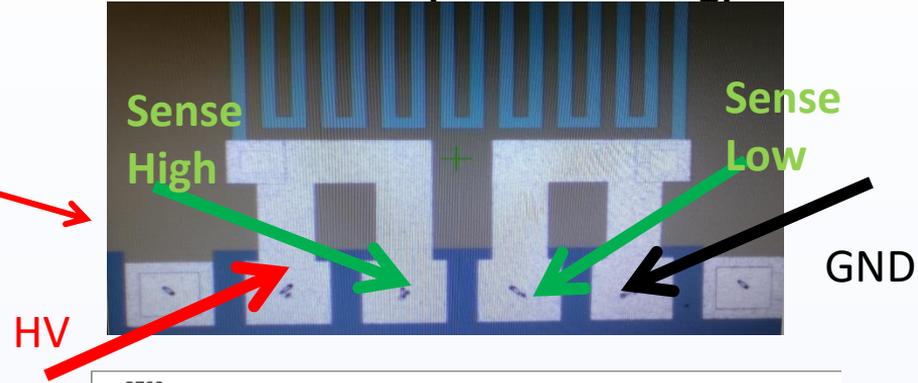
Histogram of Resistance at 20ºC
(28 samples from the batch1)



Average = 3,797kOhm

RMS = 0,043kOhm

(excl. outliers)



$$R = R_{ref} [1 + \alpha(T - T_{ref})]$$

$\alpha$ = Temperature coefficient of resistance for the conductor material.
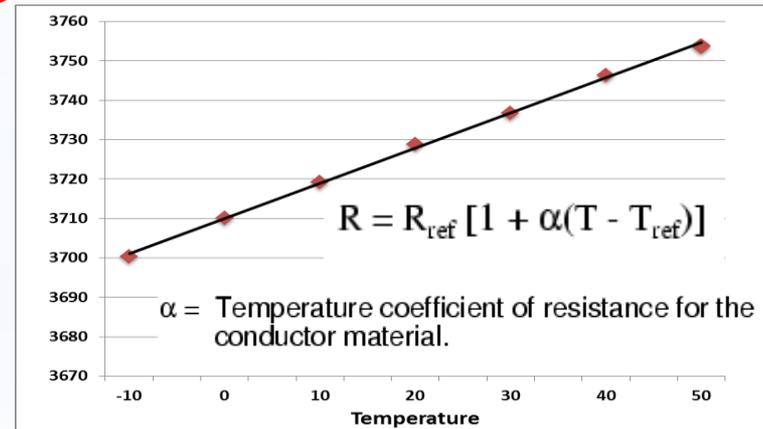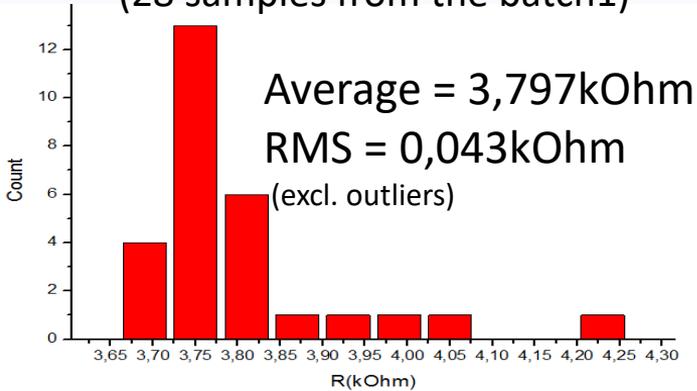
# Heaters measurements
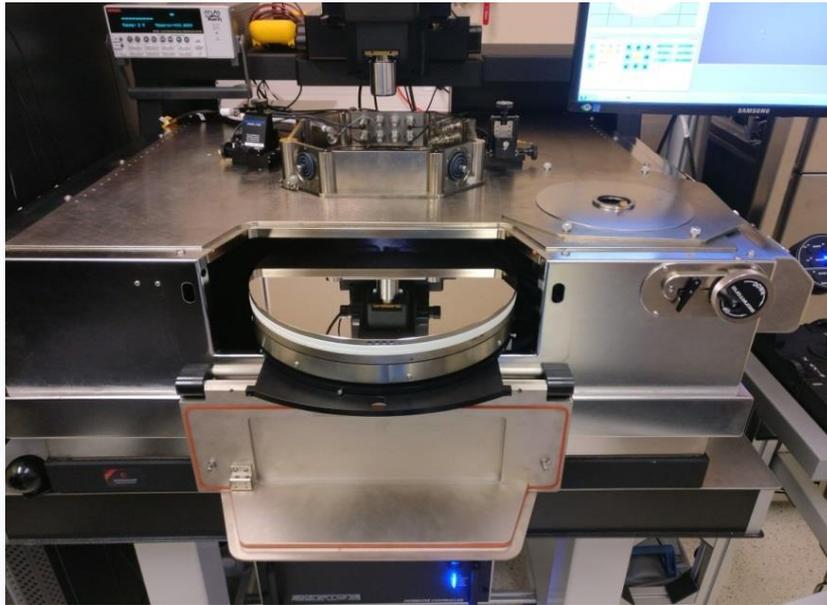


**Semi-automatic probe station** allows performing of IV and CV measurements.
- Cooling (-10° – 50° C)
- Allows measuring of the big wafers up to 30 cm in diameter



15 cm

Heater samples for the
<u>Demonstrator project</u>
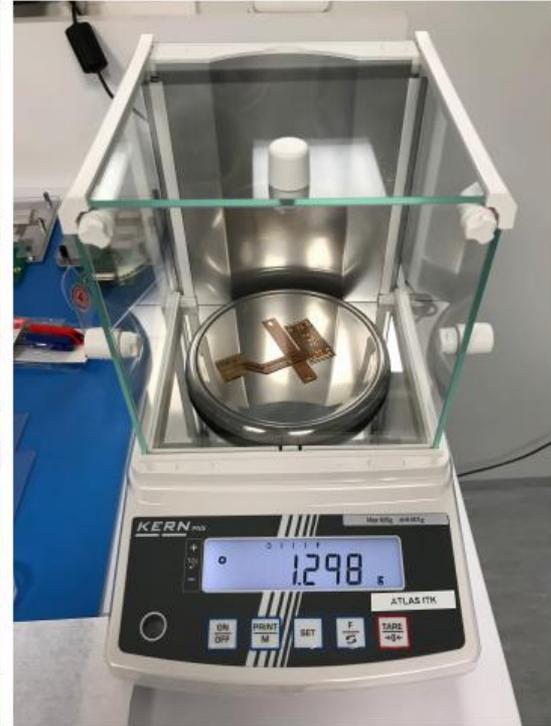
Gluing setup with 2 flex jigs + 2 sensors bridges

# Heater assembly

**Wire-bonding at Saclay**



FR-04

**Gluing**

Pheniics Fest, Hadronic and Particle Physics
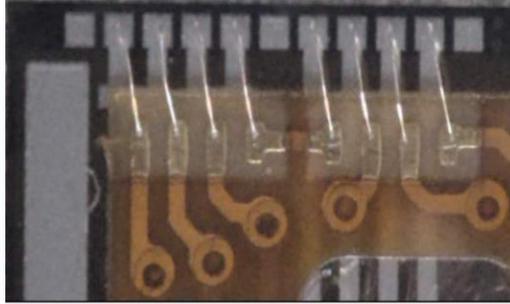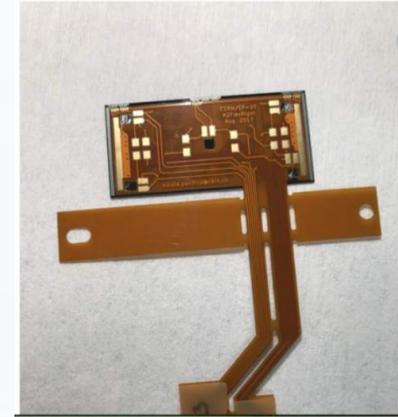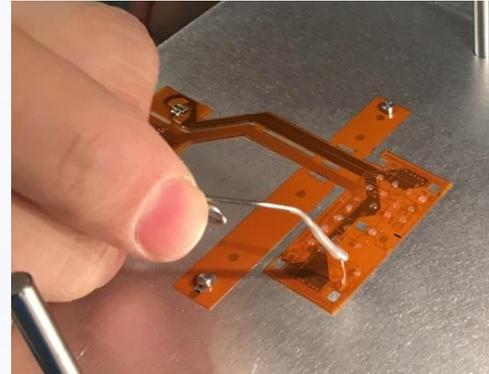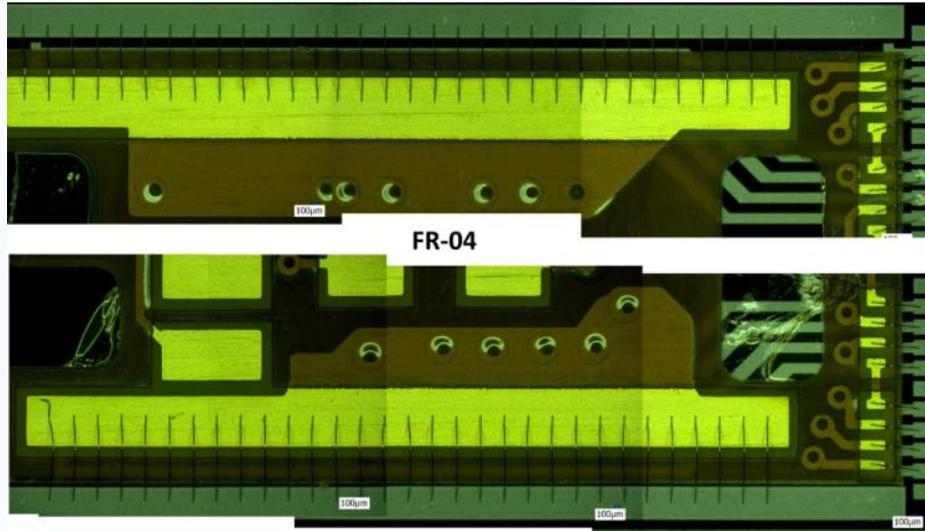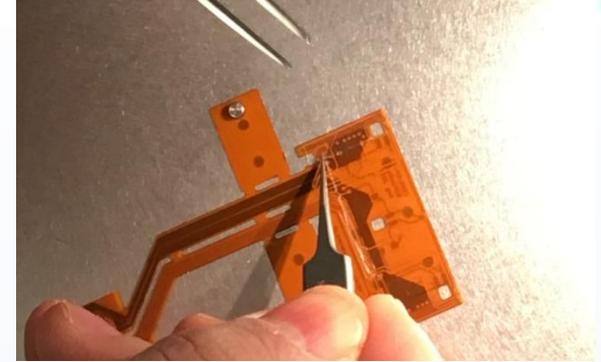
# Calibration setup



climate chamber   Keithley 2410   modules   PT100
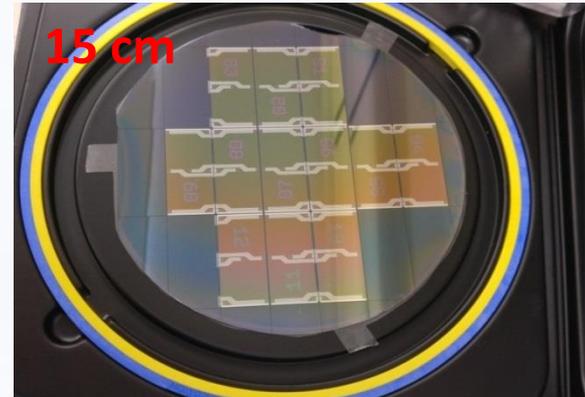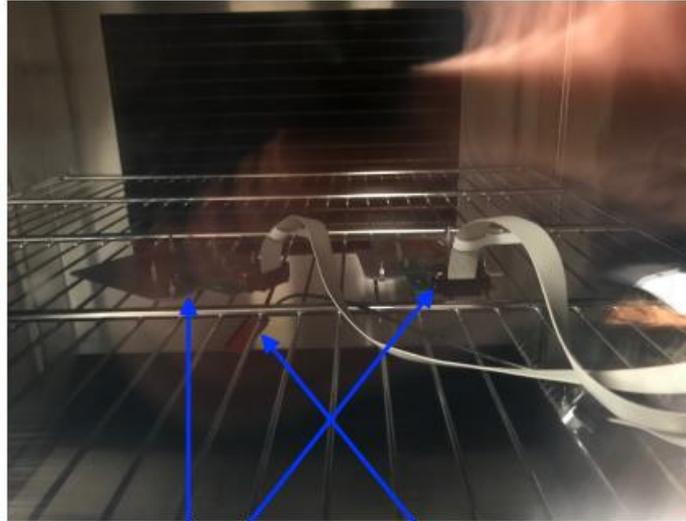
- R cross-checked with 3 different instruments;
- T cross-checked with PT100 attached to sensor put inside the climate chamber
- 4 cables =.> calibrate 4 modules in parallel

# Assembly & transportation



- 20 thermal modules were successfully glued wire-bonded and tested.
- Have been weighted before/after gluing as requested;
-  Cleaned in ultrasonic bath in isopropanol at 50ºC and 12h 120ºC in the oven;

# Integration on the long thermal demonstrator

Pheniics Fest, Hadronic and Particle Physics
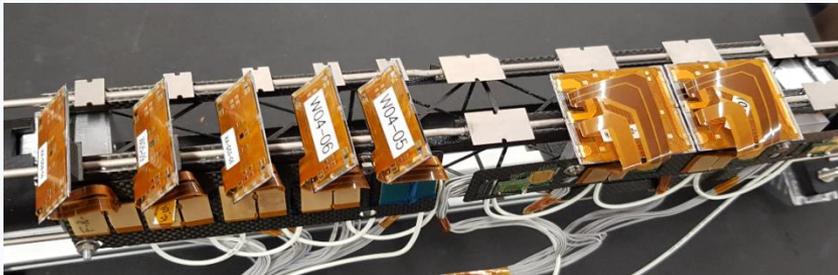
# Summary and Conclusions

- In view of the fact that in the framework of HL-LHC project it is planned to increase the integrated luminosity by a factor of 10, we will face the problem of extremely high pile-up and radiation-harsh environment. Therefore we have to build new tracker (ITk) that is expected to perform at least as well as the current one (and often better) despite the much harsher conditions.

- The various designs of sensor candidates for the ITk upgrade have been tested at test beam. The efficiency performance has been estimated.

- A new setup for laser tests in a clean room has been developed in a preliminary form. The system was adjusted, and first results were obtained, but the laser test system has to be improved.

- Demonstrator project is an important step towards building of the ITk. Considering a short timeline of the project we have to do an intensive work on thermal tests with heater modules.

## Thank you for your attention!

# BACKUP Slides

Pheniics Fest, Hadronic and Particle Physics

# Results

## Comparison of the performance of active and slim edge design sensors:

- ➢ 50 um – thick sensors:
    - Before irradiation **active edge** shows efficiency of 97,2% while **slim edge** has 94,7% (50V);
    - At *1e15 $n_{eq}$/cm²*, the efficiency of **active edge** is 86-89%, while **slim edge** is 79-84% at 120V.
- ➢ 100 um **slim edge** sensor :
    - Before irradiation provides 96,8% of hit efficiency (50V);
    - After irradiation at *2e15 $n_{eq}$/cm²* the efficiency can recover 89.5% at 180V;
- ➢ 150 um **active edge** sensor:
    - Before irradiation provides 97,8% of hit efficiency (50V);
    - After irradiation at *2e15 $n_{eq}$/cm²* the efficiency can recover 93.6% at 200V;

**Both designs had an issue during TB with the achievement of high voltage (breakdown starts and sensor becomes noisy)**
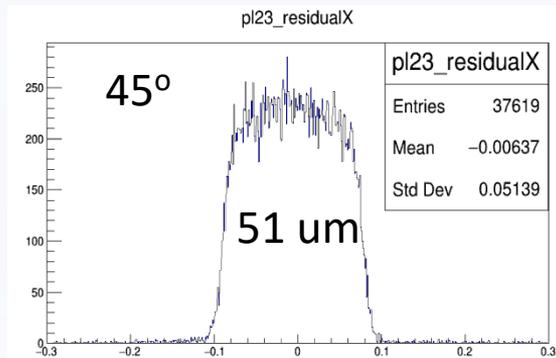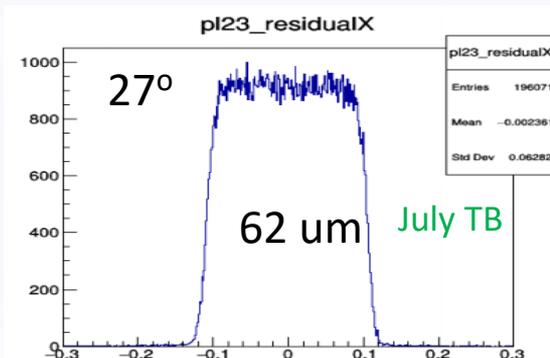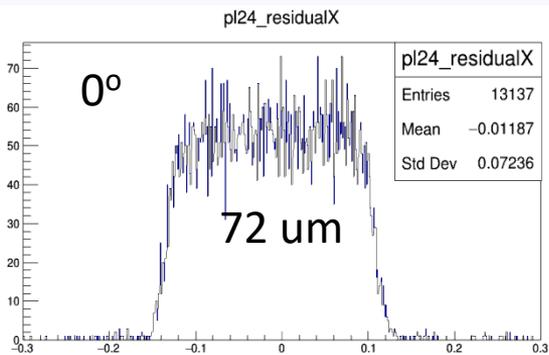
# Test beam characterization results

- Residuals comparison at different orientation angle to the beam



Short side:

Long side :

Pheniics Fest, Hadronic and Particle Physics
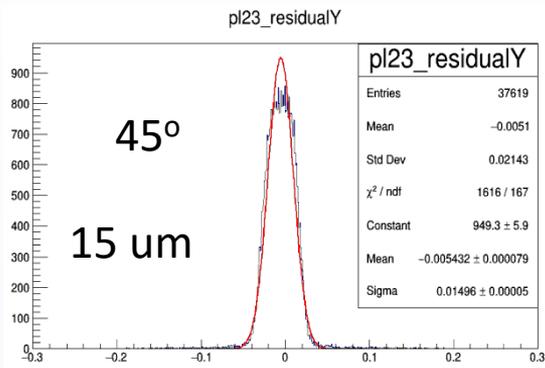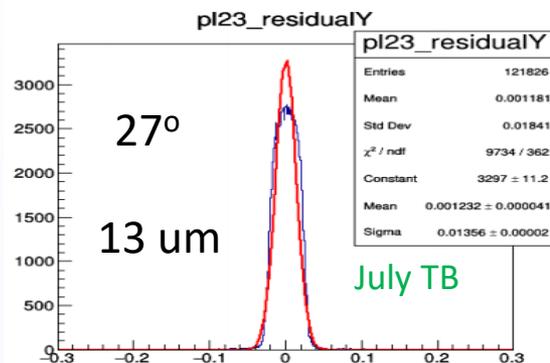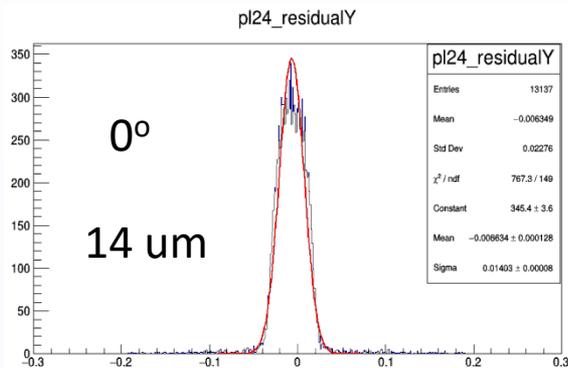
# Test beam characterization

**Our Goal:**
- Investigate the performance of the n-in-p planar pixel sensors with the active and slim edge design produced by **ADVACAM** before and after irradiation**;**
- Study the overall and edge efficiency with normal and inclined tracks.

- **Hardware**
  - Telescope at CERN
  - 120 GeV pion beam
- **Software**
  - Reconstruction: EUTelescope (*Data conversion, Cluster finding, Hitmaker, Alignment, Track fitting*)
  - Analysis: TBmon2 (Efficiency, charge sharing, residuals, ToT, etc)

- **Normal** incidence
  - Bias voltage points: 50 V, 80 V, 100 V, 120 V
  - Cooling box (-40ºC to -44ºC)
  - Dry ice cooling (approx. -40 to -50 ˚C*)

- **Inclined** tracks
  - DUT tilted at 45˚ (around y-axis)

* Only indirect temperature measurements available

# Goals

- Efficiency for **50μm-thick ADVACAM samples** with **active edge** and **slim edge** design
    - with and without irradiation $1 \times 10^{15}$ $n_{eq}/cm^2$ ;
    - on different side edges;
    - with **normal** and **inclined** incident (DUT tilted at 30˚, 45˚ (around y-axis));

- Efficiency for **100μm-thick ADVACAM sample** with **slim edge** design before and after irradiation $2 \times 10^{15}$ $n_{eq}/cm^2$ ;

- Efficiency for **150μm-thick ADVACAM sample** with **active edge** design before and after irradiation $2 \times 10^{15}$ $n_{eq}/cm^2$ ;

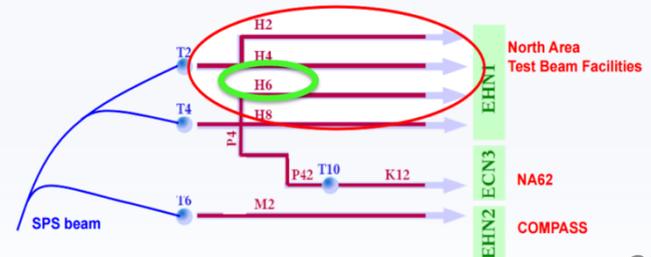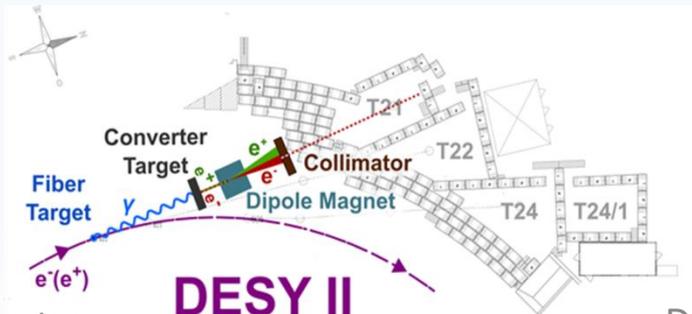Beam: CERN SPS 120 GeV pions, DESY 4 GeV electrons;

Telescopes: DURANTA (TB22) , ACONITE (H6A) and AIDA (H6B);

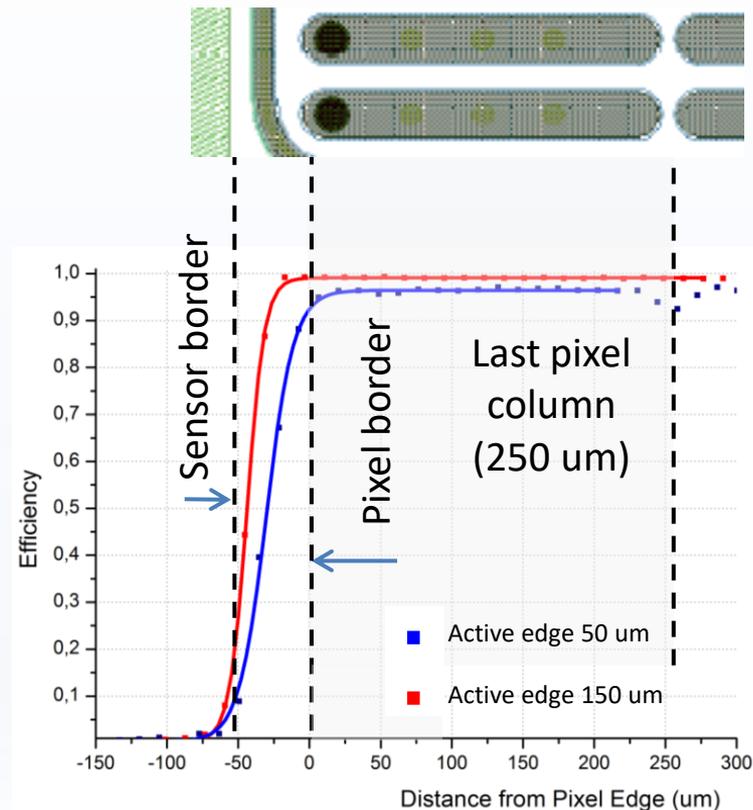Cooling: Cooling box (-40ºC to -44ºC), Dry ice cooling (approx. -40 to -50 ˚C);

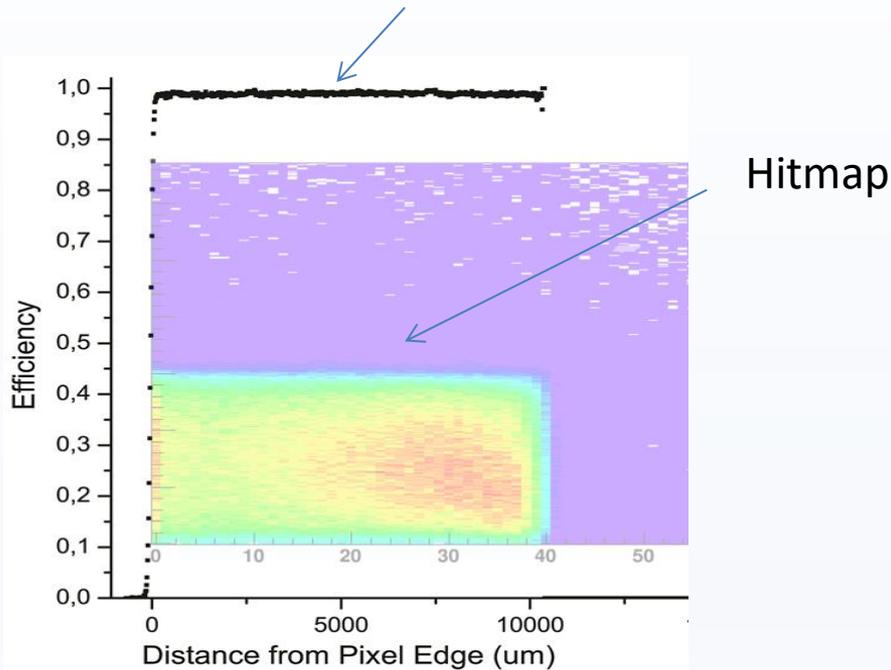Bias voltage points:

from 50 V to 120 V (for 50um);

from 50V to 200V (100um,150um)

# Test beam characterization results

- *Efficiency vs track impact position*



Hitmap



Sensor border

Pixel border

Last pixel column (250 um)

- Active edge 50 um
- Active edge 150 um

# Test beam characterization results

- *Efficiency vs track impact position*