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

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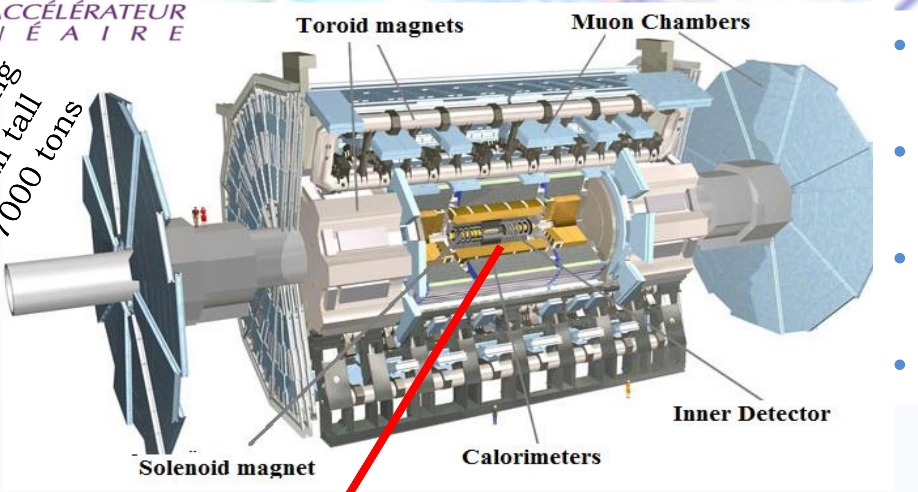
Les Jardins de l'Anjou, **La Pommeraie**

Outline

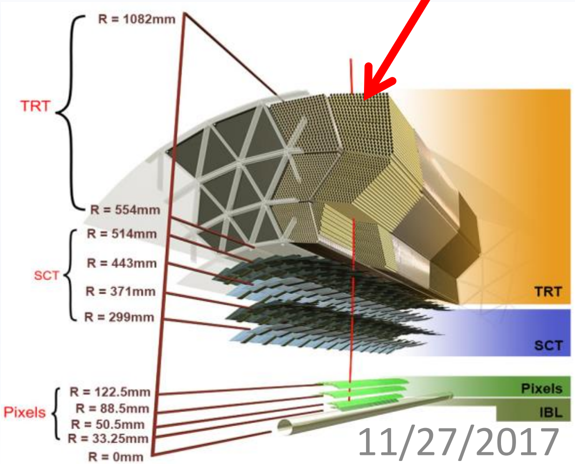
- **ATLAS project**
  - Structure of the ATLAS detector
  - ATLAS detector upgrade connected with HL-LHC project
- **Pixel detectors**
  - Working principle of pixel detectors
  - Current and future concepts of pixel detectors
- **Tests and characterization as an important stage in the pixel detector 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



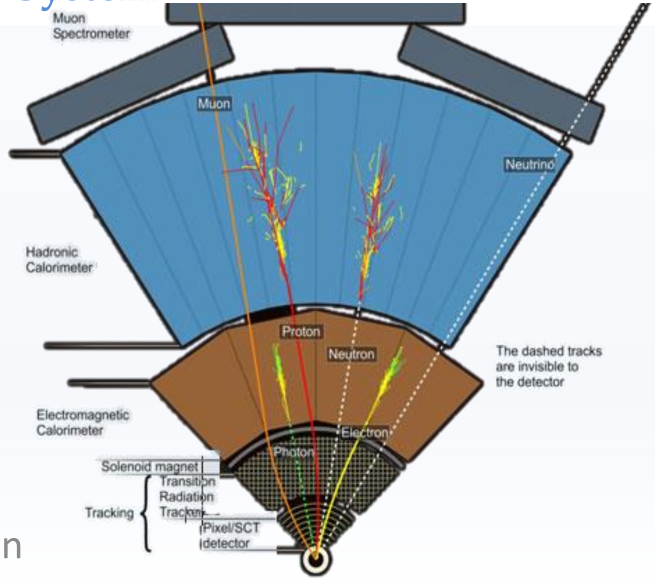
- **Inner Detector** (measures the momentum of charged particles)
- **Calorimeter** (measures the energies carried by particles)
- **Muon Spectrometer** (Identifies and measures muons)
- **Magnet System**



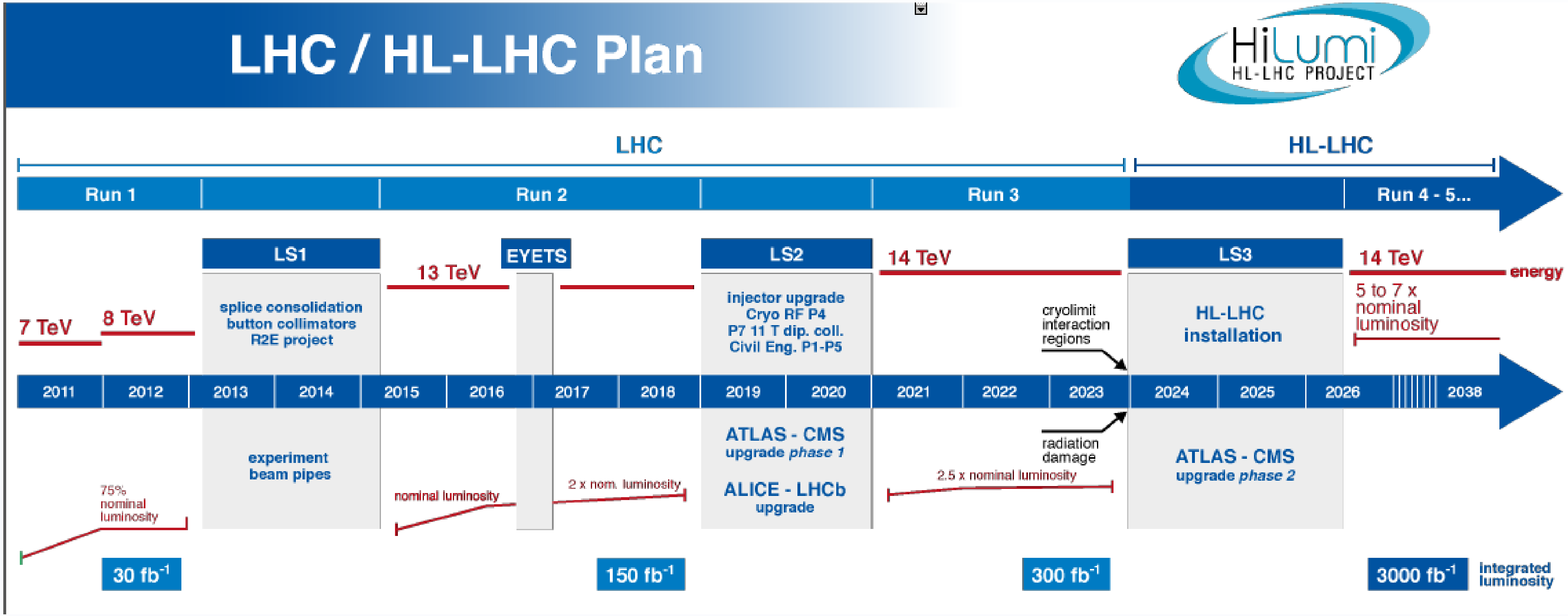
Transition Radiation Tracker

Semi-Conductor Tracker

Pixel Detector



The (HL-)LHC Timeline



Motivation for ATLAS Inner Detector upgrade

In order to increase the discovery potential of the LHC and provide more accurate measurements with increased statistics, the High-Luminosity LHC project is envisaged, called Phase 2.

Name of the upgrade	Date	Luminosity	Energy √s
LHC startup	2009	$6x10^{33}$ $cm^{-2}s^{-1}$	7-8 TeV
Phase- 0	2014	$1x10^{34}$ $cm^{-2}s^{-1}$	13-14 TeV
Phase- 1	2018	$2x10^{34}$ $cm^{-2}s^{-1}$	14 TeV
Phase- 2	2023	$7,5x10^{34}$ $cm^{-2}s^{-1}$	14 TeV

Very severe pile-up conditions expected:

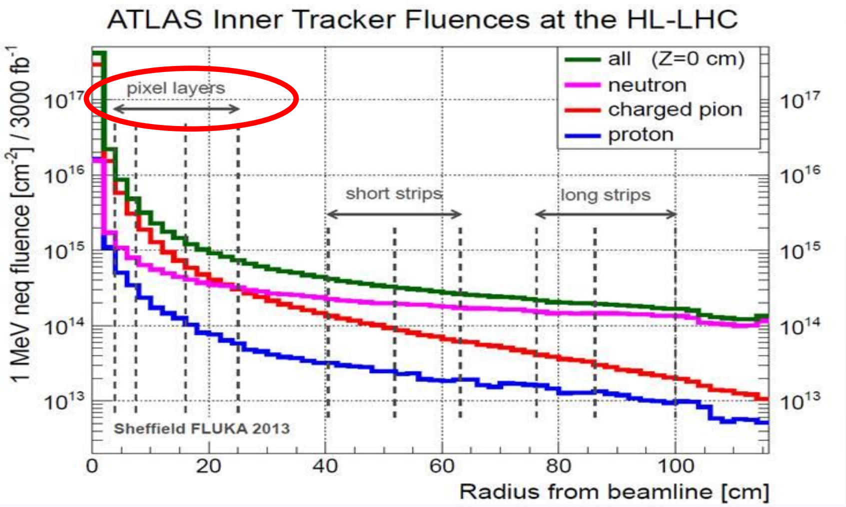
Corresponding num. of inelastic **pp** collisions per beam-crossing (25 ns) will increase : **25 -> 200**

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 **3000 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:

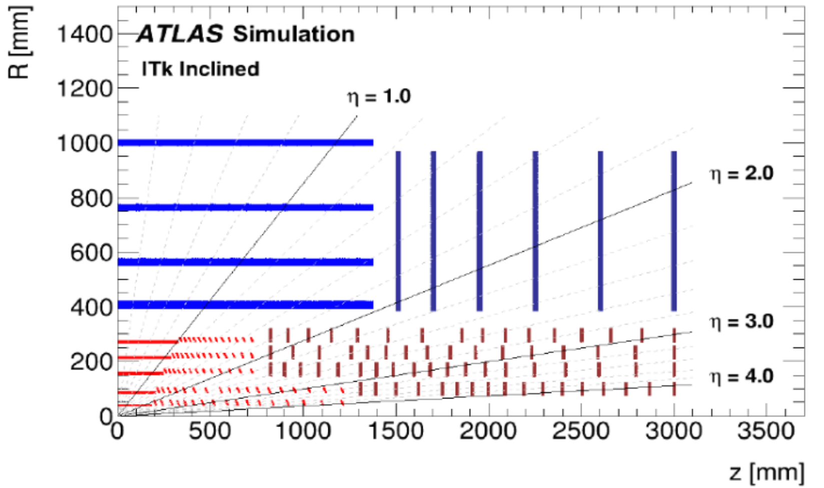
- Creation of lattice defects (loss in the charge collection due to charge capture).
- Change of depletion voltage (due to type inversion).
- Rise of leakage current (additional energy levels are being formed in the band gap region)

Motivation for ATLAS Inner Detector upgrade

The new <u>All Silicon</u> Inner Tracker (ITk), will be operational for more than ten years, consists of a pixel detector (red) close to the beam line and a large-area strip tracking detector (blue) surrounding it.

	Silicon Area	Channels [10^6]
Pixel	~13 m^2	580
Strip	160 m^2	50

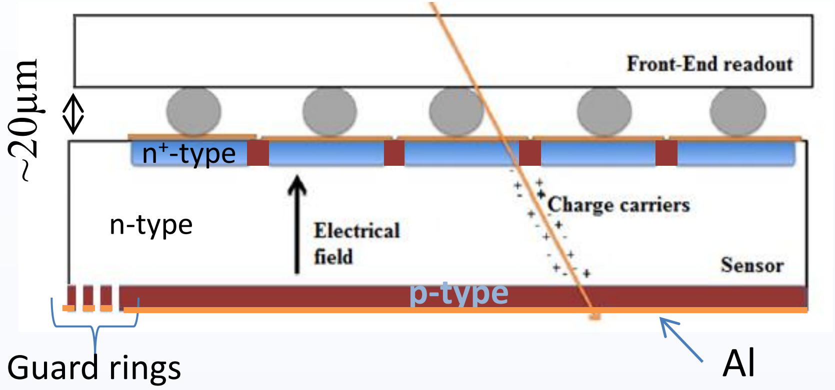
Layout for the Phase-II Inner Tracker (Apr 2017)

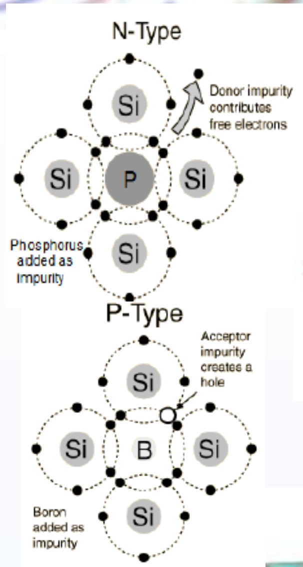


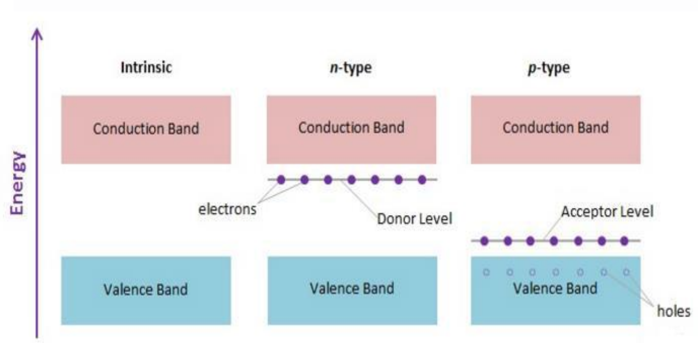
- The target acceptance has been extended to ± 4 units of pseudorapidity
- Pixel system extending to roughly twice the radius and four times the length
- Reduced material budget before calorimeters

Working principle of pixel detectors

Hybrid planar pixel detector:



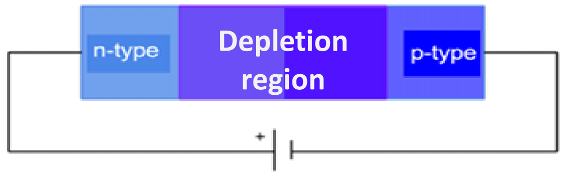


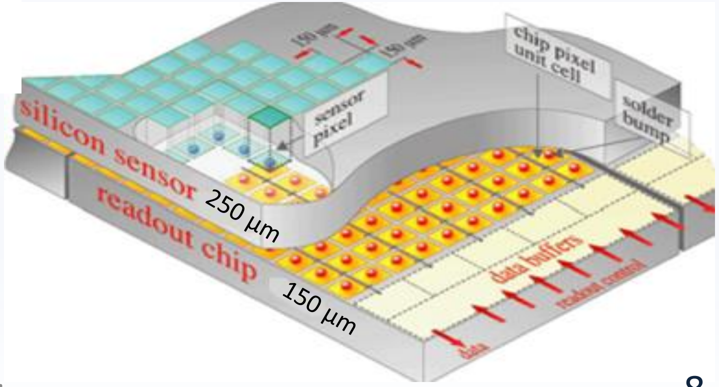


To operate, the semiconductor (silicon) must be depleted:

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

reverse biased pn-junction

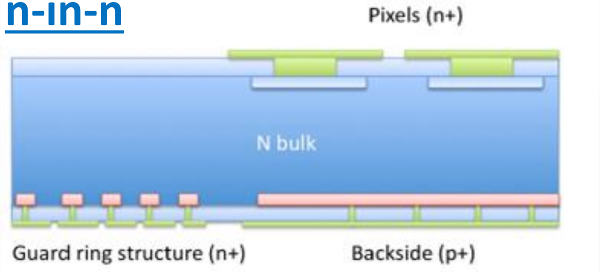




Alternatives for Planar pixel technology

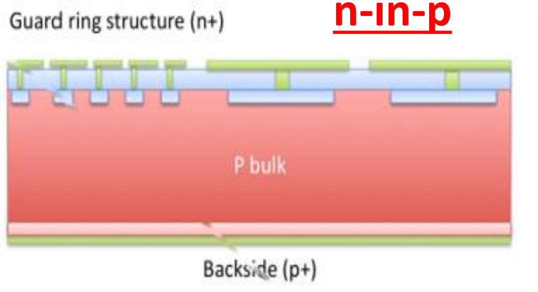
There are two planar sensor configurations that can be used for high particle fluences due to their fast charge collection : **n-in-n** and **n-in-p**.

n-in-n



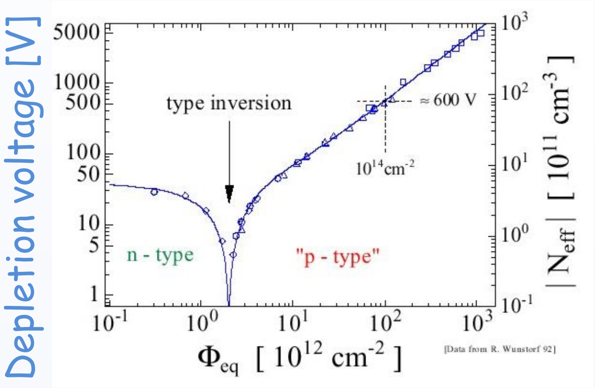
- Collect electrons (3 x faster than holes)
- Guard rings are not on front-end side
- Double-sided processing
- Type inversion of the n-doped silicon bulk

n-in-p



- Collect electrons (3 x faster than holes)
- No type inversion
- Can be operated partially depleted
- Single –sided processing
- Guard rings are not on front-end side

Type inversion effect



The change of the effective doping concentration due to irradiation

Alternatives for Planar pixel technology

- **Design parameters to improve:**

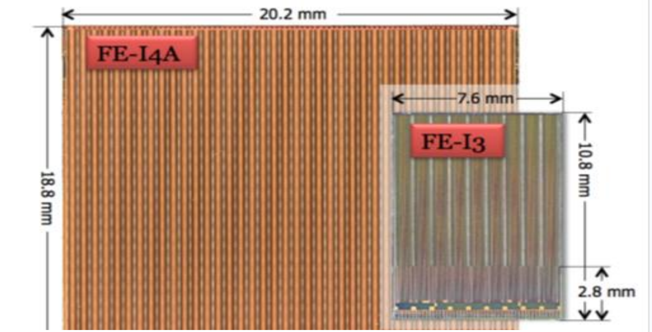
Sensors: the radiation resistance, reducing of non active area (efficiency), thinning, production cost

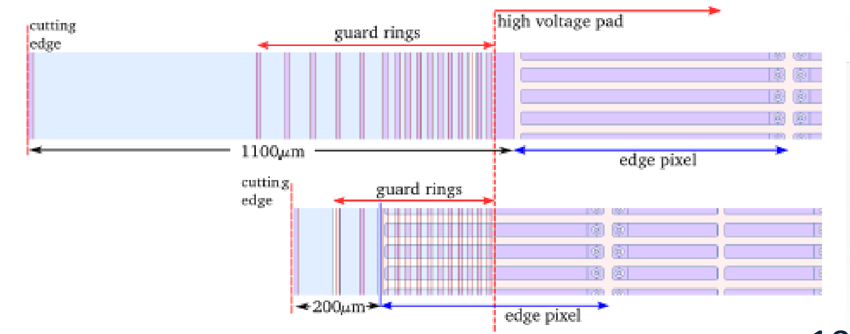
Electronics: processing speed (dead time), signal-to-noise ratio, reducing of power consumption (cooling), price

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





Alternatives for Planar pixel technology

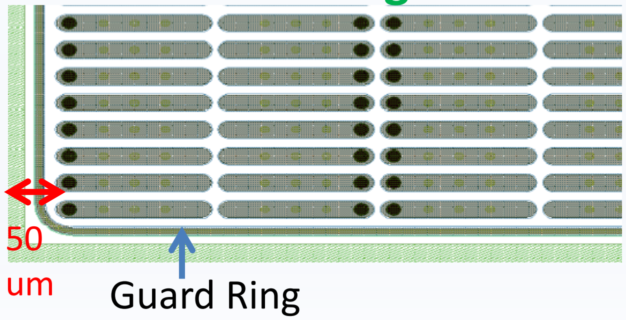
- An active edge design

- Trenches created with the Deep Reactive Ion Etching (DRIE) process allow to extend the backside implantation to the sensor edges and to create a rectifying junction reducing the defects induced by the cutting. Since the electric field is extended to the side implantation, the entire edge is fully active in the case that no bias ring is implemented.

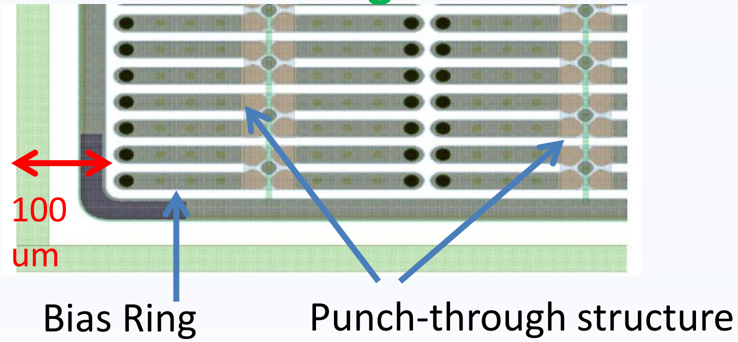
  - **Samples: an active and slim edge design 50, 100, 150 µm thickness, low threshold tuning**
    - **Irradiated**: **Irr. = 1×10^{15} n_{eq}/cm^2**
    - **Non-irradiated:**

500e-600e, 8ToT to 4ke

Active edge



Slim edge



Tests and characterization

Module characterization at test beam facilities

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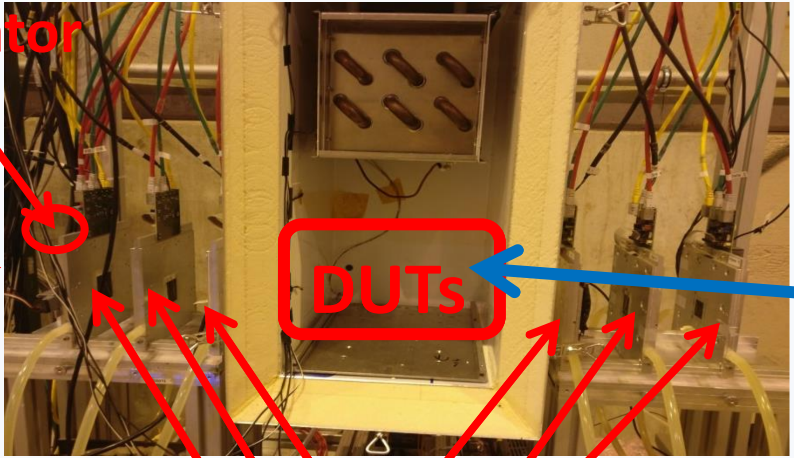
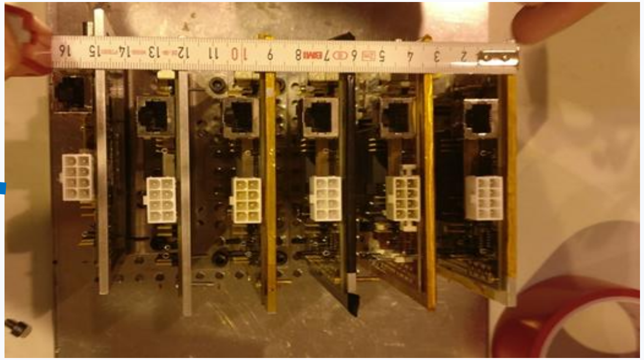
Test beam characterization

Test beam measurements allows the pixel modules to be tested in an environment similar to that which they will be exposed to within the ATLAS detector to determine how well they function.

- ***Test Beam setup***



EUDET family telescopes provide high resolution measurement of the track impact point up to 2 um.



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 (-40°C to -44°C)
  - Dry ice cooling (approx. -40 to -50 ˚C*)
- **Inclined** tracks
  - DUT tilted at 45˚ (around y-axis)

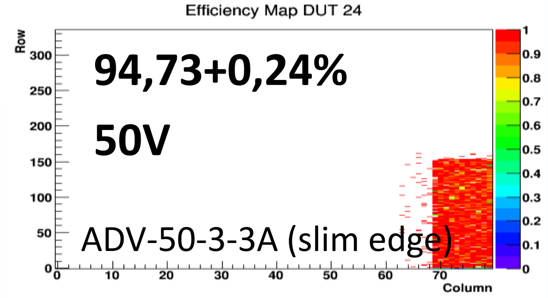
* Only indirect temperature measurements available

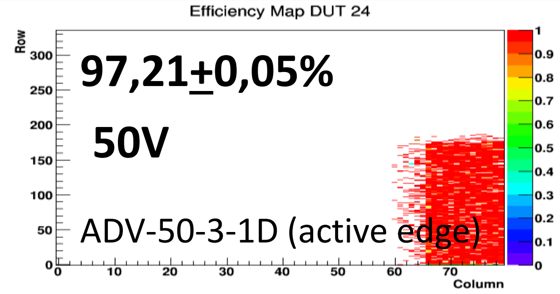
Test beam characterization results

- Hit efficiency calculated as :

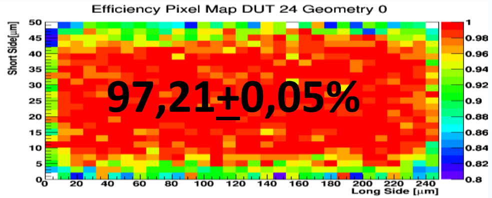
$$Efficiency = \frac{Number\ of\ Matched\ Tracks}{Number\ of\ Total\ Tracks}$$

Overall efficiency

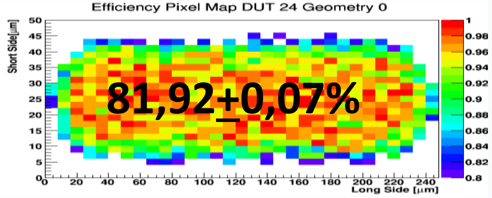




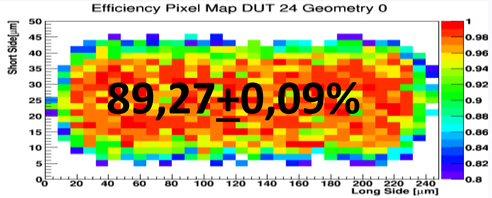
Non –irradiated and Irradiated, 1e15 n_{eq}/cm^2 ADVACAM sensors



50V, non-irrad.

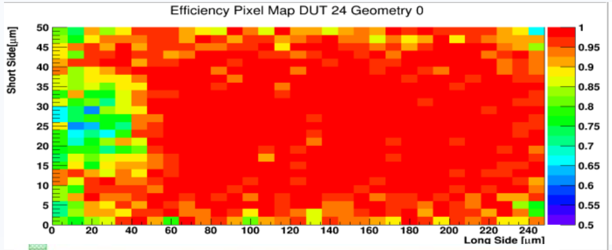


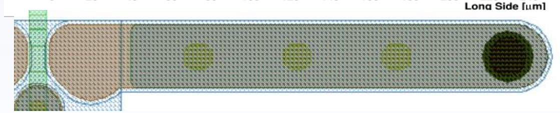
50V, irrad.

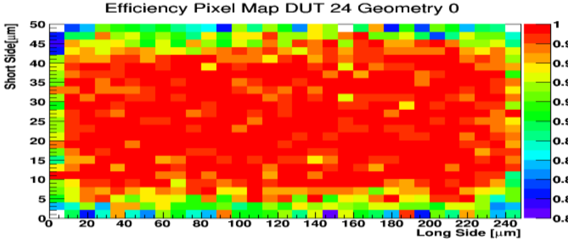


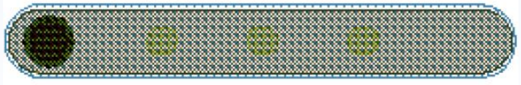
120V, irrad.

In-pixel efficiency



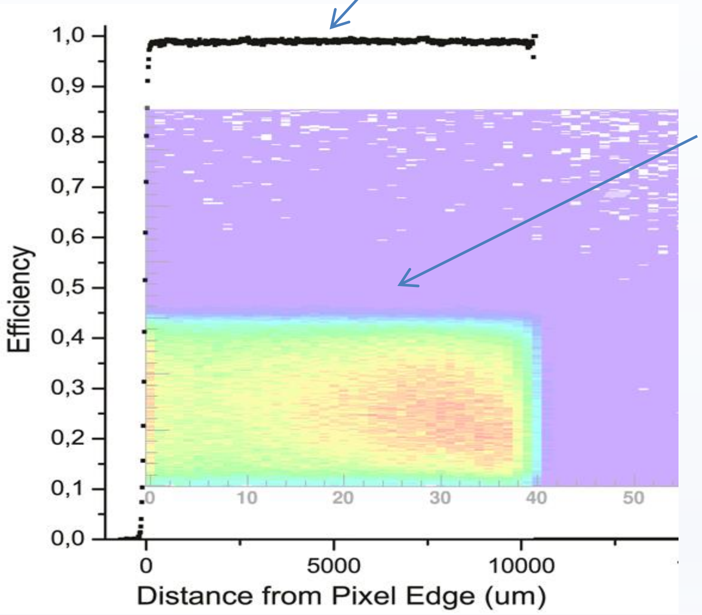




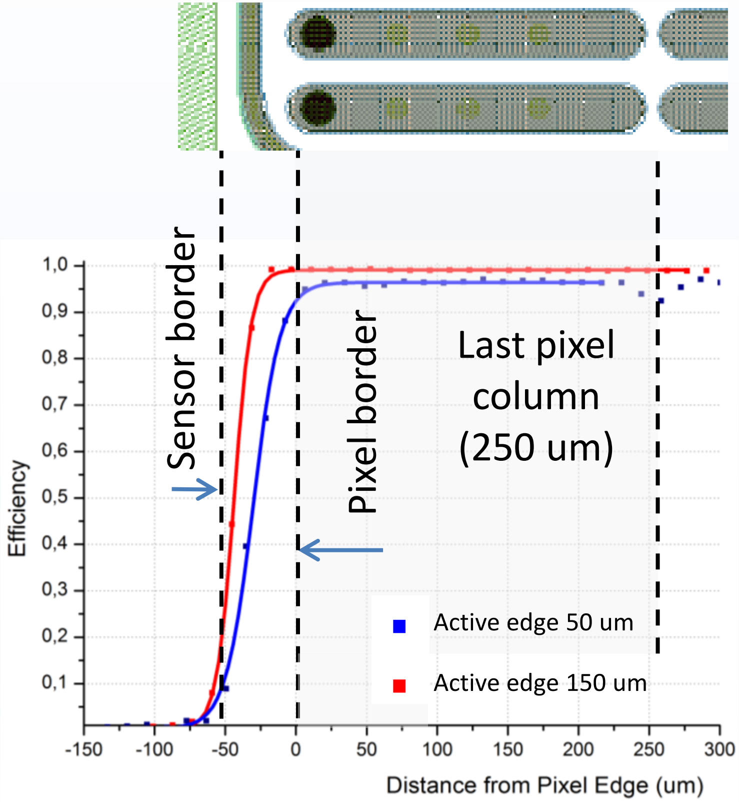


Test beam characterization results

- *Efficiency vs track impact position*

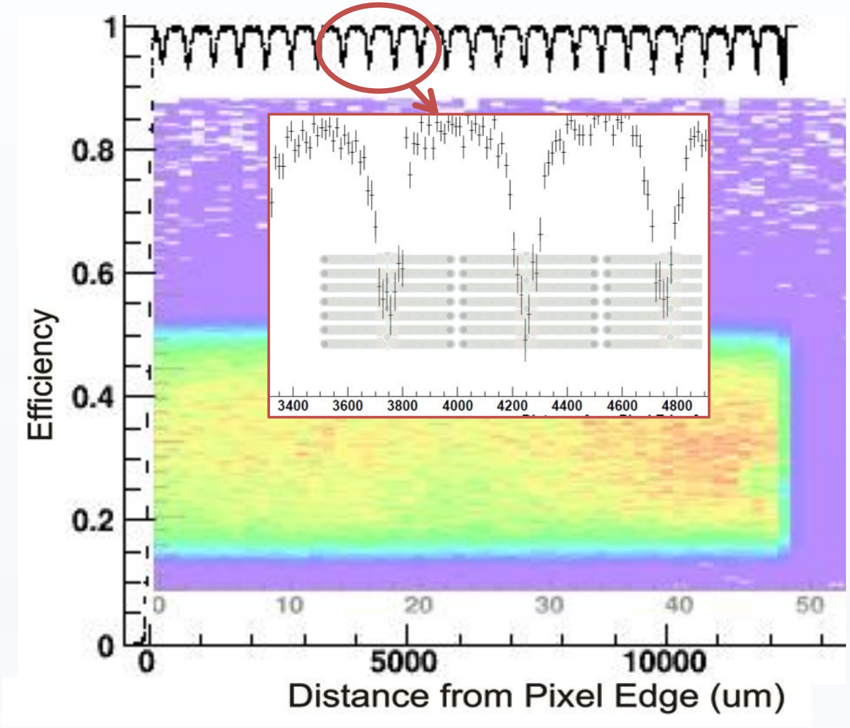


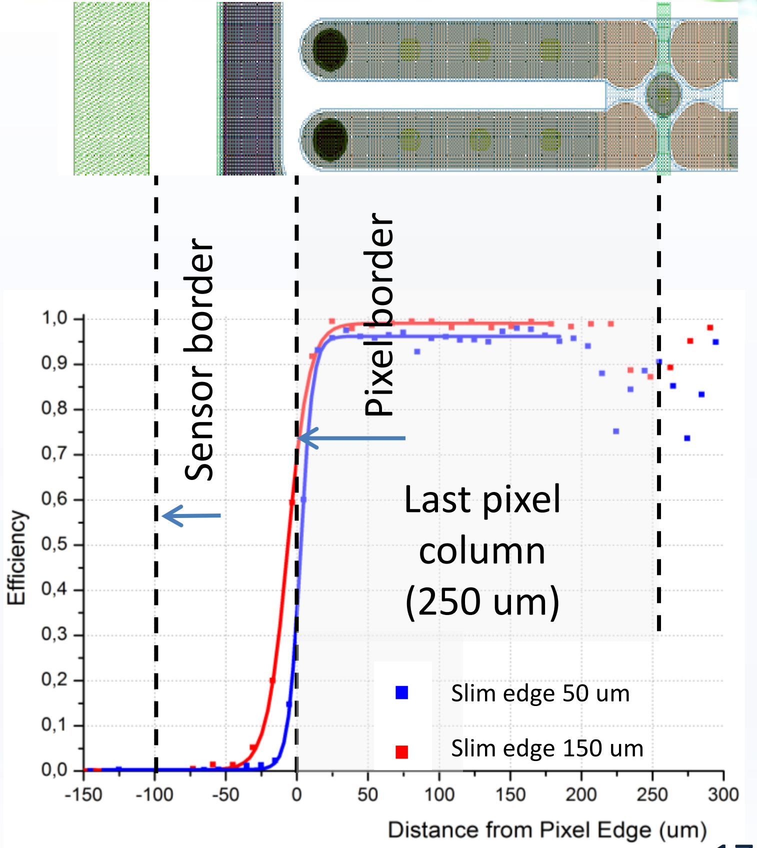
Hitmap



Test beam characterization results

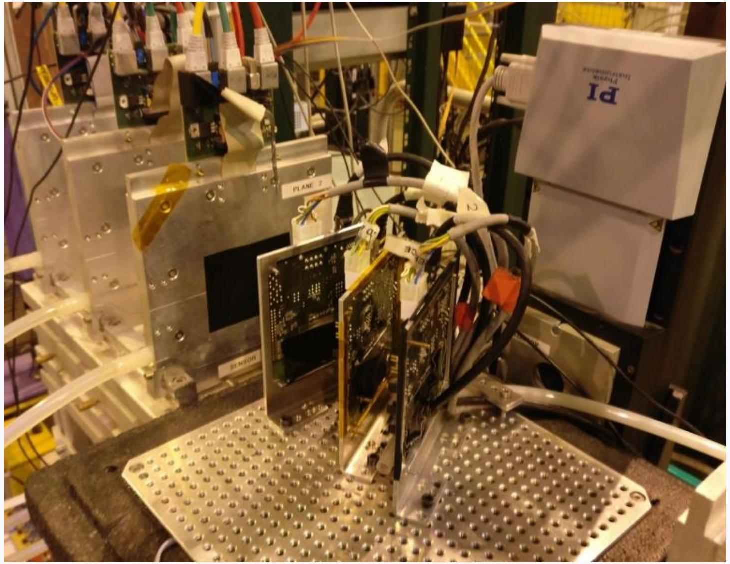
- *Efficiency vs track impact position*

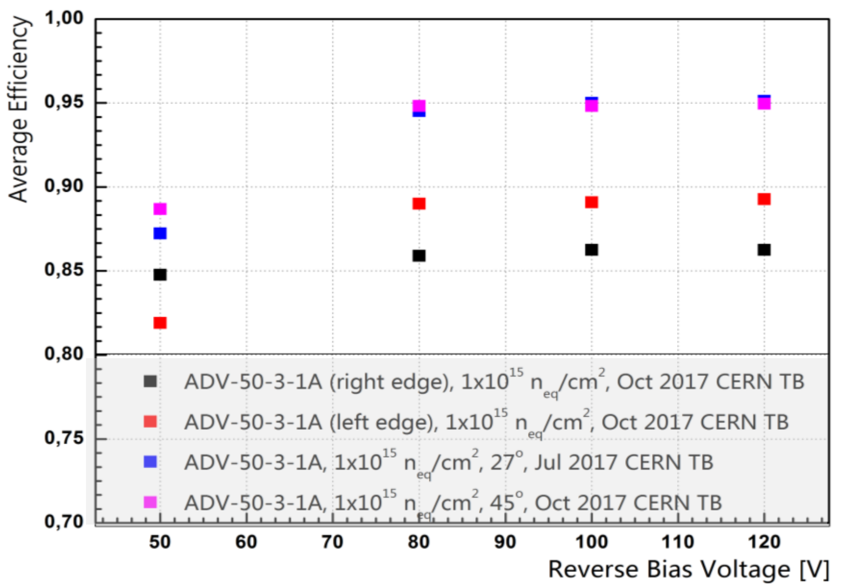




Test beam characterization results

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

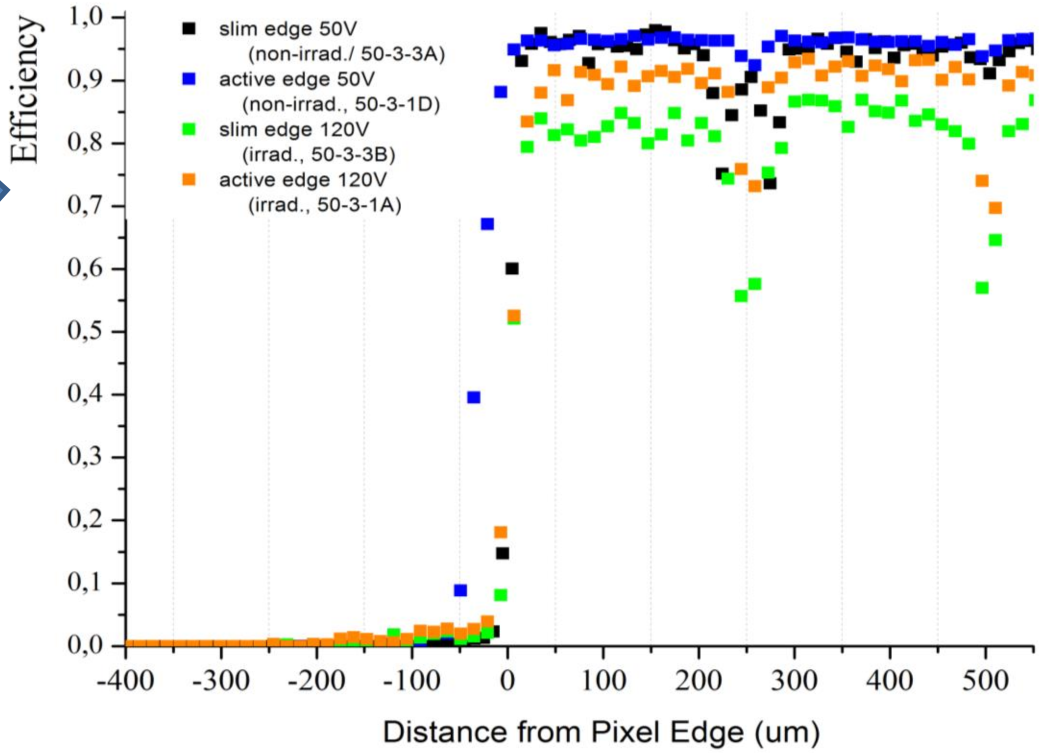




At a tilted angle of 45˚, the efficiency performance improved, reaching 95% at 80V bias voltage. The performance is very similar to the performance at 27˚ case (but with dry ice cooling).

Test beam characterization results

- Comparison of edge efficiency for active and slim edge designs before and after irradiation



The near-edge and edge efficiencies before and after irradiation are higher in active edge design sample than slim edge.

Tests and characterization

Characterization in clean room

Laser test bench setup

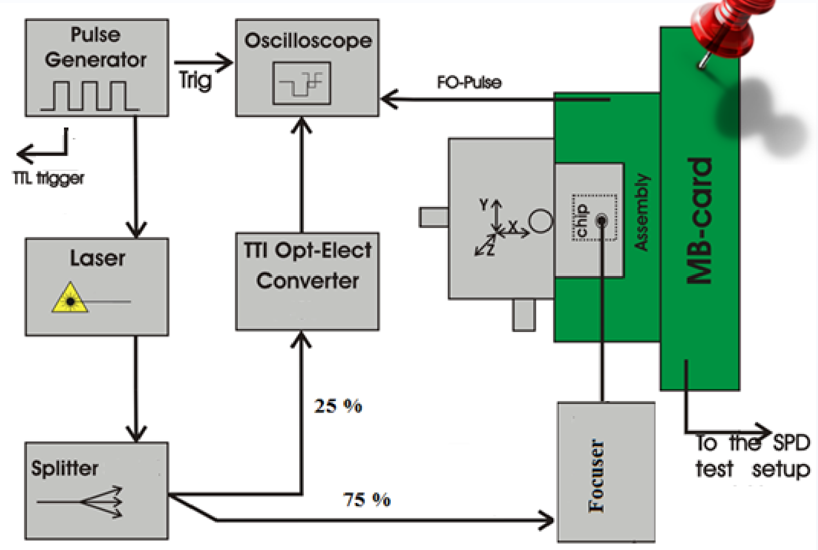
Laser test bench setup

Purpose: To have a cheap setup for the module characterization in clean room

- To study efficiency; charge sharing between adjacent pixels; performance with inclined tracks;

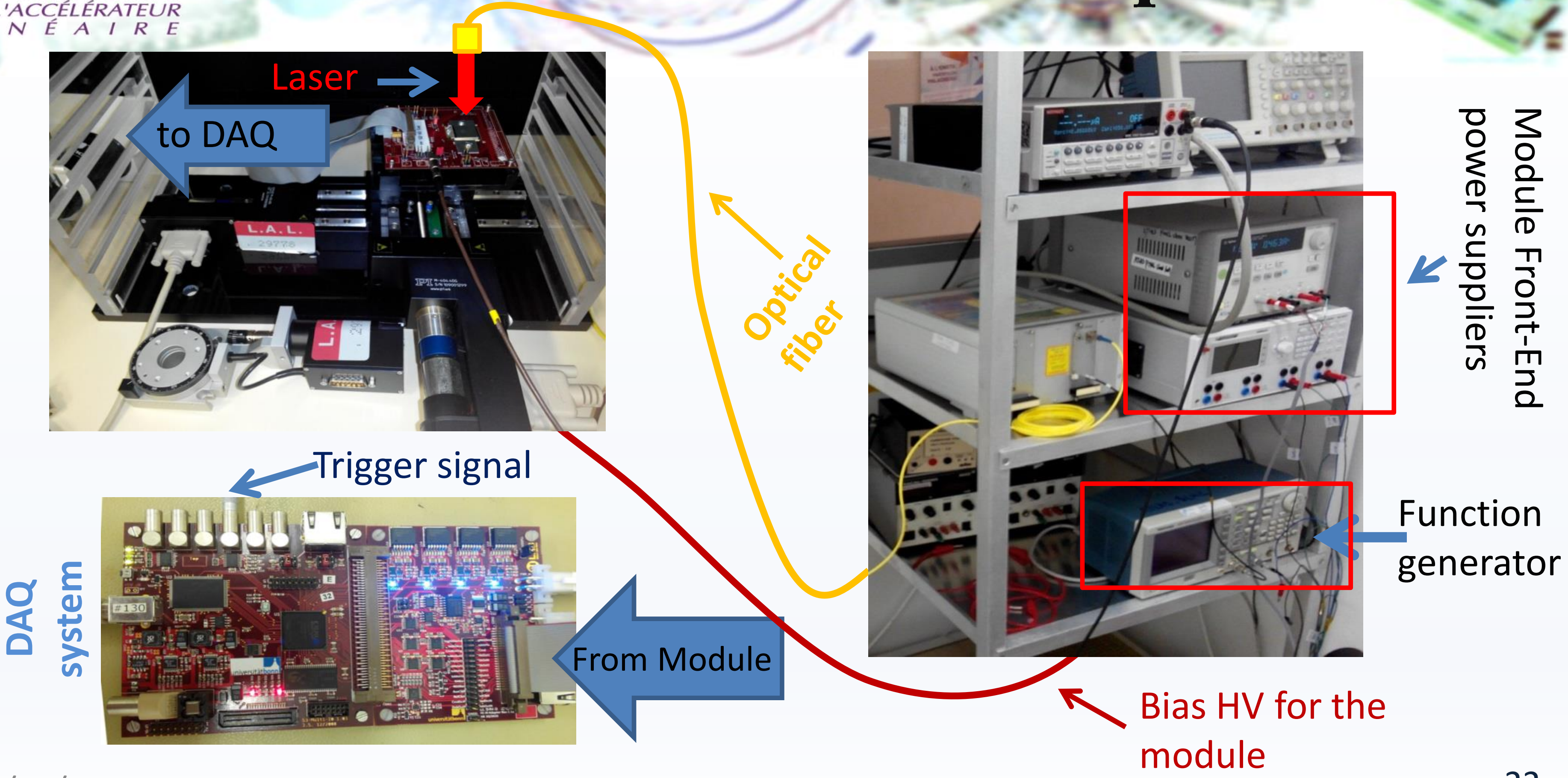
- 1060 nm - 1.17 eV; penetration depth ~ 890 µm
  - **MIP** like charge generation (ionizing density is uniform along the beam path).
- No secondary ionization.
- The interaction point can be determined without reconstruction.
- Precise spatial and time resolution.

- The photon mechanism of interaction is differ from charged particles; Refraction, reflection effects;



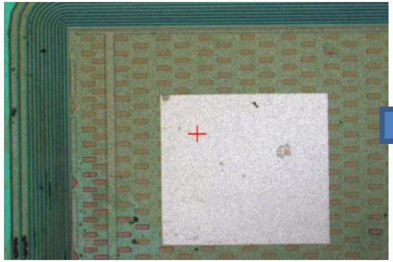
(Schematics)

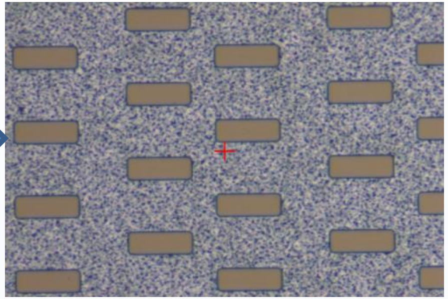
Laser test bench setup

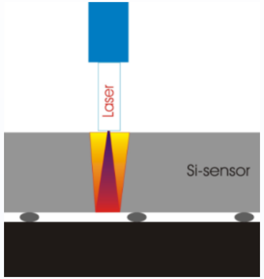


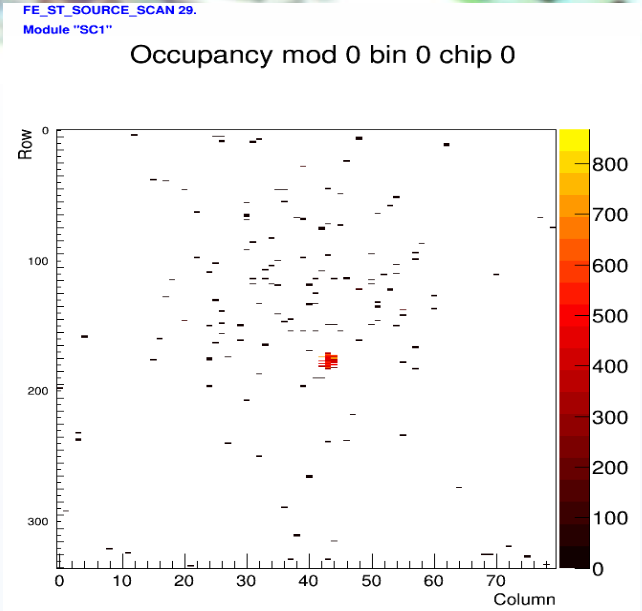
Laser test bench setup

Openings on a back side

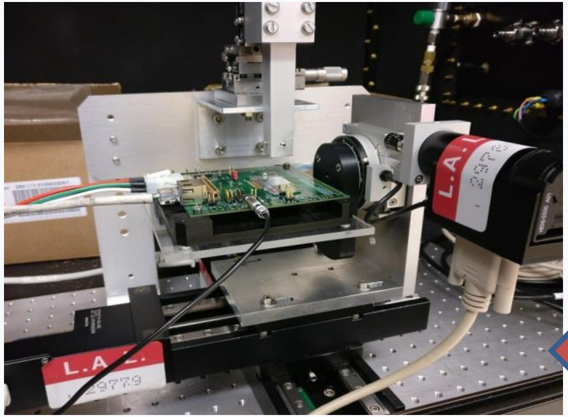








Hit map with the visible laser spot.



Detector support with rotating stage

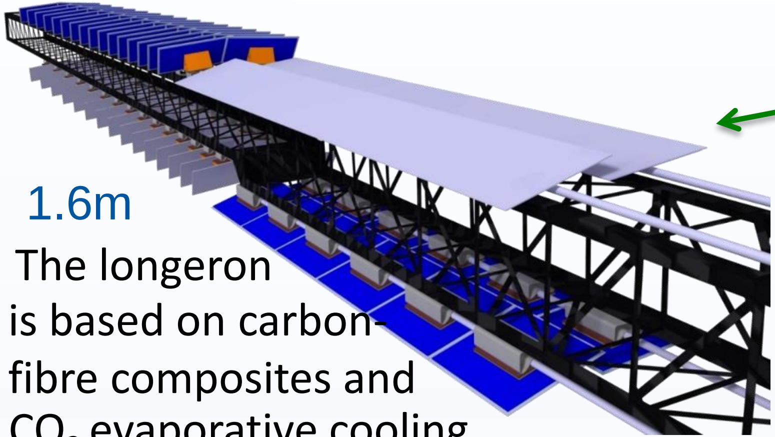
Tests and characterization

Characterization in clean room

Sensor characterization with a probe station

ITk Demonstrator project

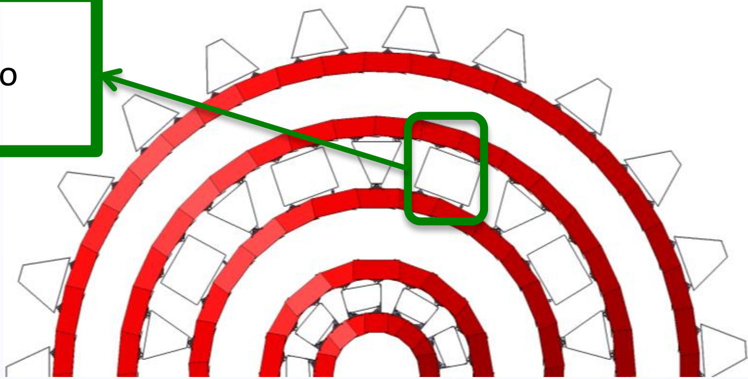
The key goal is the demonstration of the system aspect of the complete and functional ITK pixel barrel stave.



1.6m

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

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



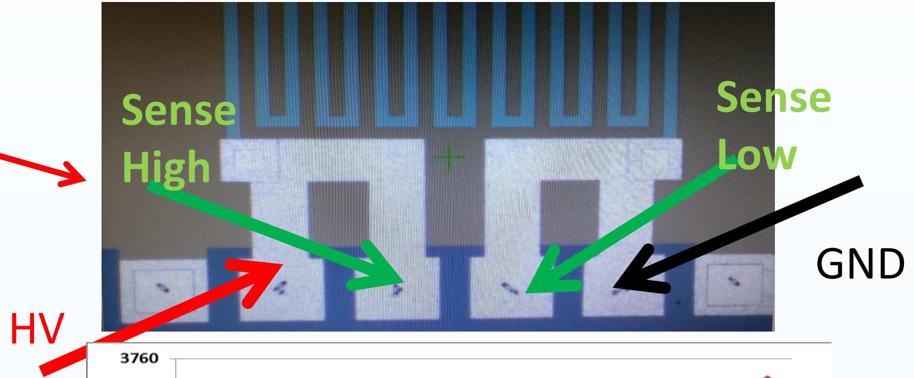
Module Cells are built with quad M4 (flat) and double-chip M2 (inclined)

Mockup heaters (minimum 48xM4 & 109xM2)

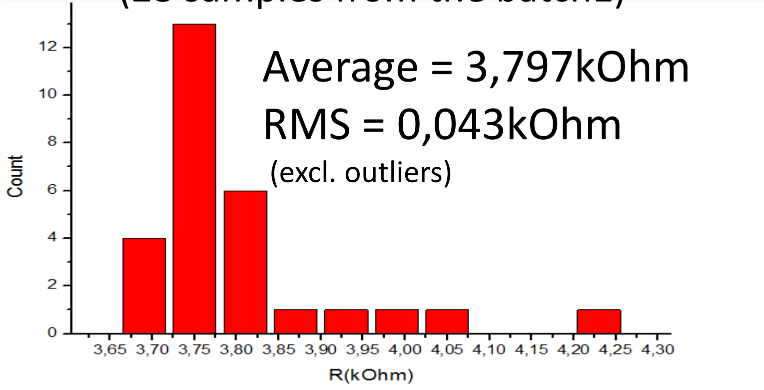
- Silicon heaters with embedded thermal sensors for thermal and thermo-mechanical testing
- Flexes to power the heaters & read the thermal sensors (similar to the actual electrical)

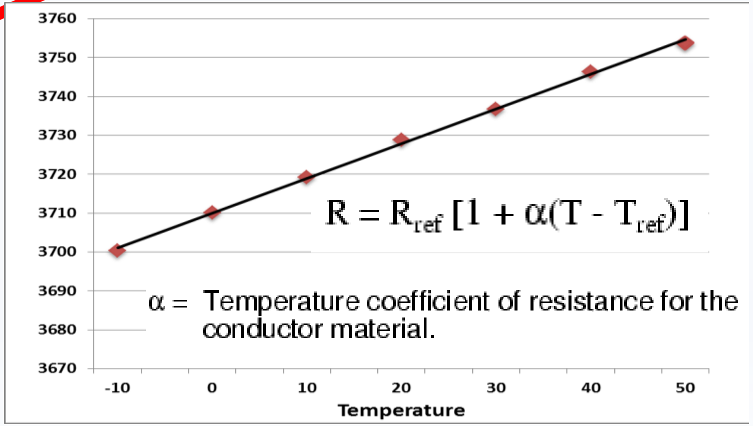
Demonstrator project

Four-terminal (Kelvin sensing)

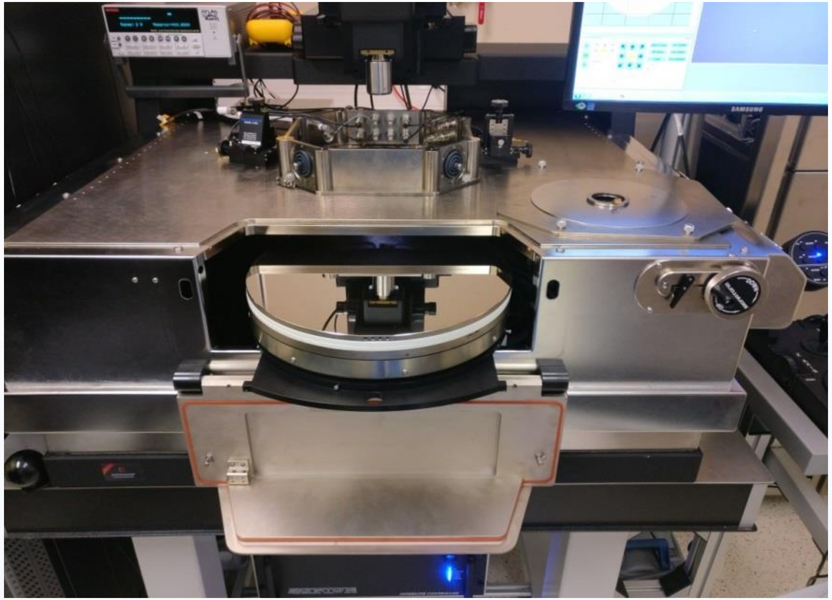


Histogram of Resistance at 20°C
(28 samples from the batch1)



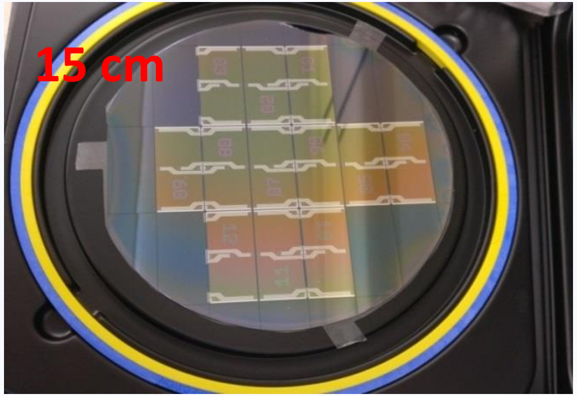


LAL clean room



Semi-automatic probe station allows performing of IV and CV measurements.

- Cooling (-10º – 50º C)
- Allows measuring of the big wafers up to 30 cm in diameter



Heater samples for the Demonstrator project

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.

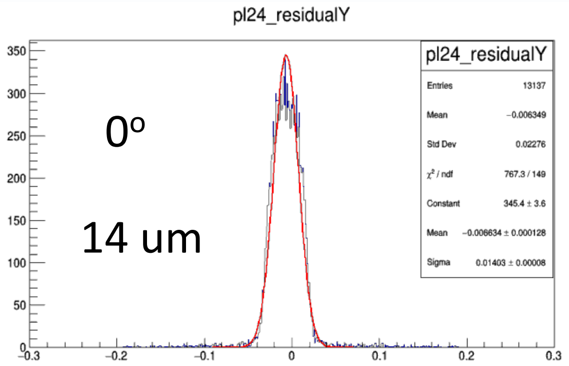
Thank you for your attention!

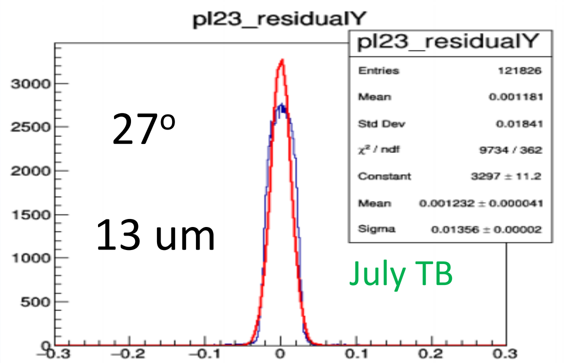
BACKUP Slides

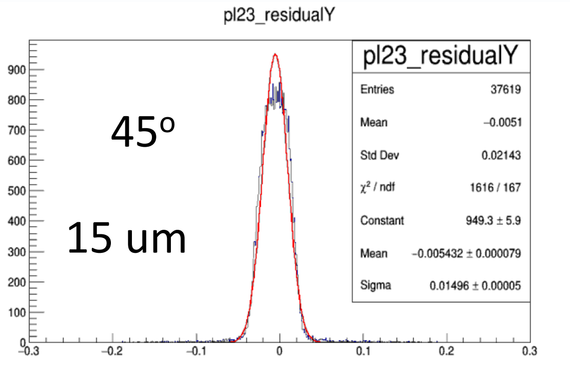
Test beam characterization results

- Residuals comparison at different orientation angle to the beam

Short side:







Long side :