Development of n-in-p Active Edge Pixel Detectors for ATLAS ITK Upgrade

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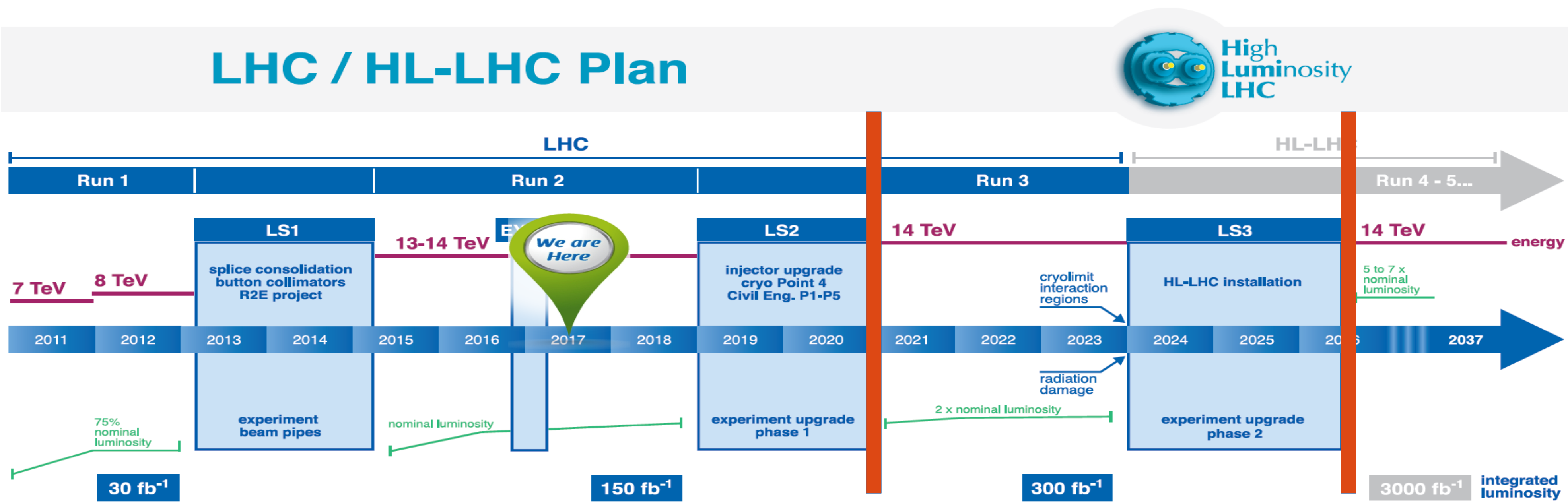
OUTLINE

- **Introduction:**
  - The Large Hadron Collider (LHC).
  - The ATLAS Detector.
- **ATLAS Inner Detector:** Current Status.
- **Motivation:** ATLAS Upgrade Project.
- **Results of R&D activities to develop new active edge pixel detectors.**
- **Conclusion**

Introduction

Large Hadron Collider at CERN

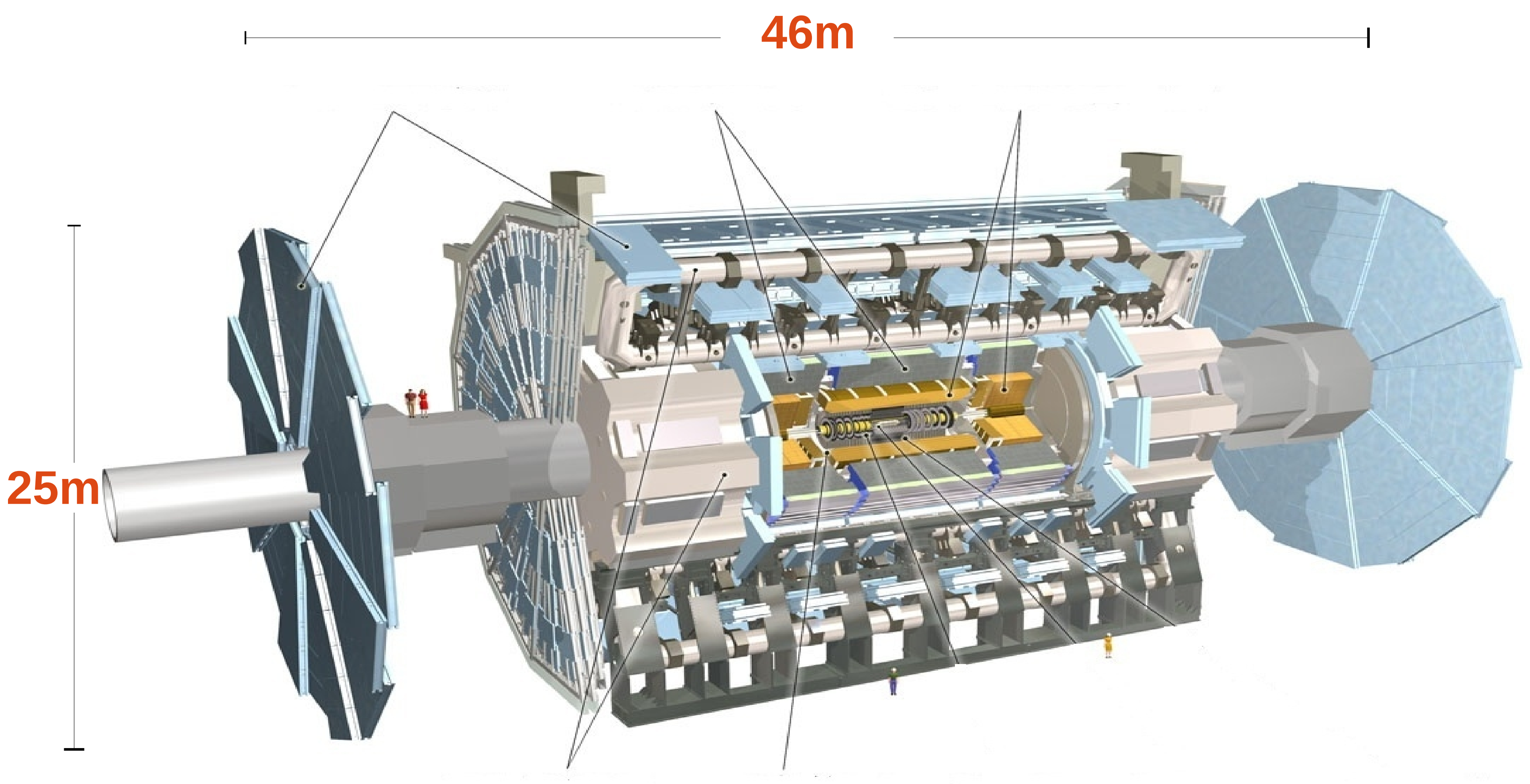
- **In 2008**, the Large Hadron Collider (LHC) started up.
- **During 2010-2013**, the first research run of the LHC with nominal energy of **7-8 TeV** and nominal operation luminosity **10^{34} cm^{-2} s^{-1}**.
- **In June 2015**, LHC start Run-2 with center of mass energy **13 TeV** after ~ 2.5 year after the start of the first Long Shutdown(LS1).
- **One weeks ago**, 2017 data taking with stable beams restarts at the LHC.



ATLAS Experiment

ATLAS (A Toroidal LHC ApparatuS) Detector

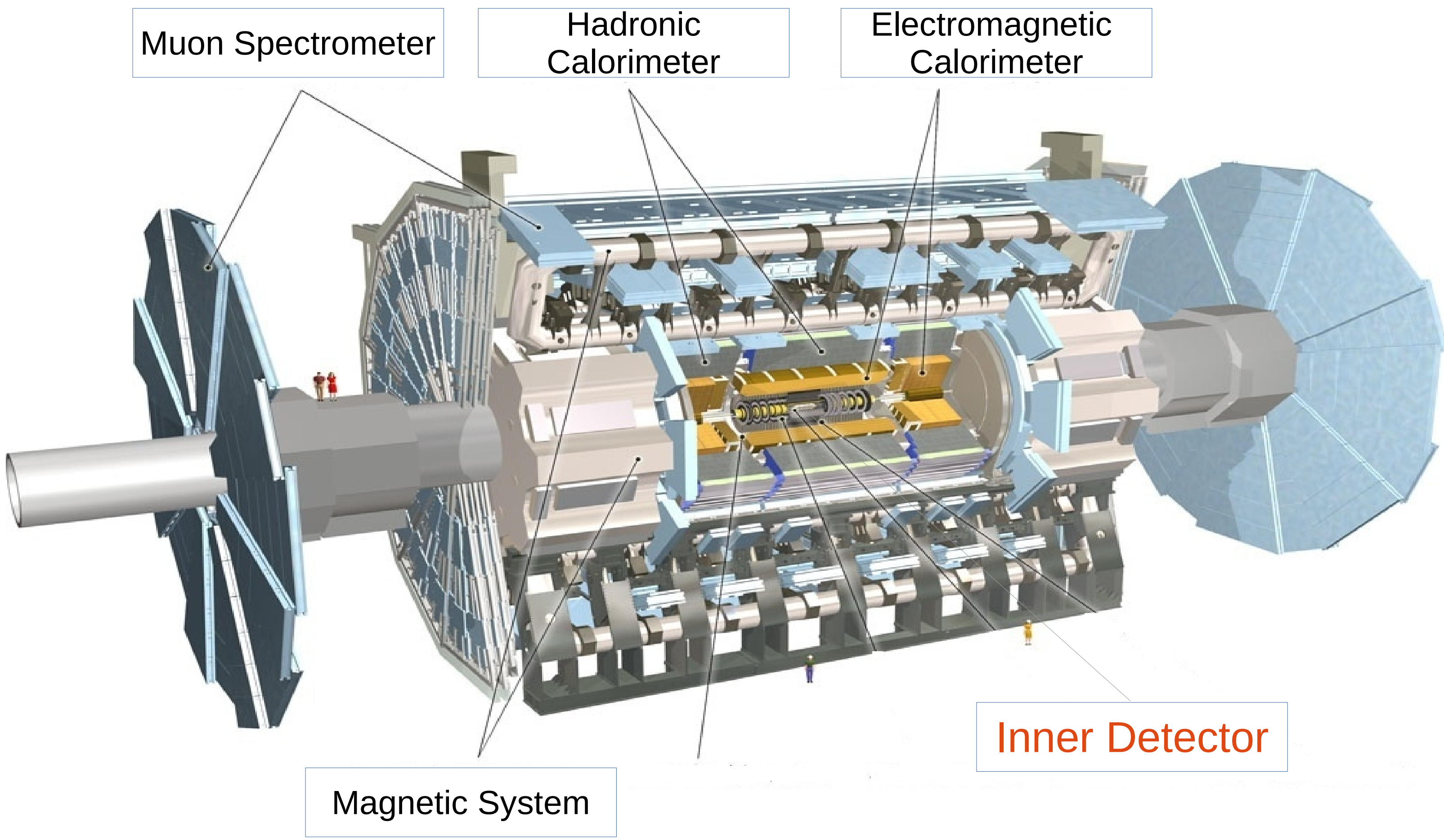
ATLAS detector is 46m length, 25m diameter and 7000 tonnes.



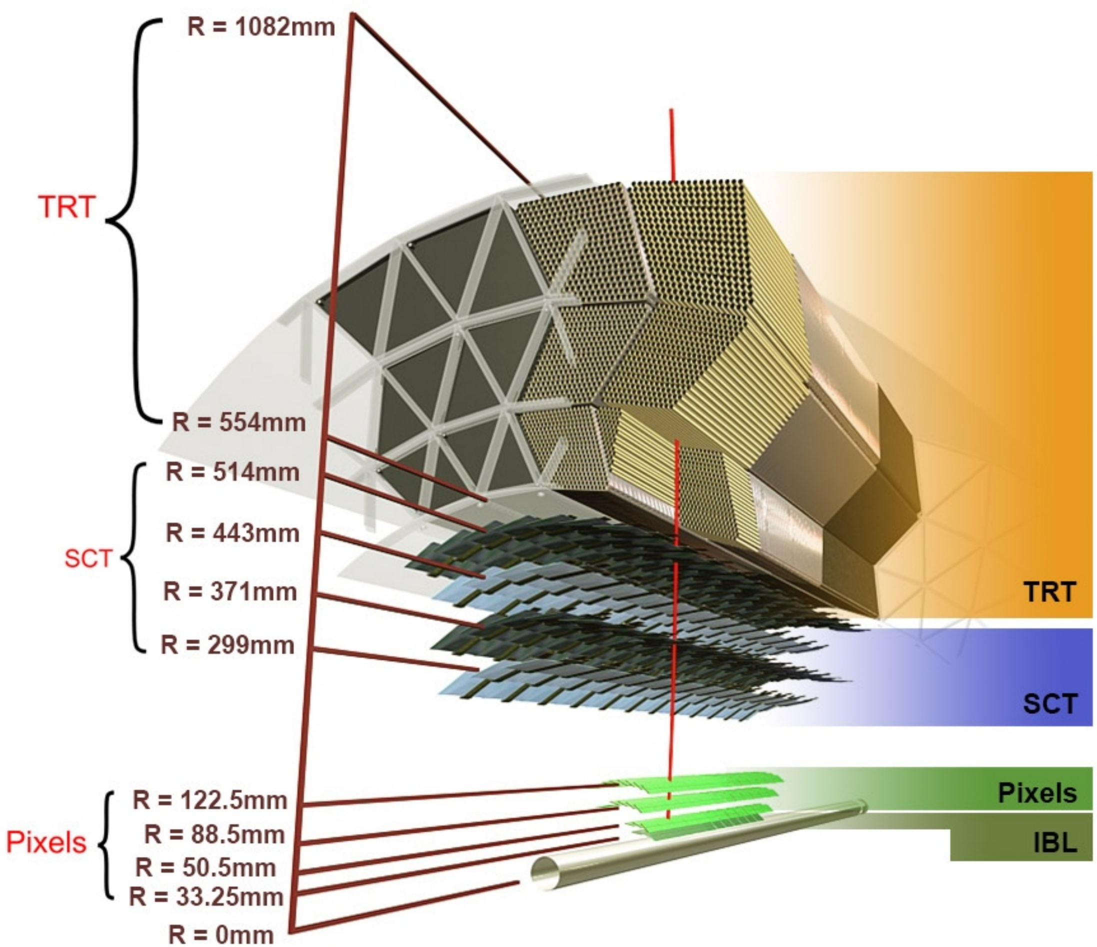
ATLAS Experiment

ATLAS (A Toroidal LHC ApparatuS) Detector

Layout of ATLAS detector with its major sub-system component.



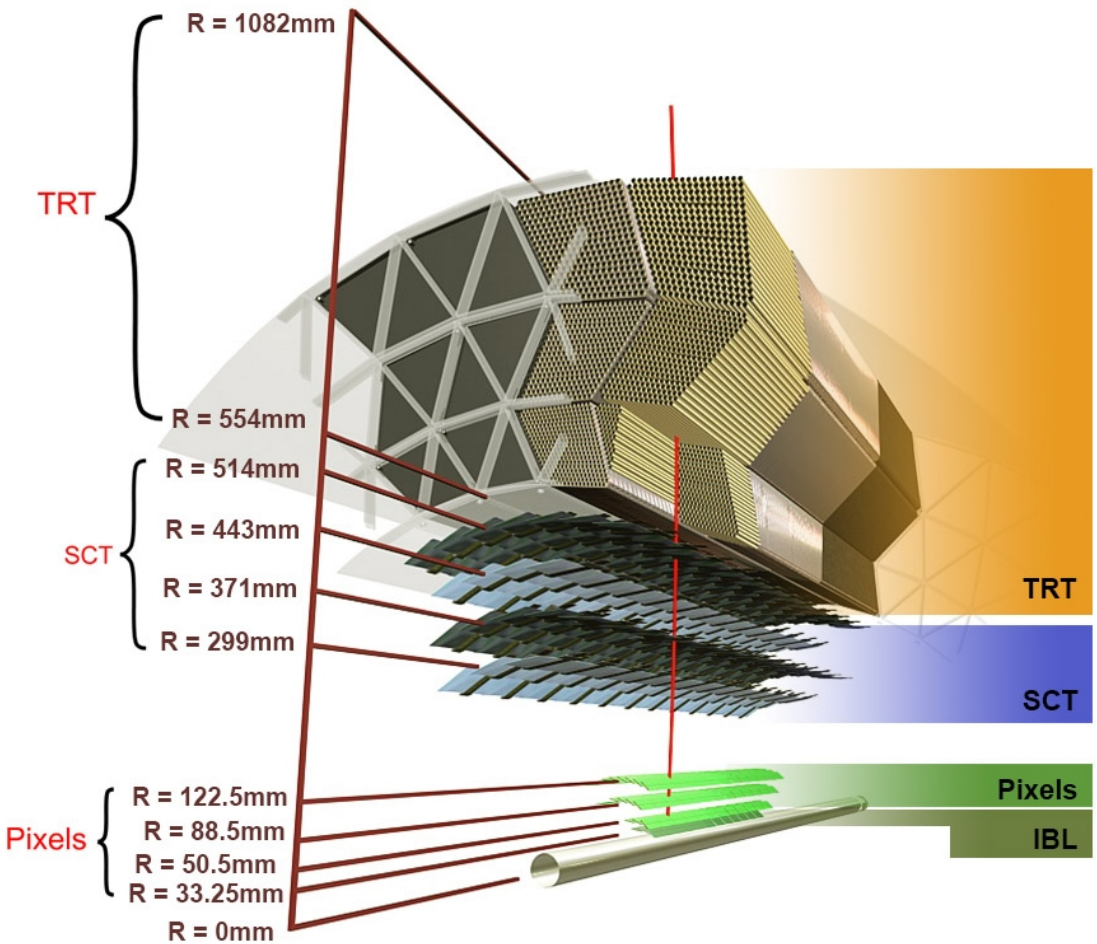
ATLAS Inner Detector: Current Status



- Inner most detector
- Silicon based detector.
- Dedicated to high precision tracking (momentum measurement) of charged particle.
- composed of three subsystems: TRT, SCT and Pixel detectors.

ATLAS Inner Detector: Current Status

Upgrade Phase 1, 2014: IBL (Insertable B-Layer)



- **Pixel Detector**
  - **Composed of 4 Si pixel layers.**
  - **Contains 92 millions of pixels.**
  - **$2m^2$ of active area.**
  - **In May 2014, the IBL became the innermost layer of ATLAS.**

Motivation: ATLAS HL-Upgrade Project

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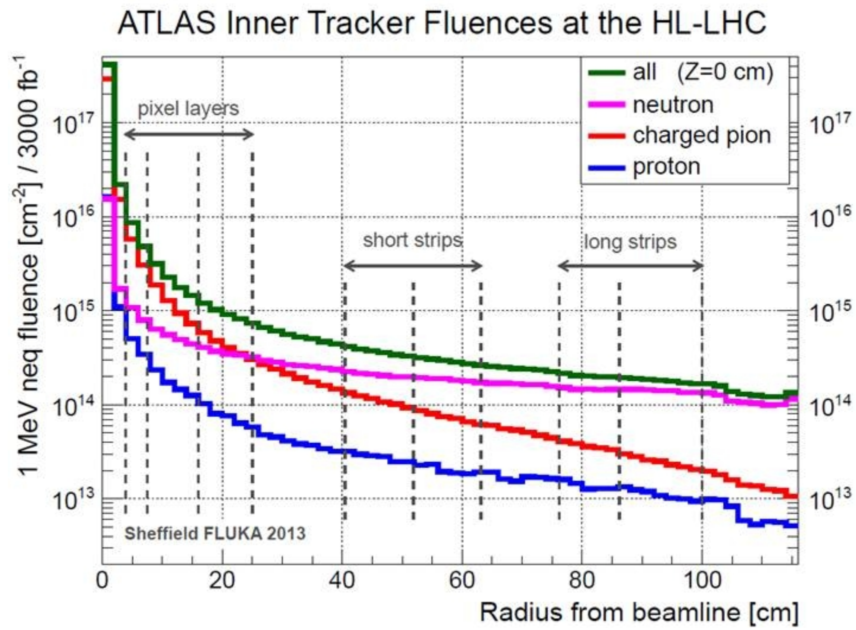
Why we need a new inner detector?

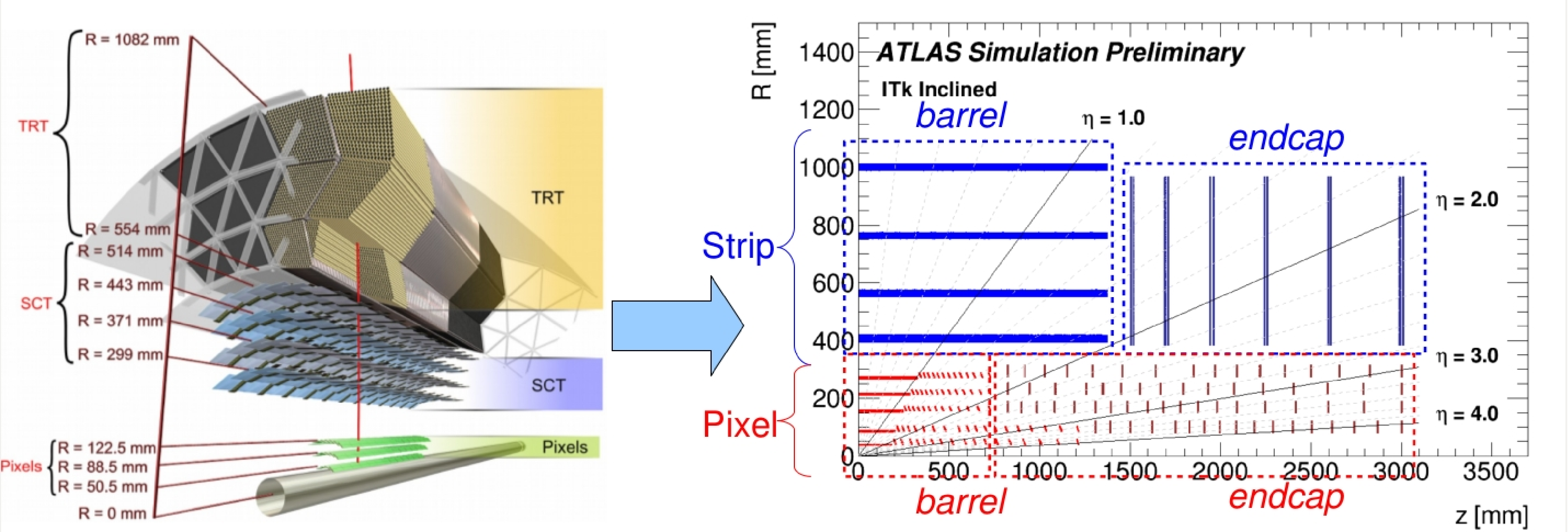
- **Expected number of interactions/bunch crossing (pile-up): 200**
  - **ATLAS design value: 25**
  - **better detector needed to maintain tracking, vertexing, b-tagging performance → increase detector granularity.**

- **Much higher radiation environment:**
  - **The radiation level at the pixel layer: 10^{16} n_{eq}/cm^2.**



Inner tracker (ITK) Upgrade

Upgrade Phase 2, 2023: Inner Tracker replacement

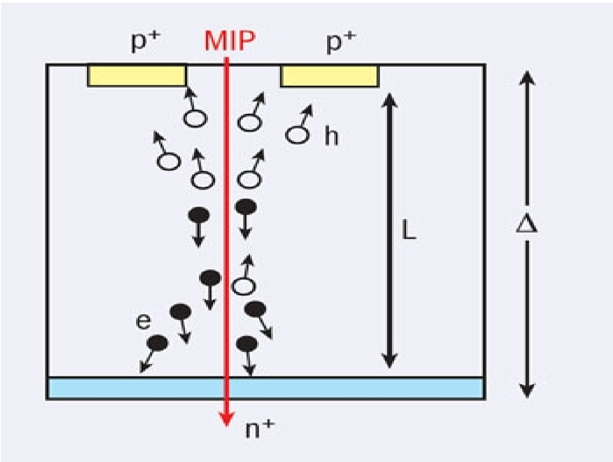


- 92 million of pixels
- 2m² of active area

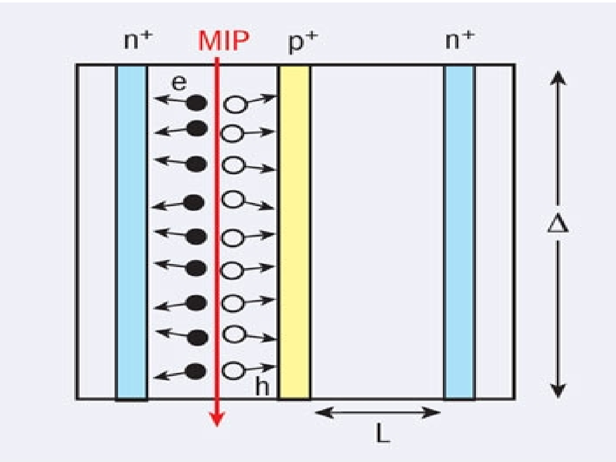
- 5 billion of pixels
- 13m² of active area

Proposed Sensor Technologies for ITK

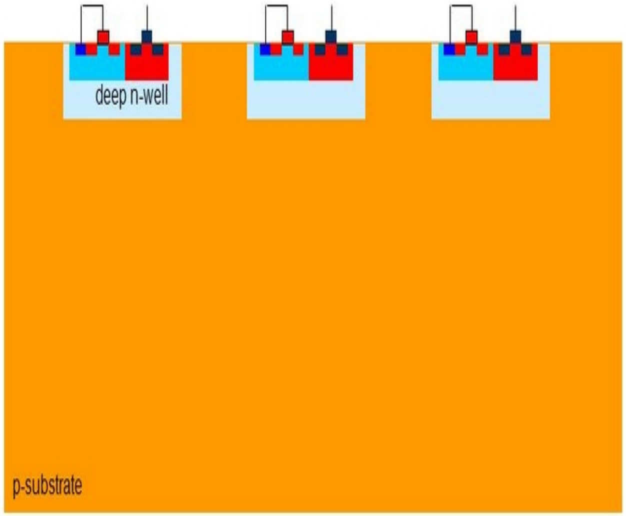
Different Pixel technologies will be used for ITK upgrade.



Planar Pixel Sensor



3D Pixel Sensor



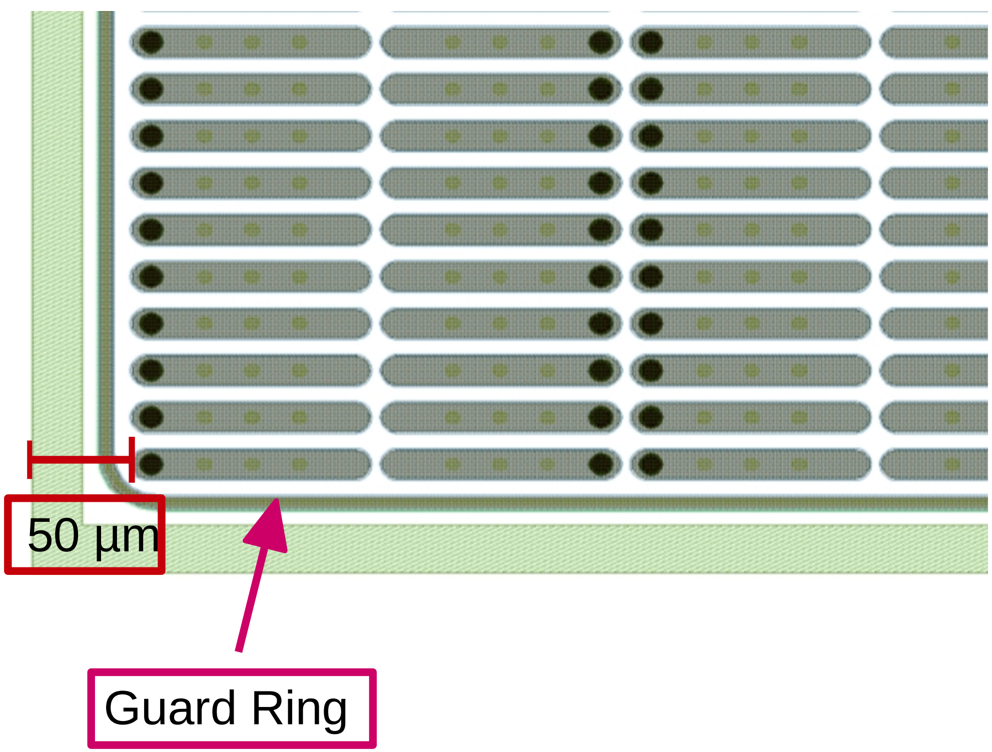
CMOS Pixel Sensor

R&D activities: Results

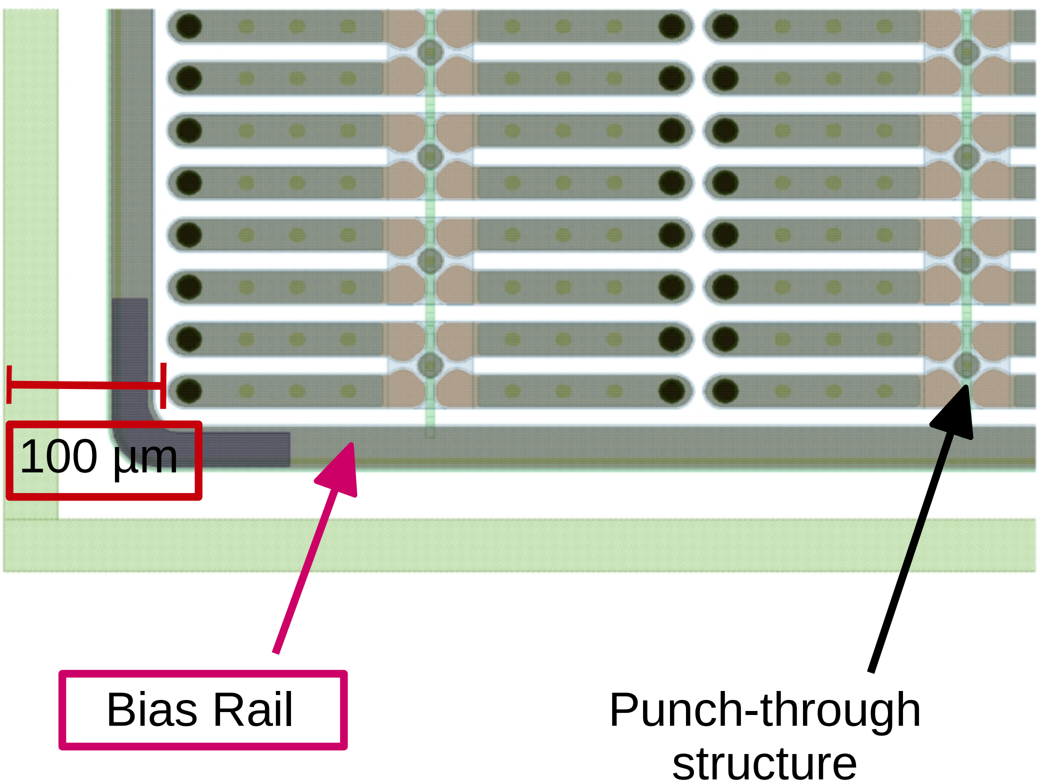
Planar Pixel: Towards New Technology

We have different technologies of Planar pixel detector: Active edge and Slim Edge.

ADVACAM NP150-6-1A
Active edge, 150 µm thickness

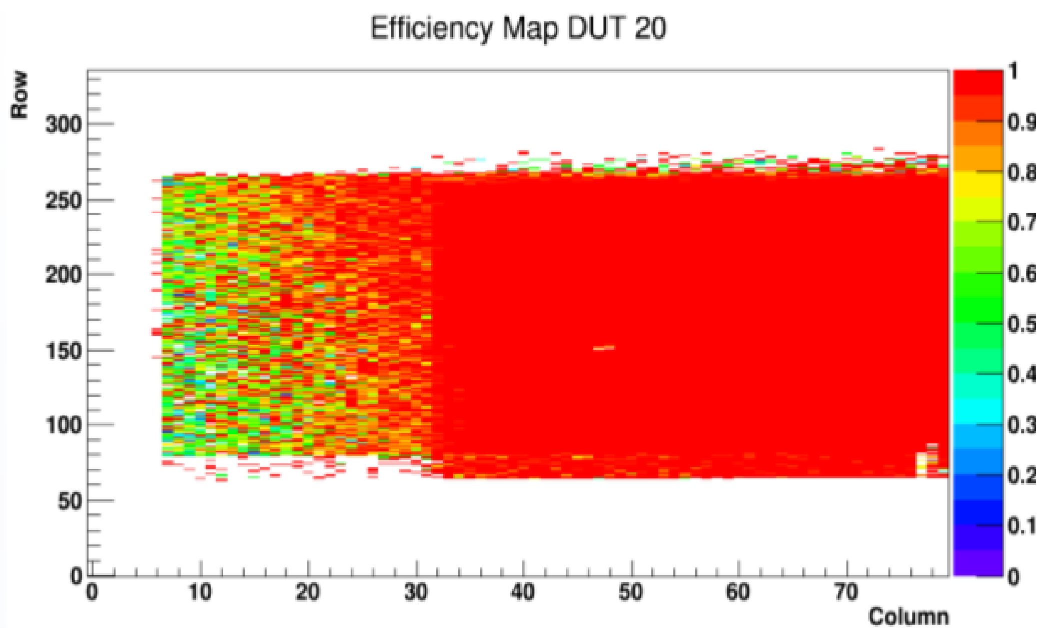


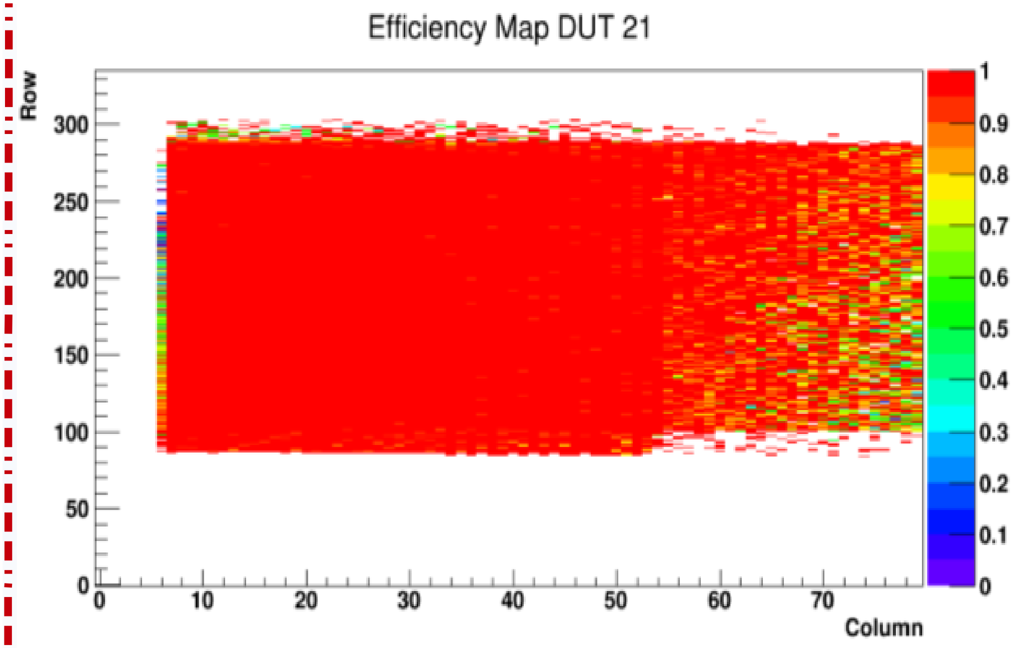
ADVACAM NP100-7-2A
Slim edge, 100 µm thickness



Testbeam: Global Efficiency

Global Hit Efficiency





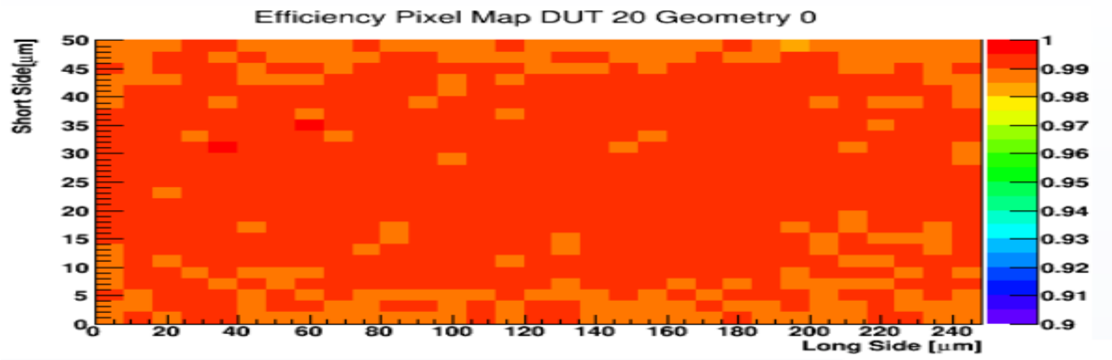
- **Active Edge**
  Efficiency = 0.98645 ± 0.00005

- **Slim Edge**
  Efficiency = 0.98558 ± 0.00004

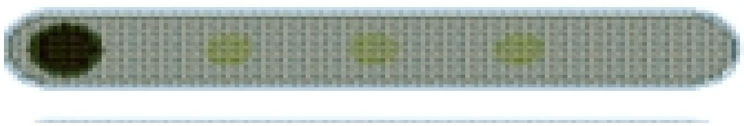
Efficiency higher than 97% for both Active and Slim Edge Design, which is the limit required for ITK

Testbeam: In-Pixel Efficiency

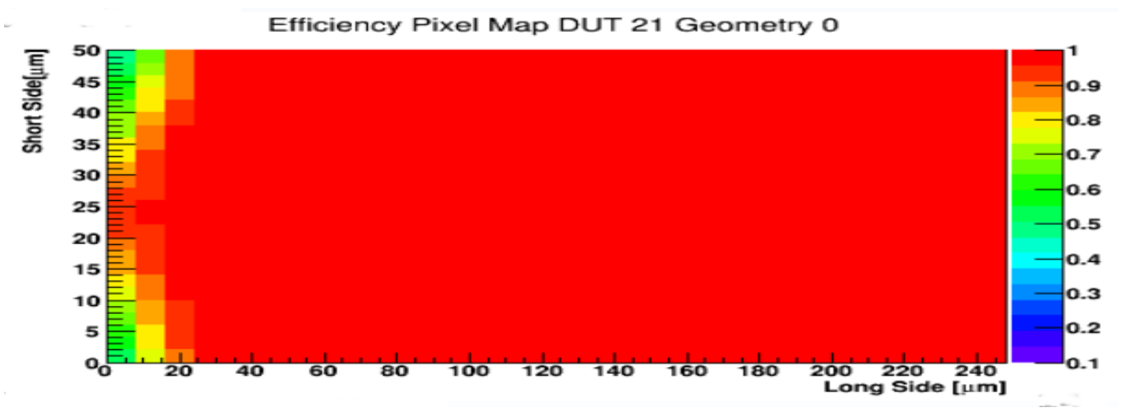
In-Pixel Efficiency



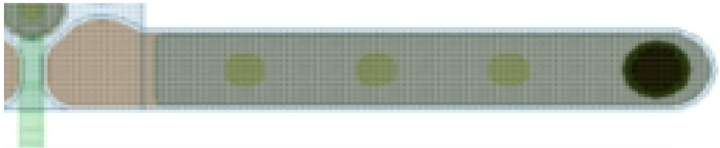
Active Edge Design



Efficiency is **uniform** all over the pixel.



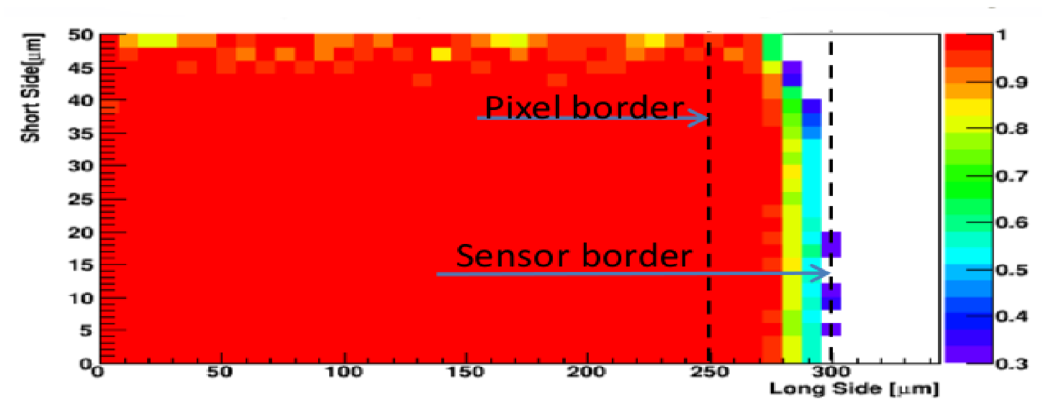
Slim Edge Design

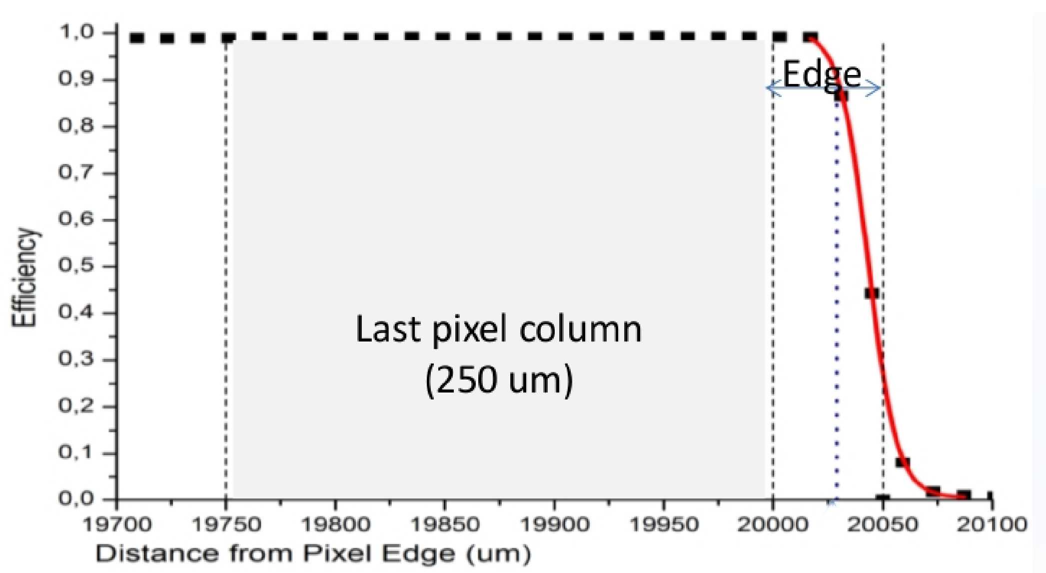


Efficiency lose at the edge of the pixel in Slim edge design due to **punch-through**

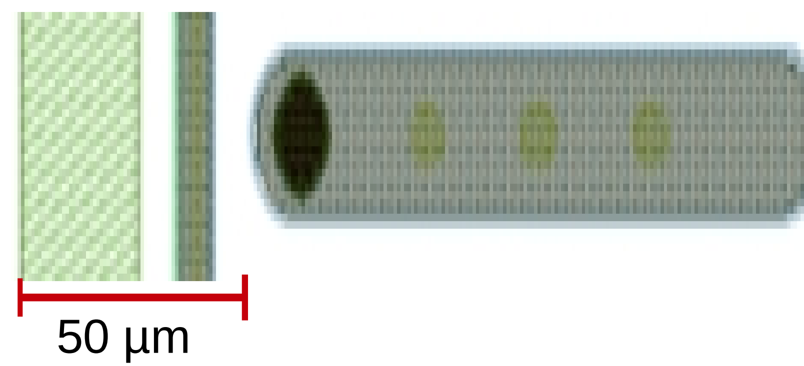
Testbeam: Active Edge Efficiency

Edge Efficiency





Active Edge Design

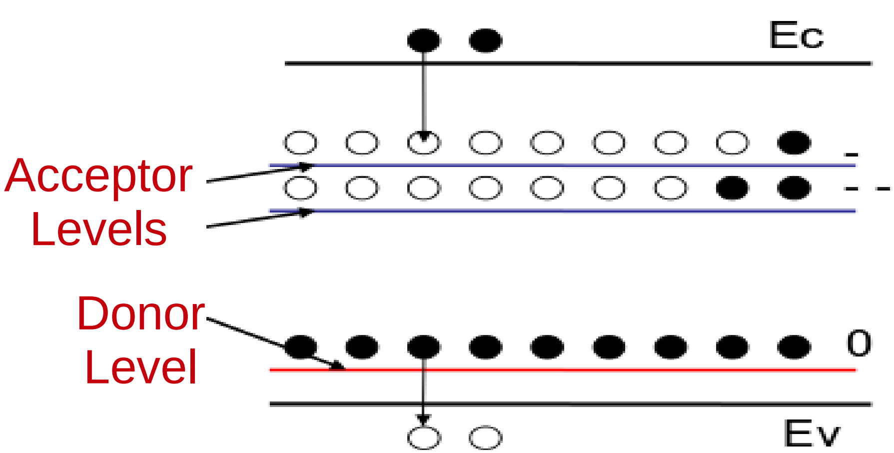


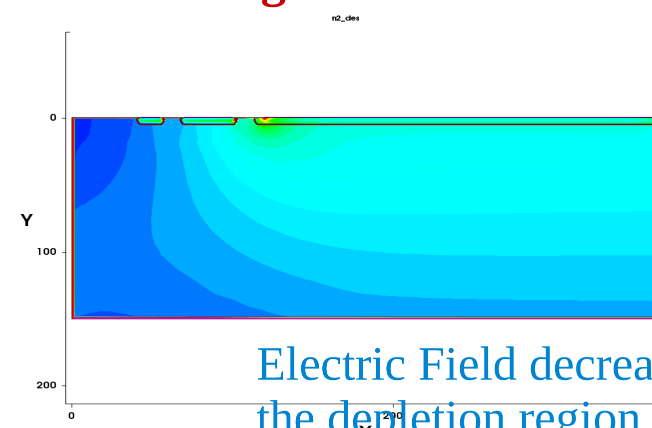
Edge region efficient to higher than 97% up to **20 µm** from last pixel.

Radiation Damage Studies

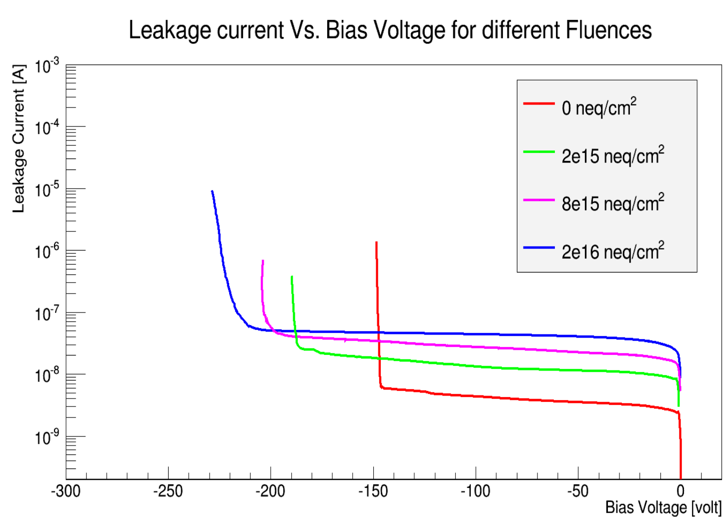
Radiation damage simulation

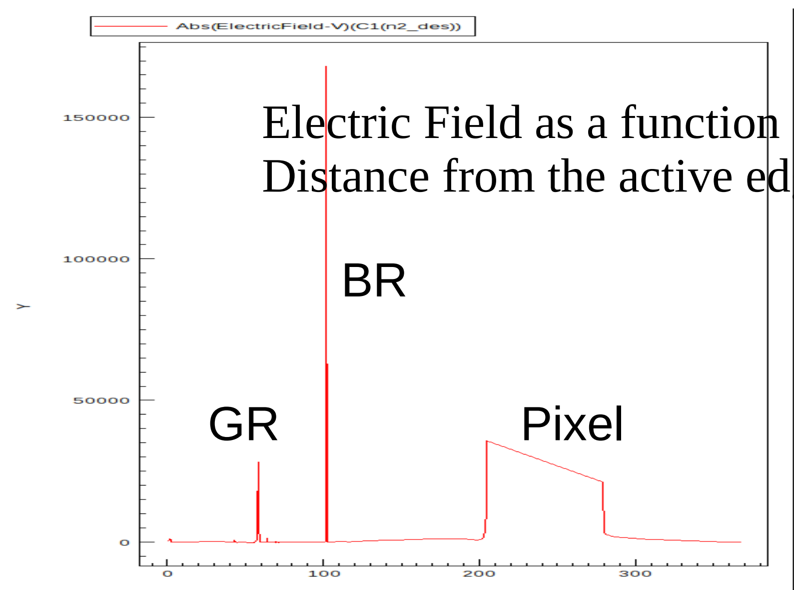
Radiation damage in the detector result in **increasing the breakdown** **voltage of detector.**





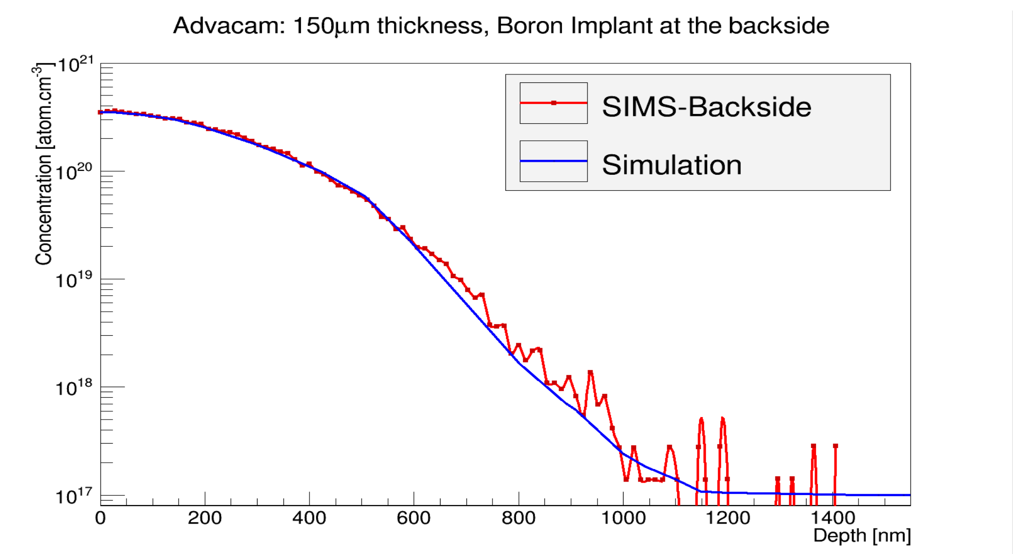
Electric Field decrease linearly in the depletion region

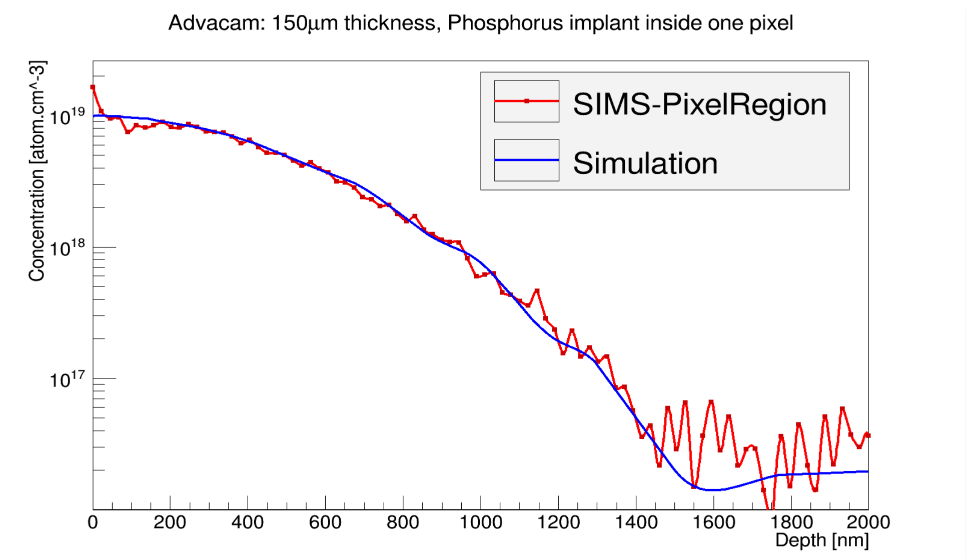


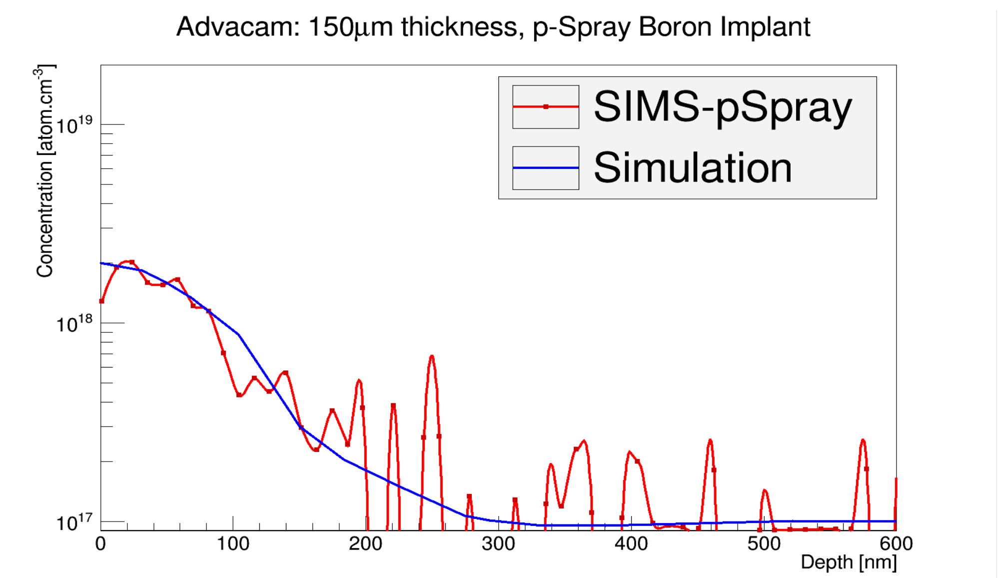


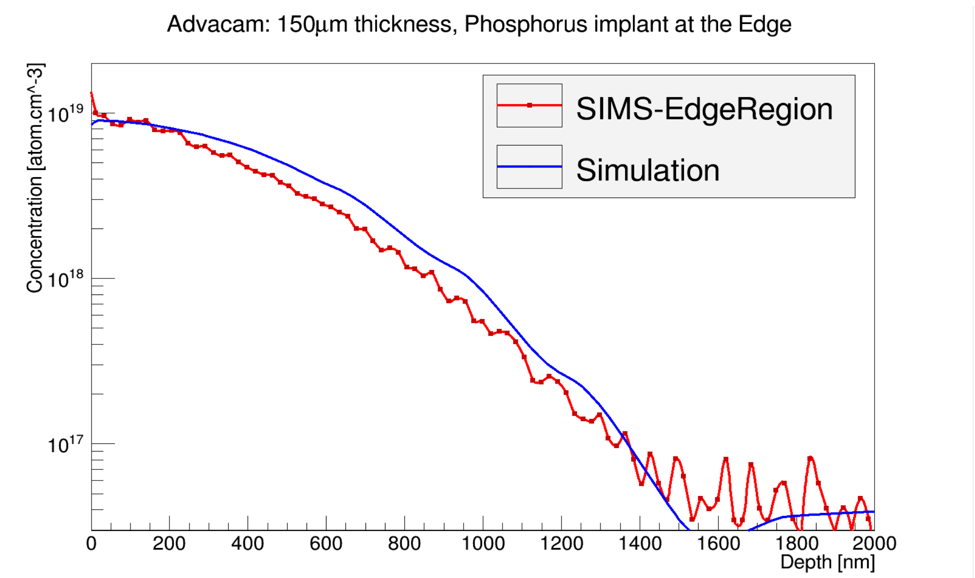
Electric Field as a function of Distance from the active edge

Developing new 3D SIMS Imaging method









Irradiation effect on active dopant concentration

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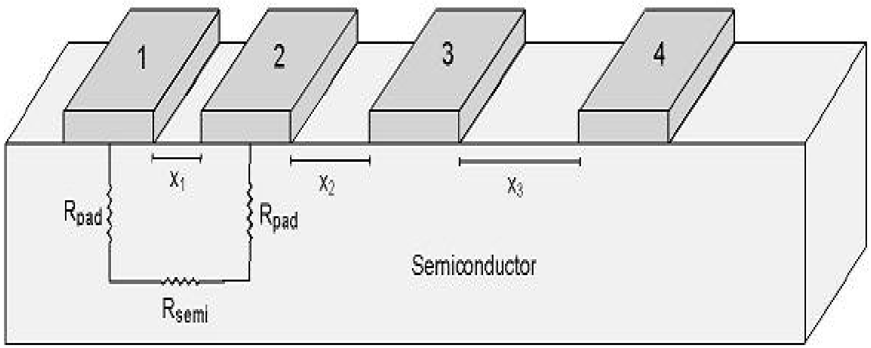
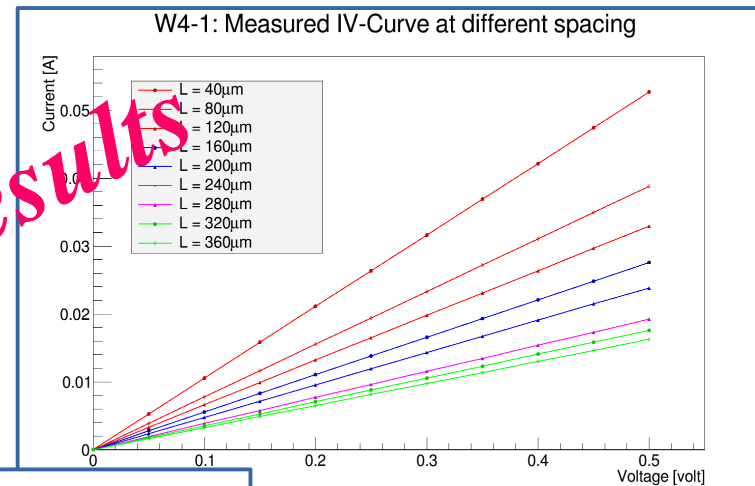
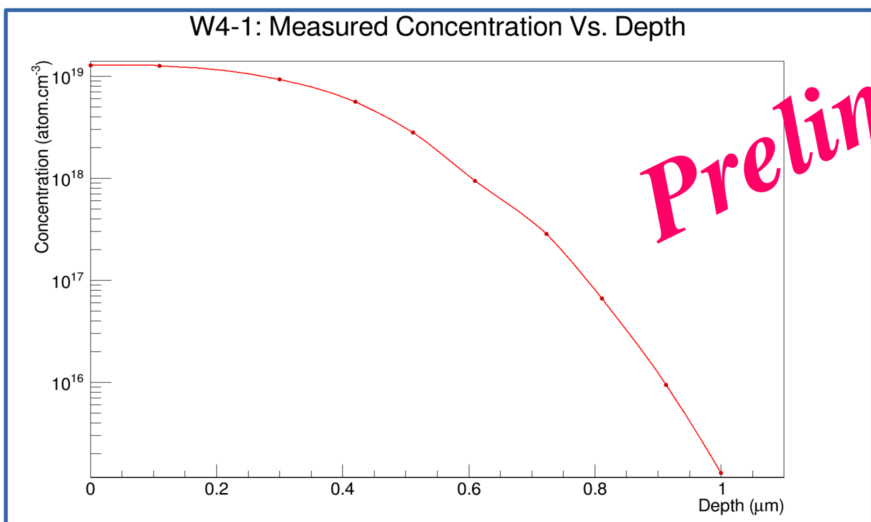
Transmission Line Matrix method

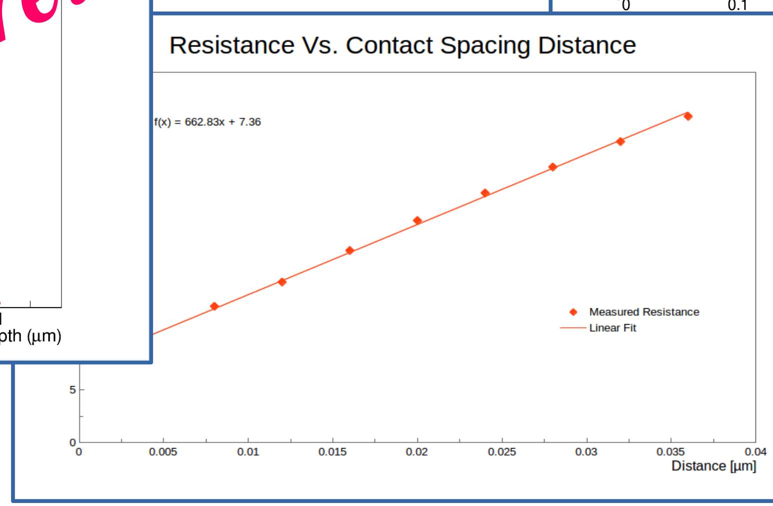
- TLM method based on measuring the resistance of doped silicon layers at depths increasing incrementally in the implanted area.







Preliminary Results

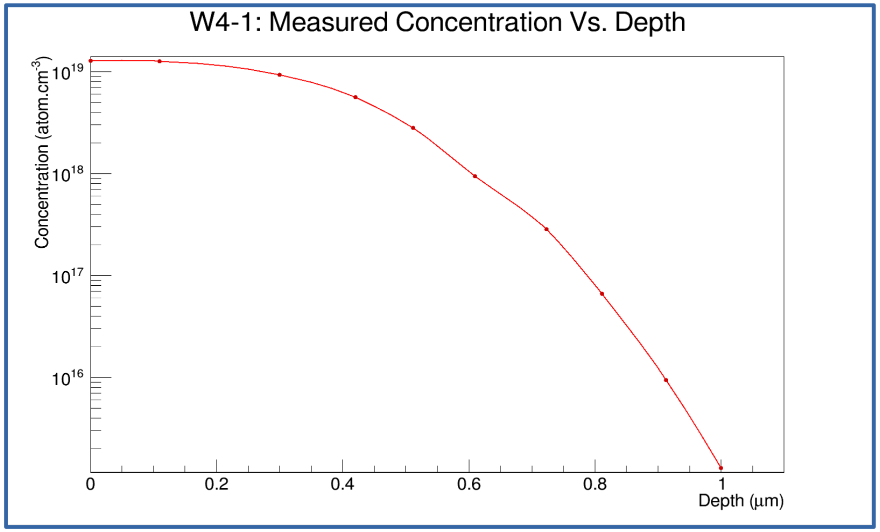


$$R = \rho \frac{L}{A}$$

$$\rho = \frac{1}{e N_D \mu_e}$$

Irradiation effect on active dopant concentration

Transmission Line Matrix method



- Slight difference have been found before/after irradiation. More samples to be measured to see if the difference is significant.

Peak Concentration	Wafer 2 $(atom/cm^3)$	Wafer 3 $(atom/cm^3)$	Wafer 4 $(atom/cm^3)$
Expected value before irradiation	$1.5x10^{19}$	$1.5x10^{18}$	$1.3x10^{19}$
Measured value before irradiation	$1.9x10^{19} \pm 1.5x10^{18}$	$3.4x10^{18} \pm 1.0x10^{17}$	$2.0x10^{19} \pm 2.8x10^{18}$
Measured value after irradiation	ongoing	ongoing	$1.8x10^{19} \pm 9.4x10^{17}$

To Conclude ….

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- The HL-LHC aims to build more powerful particle accelerator to explore the new high-energy physics frontiers.

- The ATLAS Inner Tracker (ITk) will replace the current ATLAS Inner Detector for the HL-LHC .

- The ITk will improve tracking performance compared to current ATLAS Inner Detector.

- I have shown my contribution to different R&D activities aiming to develop new efficient active/slim edge planar pixel detectors for the ITK Upgrade:
  - Testbeam characterization
  - Development of new silicon detector characterization method: SIMS Imaging method.
  - Radiation damage studies of pixel detectors: new TLM method.

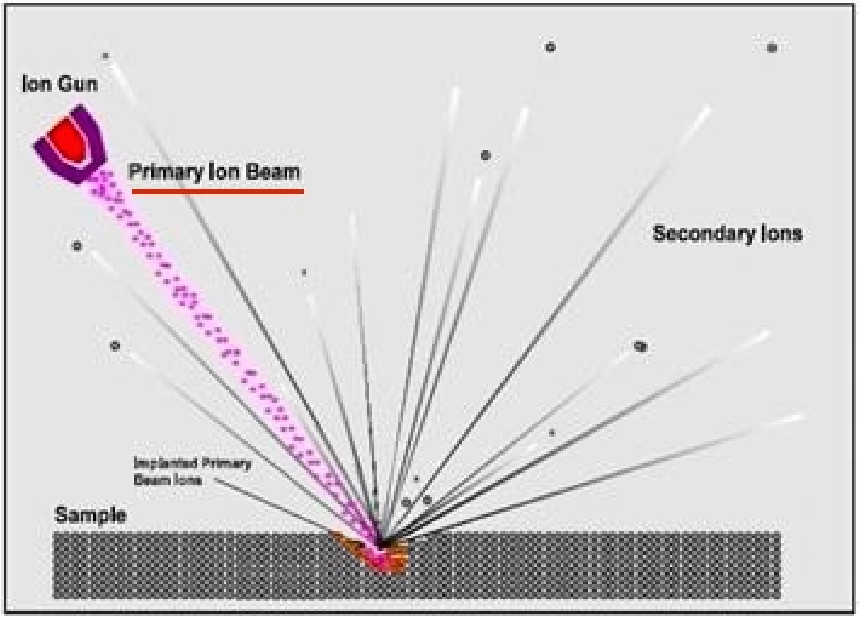
Thanks For Your Attention

Questions

Backup

Secondary Ion Mass Spectrometry (SIMS)

- SIMS Method:
  - Analysis method used to measure 1D doping profile.
  - Depending on measuring the secondary ions Intensity ejected from a sample surface when bombarded by a primary beam.



SIMS Instrument @ GEMAC laboratory at the university of Versailles

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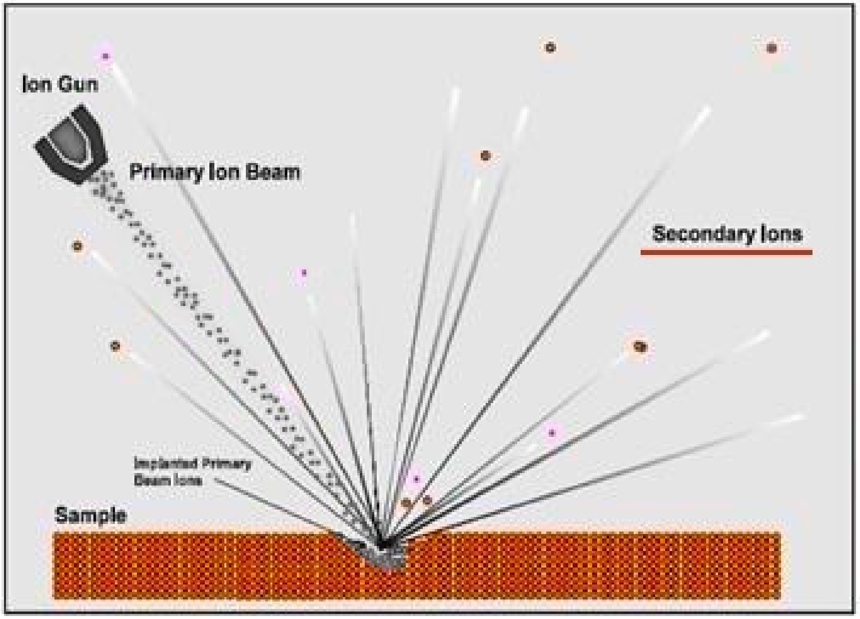
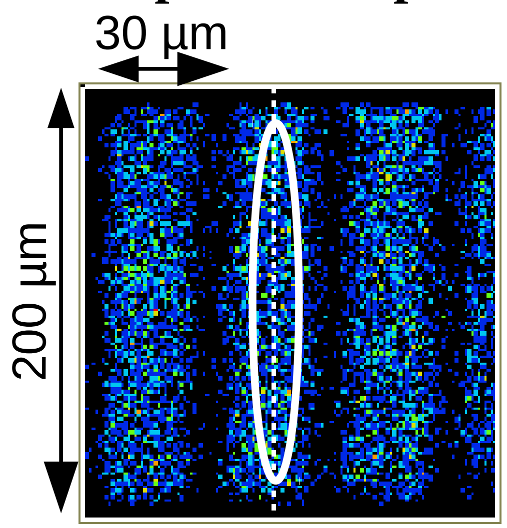
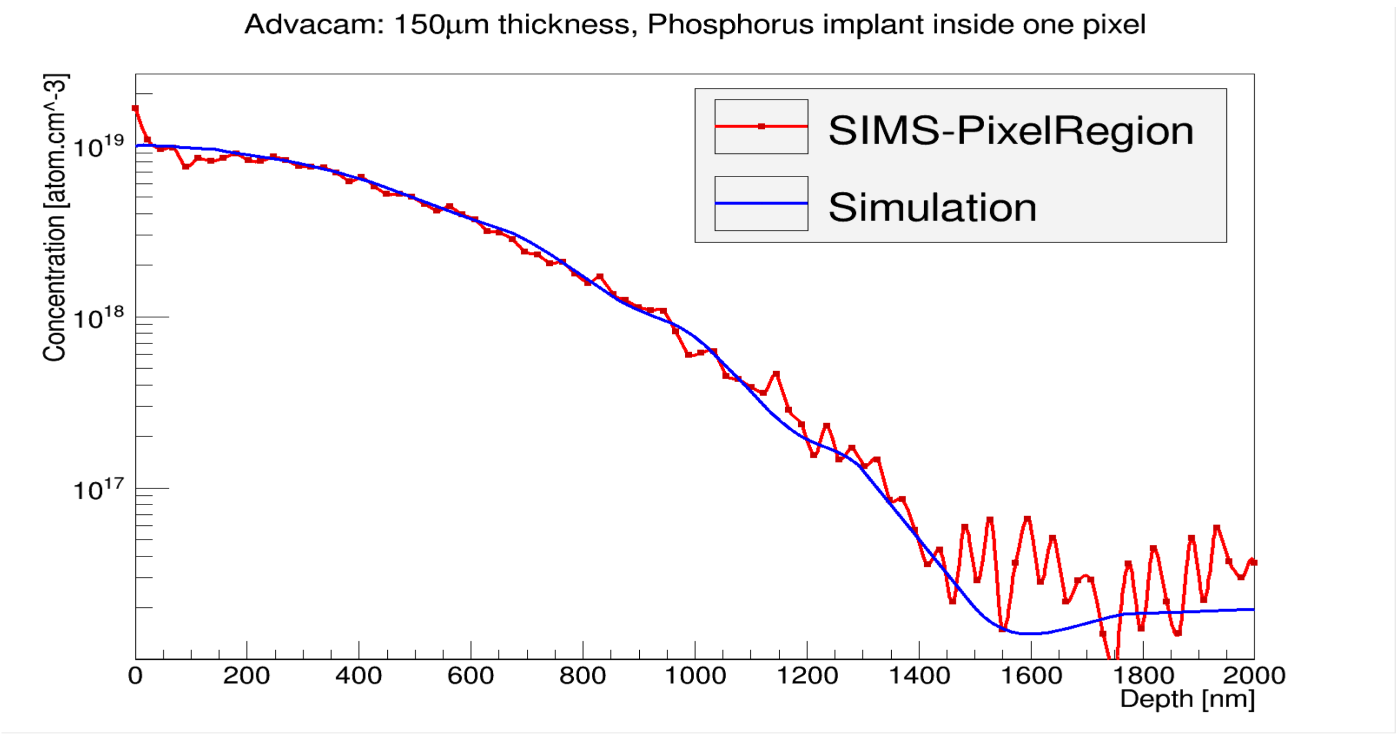


SIMS Instrument @ GEMAC laboratory at the university of Versailles

Developing new 3D SIMS Imaging method

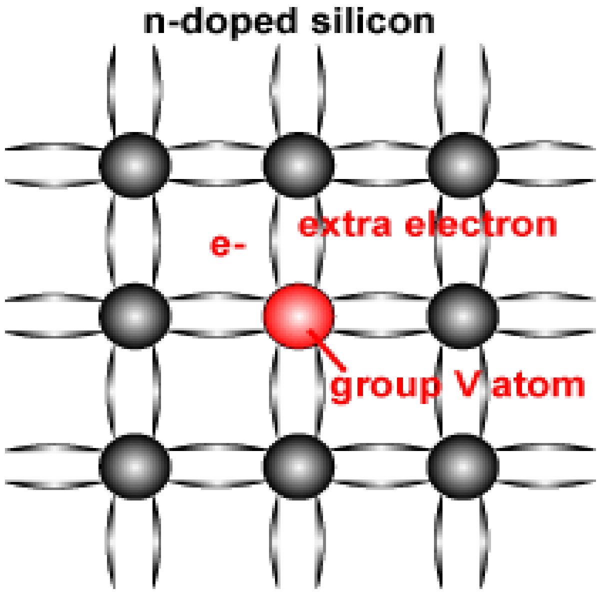
Phosphorus Implant in the Central Pixel Region:

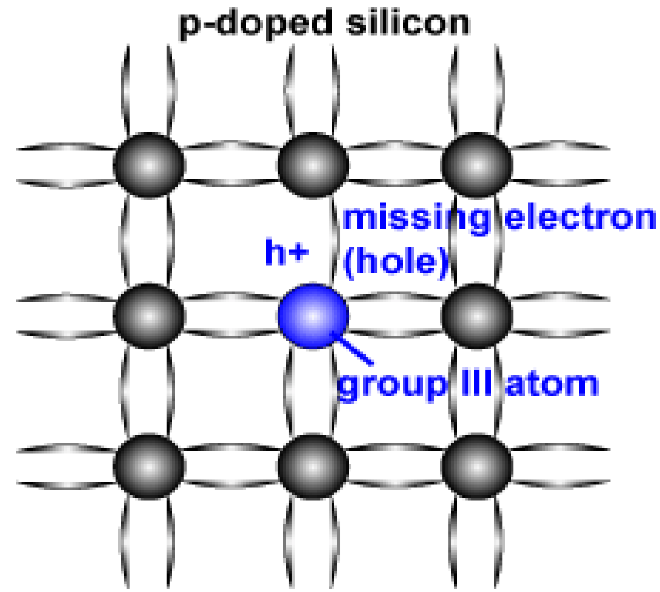




Comparing Phosphorus implant 1D doping profile from simulation (blue curve) and experiment (red curve). Peak concentration 1x10^{19} atom/cm^{-3}. Detection limit around 2x10^{16} atom/cm^{-3} at 1.5 µm in depth .

Overview: Active Dopant in Semiconductor



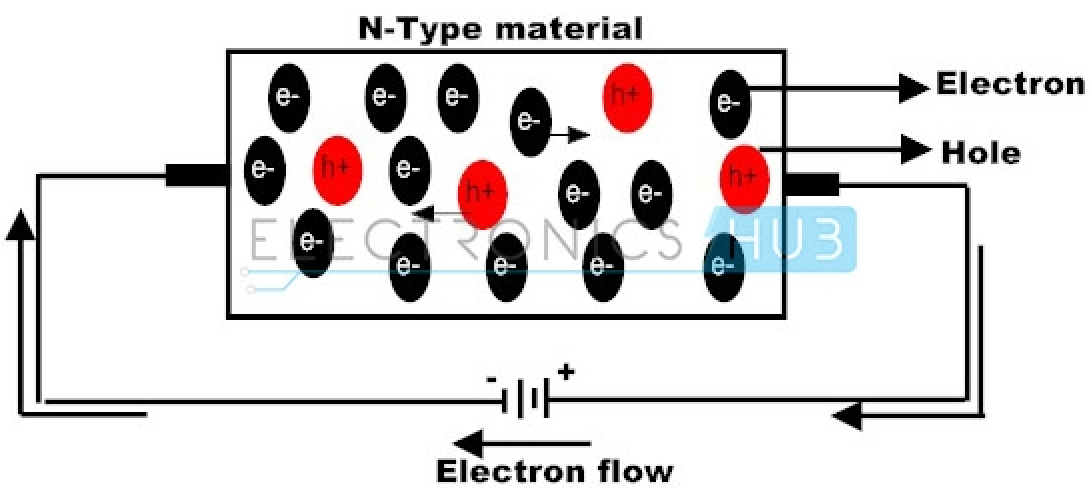


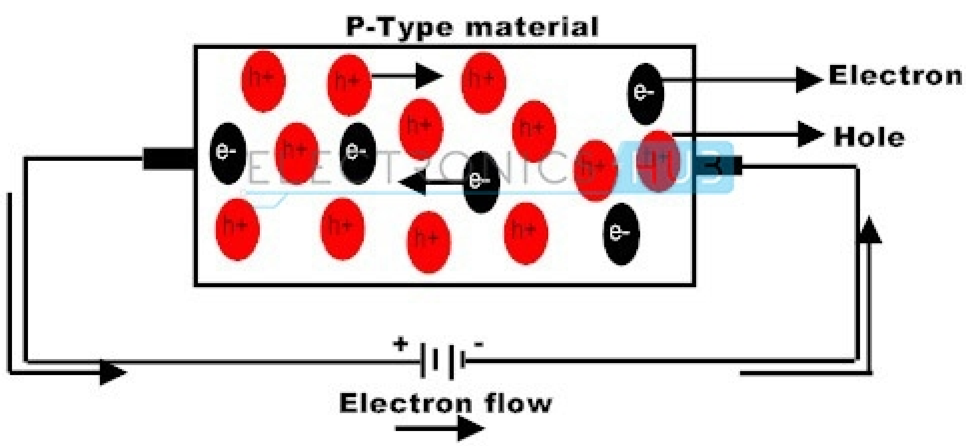
- Dopant: Group V (e.g. Phosphorous)
- extra valence electron present (Donners)
- Free carriers: e^-
- N-Type

- Dopant: Group III (e.g. Boron)
- Missing Electrons (Holes) (Acceptor)
- Free carriers: h^+
- P-Type.

Overview: Active Dopant in Semiconductor

- Once a positive potential is applied to the semiconductor, the remaining free carrier form a drift to produce an electrical current. Major contribution to the electric current flow is e^- (N-Type) and h^+ (P-Type).

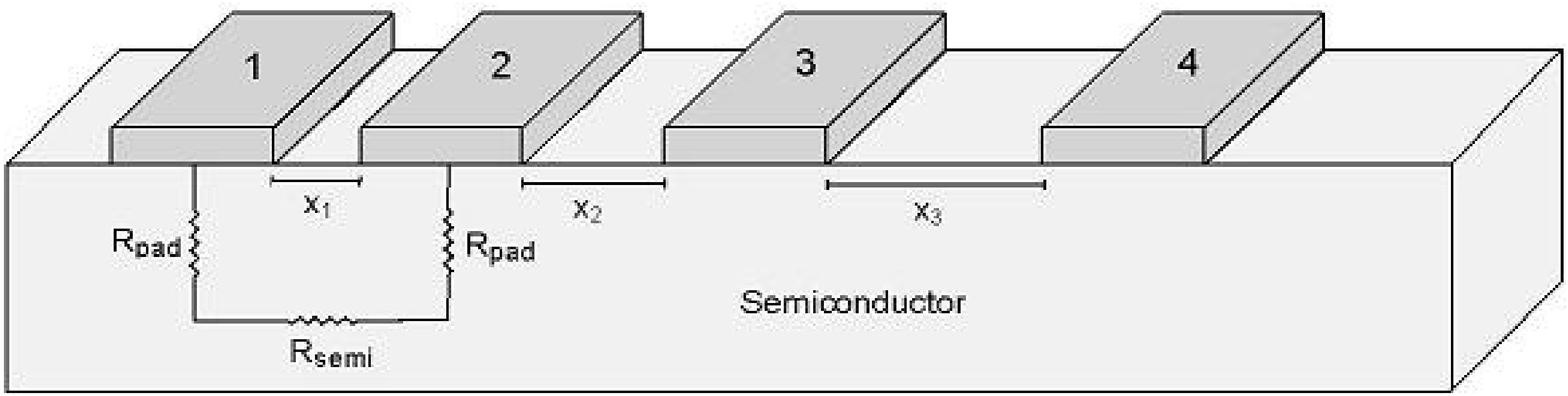




Due to electron-hole recombination, Not all dopant are electrically active !!

What is the TLM method?

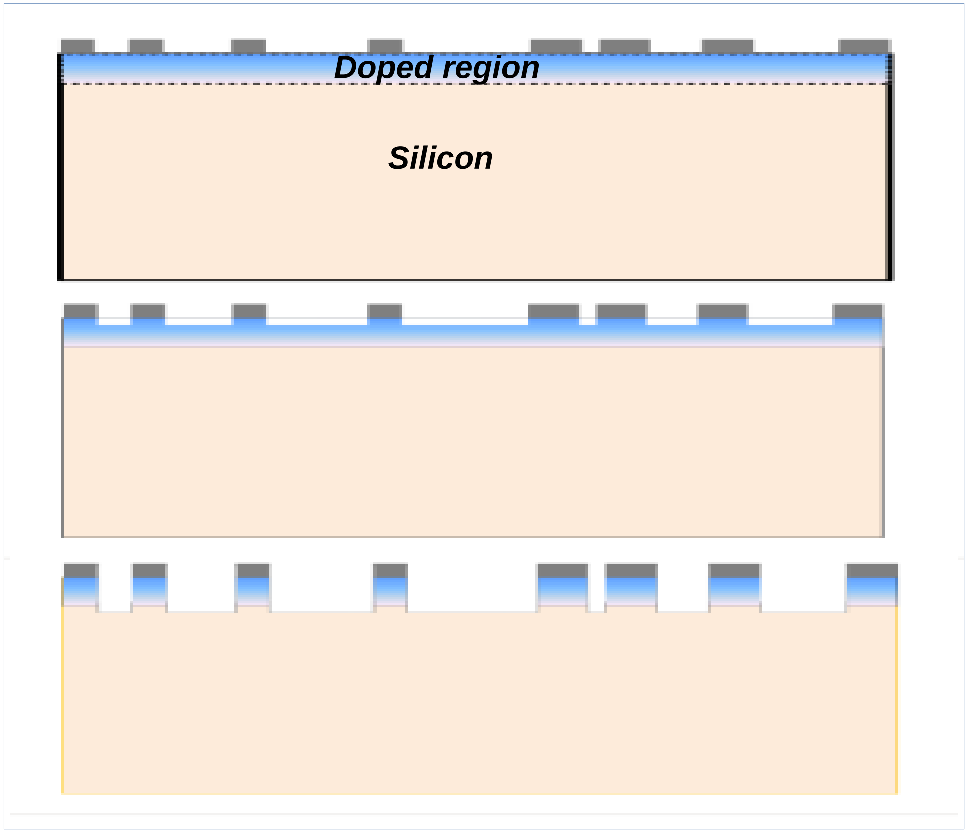
- TLM method (Transmission Line Matrix method) based on measuring the resistance of doped silicon layers at depths increasing incrementally in the implanted area.



$$R = \rho \frac{L}{A} \rightarrow \rho = \frac{1}{eN_D \mu_e} \rightarrow N_D$$

TLM measurement

- Extracting the resistivity depth profile is done by removing the doped Si layer between the contacts by anisotropic Reactive Ion Etching (RIE). Repetitively, a small layer of implant is etched and the resistance at different depths is measured.



Repetitively:

1. etch a small layer of implant.

2. measure IV between two AL electrode.

TLM samples geometry & layout

- Four wafers with special geometry have been produced in CNM, with both Phosphorus and Boron implantation:

Wafer #	Implantation Ion	Implantation Dose	Expected Peak Concentration
Wafer 1	Phosphorus	1e14 atom/cm^2	1.5e18 atom/cm^3
Wafer 2	Phosphorus	1e15 atom/cm^2	1.5e19 atom/cm^3
Wafer 3	Boron	1e14 atom/cm^2	1.3e18 atom/cm^3
Wafer 4	Boon	1e15 atom/cm^2	1.3e19 atom/cm^3

- Prototypes designed to have similar characteristic to what will be used in ATLAS ITK Upgrade, so that will help to get expectation of real sensors would behave in similar circumstances.