Development of Pixel Detectors for the Inner Tracker Upgrade of the ATLAS Experiment

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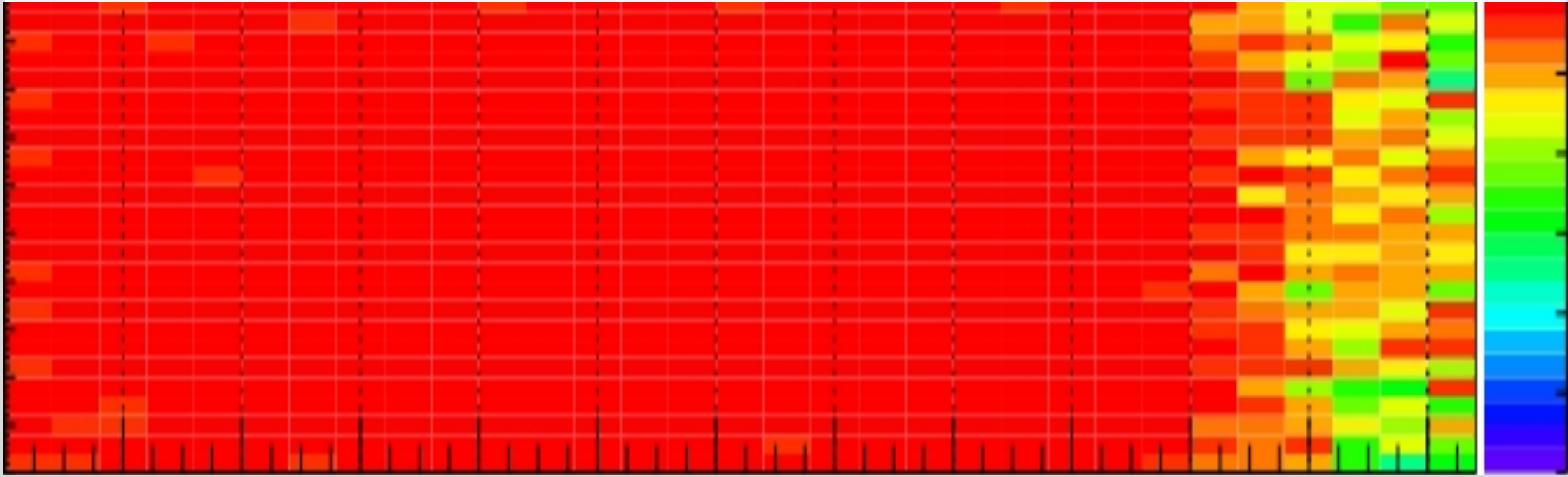
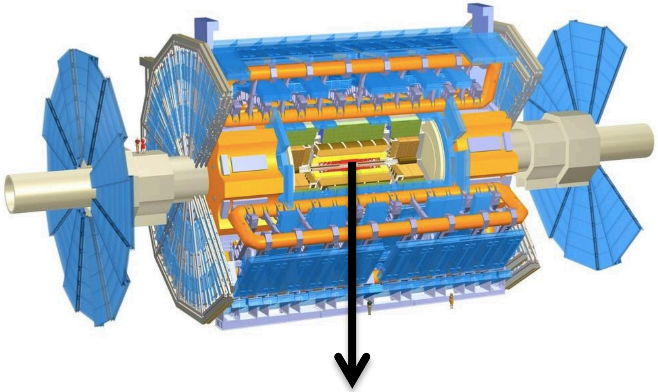


Overview

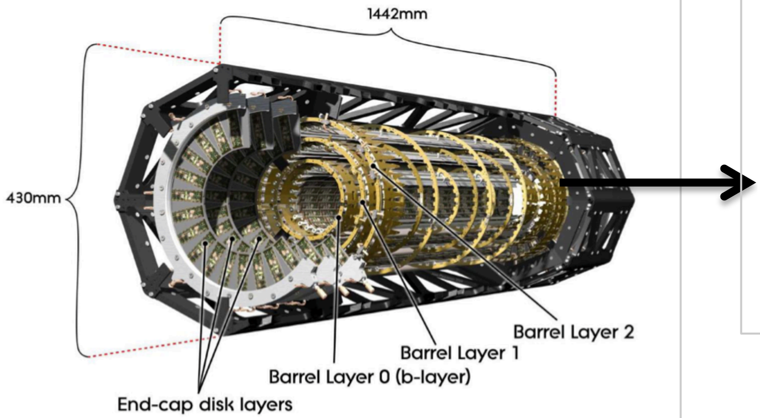
- **Introduction to the ATLAS Pixel Detector**
- **Motivation**
- **Experimental investigations of pixel modules**
    - charge collection measurements in the laboratory
    - efficiency measurement during test beam campaigns
- **Summary and Outlook**

The ATLAS Pixel Detector

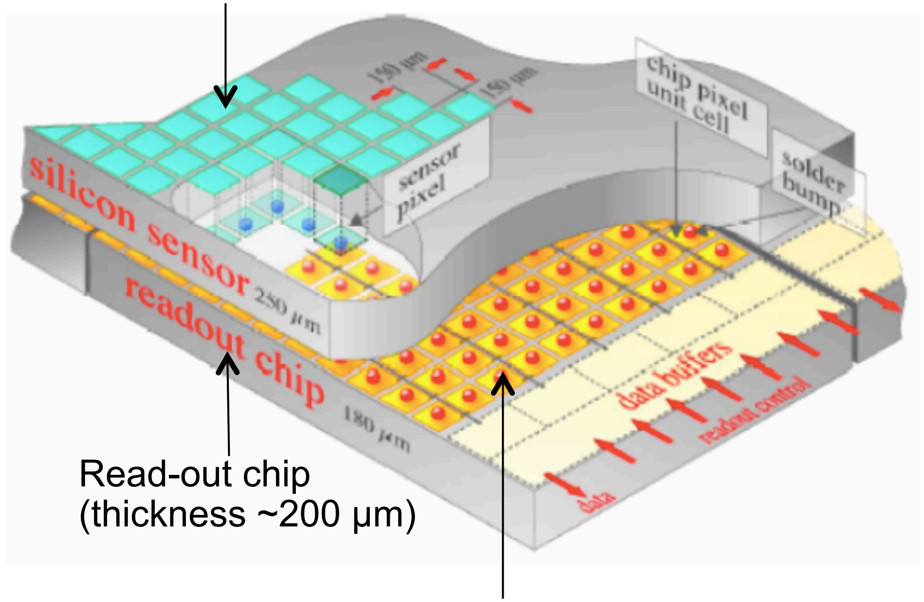
The ATLAS Detector



The Pixel Detector



The Pixel Module

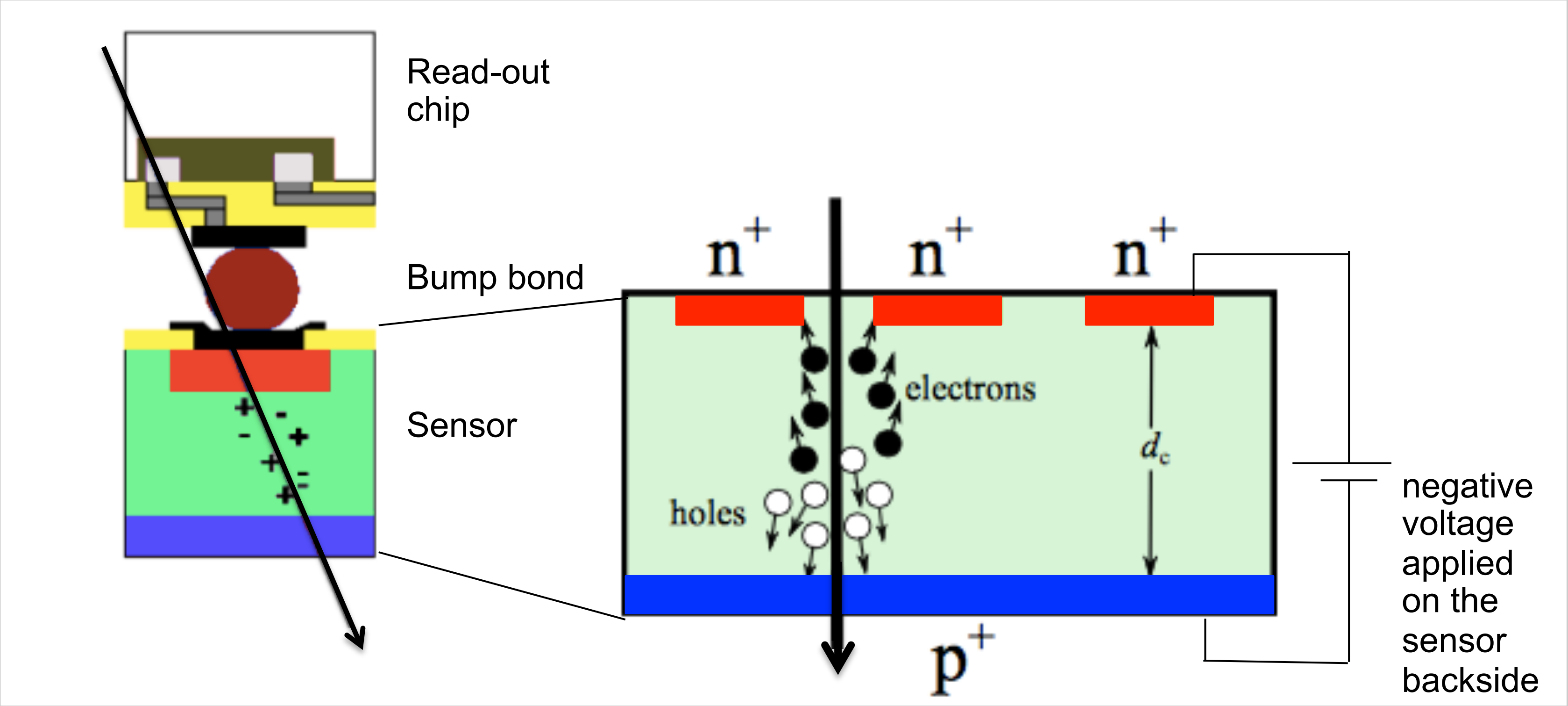


Silicon sensor (thickness ~300 μm)

Read-out chip
(thickness ~200 μm)

Sensor and read-out chip connected via bump bonds

What is a Pixel Detector?



- particles traverse the silicon sensors and release electrons and holes in the depleted bulk which move to the electrodes
  ➔ signal is created
- sensor and read-out chip are interconnected through solder bump bonds
  ➔ signal is processed

Conditions before 2013

Energy: 8 TeV

13/14 TeV

Luminosity:

$>10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

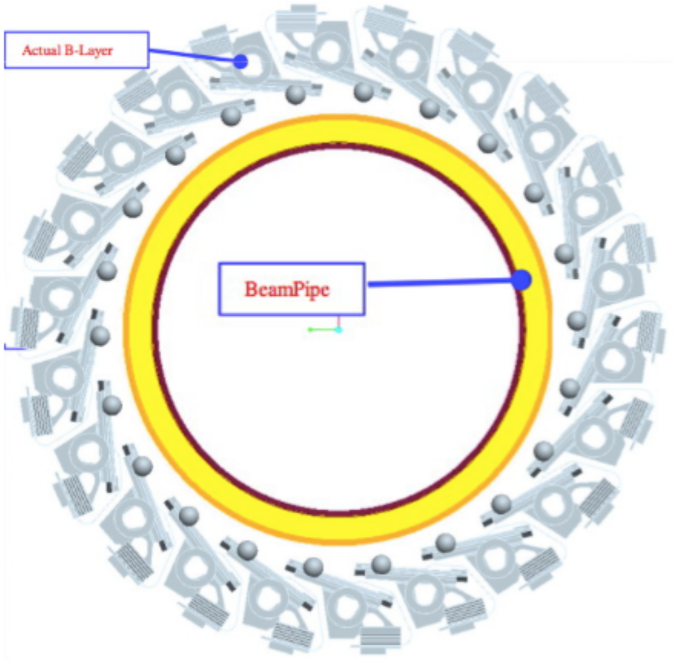
$\sim 2.5\times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

$5\times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

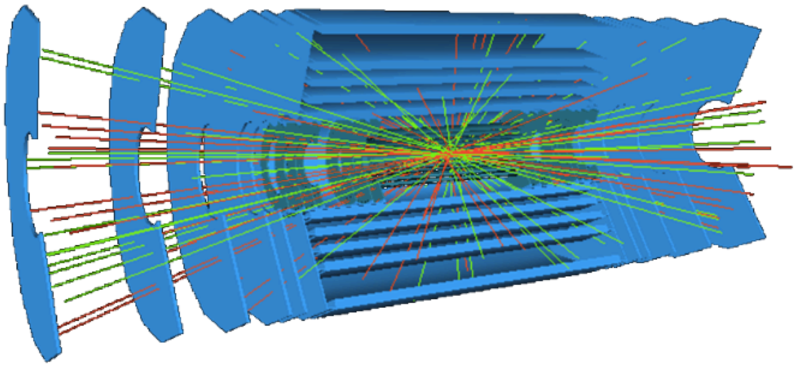
2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2035

HL-LHC

Cross section of the pixel system



20 p-p collisions ever 50 ns



Conditions in 2013

Energy: 8 TeV

13/14 TeV

Luminosity:

$>10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

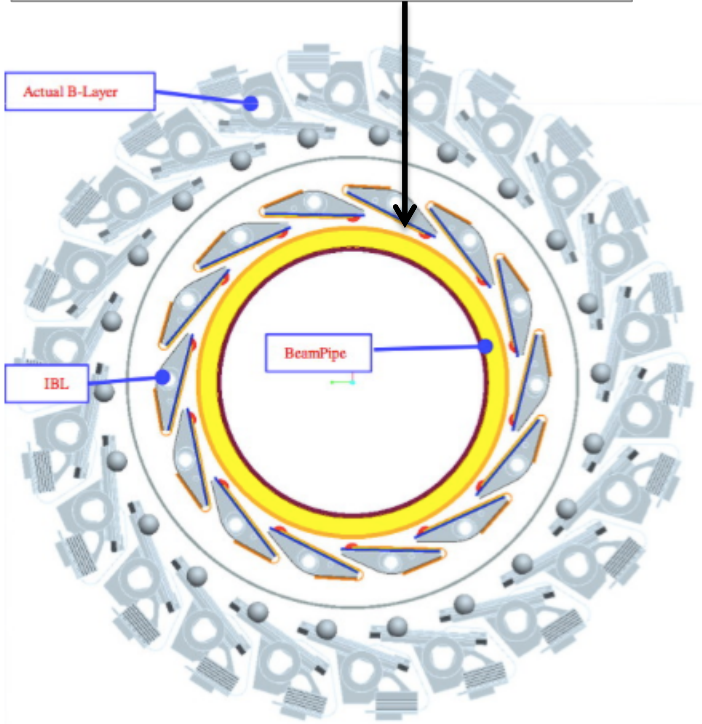
$\sim 2.5\times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$5\times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

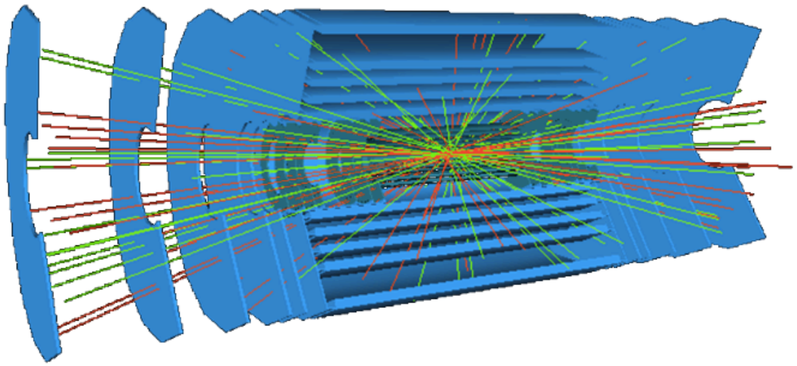
2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2035

HL-LHC

Insertable B-Layer (IBL): new pixel layer at 3.2 cm from the beamline



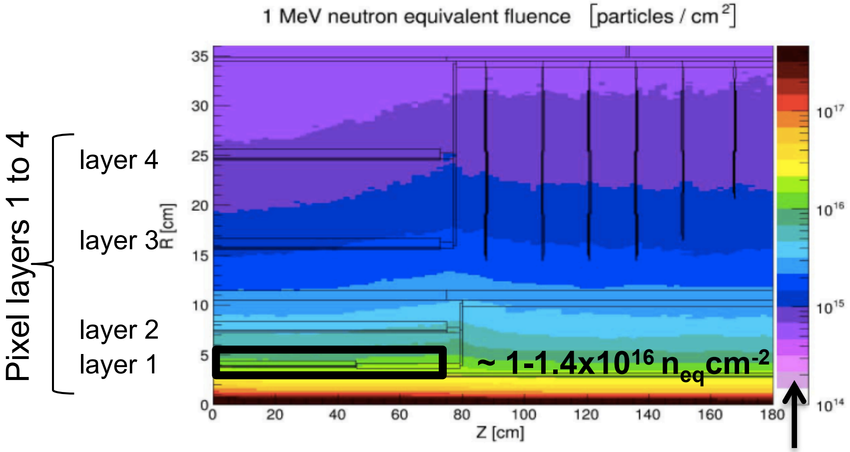
25 p-p collisions ever 25 ns



Conditions from 2024

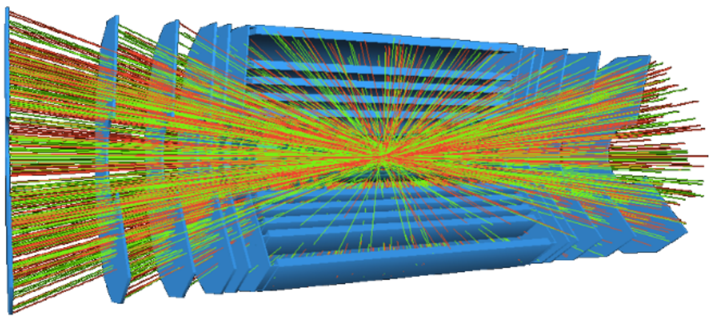
In view of the high luminosity phase of the LHC in 2024–2026 the ATLAS experiment will undergo a major upgrade of its tracker system

Expected radiation for the ATLAS detector



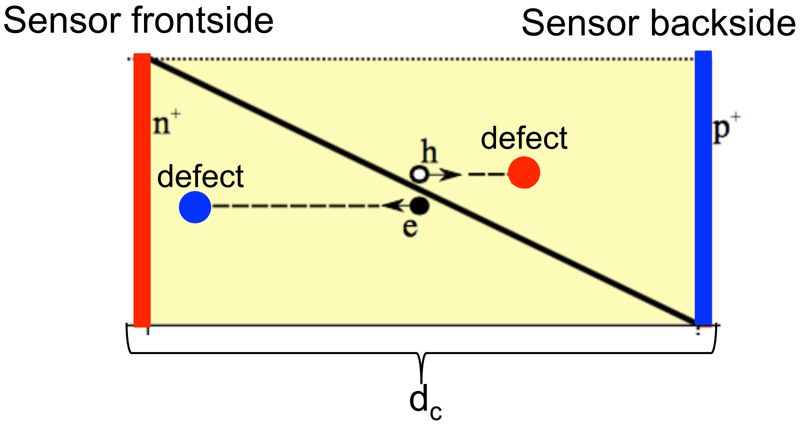
Scale of expected fluences in the different layers

140-200 pile-up events

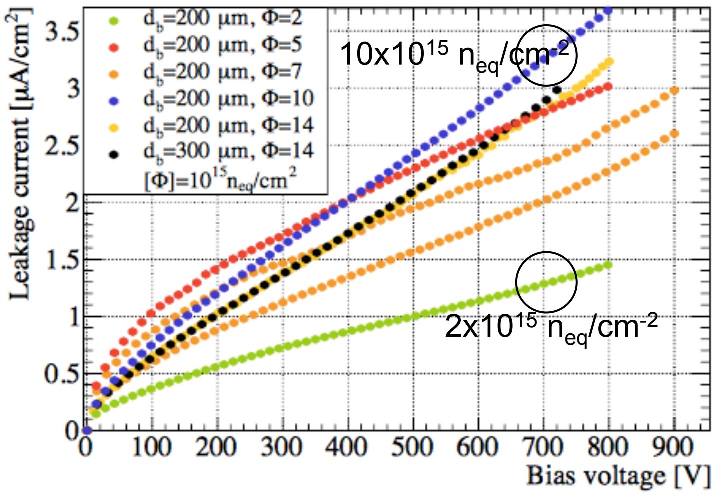


What happens to the pixel detector during irradiation?

- **Charge trapping**
  - defects act as trapping centers
    ➔ reduction of collected charge



- **Increase of the leakage current**
  - increase of the power consumption
    (P ~ I ~ ϕ ➔ P ~ I x U)
    ➔ strong cooling requirements
  - increase of the noise



Motivation

Goal: radiation hardness of the innermost silicon detector

➔ optimization of hit efficiency, leakage current and power dissipation

i. reduction of the sensor thickness
   - ➔ higher electric field and smaller charge collection distance lead to less charge trapping and hence higher efficiency
   - ➔ lower operation voltage and thus leakage current lead to less power dissipation

ii. improvement of the pixel design
   - ➔ increasing efficiencies of pixel cells
   - ➔ higher granularity

Experimental investigations

i. charge collection measurements in the laboratory

ii. efficiency measurements during test beam campaigns

Sensors with different active thicknesses at MPP

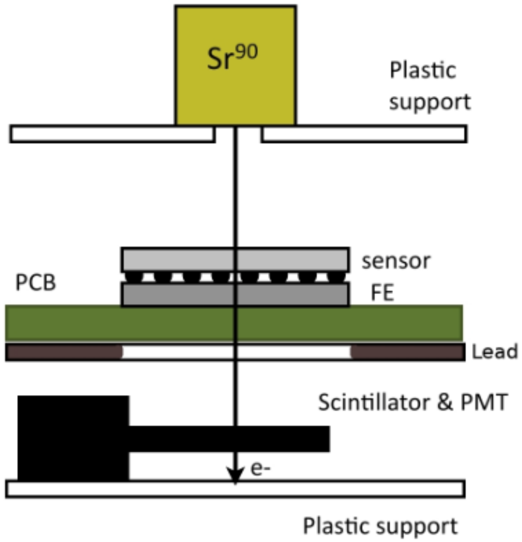
Thinning production process flow of sensors

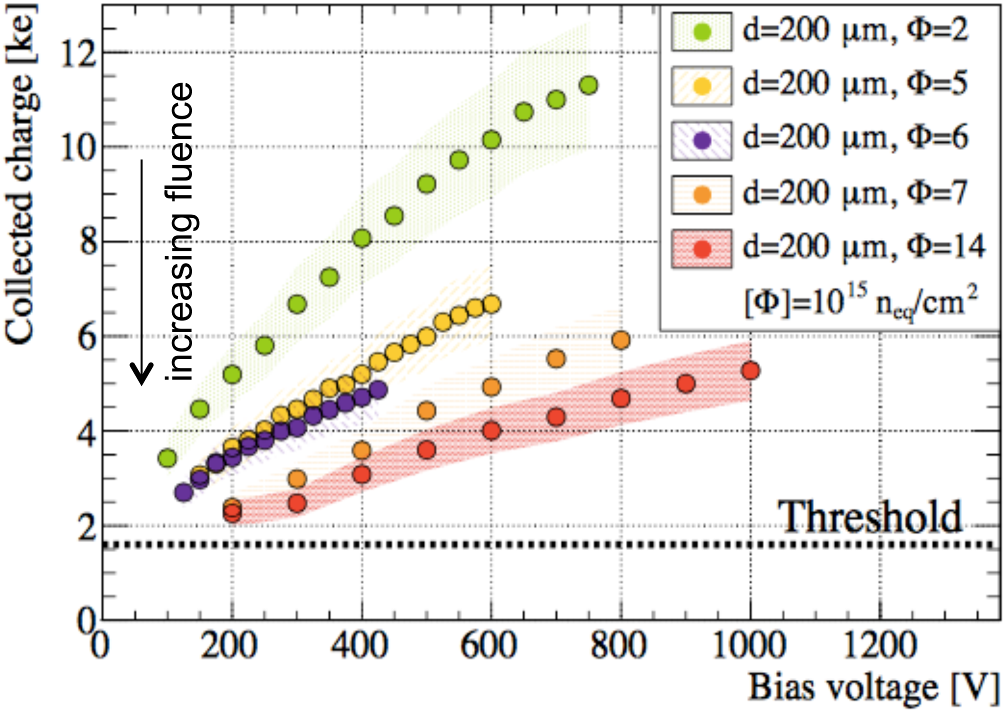
1. Implant backside on sensor
2. Bond sensor wafer to handle wafer
3. Thin sensor side to desired thickness
4. Process on top side
5. Structure resist, etch backside up to oxide/implant

- sensor active thickness: 75 to 200 µm
- afterwards bump bonded to chips

Laboratory measurements

Charge collection (CC)

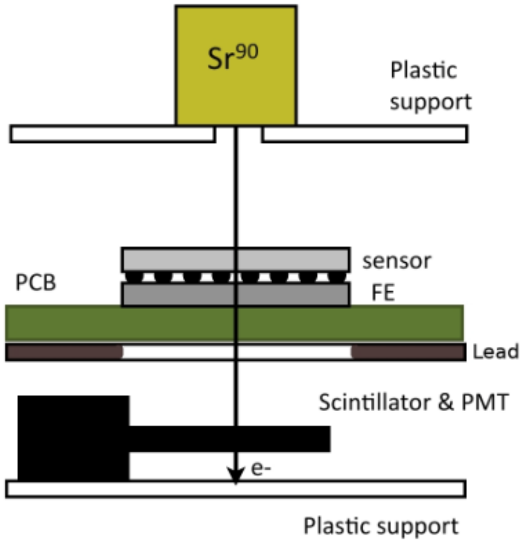


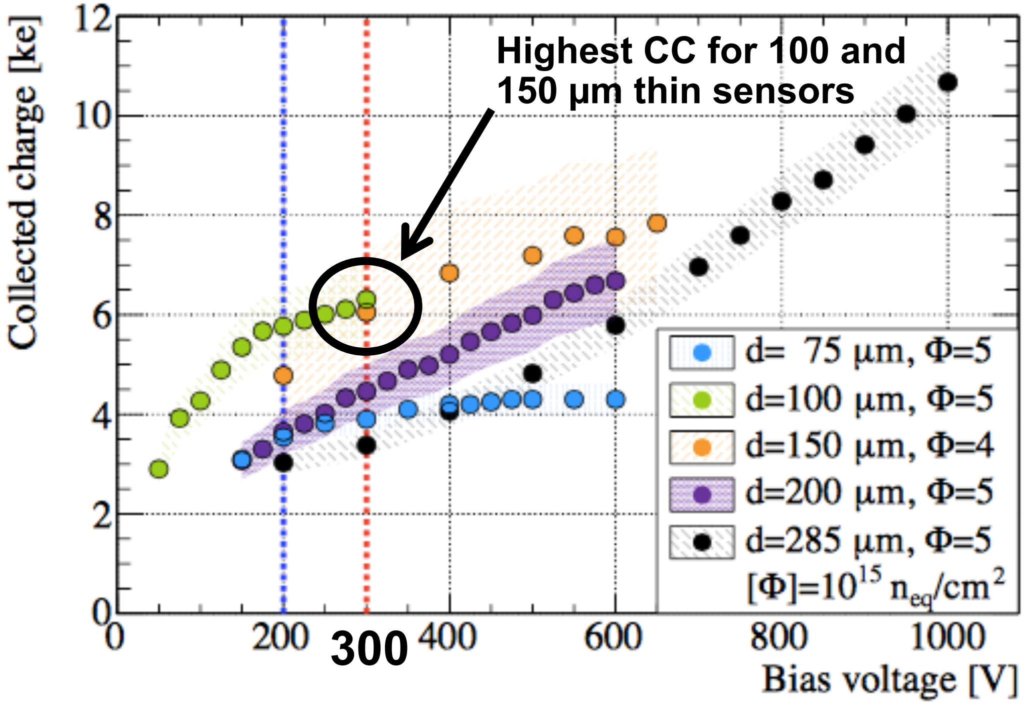


- Samples : modules with 200 µm thick sensors irradiated to different fluences
- Method : ^{90}Sr radioactive β-source with external trigger via scintillator
- Cooling : in climate chamber down to -40 °C sensor temperature

Laboratory measurements

Charge collection (CC)



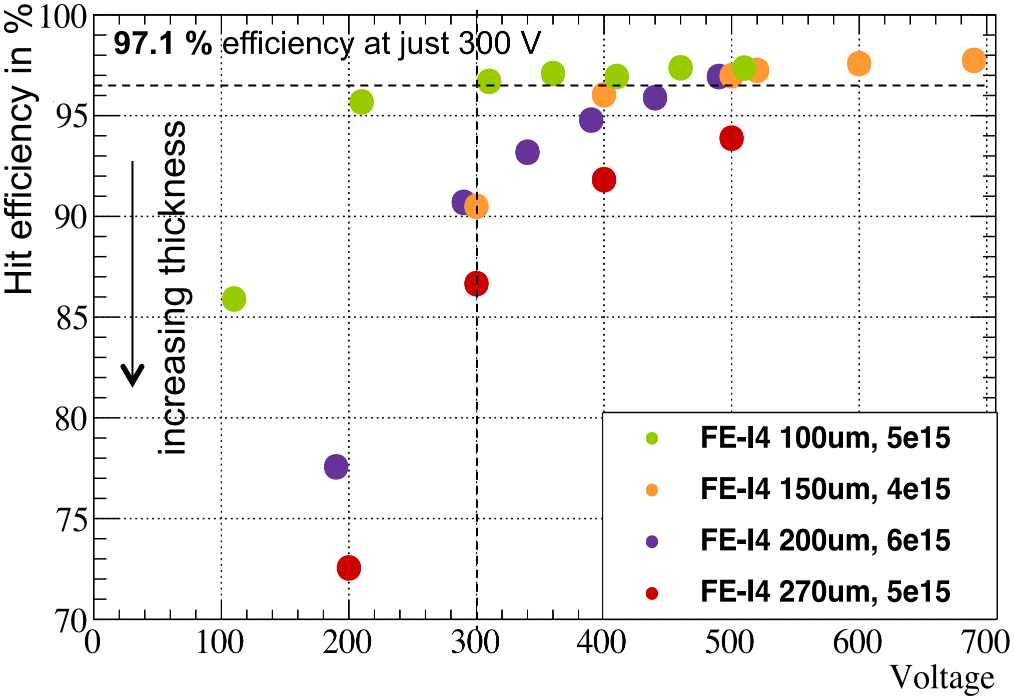


Highest CC for 100 and 150 µm thin sensors

- Samples : irradiated modules with sensor thicknesses from 75 to 285 µm

Efficiencies for different thicknesses

Efficiency measurements with the EUDET telescope at :



1) DESY in Hamburg with 4 GeV electrons

2) SpS at CERN with 120 GeV pions

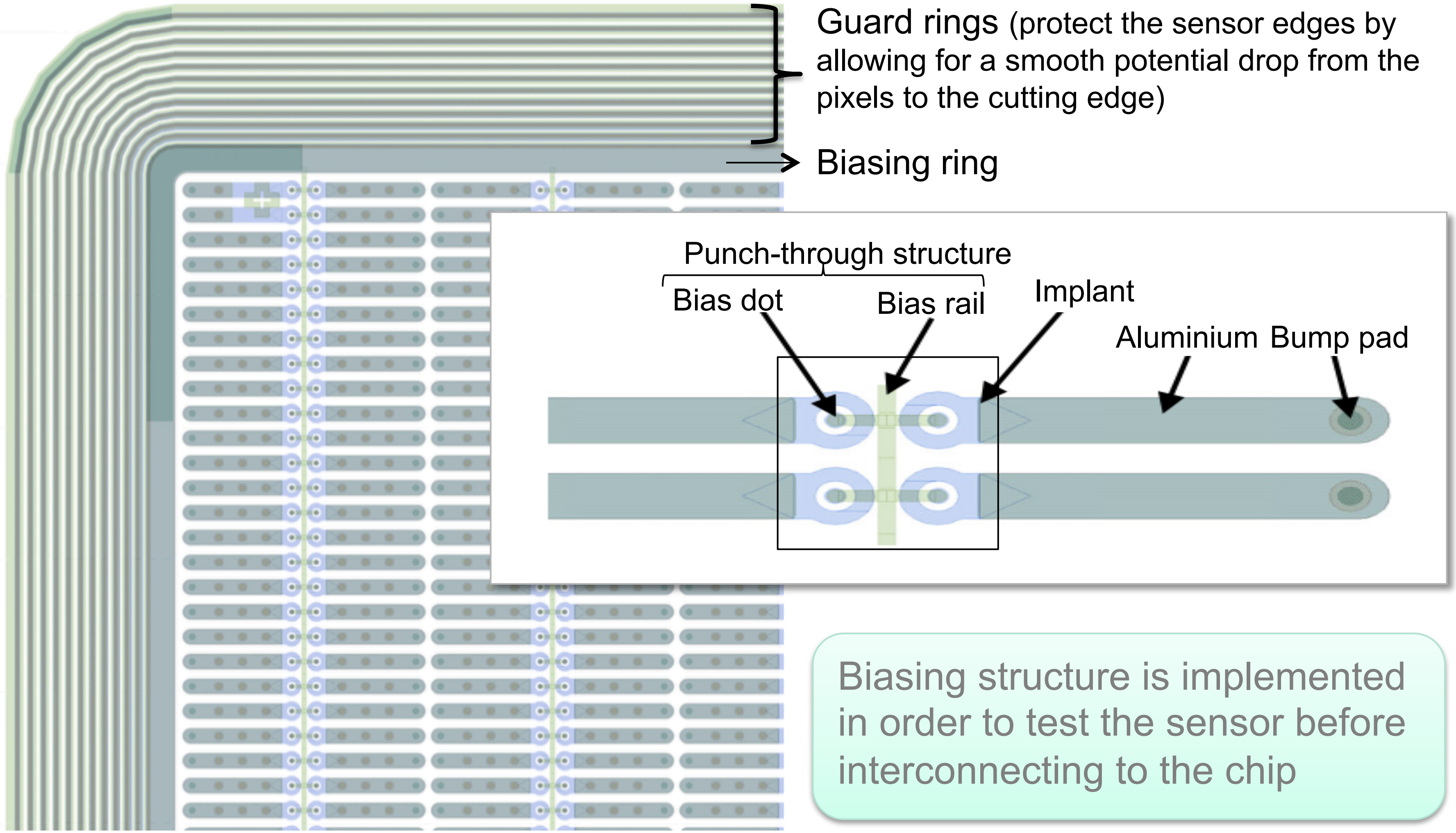
using irradiated modules with sensor thickness from 100 to 270 µm

Thinner sensors show higher charge collection and hit efficiency after irradiation.

Optimization of biasing structures and pixel pitches

Optimization of biasing structures and pixel pitches

Cut-off sensor surface



Guard rings (protect the sensor edges by allowing for a smooth potential drop from the pixels to the cutting edge)

Biasing ring

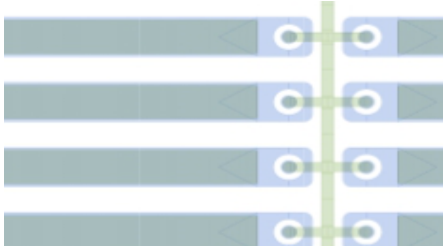
Biasing structure is implemented in order to test the sensor before interconnecting to the chip

Optimization of biasing structures and pixel pitches

MPP designed sensors of 270 µm thickness fabricated and bonded to chips

Standard 50x250 µm² pixel

Standard punch-through



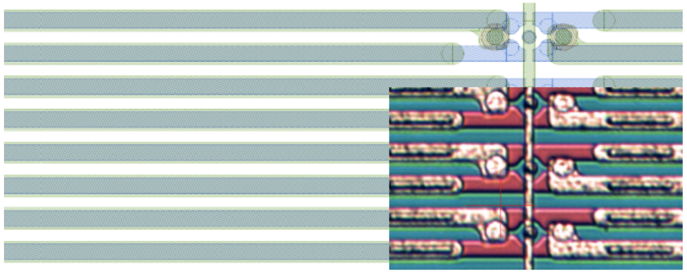
Biasline over center

Biasline over punch-through dot

individual punch-through (p-t)

Modified 25x500 µm² pixel

Common punch-through

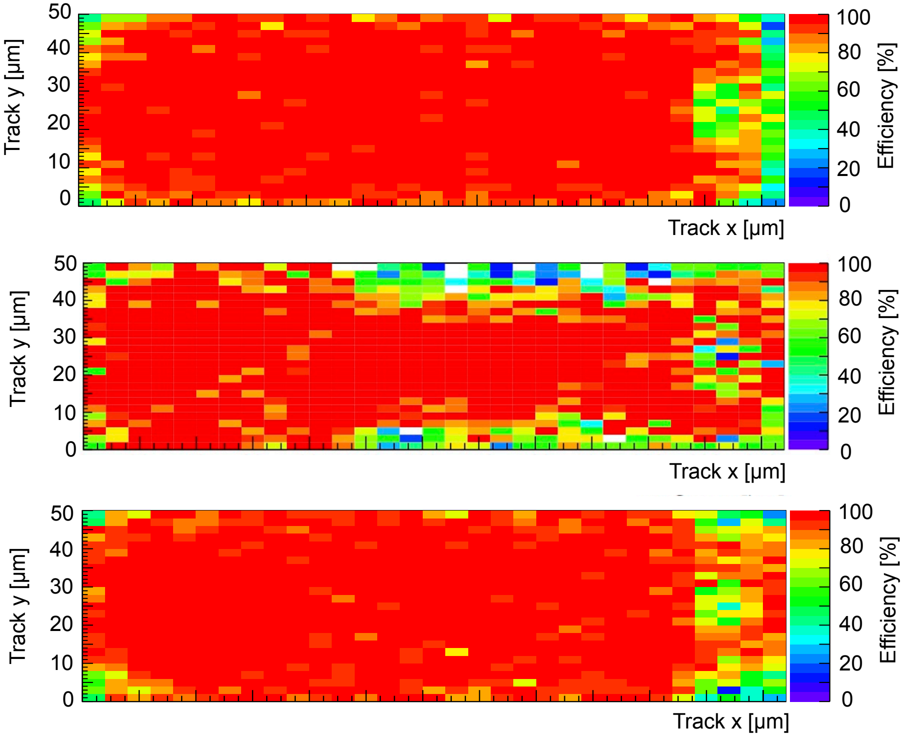


common p-t

Comparison of performance of different p-t designs

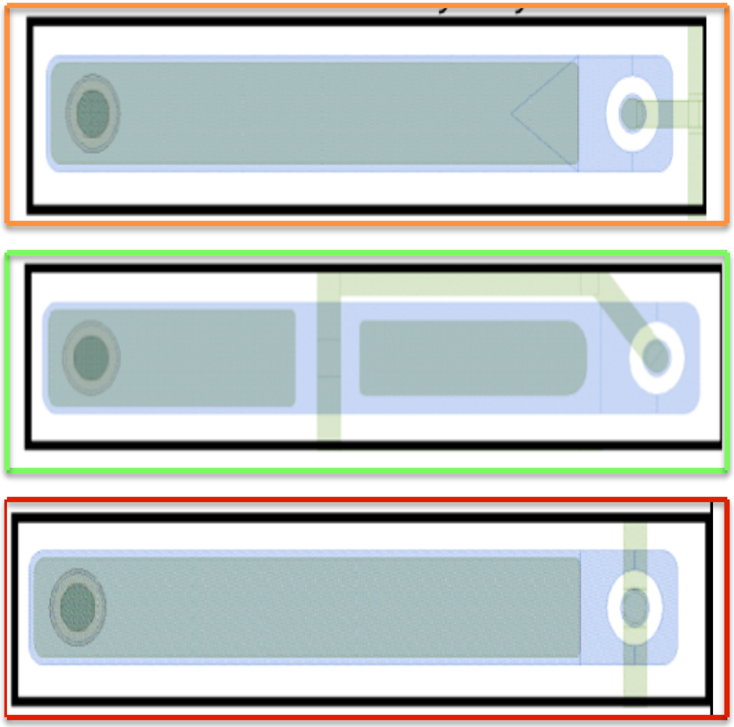
In-pixel hit efficiency

50x250 µm² pitch



Irradiated at 5x10^{15} n$_{eq}$/cm^{2}, U= 500 V

100 % hit efficiency before irradiation



all three p-t designs implemented in one module

Test beam analysis shows better hit efficiency when the p-t and bias rail is over-imposed to the pixel implant.

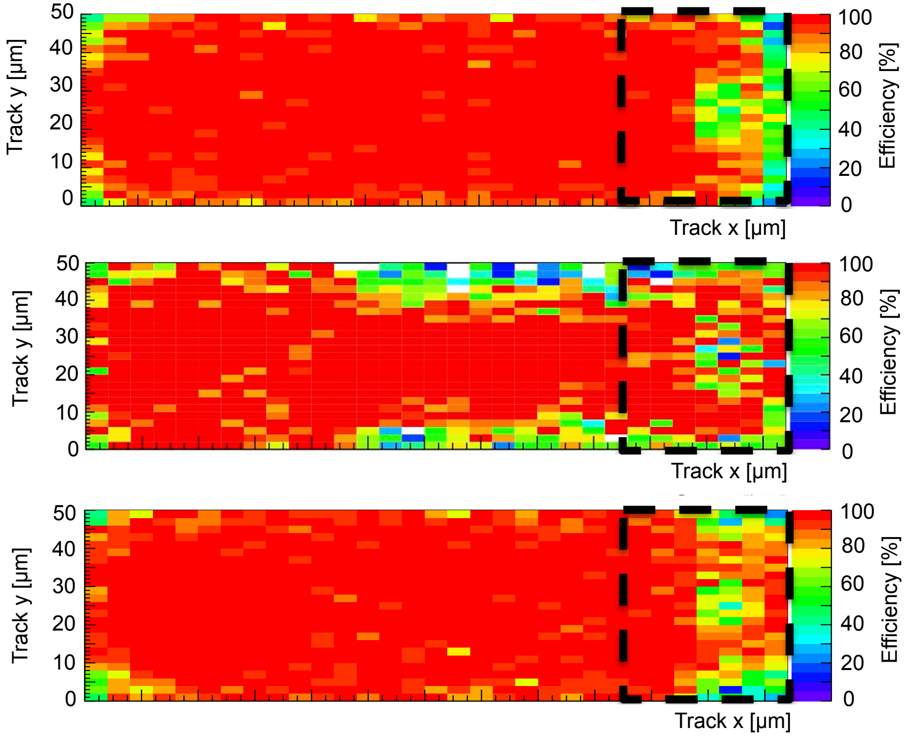
Comparison of performance of different p-t designs

In-pixel hit efficiency

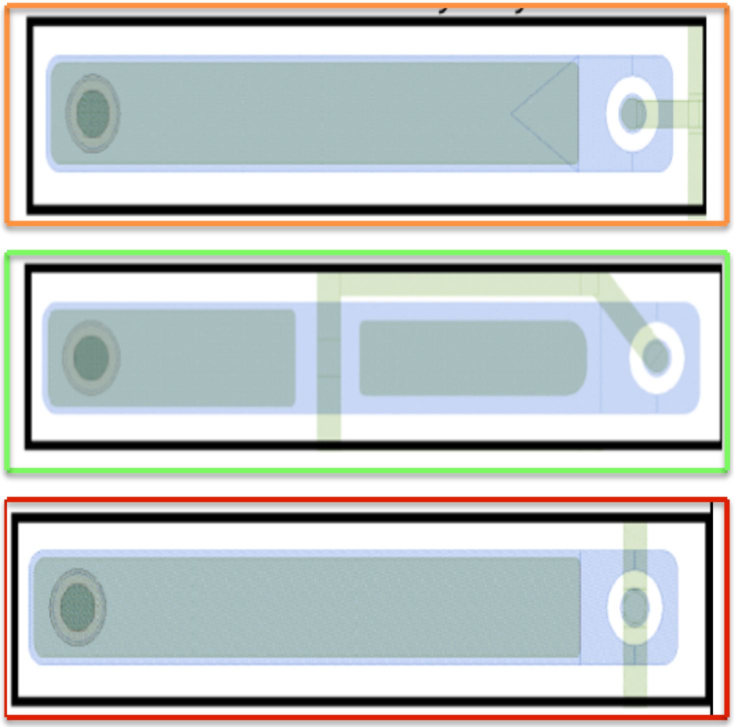
~ 100 % hit efficiency before irradiation

50x250 µm² pitch

cut-out of a 50x50 um² pitch



Irradiated at 5x10^{15} n$_{eq}$/cm^{2}, U= 500 V

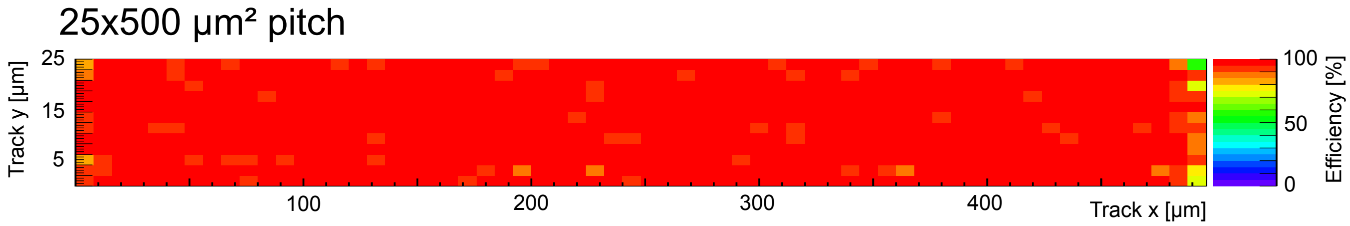


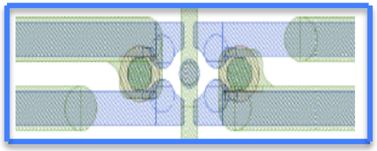
all three p-t designs implemented in one module

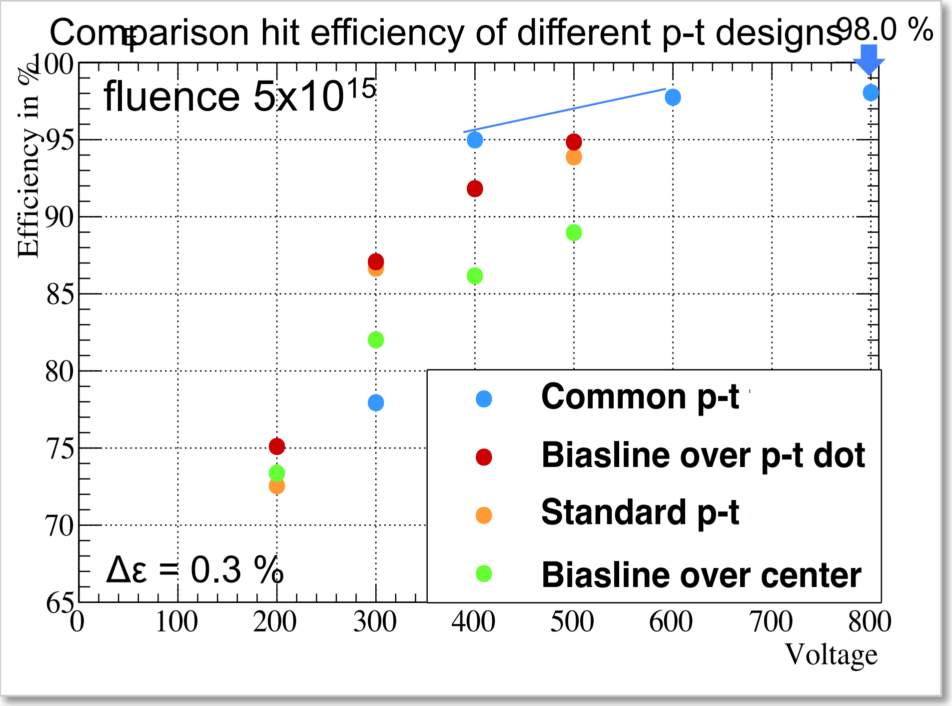
Test beam analysis shows better hit efficiency when the p-t and bias rail are overimposed to the pixel implant.

Novel p-t design for 25x500 μm^2 pixel

In-pixel hit efficiency



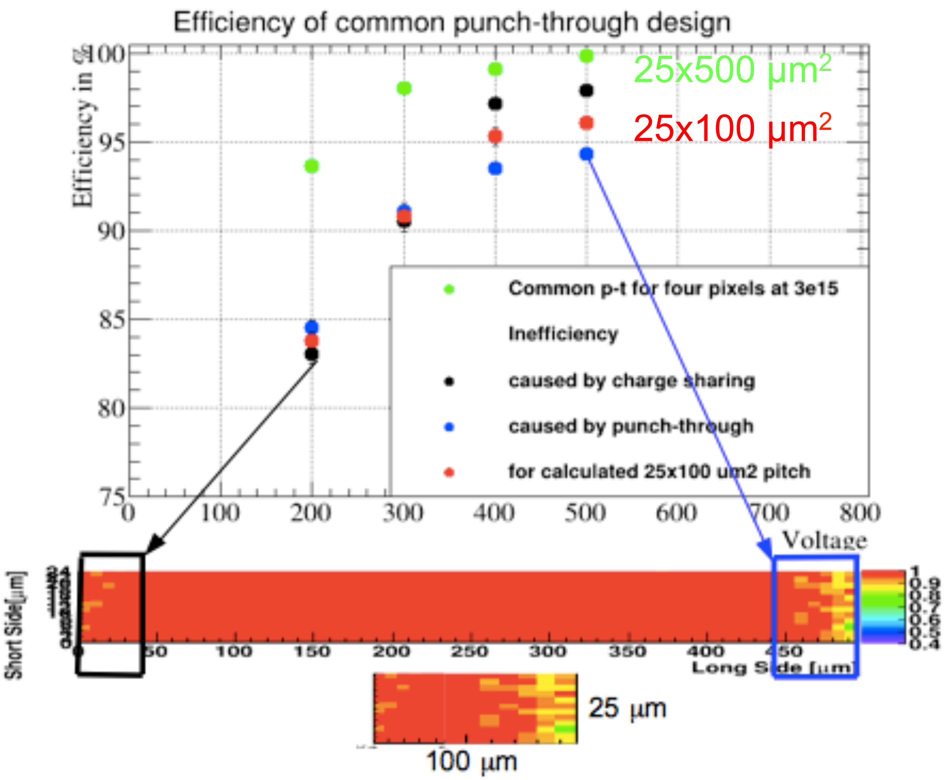




Improved hit efficiency for the biasline over the p-t dot and common p-t after irradiation.

Estimation of hit efficiency for a 25x100 μm^2 pitch at a fluence of 3x10^{15} $n_{eq}cm^{-2}$

Hit efficiency at 3x10^{15} $n_{eq}cm^{-2}$



Inefficiencies appear at the edges of the pixel

left:
first 40 μm show inefficiency caused by charge sharing

right:
last 60 μm show inefficiency caused by punch-through

- effective pitch of 25x100 μm^2 obtained by combining first 40 μm and last 60 μm of pixel cell
- example created to estimate a hit efficiency for the 25x100 μm^2 pitch

Estimated hit efficiency for 25x100 μm^2 pitch at 500 V : 96.4 % (99.8 % for 25x500 μm^2 pitch and 96.5 % for standard 50x250 μm^2 pitch and standard p-t at 3x10^{15} $n_{eq}cm^{-2}$)

New design for sensors with small pixel pitch

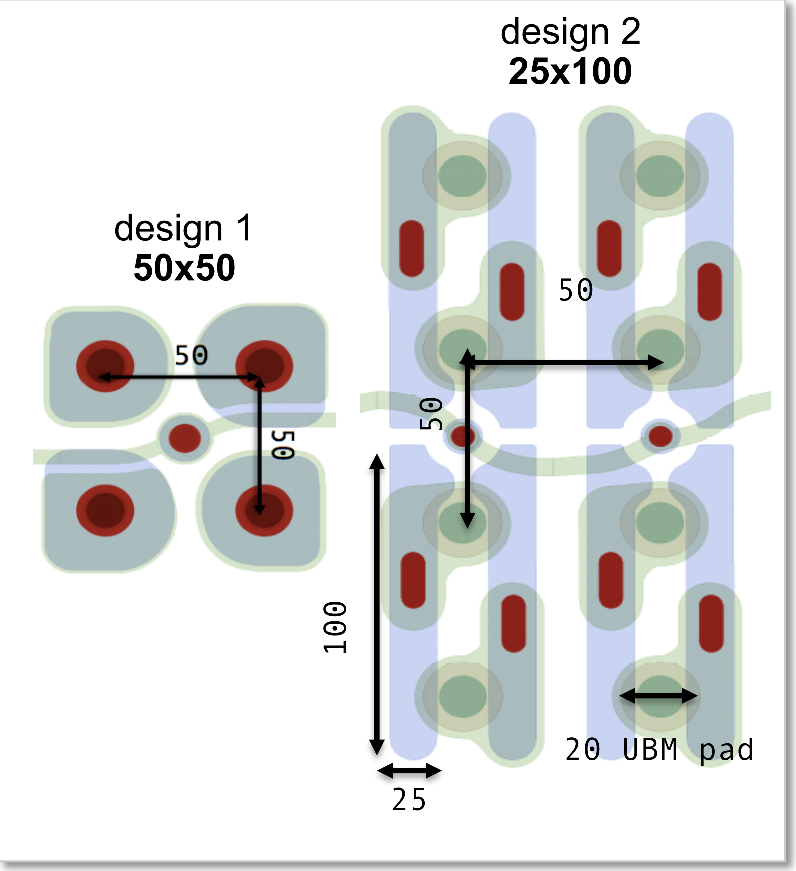
50x50 µm² and 25x100 µm² pixel pitches

- foreseen for a new radiation hard chip with a regular 50x50 µm² grid
- p-t design combination of biasline over p-t dot and common p-t (best performig ones!)

25x100 µm² pixel pitch

- design based on the existing prototype with 25x500 µm² pitch (results shown before)

SOI wafers of new production at MPG-HLL with 100 and 150 µm active thickness successfully tested



Summary and Outlook

- **Thin sensors**
  - 100 and 150 µm thick sensors show higher charge collection and hit efficiency
  - 100 µm thick sensor reaches hit efficiency of up to **97.1 %** after irradiation at 5 $\cdot 10^{15}$ n_{eq}/cm^2 at just 300 V

- **Investigations of new pixel cell design**
  - Improved hit efficiency for the biasline over the p-t and the common p-t with respect to the standard design after irradiation at 5 $\cdot 10^{15}$ n_{eq}/cm^2

- **New MPG-HLL production**
  - Combines and implements new pixel cell design and best performing biasing structures on thinner sensors

➔ Promising innovations of sensor design will be connected to the new ATLAS chips with a 50x50 grid and tested by the end of 2017

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Thank you for your attention!