# Development and performance of planar pixel sensors for the ATLAS Inner Tracker upgrade

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Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

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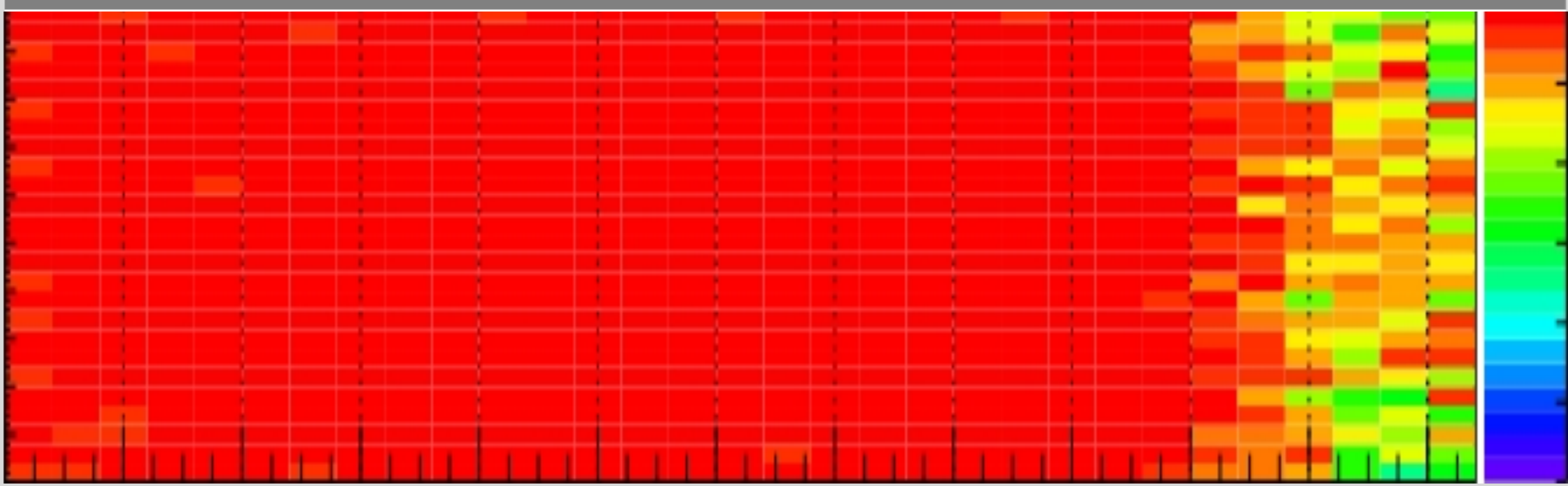

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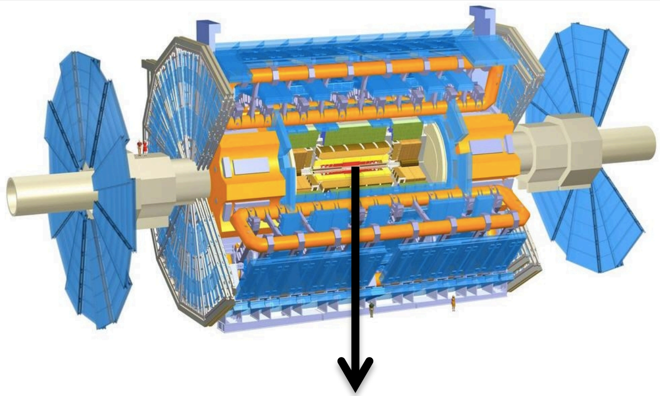
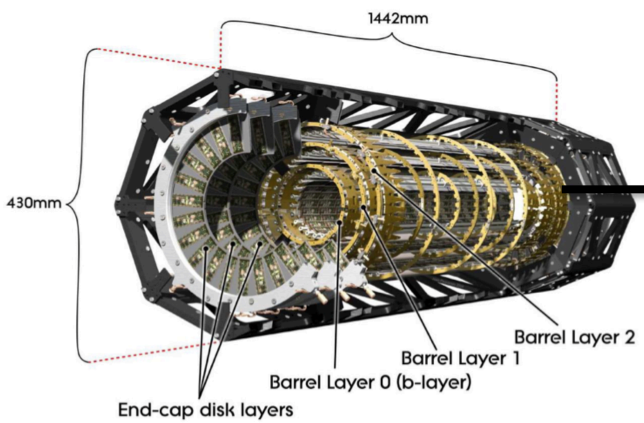
# The ATLAS Pixel Detector

## The ATLAS Detector

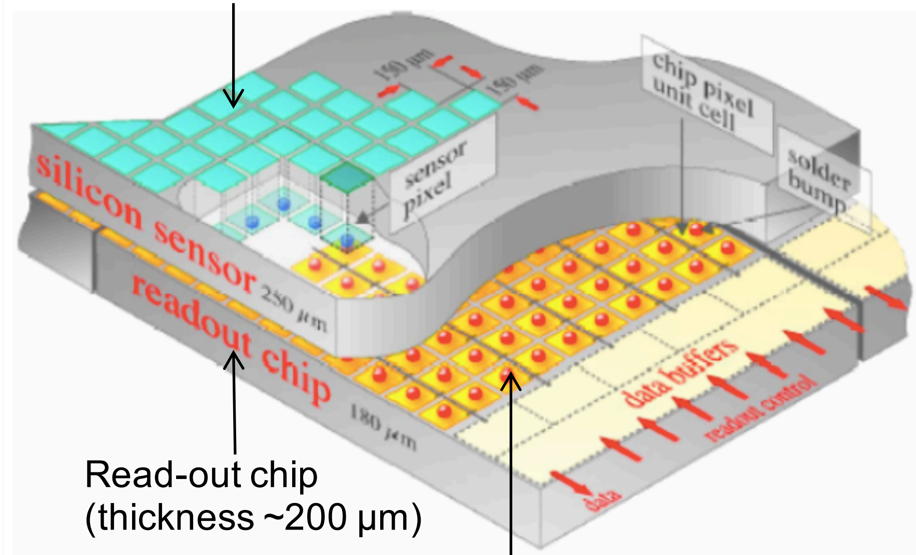


## The Pixel Detector




## The Pixel Module

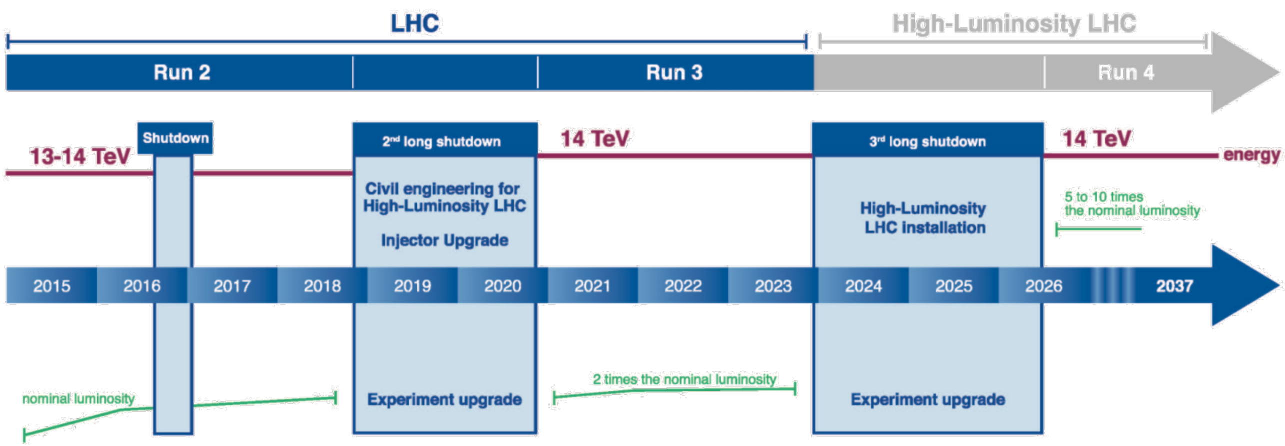
Silicon sensor (thickness ~300 µm)




Read-out chip
(thickness ~200 µm)

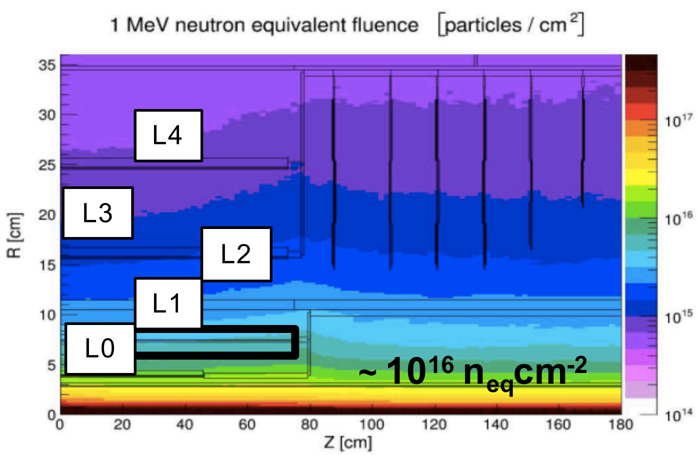
Sensor and read-out chip connected via bump bonds

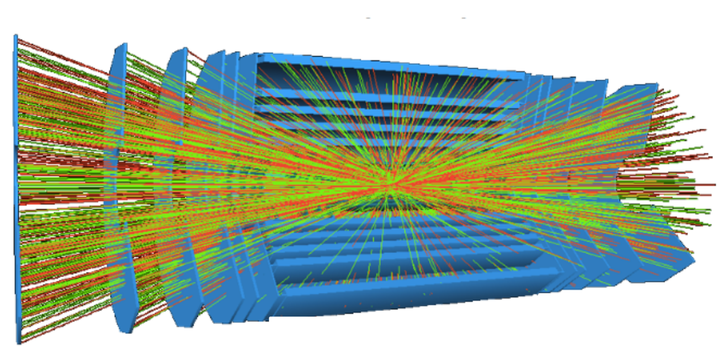
# HL-LHC and ATLAS upgrade for high luminosity




In view of the high luminosity phase of the LHC starting around 2025 the ATLAS experiment will undergo a major upgrade of its tracker system

Expected fluences in the pixel layers



~200 interactions per bunch crossing

# Motivation

**Maintain the performance of the inner tracker in a more challenging environment**

**Higher fluences**

- Thin planar n-in-p sensors baseline from second to fifth layer

**Higher track density**

- Increase granularity to ensure low occupancy: pixel cells of 50x50 $\mu m^2$ for the new ATLAS read-out chip with a 50x50 $\mu m^2$ grid

# Overview of experimental investigations

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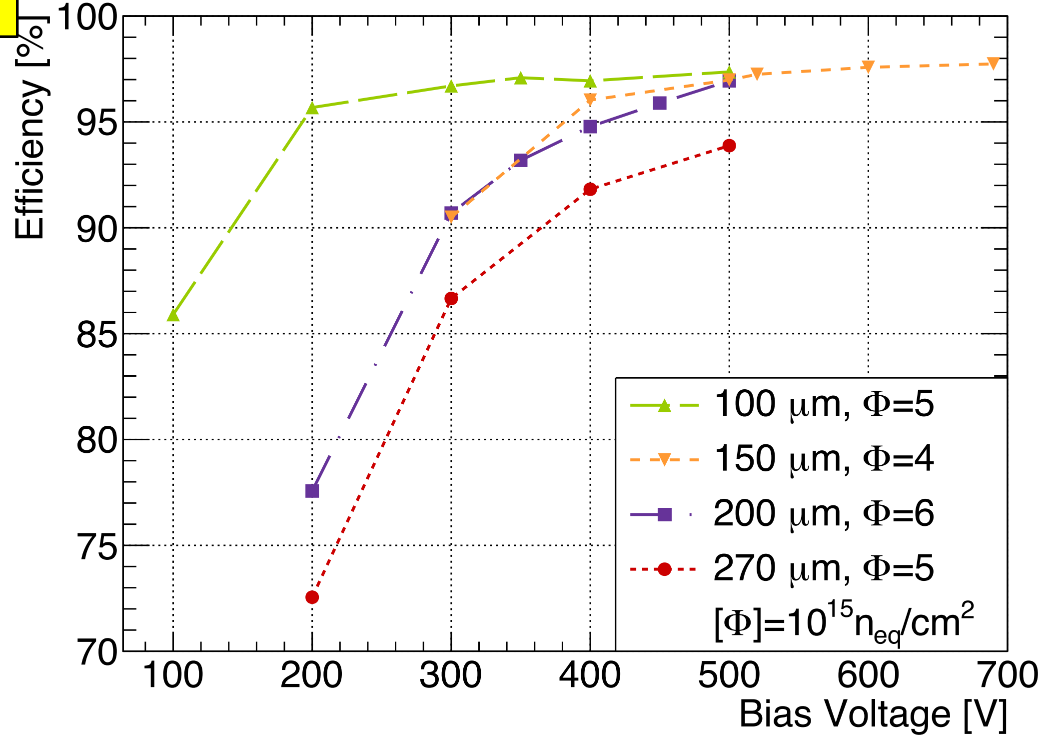
| Beam test studies at CERN |
| --- |
| • Hit efficiency measurements after high irradiations of<br>  • thin n-in-p planar sensors<br>  • 50x50 μm² pixel cells |
| **Transient Current Technique studies at JSI in Ljubljana** |
| • Charge collection measurements after high irradiations of<br>  • thin n-in-p planar sensors |

# Why thin sensors?

**$5x10^{15}$ $n_{eq}/cm^2$**



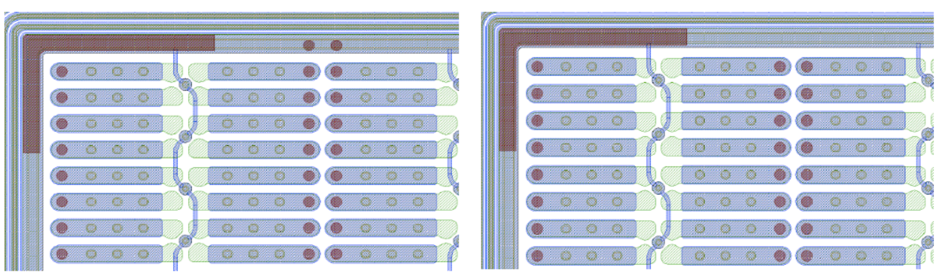

- Advantages thin sensors (of 100 μm and 150 μm sensor thickness):
- Higher hit efficiency after an irradiation to a fluence of $5x10^{15}$ $n_{eq}/cm^2$
- Saturation of efficiency at lower bias voltages
    - results in lower leakage currents and lower power dissipation
        - looser requirements on the cooling system

# Thin sensors from HLL

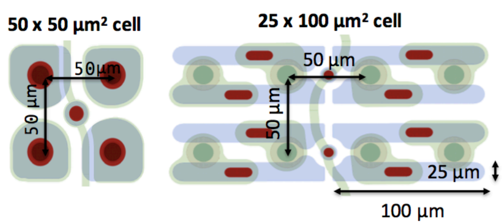
- Production on 6" wafers for 100 and 150 µm thick sensors at MPG-HLL
- Development on biasing structure (structure to test the sensor before interconnection to readout chips)

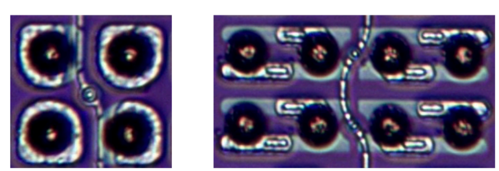

1. Implant backside on sensor
2. Bond sensor wafer to handle wafer
3. Thin sensor side to desired thickness
4. Process on top side
5. Structure resist, etch backside up to oxide/implant

Reduction of sensor thickness



Development biasing structure

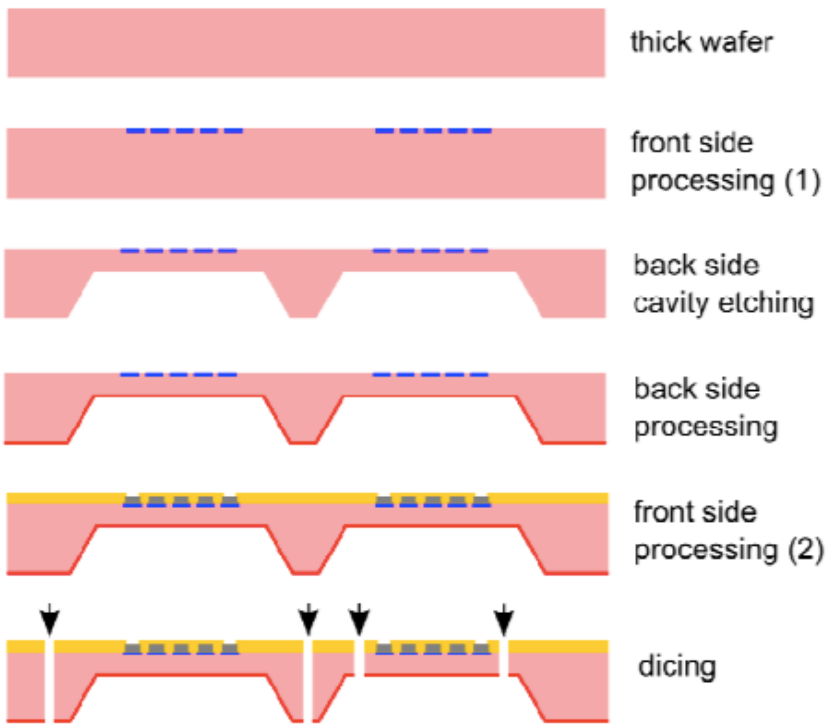


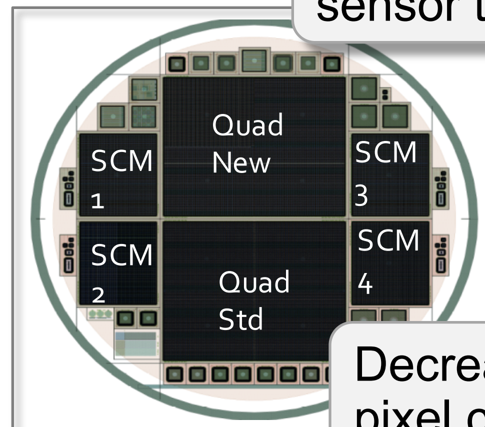
Decrease of pixel cell size

# Thin sensors with backside cavities

- Production on 4" wafers for 100 and 150 µm thick sensors at CiS-technology
- Thinning technology without using support/handling wafer by anisotropic wet etching (KOH)




Reduction of sensor thickness




Decrease of pixel cell size

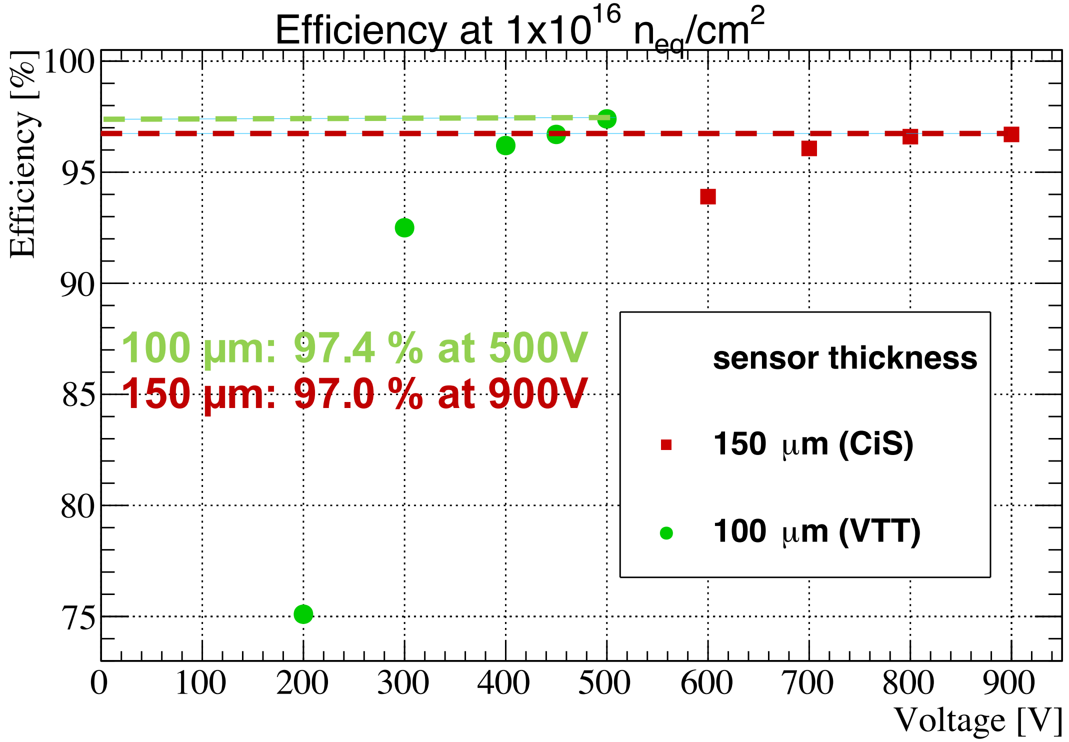
- **CiS** standard ATLAS-IBL pitch
  i. Pixel size : 50x250 µm²
  ii. Pixel matrix : 80x336
- **CiS** with 50x50 µm² cells
  i. Pixel size : 50x250 µm²
  ii. Pixel matrix : 80x336

# Beam test measurements

# Hit efficiency of 100 and 150 μm thick sensors

**$1x10^{16}$ $n_{eq}/cm^2$**

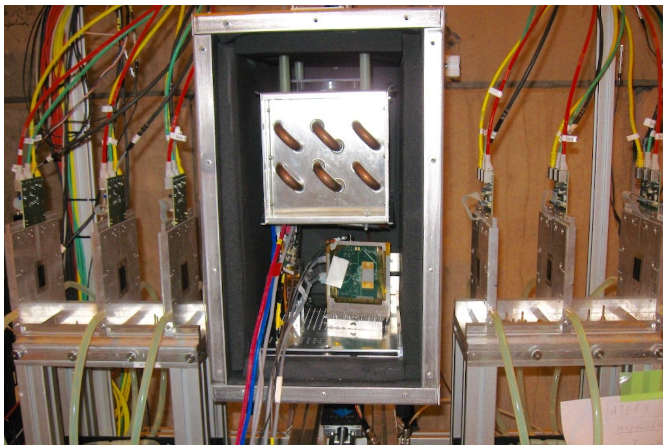
$$\text{hit efficiency} = \frac{\#\ \text{detected hits}}{\#\ \text{expected tracks}}$$

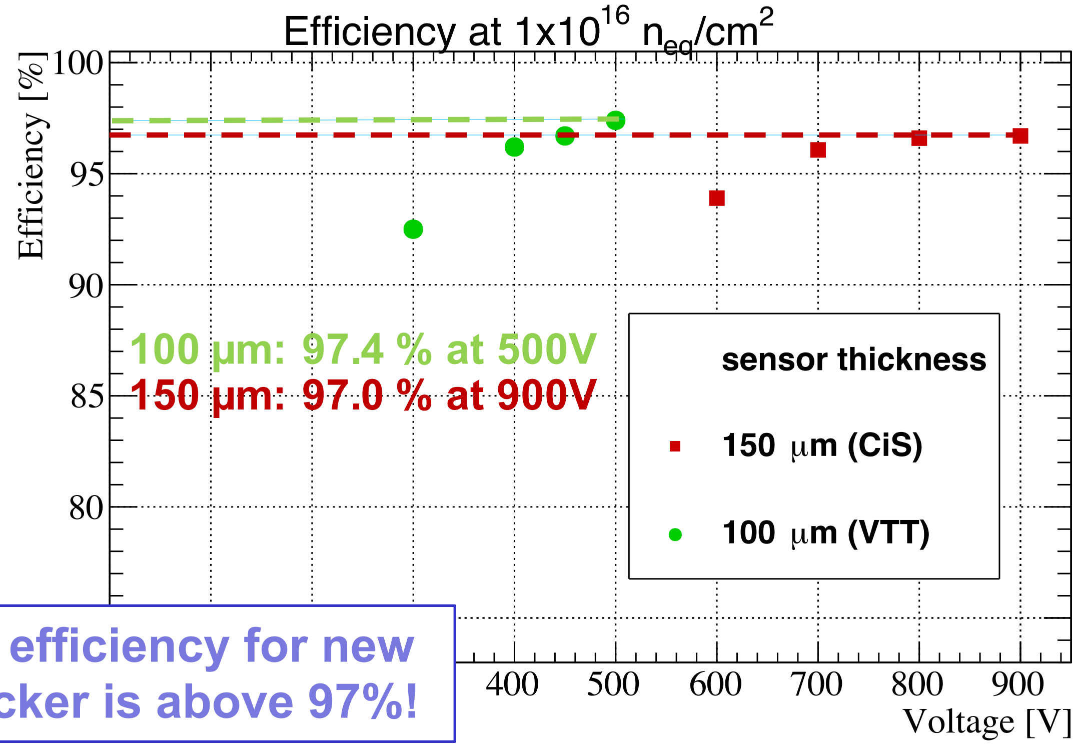



- Modules with 100 μm and 150 μm thick sensors show hit efficiencies above 97 % after an irradiation to a fluence of $1x10^{16}$ $n_{eq}/cm^2$
  - Hit efficiency of module with 100 μm thick sensor saturates at lower voltage of 500 V

# Hit efficiency of 100 and 150 µm thick sensors

**$1\times10^{16}\ n_{eq}/cm^2$**



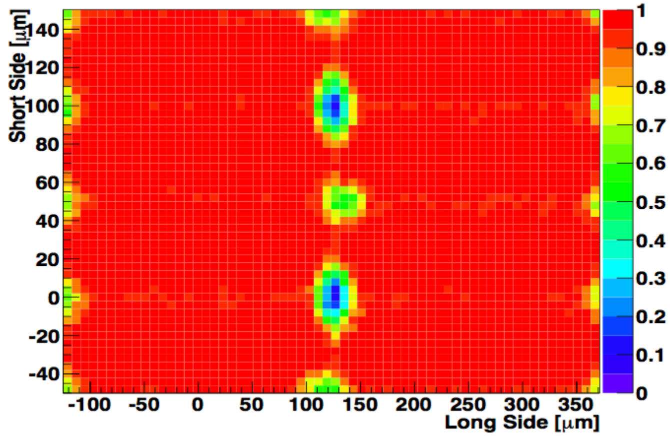



**Required efficiency for new Inner Tracker is above 97%!**

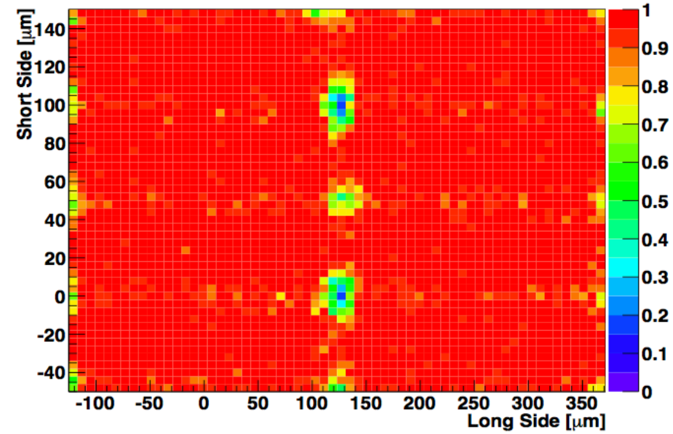
- Modules with 100 µm and 150 µm thick sensors show hit efficiencies above 97 % after an irradiation to a fluence of $1\times10^{16}\ n_{eq}/cm^2$
  - Hit efficiency of module with 100 µm thick sensor saturates at lower voltage of 500 V

# Impovement of biasing structures

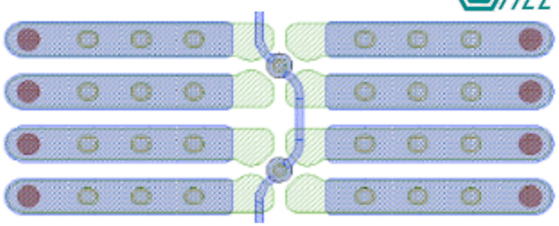
**$5\times10^{15}\ n_{eq}/cm^2$**



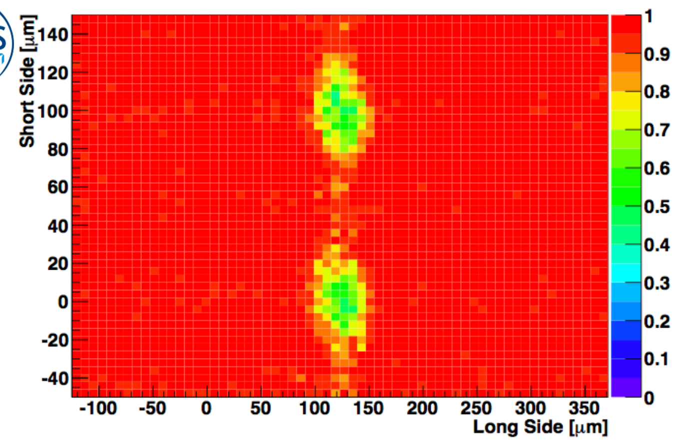

(a) SOI3 sensor with grounded bias rail



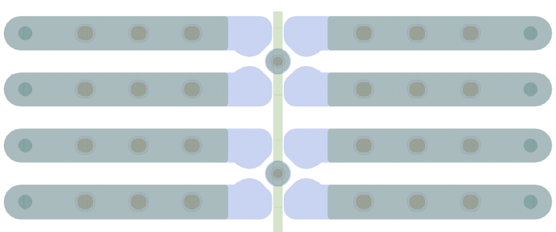

(b) SOI3 sensor with floating bias rail



- Wavy and floating bias rail gives smallest inefficient area
- ➢ efficiency loss still remains

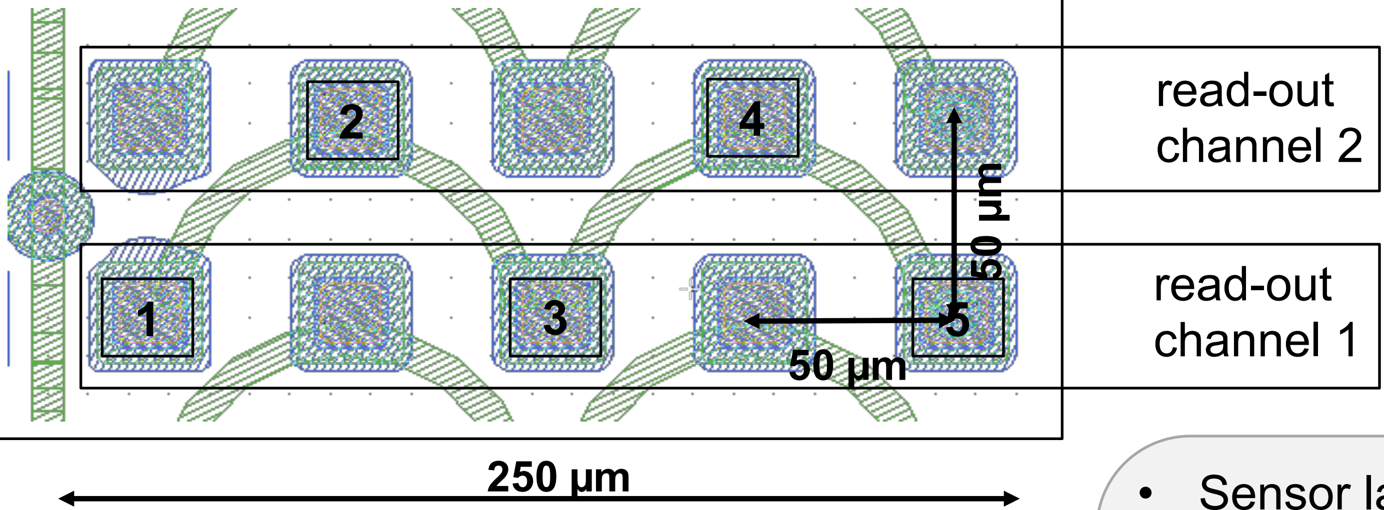



(c) CiS4 sensor with grounded and straight bias rail

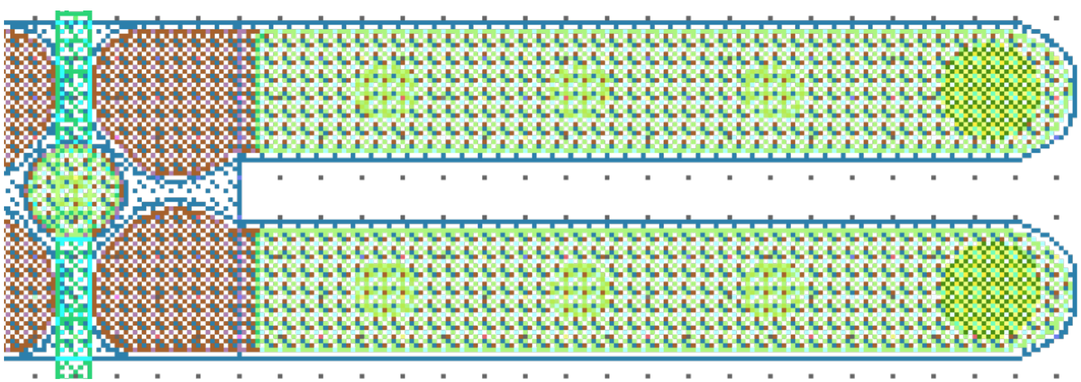


# Smaller 50x50 $\mu m^2$ pixel cells

Modified 50x250 $\mu m^2$ pixel cells with 50x50 $\mu m^2$ pixels




Standard 50x250 $\mu m^2$ pixel cells



- Sensor layout with 30x30 $\mu m^2$ pixel implants
- 5 pixel cells of 50 µm pitch are connected with a metal rail
  - to allow for a readout with current ATLAS readout chip

# In-pixel efficiency at $3x10^{15}$ $n_{eq}/cm^2$

## Test beam results of 150 µm thick sensor

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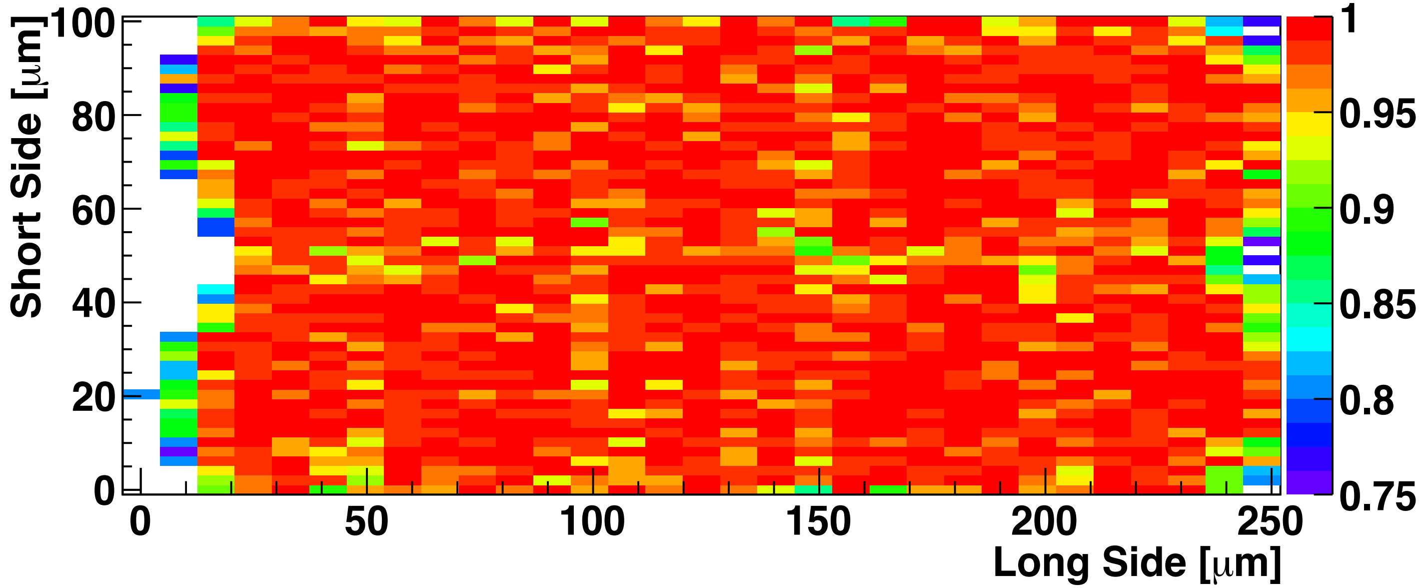
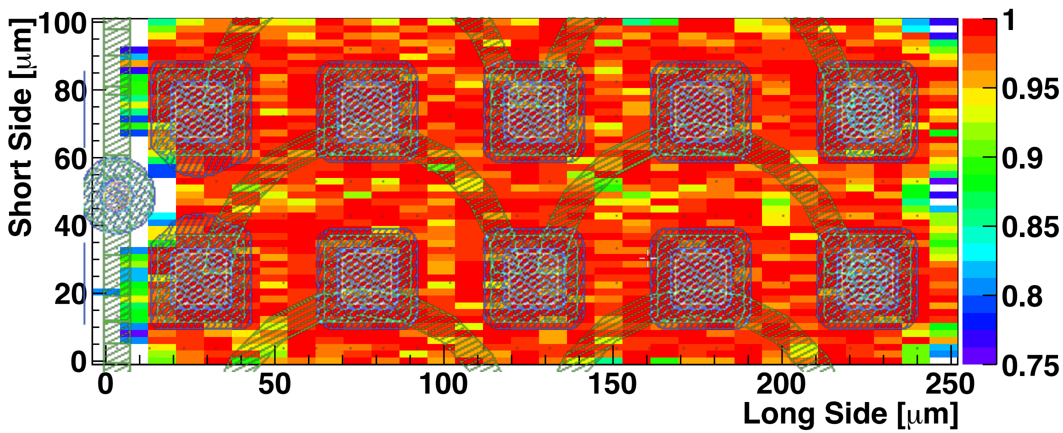
**$3x10^{15}$ $n_{eq}/cm^2$**

300V



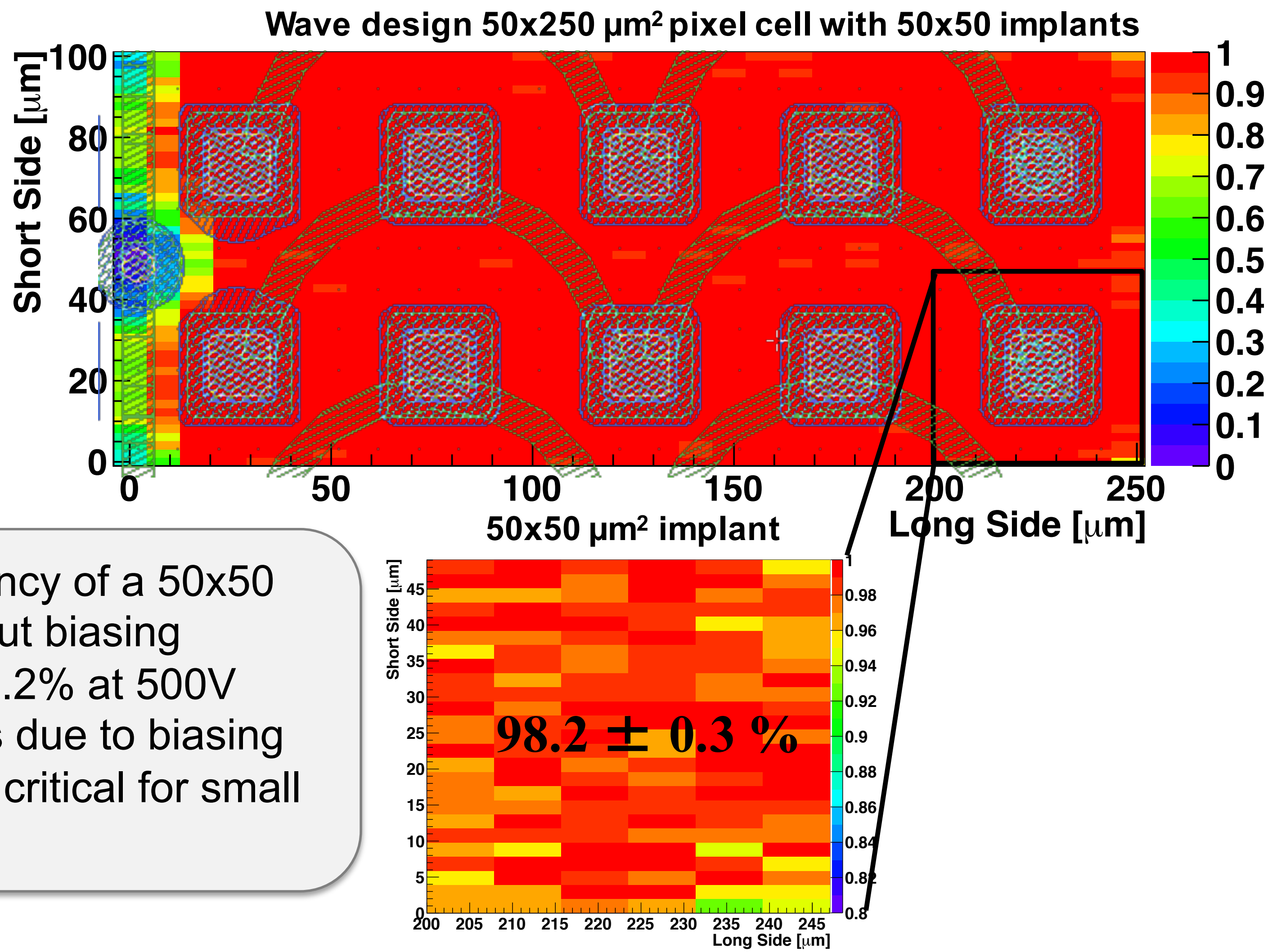

Increased effect of charge sharing for smaller pixel cells

# In-pixel efficiency at $3x10^{15}$ $n_{eq}/cm^2$

## Test beam results of 150 µm thick sensor

**$3x10^{15}$ $n_{eq}/cm^2$**

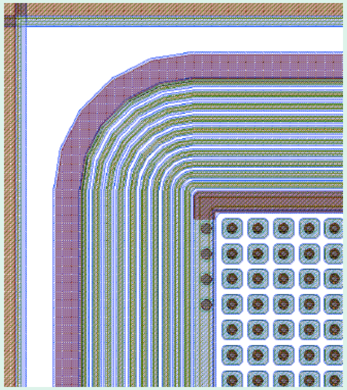
500V



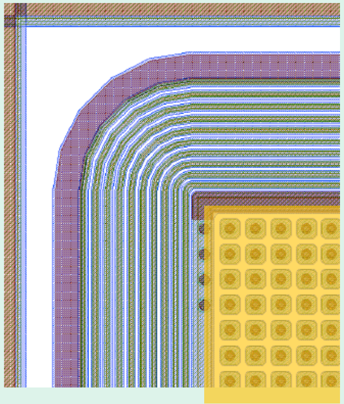

- In-pixel efficiency of a 50x50 µm² cell without biasing structure is 98.2% at 500V
- Efficiency loss due to biasing structure very critical for small pixel cells

# Impovement of biasing structures

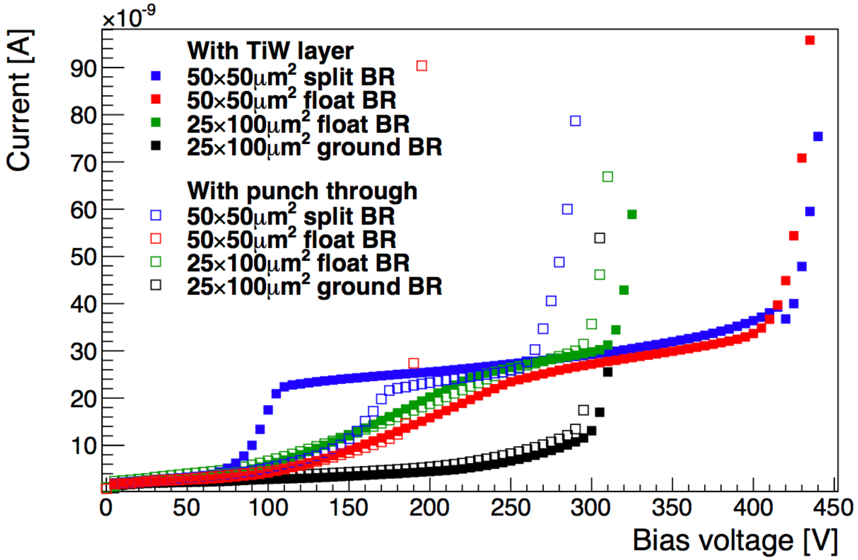
- Possible solution:
  - do not implement biasing structures and use temporary metal for quality assurance at wafer level
    - HLL is currently using TiW (Titanium Tungsten) patterning to short all the pixels



No PT



TiW patterning



# Transient Current Technique Measurements

# Edge-TCT: schematics of the measurement set-up

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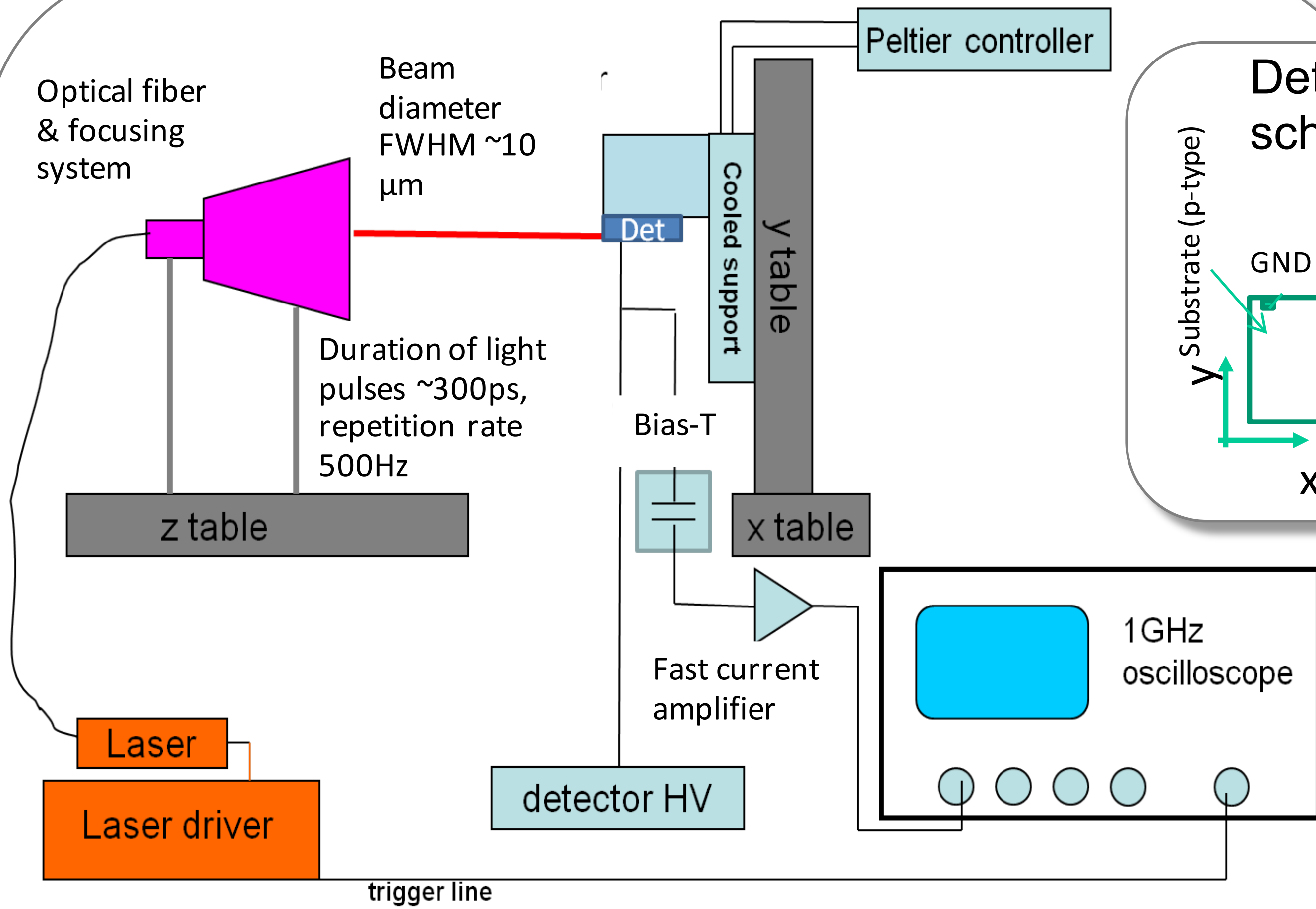
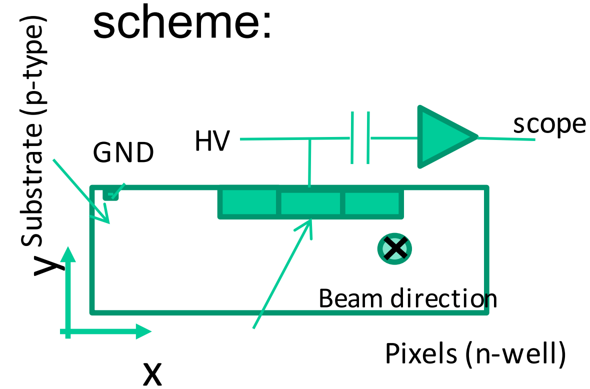
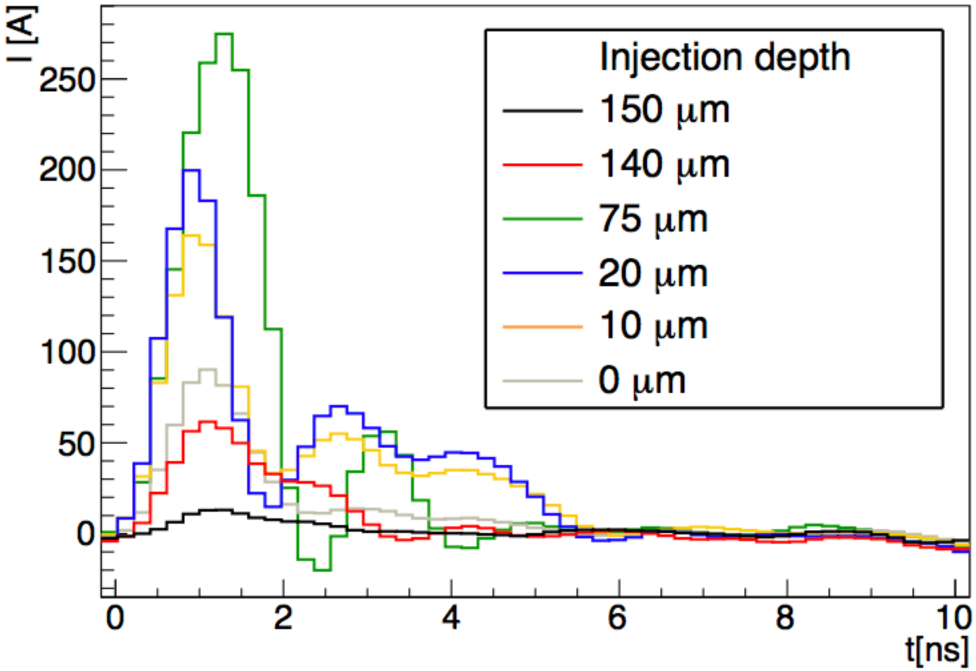



(more details: www.particulars.si )

JSI in Ljubljana gave me the opportunity to use their TCT-system in Ljubljana.

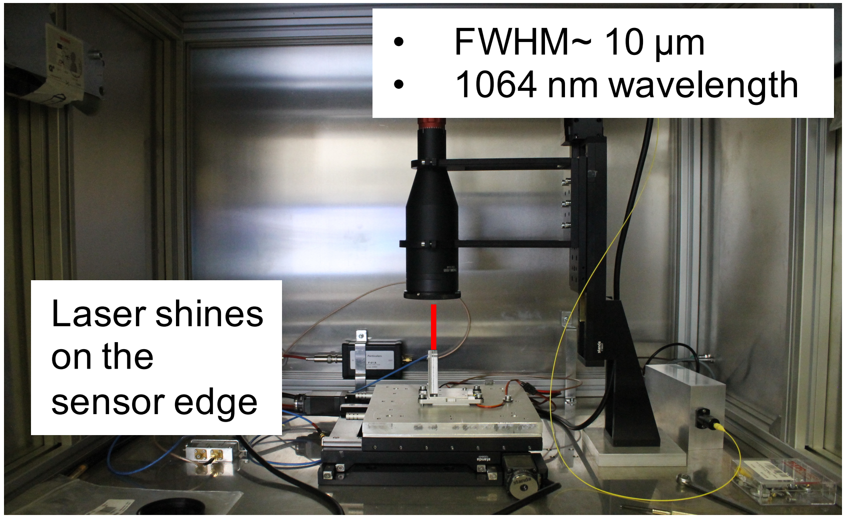
# Induced current signal

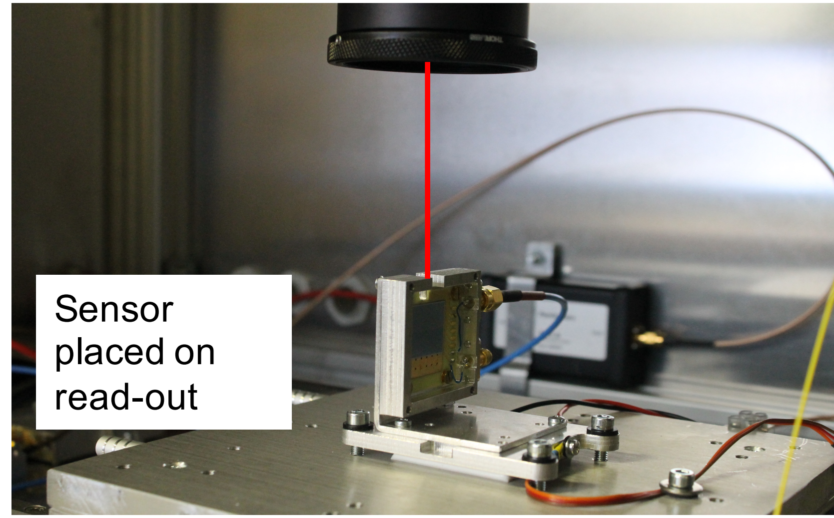


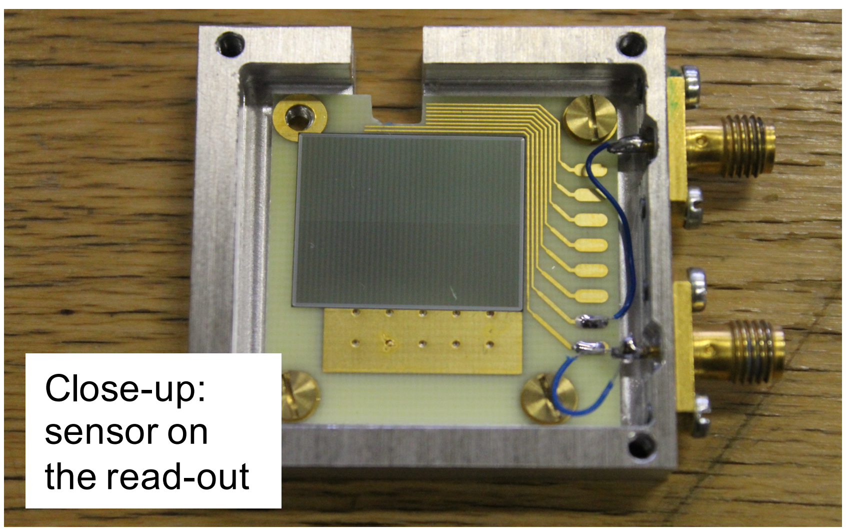

$$Q(y) = \int_{t=0}^{t_{\text{int}}} I(y,t)\,dt$$

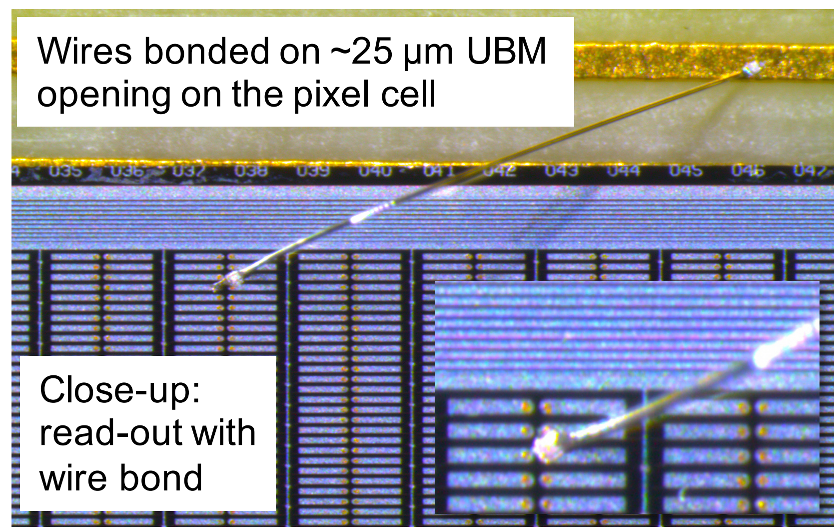
- Integration of the induced current in different sensor depth position leads to the collected charge in those positions

# Edge-TCT: images of the measurement set-up



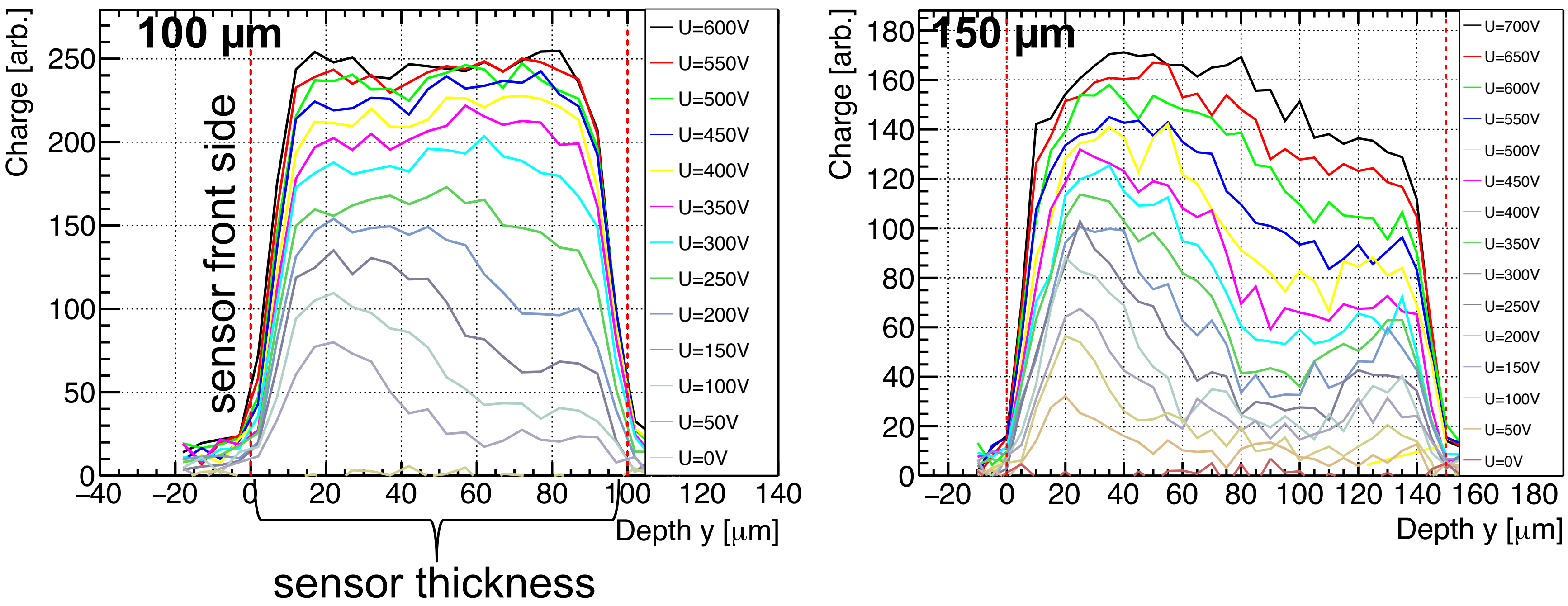



# Charge vs depth of 100 and 150 thick sensors

$1x10^{16}\ n_{eq}/cm^2$




- Comparison of charge collection of 100 and 150 µm thick sensors
  - 100 µm thick sensor fully saturated at 300V
  - 150 µm thick sensor is not fully saturated at 700V
- Results support the hit efficiency measurements obtained from the beam test measurements

# Conclusion and Outlook

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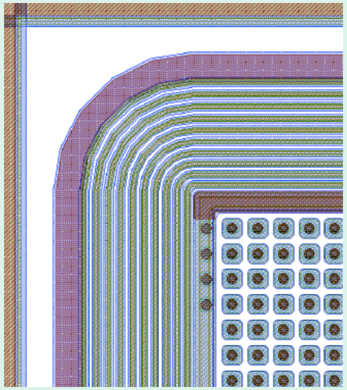
- **Thin sensors:**
  - 100 and 150 µm thick sensors show earlier charge collection and high hit efficiency saturation with respect to thicker sensors after irradiation
    - Baseline for ITk: Pixel layer 1: 100 µm thick sensors, pixel layer 2-4: 150 µm thick sensors
- **50x50 $\mu m^2$ pixel cells**
  - With modified pixel design it was possible to make first prediction of the charge sharing and efficiency of small pixel cells
- **Biasing structures**
  - The biasing structures created a localized efficiency loss after irradiation
    - a method is being developed at HLL to use TiW as a temporary metal allowing for quality assurance without biasing structures

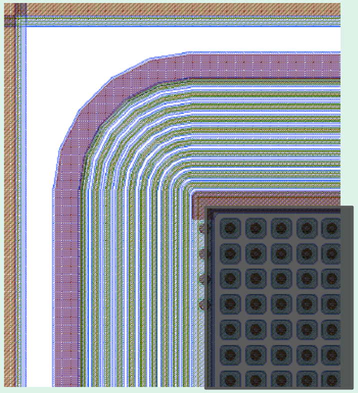
# Back-up

# Impovement of biasing structures

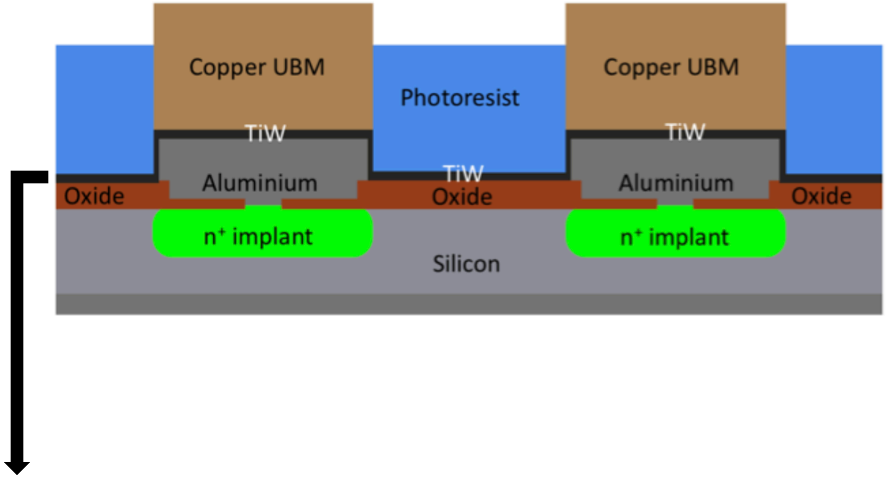
- Possible solution:
  - do not implement biasing structures and use temporary metal for quality assurance at wafer level
    - HLL is currently using TiW (Titanium Tungsten) patterning to short all the pixels



No PT



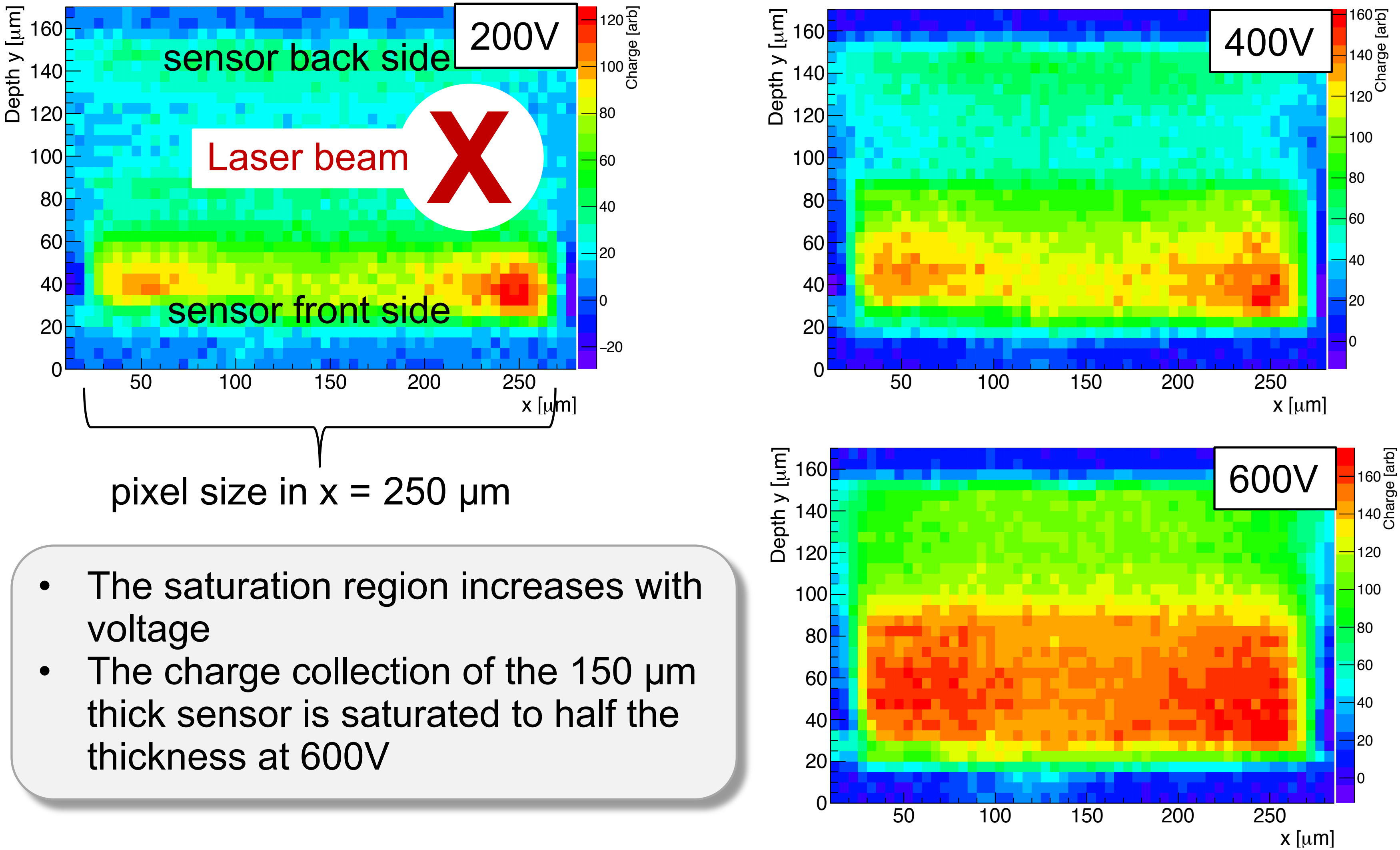
TiW patterning




TiW layer!

# 2D-charge profile at different voltages (150 μm)

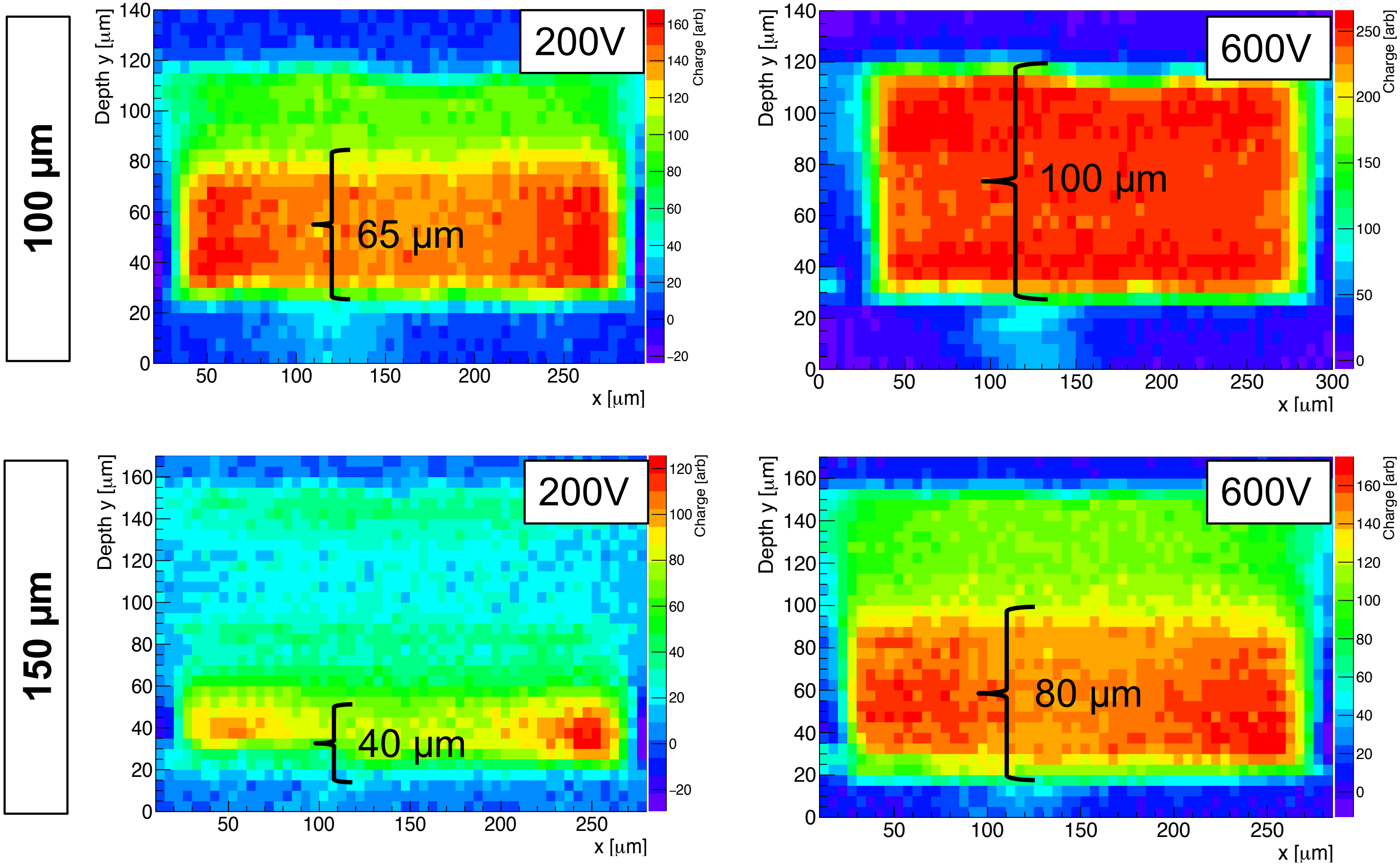
**1x10$^{16}$ n$_{eq}$/cm$^2$**




- The saturation region increases with voltage
- The charge collection of the 150 μm thick sensor is saturated to half the thickness at 600V

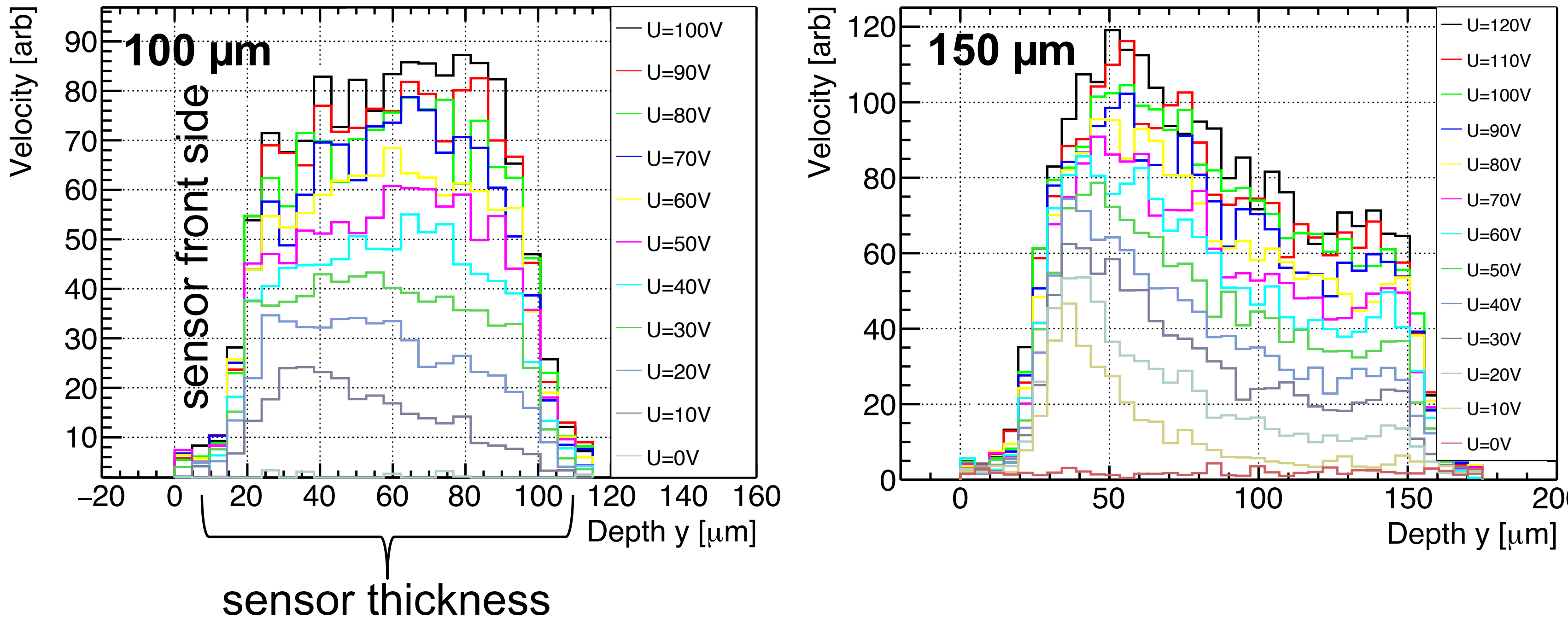
# Charge collection in 100 &150 μm thick sensors

**$1\times10^{16}\ n_{eq}/cm^2$**



# Velocity profile as a function of thickness

**not irradiated**




- Higher electric field at the front side at lower voltages for both thicknesses
- Velocity profile is flatter for the 100 µm thick sensor in the chosen range of voltages

see also: G. Kramberger et al, Modeling of electric field in silicon micro-strip detectors irradiated with neutrons and pions, JINST, Vol. 9 (2014), P10016.

# Velocity profile as a function of fluence (100 µm)

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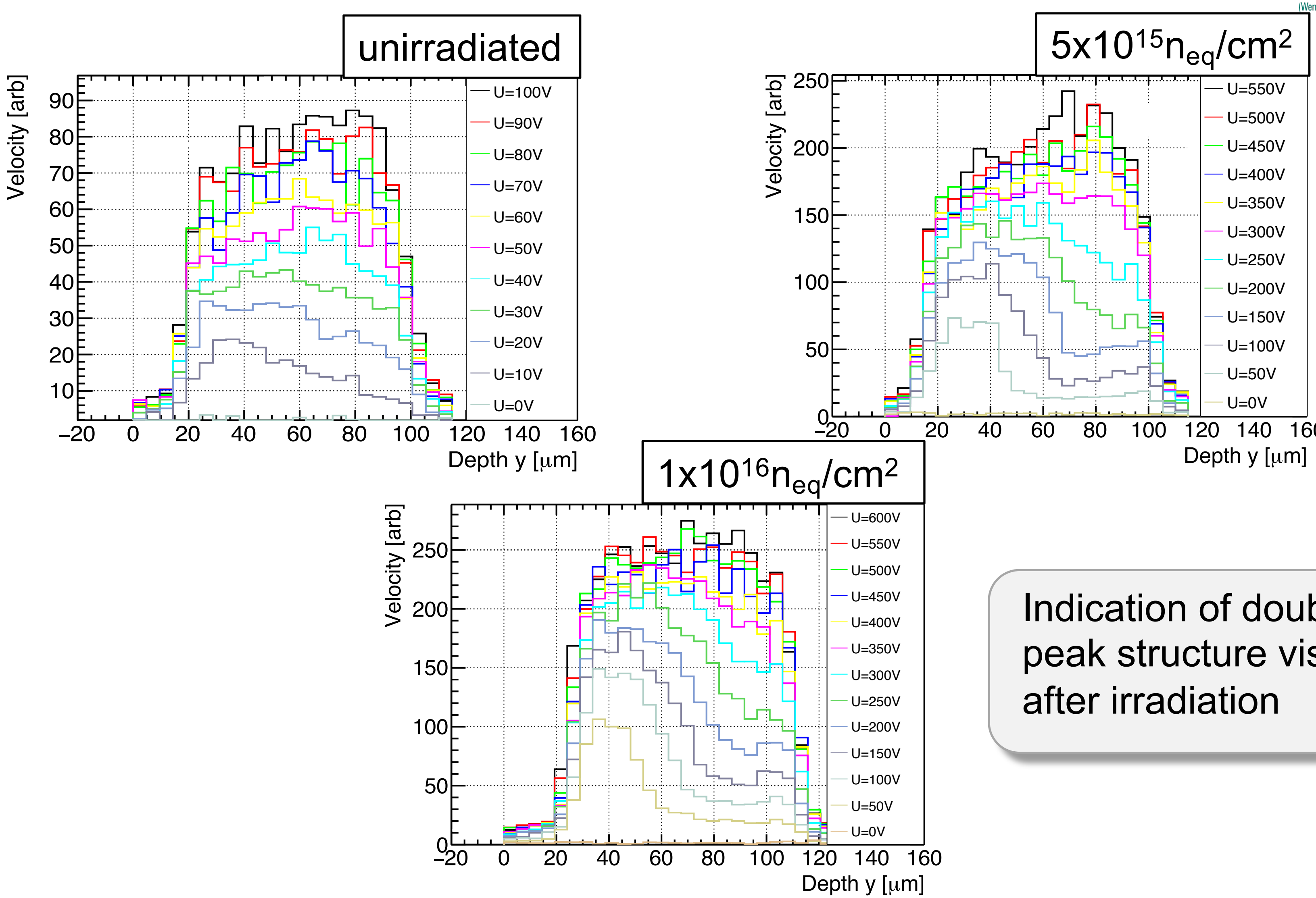


Indication of double peak structure visible after irradiation