Testbeam studies of annealed planar pixel modules and design optimisations of pixel sensors for the ATLAS ITk upgrade employing TCAD simulation

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MAX-PLANCK-GESELLSCHAFT

RD50

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(Werner-Heisenberg-Institut)

Introduction & Outline

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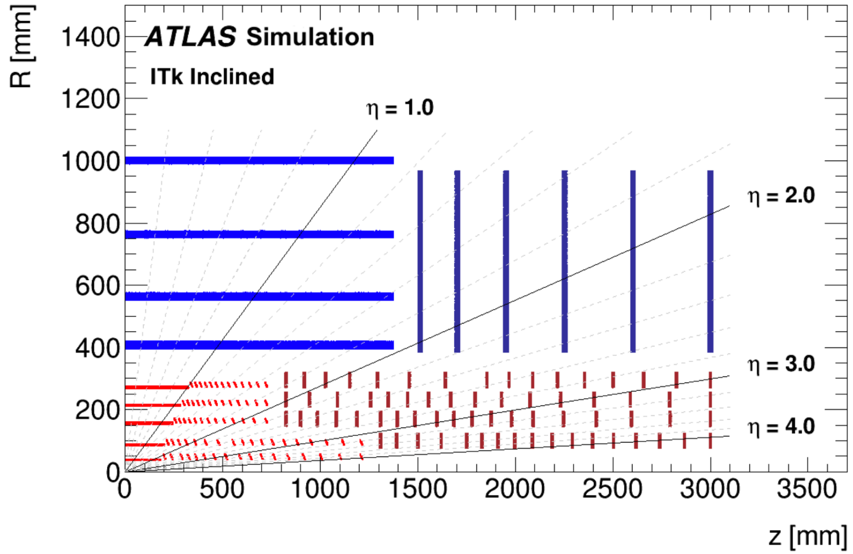
Inner Tracker (ITk) upgrade in preparation for the ATLAS experiment at the Large Hadron Collider (LHC)

- harsher conditions require smaller pixels and thinner sensors

  → Simulate thin sensors with small pixels for design optimisation

- the exchange of the innermost layers after half the lifetime of the detector might result in long times at room temperature (RT)

  → Testbeam measurements of annealed irradiated modules



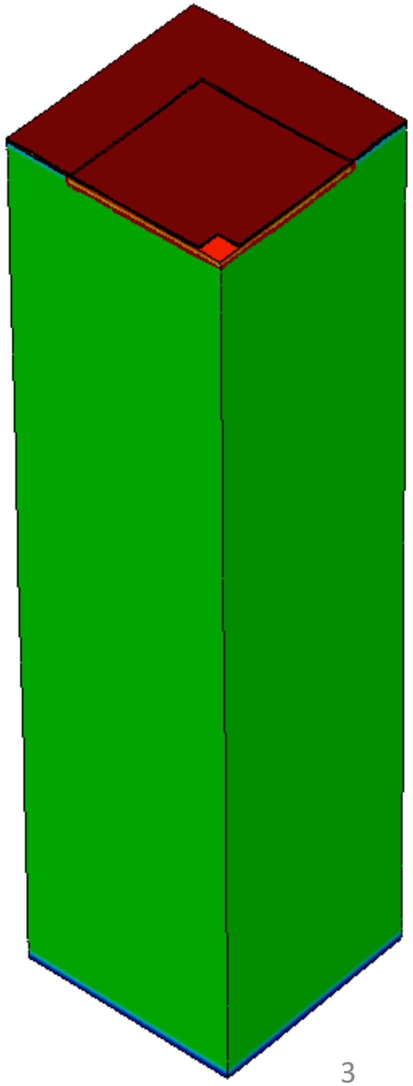
TCAD Simulation

of small pixel cells

- use a 3D TCAD model for the investigation of different properties of small pixels

- due to reasons of symmetry, simulation of ¼ pixel is sufficient (and saves time)

- radiation damage in TCAD:
  - bulk damage:
    - traps characterised by energy level, e/h cross-section and introduction rate
    - use New Delhi[1] and Perugia[2] 2017 irradiation model here
  - surface damage:
    - fixed oxide charge of $5\times10^{10}\text{cm}^{-2}$ for not-irradiated and $2\times10^{12}\text{cm}^{-2}$ for irradiated sensors[3]
    - no Si-SiO_2 interface traps



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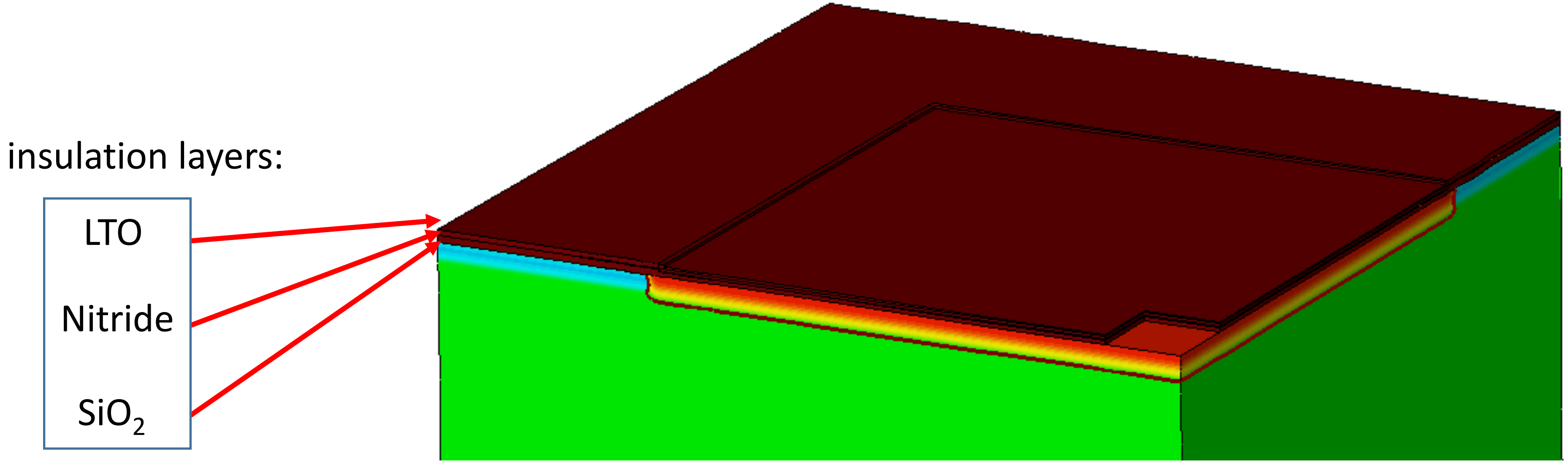
[1] R. Dalal et al., Simulation of Irradiated Si Detectors ,PoS Vertex2014 (2015).

[2] F. Moscatelli et al., Combined Bulk and Surface Radiation Damage Effects at Very High Fluences in Silicon Detectors: Measurements and TCAD Simulations

[3] J. Zhang et al., Investigations of X-ray induced radiation damage at the Si-SiO_2 interface of silicon sensors for the European XFEL, Proceedings of IWORID 2012

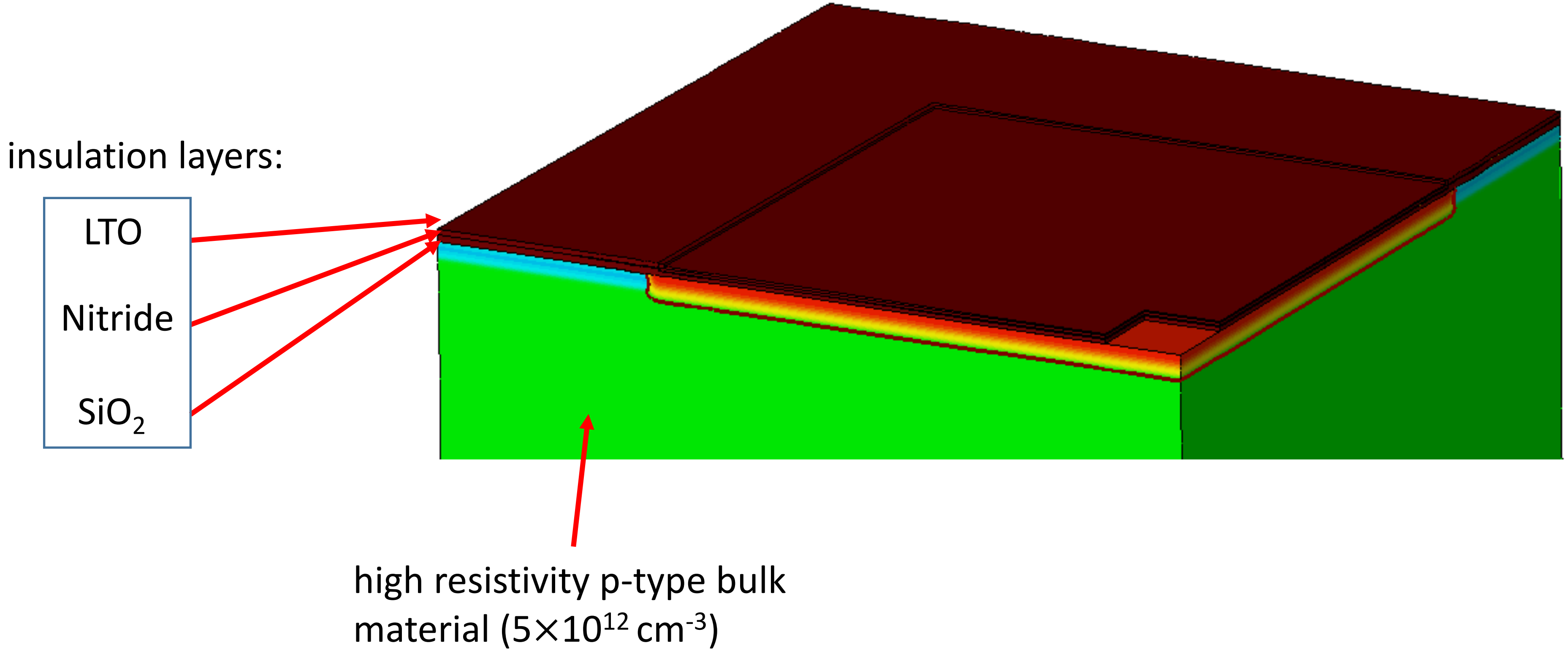
TCAD Simulation

structure of interest



TCAD Simulation

structure of interest


insulation layers:

LTO

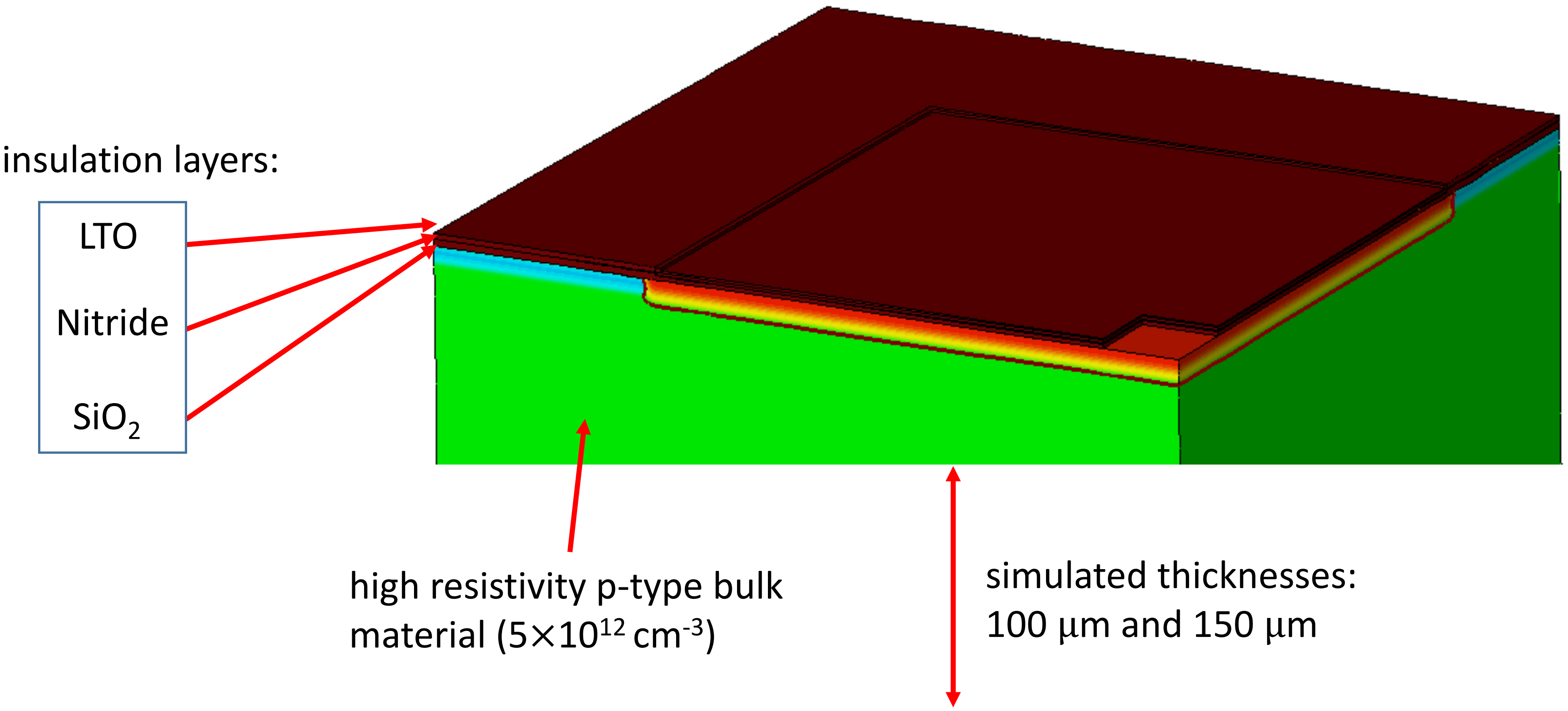
Nitride

SiO_2

high resistivity p-type bulk material (5×10^{12} cm^{-3})

TCAD Simulation

structure of interest



insulation layers:

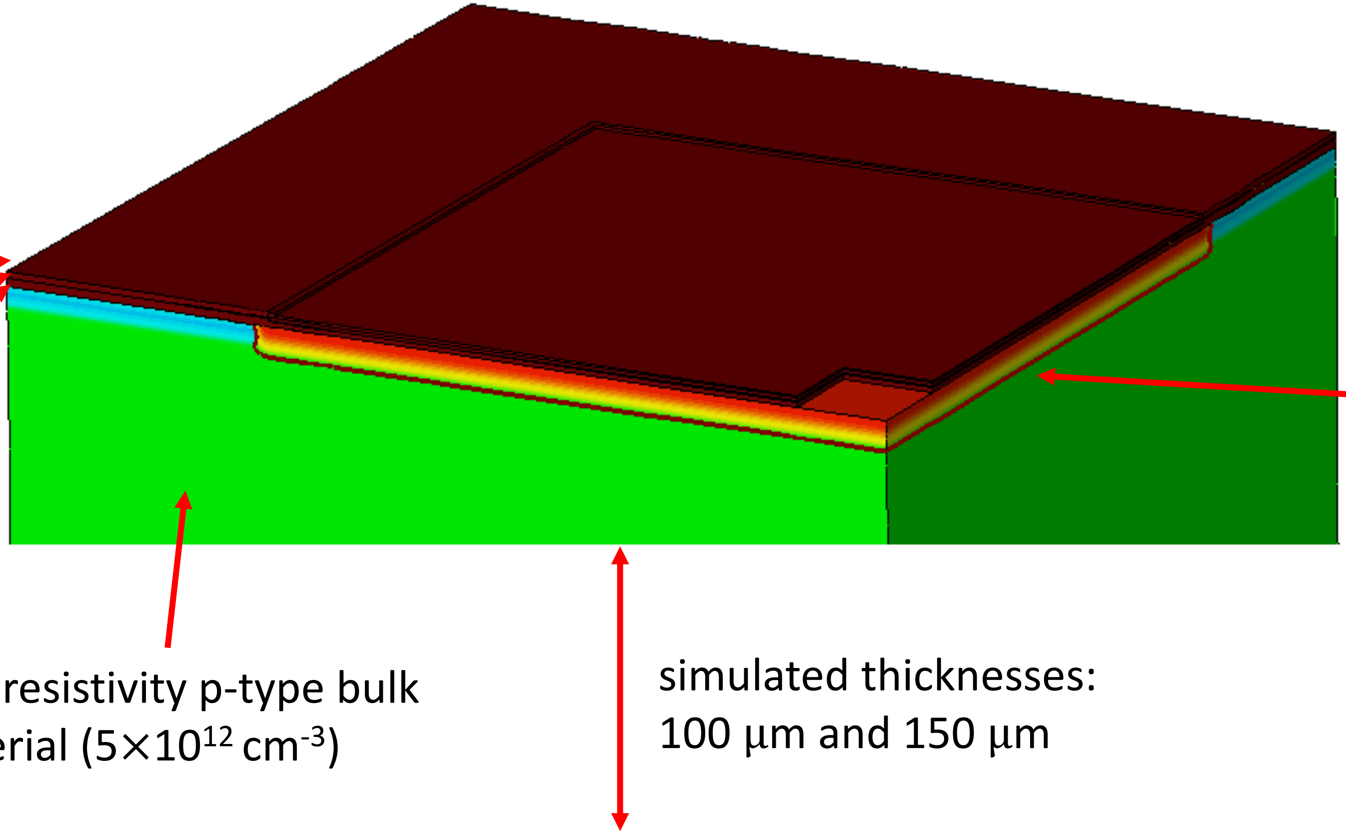
- LTO
- Nitride
- SiO_2

high resistivity p-type bulk material (5×10^{12} cm^{-3})

simulated thicknesses:
100 μm and 150 μm

TCAD Simulation

structure of interest



insulation layers:

- LTO
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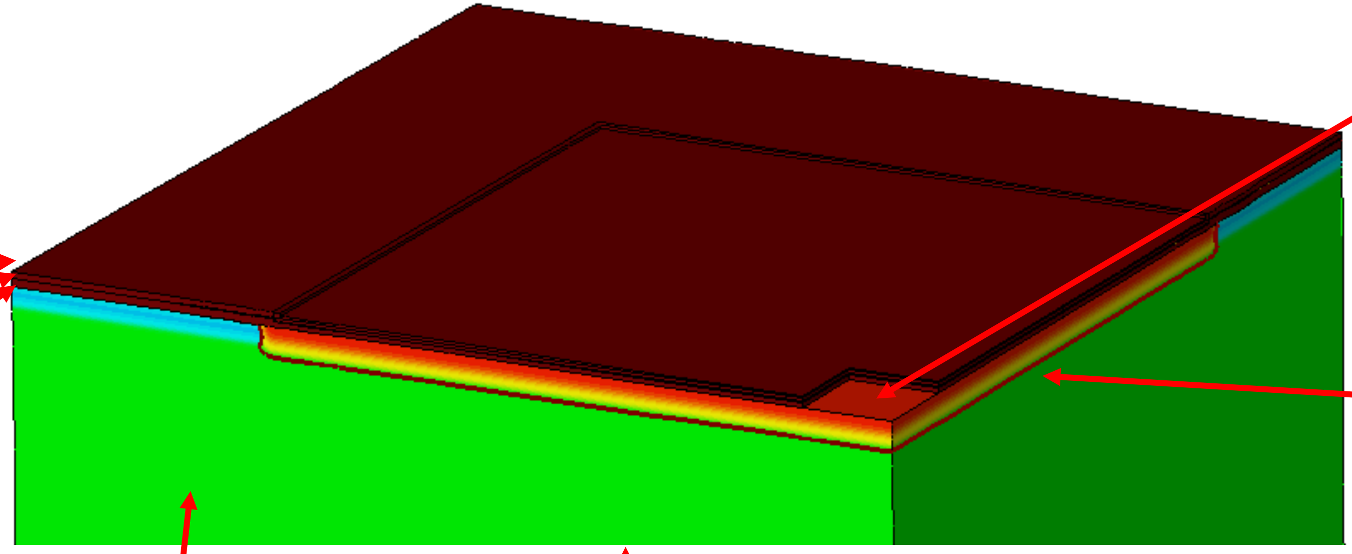
n^+ pixel implant

high resistivity p-type bulk material (5×10^{12} cm^{-3})

simulated thicknesses:
100 μm and 150 μm

TCAD Simulation

structure of interest



insulation layers:

- LTO
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- SiO_2

via to connect electrical contact with implant

n^+ pixel implant

high resistivity p-type bulk material (5×10^{12} cm^{-3})

simulated thicknesses: 100 μm and 150 μm

TCAD Simulation

structure of interest

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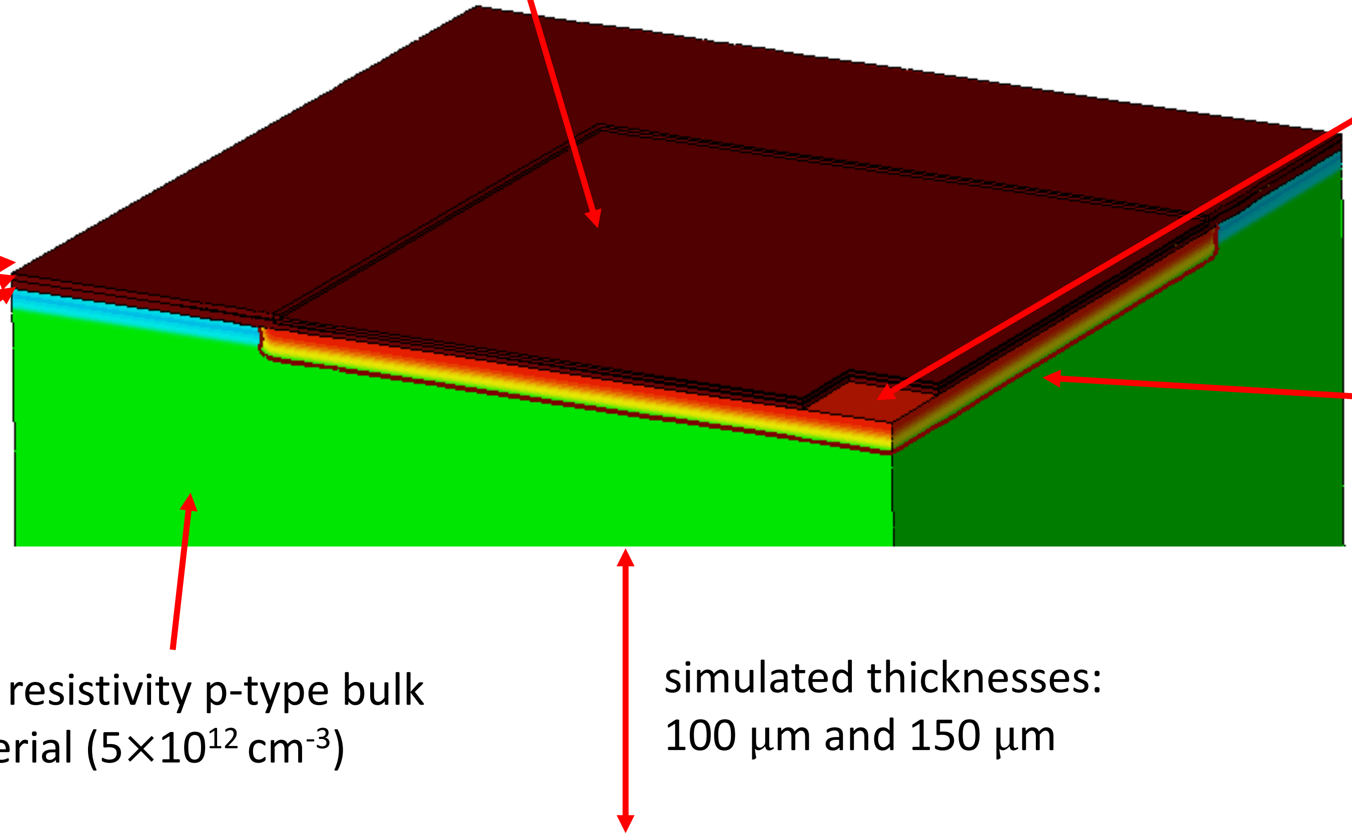


electrical contact on top of the pixel plus 2µm overhang

via to connect electrical contact with implant

insulation layers:

- LTO
- Nitride
- SiO_2

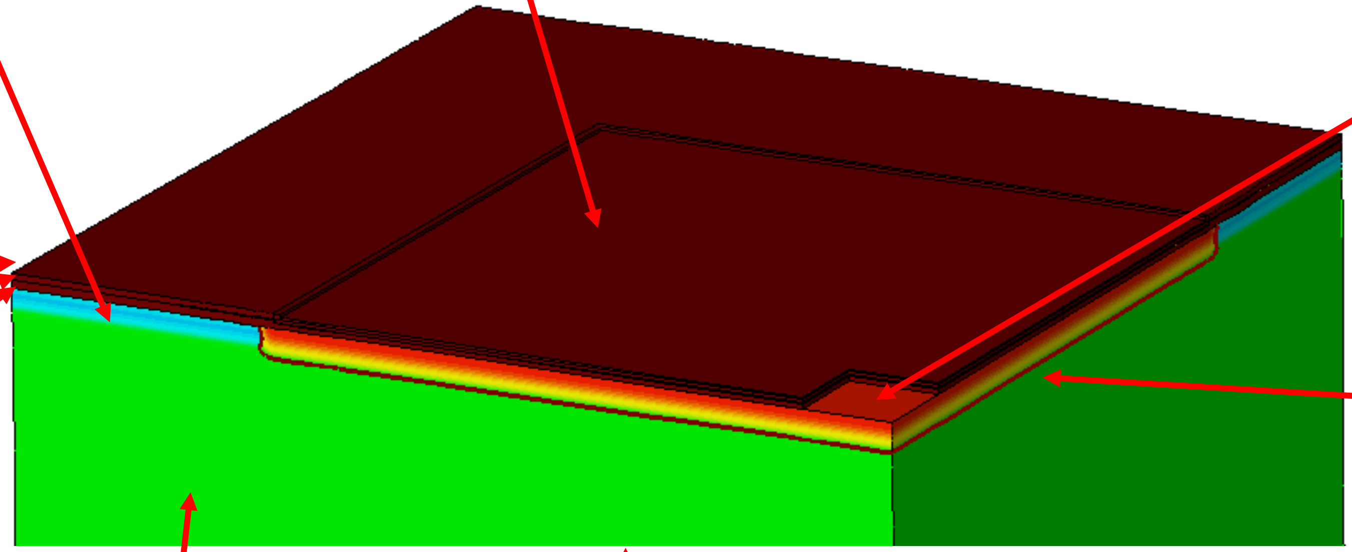
n^+ pixel implant

high resistivity p-type bulk material (5×10^{12} cm^{-3})

simulated thicknesses: 100 µm and 150 µm

TCAD Simulation

structure of interest



electrical contact on top of the pixel plus 2µm overhang

p-spray inter-pixel isolation

via to connect electrical contact with implant

insulation layers:

- LTO
- Nitride
- SiO_2

n^+ pixel implant

high resistivity p-type bulk material ($5\times10^{12}\,cm^{-3}$)

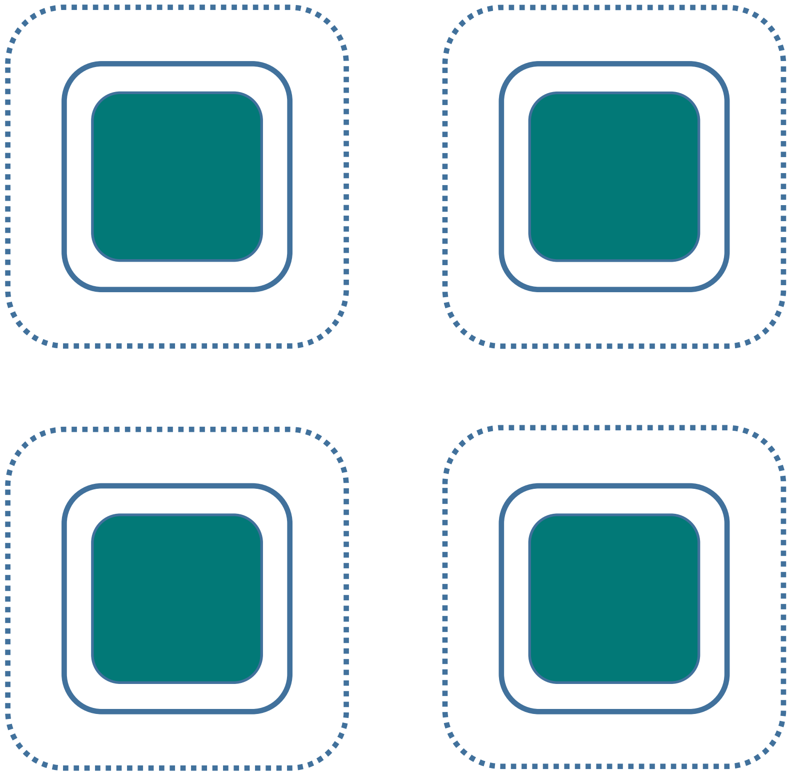
simulated thicknesses:
100 µm and 150 µm

TCAD Simulation

influence of implant size: general

- the new RD53 read-out chip will have a 50x50μm^2 bump-bond pattern
  - pixel implant size and shape can be modified within this boundary condition
- electric field becomes more homogeneous with larger implants
  - expect better charge collection efficiency (CCE)
- effect on p-spray:

top-view, pixel sizes

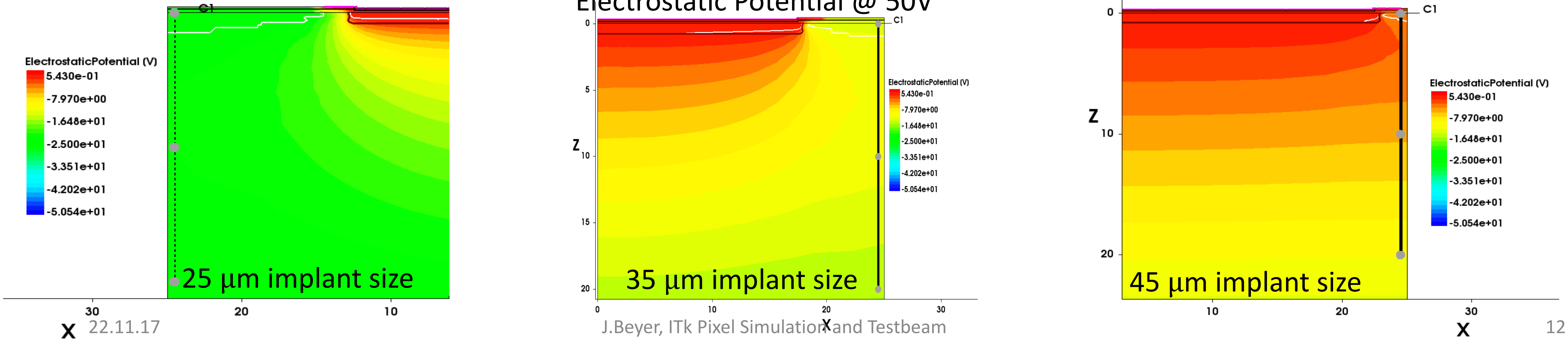


TCAD Simulation

influence of implant size on p-spray potential

- effect on p-spray:
  - larger implants prevent the p-spray layer to fall to the backside potential
  - lower potential means smaller field in the interface of pixel and p-spray
  - lower field results in higher BD voltage

Electrostatic Potential @ 50V



TCAD Simulation

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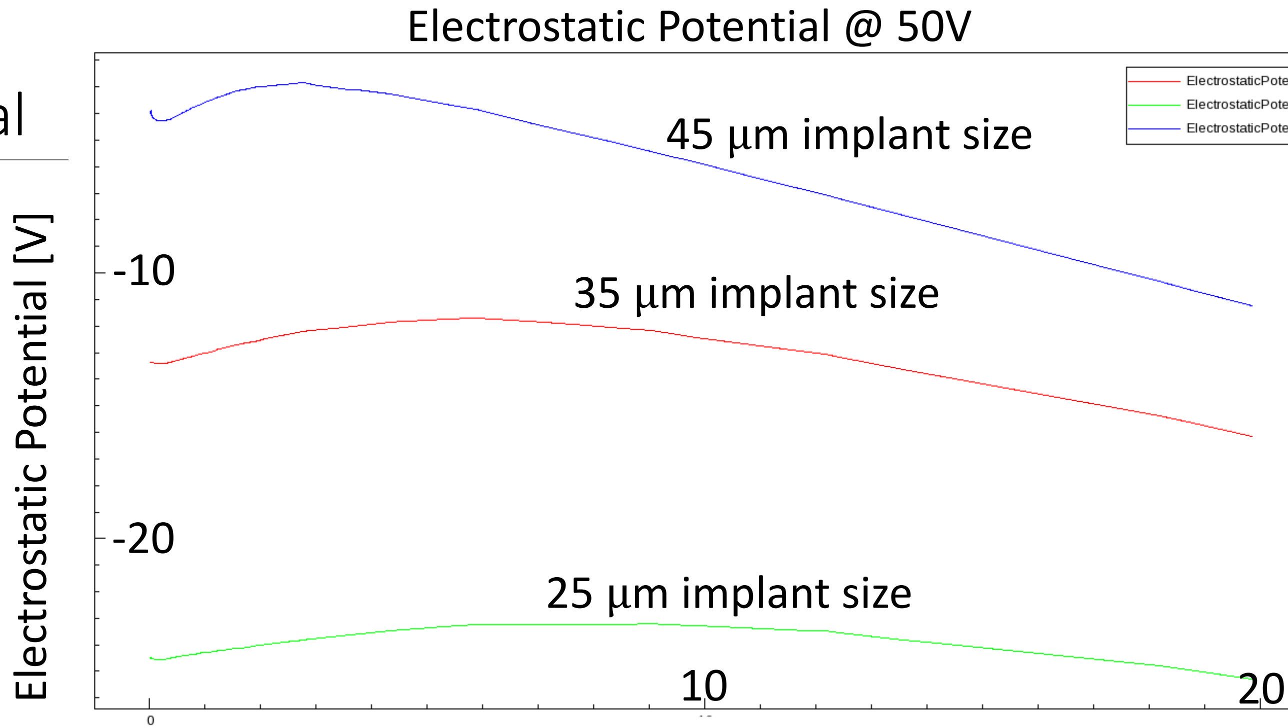
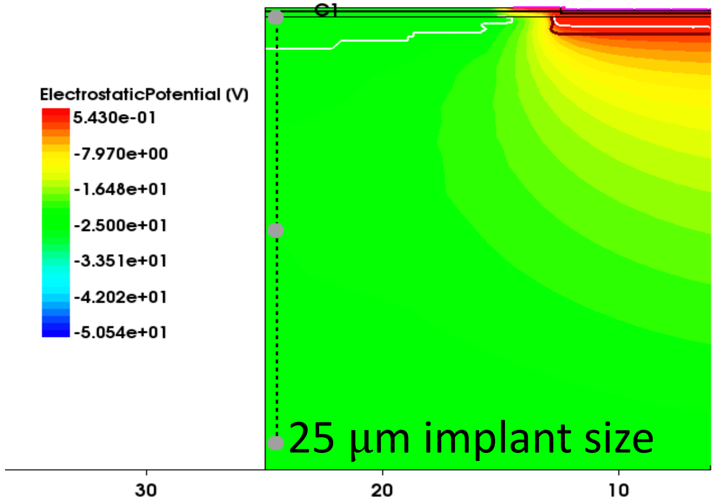
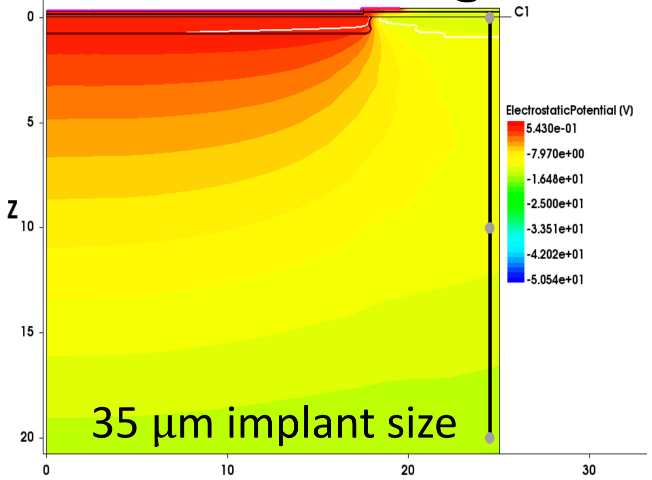
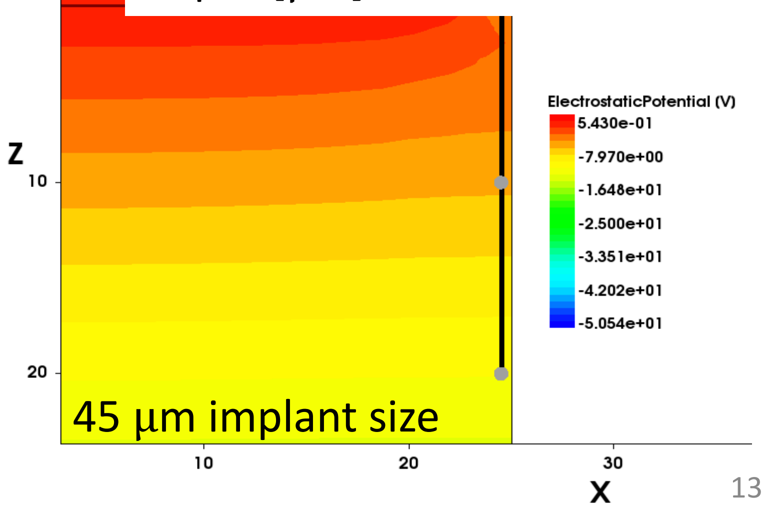


Electrostatic Potential @ 50V



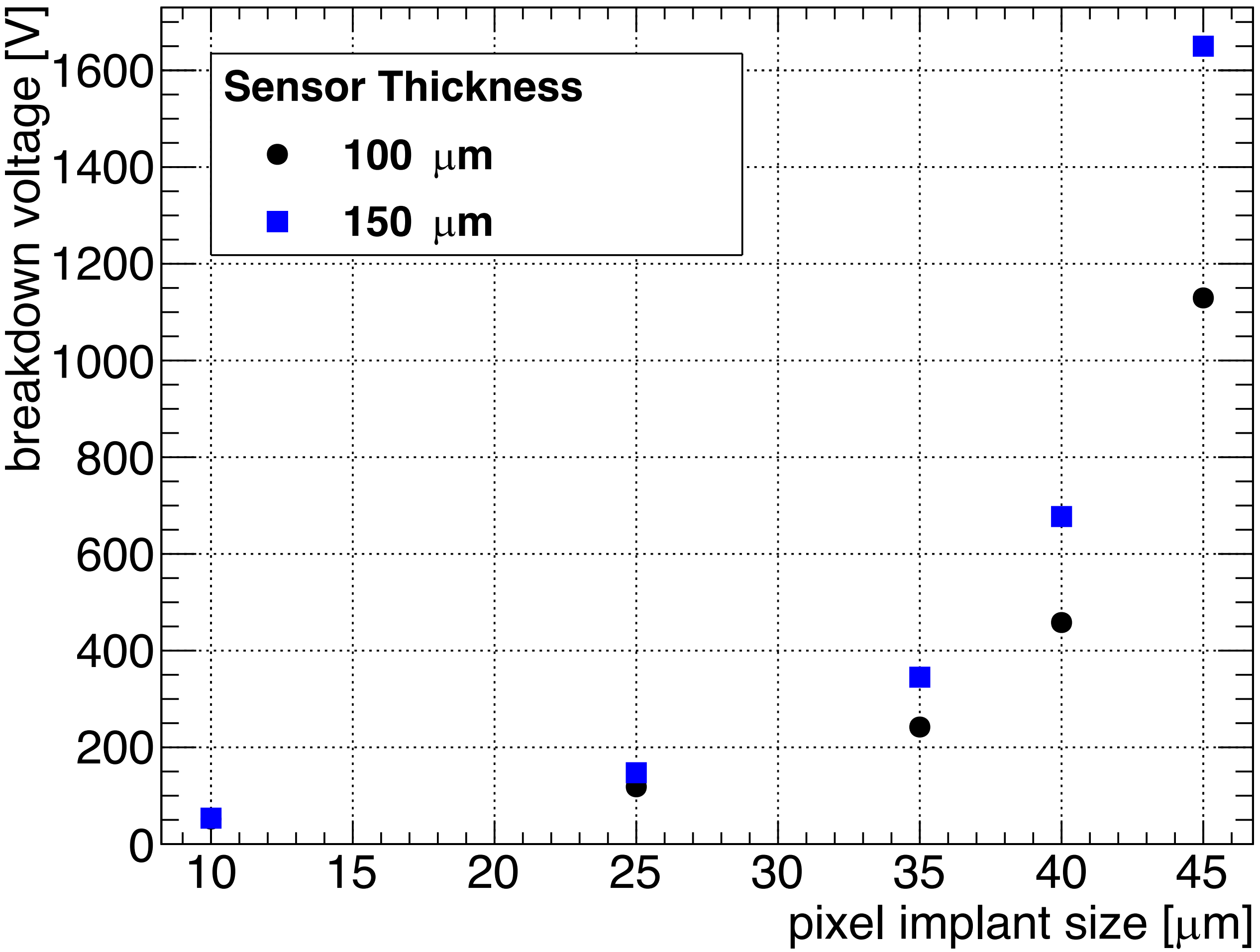




TCAD Simulation

implant size and breakdown voltage

- simulation shows the expected behaviour
    - higher BD voltages for larger pixel implants
- BD voltage also improves for thicker sensors
    - same voltage drop over a larger distance results in lower fields



TCAD Simulation

implant size and charge collection efficiency

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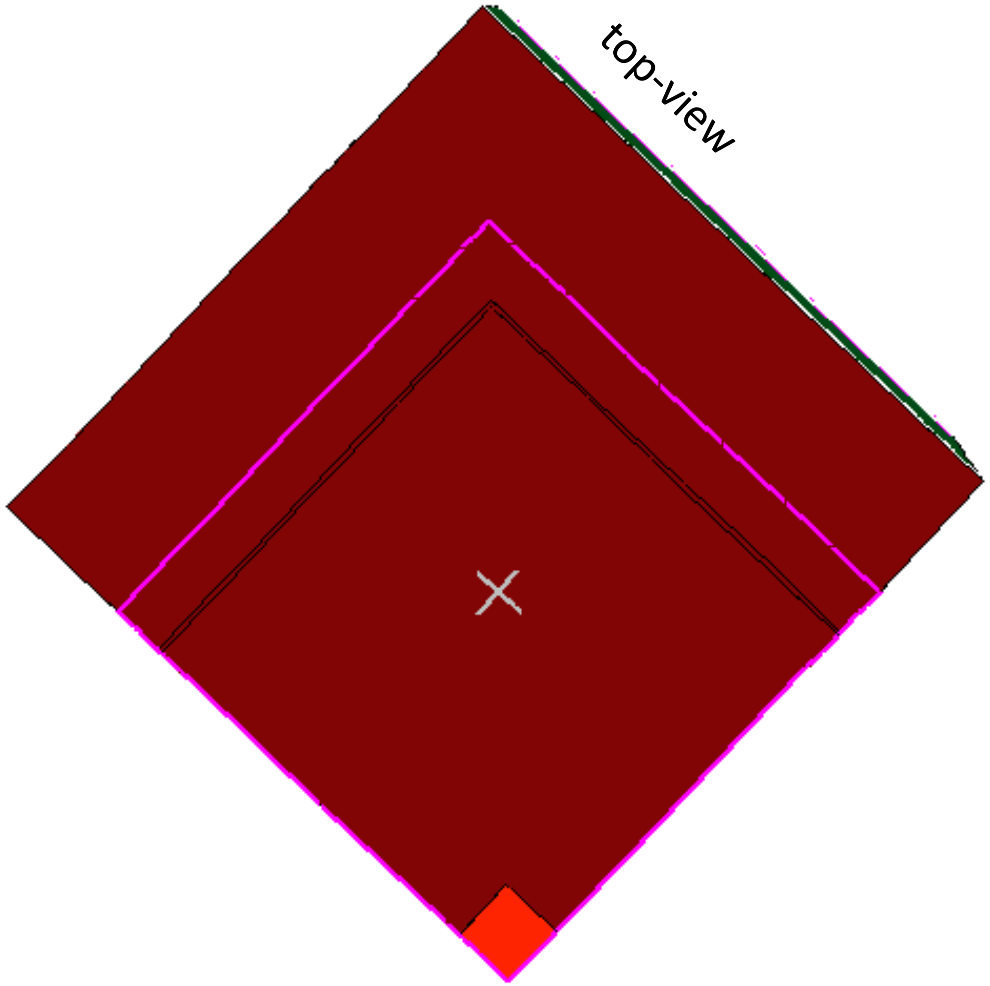
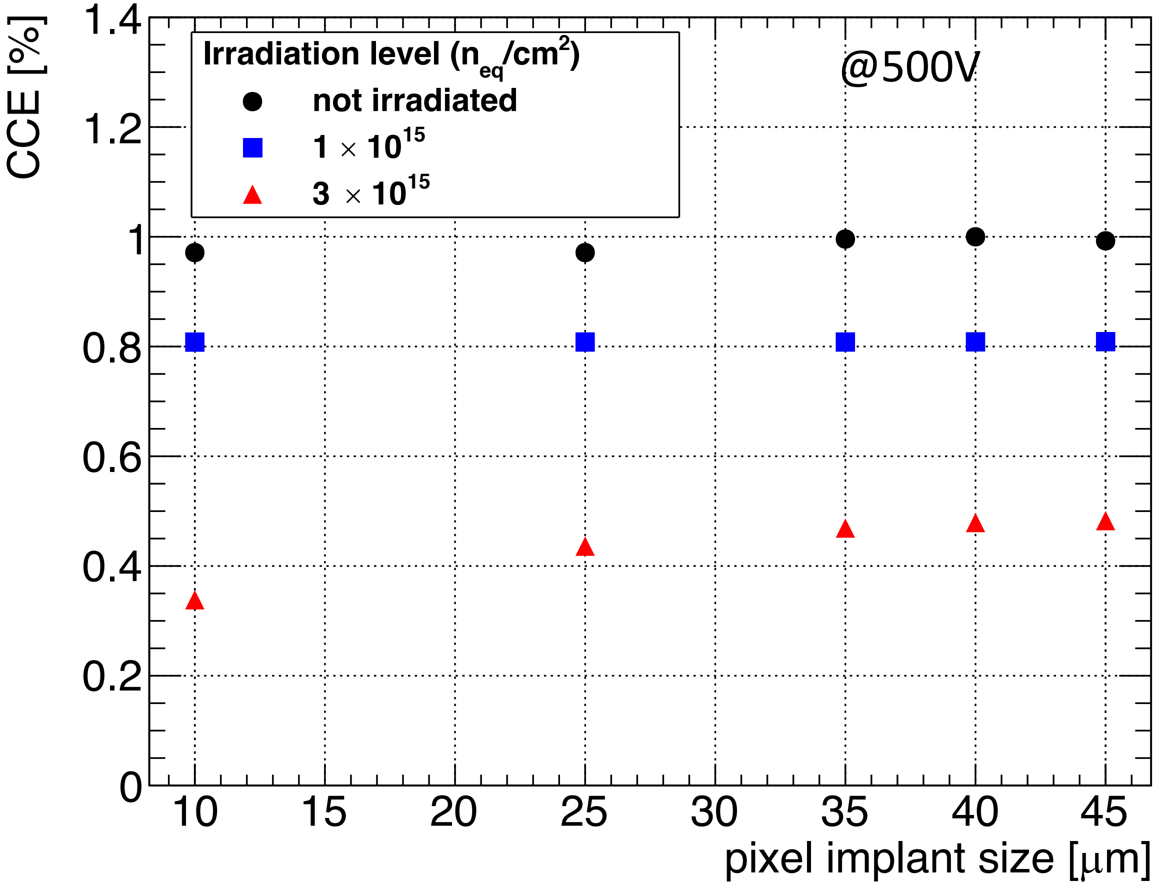


- MIP injection: 76 e/h pairs are released per µm at a position of x/y = 10µm/10µm (0/0 at pixel center) from the surface through the entire sensor
- transient simulation of the current
- collected charge: integration of signal minus leakage current baseline
- sensors are all 100µm thick
- bias voltages: 50V not-irradiated / 500V irradiated

TCAD Simulation

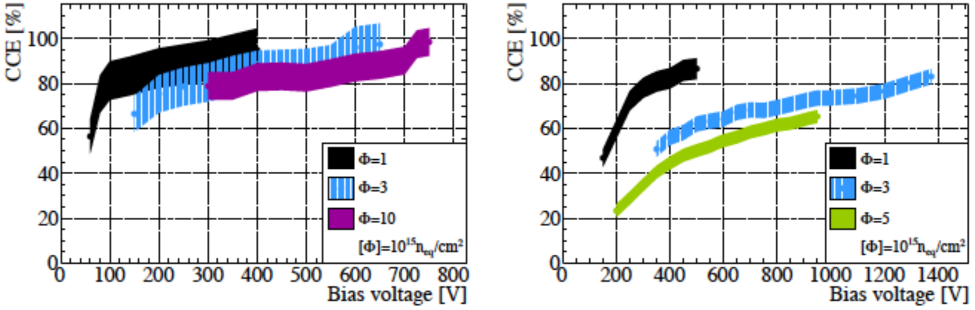
implant size and charge collection efficiency – New Delhi model

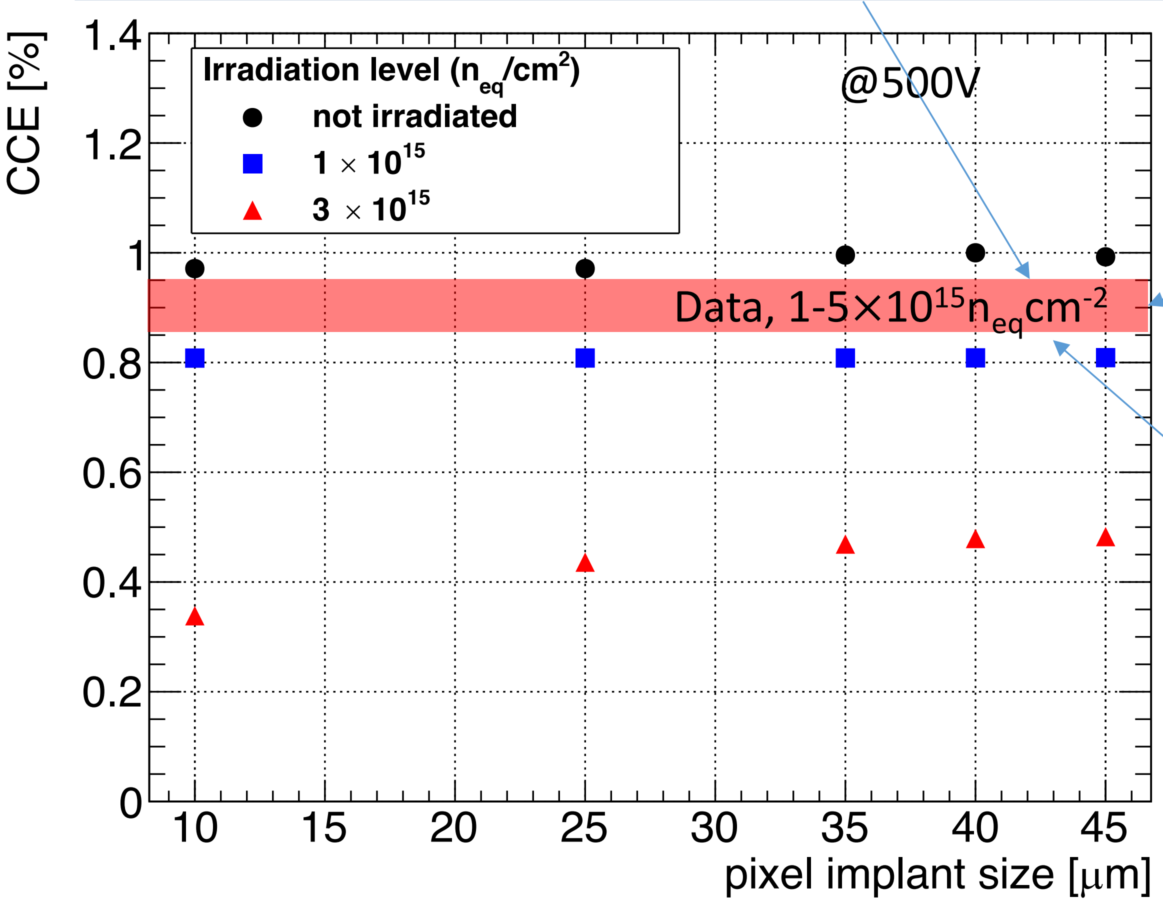


- all values are normalized to the highest value (45µm, not irradiated)
- charge decreases significantly with irradiation
- larger pixel implants perform better
- at $3\times10^{15} n_{eq} cm^{-2}$
  - 10µm - 45µm: ~15%
  - 25µm - 45µm: ~ 5%

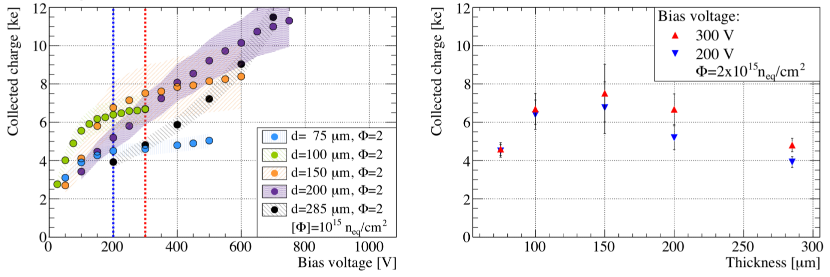
P. Weigell PhD thesis

75+150μm strips, ALIBAVA readout system

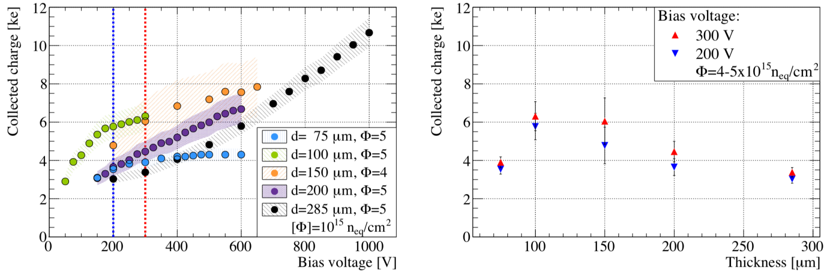




S. Terzo PhD thesis
100μm, FE-I4 read-out

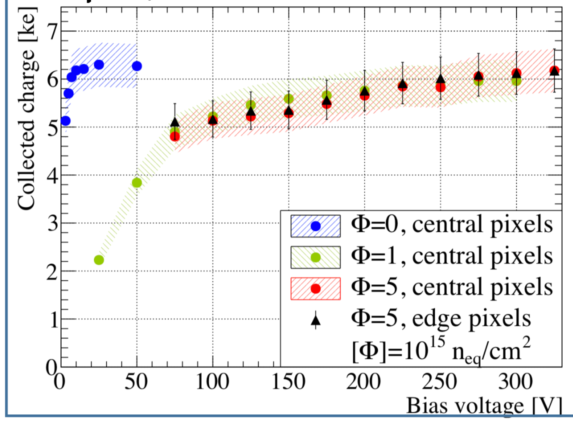


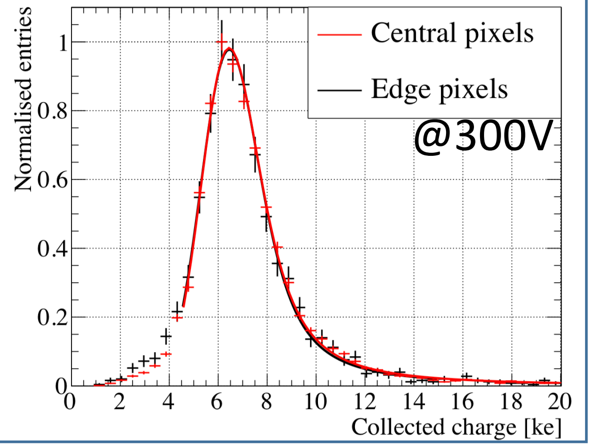
(a) $\Phi=2\times10^{15}\,\mathrm{n_{eq}/cm^2}$ (b) $\Phi=2\times10^{15}\,\mathrm{n_{eq}/cm^2}$



(c) $\Phi=4\text{–}5\times10^{15}\,\mathrm{n_{eq}/cm^2}$ (d) $\Phi=4\text{–}5\times10^{15}\,\mathrm{n_{eq}/cm^2}$

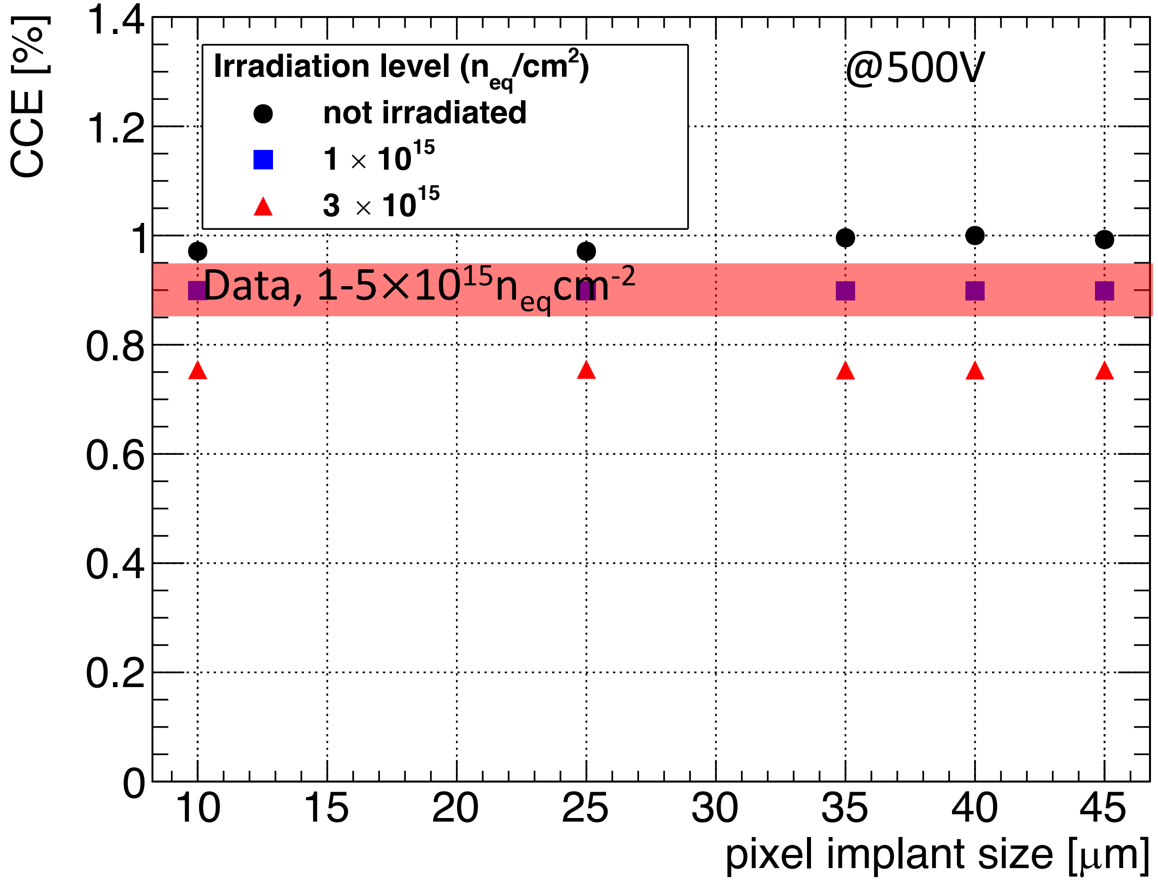
S. Terzo PhD thesis
100μm, FE-I3 read-out





TCAD Simulation

implant size and charge collection efficiency – Perugia 2017 model



- all values are normalized to the highest value (45μm, not irradiated, same as before)
- collected charge decreases with irradiation
- very small variation with implant size

TCAD Simulation

implant size and charge collection efficiency – comparison

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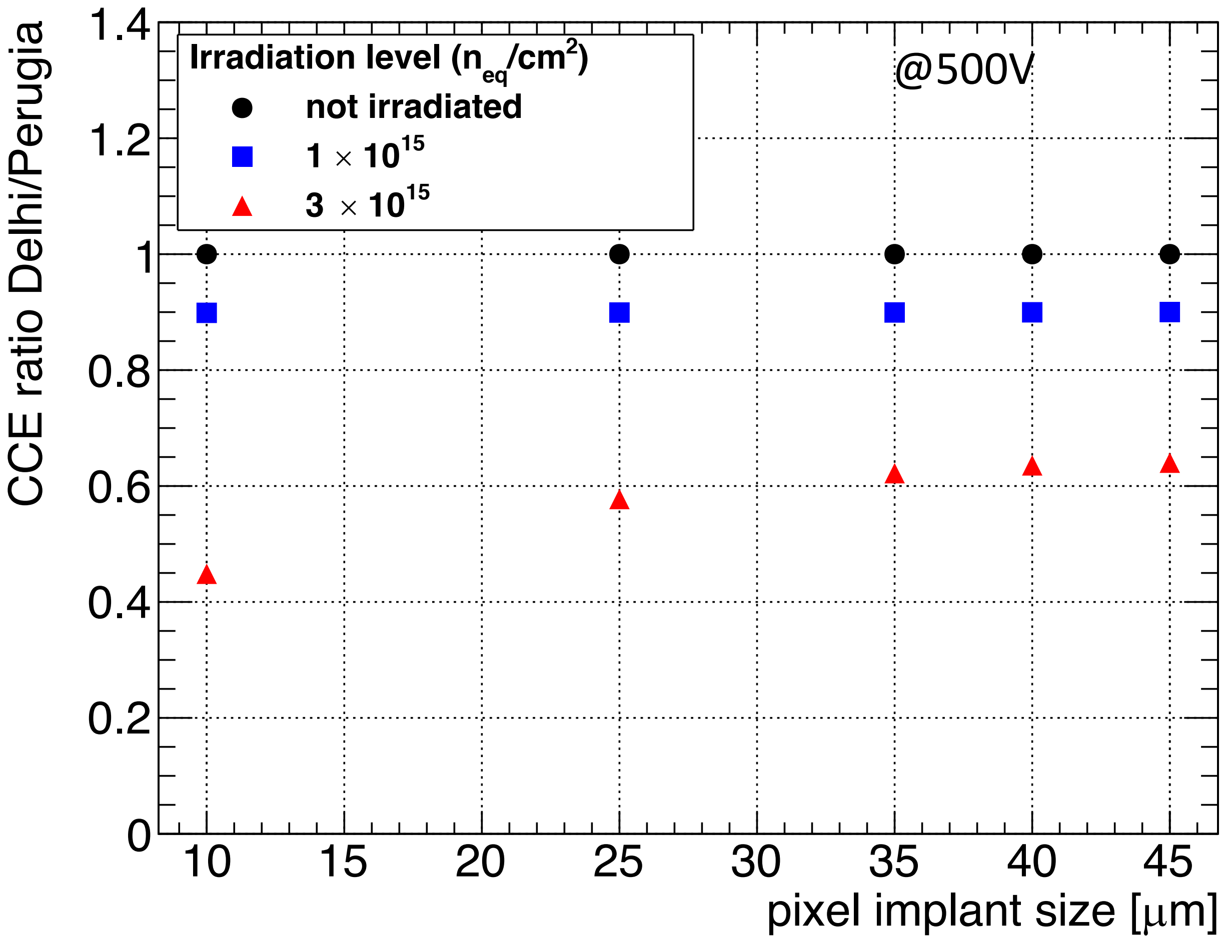
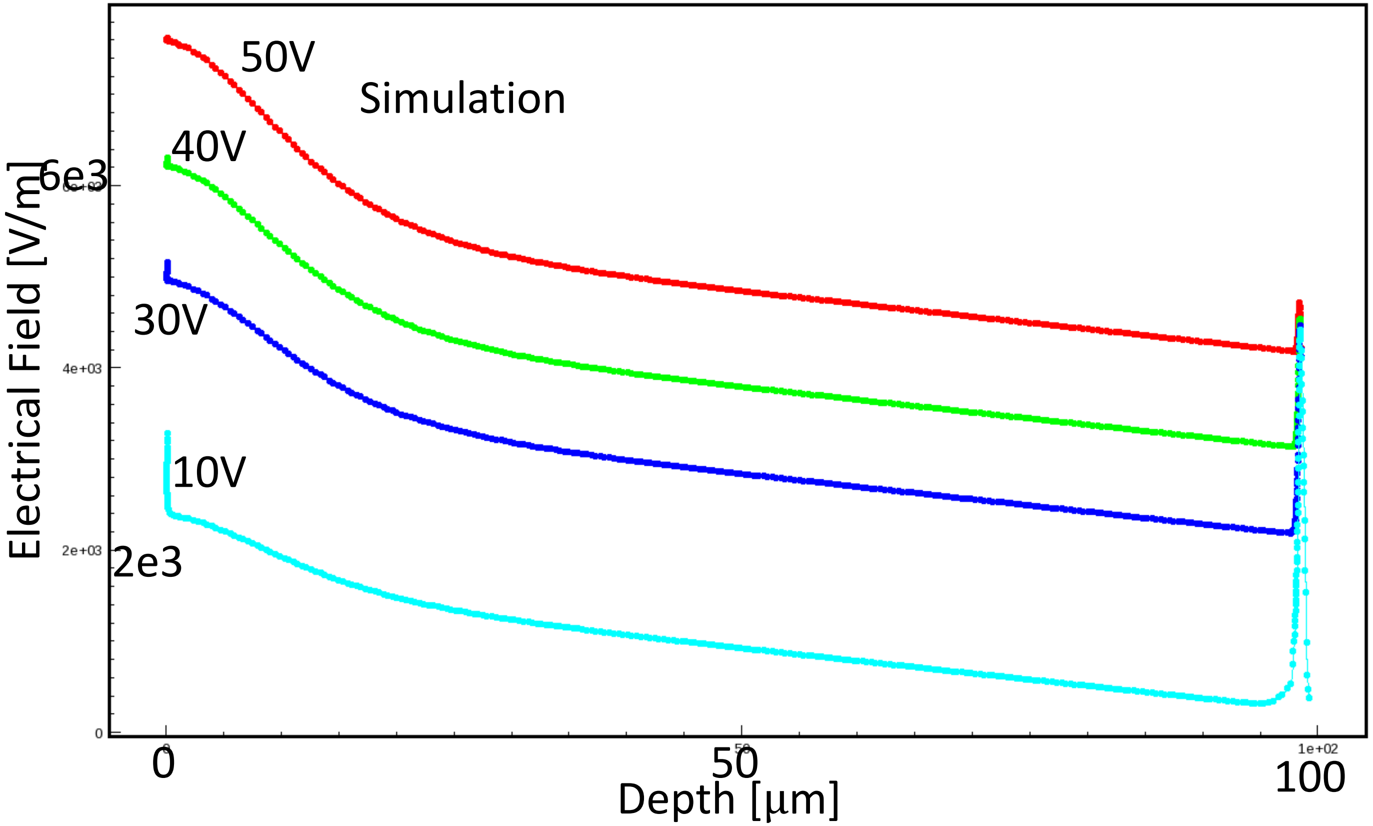


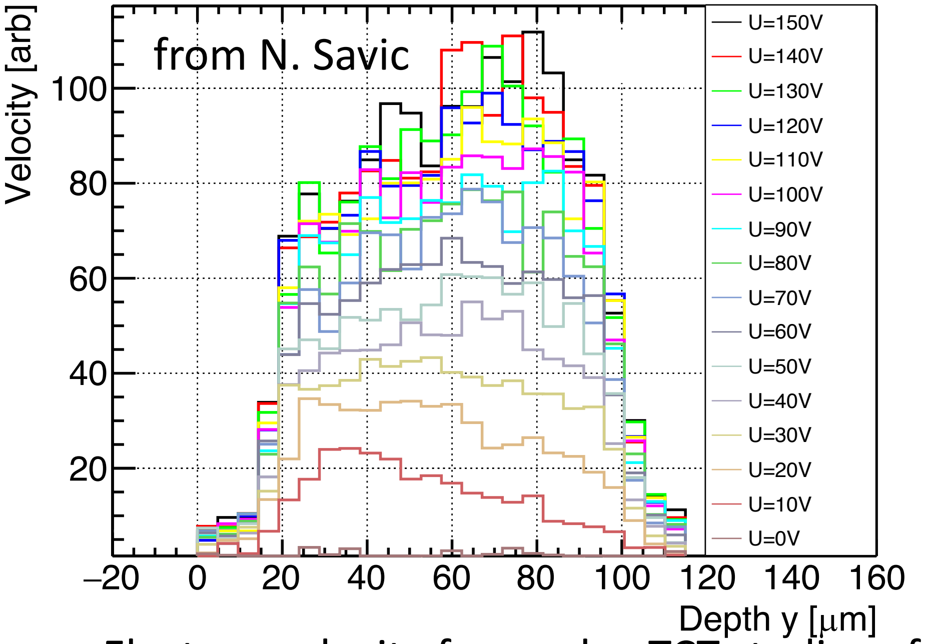
- ratio of CCE of New Delhi and Perugia 2017
- difference increasing with increasing irradiation level
- more charge collected when simulating with Perugia 2017
  - in the worst case more than twice as much
- model also change relatively with pixel size
  - Perugia sees very few influence by varying pixel size

TCAD Simulation

Electrical field – before irradiation - 100µm

- take 40µm pixel implant size as example
- electrical field along the z-axis of sensor (x/y = 5µm)
- electrical field before irradiation at 50V bias voltage

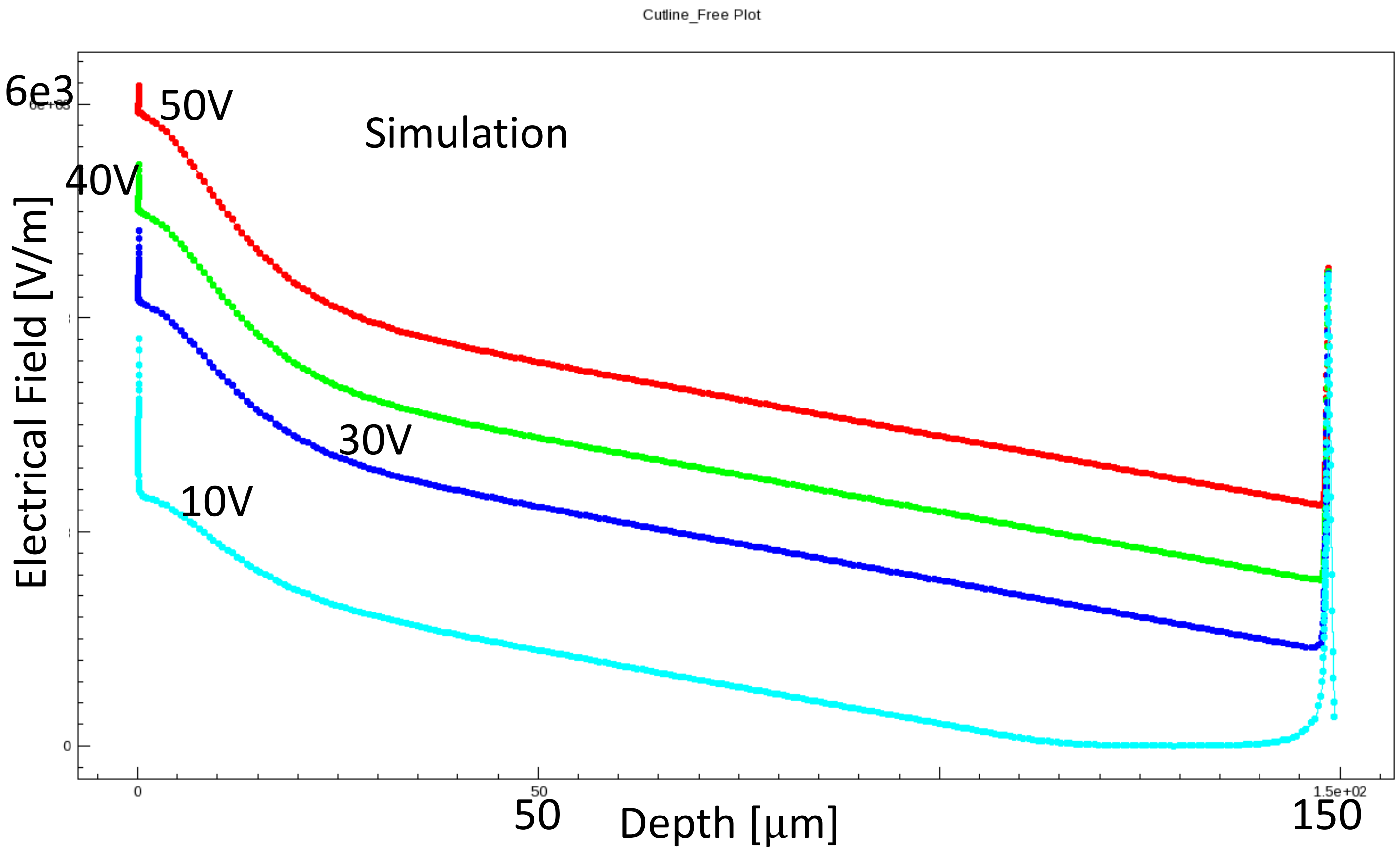




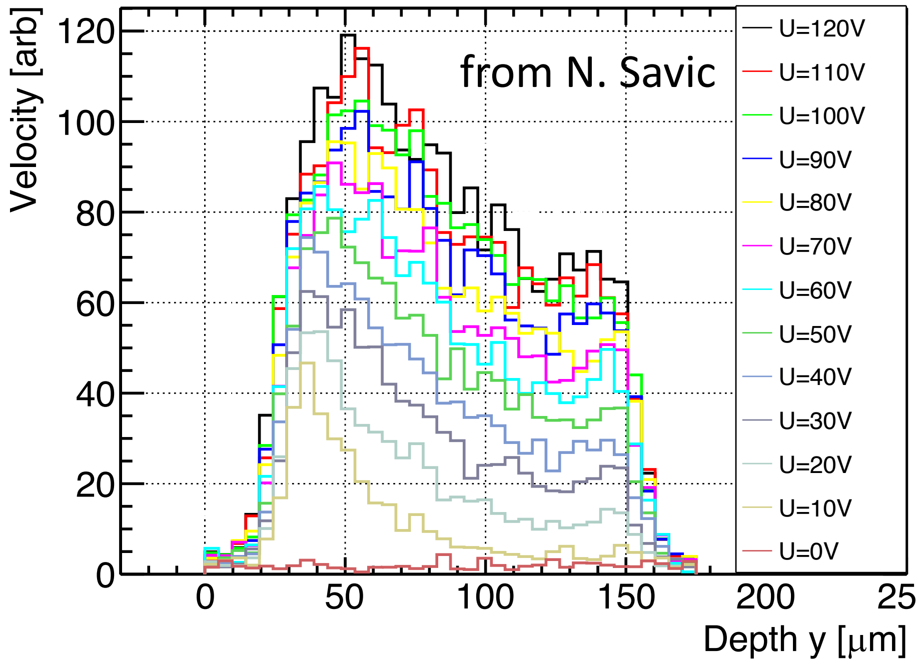
Electron velocity from edge TCT studies of a 100µm thin sensor

TCAD Simulation

Electrical fields – before irradiation - 150µm



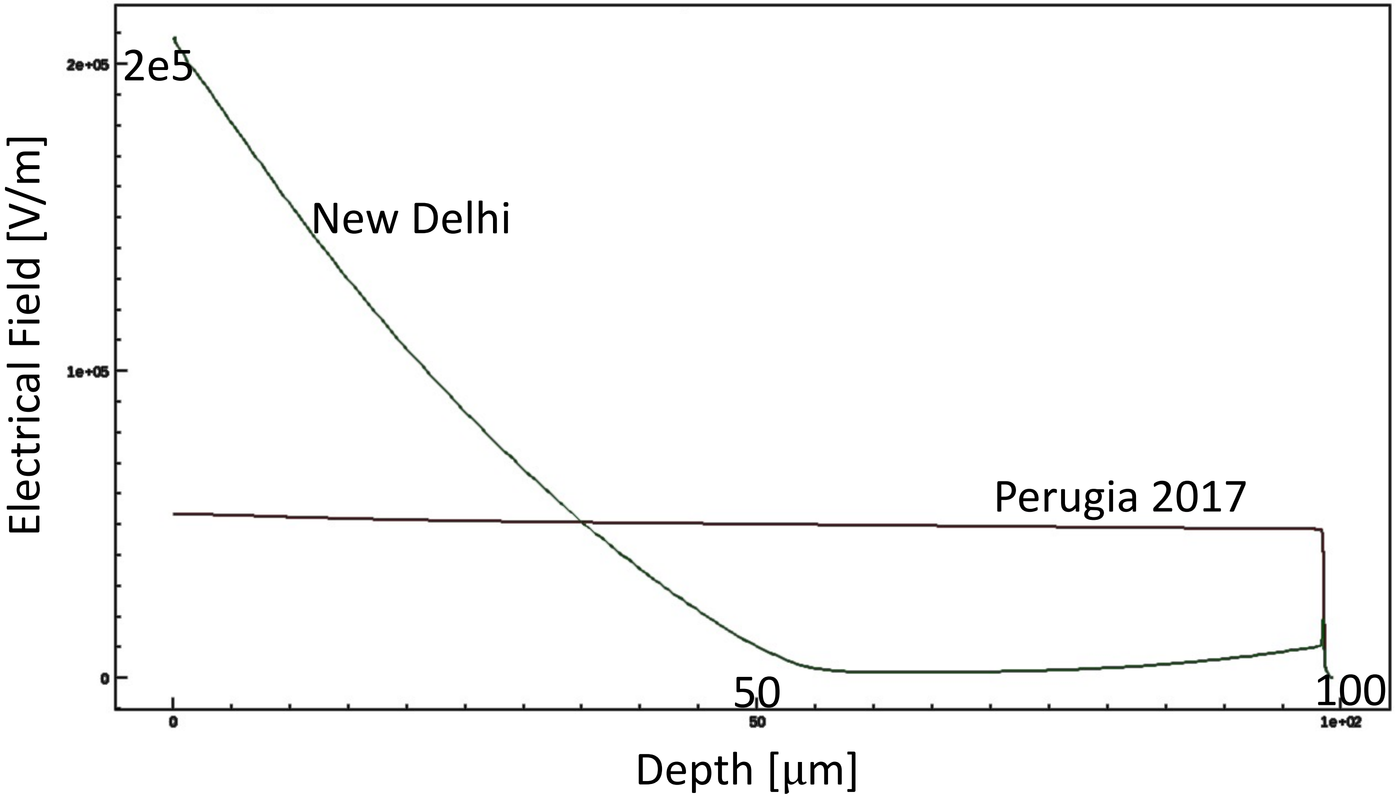
- take 40µm pixel implant size as example
- electrical field along the z-axis of sensor (x/y = 5µm)
- electrical field before irradiation at 50V bias voltage



Electron velocity from edge TCT studies of a 150µm thin sensor

TCAD Simulation

Electrical fields – comparison after irradiation



- take 40µm pixel implant size as example

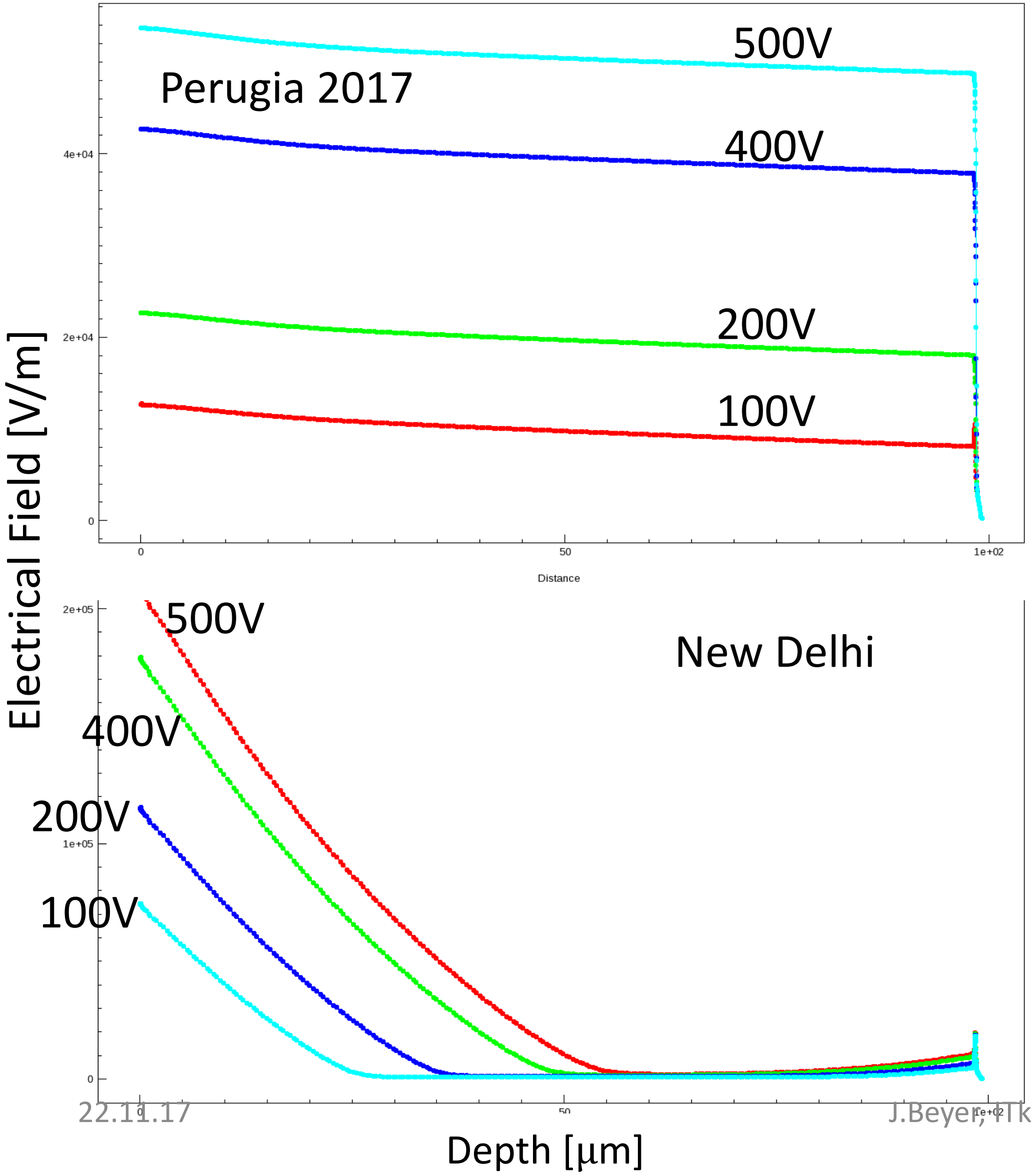
- electrical field along the z-axis of sensor (x/y = 5µm)

- field comparison at 500V bias voltage and 3×10^{15} $n_{eq}cm^{-2}$ irradiation level

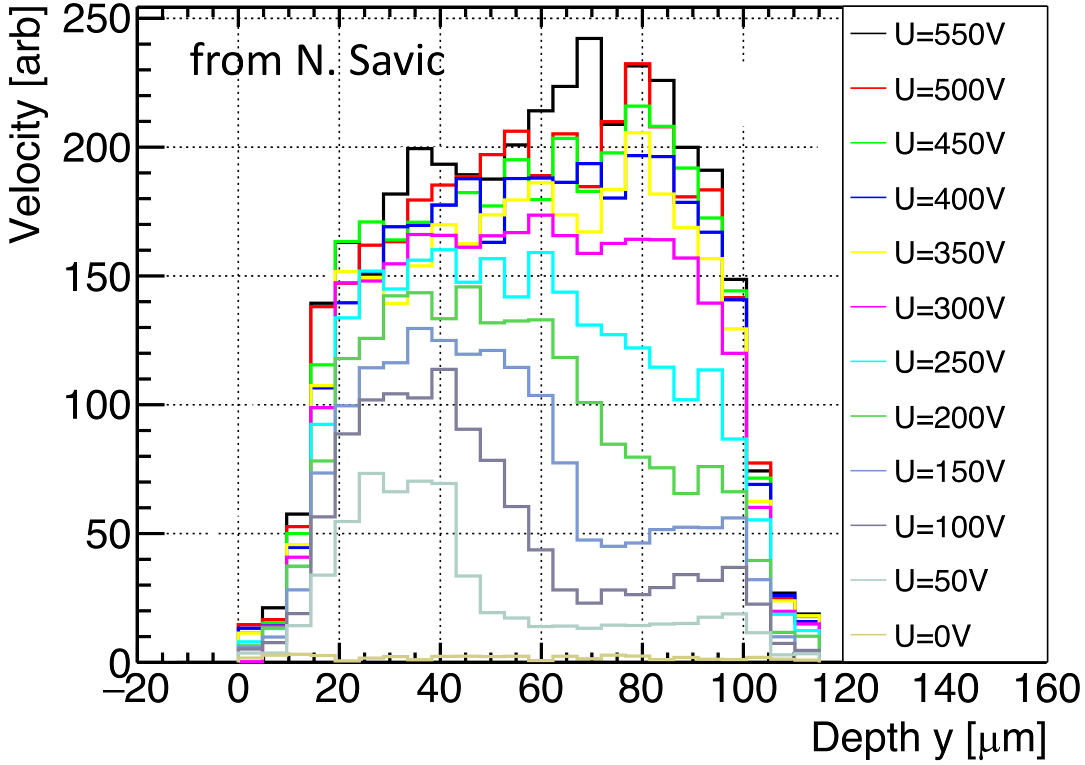
- electrical field depth dependence:
  - Perugia: small
  - New Delhi: large

TCAD Simulation

Electrical fields – comparison to edge TCT data



Electron velocity from edge TCT studies of a 100μm thin sensor at 5×10^{15} $n_{eq}cm^{-2}$



Testbeam Measurements

Testbeam studies

of annealed irradiated modules

- performance degradation expected and observed with increasing irradiation

- second parameter: annealing of defects
  - short term (days at RT): beneficial annealing leading to better performance
  - long term (weeks at RT): reverse annealing degrading the performance

- RT periods can not be avoided completely
  - maintenance of cooling systems and detector components
  - for ITk: exchange of two innermost layers (fluence of layer 2 during exchange: 1-2 $\times 10^{15}$ $n_{eq}cm^{-2}$)

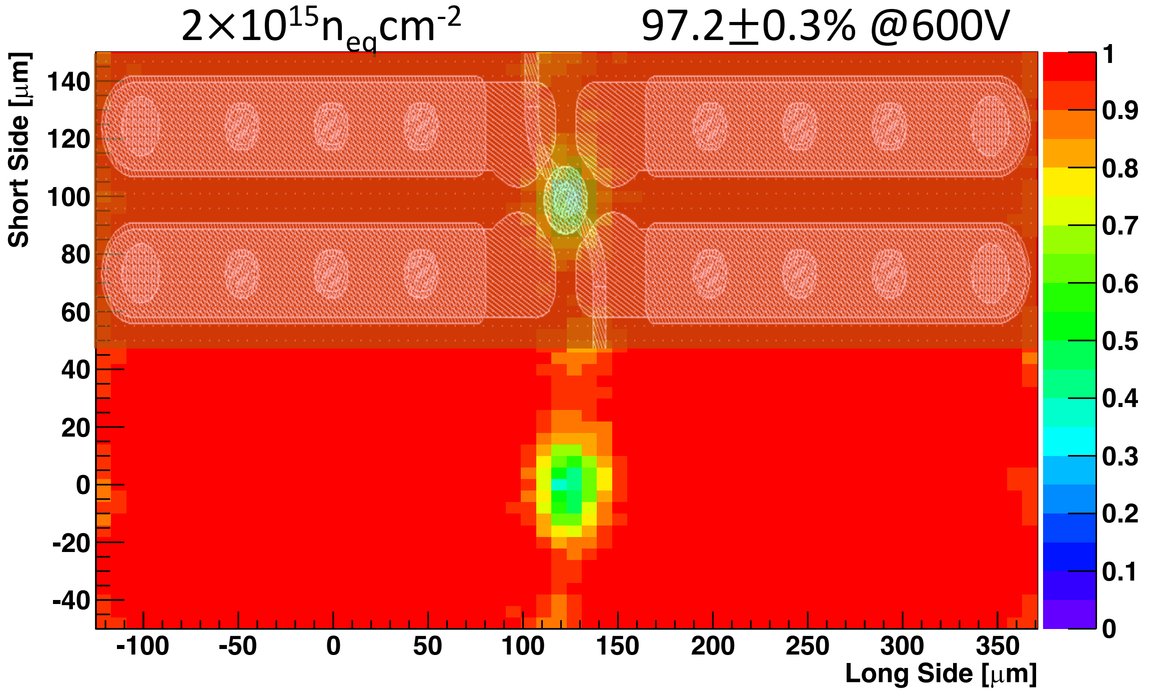
- annealing effect on hit efficiency has not yet been systematically studied

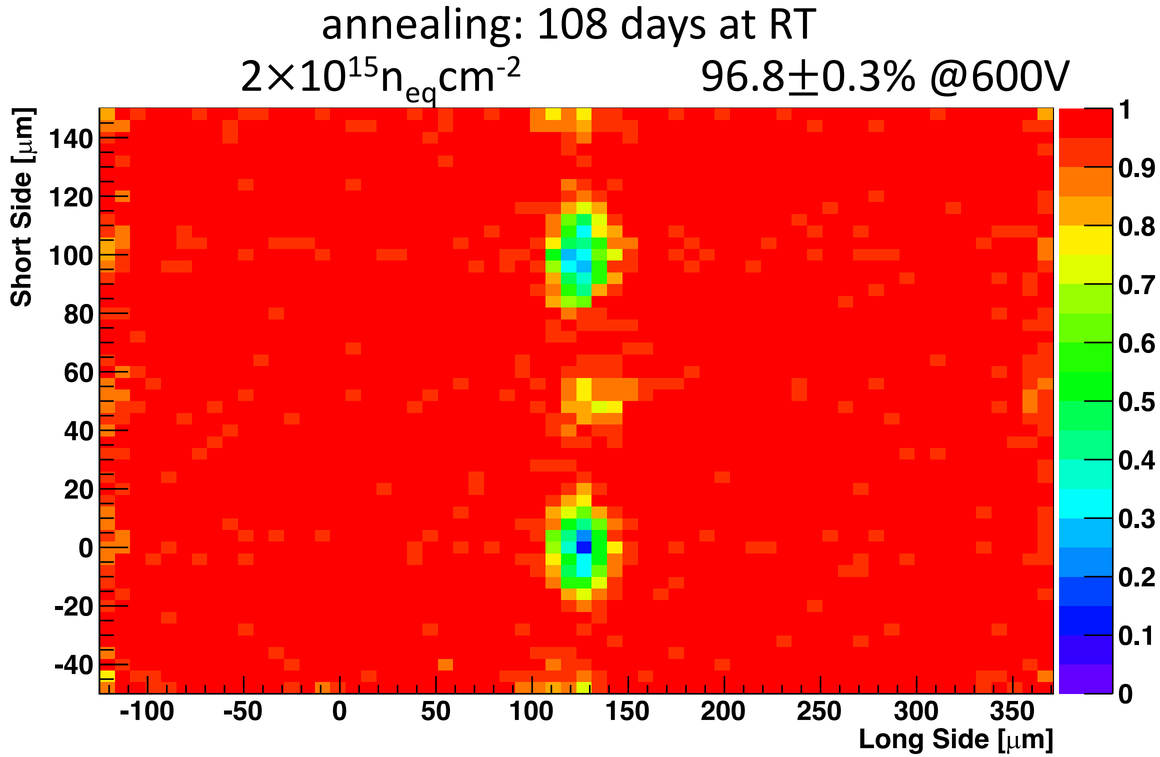
module	producer	thickness [μm]	irradiation [$n_{eq}cm^{-2}$]	annealing
1	HLL	150	2×10^{15}	108 days at RT
2	HLL	100	5×10^{15}	36 / 144 days at RT
3	CiS	150	1×10^{16}	100hrs at 60°C (13 month at RT[1])

[1] U.Parzefall, Trento meeting: scaling factor k≈100

Testbeam studies

Results: HLL, 150µm, $2\times10^{15} n_{eq} cm^{-2}$, short annealing



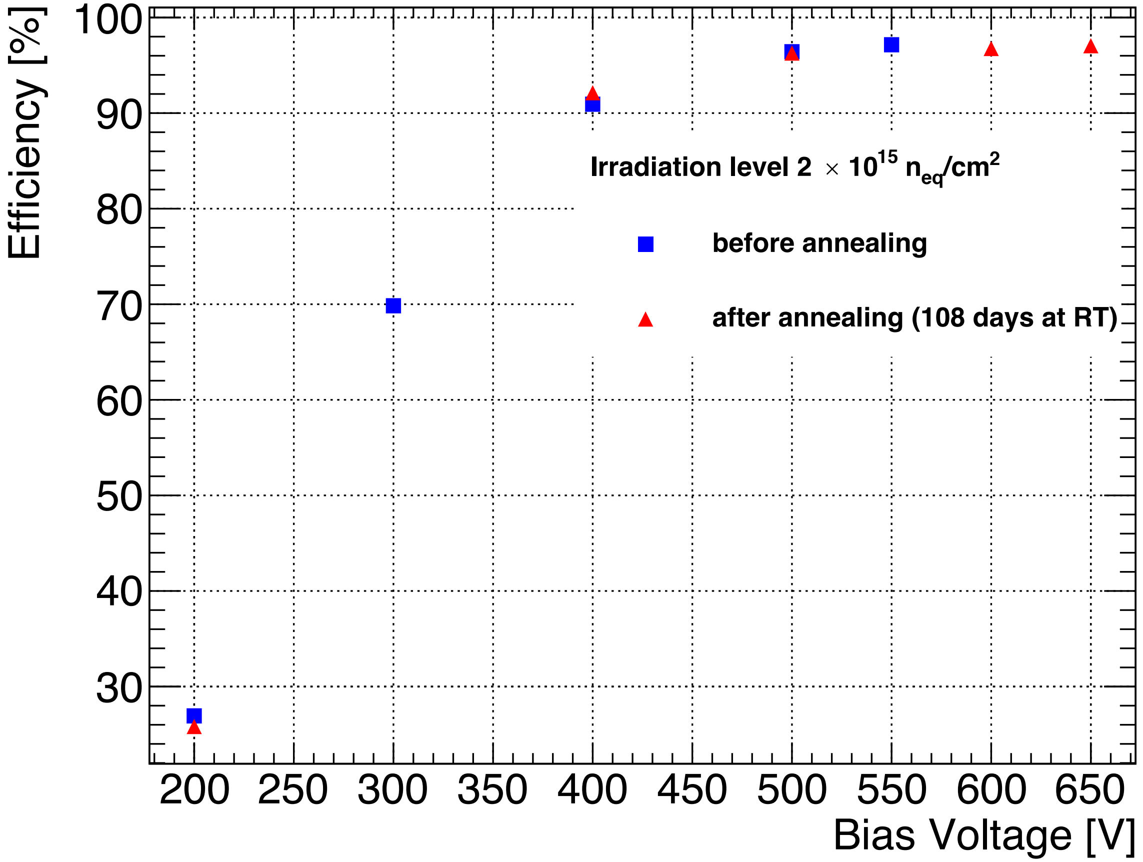


- 4x2 pixel efficiency map before (left) and after (right) annealing
- no degradation of efficiency: 97.2% → 96.8%

Testbeam studies

Results low irradiated module (1)

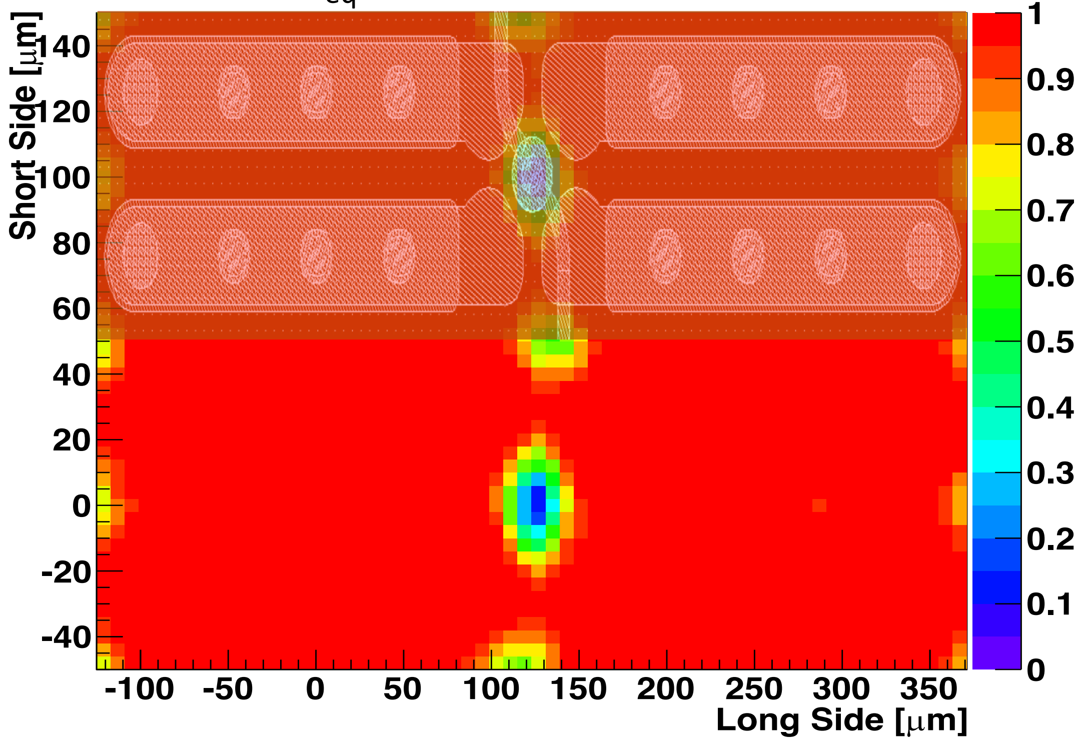
- module 1 ($2\times10^{15}n_{eq}cm^{-2}$, 108 days at RT):
  - no difference between before and after annealing



Testbeam studies

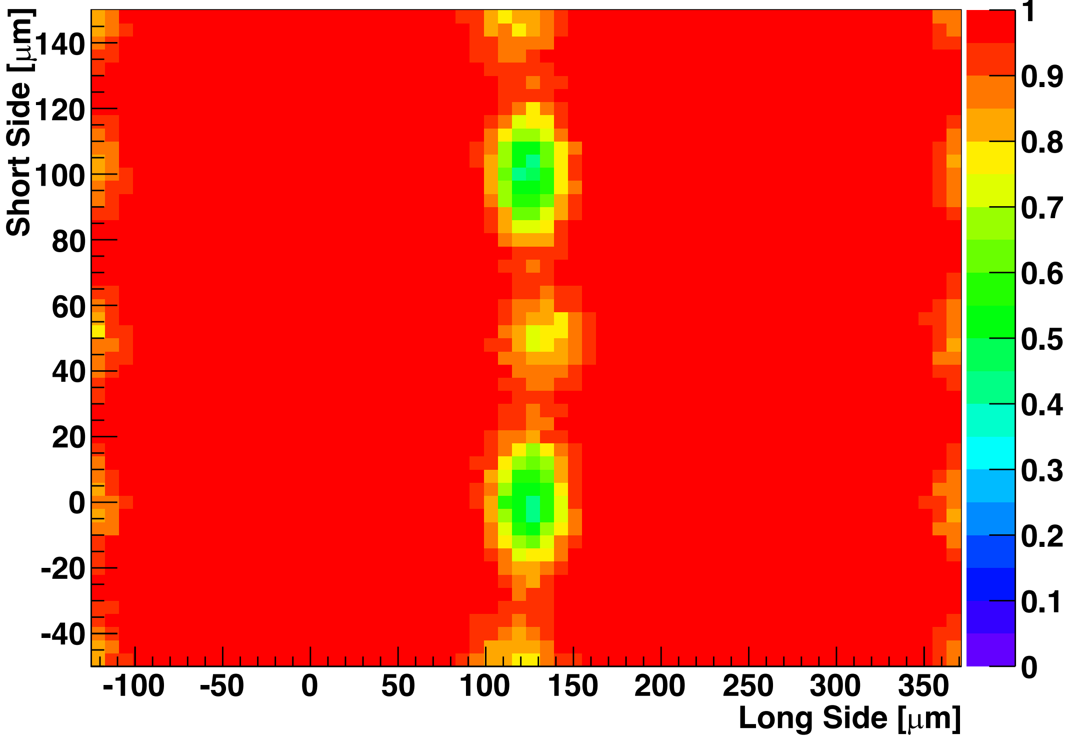
Results: 100μm, $5\times10^{15} n_{eq} cm^{-2}$, medium annealing

$5\times10^{15} n_{eq} cm^{-2}$ 97.1±0.3% @600V



annealing: 36 days at RT

$5\times10^{15} n_{eq} cm^{-2}$ 97.0±0.3% @600V

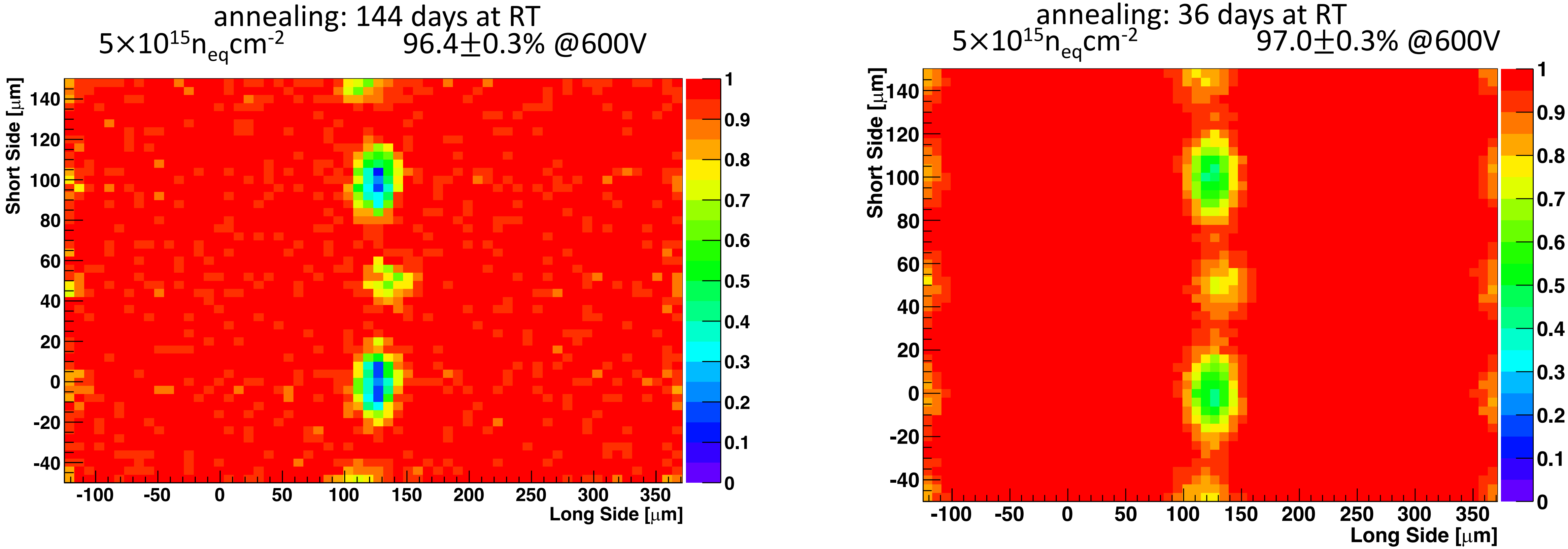


- 4x2 pixel efficiency map before (left) and after (right) annealing
- no degradation of efficiency: 97.1% → 97.0%

- efficiency loss at the PT dot reduced
  - after 36 days at RT

Testbeam studies

Results: 100µm, $5\times10^{15} n_{eq}cm^{-2}$, medium annealing



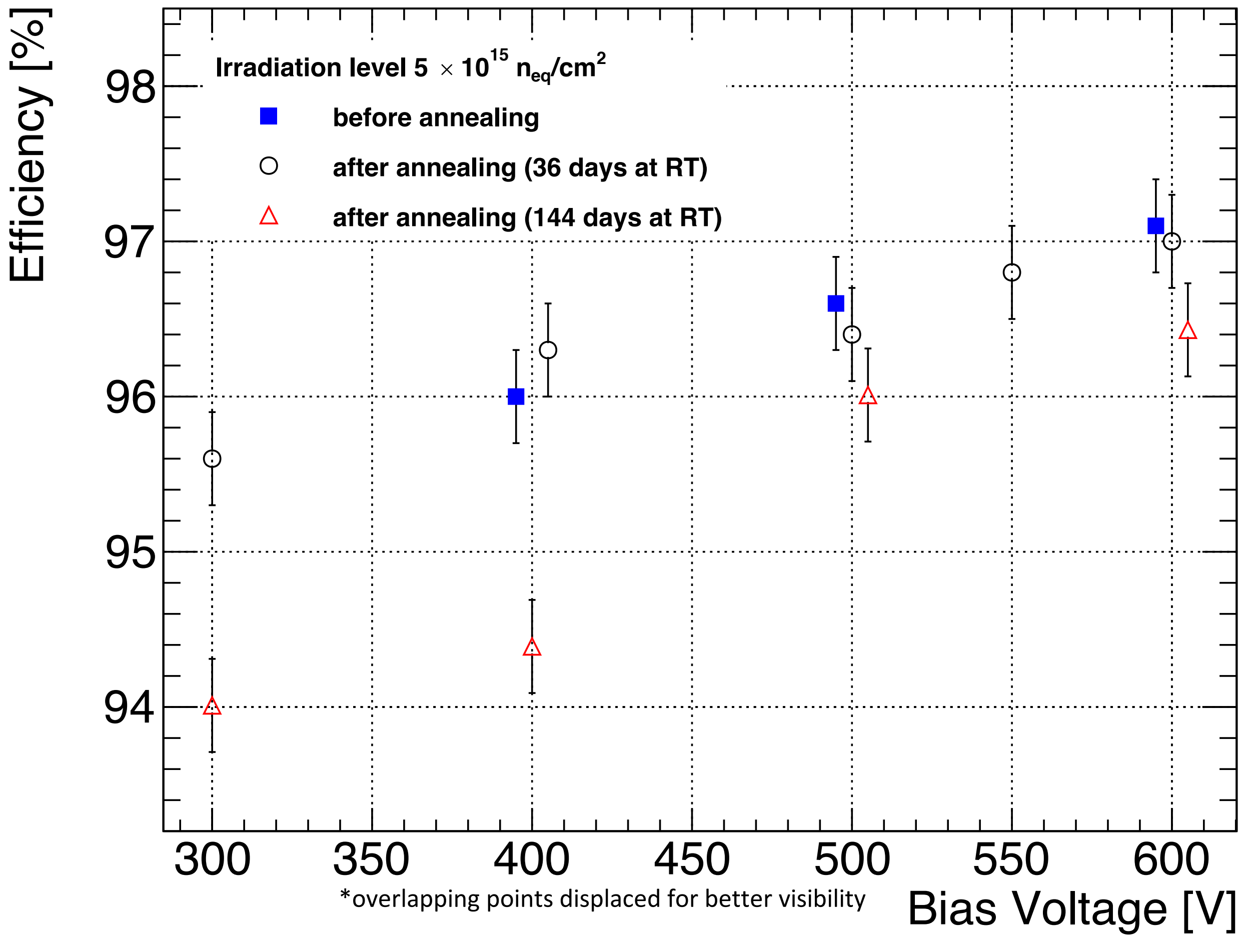
- 4x2 pixel efficiency map after 144 days (left) and 36 days (right) of annealing
- no degradation of efficiency: 97.1% → 97.0% → 96.4%

- efficiency loss at the PT dot reduced
  - after 36 days at RT
  - after 144 days at RT again increased

Testbeam studies

Results: 100µm, $5\times10^{15}n_{eq}cm^{-2}$, medium annealing

- module 2 ($5\times10^{15}n_{eq}cm^{-2}$):
  - 36 days at RT: no difference compared to no annealing
  - 144 days at RT: slightly reduced efficiency at low bias voltages, indistinguishable above 500V
    - might hint to increased depletion voltage due to reverse annealing

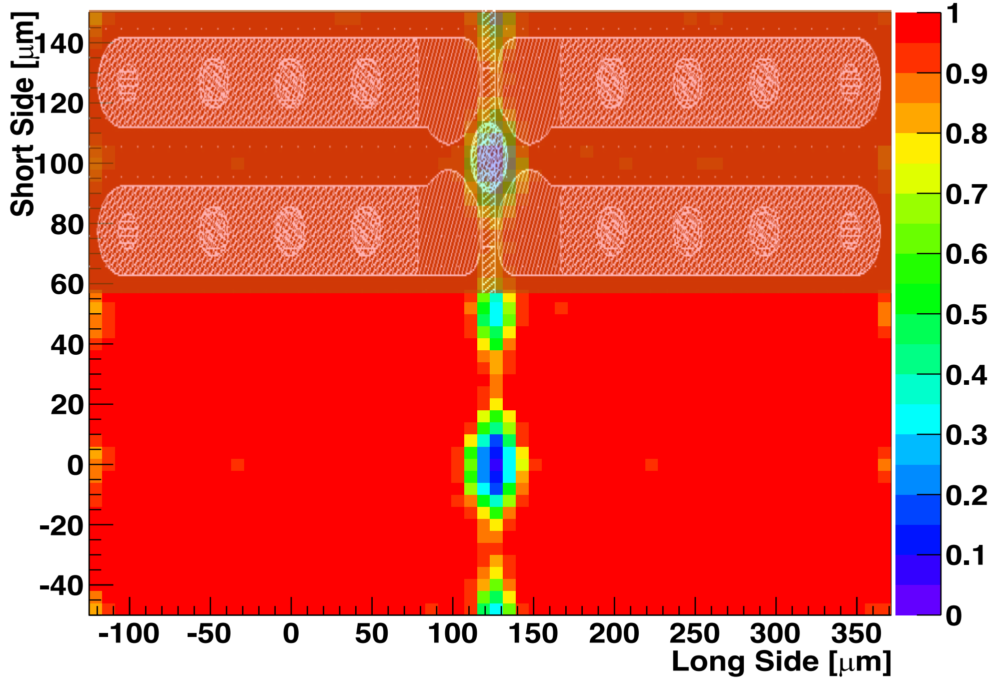


*overlapping points displaced for better visibility

Testbeam studies

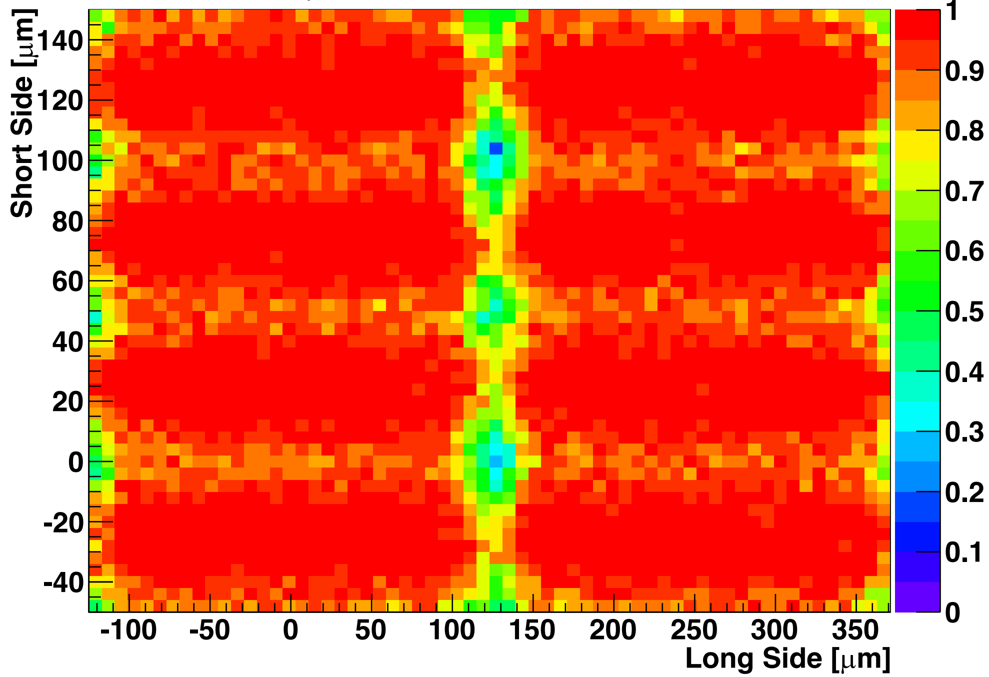
Results: 100μm, $1\times10^{16} n_{eq} cm^{-2}$, long annealing

$1\times10^{16} n_{eq} cm^{-2}$ 96.6±0.3% @800V



annealing: 13 months at RT equivalent

$1\times10^{16} n_{eq} cm^{-2}$ 92.2±0.3% @800V



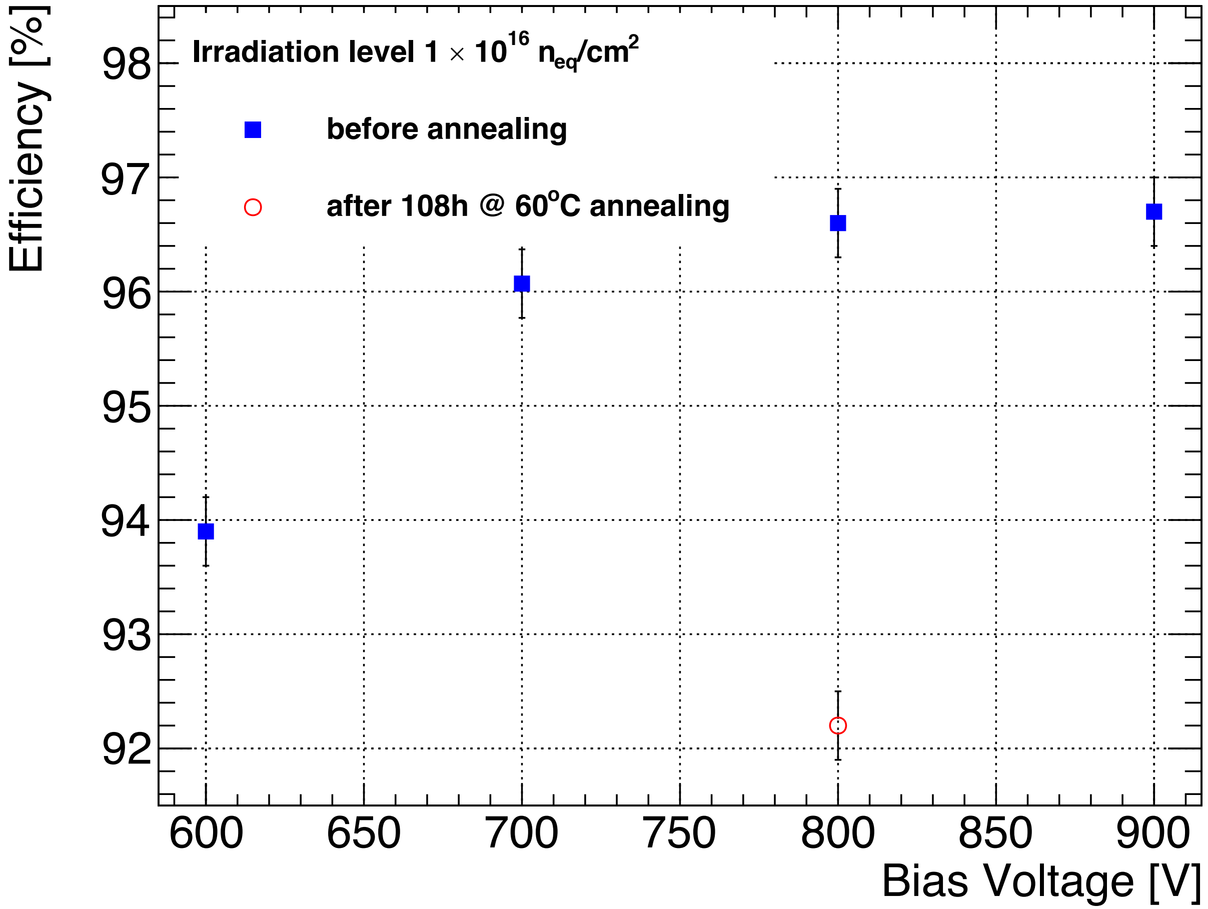
- 4x2 pixel efficiency map before (left) and after (right) annealing
- significant degradation of efficiency: 96.6% → 92.2%
- efficiency loss between two and four pixels intensified

- efficiency loss at the PT dot reduced
  - after very long annealing
  - under investigation

Testbeam studies

Results: 100µm, $1\times10^{16}n_{eq}cm^{-2}$, long annealing

- module 3 ($1\times10^{16}n_{eq}cm^{-2}$, 108h at 60°C annealing):
  - significantly reduced efficiency after accelerated annealing corresponding to 13 months at RT



Summary

1. TCAD simulation of thin sensors with small pixel cells
    - larger implants are beneficial
        - certainly for break-down voltage
        - probably for charge collection efficiency (negligible?!)
    - larger implants are detrimental
        - larger implants result in larger capacity → more noise
        - needs to be quantified by simulation

2. Testbeam measurements of annealed modules
    - insignificant degradation of efficiency up to 144 days at RT after 2/5 $\times 10^{15} n_{eq} cm^{-2}$
    - significant degradation of efficiency after 108h at 60°C (→ 13 months at RT) and $1\times 10^{16} n_{eq} cm^{-2}$

Thank you for your attention!

Backup

Title

subtitle

- text