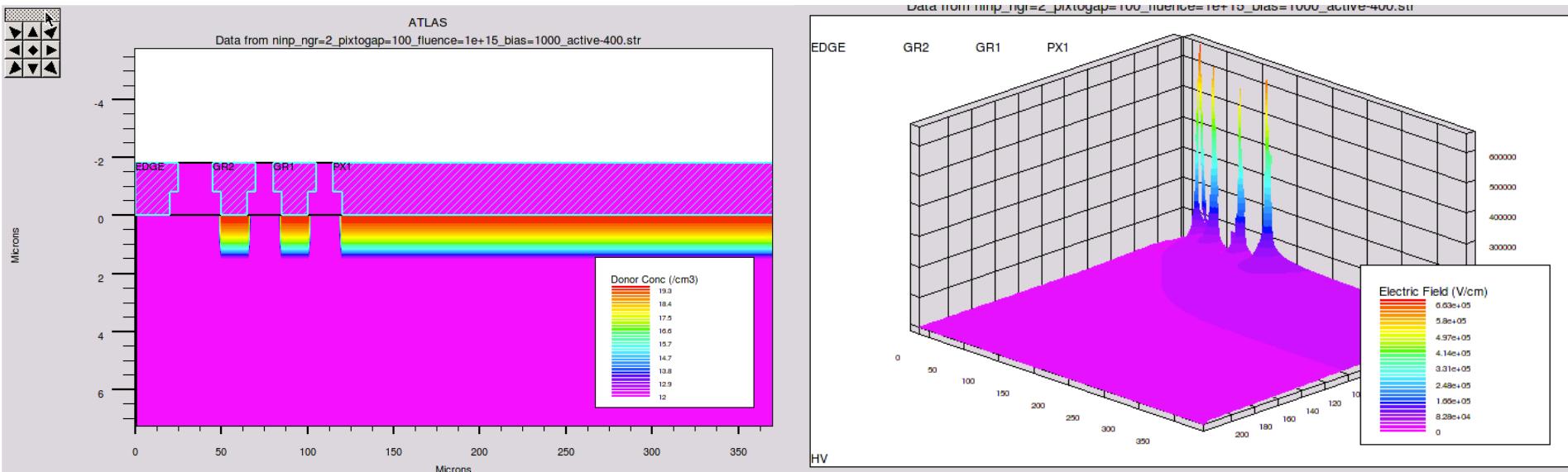


# Journée simulations du réseau semiconducteurs

## TCAD simulations of edgeless pixel sensors aimed at HL-LHC



Marco Bomben – LPNHE, Paris



# Outline

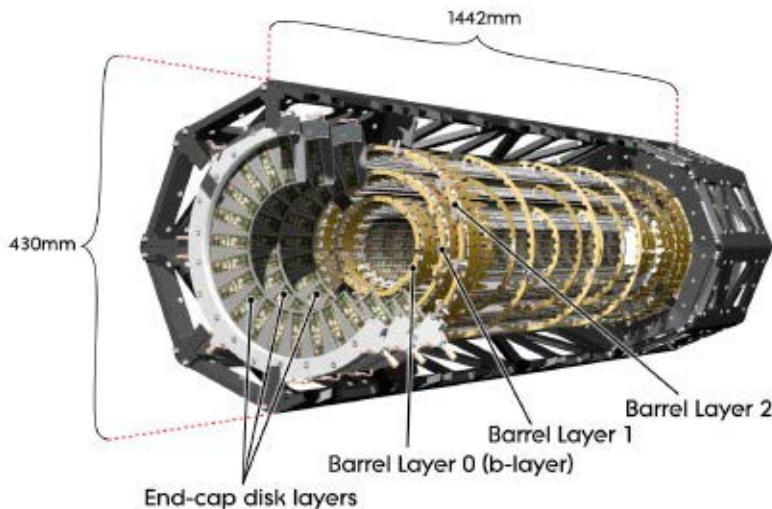
---

- Edgeless pixel sensors for the HL-LHC Atlas tracker
- Simulations of the FBK-LPNHE edgeless production
  - Introduction to SILVACO
  - Design studies
  - Electrical characterization
  - Expected behavior after irradiation
  - Simulated charge collection, before and after irradiation
  - Comparison to data whenever is possible
- Conclusions & Outlook

**SILVACO**

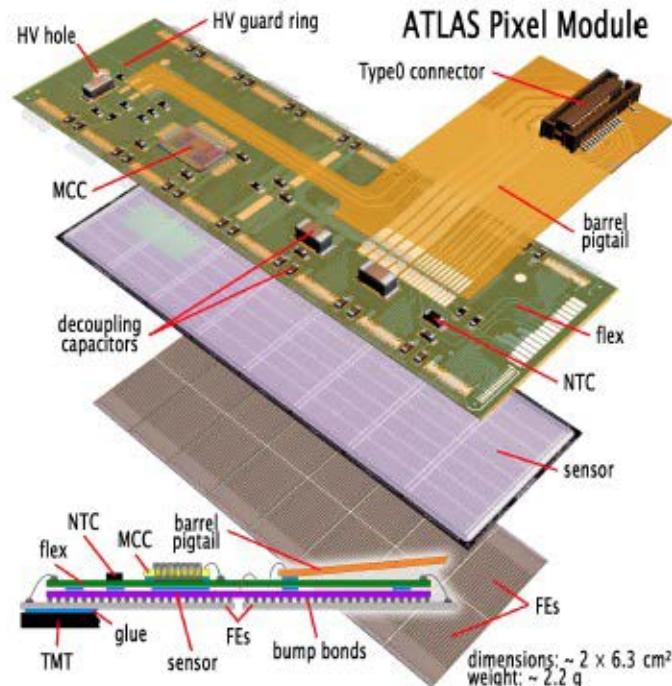
# **ATLAS PIXELS AND THE HL-LHC PHASE**

# The ATLAS Pixel detector

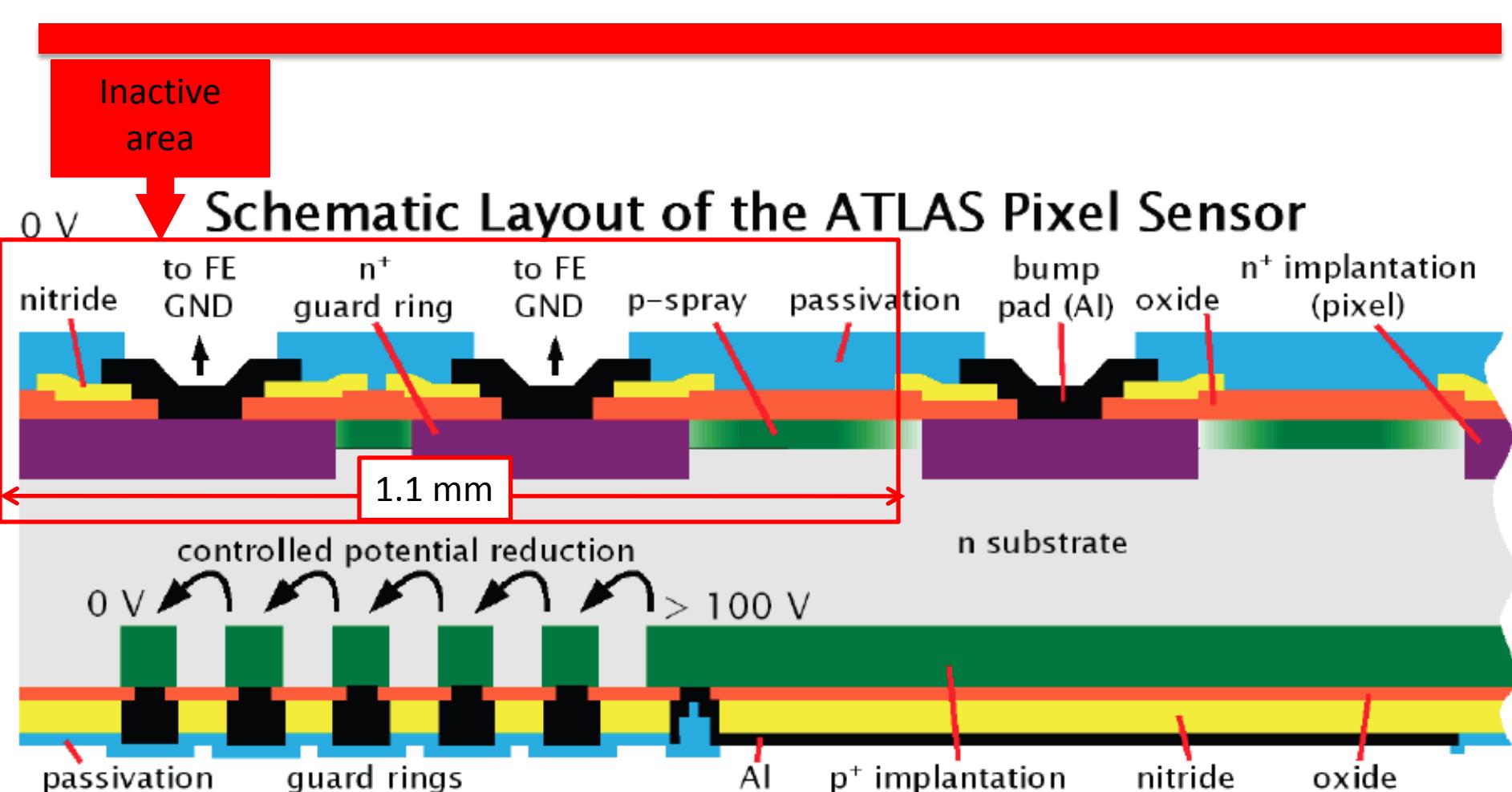


- **ATLAS Pixel Module**
  - 16 front-end chips (FE-I3) module with a Module Controller Chip (MCC)
  - 46080 R/O channels  $50\text{ }\mu\text{m} \times 400\text{ }\mu\text{m}$  ( $50\text{ }\mu\text{m} \times 600\text{ }\mu\text{m}$  for edge pixel columns between neighbour FE-I3 chips)
  - Planar n-in-n DOFZ silicon sensors, 250um tick
  - Designed for  $1 \times 10^{15}$  1MeV fluence and 50 Mrad
  - Optolink R/O: 40÷80 Mb/link

- **ATLAS Pixel Detector**
  - 3 barrels + 3 forward/backward disks
  - 112 stave and 4 sectors
  - 1744 modules
  - 80 million channels



# The current ATLAS pixel sensors



# The ATLAS long term upgrade

At the HL-LHC:  $3000 \text{ fb}^{-1}$  in 10 years;  $L_{\text{inst}} = 5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

## ➤ Physics reach for HL-LHC exp.:

Higgs: BR, couplings, self-coupling  
WW, ZZ scattering  
W', Z', quark substructure...

## ➤ Complete new tracker

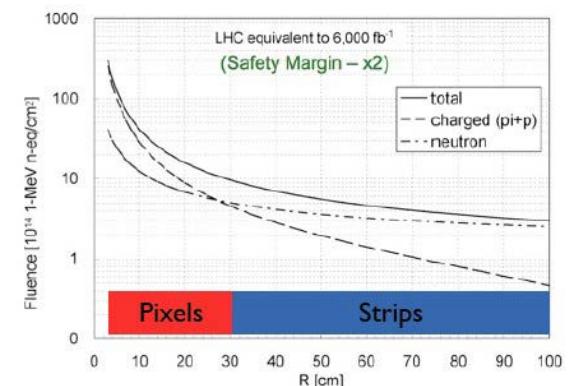
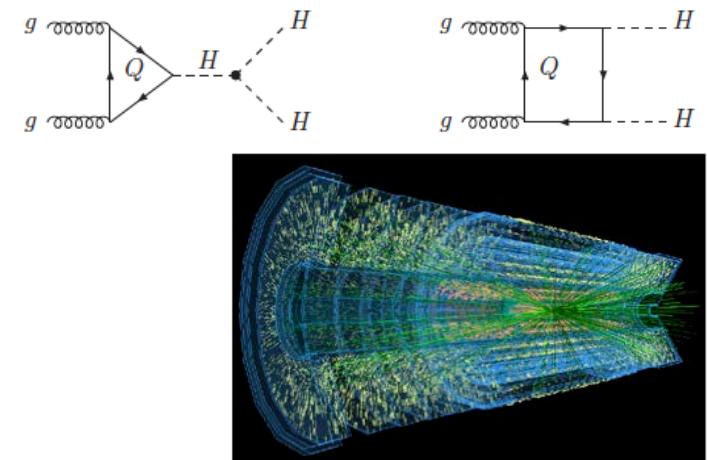
New layout: more pixel & strip layers, **forward extension**

## ➤ Critical R&D

Innermost pixel layer:

Expected **fluence** →  $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$

Expected integrated **dose** → 1 Grad



# Request on the new pixel sensors

- **Thin:** reducing the material budget, coping with charge trapping
- **Cheap:** large area to be instrumented –  $O(10 \text{ m}^2)$
- **Efficient:** very limited modules tiling in the innermost layers



## SLIM EDGE DETECTORS

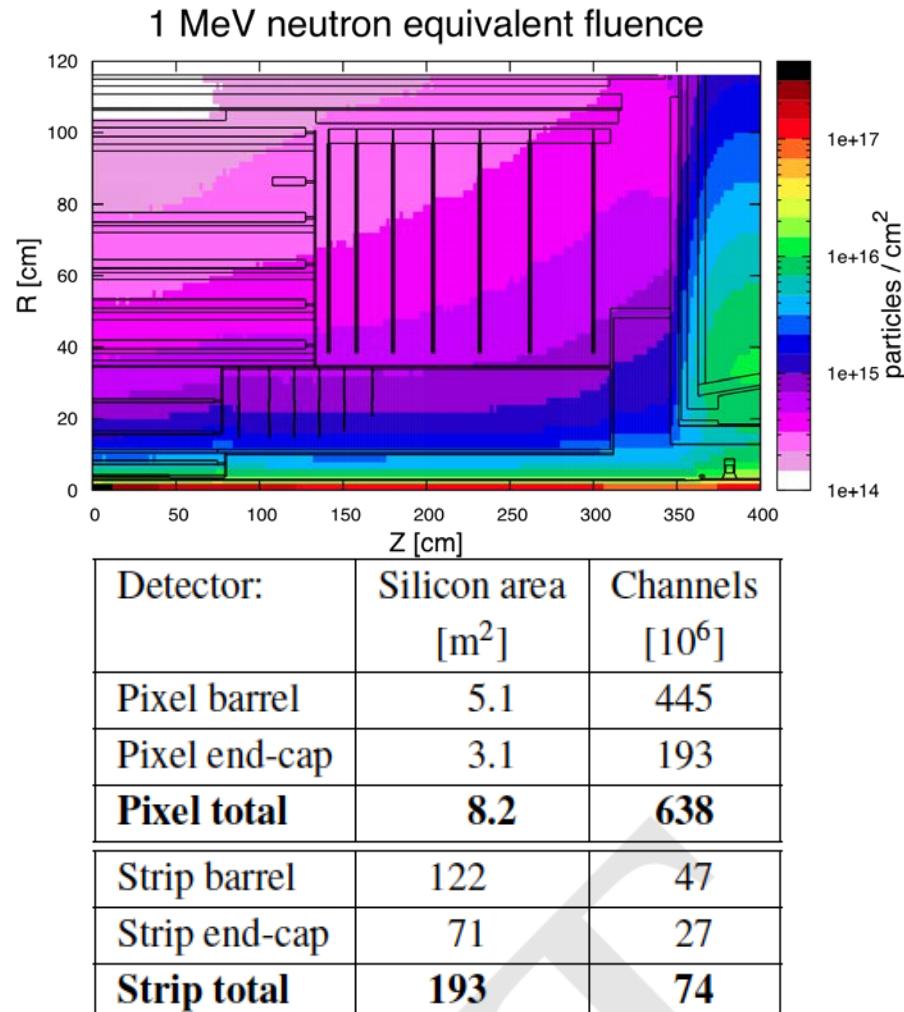


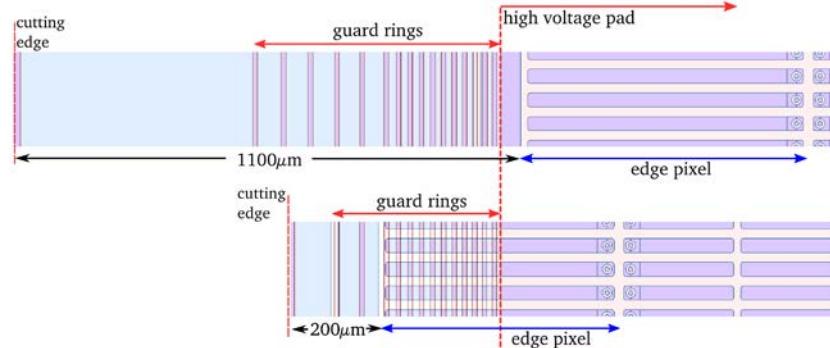
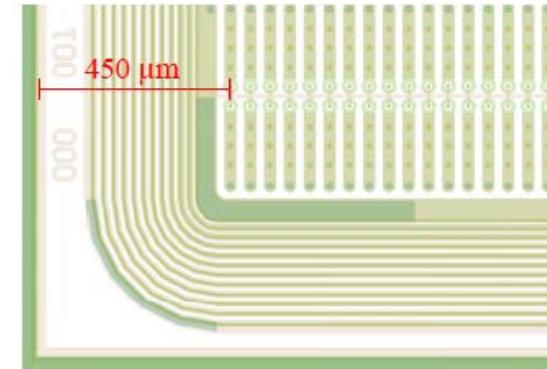
Table 6.6: Inner tracker active area and channel count.

# Slim edges: a primer

- Slim edges can be achieved by:

## ➤ Geometry optimization

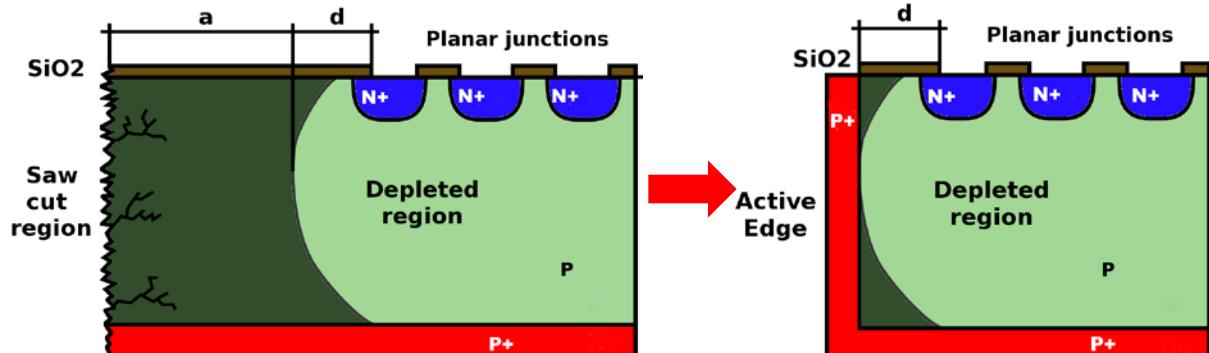
- N-on-p: Micron/Liverpool prototypes
- N-on-n: TU Dortmund/CiS → IBL
  - ✓ Dead area  $\sim 200 \mu\text{m}$
  - ✓ Approved for IBL



## ➤ Active edges

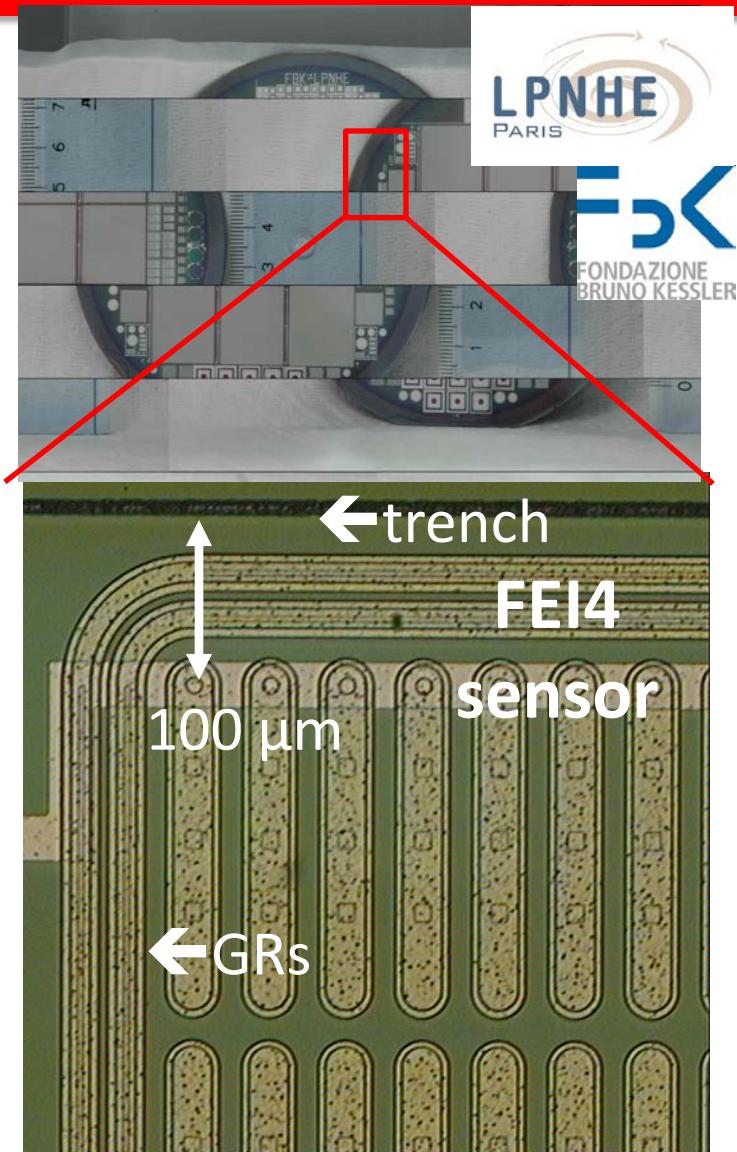
- 2 technologies

1. DRIE
2. SCP



# Deep Reactive Ion Etching: FBK-LPNHE

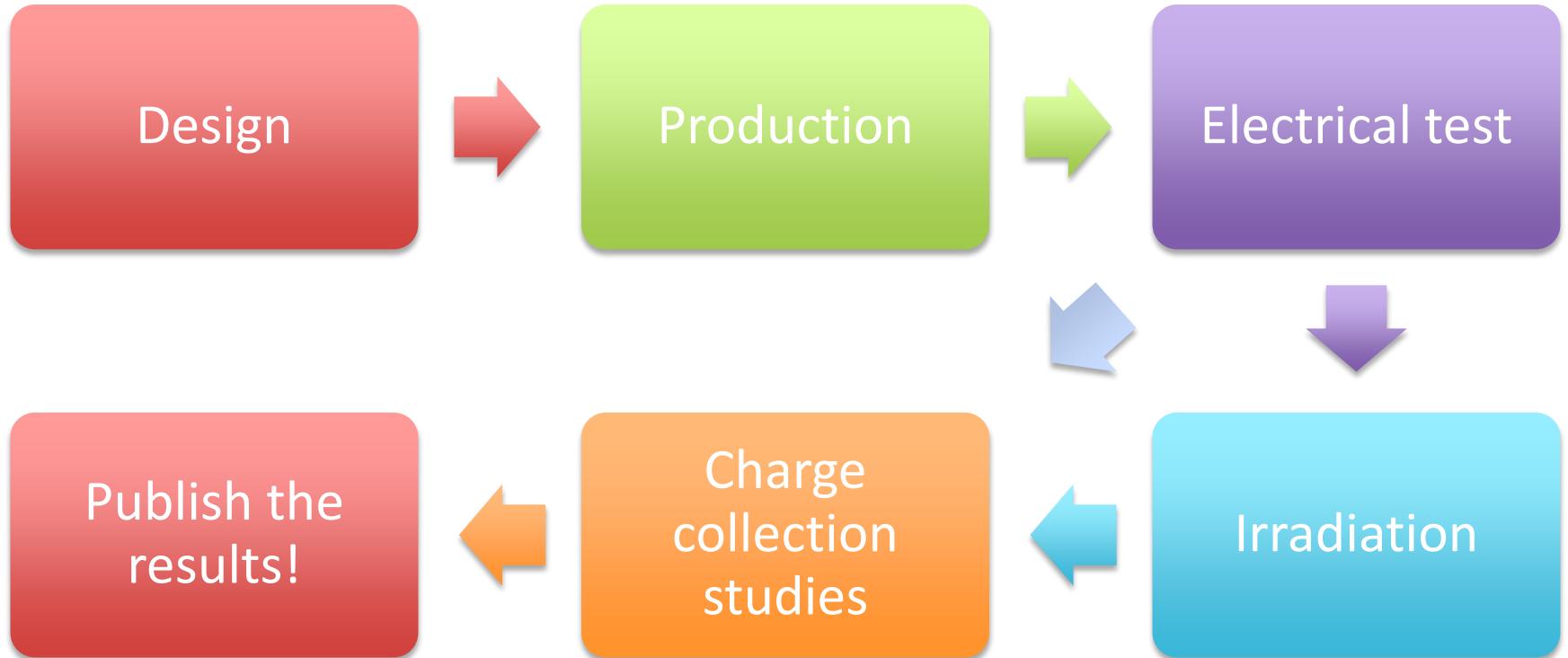
- Joint FBK-LPNHE project
- Goal: make the border a damage free ohmic contact
- How: DRIE as for 3D process
  - Trench doped by diffusion
- Target: intermediate layers (200  $\mu\text{m}$  thick production)
- Pixel-to-trench distance as low as 100  $\mu\text{m}$



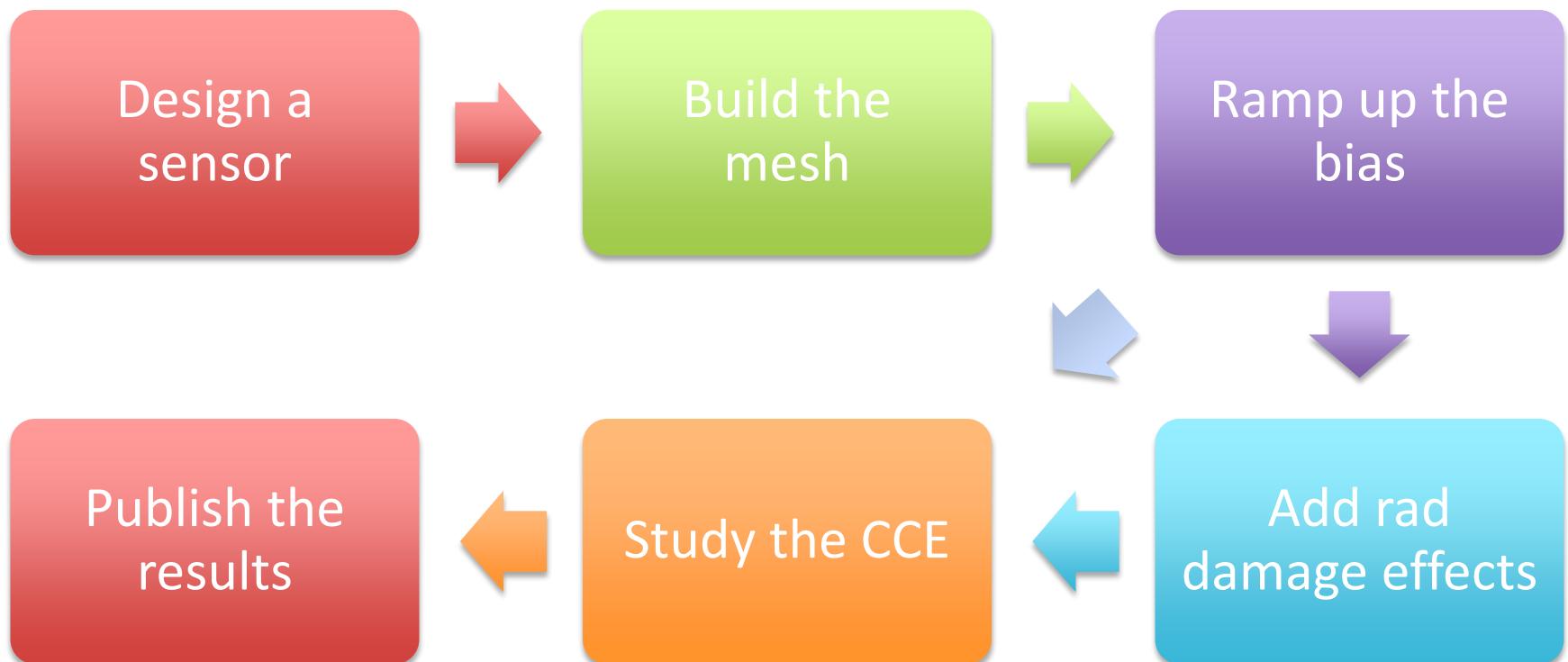
# **TCAD SIMULATIONS OF THE FBK-LPNHE EDGELESS PRODUCTION**

**SILVACO**

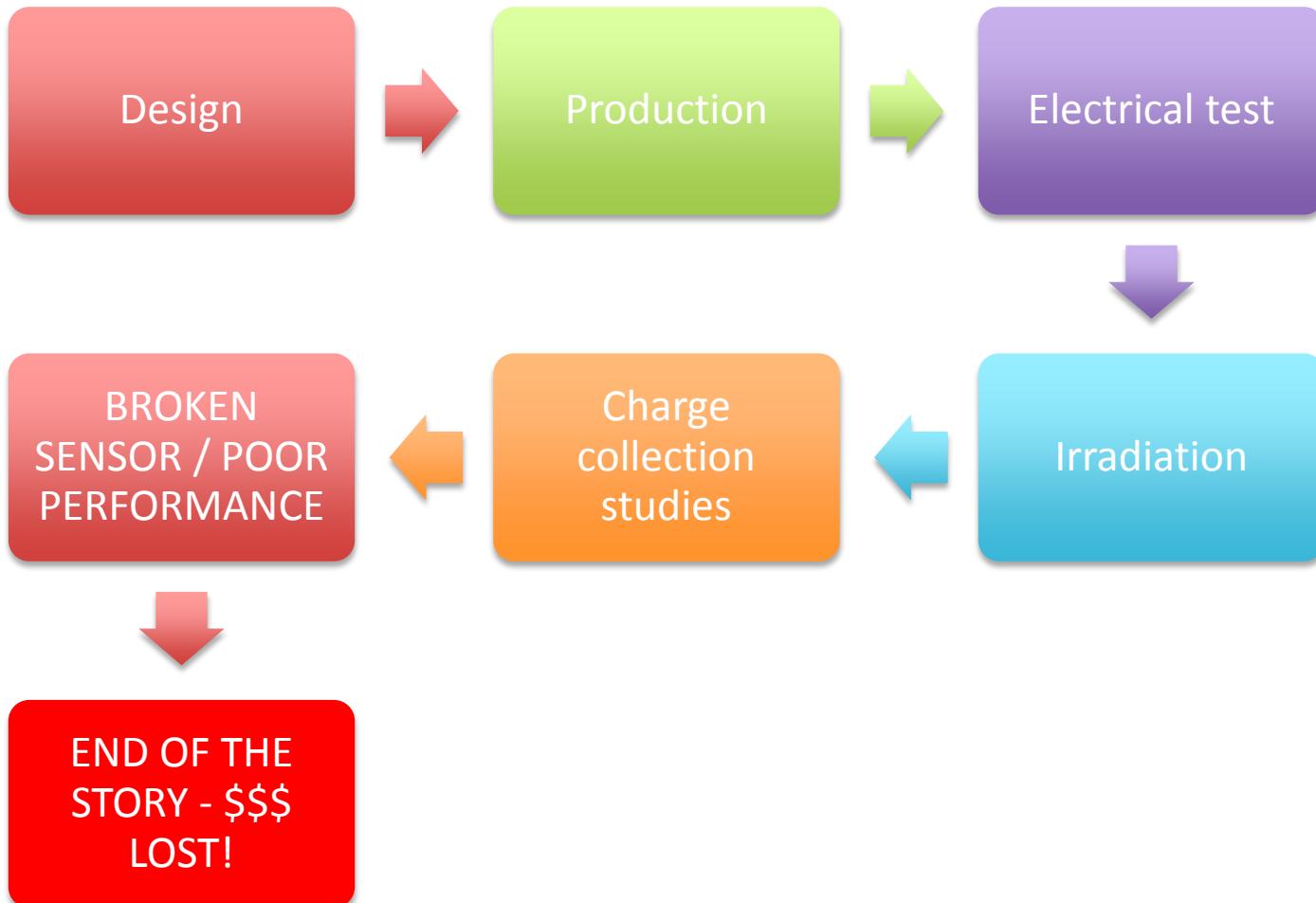
# Normal work flow for a HEP silicon sensors



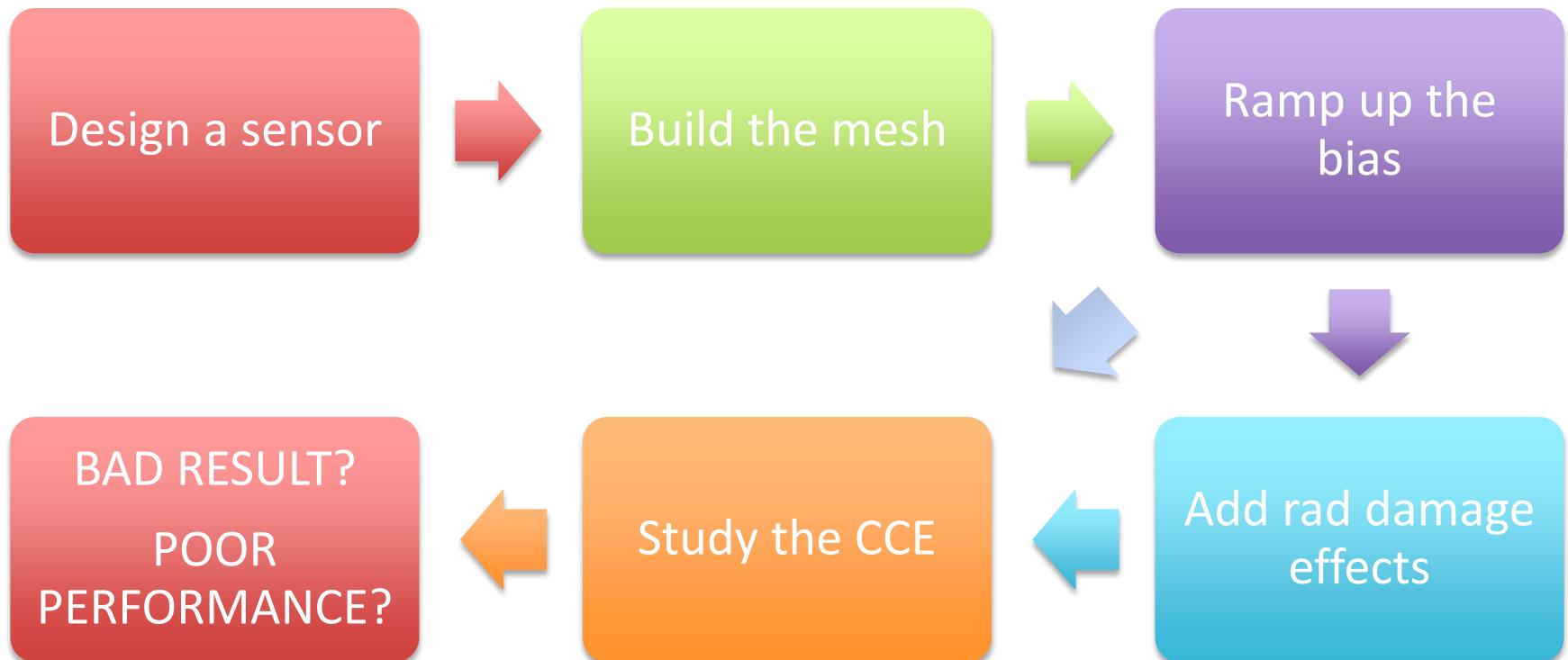
# TCAD simulation work flow



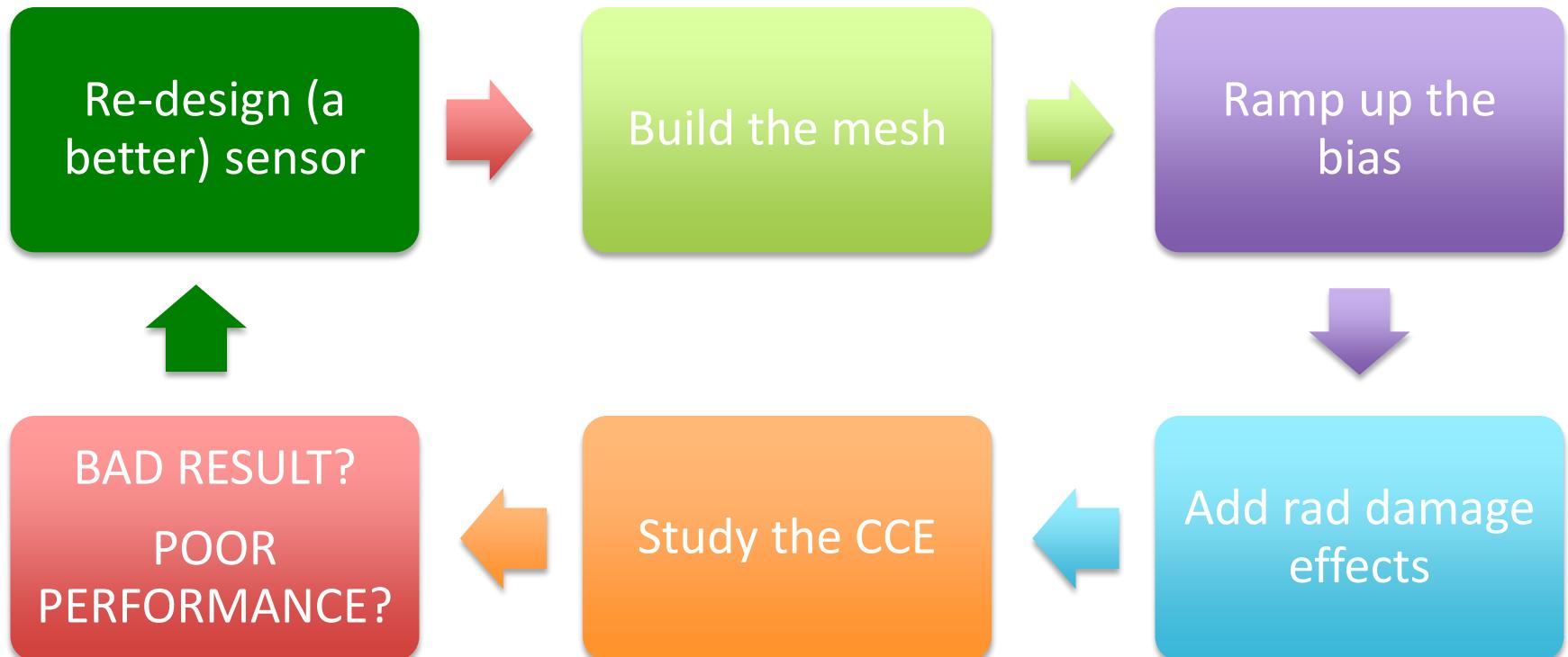
# Possible work flow for real sensors



# TCAD simulation work flow

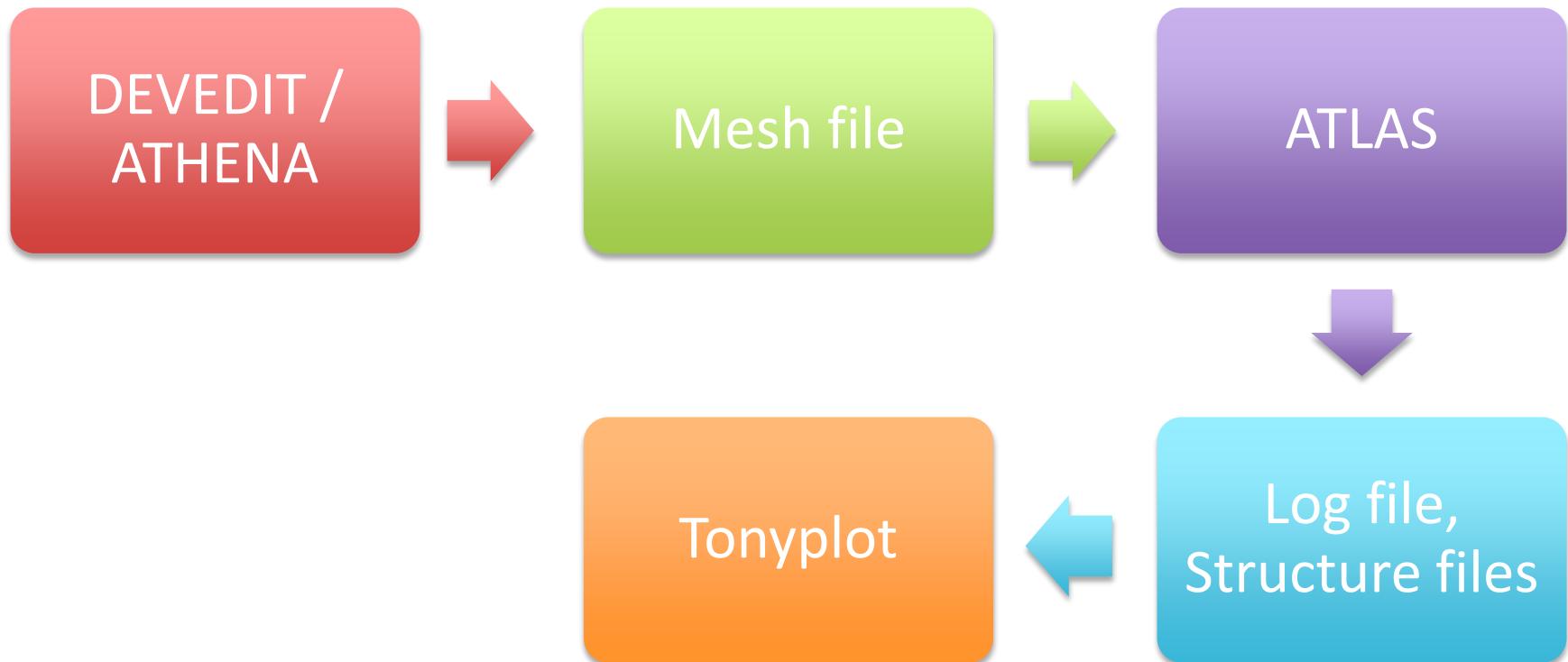


# TCAD simulation work flow



# Silvaco TCAD packages & work flow

## DECKBUILD

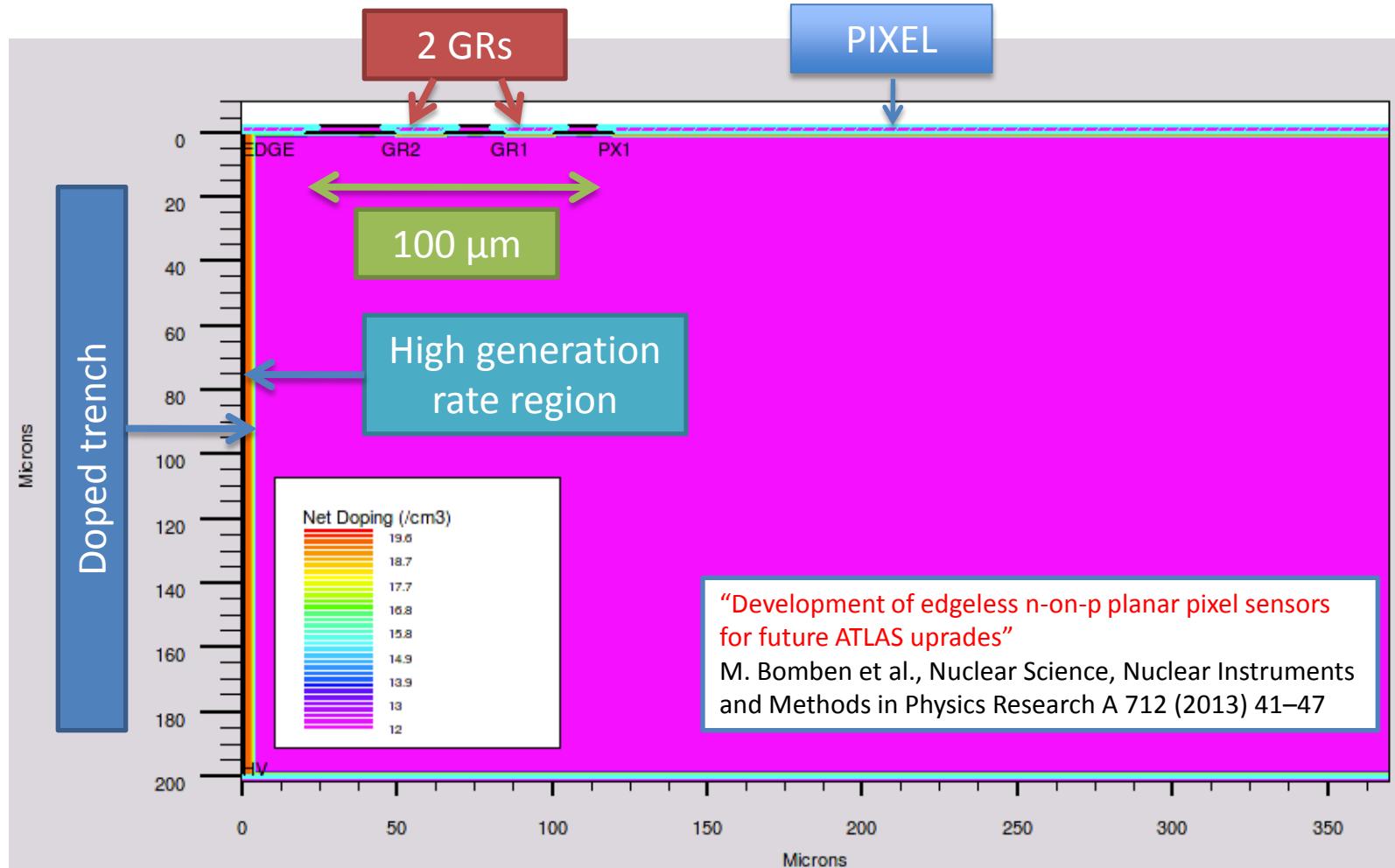


# Simulation studies for an edgeless production

## Goals of the **simulation** studies:

- Understand the **operability** of the device
  - BD voltage vs bias voltage
  - **Optimization** of: pixel-to-trench distance, # of GRs, GR relative position, etc
- Anticipate the sensor **performance**
  - Charge Collection Efficiency (CCE) at the sensor edge
  - **Simulation of CCE** with laser and MIPs
  - **Of irradiated sensors too!**

# The simulated device



# Devedit: device structure editor

Define implants, electrodes,  
oxidations, ecc using DEVEDIT

File View Edit Find Main Control Commands Tools

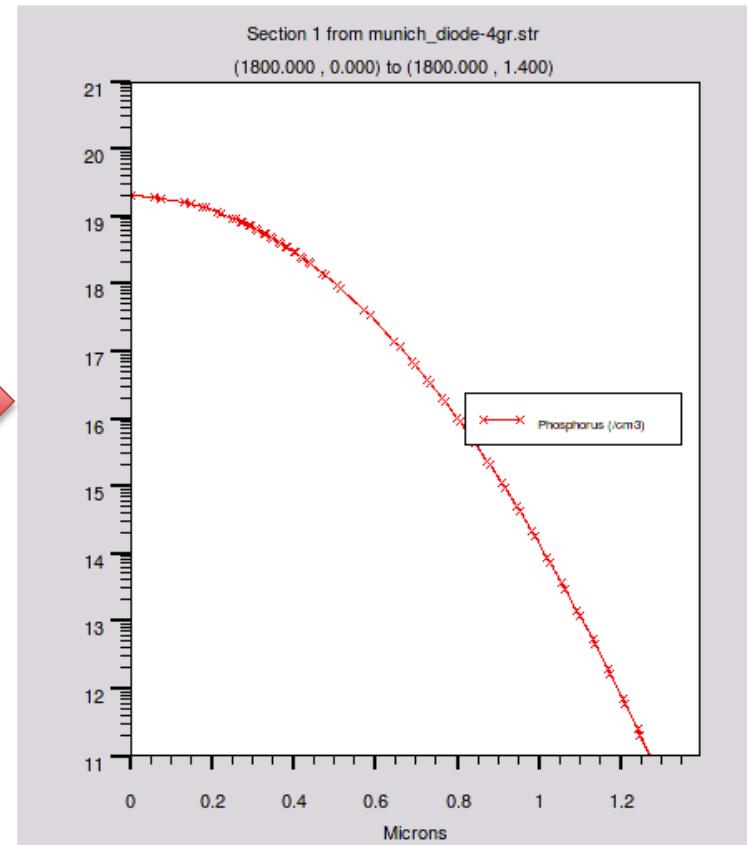
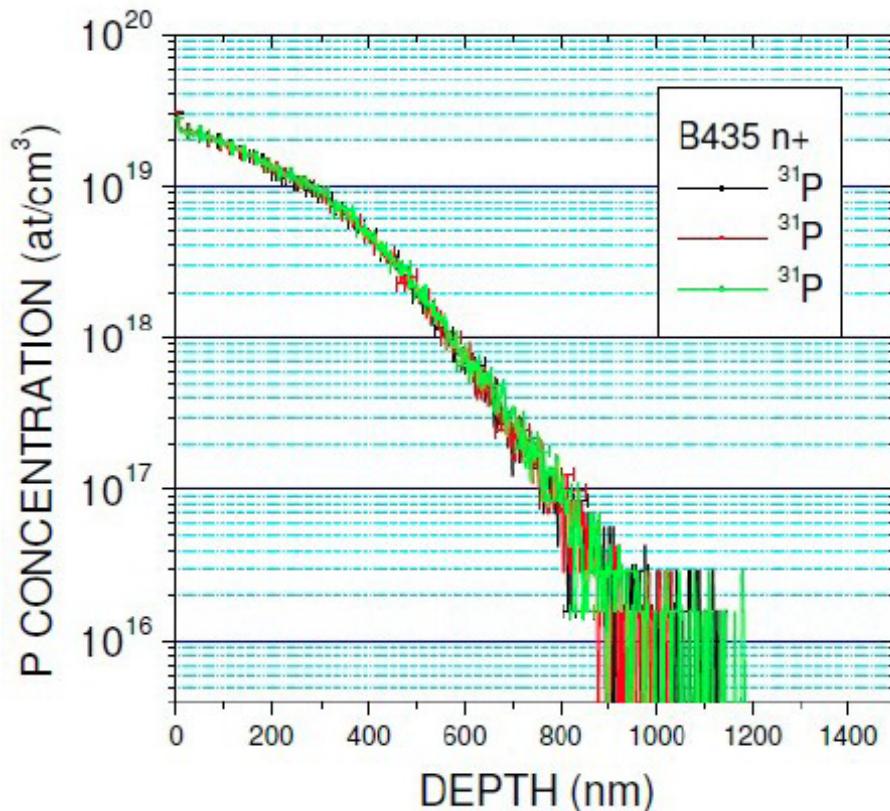
```
set pixel_rolloff = $nplus_rolloff
else
    set pixel_rolloff = $pplus_rolloff
if.end

set pix_x1=$x_left_implant-($pixel_rolloff*$nsigma_rolloff)
set pix_x2=$x_right_implant+($pixel_rolloff*$nsigma_rolloff)
set pix_y1=0-($pixel_rolloff*2*$nsigma_rolloff)
set pix_y2=0+($pixel_rolloff*2*$nsigma_rolloff)

if cond = ($pix_impurities_conc < 0)
    set pix_imp_c=$pix_impurities_conc
    impurity id=$id_impur imp=Phosphorus color=0x8c5d00 \
        peak.value=$pix_imp_c ref.value=1e16 \
        comb.func=Multiply \
        y1=0 y2=$pix_depth rolloff.y=high \
        conc.func.y=gauss.dist conc.param.y=$nplus_rolloff \
        x1=$x_left_implant x2=$x_right_implant rolloff.x=both \
        conc.func.x=gauss.dist conc.param.x=$nplus_rolloff
else
    impurity id=$id_impur imp=Boron color=0x8c5d00 \
        peak.value=$pix_impurities_conc ref.value=1e16 \
        comb.func=Multiply \
        y1=0 y2=$pix_depth rolloff.y=high \
        conc.func.y=gauss.dist conc.param.y=$pplus_rolloff \
        x1=$x_left_implant x2=$x_right_implant rolloff.x=both \
        conc.func.x=gauss.dist conc.param.x=$pplus_rolloff
if.end
```

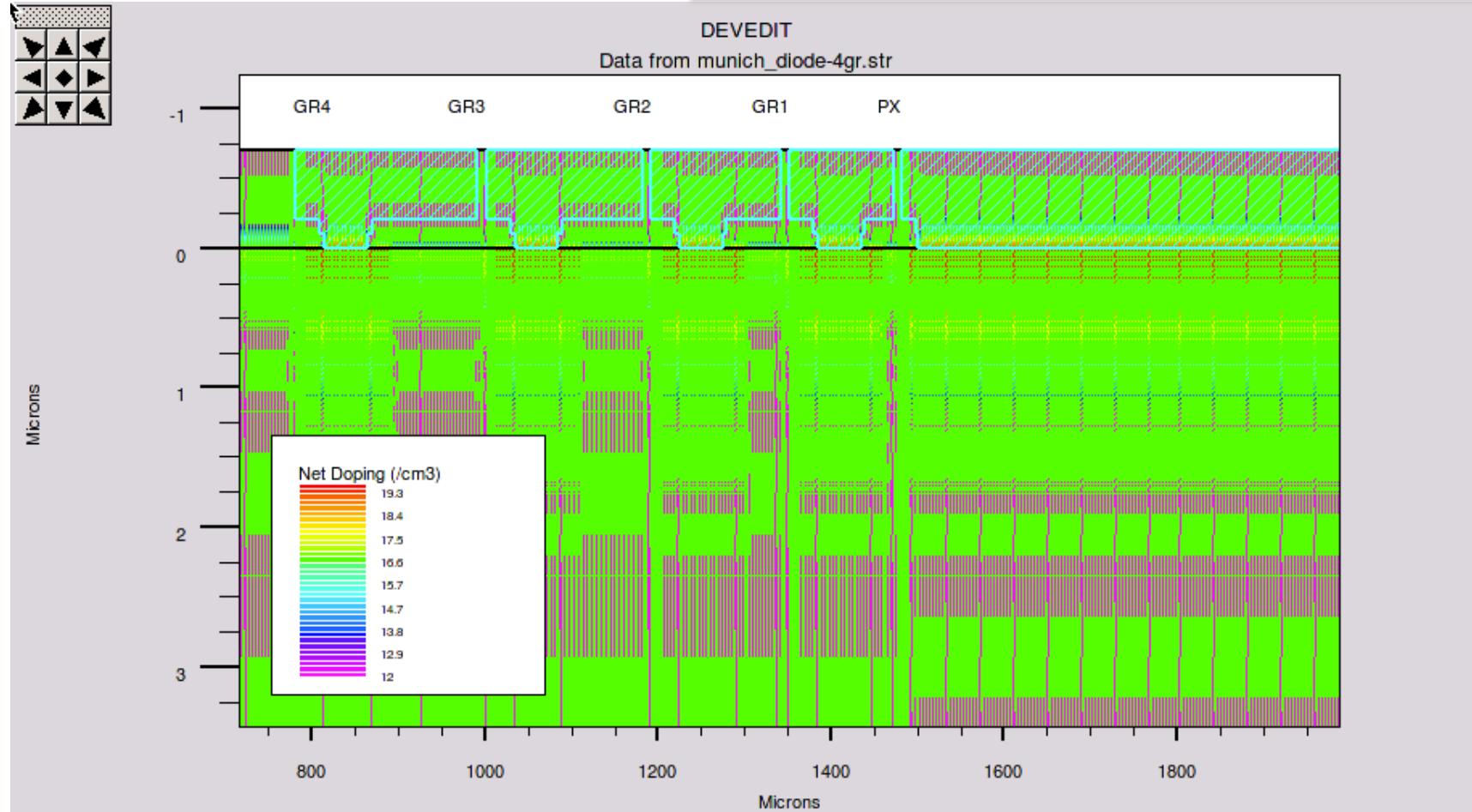
# TCAD inputs

- To get reliable predictions you need precise inputs; *e.g.* doping profiles via SIMS



# Mesh file view with Tonyplot

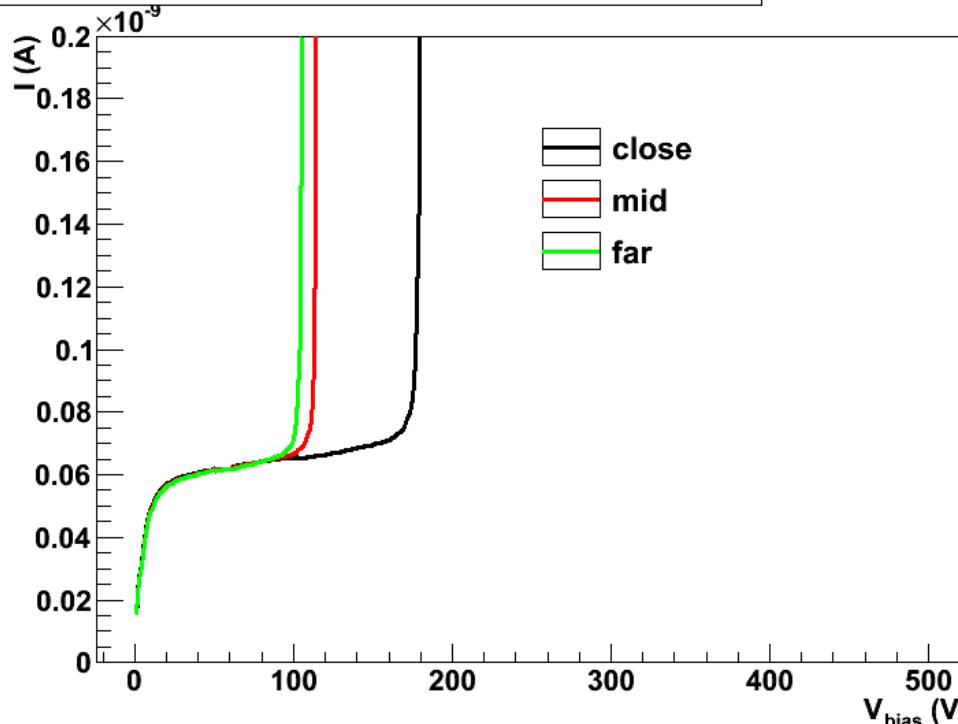
## Mesh structure



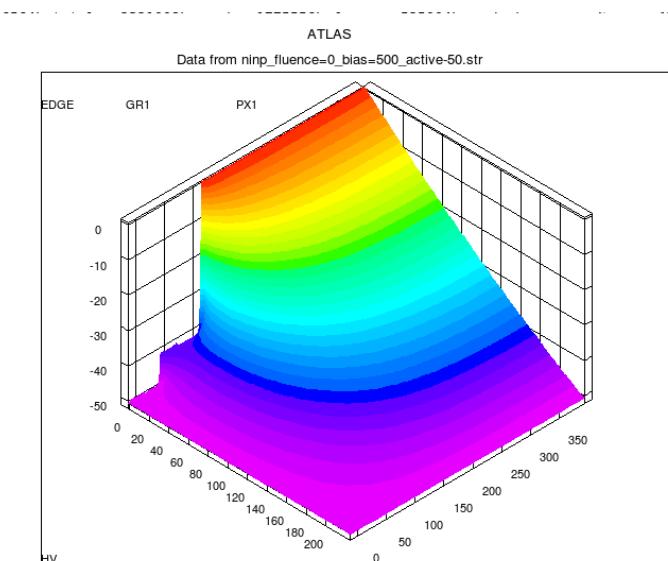
# Optimization of the GRs design

Various combinations of GR positions  
and their effect on BD

IV for devices with active edge - GR1, 100 $\mu\text{m}$  gap

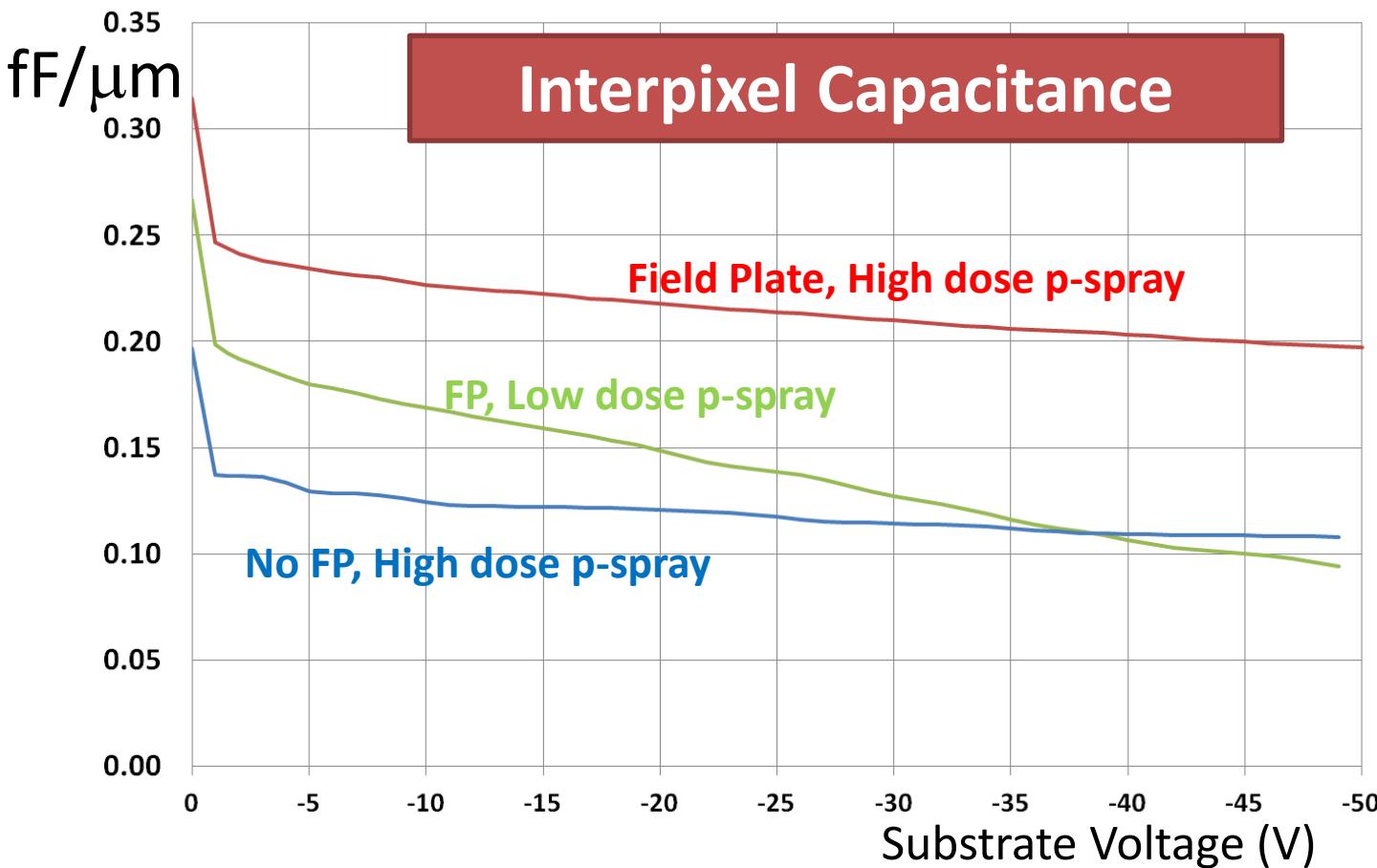


3D view of the electric potential



✓ The closer the GR to the pixel the better

# P-spray & field plate studied



➤ Prefer low p-spray dose with FP

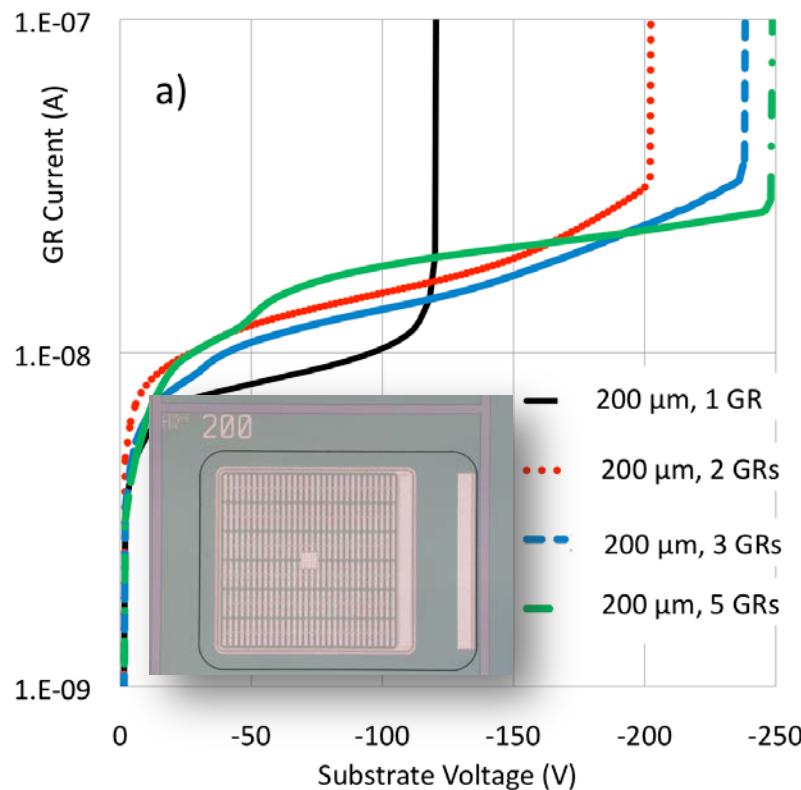
# ATLAS: device simulation

- ATLAS provides general capabilities for physically-based two (2D) and three-dimensional (3D) simulation of semiconductor devices.
- Typical simulation program structure →

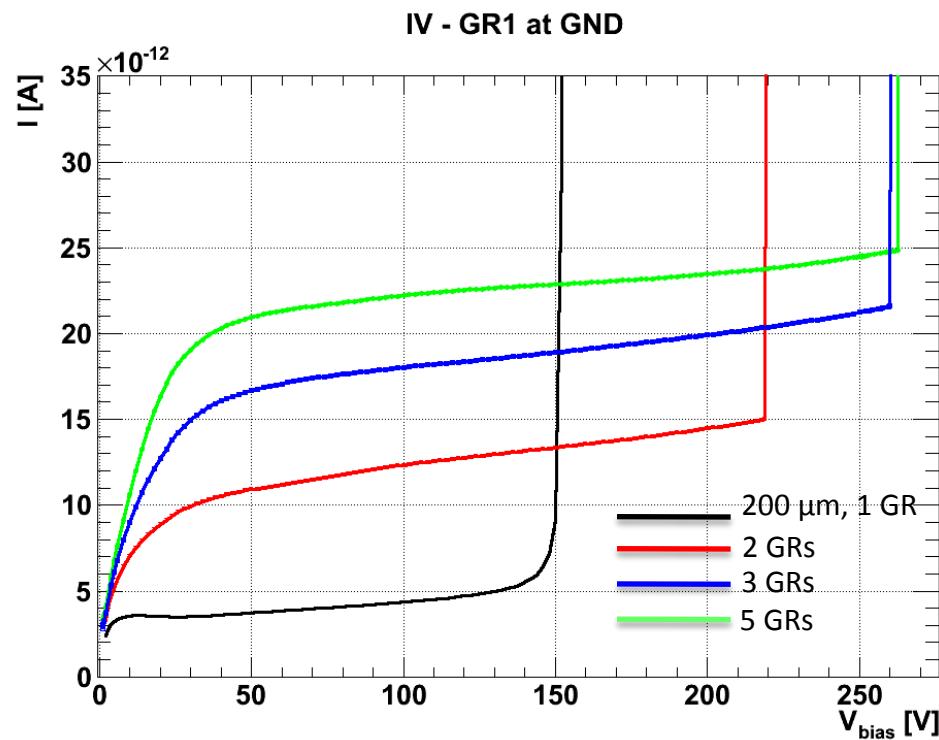
<i>Group</i>	<i>Statements</i>
1. Structure Specification	MESH REGION ELECTRODE DOPING
2. Material Models Specification	MATERIAL MODELS CONTACT INTERFACE
3. Numerical Method Selection	METHOD
4. Solution Specification	LOG SOLVE LOAD SAVE
5. Results Analysis	EXTRACT TONYPLOT

# IV curves of real sensors vs data

## DATA

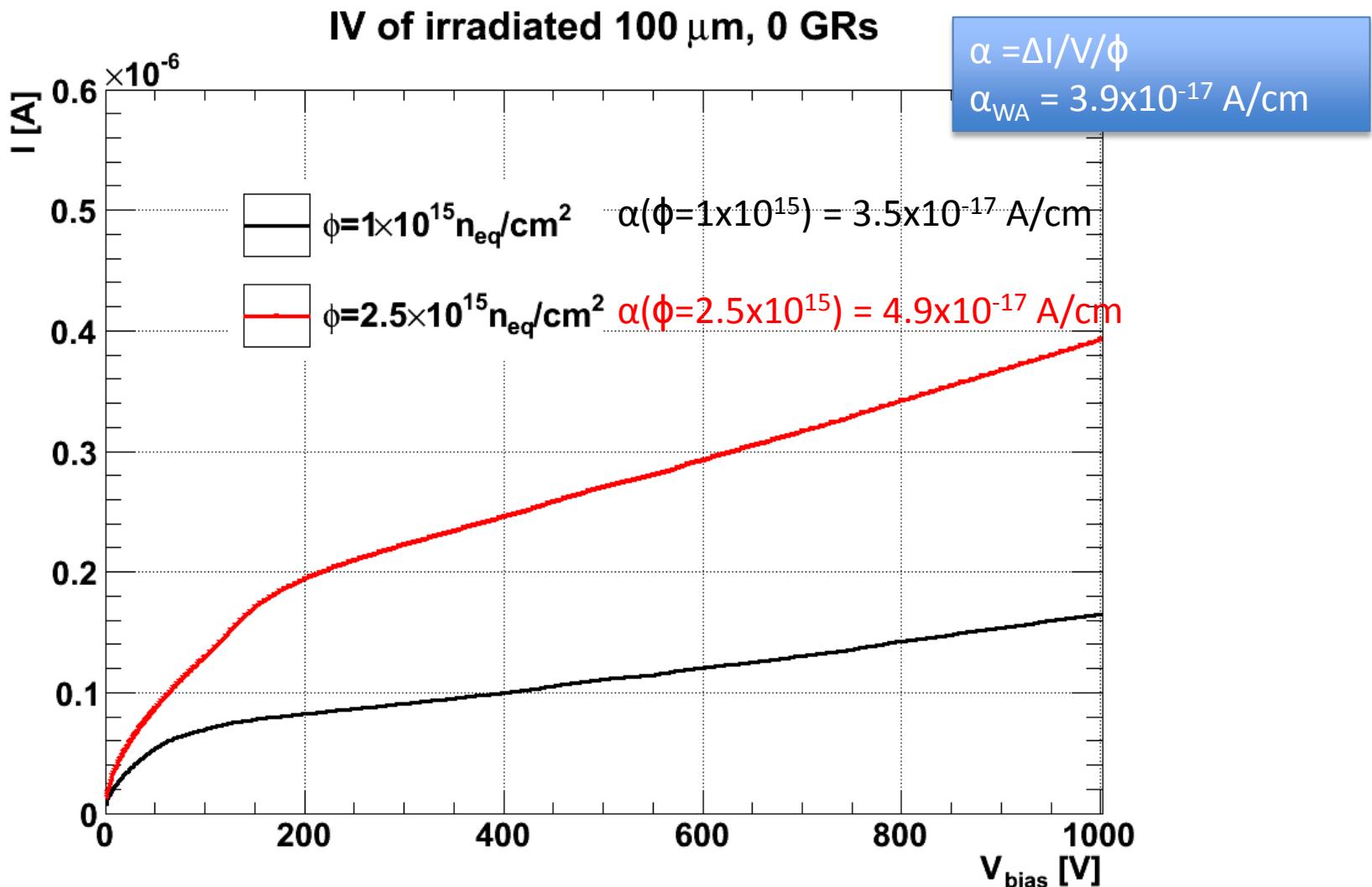


## SIMULATIONS



➤ BD: Agreement within 20% or better

# IV curves after irradiation



➤  $\alpha$ : Agreement within 20% (annealing not taken into account)

# Radiation damage effects

- Implement radiation damage effects via traps in the forbidden gap

$$N = \eta \times \phi$$

Type	Energy (eV)	$\sigma_e(\text{cm}^2)$	$\sigma_h(\text{cm}^2)$	$\eta(\text{cm}^{-1})$
A	$E_C$ -0.42	$9.5 \times 10^{-15}$	$9.5 \times 10^{-14}$	1.613
A	$E_C$ -0.46	$5.0 \times 10^{-15}$	$5.0 \times 10^{-14}$	0.9
D	$E_V$ +0.36	$3.23 \times 10^{-13}$	$3.23 \times 10^{-14}$	0.9 (1)

Radiation induced bulk damage mode by Pennicard et al.

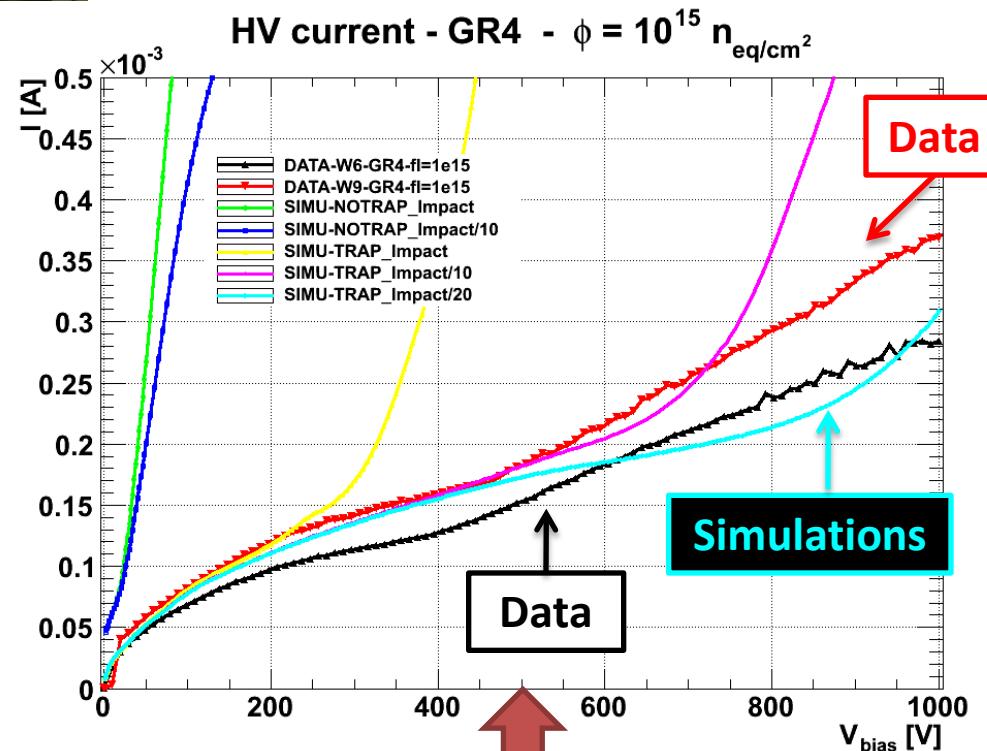
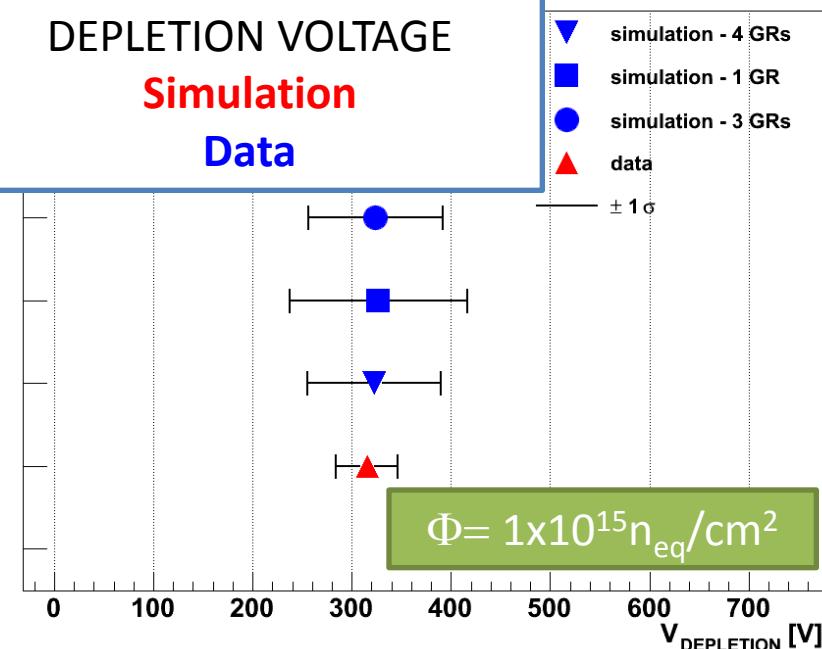
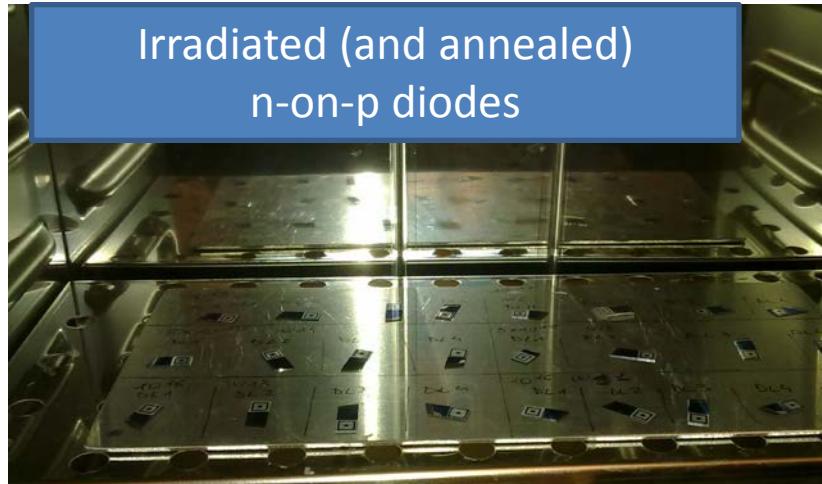


# Radiation damage effects

- Implement radiation damage effects via traps in the forbidden gap

```
# 3-level model for radiation-induced bulk damage
if cond=($fluence>0)
  if cond = ($bulk_impurities_conc < 0)
    ### n-type bulk
    set d1=13*$fluence
    set d2=0.08*$fluence
    set d3=1.1*$fluence
    trap acceptor e.level=0.42 density=$d1 degen=1 sign=2e-15 sigp=1.2e-14
    trap acceptor e.level=0.50 density=$d2 degen=1 sign=5e-15 sigp=3.5e-14
    trap donor e.level=0.36 density=$d3 degen=1 sign=2e-18 sigp=2.5e-15
  else
    ### p-type bulk
    set d1=1.613*$fluence
    set d2=0.9*$fluence
    set d3=0.9*$fluence
    trap acceptor e.level=0.42 density=$d1 degen=1 sign=9.5e-15 sigp=9.5e-14
    trap acceptor e.level=0.46 density=$d2 degen=1 sign=5e-15 sigp=5e-14
    trap donor e.level=0.36 density=$d3 degen=1 sign=3.23e-13 sigp=3.23e-14
  if.end
if.end
```

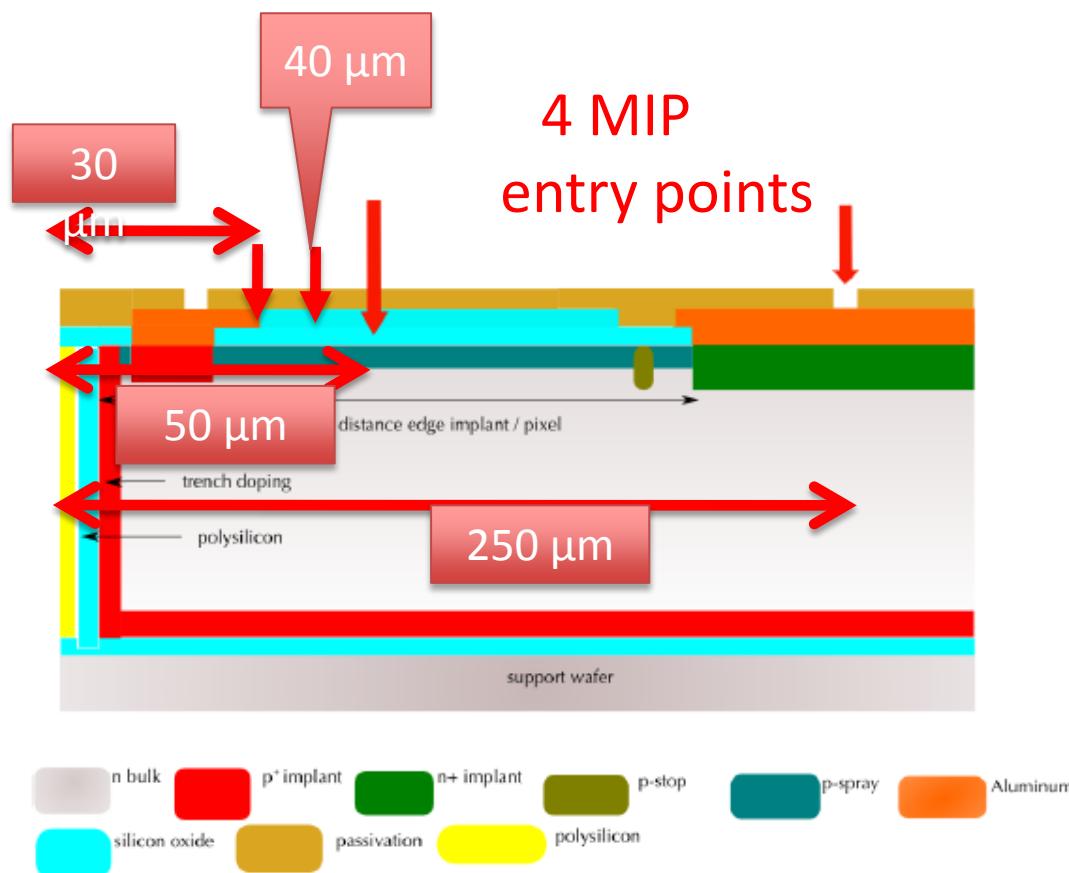
# Pennicard model validation



A lot of work for impact ionization models and interface traps and charges

# Simulated charge collection efficiency studies

- I have simulated the sensor with 100 µm between the trench and the pixel and no GRs
- Configurations:
  - a) 4 entry points
  - b) 4 bias voltages
  - c) Before and after irradiation



# Simulation of CCE studies with MIPs

```
# Specify the charge track: normal incidence through the drain
singleeventupset entry="$'MIP_origin',0" exit="$'MIP_origin',200" pcunits b.density=1.88328e-04 \
    radialgauss radius=5 t0=2.e-11 tc=0
# Log file for transient

# Early transient
#method lte.timestep tstep.incr=1.25 dt.max=2.0e-13
#solve tfinal=2.0e-12 tstep=2.5e-15 prev

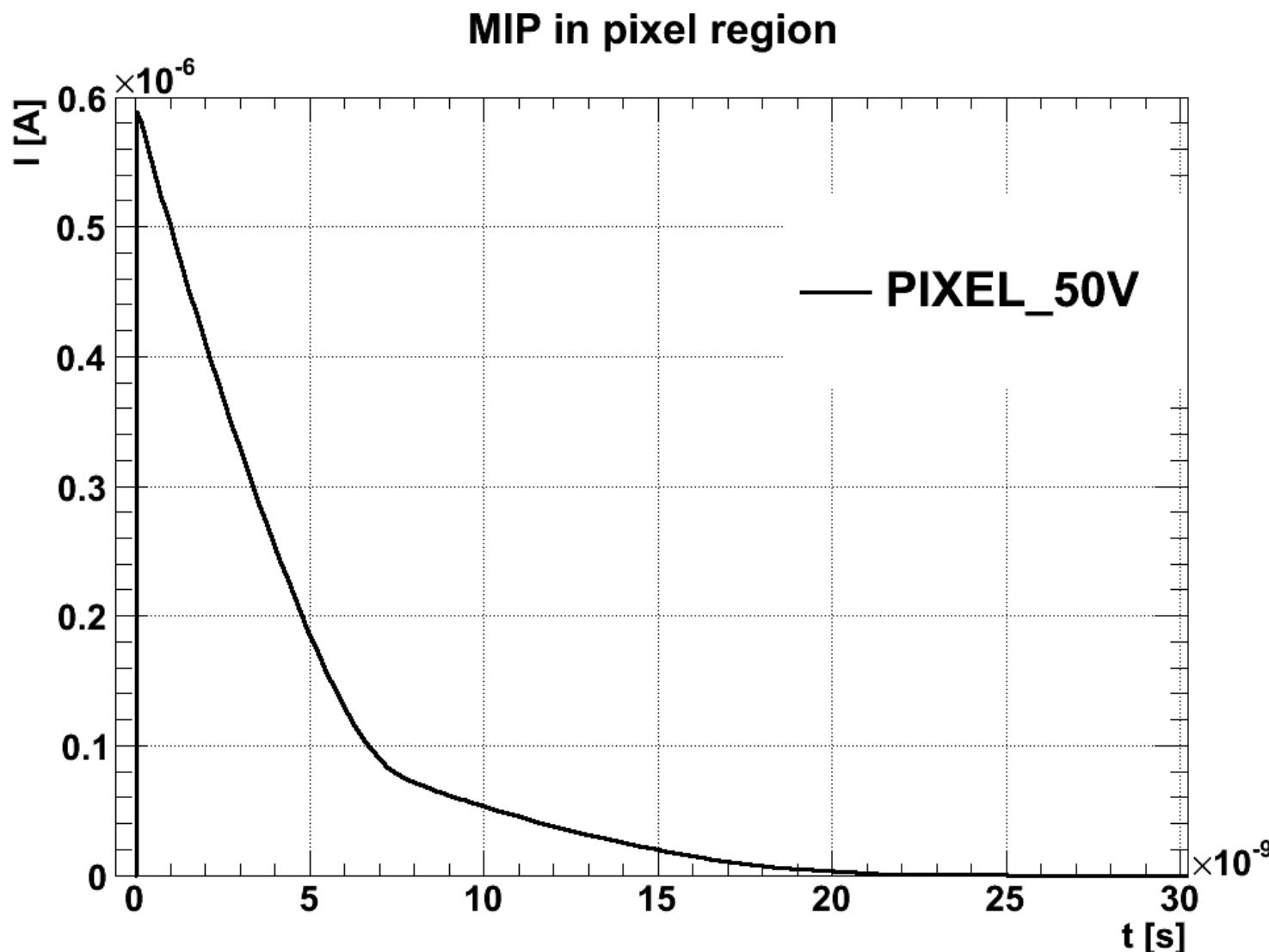
## SEU peak
#method constant.timestep
log outf="$'file_name'.log"
solve tfinal=2.0e-11 tstep=2.0e-12
save outf="$'file_name'-before-seu.str"
#
## Response to particle strike
#method lte.timestep tstep.incr=1.25 dt.max=2.5e-11
solve tfinal=5e-11 tstep=2.0e-12 prev
save outf="$'file_name'-during-seu.str"
#
## Drain voltage bounce
#method constant.timestep
solve tfinal=8e-10 tstep=1.0e-11 prev
save outf="$'file_name'-bounce.str"
#
## Convergence to final steady state
#method lte.timestep tstep.incr=1.25 dt.max=2.0e-6
solve tfinal=1e-7 tstep=5.0e-11 prev
#
# Save the final state of the structure, after the upset
save outf="$'file_name'-final.str"
```

SEU statement - specify:

- Entry & exit point
- Charge released per  $\mu\text{m}$

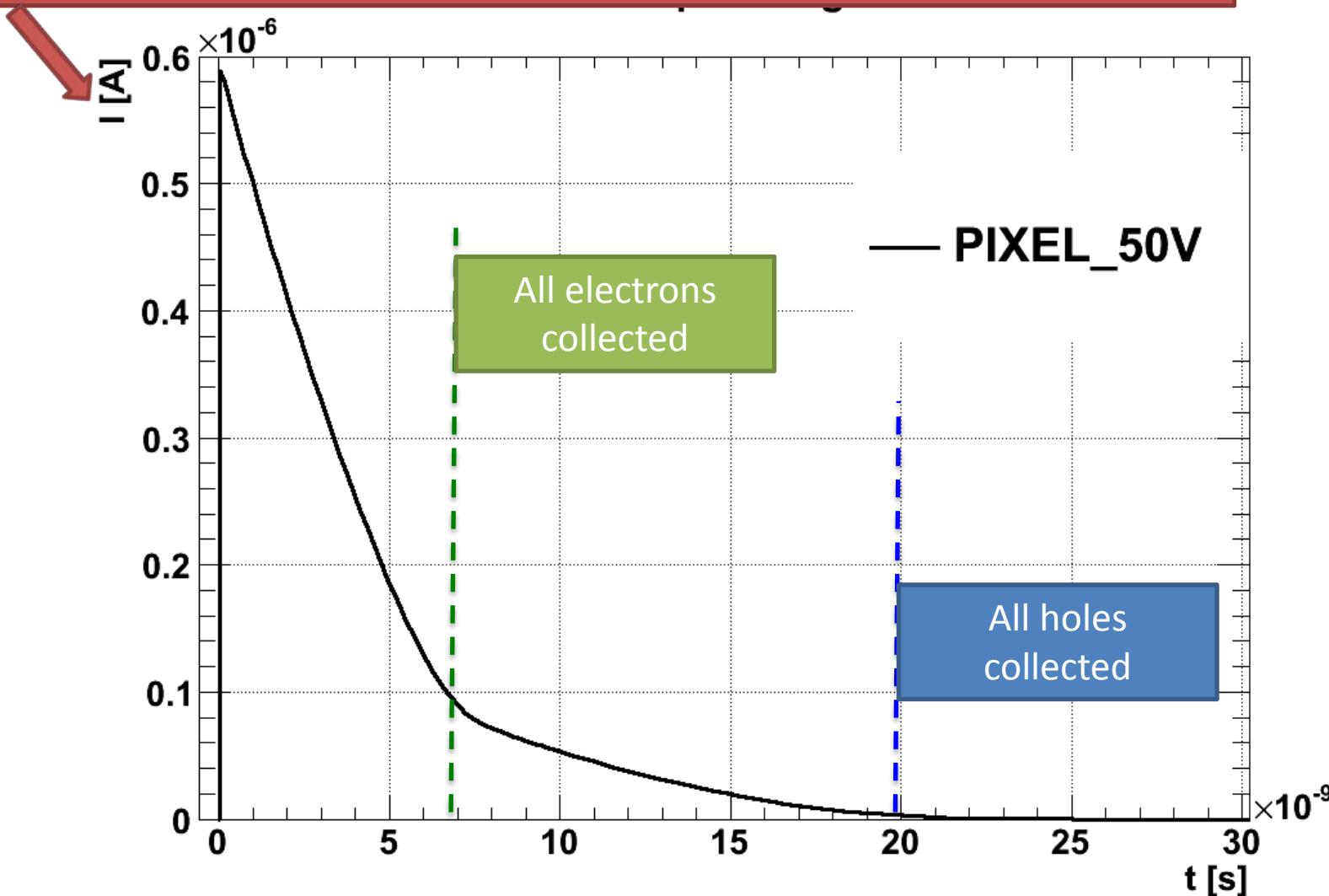
Then solution in the time domain

# Unirradiated sensor, PIXEL region, 50 V

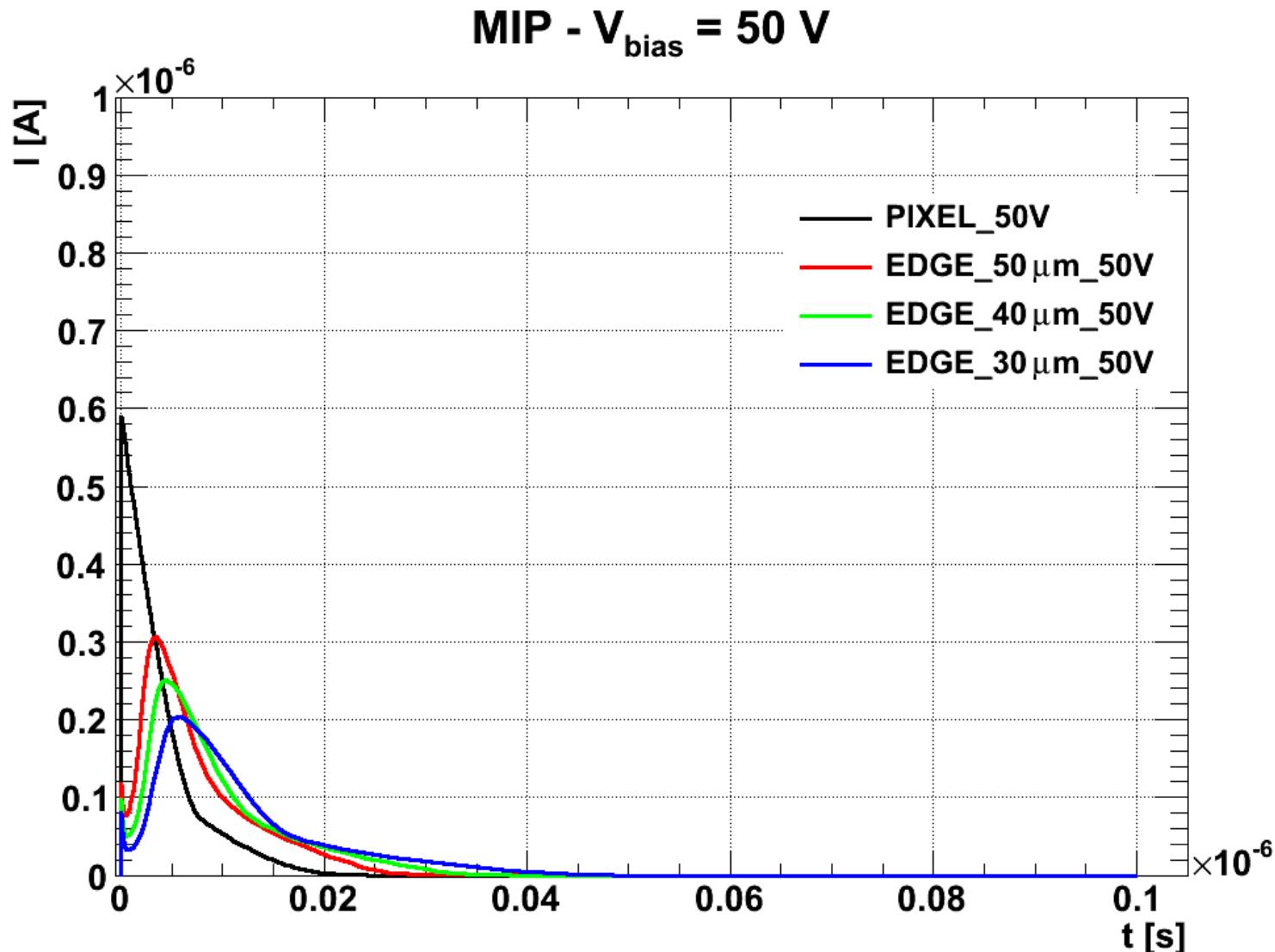


# Current peak for unirradiate, PIXEL reg., 50 V

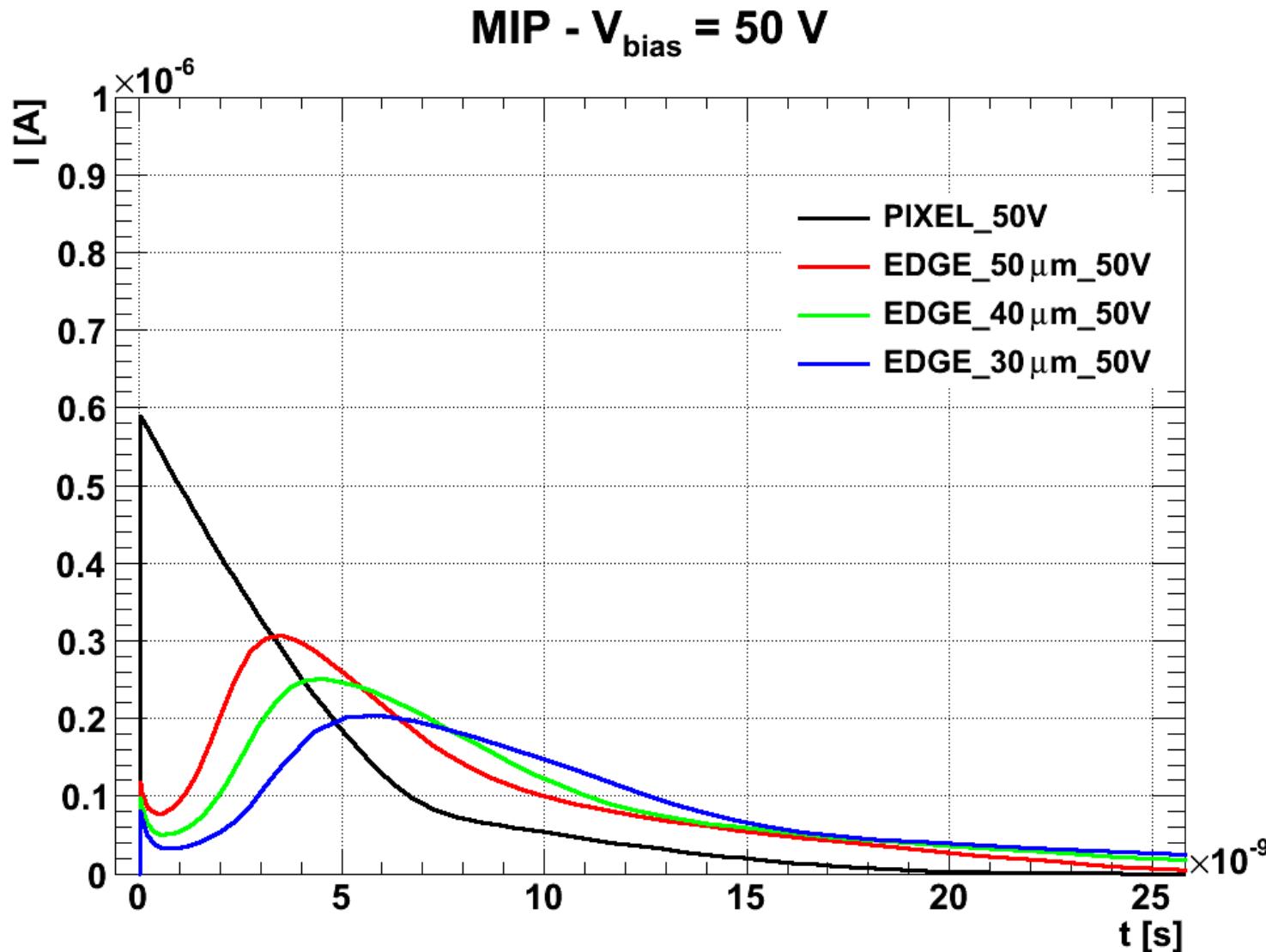
Expected Initial current  $\sim \lambda (\langle v_e \rangle + \langle v_h \rangle) = 6 \times 10^{-7} \text{ A}$  ( $\lambda = 80 \text{ e-}/\mu\text{m}$ )



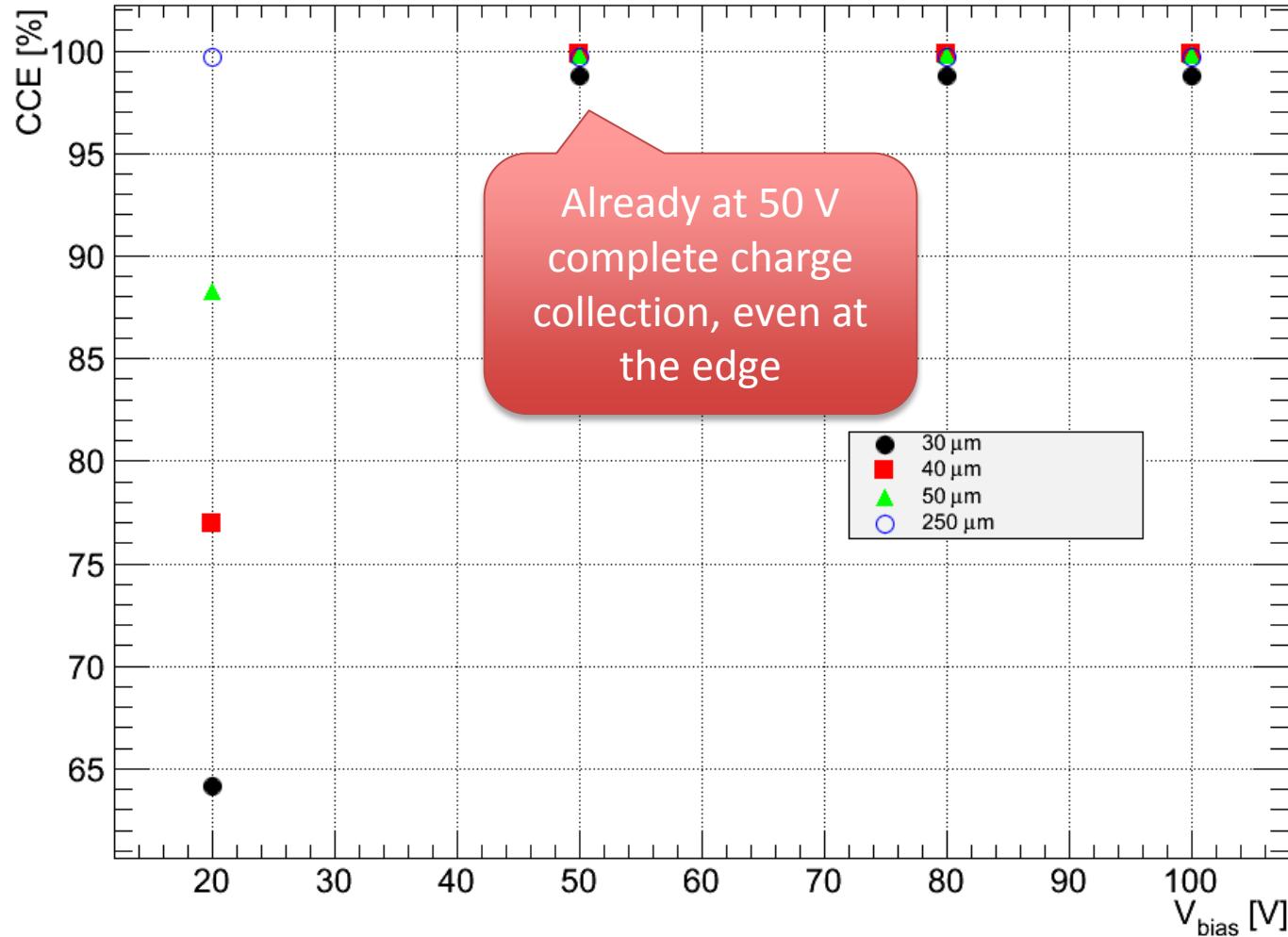
# Signal at 50 V for unirradiated sensors



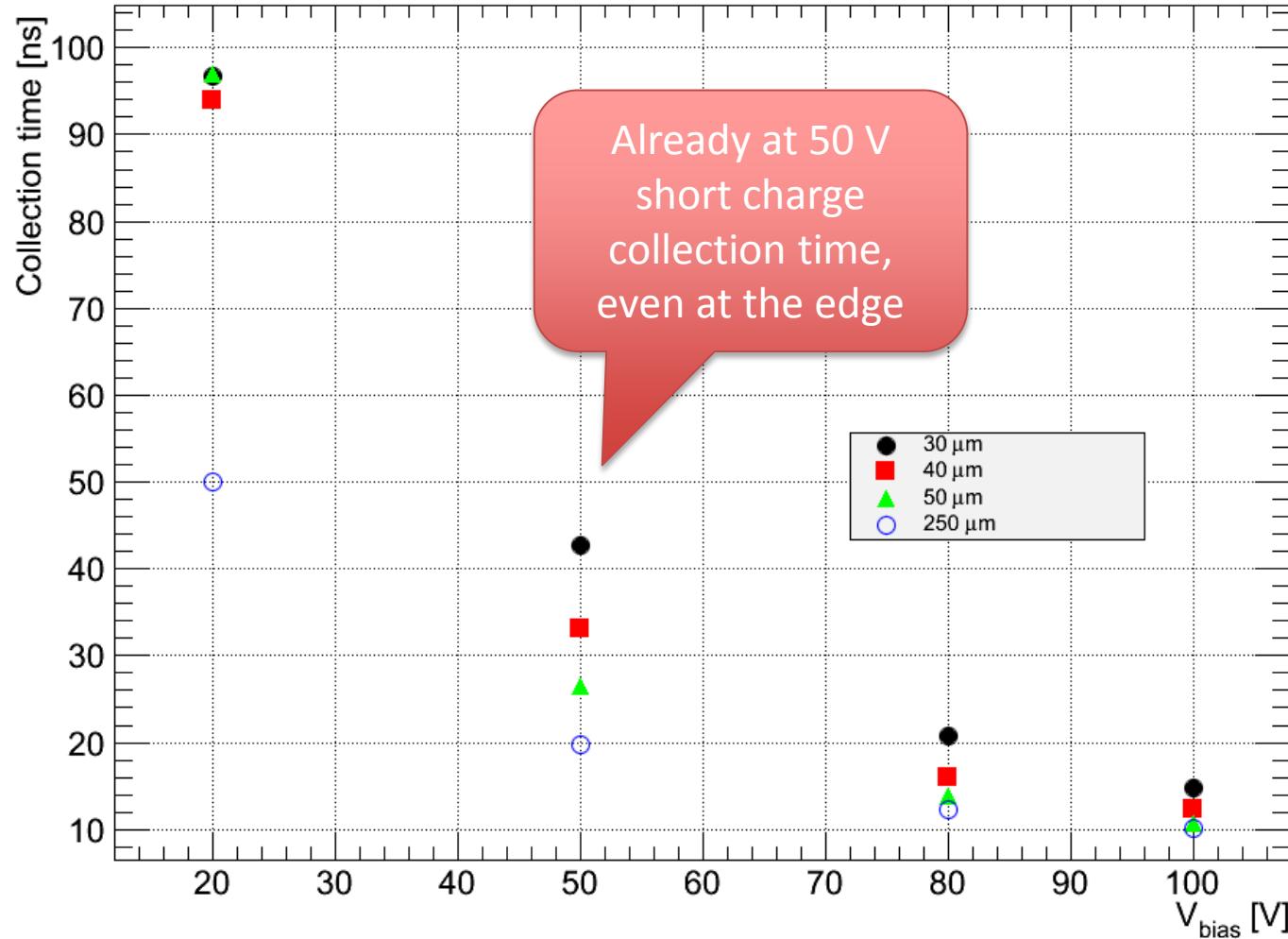
# Signal at 50 V for unirradiated sensors (zoom)



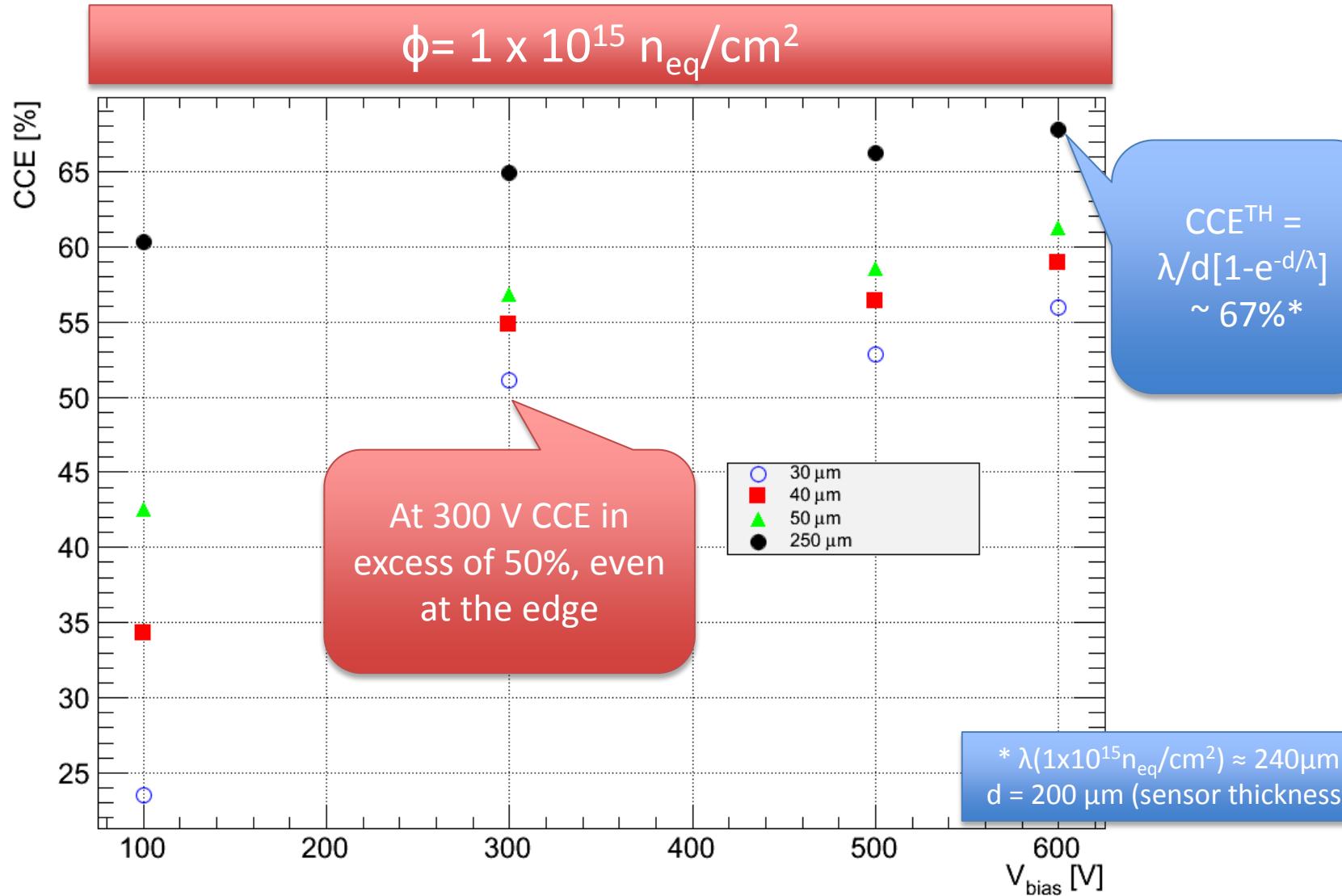
# CCE for unirradiated sensors



# Collection time for unirradiated sensors



# CCE for irradiated sensors



# **CONCLUSIONS & OUTLOOK**

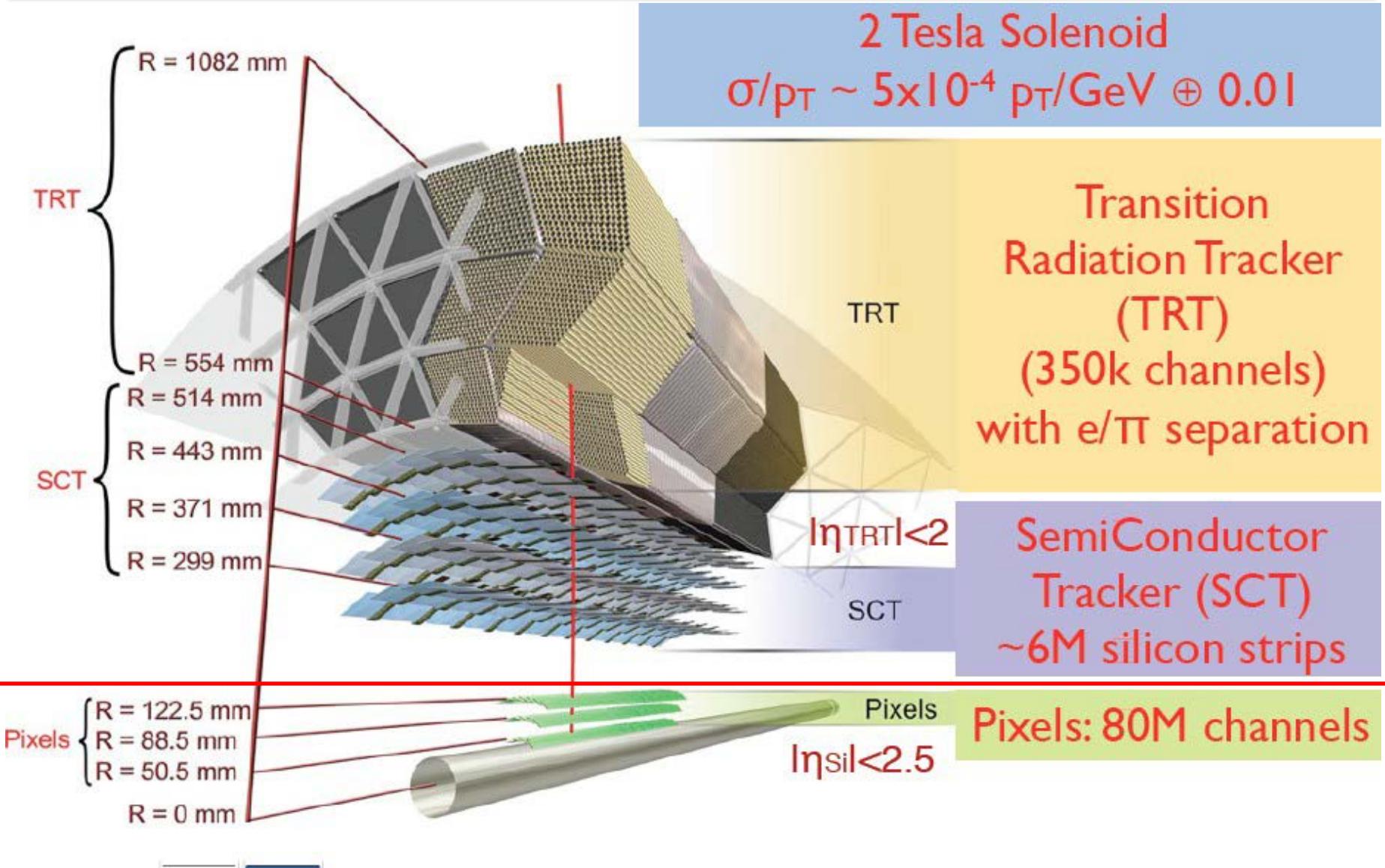
# TCAD simulations for HL-LHC edgeless sensors

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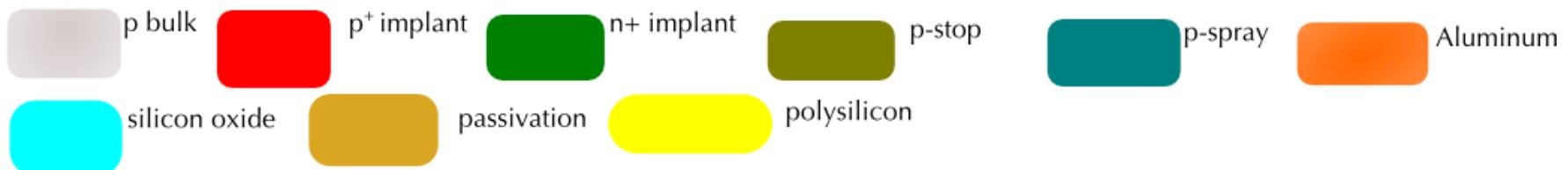
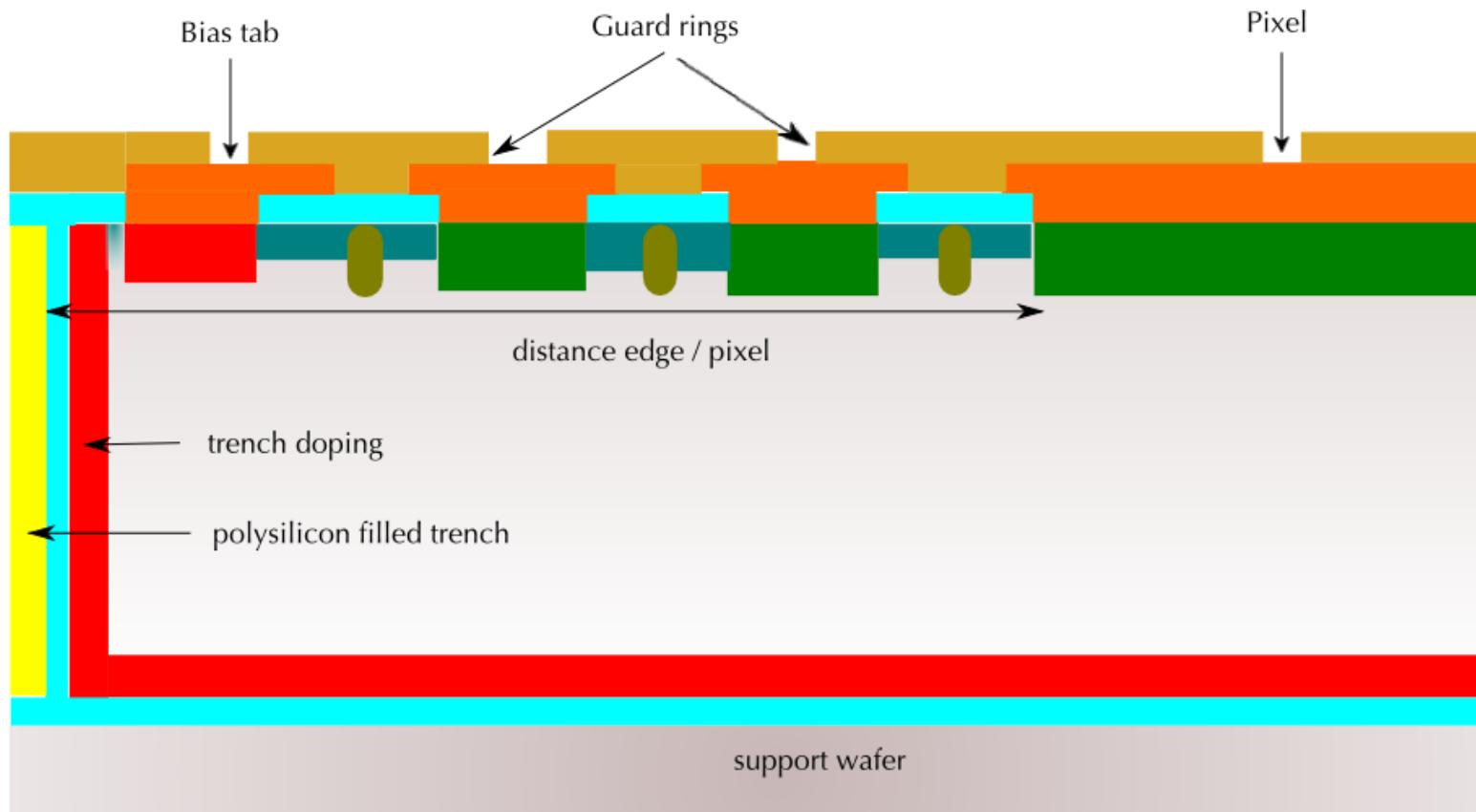
- The HL-LHC phase demands rad-hard pixel sensors, with limited inactive zones
- The LPNHE-FBK active edge n-on-p planar pixels are very good competitors for this challenge
  - The production was optimized thanks to TCAD simulations, which included studies ranging from the layout concept to the charge collection studies
  - ✓ First comparisons with data confirm the validity of the simulation results
  - Future productions will benefit of 3D simulations

# **BACKUP**

# The ATLAS Inner Detector

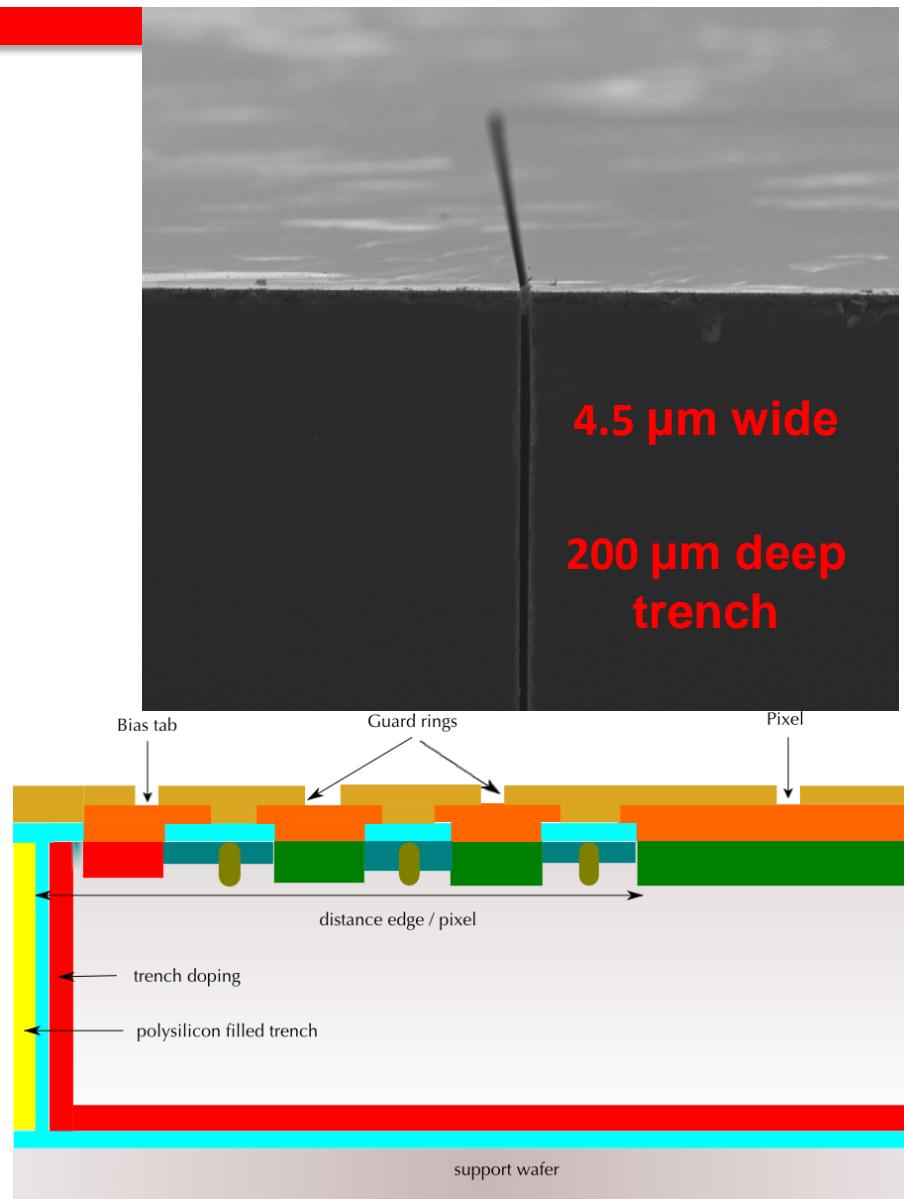


# The simulated device



# Deep Reactive Ion Etching: FBK-LPNHE

- Joint FBK-LPNHE project
- Goal: make the border a damage free ohmic contact
- How: DRIE as for 3D process
  - Trench doped by diffusion
- Target: intermediate layers (200  $\mu\text{m}$  thick production)
- Pixel-to-trench distance as low as 100  $\mu\text{m}$



# Carriers' velocity

