https://indico.in2p3.fr/e/simdet2018

SIMDET 2018

3rd school on silicon detectors simulation

Use of Silvaco in HEP experiments

M. Bomben, LPNHE & UPD - Paris

Outline

- Silvaco TCAD tool
- Example: edgeless detectors
- Radiation damage models
- From TCAD to Monte Carlo simulations
- 1D vs 2D vs 3D vs 4D simulations
- Conclusion & Outlook

SILVACO TCAD TOOL

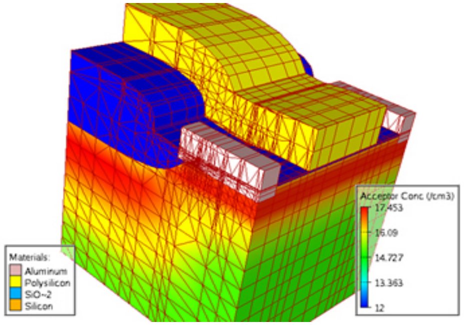
TCAD simulations

- Technology Computer Aided Design - TCAD
- Solve drift/diffusion & Poisson equations for electrons and holes:

$$J_n = qn\mu_n E + qD_n \frac{\partial n}{\partial x} \quad \frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + G_n - R_n$$

$$J_p = qn\mu_p E - qD_p \frac{\partial p}{\partial x} \quad \frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + G_p - R_p$$

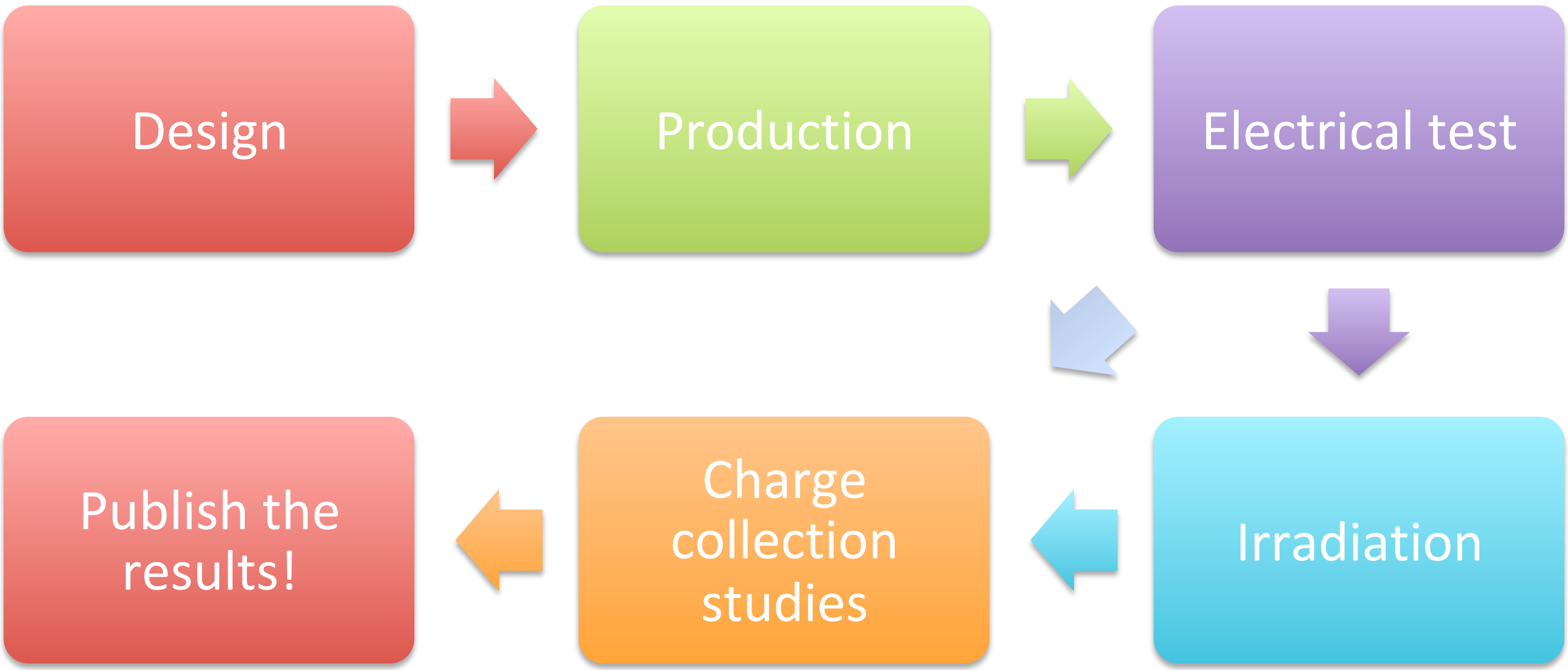
$$\frac{\partial^2 \psi}{\partial x^2} = -\frac{q}{\epsilon_{Si}\epsilon_0}(N_D + p(x) - n(x) - N_A)$$



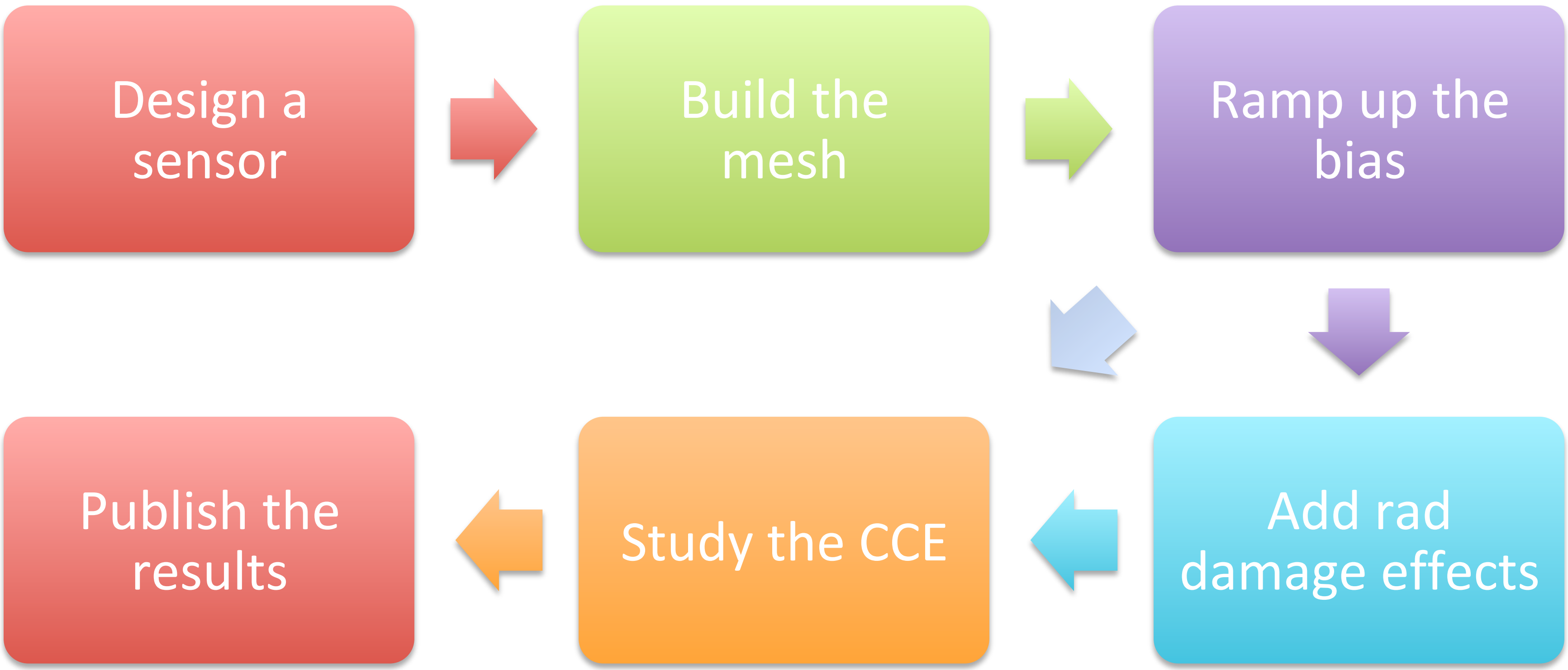
- taking into account boundary conditions
  - Electrodes' potentials, interface charges, etc
- on a grid of points

SILVACO

Normal work flow for a HEP silicon sensors



TCAD simulation work flow



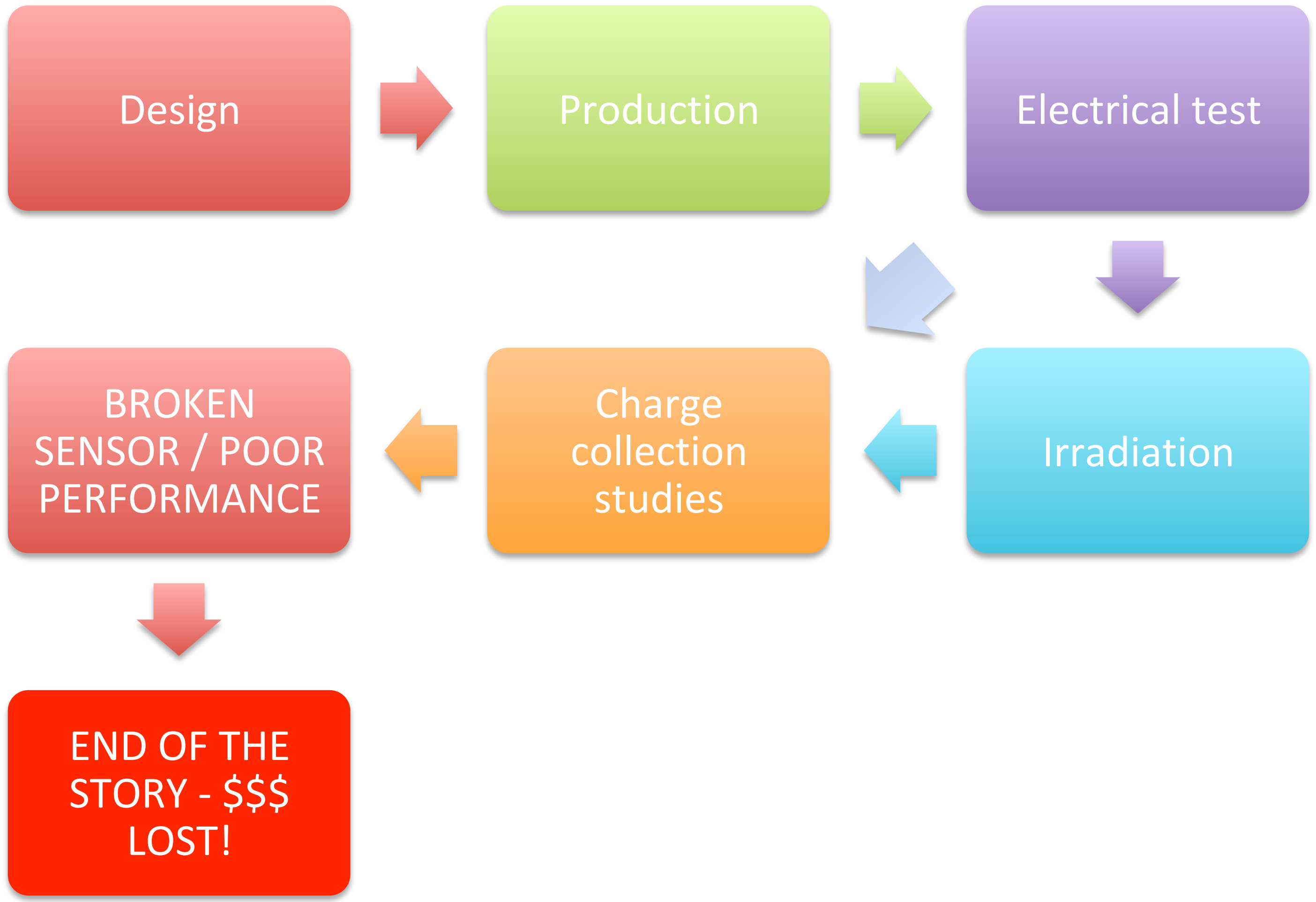
So why bother with simulations?

- You repeat all the “steps” of real sensors…

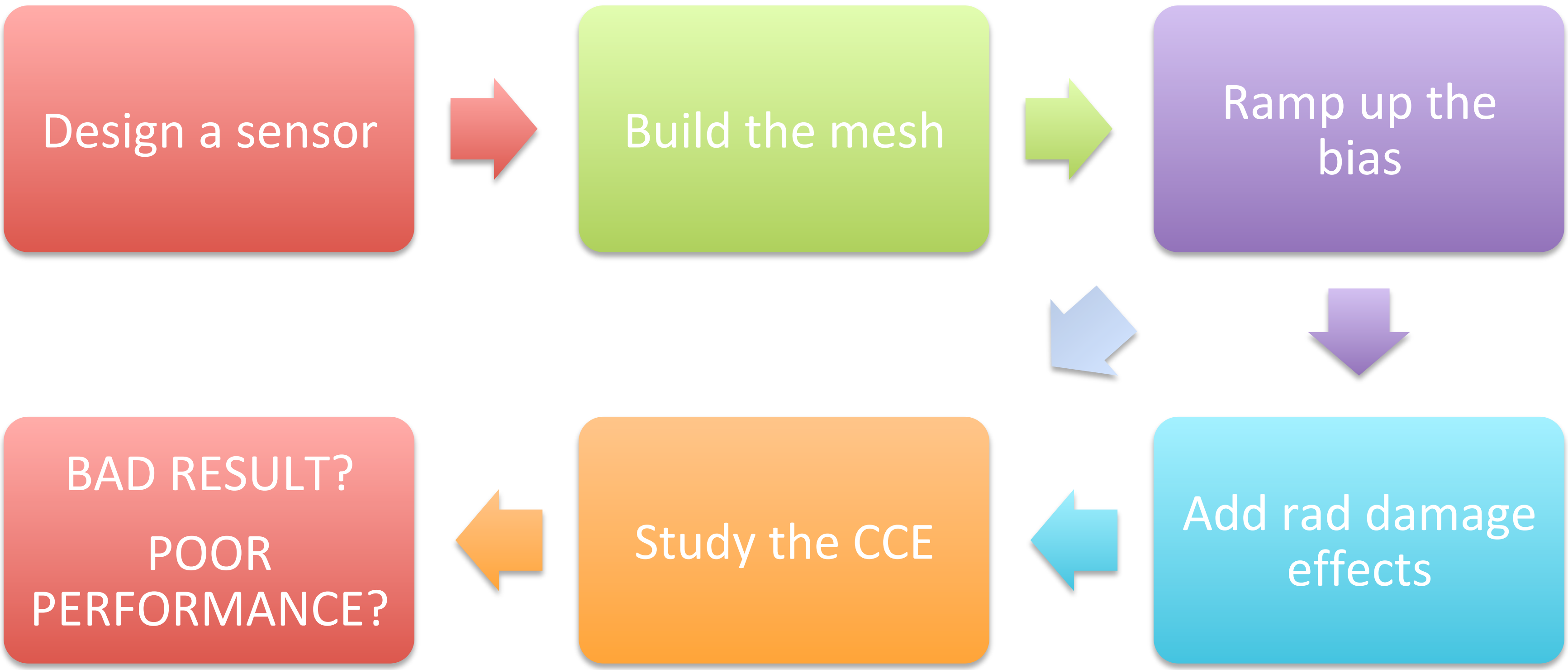
So why bother with simulations?

- You repeat all the “steps” of real sensors…
- It is not true!

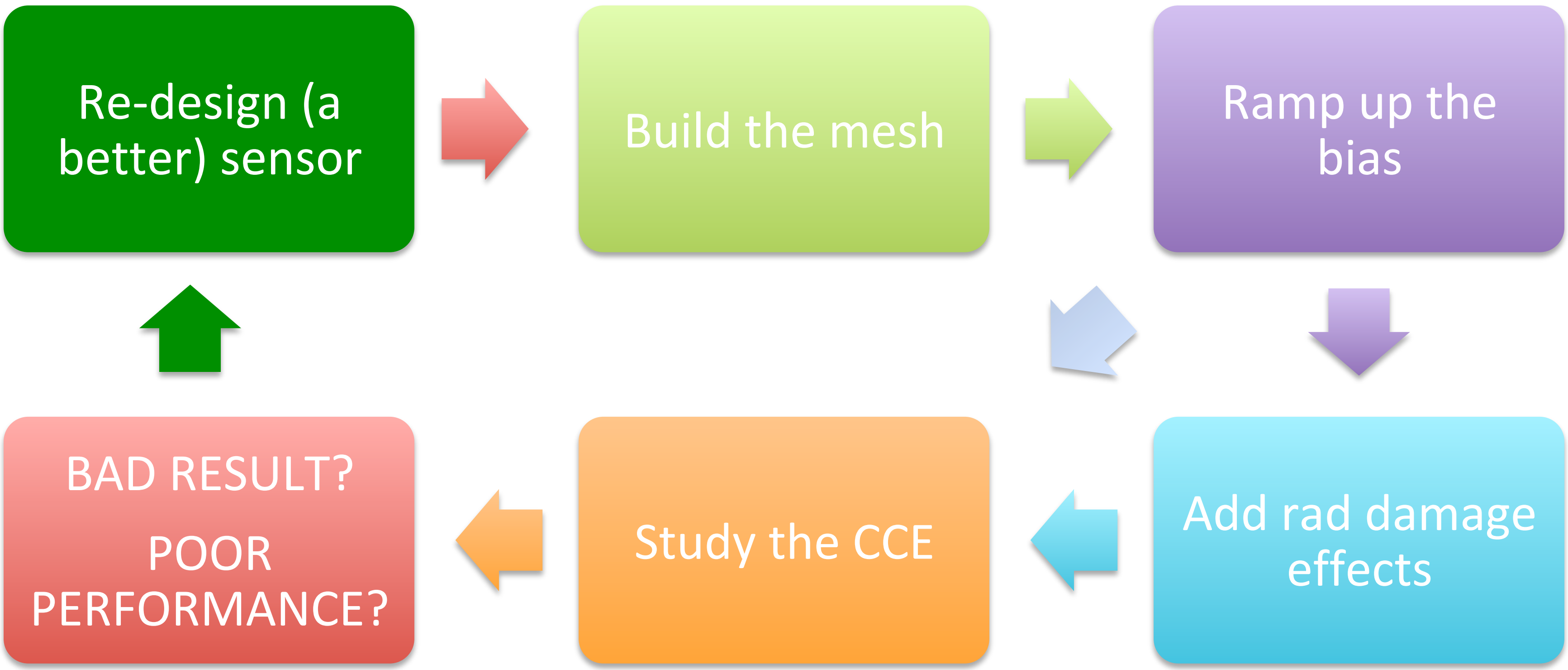
Possible work flow for real sensors



TCAD simulation work flow



TCAD simulation work flow

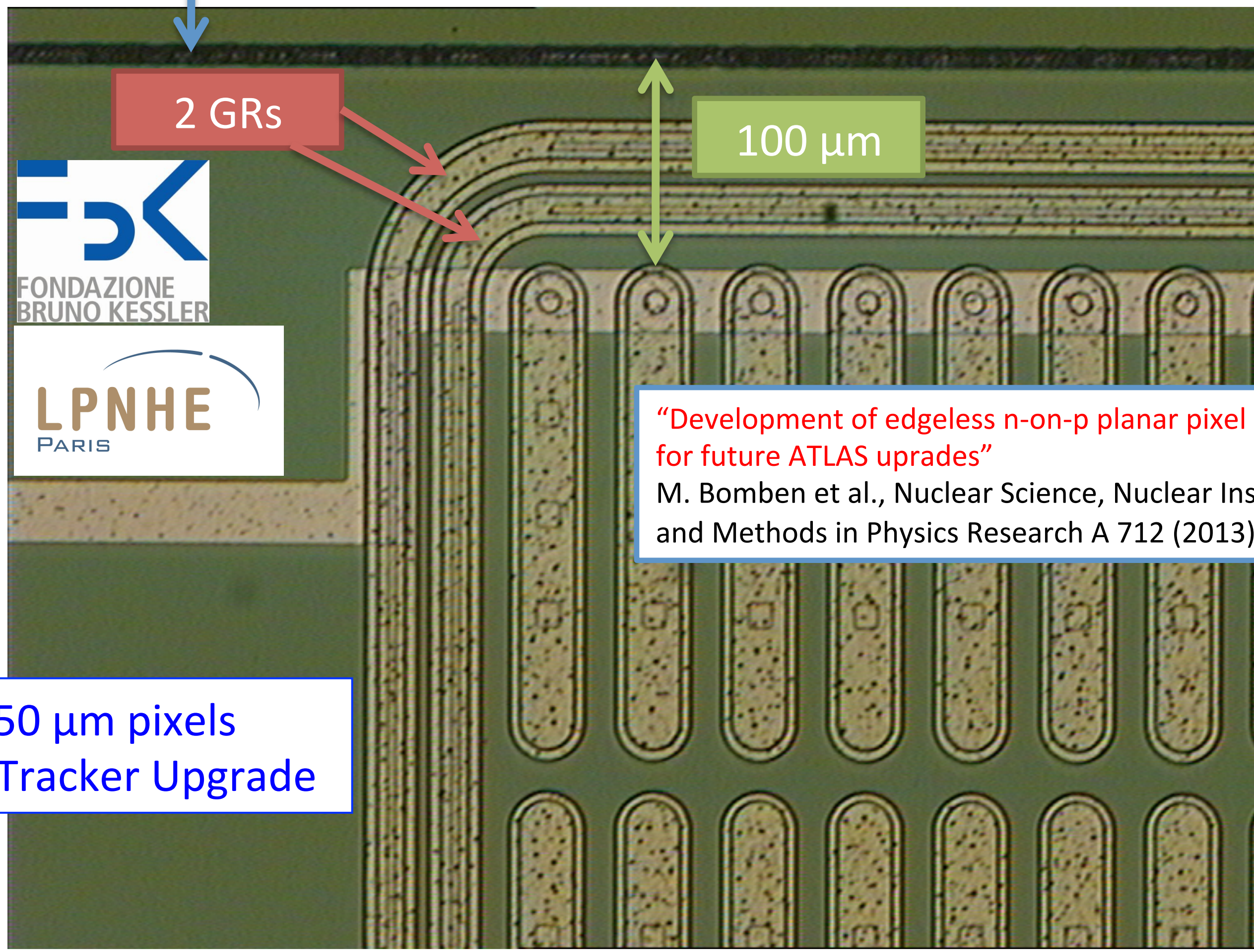


Simulations benefits

- Simulating sensors helps in saving:
  - Development time
  - Number of submissions
  - Money
- You can learn a lot in terms of:
  - Physics
    - Study quantities otherwise not accessible!
    - Examples:
      - Carrier distribution
      - Electric field distribution
      - Current densities
      - Etc.…

EXAMPLE: EDGELESS DETECTORS

Edgeless pixel detector



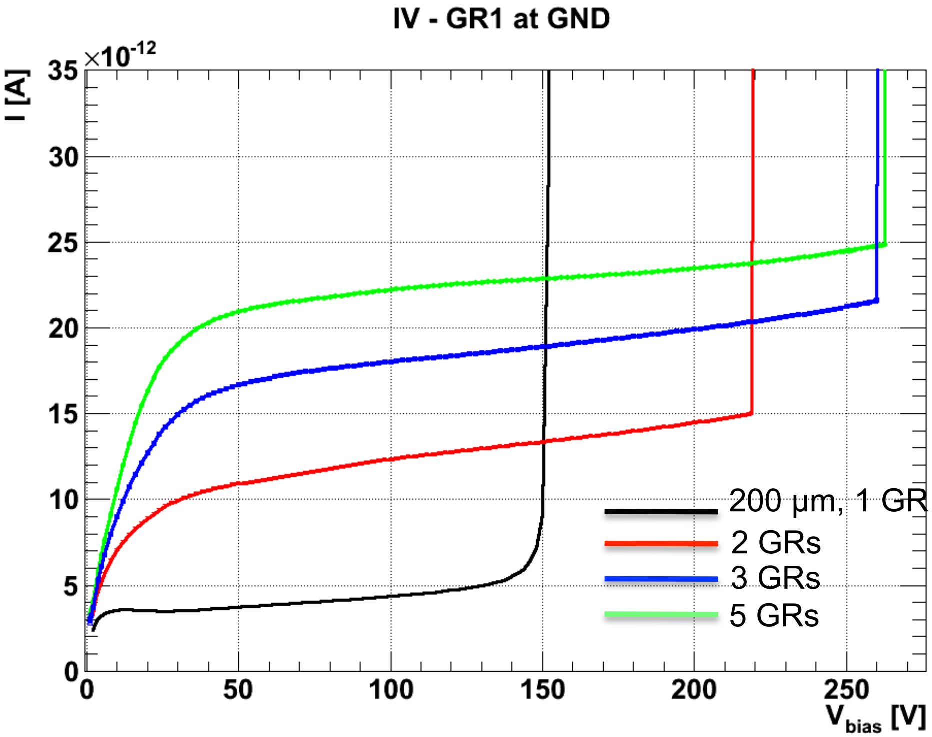
"Development of edgeless n-on-p planar pixel sensors for future ATLAS uprades"
M. Bomben et al., Nuclear Science, Nuclear Instruments and Methods in Physics Research A 712 (2013) 41–47

50 µm x 250 µm pixels
R&D for Atlas Tracker Upgrade

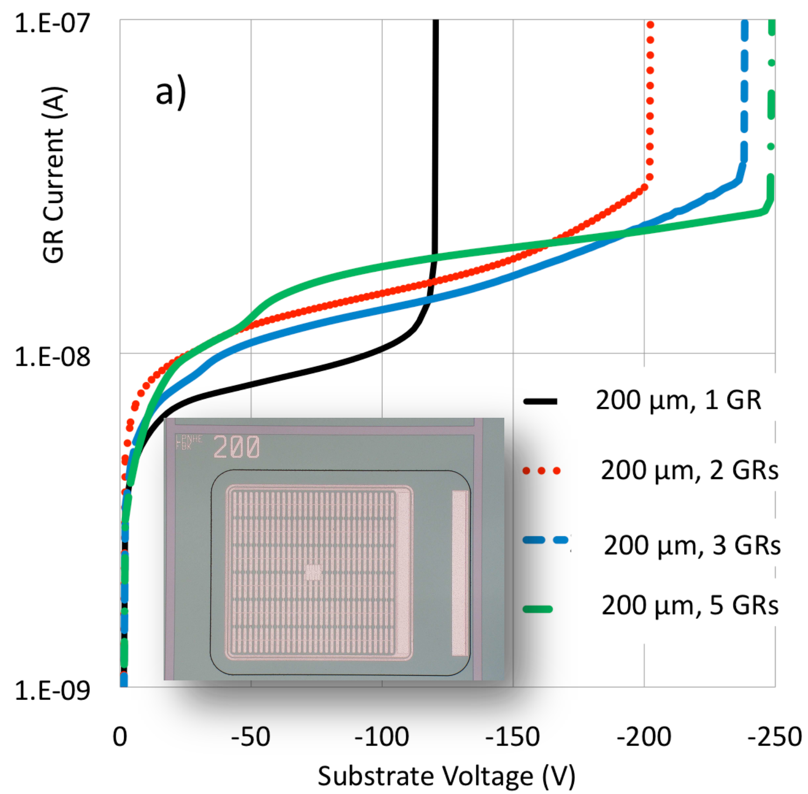
IV on test structures

Simulation drive sensor design - Focus on **breakdown (BD) voltage**

SIMULATIONS



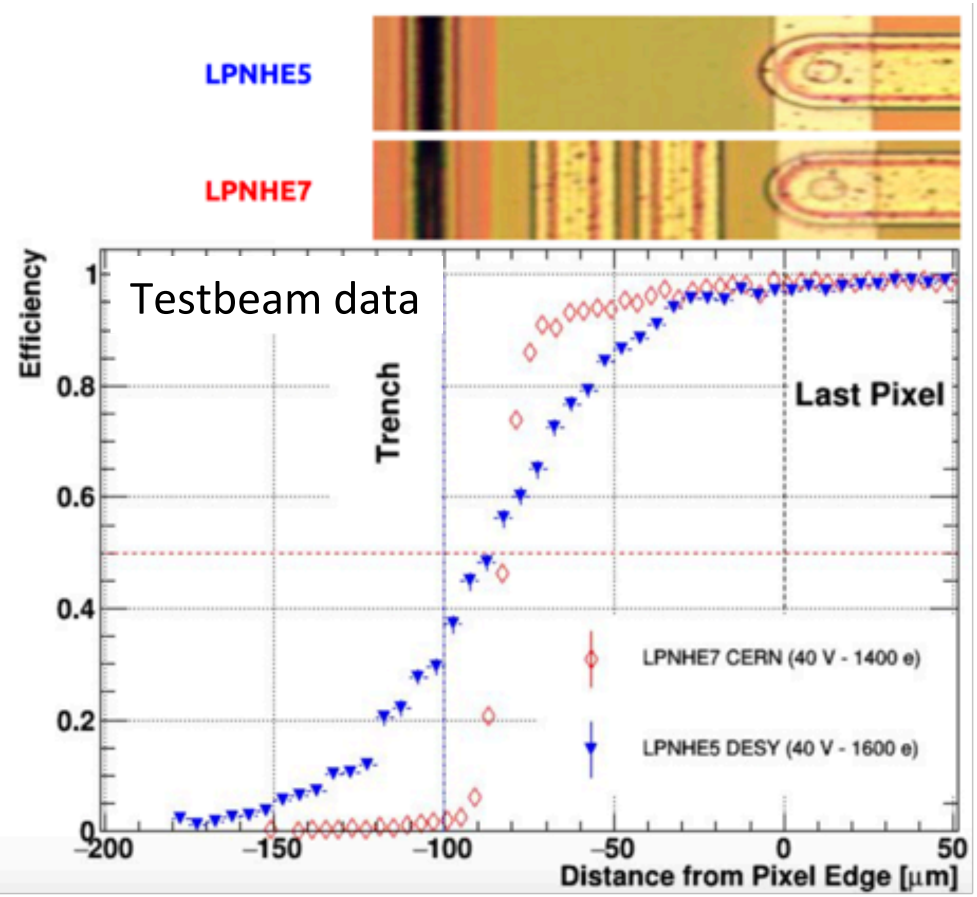
DATA

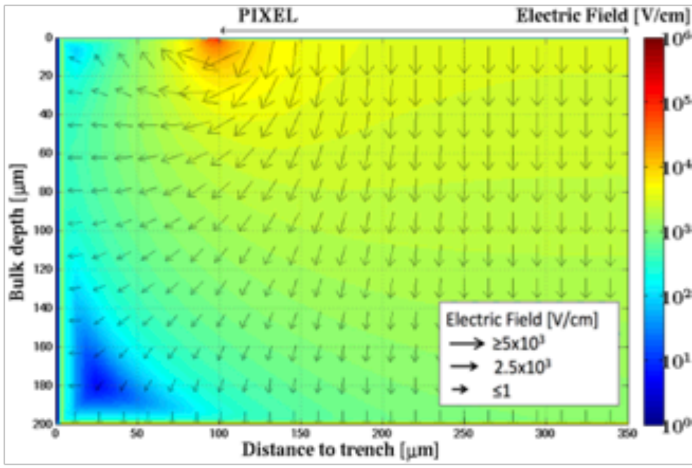


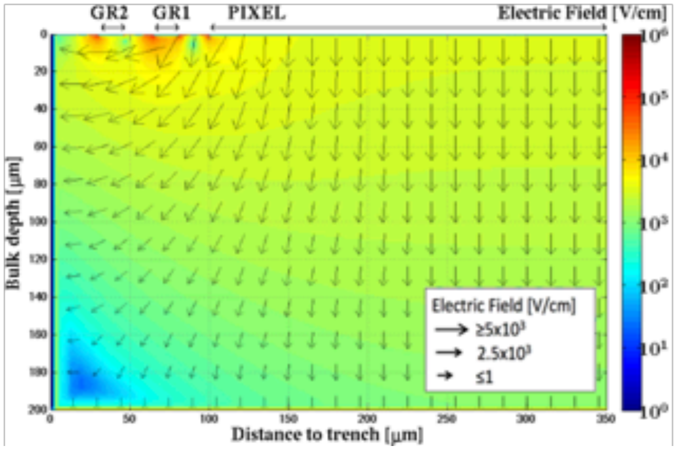
- **BD Voltage: Agreement within 20% or better**

Hit efficiency at sensor edge

JINST 12 P05006 (2017)



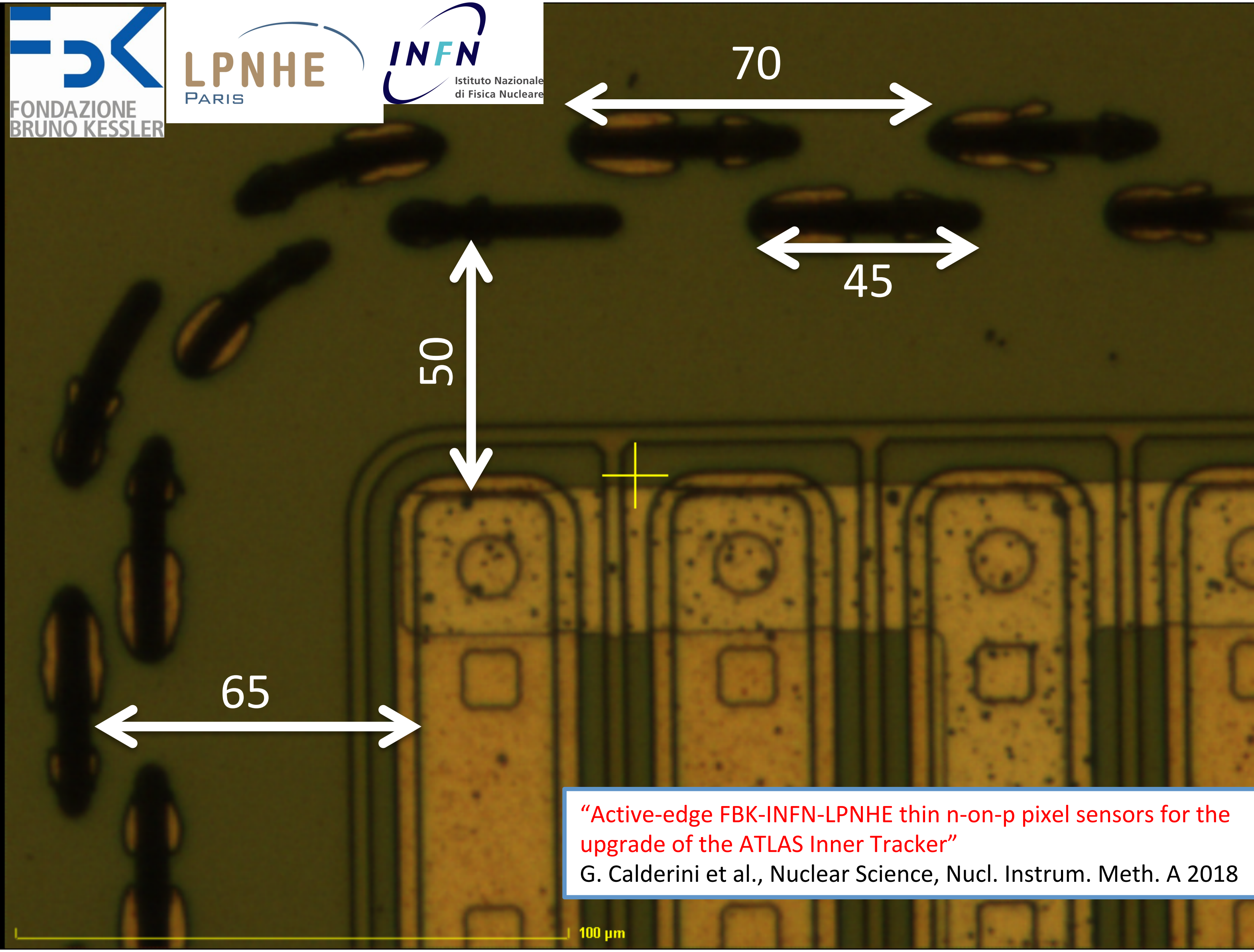




Pixel detector efficient beyond pixels area: > 80% up to 75 µm away from the last one

Reason: electric field lines closing on pixels and not on GRs!

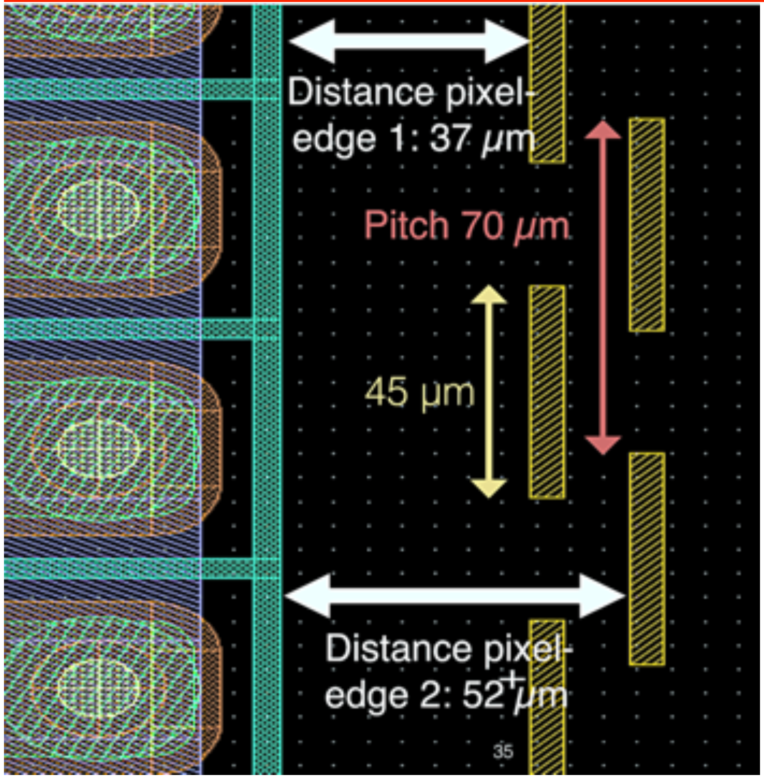
New edgeless production – staggered trenches

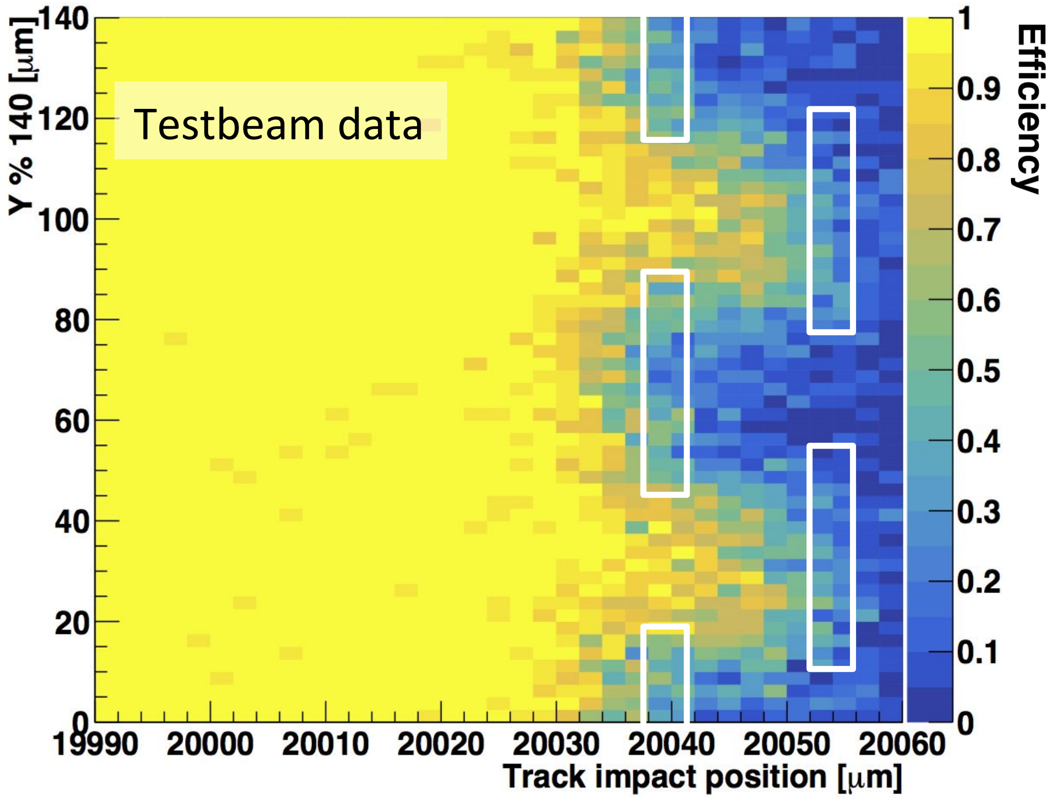


"Active-edge FBK-INFN-LPNHE thin n-on-p pixel sensors for the upgrade of the ATLAS Inner Tracker"
G. Calderini et al., Nuclear Science, Nucl. Instrum. Meth. A 2018

Hit efficiency at sensor edge

A. Ducourthial thesis
https://indico.in2p3.fr/e/18186/





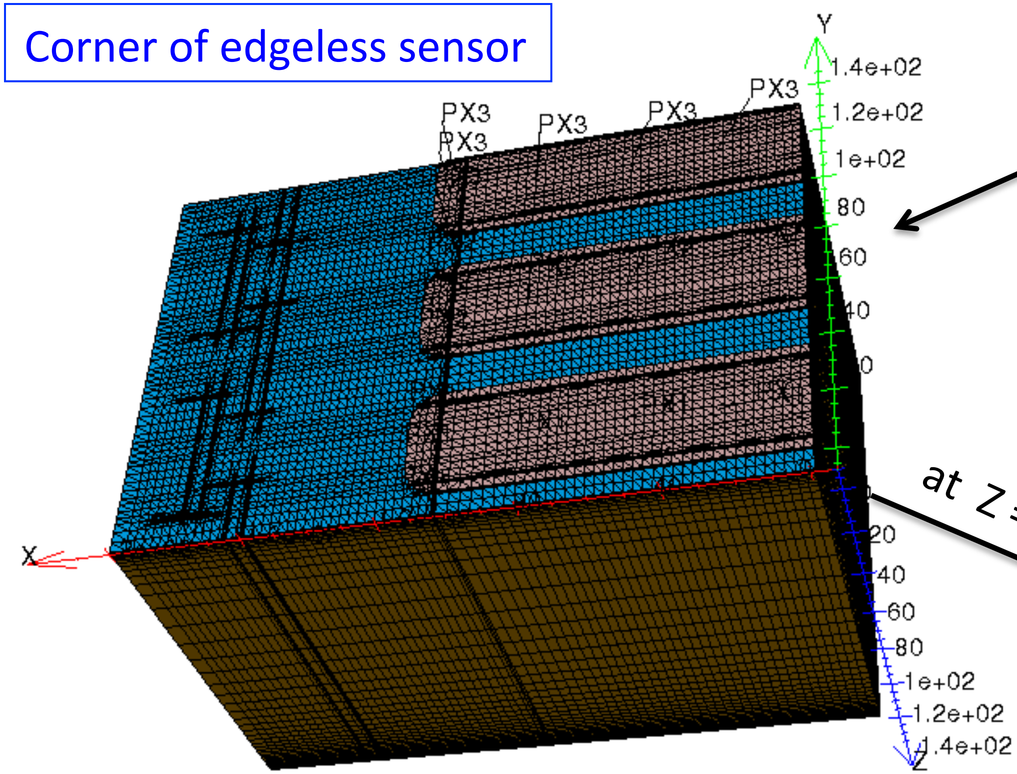
130 μm thick sensor with staggered trenches, no GRs, ~50 μm last pixel to last edge

The efficiency follows the edge pattern

The efficiency is higher than 50% up to 44 μm from the last pixel

Simulations in 3D

Corner of edgeless sensor



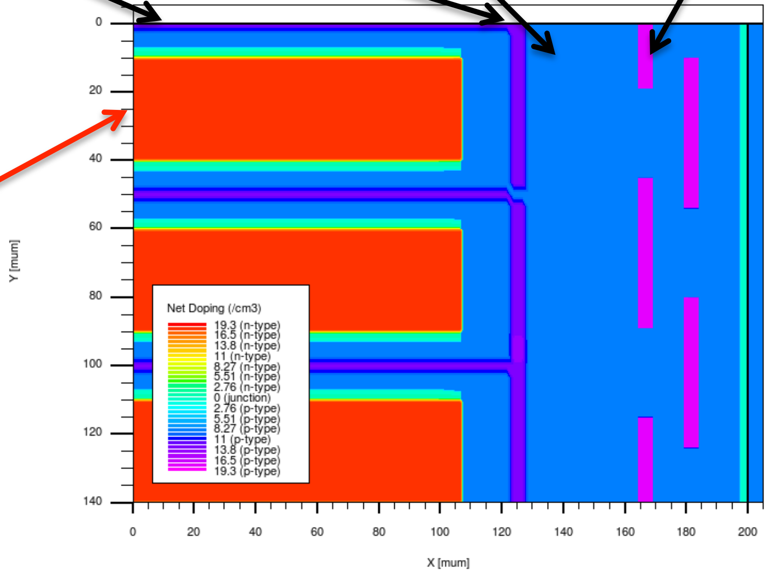
13439 points
26517 triangles

at Z = 0.2 μm

p-stop

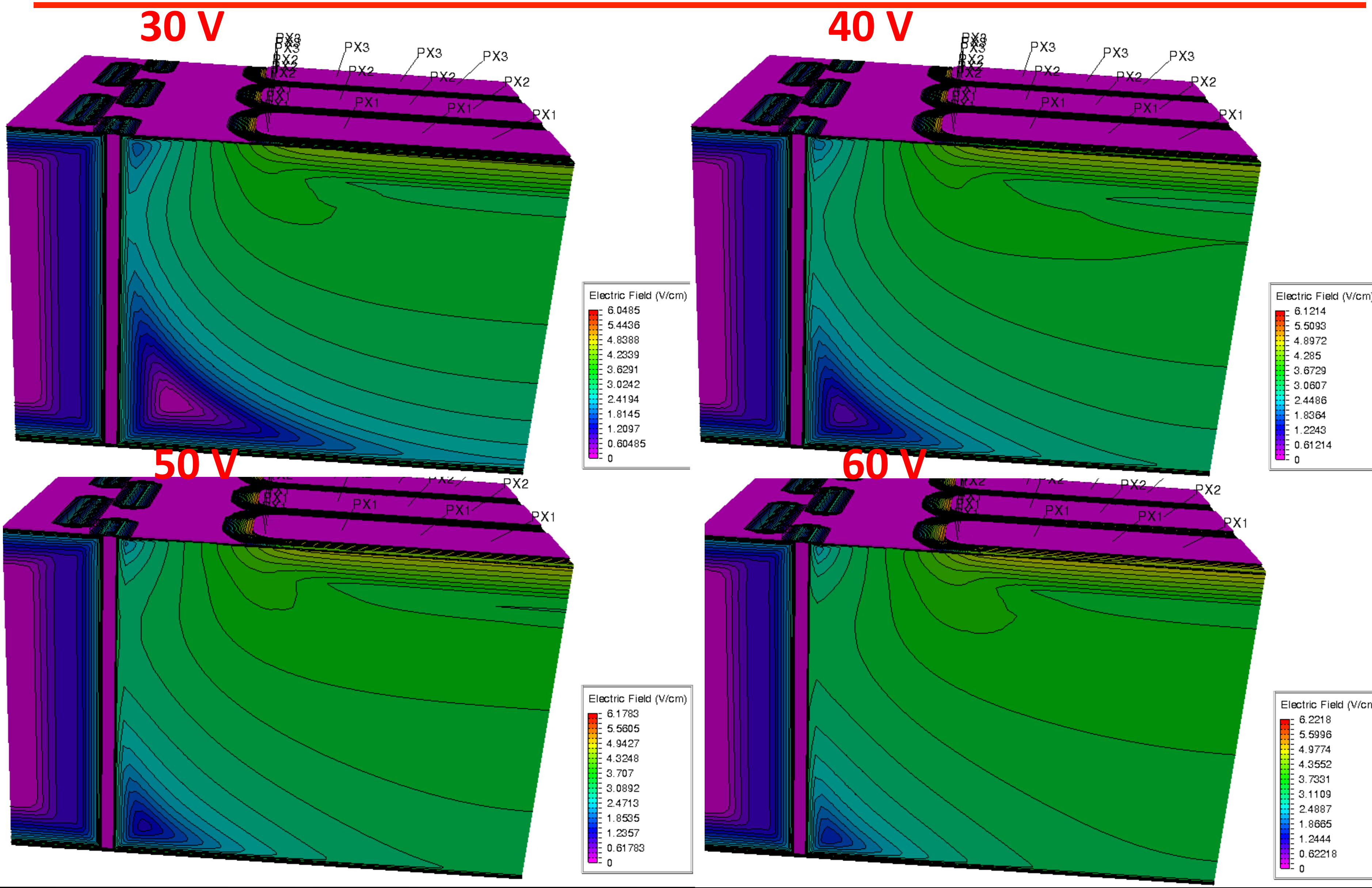
p-spray

trenches



n^+ implant

Electric field at sensor edge

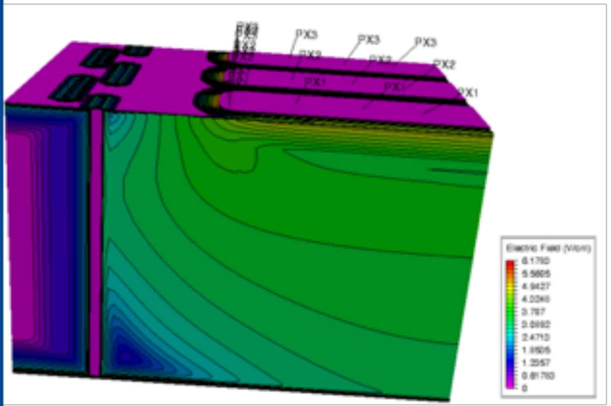


Hit efficiency at sensor edge - projections

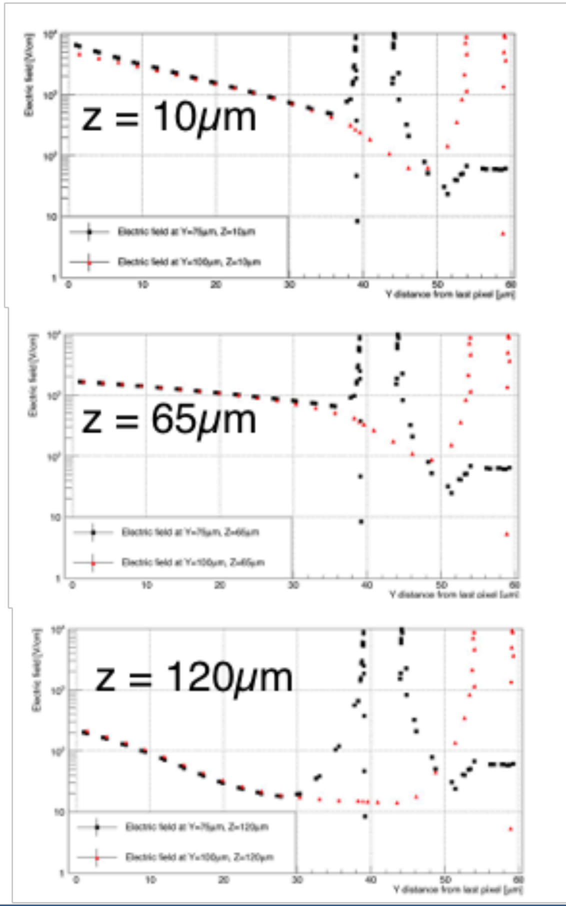
TCAD Simulations - Electric field

Simulation of the electric field for several depth z in the sensor:

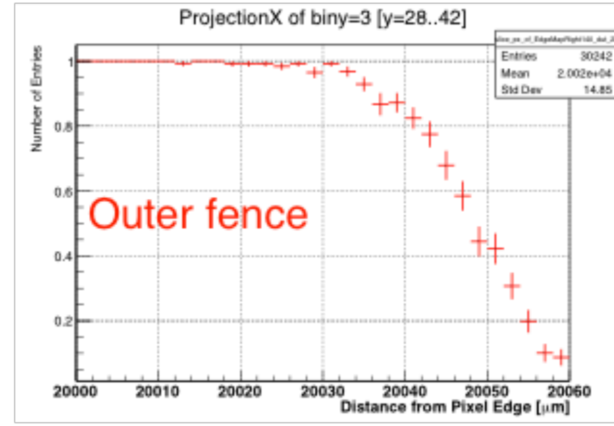
- E drops at 0 when at edge position
- low E in the bottom corner close to the edge.

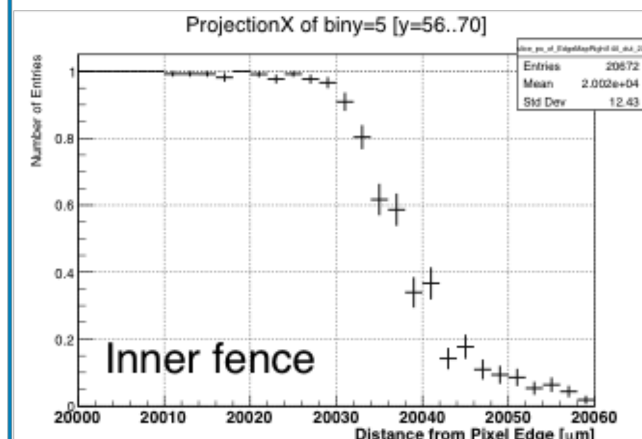


Outer fence Inner fence



Edge Efficiency





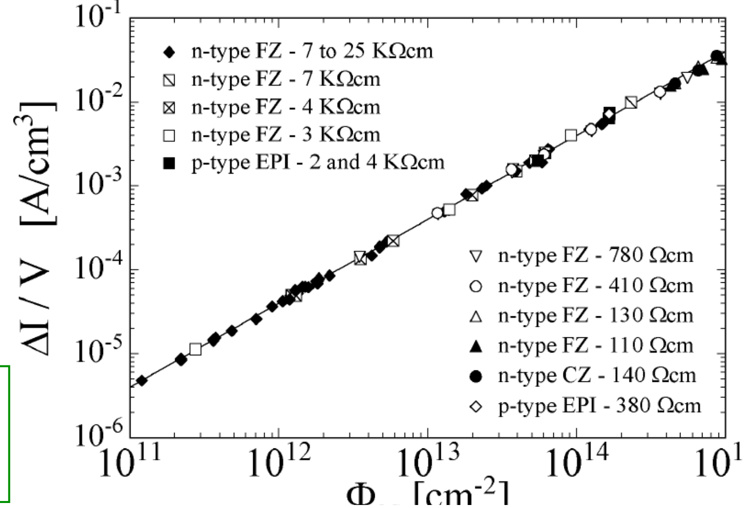
Efficiency drop matches the Electric field drop in the vicinity of the edge

RADIATION DAMAGE MODELS

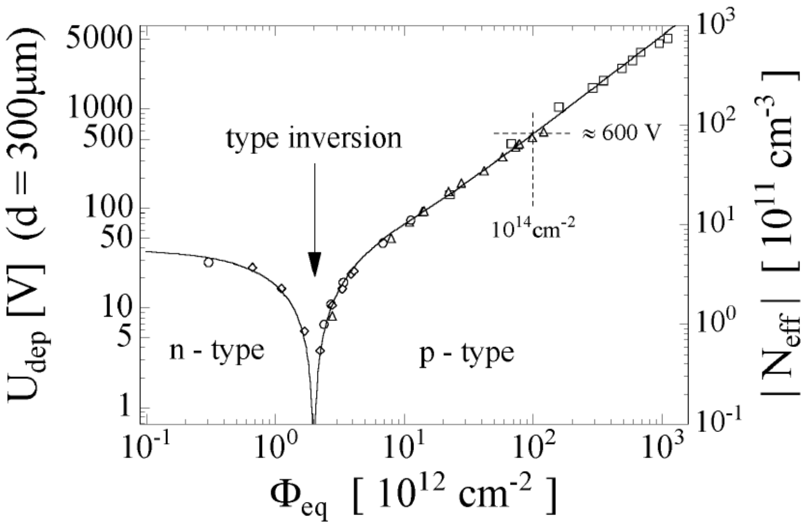
Radiation damage in silicon bulk

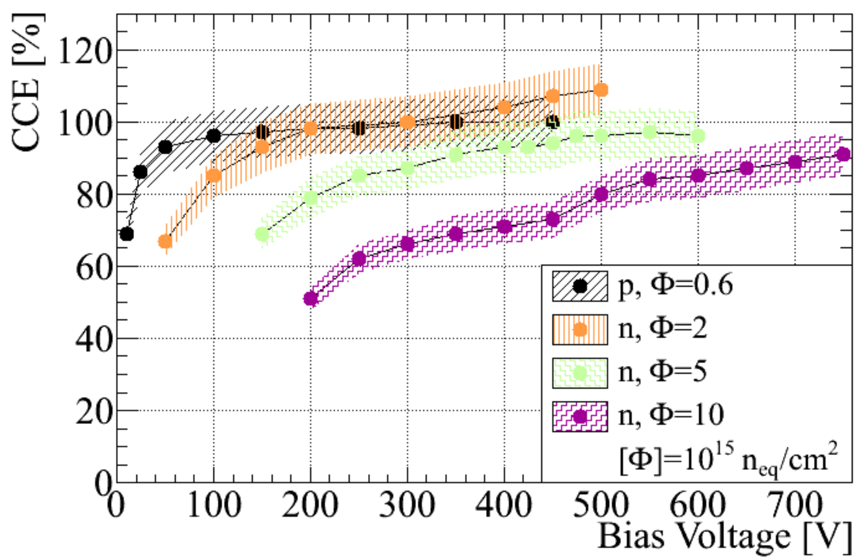
- The leakage current increase is prop. to ϕ
- The U_{dep} increases is prop. to ϕ after type inversion
- The defects acts as trapping centers

$$\alpha = \frac{\Delta I}{\Phi \cdot V} \sim 4 \times 10^{-17} A/cm$$



M. Moll thesis, MPI group

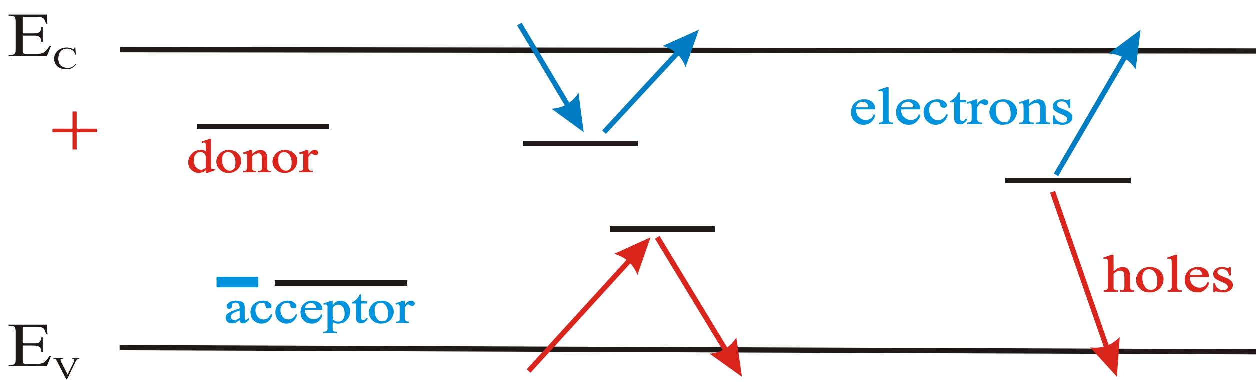




Radiation damage in silicon: microscopic level

M. Moll, Simdet 2016

Shockley-Read-Hall statistics
(standard theory)



charged defects
⇒ N_{eff}, V_{dep}
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)
⇒ CCE
shallow defects do not contribute at room temperature due to fast detrapping

generation
⇒ leakage current
Levels close to midgap most effective

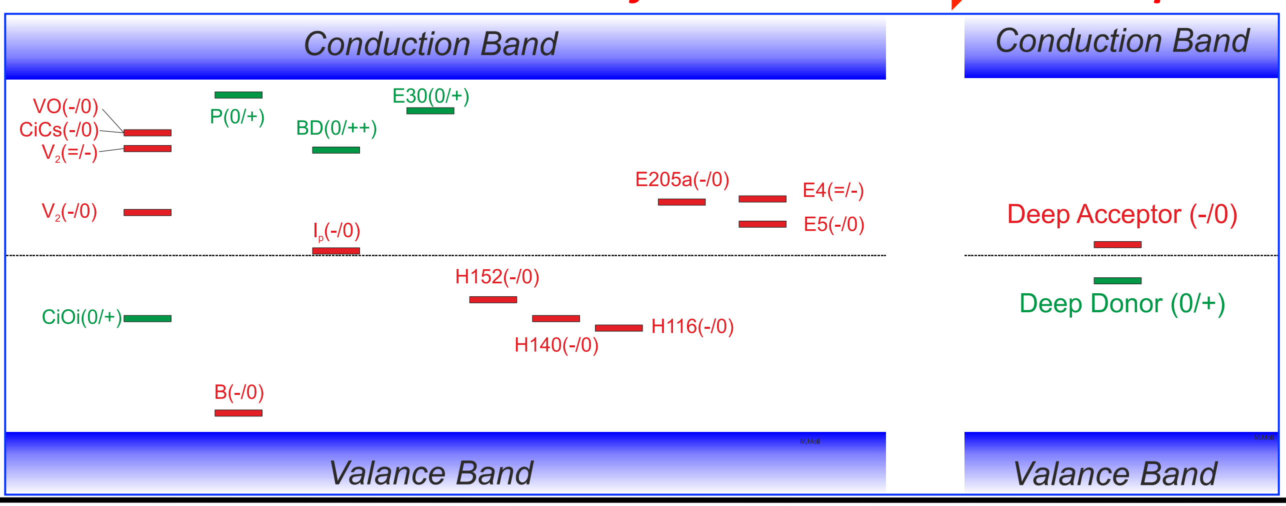
Impact on detector properties can be calculated if all defect parameters are known:

$\sigma_{n,p}$: cross sections **ΔE : ionization energy** **N_t : concentration**

TCAD – Radiation damage models

- Device simulation of irradiated sensors
  - Using: Custom made simulation software and Silvaco & Synopsis TCAD tools
    - Good progress in reproducing results on leakage current, space charge, E-Field, trapping …..
    - Enormous parameter space ranging from semiconductor physics parameters and models over device parameters towards defect parameters ➔ **Tools ready but need for proper input parameters!**
    - **…simulations are getting predictive power.**
- Working with “effective levels” for simulation of irradiated devices
    - Most often 2, 3 or 4 “effective levels” used to simulate detector behavior
    - Introduction rates and cross sections of defects tuned to match experimental data

Measured defects ➔ ***TCAD input***



M. Moll, Simdet 2016

Radiation damage models: history

- Modelling all known defects in silicon in TCAD is (still) computationally prohibitive
  - Plus: how to model defects clusters?
- Hence only a certain number of "effective states" are modelled

a. 1 acceptor-like state (q=-/0)
   - e.g. D. Passeri et al., IEEE TNS 45 (1998) 602-608

b. 2 states, 1 acceptor- and 1 donor-like (q=+/0)
   - e.g. V. Eremin et al., NIM A476 (2002) 556-564, aka EVL

c. 3 states, adding 1 acceptor wrt b., very close to mid-gap, to better control type inversion and leakage current increase rate
   - e.g. M. Petasecca et al., IEEE TNS 53 (2006) 2971-2976

d. 4 states, adding 1 acceptor more (rather unique example)
   - e.g. F. Moscatelli et al., NIM B186 (2002) 171

Radiation damage models for HL-LHC

- "Perugia" model: IEEE TNS 64 (2017) 2259-2267
  - Two acceptors and one donor
    - Interface damage modelled too (2 acc. and 1 don. again)
  - Valid up to 2.2×10^{16} n_{eq}/cm^2
- "3D" model: Pennicard et al., NIM A592 (2008) 16-25
  - Two acceptors and one donor as in Perugia model but larger cross sections wrt Petasecca et al. 2006
    - Used recently in M. Baselga et al. "Simulations of 3D-Si sensors for the innermost layer of the ATLAS pixel upgrade" NIM A847 (2017) 67-76
  - Valid up to 1×10^{16} n_{eq}/cm^2
- "LHCb model": NIM A874 (2017) 94-102
  - Two acceptors and one donor
    - One acceptor and one donor as in EVL plus one acceptor close to the valence band
  - Valid up to 8×10^{15} n_{eq}/cm^2

HPTM

Result of tuning: Hamburg Penta Trap Model (HPTM)

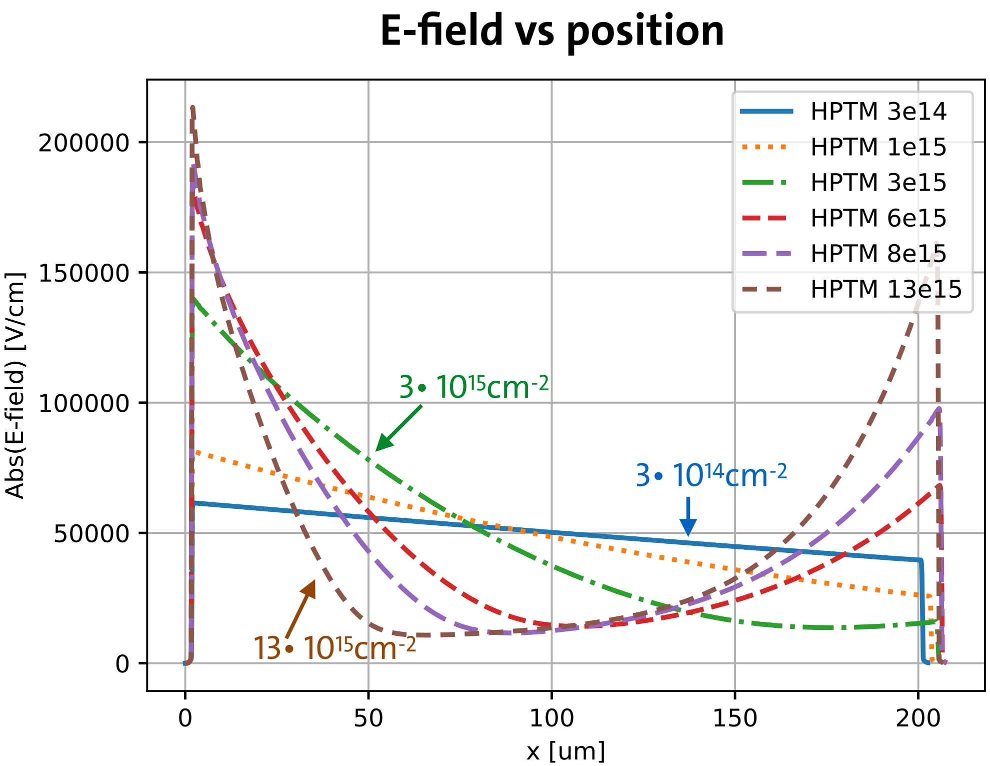
Defect	Type	Energy	g_{int} [cm^{-1}]	σ_e [cm^2]	σ_h [cm^2]
E30K	Donor	E_C-0.1 eV	0.0497	2.300E-14	2.920E-16
V_3	Acceptor	E_C-0.458 eV	0.6447	2.551E-14	1.511E-13
I_p	Acceptor	E_C-0.545 eV	0.4335	4.478E-15	6.709E-15
H220	Donor	E_V+0.48 eV	0.5978	4.166E-15	1.965E-16
C_iO_i	Donor	E_V+0.36 eV	0.3780	3.230E-17	2.036E-14

New!

- Trap concentration of defects: **$N = g_{int} \cdot \Phi_{neq}$**
- Simulations for the optimization have been performed at **T= -20 °C** with:
  1. Slotboom band gap narrowing
  2. Impact ionisation (van Overstaeten-de Man)
  3. TAT Hurkx with tunnel mass = **0.25 m_e** (default value: 0.5 m_e) in case of the I_p
  4. Relative permittivity of silicon = 11.9 (default value : 11.9)
- Both cross section for the E30K and the electron cross section for the C_iO_i were fixed
  ➔ 12 free parameter
- Optimization done with the nonlinear simplex method

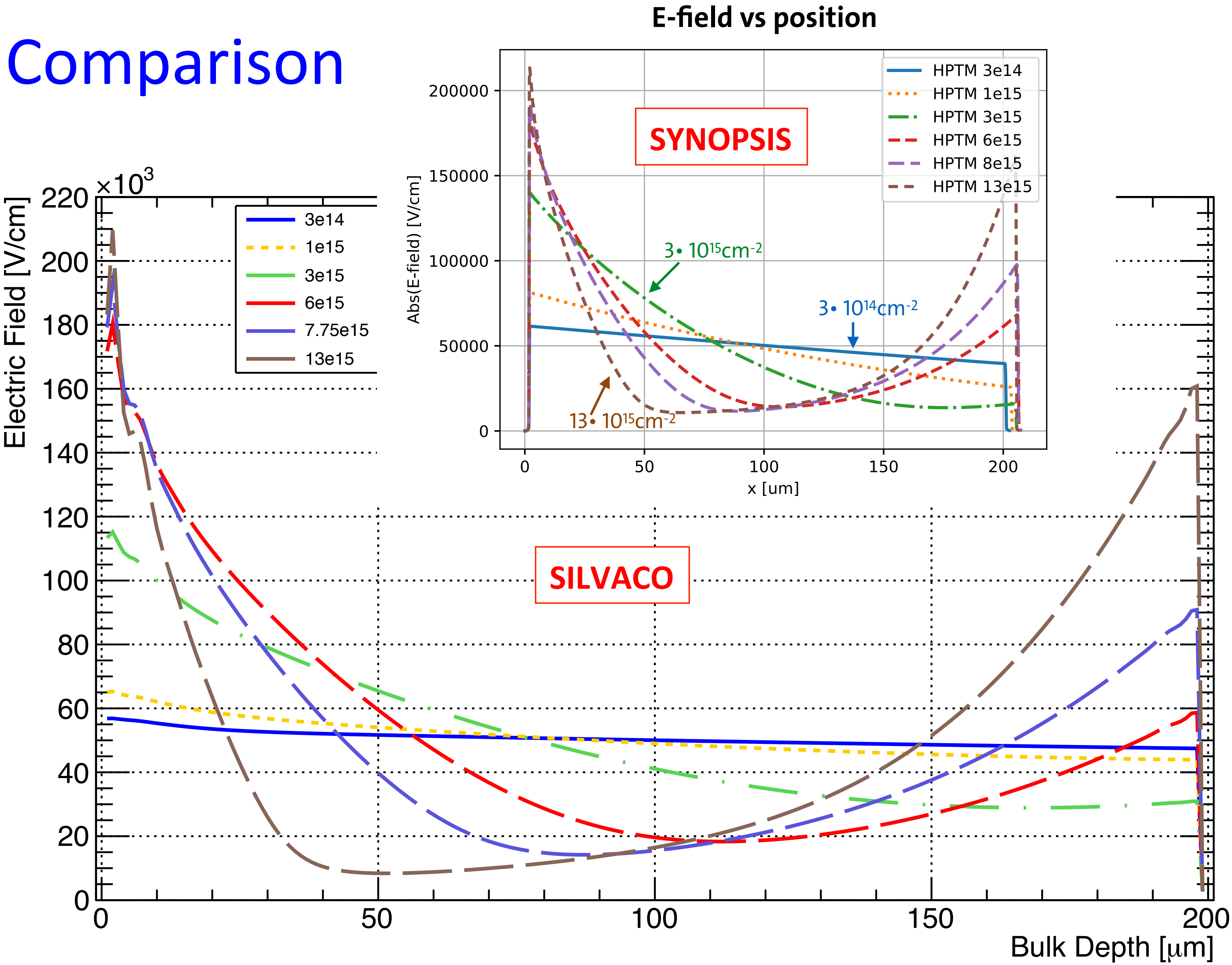
E-FIELDS FOR DIFFERENT FLUENCES

Simulated E-field as function of position for different fluences at 1000V



- Double peak structure for fluences $\geq 3 \cdot 10^{15}\, n_{eq}/cm^2$ clearly visible
- Peak field of $\approx 2 \cdot 10^5$ V/cm at the highest fluence ➔ impact ionisation

Comparison



E-field vs position
SYNOPSIS
Abs(E-field) [V/cm]
x [um]
HPTM 3e14
HPTM 1e15
HPTM 3e15
HPTM 6e15
HPTM 8e15
HPTM 13e15
3• 10¹⁵cm⁻²
3• 10¹⁴cm⁻²
13• 10¹⁵cm⁻²
SILVACO
Electric Field [V/cm]
×10³
Bulk Depth [μm]
3e14
1e15
3e15
6e15
7.75e15
13e15

Compatibility across TCAD softwares

- Most used TCAD tools in HEP are:
  - Silvaco ATLAS
  - Synospys SENTAURUS
- And that the two do not agree on some fundamental aspects ☺
  - AIDA 2020 WP7 meeting (Paris, 2/2016): https://indico.cern.ch/event/477003/contributions/1155199/attachments/1234150/1811069/bomben_comparison_160225.pdf
  - 28th RD50 WS (Torino, 6/2016): https://agenda.infn.it/getFile.py/access?contribId=3&sessionId=1&resId=0&materialId=slides&confId=11109
  - 31st RD50 WS (Geneva, 11/2017): https://indico.cern.ch/event/663851/contributions/2788159/attachments/1562199/2460062/bomben_silvaco_simulations.pdf
- **Cross-validation of radiation damage models is mandatory!**

FROM TCAD TO MONTE CARLO SIMULATIONS

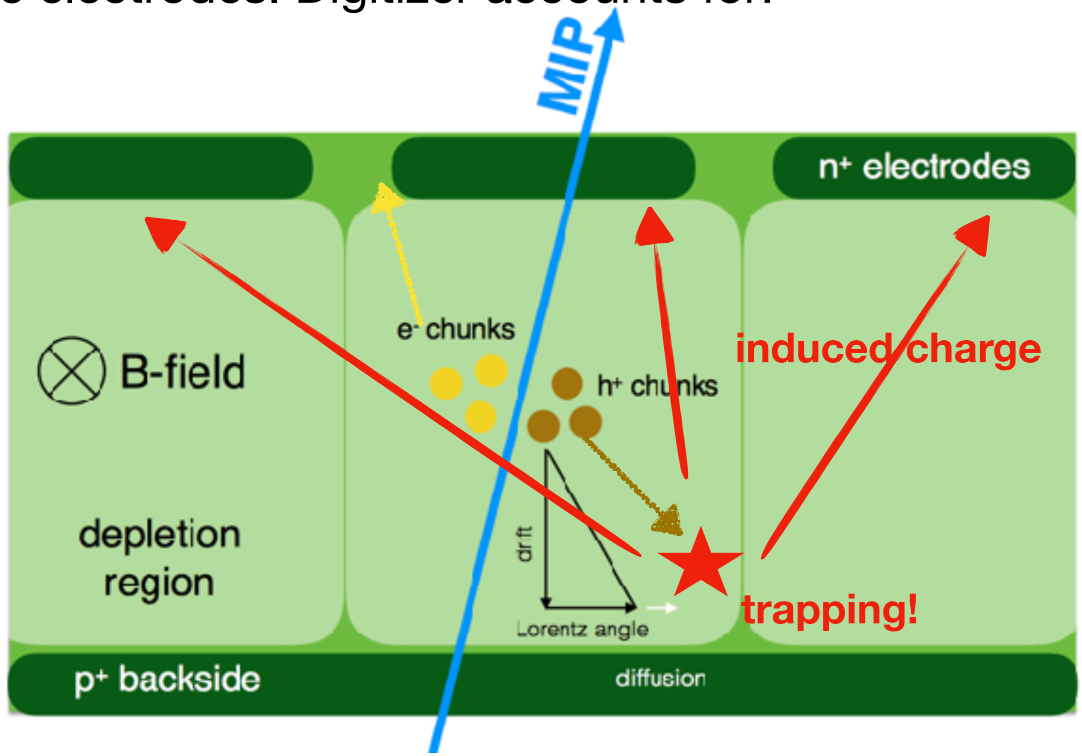
ATLAS Pixel Detector Digitizer

https://indico.cern.ch/event/666427/contributions/2881831/attachments/1603791/2543967/TrentoWorkshop_slides_RadDamDig_wl.pdf

Develop digitizer that model inside effects of radiation damage

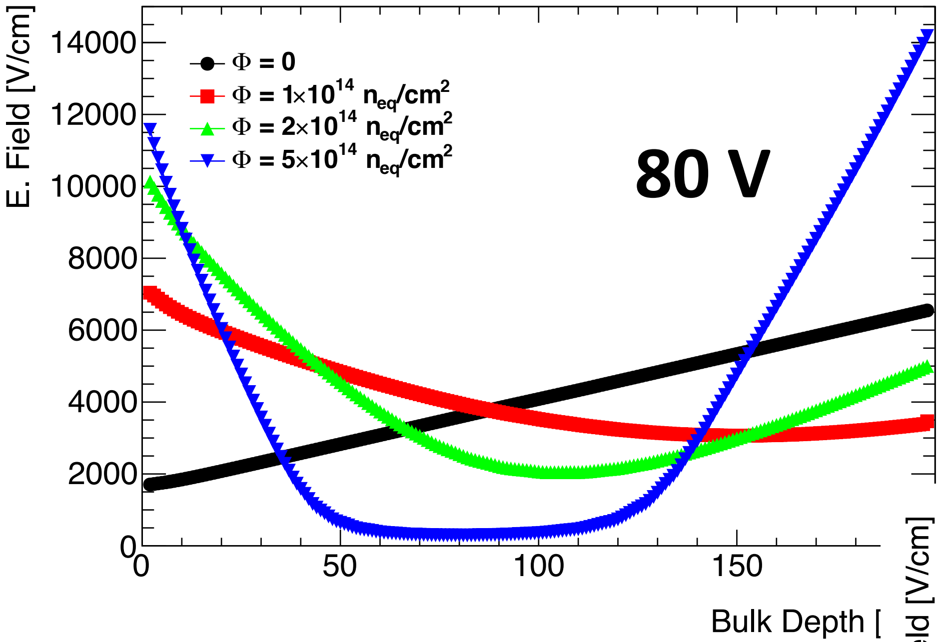
"Chunks" of charges are drifted to the electrodes. Digitizer accounts for:

- Charges drift
- E/B Field effects
- Lorentz Angle (function of E/B fields and distance in the detector)
- Trapping probability
- Ramo potential to account for induced charge
- Charge conversion to ToT
- Pixel clustered

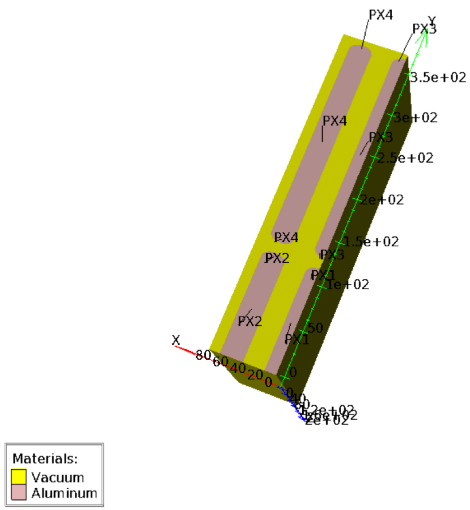


Lorenzo Rossini - INFN and Università di Milano - Trento Workshop

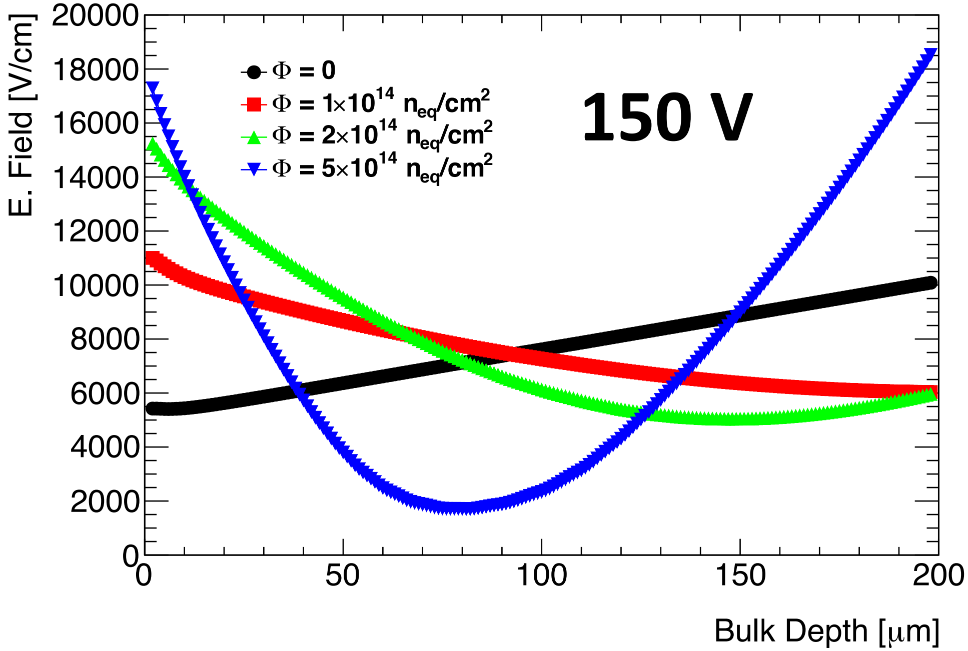
Electric field - Chiochia model



TCAD simulation based electric field



Ramo potential from TCAD too



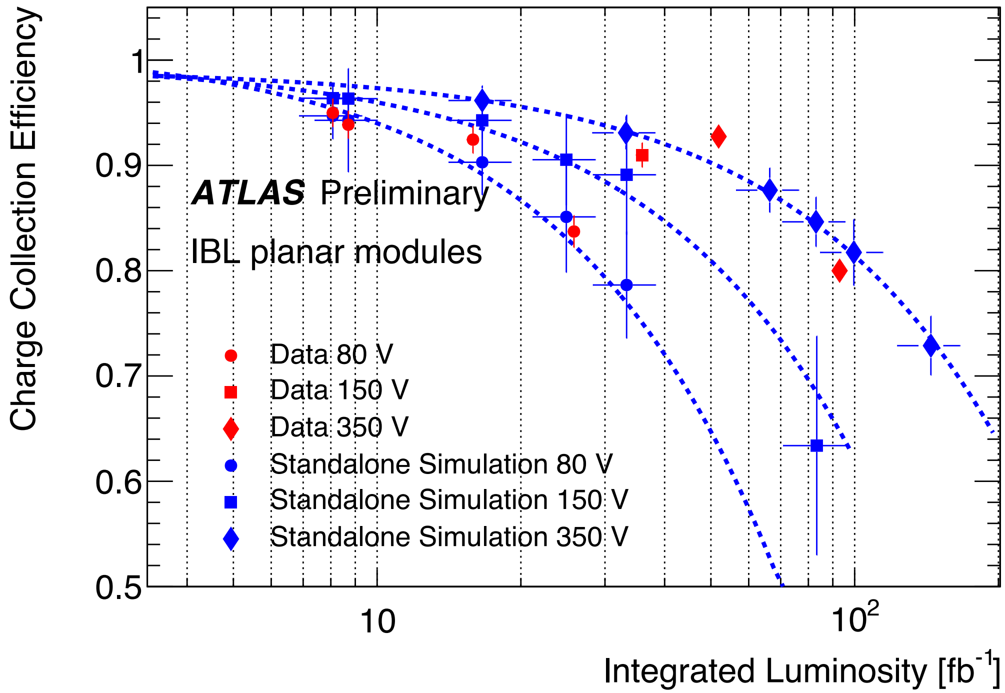
Model prediction and data comparison

https://indico.cern.ch/event/666427/contributions/2881831/attachments/1603791/2543967/TrentoWorkshop_slides_RadDamDig_wl.pdf

Charge Collection Efficiency as a function of Luminosity for IBL with data from Run 2

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2017-004/

- Simulation points error bars
  - x: 15 % on fluence-to-luminosity conversion
  - y: radiation damage parameter variations
- Data points error bars
  - x: ToT-charge calibration drift
  - y: 2% on luminosity



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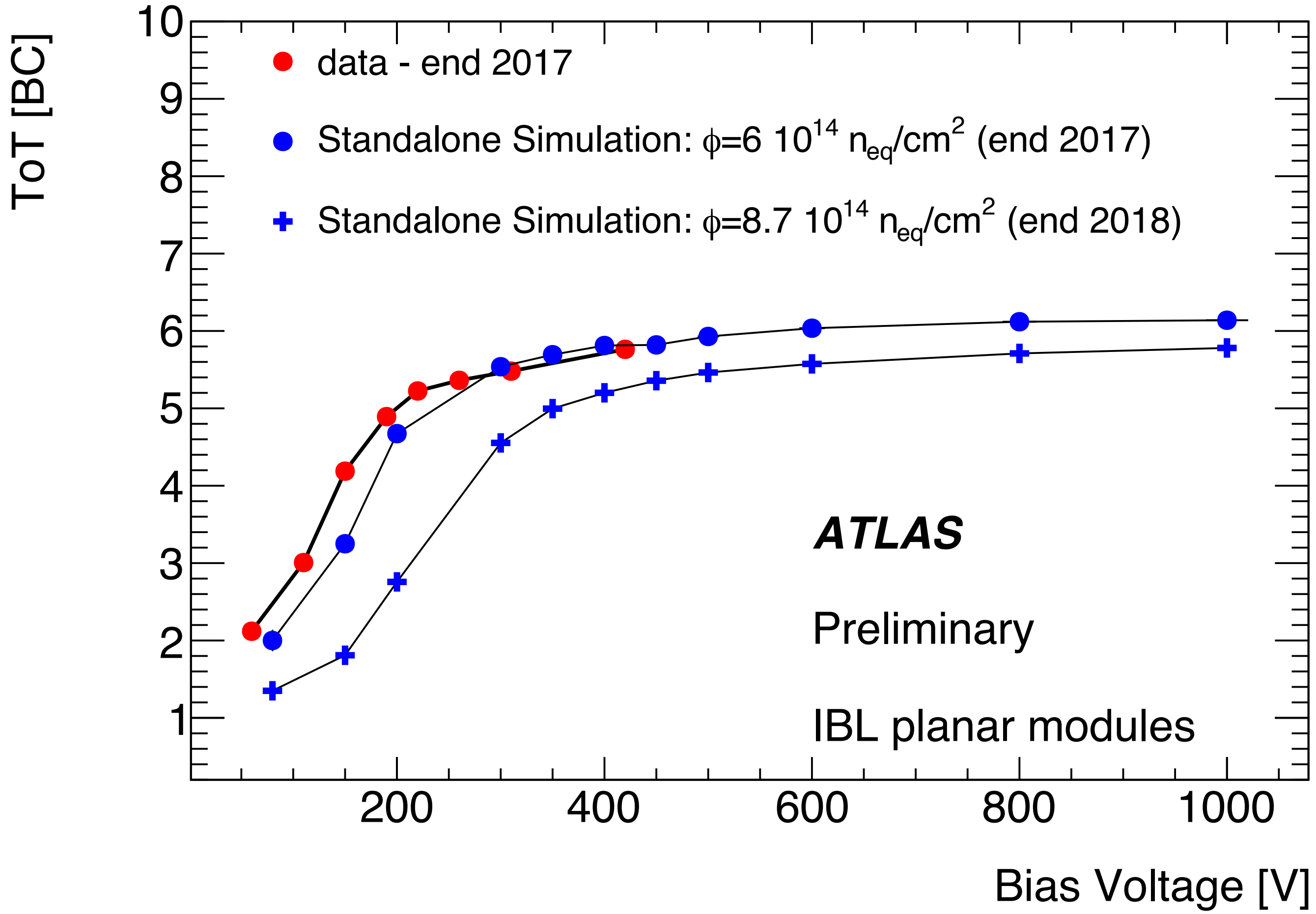
Model prediction and data comparison

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2017-004/



1D VS 2D VS 3D VS 4D SIMULATIONS

1D vs 2D simulations

1D simulations are OK for:

- Leakage current density
- Electrode to backside capacitance
- Charge collection efficiency
  - For pads
  - For strip detectors at low fluences

2D simulations are OK for:

- Interstrips capacitance
- Charge collection efficiency
  - For strip detectors
  - For pixels detectors at low fluences

2D vs 3D simulations

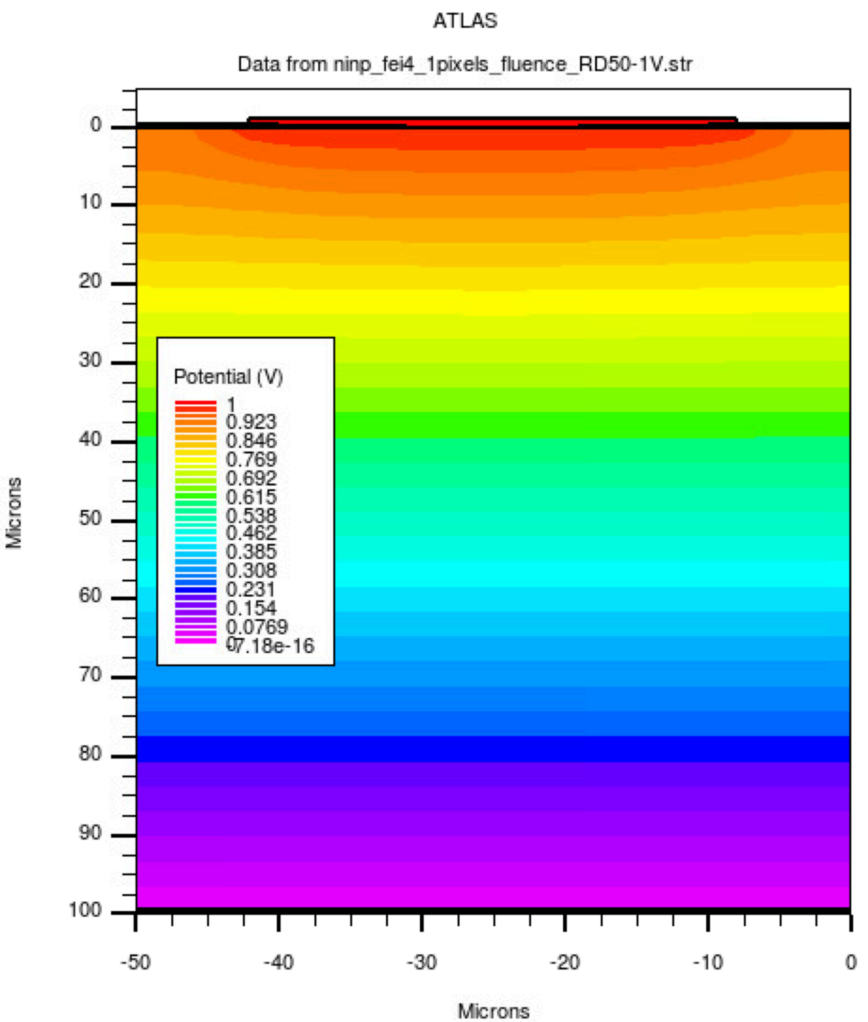
2D simulations are OK for:

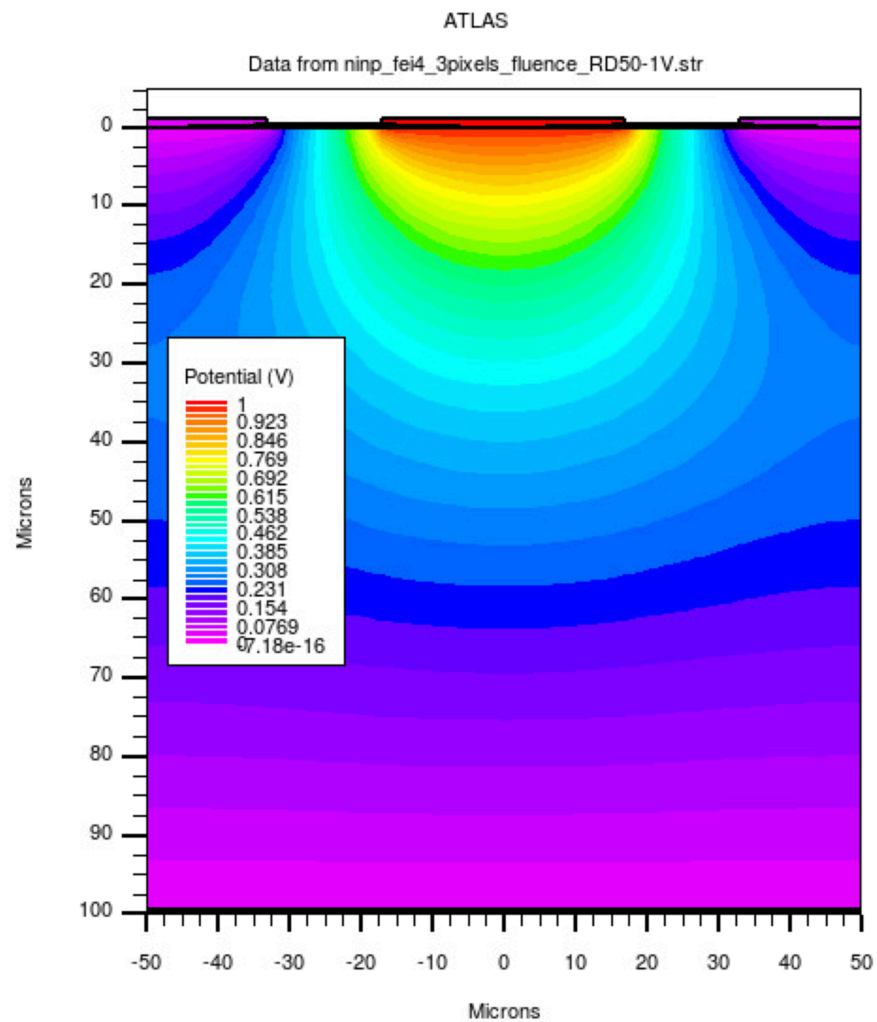
- Interstrips capacitance
- Charge collection efficiency
  - For strip detectors
  - For pixels detectors at low fluences

3D simulations are perfect for:

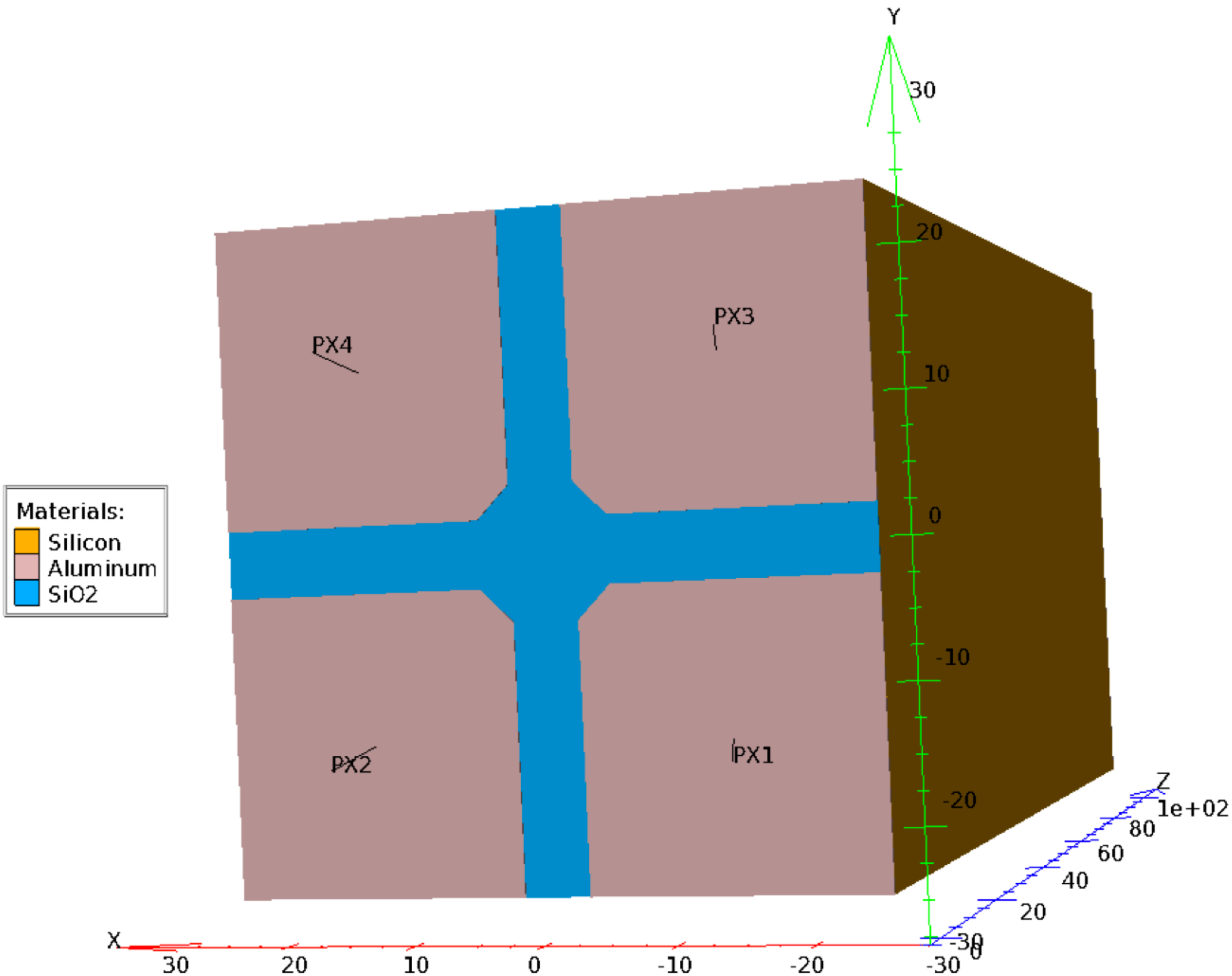
- Interpixels capacitance
- Charge collection efficiency
  - For pixel detectors

Ramo Potential: 1D vs 2D

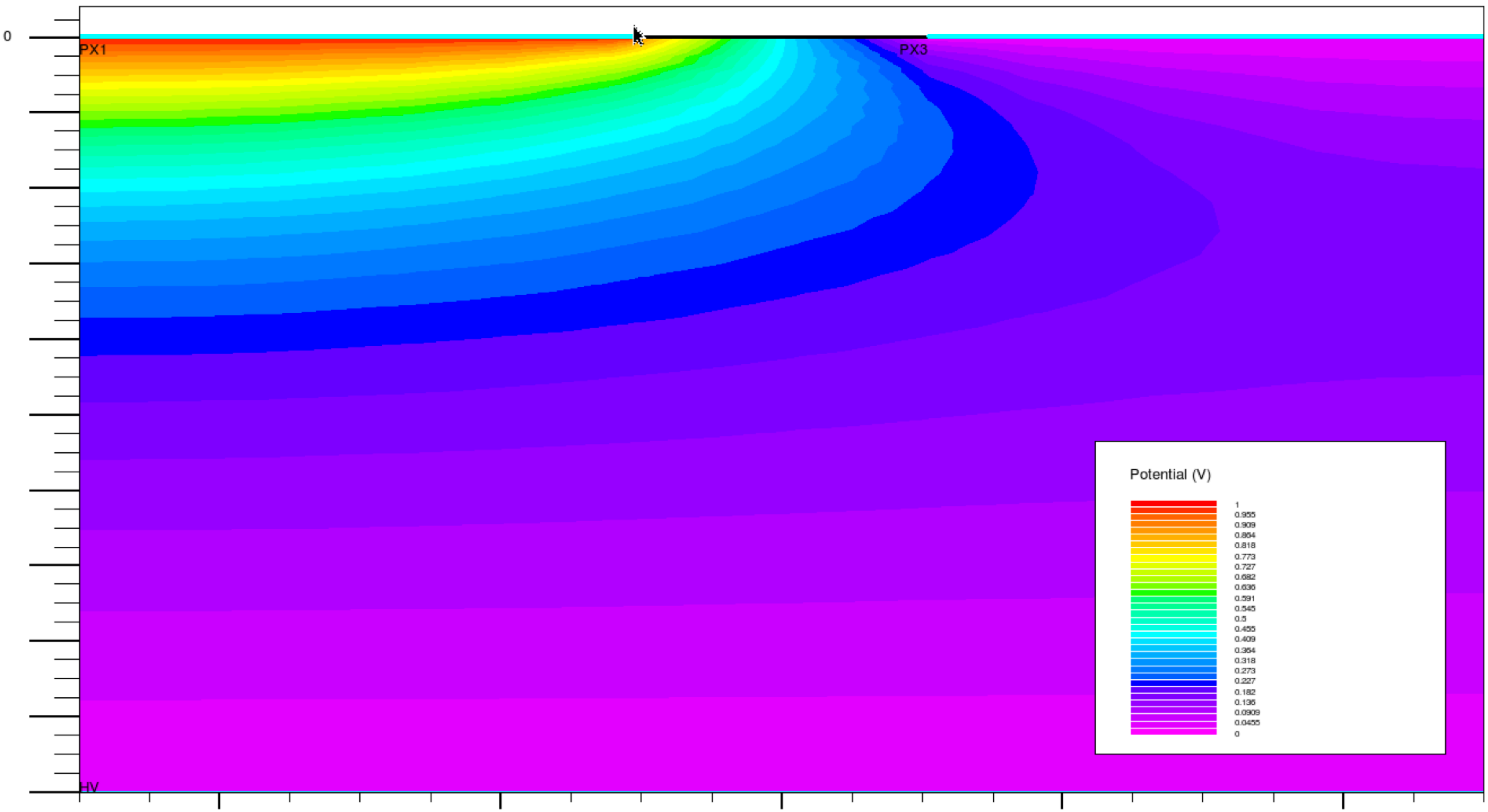




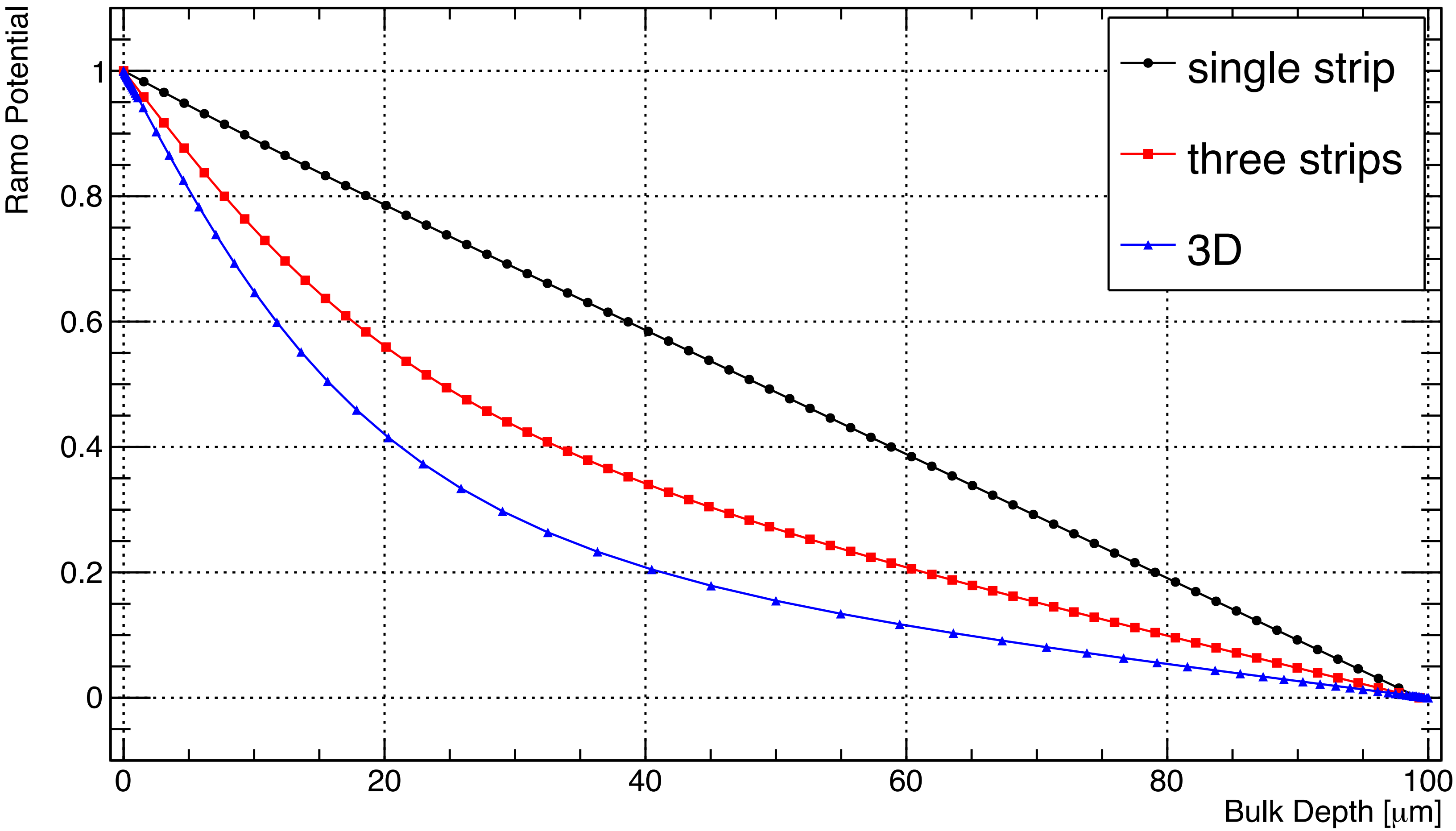
3D 50x50 μm^2 structure



Ramo Potential: 3D

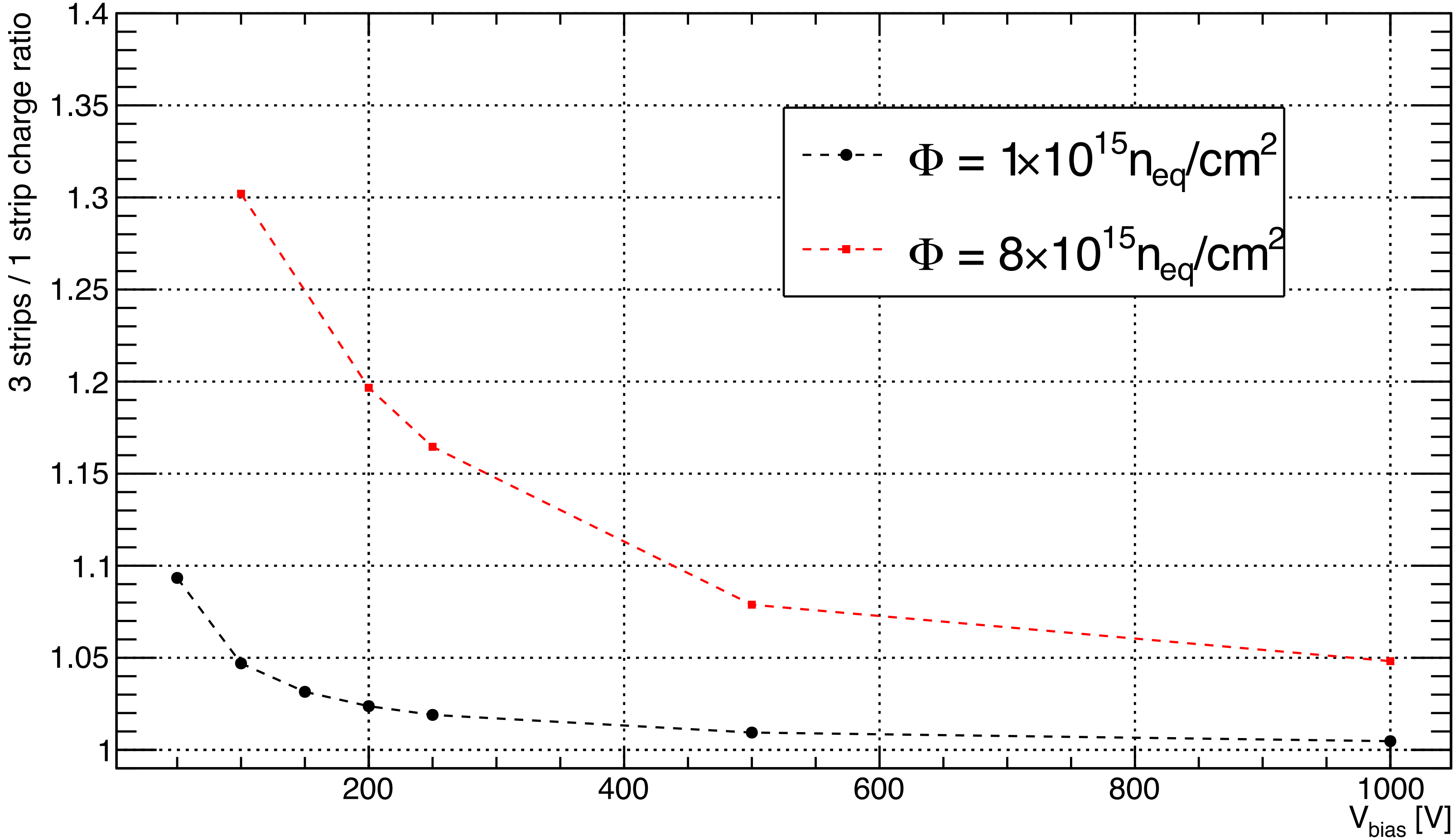


Ramo potential: comparison



Charge Collection Efficiency: comparison

Perugia model, Q(3 strips sim.)/Q(single strip)



4D simulations?

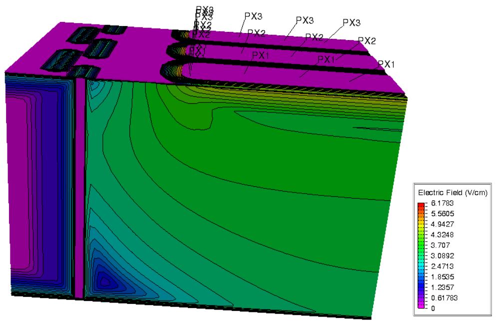
- Time dependent simulations of segmented Low Gain Avalanche Diodes (LGADs)...

- Computational complexity might be prohibitive, though

CONCLUSIONS AND OUTLOOK

Conclusions

- TCAD is a very powerful tool for HEP silicon sensors
- You can reduce the number of submission, and so cutting time and money to get results
- Combining TCAD simulations, laboratory and testbeam data can probe fundamental quantities like electric field distribution, trapping, etc. and have radiation damage models based simulation making quantitative predictions
- A solid knowledge of semiconductor physics,and good data inputs are recommended to fully exploit TCAD simulations
- If you are interested in working with TCAD simulations, feel free to contact me: marco.bomben@cern.ch



Outlook

- To understand the performance of heavily irradiated segmented detectors the combination of:
  - TCT data and/or data from a grazing angle runs at testbeams
  - Simulation of both bulk and surface damage is needed
  - Validation of models across different TCAD softwares

- Larger and larger fluences demand for new parameterisation of fundamental silicon properties (*e.g.* mobilities)
  - The new parameterisation can be added to TCAD simulation and quantitative predictions made

- Charge multiplication is exploited successfully in LGADs but the impact of radiation damage has to be understood
  - A lot of simulation work is ongoing

https://indico.in2p3.fr/e/simdet2018

SIMDET 2018

3rd school on silicon detectors simulation

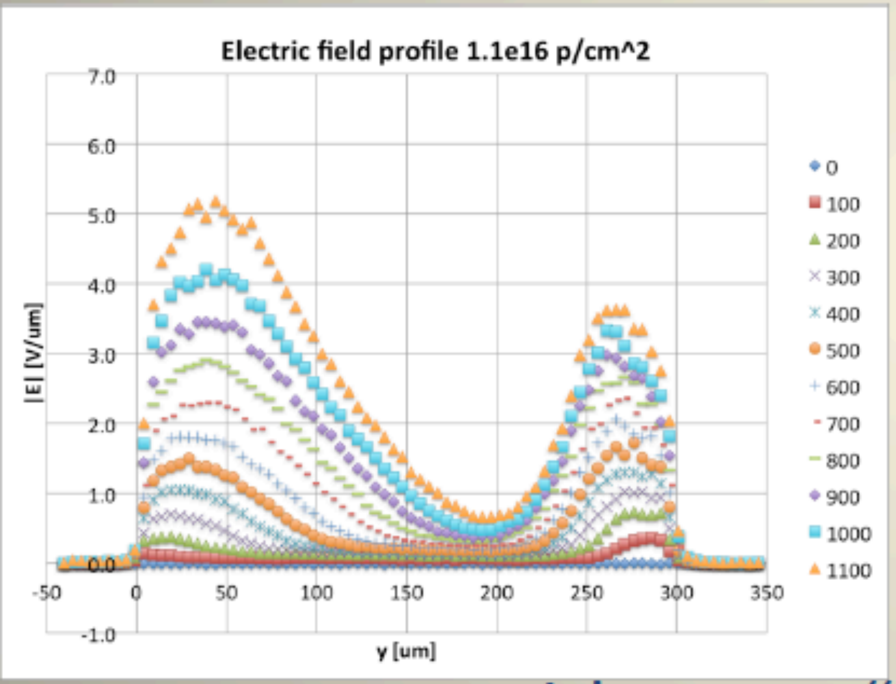
THANK YOU!

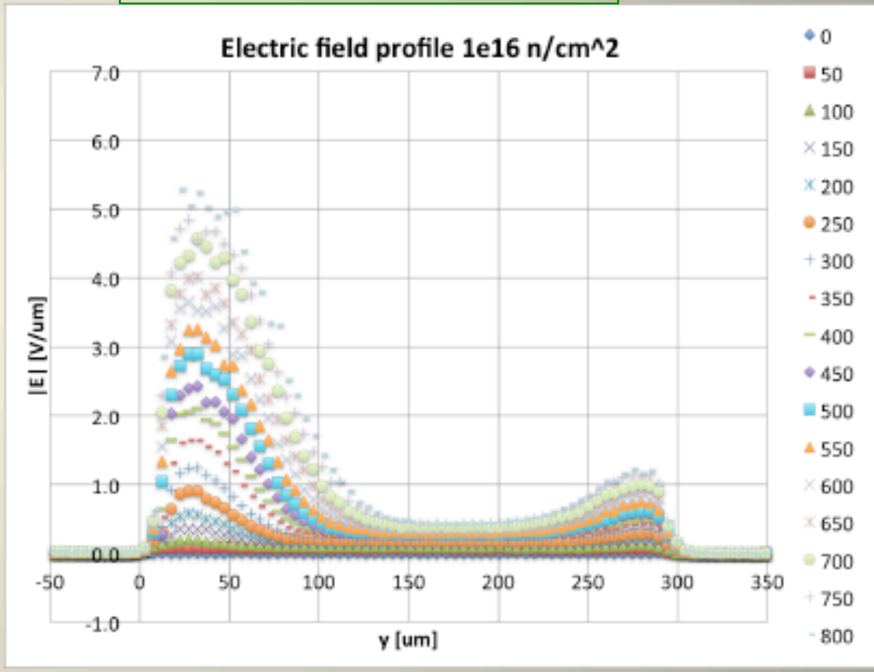
BACKUP MATERIAL

Protons <-> Neutrons ~10^{16}

- Field profiles compared

See also G. Kramberger 2014 JINST 9 P10016

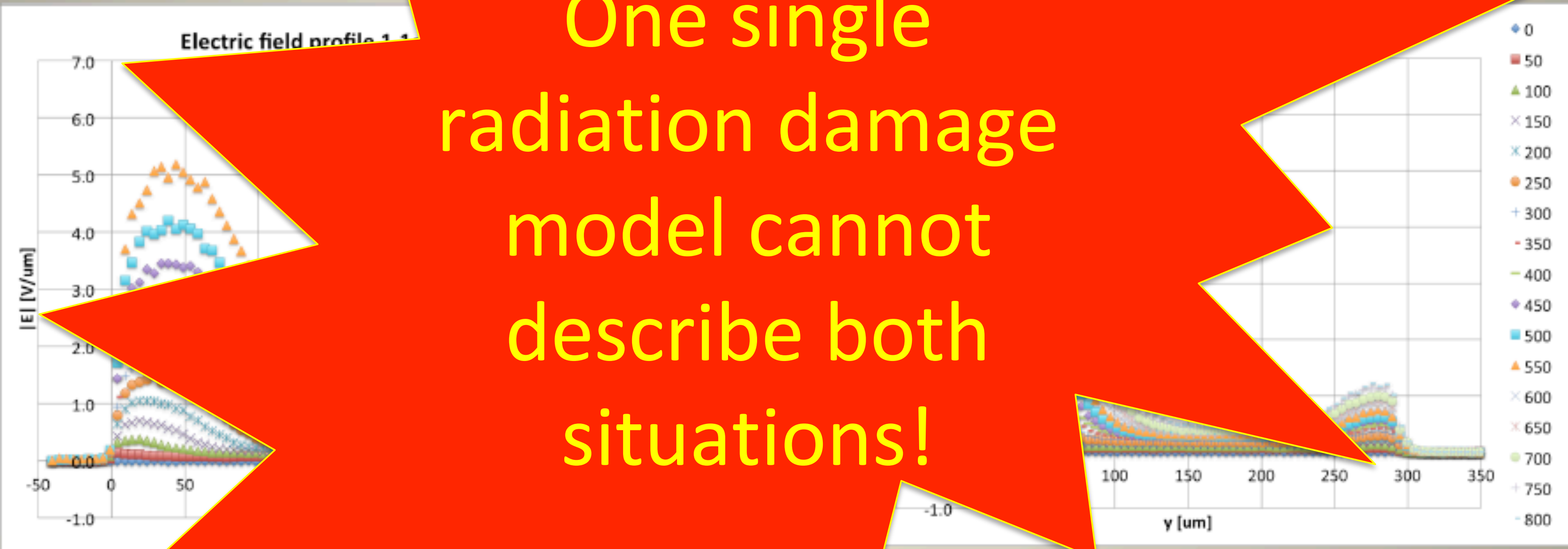




- Protons with more "double junction", flatter field, less peaked at junction

Protons <-> Neutr… ~10^{16}

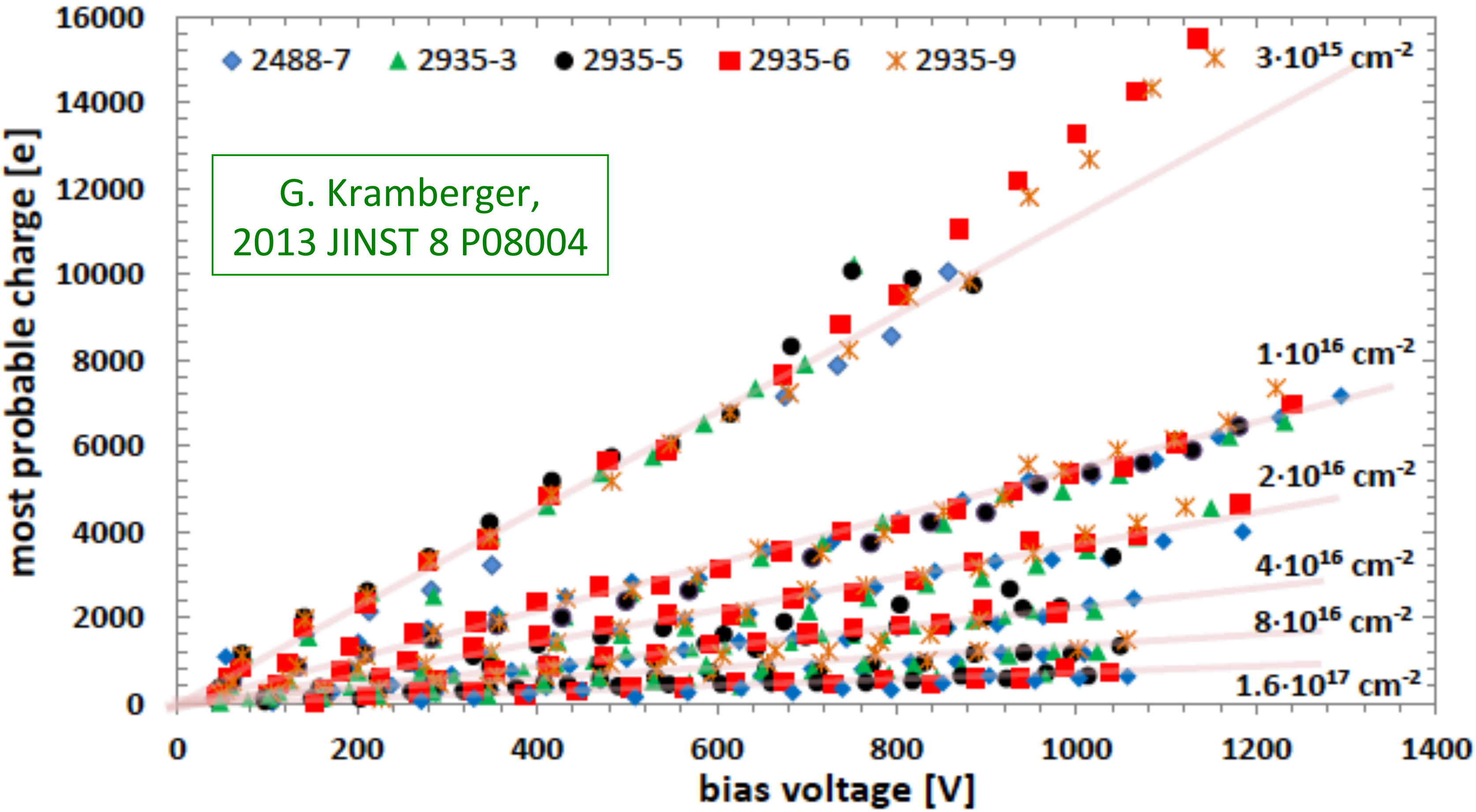
- Field pro… m…



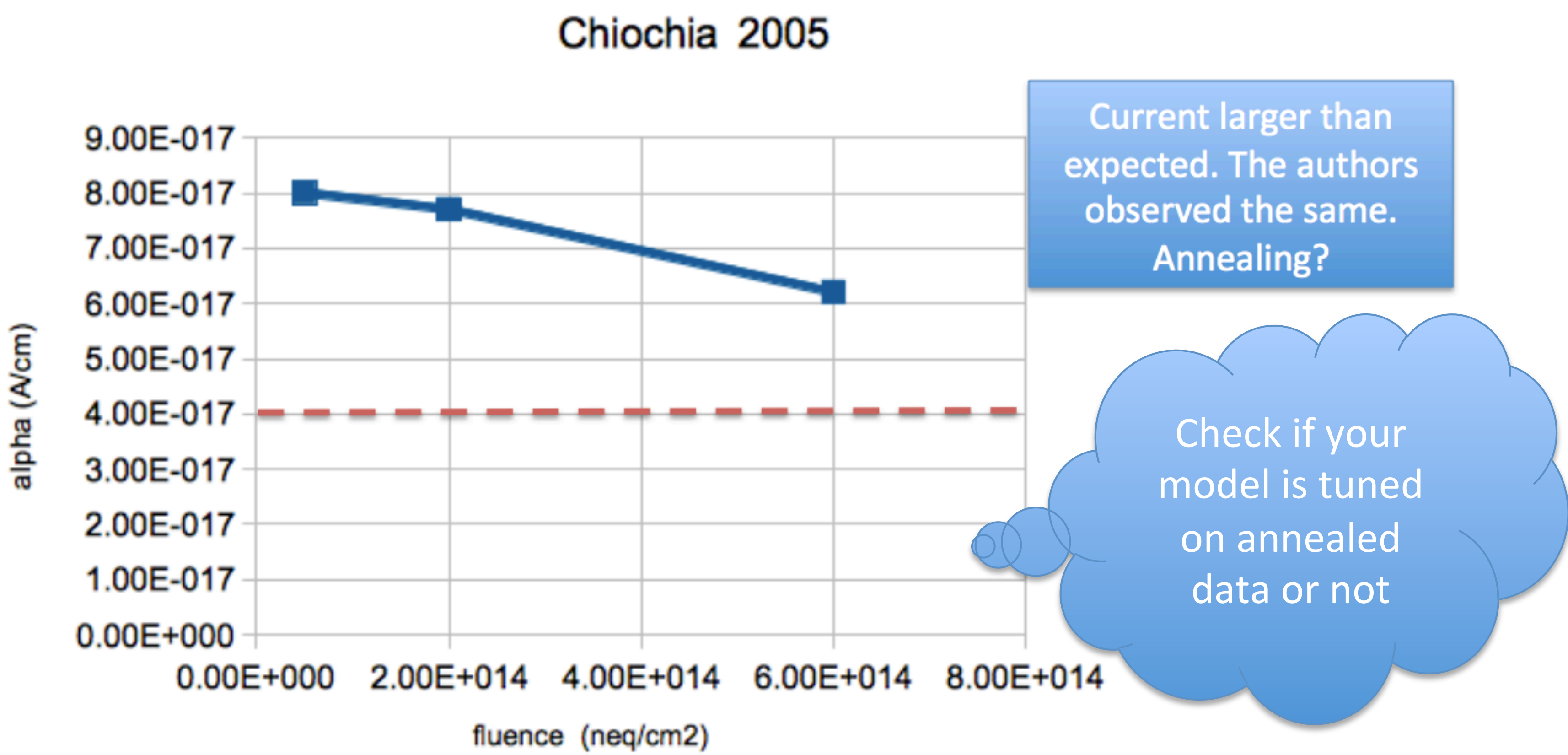
One single radiation damage model cannot describe both situations!

- … do…le junction", flatter field, les… ake… at junction

Collected charge at ultra high fluences



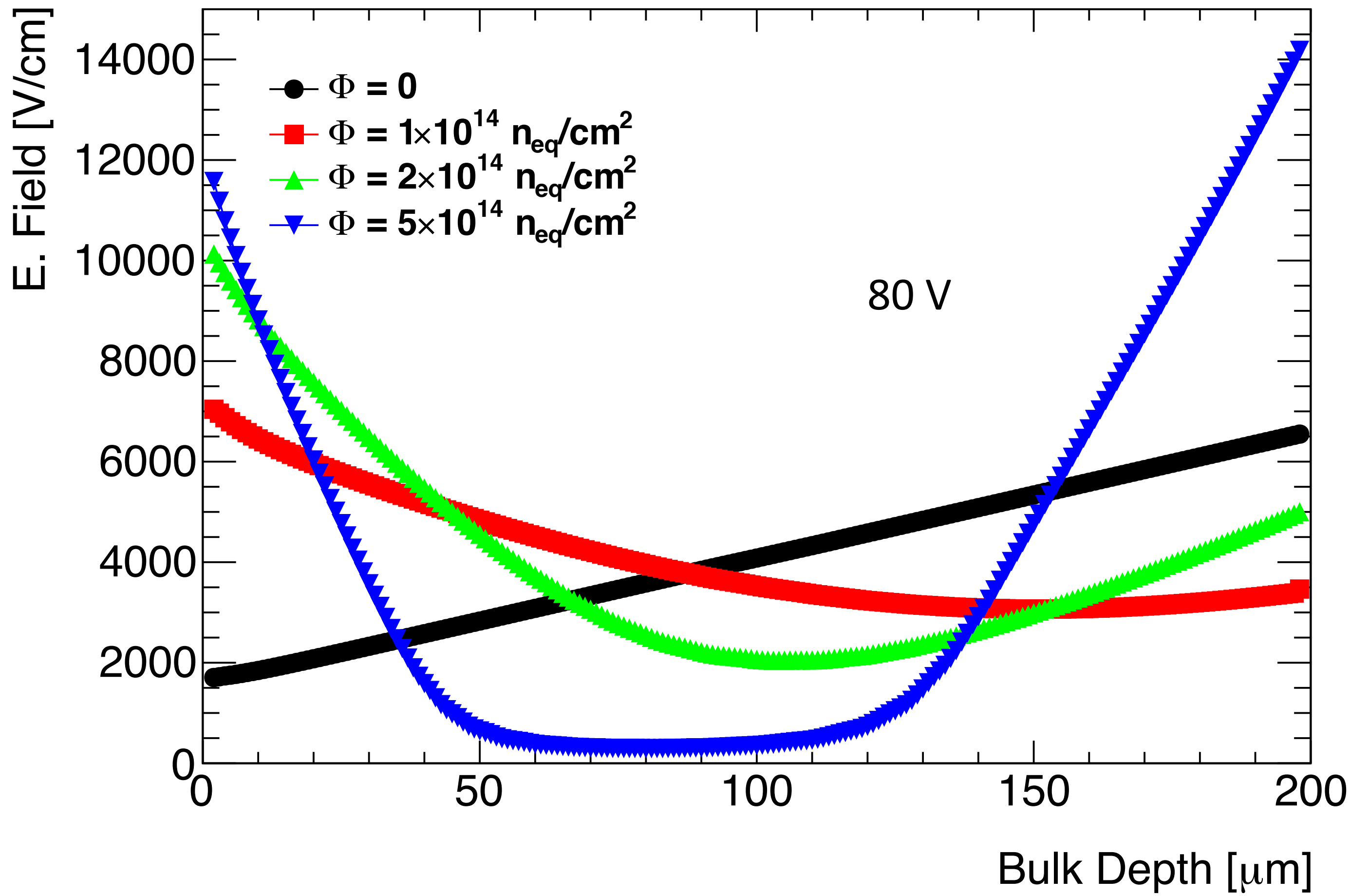
How to model annealing?



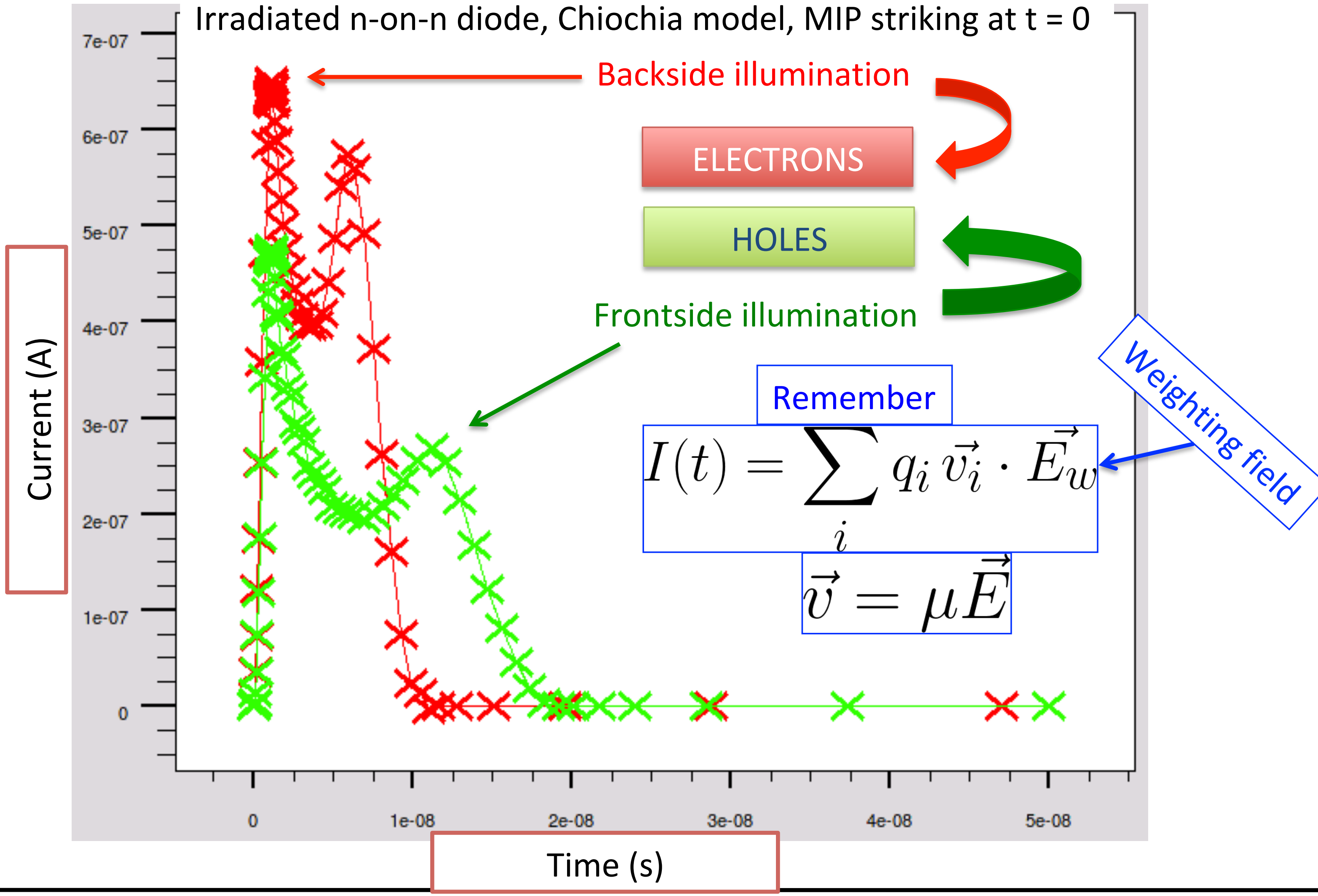
Remember that Perugia and New Delhi model predict α at the maximum of beneficial annealing

TIME DEPENDENT SIMULATIONS

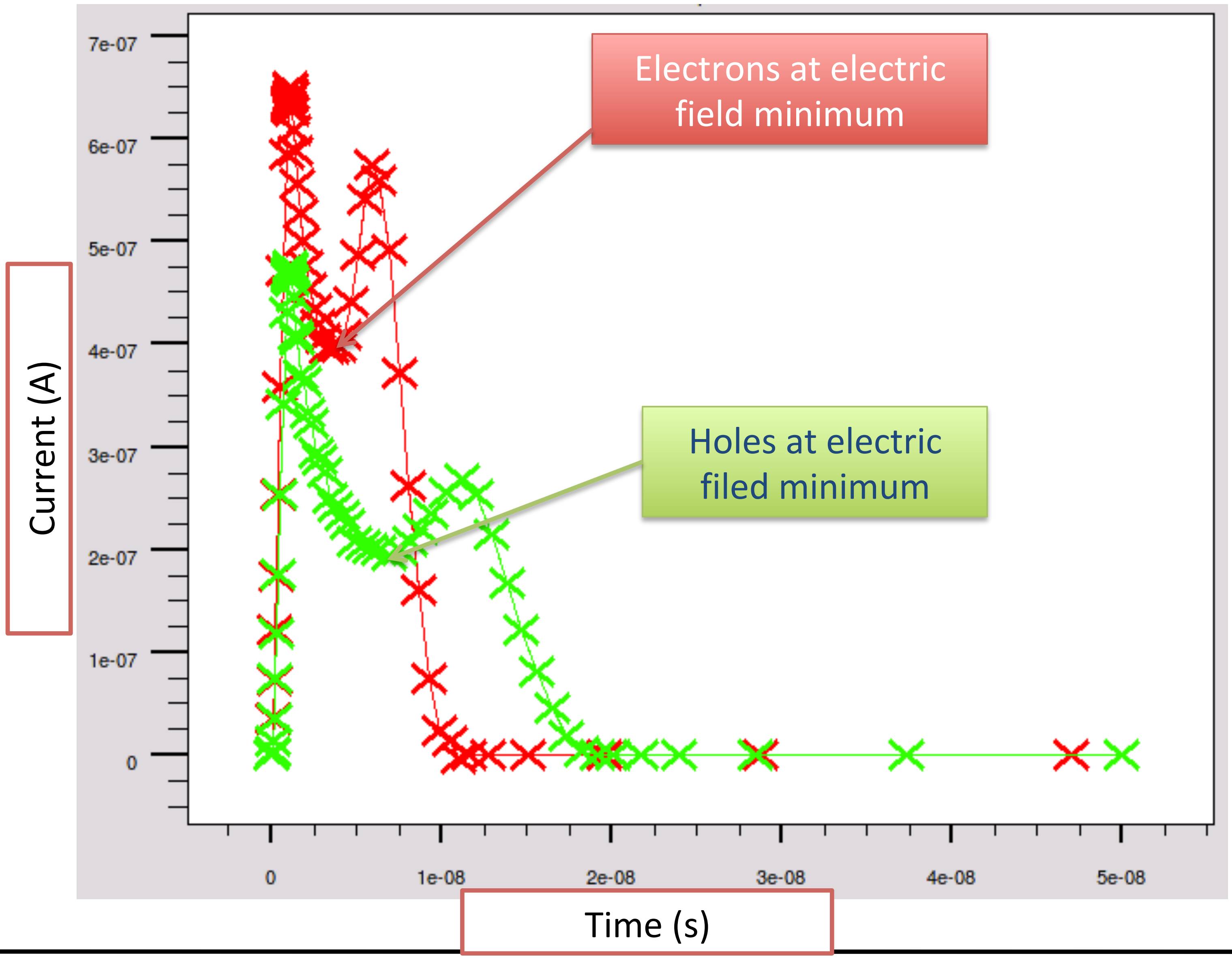
Chiochia model



Instantaneous current (Φ=1x10^{14} /cm^2)



Instantaneous current (Φ=1x10^{14} /cm^2)



Instantaneous current (Φ=1x10^{14} /cm^2)